Evaluation of harmonic generating properties of schottky barrier diodes

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EVALUATION OF HARMONIC GENERATING PROPERTIES OF SCHOTTKY BARRIER DIODES

by

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ABSTRACT

Low noise figure communication receivers require more efficient frequency converters. Frequency conversion and multiplication processes cannot take place without the existence of harmonic sources in the system and the inherent property of a nonlinear element is to generate harmonics. Such nonlinearity, in general, may be provided by semiconductor diodes. This research project deals with the theoretical analysis as well as the experimental verifications of the harmonic generating properties of a nonlinear resistive device, i.e. Schottky-barrier diode.

Laboratory measurements associated with the equivalent circuit representation of hot-carrier diodes show that their i-v characteristics can be accurately described by the modified exponential law, $i = I_s\left[\exp\alpha\,(V - iR_T) - 1\right]$, over a wide range of the applied voltage V. Using this equation, a procedure is developed for the harmonic analysis of the resistive diode and calculation of any of a finite number of harmonic currents having a single frequency sinusoidal voltage $\hat{V}_p \cos\omega_p t$ as the drive. The amplitudes of the harmonic currents are expressed as a power series in $\alpha R_T I_s \exp(\alpha R_T I_s)$, where the coefficients of the power series are represented through the modified Bessel function of the K^{th} kind of order n. The integers K and n represent the power of the series and the harmonic number respectively, e.g. $i_n \propto I_n(K\alpha V_p)\left[\alpha R_T I_s \exp(\alpha R_T I_s)\right]^K$.

The power series solutions for the exponential diodes do not normally converge quickly enough to be of practical value for numerical evaluations. A different approach is proposed which is suitable for numerical evaluations of harmonic amplitudes. The results are compared with experimental data on twelve diodes, four in each of the three groups of different types. A good agreement, within the measuring instruments tolerances, was found between the calculated and the experimental results.

Finally, it is believed that such studies were justified as the new method of approach presented here evaluates fully the capabilities of these diodes in practice. Many analyses published over the years have tended to introduce severe approximations which were only valid in practice over limited ranges of operation. In this project, attempts were made over almost two years to obtain mathematical solutions for the exponential diode law which are useful in practice and which give accurate prediction of harmonic amplitudes and spectrum. Various methods were employed to achieve the necessary convergence of the infinite series solutions. This involved a good understanding of the mathematical methods employed and computer programming. During the same period at every stage experimental verifications were being attempted, many times unsuccessfully, which finally led to a good agreement between the theory and experimental results as shown in this thesis.

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CONTENTS

APPENDICES

A1 Calculated Data for Figure 5.2 for Different Values of x.

A2 Theoretical Data for Figures 6.9 - 6.20: Diodes A1, A2, A3, A4, B1, B2, B3, B4, C1, C2, C3 and C4

A3 Experimental Data for Figures 6.9 - 6.20: Diodes A1, A2, A3, A4, B1, B2, B3, B4, C1, C2, C3 and C4

A4 Calculated Data for Figures 6.21 - 6.23: Diodes A4, B3 and C2

A5 Comparison Between Calculated and Measured DC Characteristics for Diodes A4, B3 and C2

LIST OF ILLUSTRATIONS

LIST OF SYMBOLS

E or E(t)	=	e.m.f. of signal source
V	=	voltage in general with the subscript f for forward
i	=	current in general with the subscript f for forward
q or Q	=	charge in general
ϕ	=	flux linkage in general
R	=	resistance and the subscript S for source resistance and the subscript L for load resistance and the subscript T for total
C	=	capacitance and the subscript p for package capacitance and the subscript j for junction
L	=	inductance and the subscript S for series
r_s	=	substrate series resistance; spreading resistance
R_T	=	$r_s + R_S + R_L$
b_n or $\hat{i}_n$	=	coefficient of n^{th} order term in the Fourier expansion
a_n or a'_n	=	coefficient of the n^{th} power term in power series expansion
W(o,t)	=	energy flow during the time interval zero to t
P(t)	=	power in general or energy per unit time
P_{av}	=	average power measured over the periodic interval T or $= \frac{W(o,T)}{T}$
m,n	=	positive or negative integers or zero
W_c	=	energy at the bottom of the conduction band
W_f	=	energy at the Fermi level
W_v	=	energy at the top of the valence band
ψ_m	=	thermionic work function of metal
ψ_s	=	thermionic work function of semiconductor

χ = electron affinity; e.g. energy required to remove an electron from the bottom of the conduction band and place it in free space

δ = the gap distance between metal and semiconductor caused by surface states

Δ ≑ $\psi_m - \psi_s$ potential difference across the gap δ between metal and semiconductor due to surface states

ψ_{ms} = $\psi_m - \chi - \Delta$ metal-semiconductor barrier height

ψ'_{ns} = the difference between W_c and W_f at the surface of an isolated n-type semiconductor with net negative surface charge.

ψ'_n = the difference between W_c and W_f at the surface of an isolated semiconductor without surface charge.

ϕ' = band bending potential due to surface states

W_o = width of the depletion layer at zero bias

W = width of the depletion layer at forward bias

N_d = donor density

e = electron charge = 1.6×10^{-19} Coulomb

ε = the permittivity of the semiconductor crystal

α = $\frac{e}{nKT} = 40\ V^{-1}$ for an ideal diode

n = diode ideality factor = $\frac{40}{\alpha \text{ (practical)}}$

I_s = saturation current

T = temperature in degree Kelvin (^oK)

K = Boltzman's constant = 1.38×10^{-23} (joul/^oK)

f_{cf} = cut-off frequency if $\frac{1}{\omega C_{jf}} = R_{sf}$

ω	=	frequency in Rad/sec, and the subscript p is used to indicate pump frequency in Rad/sec, and the subscript s is used to indicate signal
$R_c(t)$	=	chord resistance
$R_i(t)$	=	incremental resistance
$G_c(t)$	=	chord conductance
$G_i(t)$	=	incremental conductance
$\left(r_c\right)_n, \left(r_i\right)_n, \left(g_c\right)_n, \left(g_i\right)_n$	=	coefficients of n^{th} order term in the Fourier expansion of $R_c(t)$, $R_i(t)$, $G_c(t)$ and $G_i(t)$ respectively
x	=	$\alpha R_T I_s$
$f^{(m)}(0)$	=	the m^{th} derivative of the exponential $i = I_s\left[e^{\alpha V - \alpha R_T i} - 1\right]$ w.r.t. V evaluated about $V = 0$
$A(x)$	=	$f^{(m)}(0)/\alpha^m I_s$
S_n^m	=	Stirling number of the second kind
${}^mC_K$	=	$\binom{m}{K} = \dfrac{m(m-1)(m-2)\ldots(m-K+1)}{K!}$
$z(\omega_p t)$	=	$\alpha V \cos \omega_p t + \ln x + x$
$I_n(K\alpha V)$	=	modified Bessel function of the K^{th} kind of order n
$z(\omega_p t)$	=	$X(\omega_p t) + e^{X(\omega_p t)}$

CHAPTER 1

INTRODUCTION

Since the classic paper by Shockley in 1949, semiconductor diodes have undergone intensive investigations and evaluations of their electrical properties. Because of the nonlinear characteristics they have found numerous applications in harmonic generating and frequency-converting circuits, i.e. multipliers, dividers, mixers etc. Many analyses of semiconductor diodes as nonlinear elements, published over the years, have tended to introduce severe approximations which were only valid in practice over limited ranges of operation. The reasons for approximations were mainly due to mathematical difficulties encountered when attempts to obtain elegant and simple closed-form solutions were sought. As a result, although particular problems were apparently resolved, the understanding of the fundamental generating mechanisms of the devices was often lost due to nonrigorous methods of approach.

In general, most of the semiconductor diodes are positive, non-linear resistors (varistors) whose I-V characteristics usually satisfy exponential laws. In a.c. applications the most important parameters of a semiconductor diode are the incremental quantities. It is essential to harmonic generation processes that at least one of the incremental parameters behaves in a nonlinear manner. It is also apparent that no frequency conversion can take place unless the initial harmonic spectrum is produced. The incremental parameters are functions of the applied a.c. voltages and currents and thus are indirectly time-dependent. Once the harmonic spectrum has been established by the high level applied current or voltage, known as the pump, the nonlinear device appears as a time-varying element to any low-level signal. This linearisation process makes the use of most linear network theorems possible in small signal analysis.

According to their intended functions in electrical circuits, the diodes may be divided into three main groups. The first group consists of planar p-n junction, point-contact, backward and Schottky-barrier diodes, whose use is predominantly as a nonlinear resistance. The diodes in the second group are used as nonlinear reactances and include abrupt and graded planar junctions (back-biased), point-contact varactors, step recovery diodes, Schottky-barrier and MOS or space charge varactors. The third group of diodes exhibits a negative-resistance effect, and tunnel, IMPATT and Gunn devices fall into this category. The required characteristics are achieved by a deliberate enhancement of properties employing appropriate fabricating techniques, structures and different materials.

At the present time there is no detailed quantitative analysis for the harmonic generated within the foregoing diodes to enable exact comparison between calculated and measured results. Therefore, the purpose of this research project is to present the harmonic analysis of a voltage-driven nonlinear hot-carrier diode (Schottky-barrier diodes) and compare the theoretically deduced expressions with the experimental results of practical devices.

In Chapter 2, the fundamentals of nonlinear elements are presented. Definitions and early researches of nonlinear phenomena in every field of scientific interest are given together with a logical classification system based on the nonlinear characteristic curves in the i-v, v-q and i-ϕ planes. Consequently, chord and incremental values are defined and their application to frequency multiplication and conversion processes are explained. The energy relations and the application of nonlinear elements are discussed as a search for the best semiconductor diode to be used for a specific application.

A comprehensive study of metal-semiconductor junctions is introduced in Chapter 3, with the emphasis on the physical and electrical properties of Schottky-barrier diodes. A complete justification on the validity of the modified exponential law is given on the basis that the constants of a diode can be calculated accurately from the dc measurements.

In Chapter 4, the basis of harmonic generating and frequency converting circuits are investigated. The major difficulties encountered with a practical current-driven diode are explained to justify the adoption of the voltage-driven diode. Consequently, the harmonic currents, the chord, and incremental conductances are calculated for an arbitrary voltage-driven nonlinear resistive element.

In Chapter 5, the analysis of a voltage-driven hot-carrier diode is considered. The diode equivalent circuit used for analysis consists of the nonlinear junction resistance in series with a total series resistance which includes the source, the load, and the diode substrate series resistances. The exponential law which is modified by such a total series resistance is expanded as a power series in terms of the voltage drive. One of the new results is the independent relations of the coefficients of the power series expansion. Also, the harmonic currents are derived, for the first time, in power series forms whose coefficients are proportional to the modified Bessel functions.

Another closed form solution is deduced suitable for numerical evaluation and for understanding the mechanism of the diode in situ. From the formulas derived it is possible to compute the amplitudes of the harmonic currents, to specify the optimum nonlinear characteristic for a given circuit and harmonic number, and to predict the conditions for maximum efficiency.

Experimental verifications of the analysis are worked out in Chapter 6. Initially the validity of the modified exponential law in the case of hot-carrier diodes is demonstrated by means of dc measurements. The amplitudes of the harmonic currents are measured selectively for a wide range of applied voltages at the fundamental frequency of 50 KHz. Representative curves of measured harmonic vs applied voltage are compared with the calculated results. The curves illustrate the general effects of the various parameters which support the theory of the analysis.

Chapter 7 includes conclusions and suggested topics for further research. Appendices are given in Chapter 8, which form the integral part of this research.

CHAPTER 2

FUNDAMENTALS OF NONLINEAR CIRCUIT ELEMENTS

2.1 Nonlinear Phenomena and Early Researches

Any physical phenomenon whose independent variables cannot be described by ordinary linear relationships is called nonlinear. In fact, linear behaviour is an idealization. For example, an electrical resistance is a function of temperature, which depends upon heating, and heating depends upon the square of the current. Thus when a resistance is considered one is usually idealizing by limiting the range of the variables within which the resistance has a constant value. In the pendulum problem, as another example, x is substituted for sin x whenever the angle x is very small and as a result the mathematical formulation is simplified to a second order linear differential equation.

Since there are so many nonlinear elements or nonlinearities in every field of scientific interest one may remark that Nature is fundamentally nonlinear. Systems exhibiting nonlinear behaviour are found in astronomy, applied physics, mechanical, electrical and electronic engineering and in many other fields. The modern branches of electrical engineering such as data processing, communication, control systems etc. depend in many instances for their operation on nonlinear devices. Such devices could not have been developed unless the existence of nonlinearity had been recognized. It is apparent, therefore, that the study of nonlinear systems and elements gives the researcher and the designer much better understanding of the new and unusual phenomena observed experimentally.

Nonlinearity has been seriously studied since the second half of the ninteenth century. One of the first areas in which nonlinear problems were investigated was in the theory of sound by S. Earnshaw[1] in 1860. In astronomy, the gravitational equilibrium of stars was investigated by J. Homer Lane[2] in 1870 and later by Lord Kelvin[3] in 1907. Poincare[4] in 1892 and 1893 discussed the nonlinear problems in the field of celestial mechanics which involved calculations of orbits of celestial bodies under their mutual forces of attraction. The perturbation method for obtaining periodic solutions of nonlinear differential equations was first developed by Poincare[4] in 1882 and Lindstedt[4] in 1882. A paper was published in 1883 by Lord Rayleigh[5] on maintained vibrations followed by his thesis on the 'Theory of Sound' in 1894 in which he discussed nonlinear problems. Bernoulli[4], Euler[4], and Lagrange[4] contributed to the early research on problems in elasticity. The finite deformation of solids was analyzed by M. Biot[4], J. Boussinesq[4], G. Kirchhoff[4], and F.D. Murnaghan[4]. L. Prandtl[4], O. Reynolds[4], Th. von Karman[4] and G.I. Taylor[4] were among the contributors to the solutions of nonlinear problems in hydrodynamics and aerodynamics. The analysis of wave motion was conducted by Lord Rayleigh[4], G. G. Stokes[4] and T. Levi-Civith[4]. The propagation of impulses in a gas was the subject of Riemann[4]. The vibration of mechanical systems having nonlinear restoring forces was investigated by G. Duffing[4], J. P. den-Hartog[4] and C.A. Ludeke[4]. Appleton[7] and Van der Pol[7] first gave a nonlinear differential equation on sustained oscillations in a simple electronic circuit. Electrical and mechanical systems having nonlinear elements were analyzed by A. Andronow[4], S. Chaikin[4],

L. Mandelstam[4], N. Papalexi[4], A. Witt[4], N. Kryloff[4], and N. Bogoliuboff[4].

During this latter period a close relation existed between the electrical engineer and the mathematician because electrical networks provided the best confirmation of mathematical results. Therefore, many papers have been written on the theory of nonlinear networks, but relatively few books which give a comprehensive treatment. It seems that the attention of the analyst is to find out about the existence of periodic solutions, the limitation of particular types of components, convergence of iterative or power series procedures, and the most efficient way in which a computer can handle the data.

2.2 General Network and Classification of Elements

An electrical network is composed of two-terminal elements linked together by ideal lossless connectors. Actually, there are some elements which have more than two-terminals, such as transistors, but in the analysis only two of the three are normally considered at a time. The two-terminal elements of components are known as the network branches. The electrical behaviour of each element is defined by the voltage across the terminals and the current through the branch. A network branch may be characterized by a curve in either the v-i, the v-q, or the i-ϕ plane. These characteristics correspond, respectively to the three basic types of two-terminal elements, namely, the resistance, the capacitance and the inductance. If all possible data points, which are not in a straight line in the x-y plane, can be connected by a smooth curve then the branch represents a nonlinear element. An element whose characteristic at all times consists of straight lines in the x-y plane is called linear. Both linear or nonlinear elements are said to be either passive or active depending whether the characteristics pass through the origin or not, respectively.

Although the x-y curve, characterizing a two-terminal element, is assumed to be stationary, there exist some cases when the characteristic of an element is an explicit function of time, i.e. $y(t) = f[X(t),t]$. In view of this one should not be misled with the case when both independent variables defining the element are function of time, i.e. $y(t) = f[X(t)]$. This means that the linear or nonlinear elements may be tabulated into either time-invariant or time-varying elements. The simplest example of a linear time-varying element is the mechanically-varying potentiometer.

In order to use the nonlinear elements properly it is necessary to distinguish the x-y curves according to their general shapes. The examination of a large number of curves of some devices shows that they are non-symmetrical about the origin. These devices include most of the rectifying and p-n junction diodes. It is the flow of current in one direction which gives them the name UNILATERAL elements. Another class of elements whose characteristics are symmetrical about the origin are called odd-symmetrical elements such as iron-cored coils, glow tube and some of the ferromagnetic devices. Most of the above mentioned devices are passive elements whose slopes are positive at all points along their x-y curves. Another important class of nonlinear elements, called the negative elements, exists whose portion of their characteristic has a negative slope ($dy/dX < 0$). Needless to say that such class of elements includes tunnel diodes.

2.3 Properties of Nonlinear Elements and Systems

A property of a linear element is that the value of the element (R, C or L) remains constant throughout the variation of the two independent variables (i-v, v - q or i-ϕ) and is given by their ratios. Consequently, the steady-state response is a replica of the excitation frequencies. However, for a nonlinear characteristic, the slope at a point of the curve gives the incremental value of the element of that point. The straight line from the origin to that point is known as the chord value. Accordingly, the value of the element cannot be given by a single constant and a mathematical representation of the actual curve is required over the whole range of operation which is called the characteristic equation. The value of the incremental component may be specified by differentiating the characteristic equation with respect to its independent variable. Therefore, one or a set of nonlinear differential equations is usually formulated to define a nonlinear system.

The methods of solving such equations depend on whether they contain the time independent variable explicitly or not. These two types of equations distinguish a nonautonomous from an autonomous network respectively. The nonautonomous system of equations is normally associated with a.c. circuits because of the appearance of the independent time variable 't' in the equations of the form A cos ωt. The solution to such an oscillatory system is composed of frequencies which are related harmonically or commensurably to the frequencies of the excitation sources. These important properties of nonlinear devices are extensively used in the analysis of frequency multiplying and converting circuits.

The approach in such applications, in addition to the rectification properties, may be better understood by expressing the characteristic equation of a nonlinear element as a power series, i.e.

$$y = a_o + a_1X + a_2X^2 + a_3X^3 + \ldots\ldots\infty \qquad (2.1)$$

Then upon substituting $X = A\cos\omega t$ and with the help of various standard trigonometric identities, the expression

$$y = b_o + b_1\cos\omega t + b_2\cos 2\omega t + b_3\cos 3\omega t + \ldots\ldots\infty \qquad (2.2)$$

is obtained (Ch.5). Where b_o and b_n represent the dc and harmonic components, i.e.

$$b_o = \sum_{m=0,2,4,..}^{\infty} \frac{a_m A^m}{2^m} \, {}^{m}C_{\frac{m}{2}} \qquad (2.3)$$

$$b_n = 2\sum_{m=n,n+2,n+4,..} \frac{a_m A^m}{2^m} \, {}^{m}C_{\frac{m-n}{2}} \qquad (2.4)$$

This indicates that the essential process of a nonlinear element is to generate harmonic spectrum since any nonlinear characteristic can be represented by such power series whatever the complexity of the operation.

In the conversion case, the small signal, at a fequency other than the frequency of the pump or its harmonics, sees the nonlinear time-invariant element as a linear time varying element. Consequently, the small signal is translated in frequency by the time-varying element and the linear network laws can be used in its analysis. Such a time-varying element is also a harmonic generator and hence no conversion or multiplication can take place without the existence of harmonic sources. Therefore, it is thought that the best way to predict the performance of a nonlinear element is through its harmonic spectrum.

2.4 Energy Relations in Nonlinear Elements

The energy supplied to, and dissipated by a network is given by the time integral of the instantaneous power, namely:

$$W(o,t) = \int_0^t P(t)\, dt \qquad \ldots \qquad \ldots \qquad (2.5)$$

where the product of the instantaneous voltage and current is the power

$$P(t) = v(t) \cdot i(t) \qquad \ldots \qquad \ldots \qquad (2.6)$$

The knowledge of such oscillating power is of little practical value and the important quantity is the absolute or the average power measured over the periodic interval T. Thus

$$P_{av} = \frac{1}{T} \int_0^T V(t) \cdot i(t)\, dt \qquad \ldots \qquad (2.7)$$

where T is the minimum period of the product $V(t) \cdot i(t)$. This expression shows that although the product $V(t) \cdot i(t)$ is oscillating periodically there exists a net power flowing into a resistive element which must be lost in heat energy since energy cannot be destroyed. For a capacitive or an inductive element the average power is given respectively by

$$P_{Cav} = \frac{1}{T}\int_{o}^{T} v(t) \cdot \frac{dq(t)}{dt}\, dt = \frac{1}{T}\int_{q(o)}^{q(T)} v(q)\, dq \quad \ldots \quad (2.8)$$

$$P_{Lav} = \frac{1}{T}\int_{o}^{T} i(t) \frac{d\phi(t)}{dt}\, dt = \frac{1}{T}\int_{\phi(o)}^{\phi(T)} i(\phi)\, d\phi \quad \ldots \quad (2.9)$$

These equations will integrate to zero for periodic waveform of Period T since $q(T) = q(0)$ and $\phi(T) = \phi(0)$ respectively. For example, in the case of a linear capacitor, equation (2.8) can be reduced to:

$$W(0,T) = \int_{q(0)}^{q(T)} \frac{q}{C}\, dq = \frac{1}{2C}\left[q^2(T) - q^2(0)\right]$$

$$= 0 \quad \ldots \quad \ldots \quad \ldots \quad (2.10)$$

Consequently, the average power, entering a purely capacitive or an inductive element, is zero.

The usefulness of such information was exploited by R.V.L. Hartley[8] (1916) and his results were derived by Manley and Rowe[8] (1956) under much more general conditions. The important result of such analysis is the amount of power at a particular frequency that can be obtained from any nonlinear lossless reactance by mixing two sinusoidal waveforms of incommensurate frequencies ω_1 and ω_2. The product of the current (dq/dt), flowing into the nonlinear reactance, and the voltage ($d\phi/dt$), across it, contains all frequency components $\pm(m\omega_1 + n\omega_2)$. Thus, the total average power entering a lossless element can be represented by

$$\sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} P_{m,n} = 0 \ldots \quad \ldots \quad \ldots \quad (2.11)$$

Multiplying and dividing equation (2.7) by $(m\omega_1 + n\omega_2)$ yields the two independent Manley-Rowe equations:

$$\sum_{n=-\infty}^{\infty} \sum_{m=0}^{\infty} \frac{m P_{m,n}}{(m\omega_1 + n\omega_2)} = 0 \quad \dots \quad \dots \quad \dots \quad (2.12)$$

$$\sum_{m=-\infty}^{\infty} \sum_{n=0}^{\infty} \frac{n P_{m,n}}{(n\omega_1 + n\omega_2)} = 0 \quad \dots \quad \dots \quad \dots \quad (2.13)$$

If the nonlinear reactor is excited only at ω_1 with power P_1 then n is zero and equation (212) becomes

$$P_1 = - \sum_{m=2}^{\infty} P_m \quad \dots \quad \dots \quad \dots \quad (2.14)$$

Therefore the total harmonic output power is equal to the fundamental input power introduced to a lossless nonlinear reactance. If the circuit is so adjusted that only a desired harmonic output power is delivered to the load and other powers are reactively terminated, the conversion efficiency for the desired harmonic can approach 100 percent. For a nonlinear dissipative element, however, Page[9] in 1956 and Pantell[10] in 1958, have shown that the efficiency of generating harmonic cannot exceed $1/n^2$ namely:

$$\frac{|P_n|}{P_1} \leqslant \frac{1}{n^2}$$

where n is the harmonic number of interest.

2.5 Applications and Discussion

Semiconductor diodes provide, in general, three common behaviours. These are, nonlinear resistance (varistors), nonlinear reactance (varactors) and negative resistance. Although a diode may exhibit two or more of the three above mentioned characteristics simultaneously, the classification under which a diode can be put depends on its predominant effect.

The ordinary conception of rectifiers, where a diode can convert ac power into dc power, is called varistors. For an ideal varistor, a diode derives its usefulness from the nonlinearity of the current-voltage characteristics. The instantaneous current i(t) is a function only of the instantaneous voltage V(t), given by

$$i(t) = i_o \left[\exp\left(\frac{ev(t)}{nKT}\right) - 1\right] \quad \ldots \quad \ldots \quad (2.15)$$

These diodes include backward diodes, most Schottky barrier and point contact diodes. They have been extensively used for frequency down conversion, detection, low noise reception, high speed clipping or rectification and sensing.

A capacitive varactor is a semiconductor junction diode with a useful nonlinear reverse-bias capacitance. The operation of such devices can be analyzed by assuming that the instantaneous charge on the device is a single-valued nonlinear function of the instantaneous voltage applied to each terminal. Since $\frac{dq}{dV}$ is the small signal capacitance, the voltage dependent capacitance is given by

$$C = C_o\left(1 - \frac{V}{\phi}\right)^{-\gamma} \quad \ldots \quad \ldots \quad \ldots \quad (2.16)$$

where V is the applied voltage, ϕ is the contact potential of the junction and γ is a coefficient whose value depends on the doping profile of the junction ($\gamma = \frac{1}{3}$ for a graded junction, $\gamma = \frac{1}{2}$ for an abrupt junction, $\gamma = 1$ for a hyperabrupt junction). Although the development of varactor diodes was mainly for parametric amplifiers, they have found use in other applications. Some of these are harmonic generation, modulation or up conversion, pulse generation and pulse shaping.

The inductive varactor is used in frequency converting circuits. It has the same efficiency, as does the capacitive one, of generating harmonics and subharmonics which are widely used in telephone systems. A combination of nonlinear inductors has been used in a digital computer to store information for future use.

The third and the last class is the negative resistance diode. It is defined as a nonlinear resistance whose slope over a portion of the characteristic is less than zero, i.e. the element is negative over that range. This property can be used for amplification purposes. Some negative resistance diode amplifiers use tunnel, IMPATT and Gunn diodes. Tunnel diodes are preferred for low noise amplification in spite of their very low power output which rules them out for oscillator use. The other two have more power capability for use as local oscillators.

CHAPTER 3

PHYSICAL AND ELECTRICAL PROPERTIES OF A METAL-SEMICONDUCTOR JUNCTION

3.1 Early Researchers

Semiconductors were already in use before the beginning of this century. The initial step was probably taken in 1883 when Faraday[11] discovered that silver sulphide exhibited a negative temperature coefficient. Six years later, in 1839, the photovoltaic effect was discovered by Becquerel[11]. No progress had been reported for more than thirty years until W. Smith[11] established the principle of photoconductivity. In 1973, while researching into the insulating properties of selenium, he observed that the electrical resistance of selenium changed under the influence of light. But the most important contribution to semiconductor devices was made, in 1874, by F. Braun[11]. He discovered that when a contact between certain materials had been made, the current flowed in one direction. In the same year, a similar effect was noticed by Schuster[11], when an intimate contact between clean and oxidised copper was made. The development of copper-oxide rectifiers was not fully established until fifty years later, in1927, by Grondahl and Geiger[11]. The first practical photo-element and dry rectifier, however, were already made by Adams and Day[11], in 1875, from selenium and by Fritte[11], in 1883, respectively.

When Hertz[11], in 1888, had observed radio waves the importance of semiconductor rectifiers was fully realized. Base[11] (1904), Dunwoody[11] (1905), Austin and Pierce[11] (1907), made the point contact detector a reality. The discovery of the electron valves in 1897aattracted many workers to such fields. As a result the progress in the development of semiconductor devices was retarded until the 1939-1945 war years.

Nevertheless, some basic theories and experiments were postulated during the pre-war period. The significance of Hall effect, originally discovered in 1879, was not fully realised until the 1930's. By means of Hall effect, the distinction between metals and semiconductors was established and the prediction of conduction current by two kinds of charge carriers (electrons and holes) was verified. The total conductivity was represented by the relation $q \times n \times \mu_n + q \times p \times \mu_p$. All of these have been explained with the help of quantum mechanical models for semiconductors, proposed by Sommerfeld et al[11] (1928) and Wilson[11] 1931 (1961).

Schottky and Deutschman[11], in 1929, explained that the rectification processes occurred within the junction and were not distributed over the entire volume. In 1938, the importance of minority carriers was recognised by Davydov[11] while he was working on the unipolar effect at the p-n junction. The existence of potential barriers at the junction was suggested by Schottky, Mott and Davydov[11] in 1939. Hence, the rectification mechanism was almost fully explained.

In 1948, Torrey and Whitmer[12] published a comprehensive treatment of the progress made during the war years. During that period, silicon detectors and point contact rectifiers had been used for radar and high frequency rectification, respectively. The results of many experiments were not entirely consistent with the theoretical deductions of the early years. The prediction of surface states made by Tamm[11] (1932), Shockley[11] (1939) and Bardeen[11] (1937), was not proved until 1948 when Brattain and Shockley[11] performed a successful experiment verifying the existence of a space charge layer at the free semiconductor surface. Further experiments, by Bardeen and

Brattain[13] in 1948, have made transistors a reality. One year later, in 1949, a major contribution to the theory of p-n junctions was made by Shockley[14]. In the same year, papers on Ge point contact diodes and on the electrical properties of silicon were published by Bardeen and Brattain[11] and by Pearson and Bardeen[11], respectively.

In 1950, Hall and Dunlap[11] used the metal-alloy diffusion technique in p-n junction devices. The grown-crystal method was adopted by Shookley and others[11], in 1951, for p-n-p transistors. In the same year, Scaff and Theurer[11] used the gaseous diffusion technique in silicon power rectifiers. In 1954, Pearson and Chapin[11] adopted the same technique for solar energy converters.

The effect of impurities on the energy levels of semiconductor had been determined after a comprehensive study made by Lark-Horovitz and Johnson[11] on Ge in 1945, and Pearson and Bardeen[11], on Si, in 1949. By 1953, the impurity content of a crystal was successfully controlled using a zone refining process which was introduced in 1952 by Pfann[11].

The internal field emission was suggested, in 1934, by Zener[11] as an explanation for electrical breakdown. In 1951, Mcafee and others[11] proposed that the internal field emission may be responsible for the avalanche current in a p-n junction. In 1953, Mackay and Mcafee[15] explained further that avalanche current was not confined to Zener effect only and could also be due to electron multiplication (ionisation). Furthermore, in 1954, Mackay[16] deduced a simple expression accounting for the breakdown in a p-n junction. This was in reasonable agreement with Wolf's[11] theoretical calculation of the ionization rate for silicon which was made in the same year. In 1957, Chynoweth and Mackay[17] for the first time, eatablished the threshold energy required for multiplication processes. It was shown by Chynoweth[18], in 1958, that the ionization rate for holes was less than that for electrons which agreed with Miller's[11] experimental results published in 1955. In 1962 Kennedy and o'Brien[47] deduced the avalanche conditions for diffused type p-n junctions.

The presence of noise at breakdown has been observed by many workers. It was suggested by Chynoweth and Pearson[19], in 1958, that such noise was due to lattice dislocations. This was confirmed by Baldorf[11] and others, in 1950, when they had constructed some junctions free of lattice dislocations and the devices were almost free of noise.

Esaki[20], in 1957, proposed a device utilizing a negative resistance called a tunnel diode. The application of such a diode to microwaves was first described by Sommers[21] in 1959. Devices which depend on tunnelling processes such as the backward diode and the application of this to microwave mixing and detection was reported by Eng[22] in 1961.

W.T. Reed[23], in 1958, described another negative resistance device called the IMPATT diode. A modified form of this device was reported by Johnston, De Loach and Cohen[24]. More than one watt of continuous power was reported by Misawa[25] in 1966. Another type of negative resistance device was reported by Hilsum[25] in 1962. This was explained by Gunn[26] in 1963, when he found that microwave oscillation resulted from bulk GaAs at a critical field.

Mill, Krakauer and Shen[27] first described the charge-storage diode in 1962. This was followed by step-recovery diodes with a potential for use as high-order harmonic generators. R.D. Hall[25], in 1965, claimed 20 mW of C.W. power in the 3 cm band. C.B. Swann[25], in 1967, obtained 5 w at 2 cm wavelength.

Although the introduction of p-n junction diodes for varactor applications below 5 GHz in 1957 had attracted many workers, point contact diodes continued to improve in performance as varistors at higher frequencies (up to 2,000 GHz). In point contact diodes, a sharp metal whisker is pressed against the semiconductor face to produce the hemispherical rectifying contact. The contact may be formed by a simple mechanical or electrical discharge process which may result in a small alloyed p-n junction. Wlatz[28] (1952), Kikuchi and Onishi[29] (1953) have confirmed, experimentally, the formation of the p-n junction in Ge point-contact diodes. Nelson[30] (1958) and others have treated point-contact diodes as small hemispherical p-n junction diodes. But the conduction mechanism has not been fully explained due to the contact complexity. The advances in semiconductor technology, in the past ten years, have produced the new type of metal-semiconductor devices which are known as Schottky-barrier diodes. They are based on majority carrier conduction and in normal applications have replaced point contact diodes. Unrestricted by the charge storage phenomenon they competed successfully against point-contact diodes in uniformity, reproducibility and reliability. Such devices are sometimes called the hot-carrier diodes because of the large kinetic energies (or high temperature) of the electrons in the conduction band which overcome Schottky barrier potential. They are also called Schottky-barrier diodes because of the early analysis of this kind of majority-carrier rectification by W. Schottky[11] in 1938. It is also described by Kahng[31] in 1963. H.F. Cooke[25] in 1965 described such devices as mixers of much better noise figures than any previous point contact diodes.

The conduction in Schottky diodes was first explained using the diffusion theory of Wagner[32] (1931), Schottky and Spenke[32] (1939).

The thermionic emission theory was proposed by Bethe[33] in 1952. The combination of both theories were considered by Schultz[34] (1954), Gossick[34] (1963), and Crowell and Sze[35] (1966). Although there are still several unexplained disagreements in the experimental data (e.g. Padovani and Summer 1965)[36], it appears that these cannot be resolved by adopting the diffusion theory alone. Rhoderick's[37] analysis (1972) of data by Smith[38] (1968) shows that the controlling mechanism in moderately doped GaAs Schottky diodes at room temperature is almost certainly due to thermionic emission. The only results which appeared to confirm the diffusion theory were those which related to copper oxide.

3.2 Physics of Metal-semiconductor Contact [11,25,31,32,34]

The current in a metal is due to the flow of negative charge (electrons), whereas the current in a semiconductor results from the movement of both electrons and positive charges (holes). When a semiconductor crystal is very pure, the hole and the electron densities are nearly equal, and the crystal is called an intrinsic semiconductor. If such a crystal, from the fourth column of the periodic table, is doped with an element from the third column (boron, gallium or indium), the density of holes is increased by approximately the density of the doping atoms and the density of electrons is decreased by the same ratio. This is because the three outer shell electrons of the impurity atom are shared in covalent bonds with the four neighbouring atoms. However, still one more electron is needed for saturating the four covalent bonds. Therefore, an electron from the valence band will be captured by the impurity atom leaving behind a hole. The hole becomes a mobile charge carrier while the impurity atom becomes an immobile (fixed) negative charge caused by the captured electron. The impurity atom therefore is called an acceptor impurity because it accepted an electron from the valence band. The crystal is said to have p-type conductivity. The holes are called the majority carriers and the electrons are called the minority carriers. But when an atom of the fifth column (antimony, phosphorus or arsenic) is introduced to a crystal of the fourth column, four covalent bands will be formed. The extra electron will be excited to the bottom of the conduction band producing a negative mobile charge carrier. An example is when silicon atoms are doped with phosphorus atoms to produce a crystal of n-type conductivity. The impurity atoms are called donor atoms because they give electrons to the conduction band. The electrons are the majority carrier and holes are the minority carriers.

The performance of metal-semiconductor devices is best understood by considering various energy levels in the isolated metal and n-type semiconductor. Figure (3.1a) shows such energy in an isolated metal at equilibrium. ψ_m is the energy required for the escape of an electron into free space with energy (W_F) corresponding to the Fermi-level of the metal. It is known as the thermionic or vacuum work function of the metal. The value of ψ_m is constant for atomically clean metal but very sensitive to surface contamination. It varies between 1.93 eV for caesium and 5.36 eV for platinum. The escaped electron induces a positive charge (image) within the metal surface and the attractive force between them is known as the image force.

The thermionic work function ψ_s is a similar quantity for semiconductors, as shown in Fig. (3.1b). But the position of the Fermi level changes with changing the impurity of atoms. Therefore, ψ_s will depend on the carrier density besides the influence of surface contamination. In view of this, the electron affinity (χ), that does

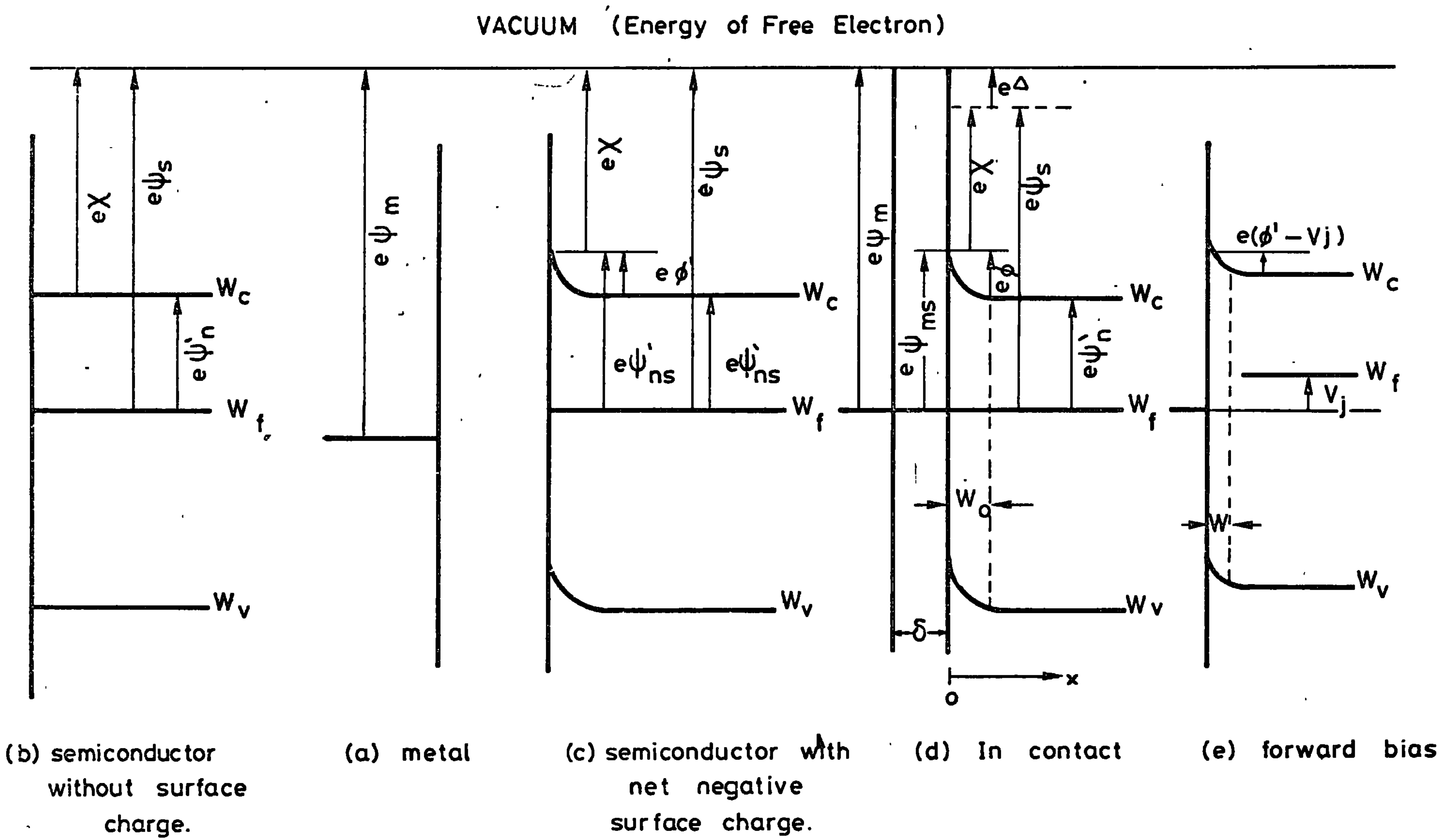


FIG 3·1. ENERGY LEVEL DIAGRAM OF METAL AND SEMICONDUCTOR.

not vary directly with doping, is likewise defined as the energy required to remove an electron from the bottom of the conduction band and place it at rest in free space.

Practical semiconductor surfaces always adsorb layers of foreign material. The imperfections or impurity in such an adsorbed layer near the interface is responsible for what is called surface states. Although the physical structure and the origin of surface states are not fully understood, experimental observations have considered the surface state as neutralized donor or acceptor atoms or ionized donor or acceptor charges. The surface charge may be positive or negative depending on the chemistry of the film on the surface. The bending of energy bands in semiconductors is due to surface states.

If a semiconductor does not have surface states, the potential energy diagram at the surface will be as in Fig. 3.1b. This is very difficult to attain in practice. In the case of an n-type semiconductor, the surface states may be occupied by electrons. To maintain charge neutrality, there must be a corresponding number of electrons missing in the bulk of semiconductors. Therefore, a depletion layer of (positively) ionized donors will be formed just beneath the surface and the band edges are distorted, as shown in Fig. 3.1c.

When the metal and semiconductor are brought into contact, as shown in Fig.(3.1d), there will be an exchange of electrons between them as in the case of metal-metal contact. The mechanism of electron flow is analogous to the thermionic emission from a hot cathode into vacuum. The semiconductor in this case is acting as the cathode and the metal as the vacuum. For the n-type semiconductor, the flow of electrons from the semiconductor to the metal results in a current I_s which is called the saturation current. As a result, positive charges will be left inducing negative charges on the surface of the metal. The resultant electric field increases the energy required to remove the electrons from the semiconductor and so lowers the level of the conduction band. The field will increase, and the level of the conduction band will fall, until equilibrium is achieved. Under such equilibrium, the Fermi-levels must be at the same height in the metal and semiconductor, such as in the case of two metals. The net current across the junction must be zero and hence an equal and opposite current, I_s, will flow from the metal to the semiconductor. The barrier height ψ_{ms} is simply given by

$$\psi_{ms} = \psi_m - (\chi + \Delta) \tag{3.1}$$

where $\Delta = (\psi_m - \psi_s)$ is the potential difference across the gap δ produced by surface states. The bending of the band ϕ' is related to the width of the depletion layer (W_o) by

$$\phi' = \frac{N_d e W_o}{2\varepsilon} \tag{3.2}$$

where N_d is the donor density and ε is the permittivity of the semiconductor.

If an external voltage V_a is applied so as to make the metal positive (forward bias) and the semiconductor negative, the conduction band will rise again as shown in Fig.(3.1e). This rise is equivalent to a reduction in the potential barrier, on the semiconductor side by an amount $V_j = V_a - ir_s$, where V_j and ir_s are the voltage drop across the junction and the semiconductor substrate resistance respectively. Therefore, the electrons in the conduction band of the semiconductor will require less energy to overcome the barrier potential and to be injected into the metal. The current will be increased exponentially with the applied voltage according to the following relation:

$$i = I_s \left[e^{\alpha(V_a - ir_s)} - 1 \right] \qquad (3.3)$$

The bending of the band ϕ' is related to the width of the depletion layer W by

$$\phi' - (V_a - ir_s) = \frac{Nd\, e\, W^2}{2\varepsilon} \qquad (3.4)$$

from which

$$C_j = A \left[\frac{\varepsilon\, e\, N_d}{2\,(\phi - V_j)} \right]^{\frac{1}{2}} \qquad (3.5)$$

is the junction capacitance,

where $V_j = V_e - ir_s$ is the voltage across the junction

$\alpha = \frac{e}{nKT} = 40\ V^{-1}$ for an ideal diode

I_s is the saturation current in the order of 10^{-9} amps

e is the electron charge $= 1.6 \times 10^{-19}$ Coulomb

T is the temperature in degree Kelvin (^oK)

K is the Boltzman's Constant $= 1.38 \times 10^{-23}$ (joule/^oK)

n is the diode ideality factor $= \frac{40}{\alpha \text{ (practical)}}$

When a reverse bias is applied, the conduction band will be lowered and the electrons, having originally sufficient energy to surmount the barrier, will now require higher energies. The component of the electron current from the semiconductor to the metal will be very small compated to $-I_s$ from the metal to the semiconductor. The net current is therefore

$$i_{rev} = I_s \left[e^{-\alpha(V_a - ir_s)} - 1 \right] \quad \ldots \quad (3.6)$$

Thus, the reverse current is expected to be a constant in the order of $-I_s$.

To compare diodes of different values of ϕ', it is useful to define a forward bias cut-off frequency f_{cf} by

$$f_{cf} = \frac{1}{2\pi C_{jf} R_{sf}} \tag{3.7}$$

It is the frequency at which the capacitive reactance of the junction becomes equal to the series resistance.

3.3 Technology of Schottky Barrier Diodes [25,32,39]

The metal-semiconductor interface may consist of a variety of metals in conjunction with either p-type or n-type semiconductors. Schottky-barrier diodes, using gold, platinum, palladium, silver and many other metals, have been built for a variety of specific applications. Semiconductor materials which have proved suitable for such devices are silicon, germanium, and gallium arsenide. In general, n-type silicon is preferred because its higher electron mobility permits better high frequency performance. Metal-semiconductor junctions with planar areas approaching those of point contact devices have been fabricated which are sometimes referred to as the hot carrier diodes. Some of the important junction fabrication methods involve depositing metal upon the semiconductor by evaporation, by sputtering, or by electrochemical means. The general procedures, in each case, require a single-crystal wafer on which metal is deposited to form the barrier. This wafer is heavily doped throughout its volume and has a high-resistivity film on one face.

To make a silicon wafer, a thin slice of heavily doped crystal is smoothed and chemically polished on one side which is called a substrate. This substrate is placed, with the polished face upwards on a platform, in a bell-jar apparatus. Pure hydrogen gas flows through the apparatus and the platform is heated in 1250°C. The temperature is dropped to 1200°C after a few minutes. Such heating processes serve to reduce the few atomic layers of oxide (SiO_2) on the polished surface of the substrate. The hydrogen gas then is mixed with silicon tetrachloride ($SiCl_4$) to deposit atomic silicon on the substrate.

$$2H_2 + SiCl_4 \longrightarrow Si + 4HCl \qquad (3.8)$$

This growth of single-crystal semiconductor material on to such a polished surface of the substrate from the gas phase is called epitaxial growth. The high resistivity deposited layer, compared to the substrate, is called the epitaxial layer. Thus, the final form of the slice is called the single-crystal wafer.

The fabrication of hot carrier diodes consists of a heavily doped n^+ silicon substrate on which an n-type epitaxial layer of a specific resistivity is grown on the polished surface and an ohmic contact is formed on the opposite surface. The slice is then washed and immediately transferred to an evaporator, where a matrix of metal dots is deposited on the heated epitaxial surface to form the barrier. The prepared material is diced and each chip is soldered to a pedestal on one of the package leads. A gold-plated metal whisker, which makes an ohmic-controlled-pressure contact to the top-surface of the metal dots, is connected to the other pedestal of the package leads. The package is then sealed in a controlled environment. The small size of the diode case and the gold plated wire leads assure its adaptability to a variety of circuit packaging techniques.

3.4 Practical Schottky Barrier Diode

The non-linear electrical properties of semiconductor diodes are determined by the exponential law of the type:

$$i = I_s \left[\exp \frac{e V_j}{kT} - 1 \right] \quad \ldots \quad \ldots \quad (3.9)$$

This relation has been approached by two derivations credited to Schottky and Spenke[32] (1939) and later by Bethe[32] (1942) for metal-semiconductor Schottky barrier diodes applications. These two approaches have led to the same slop (e/kT) and differ only in the saturation current (I_s). A more sophisticated theory, allowing for image force, shows that the above factor should be taken as (e/nkT). The value of n depends on the donor density N_d and it is 1.02 for $N_d = 10^{17}$ cm^{-3} (Sze et al, 1964)[34]. Although values of n, slightly greater than that attributed by the image force alone, have been recorded by many workers the small differences may be explained in terms of a component of current due to recombination in the depletion region (YU and Snow, 1968)[34] or tunnelling through the narrow barrier at the edge of the metal contact (Wilson, 1932)[34].

As far as the validity of equation (3.4) is concerned, Kahng (1963)[31], has carried out a critical experimental investigation, in which he found that the law is obeyed over a certain range of current up to about 10^{-5} amp. The deviation of the characteristics at larger values of current is due to the substrate series resistance (r_s). Usually the resistance of a practical diode reaches a constant low value at forward voltages exceeding some particular value, generally greater than 0.5 volt, and this value is known as the series resistance. From this consideration it seems that the voltage V, in equation (3.9) is not the applied voltage V_a across the diode, but it is less than V_a

by the voltage drop ir_s developed across the ohmic resistance r_s of the semiconductor substrate. Therefore equation (3.9) may be rewritten as

$$i_f = I_s \left[\exp. (\alpha V_a - \alpha i_f r_s) - 1) \right] \quad \ldots \quad (3.10)$$

where $\alpha = \frac{e}{nKT}$ and $V_j = V_a - ir_s$.

From equation (3.9) it is evident that, for current (i_f) greater than several times the saturation current (I_s) and lower than 10^{-5} amp, α may be given by:

$$= \frac{\ell n \; i_f}{V_a} \quad \ldots \quad \ldots \quad \ldots \quad (3.11)$$

For currents higher than 10^{-5} amp, equation (3.10) can be written as

$$\ell n \left[\frac{i_f}{e^{\alpha V_a}} \right] = \ell n \; I_s - (r_s) \; i_f \quad \ldots \quad \ldots \quad (3.12)$$

This is the equation of a straight line whose slope is $-(\alpha r_s)$ and whose intercept at $i_f = 0$ is $\ell n \; I_s$. Thus, equation (3.11) and equation (3.12) provide ready means of determining the constants α, r_s and I_s.

CHAPTER 4

HARMONIC GENERATING AND FREQUENCY CONVERTING CIRCUITS

4.1 Introduction

In communication, the information-bearing signals are usually conveyed from one point to another via a transmission medium. The medium may be a twin-line, a coaxial cable, a waveguide, or it may be a free space. The fundamental requirement of any transmission medium is to propagate as efficiently as possible a particular band of the electromagnetic wave spectrum. To achieve this, when the medium is the free space, there is a need for relatively small and efficient radiators (antennas) which lead to the use of Shorter Wavelengths, i.e. higher frequencies. Another important reason for employing high frequency transmission systems is that the losses in free space at audio frequencies are very high. The process of producing higher frequency sources, which are usually modulated by low frequency signals, can be done using methods of harmonic generation or frequency multiplication. This technique of shifting a given low frequency band up in frequency is known as frequency translation.

In controlled harmonic generators, the power at a frequency ω supplied to a nonlinear element is converted to powers at frequencies harmonically-related to ω. Such a method seems to be a convenient way of obtaining signal sources at high frequencies, whenever it is difficult to generate these directly. The property of a nonlinear device and its analysis are essential to the understanding of harmonic generation. Two classes of nonlinear elements have been analysed, theoretically, by various researchers, i.e. nonlinear resistances and

and nonlinear reactances. The former include point contact diodes and the latter varactor diodes. Page[9], in 1956, has shown that the efficiency for a nonlinear resistor cannot exceed $1/n^2$, where n is the harmonic number of interest. Manley and Rowe[8] (1956) have shown that the total harmonic output power is equal to the fundamental input power introduced into a lossless nonlinear reactance (conservation of energy). If the nonlinear reactance is excited only at ω_1 with power P_1 then from equation (2.10)

$$P_1 = \sum_{m=2}^{\infty} - P_m \quad \ldots \quad \ldots \quad \ldots \qquad (4.1)$$

where negative sign $(-P_m)$ indicates that harmonics are supplied by the nonlinear reactance.

The basic block diagram for generating the mth harmonic is shown in Figure 4.1. A sinusoidal generator feeds a network containing a nonlinear element through a bandpass filter tuned to a frequency ω. The output of the network is connected to a dissipative load through a bandpass filter tuned to the required frequency $m\omega$. When the sinusoidal source drives the nonlinear element, it will generate harmonics. All unwanted harmonics will be reactively terminated by the bandpass filter while the required mth harmonic will be delivered to the load. In the case of a nonlinear reactance, the power is exchanged only at the two frequencies ω and $m\omega$ if the element and filters are lossless. Therefore, generation of a particular harmonic may be achieved with almost 100% efficiency from a nonlinear-reactance circuit.

In frequency converters, a large and small signal at different frequencies are applied to the nonlinear element. The large signal, which is normally called the pump, drives the nonlinear element whose

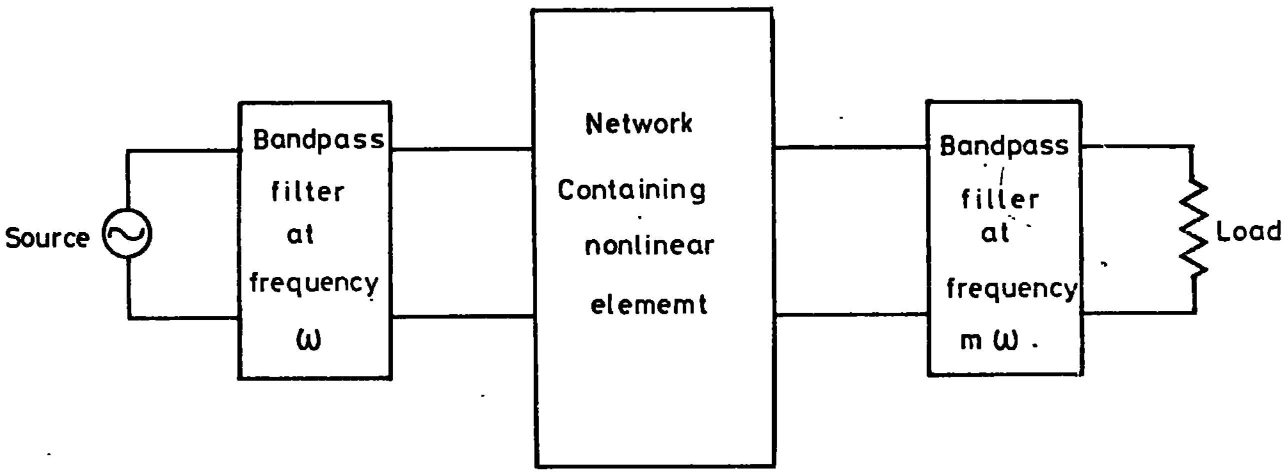


FIG 4·1 Block Diagram for Generating the mth Harmonic response will be a harmonic spectrum. The small signal introduced will be translated in frequency by the harmonically varying components of the incremental equivalent circuit. The nonlinear element will be seen as a time-varying device by the small signal source. This fact suggests clearly that the harmonic generation is the essential initial step in any frequency converting process.

In a frequency converter, the shift in frequency occurs by combining the frequency of the pump ω_p with that of the small signal at ω_s. The resulting response, in addition to the harmonic spectrum of the pump, contains the sum and the difference components of the form

$$n\,\omega_p \pm \omega_s$$

where n is normally an integer. The signal is at such a relatively low level that there is negligible generation of its harmonics. When the frequency is shifted down, nonlinear resistances are often preferred and the network is called mixer, but when the frequency is shifted up, nonlinear reactances (varactors) are preferred and the network is referred to as a parametric frequency changer.

In a parametric frequency changer, the two Manley and Rowe equations provide two independent relations among the powers flowing in and out of the nonlinear reactance at various frequencies. They also contribute useful information to the principles of parametric amplifiers, frequency up- and down-converters, in addition to harmonic generators. The general properties may be deduced from these relations by some simple examples. If it is assumed that two generators are connected to the nonlinear reactance at frequencies f_1 (signal) and f_2 (ℓ.o.) and a third frequency $f_3 = f_1 + f_2$ is generated, all other sidebands are reactively terminated, then the two Manley-Rowe equations reduce to

$$\frac{P_1}{f_1} + \frac{P_3}{f_3} = 0 \quad \ldots \quad \ldots \quad \ldots \quad (4.2)$$

and

$$\frac{P_2}{f_2} + \frac{P_3}{f_3} = 0 \quad \ldots \quad \ldots \quad \ldots \quad (4.3)$$

It must be noted that $P_{m,n} = 0$ for all but P_1, P_2 and P_3. The power P_1 and P_2 are positive because they are supplied to the nonlinear reactance while the power P_3 must be negative because it is supplied by the nonlinear element. Therefore, the device is said to be stable and the maximum power gain is given by

$$G_{13} = \frac{f_3}{f_1} = \frac{f_1 + f_2}{f_1} \quad \ldots \quad \ldots \quad \ldots \quad (4.4)$$

This type of parametric amplifier is called the noninverting or upper-sideband up-converter (modulator).

When the operation is reversed such that a small signal power P_3 is supplied to the nonlinear reactance, the powers P_1 and P_2 will be negative and a negative resistance, therefore, will be introduced in the pump (ℓ.o.) circuit which makes the device potentially unstable. In this case, the device is called the noninverting down-converter (demodulator).

If the power supplied by the nonlinear reactance is still P_3, resulting from P_1 and P_2 supplied to the nonlinear reactance and $f_3 = f_2 - f_1$ is the required frequency, the two equations will take the form

$$\frac{P_1}{f_1} - \frac{P_3}{f_3} = 0 \ldots \quad \ldots \quad \ldots \quad (4.5)$$

and

$$\frac{P_2}{f_2} + \frac{P_3}{f_3} = 0 \ldots \quad \ldots \quad \ldots \quad (4.6)$$

From the first of these two equations the signal power P_1 must be negative and the gain, therefore, is given by

$$G_{13} = -\frac{f_3}{f_1} = \frac{-(f_2 - f_1)}{f_1} \quad \ldots \quad \ldots \quad (4.7)$$

The input power from the pump (ℓ.o.), therefore, flows out of the nonlinear element at the two frequencies f_1 and f_2 in which most of P_2 appears at f_3 and a small amount appears at f_1. This results in a negative resistance in the small signal circuit. Thus, the circuit is said to be potentially unstable and it will oscillate under certain conditions. Such a circuit is called an inverting or lower-sibeband up-converter if $f_3 >> f_1$ and it is called an inverting or lower side-band down converter if $f_3 < f_1$. In both cases the signal f_1 has been inverted and hence the name inverting up or down converter.

When f_3 is approximately equal to f_1 the signal circuit will pass both the signal and f_3 (called idler) and the amplifier is called a degenerate amplifier. If, on the other hand, the signal circuit will not pass f_3 then the amplifier is called a nondegenerate amplifier.

4.2 Basic Resistive Circuit

One of the major difficulties encountered with the nonlinear element is to find its ac equivalent circuit. The analysis of a network, in general, is to find the currents and voltages in its elements when the source and the imbedding networks are known. A nonlinear element may be considered as a network with unknown elements. These elements are function of the applied voltage or current and can be represented by the dc and time-varying admittances or impedances. In order to define such elements, the currents and voltages generated within and across each element must be found. In the analysis one may either choose a sinusoidal voltage or sinusoidal current drive. The two basic circuits for resistive harmonic generators are shown in Figure 4.2a and b, respectively. The two parallel (or series) resonance circuits are tuned to ω and nω respectively, and are assumed to be ideally selective and present short (or open) circuits to all other frequencies. The ideal choke across the nonlinear resistive element, in the current-driven case, is necessary to allow the dc current to flow.

In the voltage driven case, if the parallel resonances are removed, as shown in Figure 4.3, then the harmonic currents passing through the source and the load resistance, $R_s + R_L$, will develop harmonic voltages across the nonlinear resistive element and then the element is driven by a Fourier voltage

$$V(t) = E\cos\omega t - (R_s + R_L)\sum_{0}^{\infty} i_n \cos n\omega t \quad \ldots \quad \ldots \quad (4.8)$$

In order to avoid such a complex drive, it is assumed that a diode of total series resistance $R_s + R_L + r_s$ is driven by the ideal voltage generator $E\cos\omega t$. The diode may be then represented by the characteristic shown in Figure 4.4(c).

As it was shown in Chapter 2, the i-v curve can be described by a Fourier series based on the fundamental frequency ω of the applied voltage. The current is then given by :

$$\dot{i}(t) = \sum_{0}^{\infty} \hat{i}_n \cos n\omega t \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (4.9)$$

where

$$\dot{i}_o = \sum_{m=2,4,6,..}^{\infty} a'_m \frac{\hat{V}^m}{2^m}\, {}^mC_{\frac{m}{2}} \quad \ldots \quad \ldots \quad \ldots \quad (4.10)$$

and

$$\hat{i}_n = 2\sum_{m=n,n+2,n+4,..}^{\infty} a'_m \frac{\hat{V}^m}{2^m}\, {}^mC_{\frac{m-n}{2}} \quad \ldots \quad \ldots \quad \ldots \quad (4.11)$$

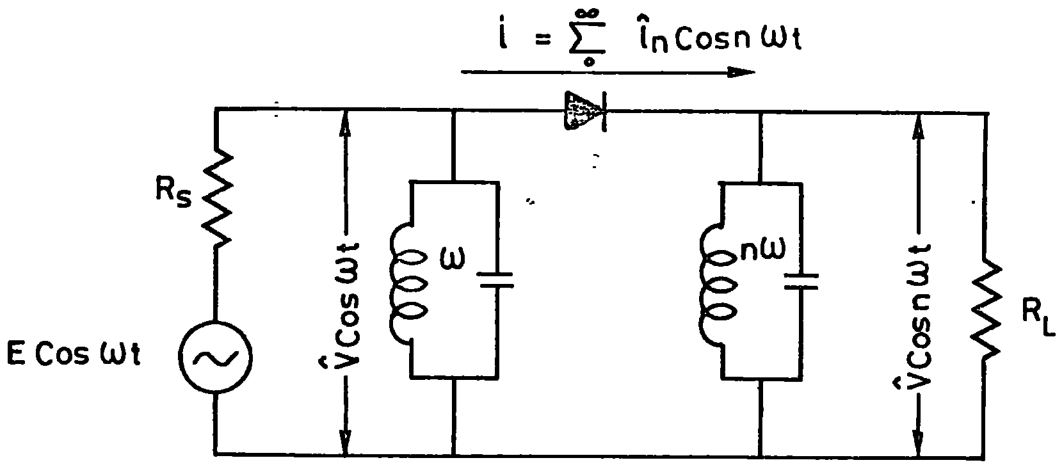


FIG 4·2 a. VOLTAGE - DRIVEN CIRCUIT.

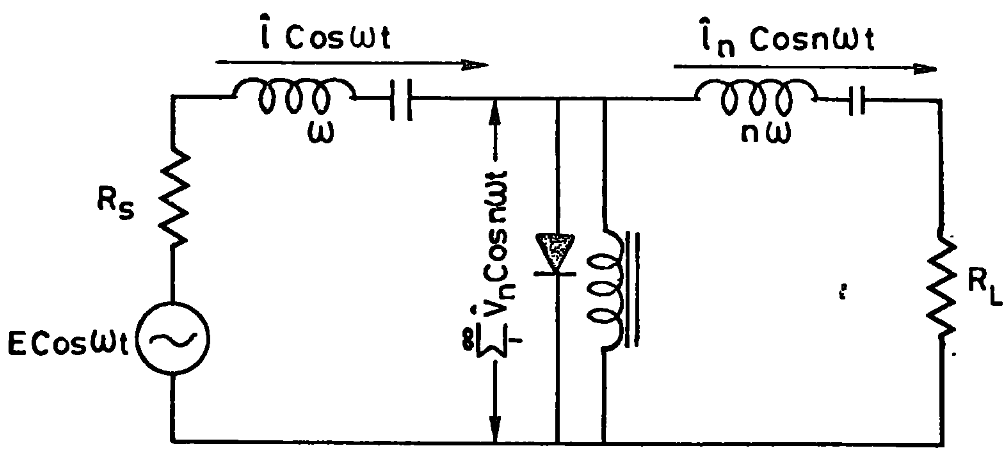


FIG 4·2 b. CURRENT - DRIVEN CIRCUIT.

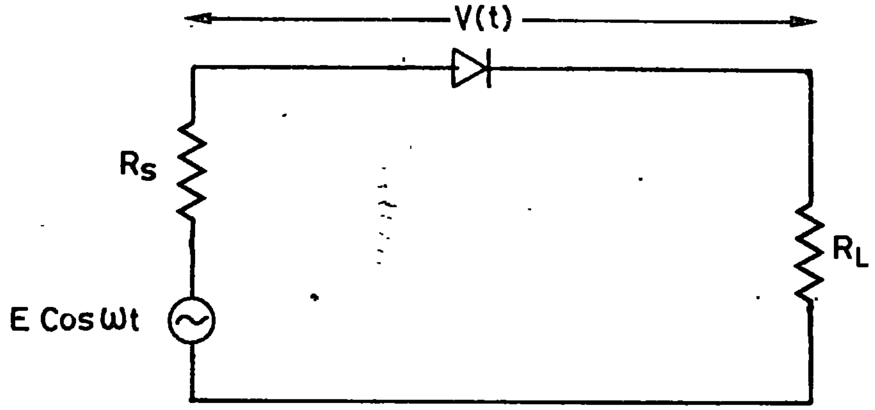


FIG. 4·3 VOLTAGE – DRIVEN DIODE.

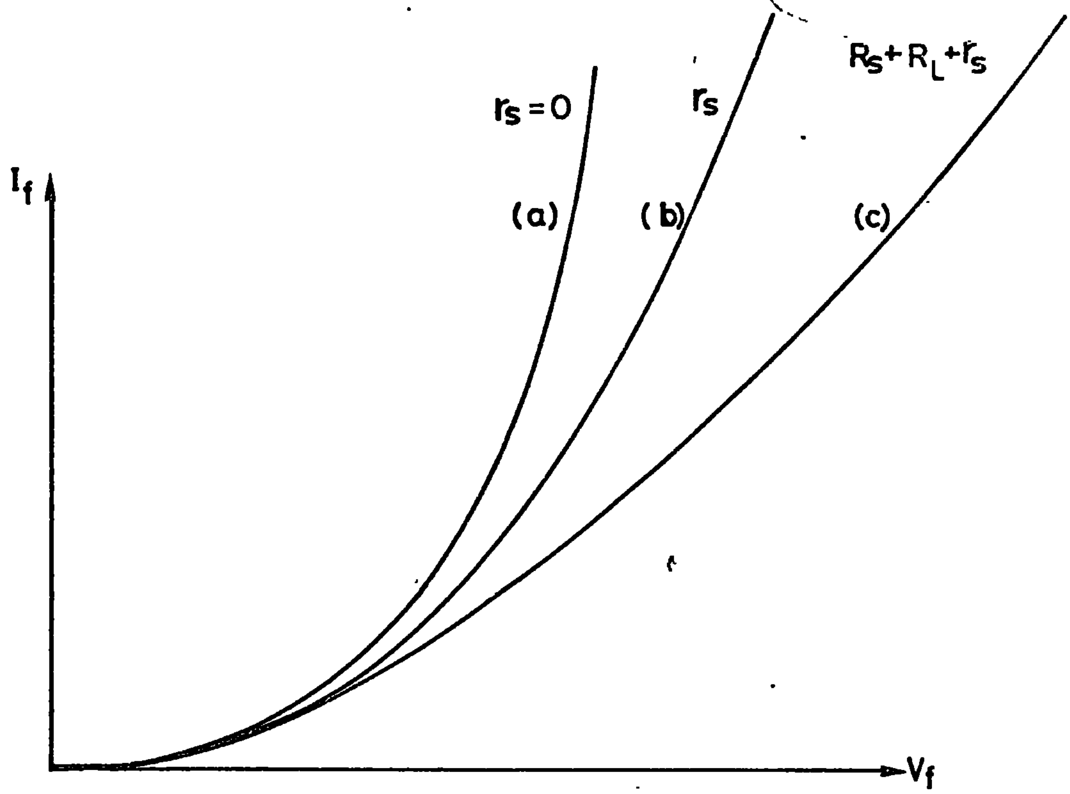


FIG. 4·4 D.C. CHARACTERISTICS.

The coefficient a'_m depends on the characteristic equation of the diode which will be calculated in Chapter 5 for the exponential diode. Consequently, the chord and the incremental resistance or conductances may also be represented by a Fourier series based on the fundamental frequency ω of the type:

$$\frac{V(t)}{i(t)} = R_c(t) = \sum_0^\infty (r_c)_n \cos n\omega t \quad \ldots \quad \ldots \quad (4.12)$$

$$\frac{i(t)}{V(t)} = G_c(t) = \sum_0^\infty (g_c)_n \cos n\omega t \quad \ldots \quad \ldots \quad (4.13)$$

or

$$\frac{dV(t)}{di(t)} = R_i(t) = \sum_0^\infty (r_i)_n \cos n\omega t \quad \ldots \quad \ldots \quad (4.14)$$

$$\frac{di(t)}{dV(t)} = G_i(t) = \sum_0^\infty (g_i)_n \cos n\omega t \quad \ldots \quad \ldots \quad (4.15)$$

The chord conductance, $G_c(t)$, is the component that generates the harmonic currents. Therefore, the best representation of equation (4.13), which relates the harmonic currents and the applied voltage $E \cos \omega t$, is given by the circuit shown in Figure 4.5. Thus equation (4.13) may also be rewritten as

$$\sum_0^\infty \hat{I}n \cos n\omega t = E_1 \cos \omega t \sum_0^\infty (g_c)_n \cos n\omega t \ \ldots \ (4.16)$$

Upon equating the coefficients of the same frequency, the following set of equations is obtained:

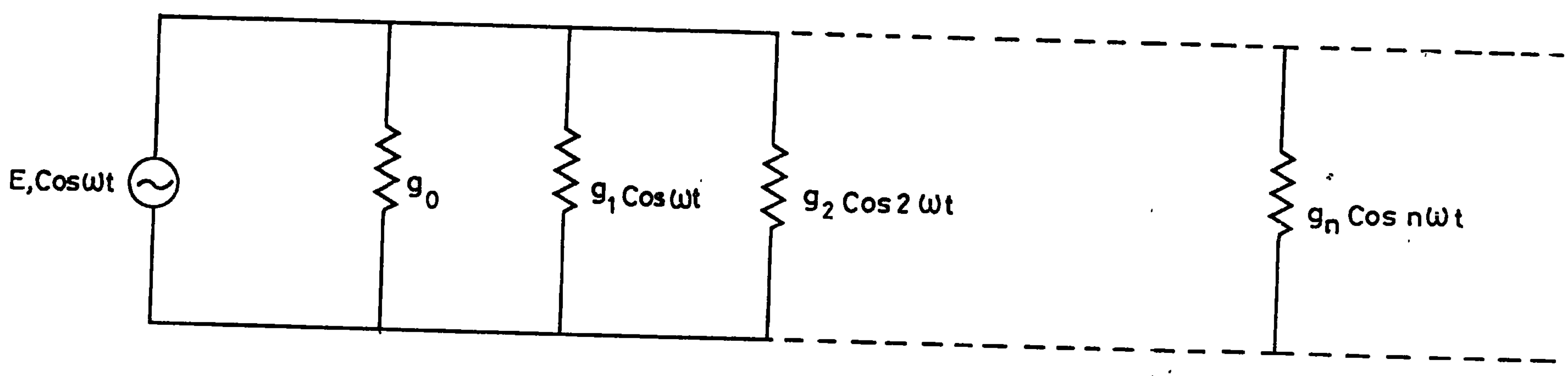


FIG 4·5. THE CHORD CONDUCTANCE.

$$\begin{aligned}
\hat{i}_o &= \frac{1}{2}\ E_1\ g_1 \\
\hat{i}_1 &= \frac{1}{2}\ E_1\ (2g_o + g_2) \\
\hat{i}_2 &= \frac{1}{2}\ E_1\ (g_1 + g_3) \\
\hat{i}_3 &= \frac{1}{2}\ E_1\ (g_2 + g_4) \\
&\vdots \\
\hat{i}_n &= \frac{1}{2}\ E_1\ (g_{n-1} + g_{n+1})
\end{aligned} \qquad (4.17)$$

This set of equations gives the harmonic currents as functions of the harmonic conductances. In practice, however, it is possible to measure or even calculate the harmonic currents. Therefore, it is desirable to obtain the harmonic conductances as functions of the harmonic currents. This is achieved by solving the set of equation (4.17) for g_o, g_1, g_2, ... etc. Then the harmonic chord conductances can be shown to take the following forms:

$$(g_c)_o = \frac{1}{E_1}\ (\hat{i}_1 - \hat{i}_3 + \hat{i}_5 - \hat{i}\ \ \ldots .\infty)\ \ \ldots \qquad (4.18)$$

and

$$(g_c)_n = \frac{2}{E_1}\ (\hat{i}_{n+1} - \hat{i}_{n+3} + \hat{i}_{n+5} \ldots \infty)\ \ldots \qquad (4.19)$$

If one compares the first and the third of equation (4.17) with equation (4.19) then the following relations are found:

$$\dot{i}_o = \hat{i}_2 - \hat{i}_4 + \hat{i}_6 - \hat{i}_8\ \ \ldots\ldots\infty\ \ \ldots \qquad (4.20)$$

$$(g_c)_{n\,(even)} = \frac{2}{E_1} \sum_{m=n+1,n+3}^{\infty} (-1)^{\frac{m+n-1}{2}}\ \hat{i}_m \qquad (4.21)$$

and

$$(g_c)_{n\,(odd)} = \frac{2}{E_1} \sum_{m=0,2,4}^{n-1} (-1)^{\frac{m+n-1}{2}}\ \hat{i}_m \qquad (4.22)$$

These relations can be deduced by the application of Fourier analysis techniques to the chord conductance equation, i.e.

$$G_c(t) = \frac{\sum \hat{i}n \cos n\omega t}{E_1 \cos \omega t} \quad \ldots \quad \ldots \quad \ldots \quad (4.23)$$

The harmonics produced by the high level local oscillator source are an essential part of the mixing process. The voltage and current-driven mixers can be obtained by a slight modification in the frequency-selective imbedding networks of the corresponding harmonic generators. The small signal circuit at ω_s is added as shown in Figure 4.6.

The small signal input at ω_s is mixed with the ℓ.o. frequency and its harmonics producing the sum $(\omega_s + \omega_p)$, the difference $(\omega_p - \omega_s)$ and the image $(2\omega_p - \omega_s)$ frequencies, in addition to many other product frequencies. The difference or the intermediate frequency is the most important component in mixers and the other frequencies are usually considered as parasitics. The harmonic spectrum generated by the ℓ.o. and the final one generated after the mixing process took place, are shown in Figure 4.7, respectively.

The amplitudes in Figure 4.7 are not drawn to scale. The ratio of the available power at the signal frequency to that at the I-F frequency is the conversion power loss, c.p.ℓ. The efficiency may be improved by preventing power loss at the parasitic components, especially at the image frequency. When the ℓ.o. termination is identically equal to the signal and image frequency terminations, the mixer is called broad-band. If there is an open or short circuit termination presented to the image frequency, it is called a narrow-band mixer.

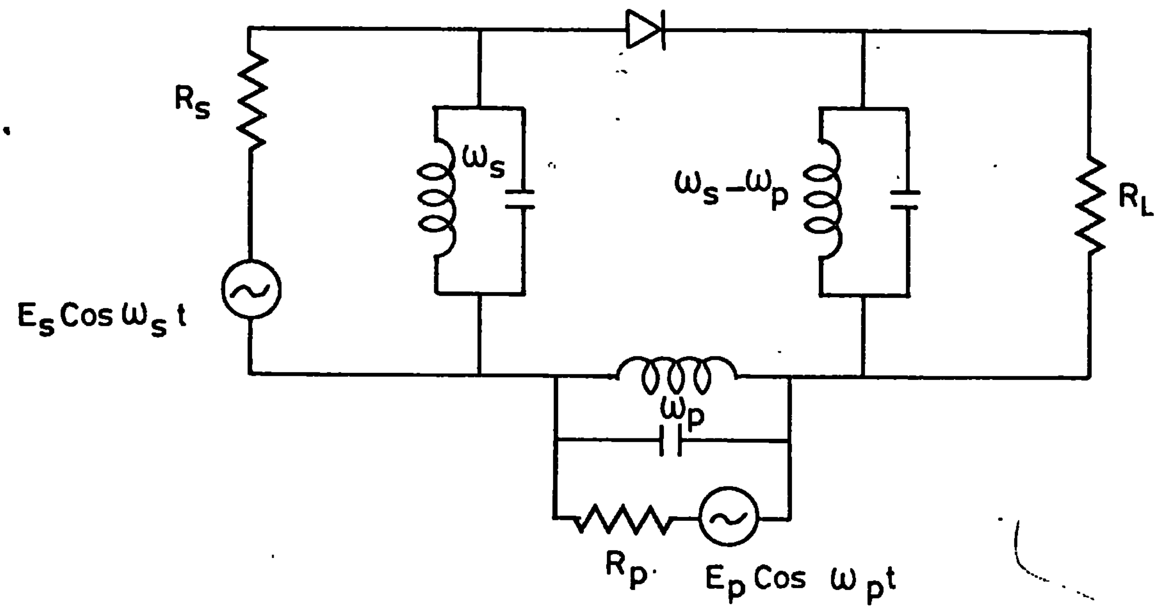


FIG 4·6 a. VOLTAGE - DRIVEN MIXER.

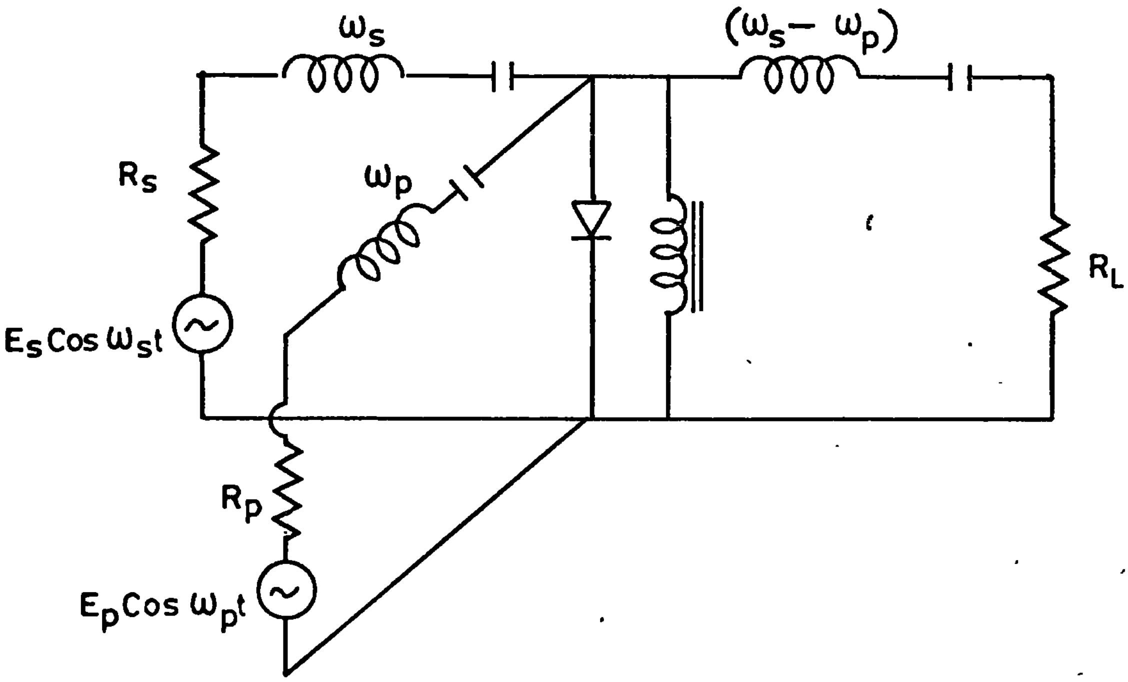


FIG 4·6 b. CURRENT - DRIVE MIXER.

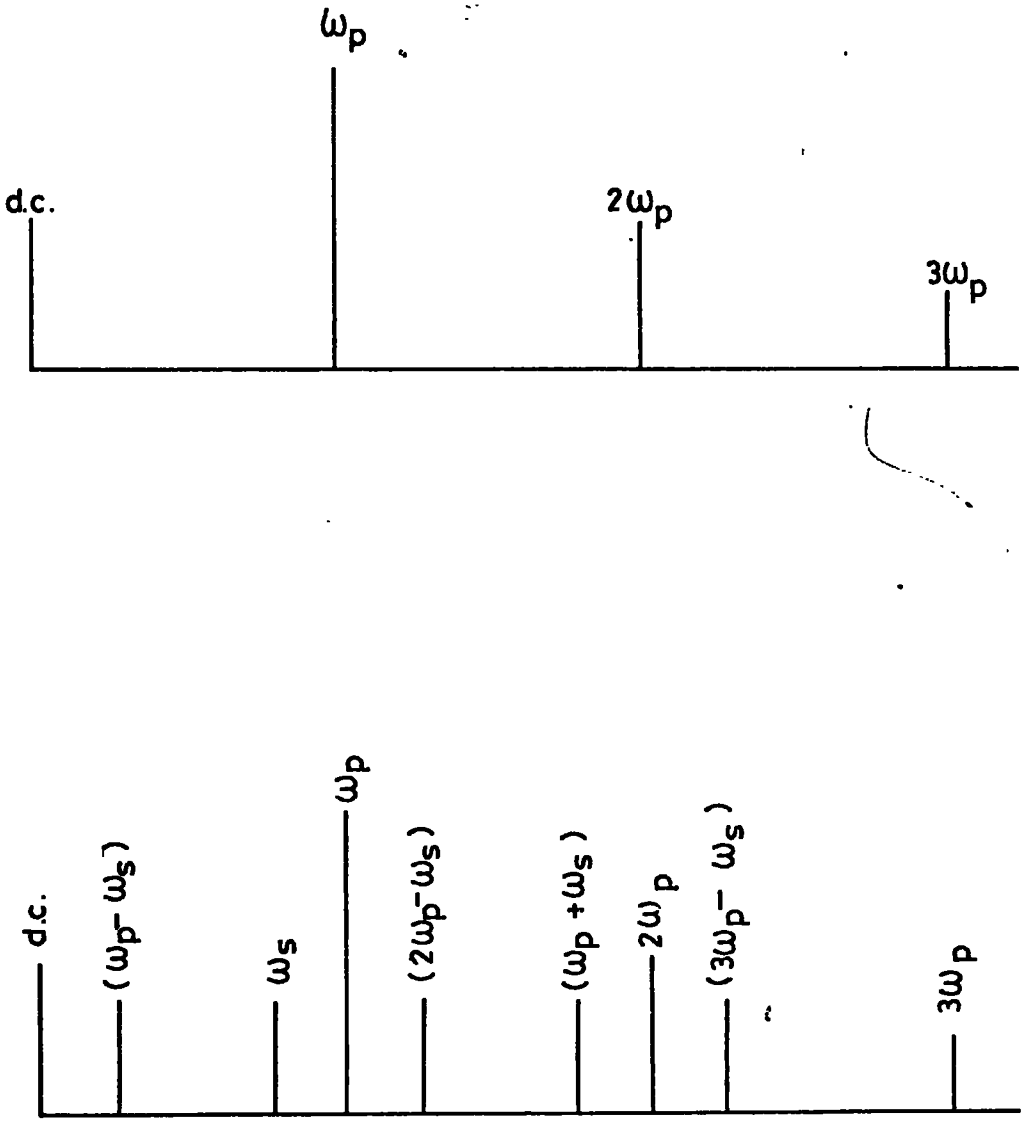


FIG 4·7 HARMONIC SPECTRUM AND FREQUENCIES GENERATED AFTER THE MIXING PROCESS.

The basis for mixing the frequency ω_s of the signal voltage $E_s \cos \omega_s t$ with the frequency ω_p of the ℓ.o. voltage $E_p \cos \omega_p t$ is simply demonstrated by the well-known trigonometric identity:

$$(E_s \cos \omega_s t) \cdot (E_p \cos \omega_p t) = \frac{E_s E_p}{2} \left[\cos(\omega_s + \omega_p)t + \cos(\omega_s - \omega_p)t \right] \quad \ldots \quad (4.24)$$

Such products result from the infinite power series representation of the i-v curve given by

$$i(v) = \sum_{o}^{\infty} a_m V^m \quad \ldots \quad \ldots \quad \ldots \quad (4.25)$$

where

$$V = E_s \cos \omega_s t + E_p \cos \omega_p t$$

The incremental conductance $G_i(t)$ of the nonlinear element is seen by the small signal superimposed on the ℓ.o. drive. This is given by

$$G_i(t) = \frac{di}{dv} = \sum_{1}^{\infty} m\, a_m\, V_s^{m-1} (\cos \omega_s t)^{m-1} \quad \ldots \quad \ldots \quad (4.26)$$

With the help of some standard trigonometric identities it can be shown that:

$$(g_i)_o = \frac{1}{\hat{V}_s} \sum_{m=1,3,5}^{\infty} m \hat{i}_m \quad \ldots \quad \ldots \quad (4.27)$$

and

$$(g_i)_n = \frac{1}{\hat{V}_s} \sum_{m=n+1,n+3,..}^{\infty} m \hat{i}_m \quad \ldots \quad \ldots \quad (4.28)$$

Where $\dot{i}_o$ and $\hat{i}_n$ have the general form of equations (4.10) and (4.11) These relations can also be proved by the application of Fourier analysis technique to the incremental conductance expression

$$\frac{di}{dV} = \frac{\sum_{1}^{\infty} n\, i_n \sin (n\omega t)}{\hat{V}_s \sin \omega_s t} \qquad \ldots \qquad \ldots \qquad (4.29)$$

A detailed analysis of a general nonlinear resistive element is currently under consideration by Dr. Kulesza and his research group in the Department of Applied Physics and Electronics, University of Durham.

The modification incorporated in the voltage driven circuit to the total series resistance cannot be easily considered in the current-driven case since an ideal current source is difficult to achieve in practice. In the voltage-driven circuit it is assumed that the voltage drive is $E_p \cos \omega_p t$ and in the current-driven case the current drive must also include the d.c. current component, i.e. $i_o + \hat{i}_p \cos \omega_p t$. Although the solution to the current-driven equation of an exponential diode is easier than that of the voltage driven case, the measurements of harmonic voltages across a high impedance circuit ~~is~~ are very difficult to carry out experimentally. The measurements of harmonic currents in the voltage-driven case are easy to obtain using frequency selective instruments and the only problems that remain are of mathematical nature in finding the solution to the diode equation. Therefore, the aim of the next chapter is to present a method of solving the exponential equation for the harmonic currents generated in the diode and show the validity of the approach by comparing the theoretically-calculated values with the experimental results.

CHAPTER 5

ANALYSIS OF A VOLTAGE-DRIVEN SCHOTTKY BARRIER DIODE

5.1 General

The analysis considered previously assumed a general nonlinear resistive element. In fact, a practical device such as a Schottky-barrier diode comprises apart from a linear series resistance (r_s) and a nonlinear junction resistance (R_j) also the junction and package capacitances (C_j, C_p) and, due to leads, a series inductance (L_s). Therefore, the device in general may be represented by an equivalent circuit as shown in Figure (5.1).

The individual values of the circuit components are dependent on the specific design. The capacitance lies, normally, in the range from 0.2 to 2.0 Pf, and the inductance is of a few nanohenries (e.g. 3 nh). At dc and frequencies less than 30 MHz, therefore, the magnitude of the capacitive reactance is very large compared to small forward junction resistance and the magnitude of the inductive reactance is considered to be very small. At such low frequencies, then, there is no loss of generality in taking the simplified equivalent circuit of the diode as a linear resistance in series with the nonlinear resistance.

Laboratory experience shows that the i-v characteristic of a hot carrier diode can be accurately described, within 0.2%, by the exponential law of the type:

$$i = I_s \left[\exp\,(\alpha V - \alpha r_s i) - 1 \right] \quad \ldots \quad \ldots \quad (5.1)$$

where ir_s is the voltage drop across the diode spreading resistance and $\alpha = \frac{e}{nKT}$. In practice the measurements are usually taken across an additional resistor (R_L) in series with the diode and the source.

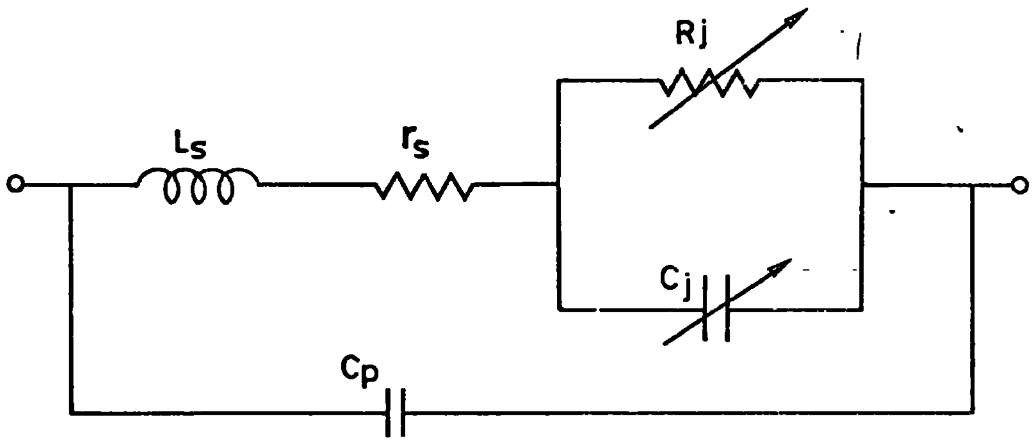


FIG 5·1 Equivalent Circuit of Schottky - Barrier Diode .

It is logical, therefore, to include this resistance also in the diode equation, i.e.

$$i = I_s \left[\exp\,(\alpha V - \alpha R_T i) - 1 \right] \quad \ldots \quad \ldots \quad (5.2)$$

where $R_T = r_s + R_s + R_L$ and R_s is the resistance of the energising source.

For the reverse characteristic, the deviation from theory may be avoided by considering that the incremental resistance is of sufficiently high value not to interfere in most applications with the operation of the harmonic generating circuits. This is especially true for commercial Schottky-barrier diodes at and below the 2 volts of the applied peak drive.

In most ac applications the diode is energised by a single frequency sinusoidal pump while the response contains all possible harmonics. Therefore, the response of a single frequency voltage-driven diode is a spectrum of harmonic currents. In order to derive a useful mathematical representation for the individual harmonic component, the current may be expanded as a power series of the applied voltage, i.e.

$$i = \sum_{m=0}^{\infty} a_m V^m \quad \ldots \quad \ldots \quad (5.3)$$

To simplify the analysis, it is convenient to restrict both the voltage and the Fourier currents to cosine terms. The coefficients of the power series are given by the derivatives of the modified exponential law (equation (5.2)), with respect to V, evaluated at V = 0. The first six derivatives have been calculated directly by Orloff[(41)] in 1963. In 1967, Mills[(42)] has determined higher derivatives as polynomials in $\frac{di}{dV}$ whose coefficients satisfy a recursion relation. In both methods the computation of the mth derivative depended on the (m-1)th derivative.

An attempt has been made by the author to test the convergence of the power series under the assumption that the magnitude of the mth coefficient must decrease as m gets larger. Hence a computer programme has been proposed to calculate the coefficients for a practical diode using a matrix formula of the type:

$$A = B\,X \qquad \ldots \qquad \ldots \qquad \ldots \qquad \ldots \qquad (5.4)$$

where:

$$A = \begin{pmatrix} a_1 \\ a_2 \\ \vdots \\ a_m \end{pmatrix}, \qquad B = \begin{pmatrix} b_{11} & b_{12} \cdots & b_{1n} \\ b_{21} & \cdots & \vdots \\ \vdots & & \vdots \\ b_{m1} & & b_{mn} \end{pmatrix}, \qquad X = \frac{(-1)^{n-1}}{(1-x)^{2m-1}} \begin{pmatrix} 1 \\ x \\ x^2 \\ \vdots \\ x^{n-1} \end{pmatrix}$$

and $x = \alpha R_T I_s$.

The absolute values of the matrix elements can be calculated from:

$$b_{m,n} = \frac{I_s\,\alpha^m}{m!}\left[n\,b_{(m-1),n} + (2m-n-2)\,b_{(m-1),(n-1)}\right] \qquad (5.5)$$

using as initial values

$$b_{m,n} = 0 \quad \text{for} \quad m \leqslant n$$

and

$$b_{m,1} = 1 \quad \text{for} \quad m = 1, 2, 3, \ldots\ldots$$

The values for x used in the computations were taken from the parameters of practical diodes and covered the range extending from 10^{-4} to 10^{-7}.

The computed coefficients resulted in alternating sequences. The first one contained decreasing positive values of $|a_m|$ with increasing m. The second sequence began with increasing negative values of $|a_m|$ as m increased further. Then, the increase of $|a_m|$ continued indefinitely for the rest of the alternating sequences, up to the computer limit.

The uncertainty, experienced by such sequences, creates problems in converging the power series. However, the series must converge to a definite value, for any given applied voltage, determined from the finite closed form of the exponential law. Therefore, it was thought that a closed form of $a_m(x)$ would result in rapid convergence of the power series. Many different attempts have been made to derive such relations and one of the best will be the subject of Section 5.3.

5.2 Basic Relations

Let, for simplicity, the driving voltage and the resulting current functions be represented as v and i, respectively, i.e. for the voltage driven circuit

$$i = \sum_{0}^{\infty} \hat{i}_n \cos n\omega_p t \quad \text{and} \quad V = \hat{V}_p \cos \omega_p t \ .$$

Since the current is a continuous single-valued function of the applied voltage and its m^{th} derivation with respect to V exists, the current may be expanded as an infinite power series (equation (5.3))

$$i(v) = \sum_{0}^{\infty} a_m v^m$$

where $a_o = 0$ (as no biasing current has been assumed), and a_1, a_2, a_3, ... etc. are dimensionally in amp./volt, amp./volt^2, amp./volt^3, etc. ... respectively.

In general $i(v(t)) = f(v)$ and using Maclaurin's expansion yields

$$f(v) = f(o) + \frac{f^{(1)}(o)}{1!} v + \frac{f^{(2)}(o)}{2!} v^2 + \frac{f^{(3)}(o)}{3!} v^3 \ldots + \frac{f^{(m)}(o)}{m!} v^m \ldots \quad (5.6)$$

where $f^{(m)}(o)$ is the m^{th} derivative w.r.t. v evaluated about v = 0.

The coefficients in the power series expansion are consequently given by

$$a_m = \frac{1}{m!} f^{(m)}(o) = \frac{1}{m!} \left. \frac{d^m i}{dV^m} \right|_{V=0} \quad \ldots \quad (5.7)$$

If next, the diode equation is differentiated successively w.r.t. V then

$$f^{(1)}(o) = \alpha I_s \frac{1}{(1 + x)}$$

$$f^{(2)}(o) = \alpha^2 I_s \frac{1}{(1 + x)^3}$$

$$f^{(3)}(o) = \alpha^3 I_s \frac{1 - 2x}{(1 + x)^5} \quad \ldots \quad \ldots \quad (5.8)$$

$$f^{(4)}(o) = \alpha^4 I_s \frac{1 - 8x + 6x^2}{(1 - x)^6}$$

etc.

where $x = \alpha R_T I_s$ and the numerical coefficients of x follow a particular sequence which will be examined and discussed in detail later.

Introducing another coefficient A which is a function of x, such that

$$f^{(m)}(o) = \alpha^m I_s A_m(x) \quad \ldots\ldots \quad \ldots \quad \ldots \quad (5.9)$$

the power series expansion may be rewritten as

$$i = I_s \sum_{1}^{\infty} A_m(x) \frac{(\alpha V)^m}{m!} \qquad \dots \qquad \dots \qquad (5.10)$$

and, under the assumption that $A_o = 1$, the diode equation can then be expressed as

$$i = I_s \left(\sum_{o}^{\infty} A_m(x) \frac{(\alpha V)^m}{m!} - 1 \right) \qquad \dots \qquad (5.11)$$

or

$$\exp(\alpha V - \alpha R_T i) = \sum_{o}^{\infty} A_m(x) \frac{(\alpha V)^m}{m!} \qquad \dots \qquad (5.12)$$

where

$$A_o = 1$$

$$A_1 = \frac{1}{(1 + x)}$$

$$A_2 = \frac{1}{(1 + x)^3}$$

$$A_3 = \frac{1 - 2x}{(1 + x)^5} \qquad \dots \qquad \dots \qquad (5.13)$$

$$A_4 = \frac{1 - 8x + 6x^2}{(1 + x)^7}$$

$$A_5 = \frac{1 - 22x + 58x^2 - 24x^3}{(1 + x)^9}$$

⋮

etc.

5.3 Expansions for the A(x) Coefficients

As it has been seen, the coefficients $A_m(x)$ are given by the quotient of two polynomials. The denominator of each quotient is in a closed form while the numerator cannot be found in a closed form. Because of the latter case, and in addition to the difficulties experienced in an attempt to evaluate the A(x) coefficient numerically, it was decided to transform the finite quotients into an infinite series by multiplying the polynomial in the numerator by the infinite power series expansion of the quotient

$$\frac{1}{(1 + x)^{(2n-1)}} \quad ,$$

which resulted in

$$\begin{aligned}
A_o &= 1 \\
A_1 &= 1 - x + x^2 - x^3 + x^4 \ldots\ldots \\
A_2 &= 1 - 3x + 6x^2 - 10x^3 + 15x^4 \ldots\ldots \\
A_3 &= 1 - 7x + 25x^2 - 65x^3 + 140x^4 \ldots\ldots \qquad (5.14) \\
A_4 &= 1 - 15x + 90x^2 - 350x^3 + 1050x^4 \ldots\ldots \\
&\vdots \\
\text{etc.}
\end{aligned}$$

It was found that the coefficients of x in the new series are the Stirling Numbers[43] of the second kind. Rewriting the above set of series using the Stirling Numbers, S_n^m , gives

$$
\begin{aligned}
A_o &= S_o^1 \\
A_1 &= S_1^1 - S_2^2 x + S_3^3 x^2 - S_4^4 x^3 + \ldots\ldots \\
A_2 &= S_2^1 - S_3^2 x + S_4^3 x - S_5^4 x^3 + \ldots\ldots \\
A_3 &= S_3^1 - S_4^2 x + S_5^3 x - S_6^4 x^3 + \ldots\ldots \\
&\vdots
\end{aligned}
\qquad (5.15)
$$

for $n \geqslant 1$

$$A_n(x) = \sum_{m=1} (-1)^{m-1} \; S^m_{n+m-1} \; x^{m-1}$$

where

$$S^m_n = \frac{1}{m!} \sum_{K=0}^{m} (-1)^{m-K} \; {}^mC_K \; K^n \quad \ldots \quad \ldots \qquad (5.16)$$

Further, using the general expansion for the Stirling numbers and rearranging the terms it was found that A(x) coefficients may be also expressed as series of exponentials of the form:

$$
\begin{aligned}
A_1 &= e^x - 2\frac{(2x)}{2!}e^{2x} + 3\frac{(3x)^2}{3!}e^{3x} - 4\frac{(4x)^3}{4!}e^{4x} + \ldots. \\
A_2 &= e^x - 2^2\frac{(2x)}{2!}e^{2x} + 3^2\frac{(3x)^2}{3!}e^{3x} - 4^2\frac{(4x)^3}{4!}e^{4x} + \ldots. \\
A_3 &= e^x - 2^3\frac{(2x)}{2!}e^{2x} + 3^3\frac{(3x)^2}{3!}e^{3x} - 4^3\frac{(4x)^3}{4!}e^{4x} + \ldots. \\
A_4 &= e^x - 2^4\frac{(2x)}{2!}e^{2x} + 3^4\frac{(3x)^2}{3!}e^{3x} - 4^4\frac{(4x)^3}{4!}e^{4x} + \ldots. \\
&\vdots
\end{aligned}
\qquad (5.17)
$$

etc.

from which the general expression is given by

$$A_n(x) = e^x \sum_{K=0}^{\infty} (-1)^K \frac{(K+1)^{n+K}}{(K+1)!} (x\,e^x)^K \quad \ldots \qquad (5.18)$$

The expansions just developed for the A(x) coefficients still do not converge sufficiently quickly to be of practical value. However, the formulae are necessary for further stages of the analysis, in addition to their usefulness in computing the n^{th} derivative of the exponential law, evaluated at V = 0, independently.

5.4 Infinite Series Solutions for the Harmonic Currents

Since the harmonic currents that result from the exponential diode are defined by Fourier series, it has been found necessary to study the properties of the modified exponential law given in the form of an infinite series. The expression used to obtain the amplitude of the harmonic currents is given in equation (5.10). In this case the power series expansion in terms of the driving voltage $V = \hat{V}_p \cos \omega_p t$ is given by

$$i = I_s \sum_{m=1}^{\infty} A_m(x) \frac{(\alpha \hat{V}_p)^m}{m!} (\cos \omega_p t)^m \quad \ldots \quad \ldots \quad (5.19)$$

The term $(\cos \omega_p t)^m$ can be evaluated in terms of its harmonic components using the trigonometric expansion

$$(\cos \omega_p t)^m = \frac{1}{2^m} \left[\sum_{K=0}^{m} \binom{m}{K} \cos (m - 2K) \omega_p t \right] \quad \ldots \quad (5.20)$$

where $^mC_K = \binom{m}{K} = \frac{m(m-1)(m-2) \ldots\ldots (m-K+1)}{K!}$ and $\binom{m}{o} = 1$

Substituting the results of (5.20) into (5.19) and arranging terms of the sum yields

$$i = I_s \sum_{m=2,4,..}^{\infty} A_m(x) \frac{(\alpha\hat{V}_p)^m}{m!} \cdot \frac{1}{2^m} {}^mC_{\frac{m}{2}} + 2I_s \sum_{n=1}^{\infty} \left[\sum_{m=n,n+2,..}^{\infty} A_m(x) \frac{(\alpha\hat{V}_p)^m}{m!} \cdot \frac{1}{2^m} {}^mC_{\frac{m-n}{2}} \right] \cos n\omega_p t$$

(5.21)

This is identical to the Fourier cosine series of the type:

$$i = i_o + \sum_{n=1}^{\infty} \hat{i}_n \cos n\,\omega_p t \quad \ldots \quad \ldots \quad (5.22)$$

Thus, the amplitudes of the harmonics can now be extracted directly by equating the coefficients at the same frequency on both sides of the equation, i.e.

$$i_o = I_s \sum_{m=2,4,6,..}^{\infty} A_m(x) \frac{(\alpha\hat{V}_p)^m}{m!} \frac{1}{2^m} {}^mC_{\frac{m}{2}} \quad \ldots \quad (5.23)$$

and for $n > 1$

$$\hat{i}_n = 2I_s \sum_{m=n,n+2,n+4,..}^{\infty} A_m(x) \frac{(\alpha\hat{V}_p)^m}{m!} \frac{1}{2^m} {}^mC_{\frac{m-n}{2}} \quad \ldots \quad (5.24)$$

For a nondissipative diode, (i.e. $A_m(x) = 1$ when $R_T = 0$), the two summations are the modified Bessel Functions of the first kind of order zero and n respectively. In order to determine similar relations for the practical diode in situ, the series for the coefficient $A_m(x)$, i.e.

$$A_m(x) = e^x \sum_{K=0}^{\infty} (-1)^K \frac{(K+1)^{m+K}}{(K+1)!} (x\,e^x)^K \quad \ldots \quad (5.25)$$

is substituted into the equations (5.23) and (5.24). Rearranging terms and using the identity[44]

$$e^{-x} = 1 - \frac{2}{2!}(x\,e^x) + \frac{3^2}{3!}(x\,e^x)^2 - \frac{4^3}{4!}(x\,e^x)^3 \quad (5.26)$$

the dc and harmonic components may also be written in terms of the modified Bessel functions, i.e.

$$i_o = I_s e^x \left[\mathcal{I}_o(\alpha V_p) - \frac{2}{2!}(x e^x) \mathcal{I}_o(2\alpha \hat{V}_p) + \frac{3^2}{3!}(x e^x)^2 \mathcal{I}_o(3\alpha \hat{V}_p) - \frac{4^3}{4!}(x e^x)^3 \mathcal{I}_o(4\alpha \hat{V}_p) + \ldots\ldots\infty \right] - I_s \ldots \quad (5.27)$$

or

$$i_o = I_s e^x \left[\sum_{K=1}^{\infty} (-1)^{K-1} \mathcal{I}_o(K\alpha \hat{V}_p) \cdot \frac{K^{K-1}}{K!} (x e^x)^{K-1} \right] - I_s \quad (5.28)$$

and

$$\hat{i}_n = 2I_s \left[\sum_{K=1}^{\infty} (-1)^{K-1} \mathcal{I}_n(K\alpha \hat{V}_p) \frac{K^{K-1}}{K!} (x e^x)^{K-1} \right] \quad (5.29)$$

The above solutions, although elegant in form, again do not converge quickly enough to be of practical value for numerical evaluations. Any further attempts to make them converge faster proved unsuccessful. However, a different initial approach, described in the next section, has eventually produced the required expressions suitable for numerical evaluation of the harmonic amplitudes.

5.5 The Solution

The aim is to devise a method for obtaining a closed form expression which provides the fastest and most easily programmable solution. A direct approach is to consider the diode power series solution of the current as a function of the applied voltage which is given by

$$i(V) = I_s \sum_{1}^{\infty} A_m(x) \frac{(\alpha V)^m}{m!} \quad \ldots \quad \ldots \quad (5.30)$$

where $V = V_p \cos \omega_p t$

and

$$A_m(x) = e^x \sum_{o}^{\infty} (-1)^K \frac{(K+1)^{m+K}}{(K+1)!} (x\ e^x)^K \quad \ldots \quad (5.31)$$

Expanding equation (5.30) with the substitution of $A_m(x)$ from equation (5.31) gives the following expansions:

$$i(V) = I_s e^x \Bigg[\left[\frac{(\alpha V)}{1!} + \frac{(\alpha V)^2}{2!} + \frac{(\alpha V)^3}{3!} + \ldots\ldots \infty \right]$$

$$- \frac{2}{2!}(x\ e^x) \left[\frac{(2\alpha V)}{1!} + \frac{(2\alpha V)^2}{2!} + \frac{(2\alpha V)^3}{3!} + \ldots\ldots \infty \right]$$

$$+ \frac{3^2}{3!}(x\ e^x)^2 \left[\frac{(3\alpha V)}{1!} + \frac{(3\alpha V)^2}{2!} + \frac{(3\alpha V)^3}{3!} + \ldots\ldots \infty \right] -$$

$$- \ldots\ldots\ldots\ldots\ldots\ldots \infty \Bigg] \quad (5.32)$$

Replacing each series in the brackets $[\ldots\ldots\ldots]$ by an exponential of the same arguments results in

$$i(V) = I_s e^x \left[(e^{\alpha V} - 1) - \frac{2}{2!}(xe^x)(e^{2\ V} - 1) + \frac{3^2}{3!}(xe^x)^2 (e^{3\alpha V} - 1) \ldots\ldots \infty \right] \quad (5.33)$$

Rearranging and using the expansion given in equation (5.26) yields finally

$$i(V) = I_s\ e^{\alpha V + x} \left[1 - \frac{2}{2!}(x\ e^{\alpha V + x}) + \frac{3^2}{3!}(x\ e^{\alpha V + x})^2 \ldots\ldots \infty \right] - I_s \quad (5.34)$$

or in a summation form

$$i(V) = I_s e^{\alpha V+x}\left[1+\sum_{K=1}^{\infty}(-1)^K \frac{(K+1)^K}{(K+1)!}(x\, e^{\alpha V+x})^K\right] - I_s \qquad (5.35)$$

If the new variable y is introduced such that

$$x\, e^{\alpha V+x} = y\, e^{y} \quad \ldots \quad \ldots \quad \ldots \quad (5.36)$$

then

$$i(V) = I_s e^{\alpha V+x}\left[1+\sum_{K=1}^{\infty}(-1)^K \frac{(K+1)^K}{(K+1)!}(y\, e^{y})^K\right] - I_s \qquad (5.37)$$

Since the above expression now satisfies the expansion for e^{-y}, it can be written in a closed form, i.e.

$$i(V) = I_s e^{\alpha V+x} . e^{-y} - I_s \quad \ldots \quad \ldots \quad (5.38)$$

where the value of y must satisfy the indicial equation

$$\alpha V + \ell nx + x = y + \ell ny \quad \ldots \quad \ldots \quad (5.39)$$

Letting

$$\ell ny = X \quad \ldots \quad \ldots \quad \ldots \quad (5.40)$$

it is immediately clear that

$$Z = e^{X} + X \ldots \quad \ldots \quad \ldots \quad (5.41)$$

where $Z = \alpha V + \ell nx + x$ and X is a function of $\omega_p t$.

If this new variable is substituted into equation (5.38), then the equation for the current through the diode can be rewritten as

$$i(\omega_p t) = I_s\left(\frac{e^{X(\omega_p t)}}{x} - 1\right) \quad \ldots . \quad \ldots \quad (5.42)$$

or

$$i(\omega_p t) = I_s\left[\frac{Z(\omega_p t)}{x} - \frac{X(\omega_p t)}{x} - 1\right] \quad \ldots \quad (5.43)$$

It is clear, from the relation $Z(\omega_p t) = \hat{V}_p \cos \omega_p t + \ell n\, x + x$, that the function represented by $Z(\omega_p t)$ is periodic and has the period 2π of the applied voltage $\hat{V}_p \cos \omega_p t$. Thus, the function $X(\omega_p t)$ is periodic and it can be determined, numerically, from $Z(\omega_p t) = e^{X(\omega_p t)} + X(\omega_p t)$ for any fixed value of $\omega_p t$. The graph of $X(\omega_p t)$, shown in Figure 5.2 can be repeated periodically in any interval of length 2π, i.e. $X(\omega_p t + 2n\pi) = X(\omega_p t)$. The Fourier coefficients of such an even function, i.e. $X(-\omega_p t) = X(\omega_p t)$, are given by

$$\hat{i}^{1}_{K} = \frac{2}{N} \sum_{r=0}^{N-1} X(r \cdot \frac{\pi}{N}) \cdot \cos K(r \cdot \frac{\pi}{N}) \quad \ldots \quad \ldots \qquad (5.44)$$

where N is the number of ordinates taken in the interval o to π and $X(r \cdot \frac{\pi}{N})$ is the value of X evaluated at $(r \cdot \frac{\pi}{N})$.

Hence the amplitudes of the harmonic currents, are finally given, using equation (5.43), by

$$i_o = \frac{I_s}{x} \left[(\ln x + x) - \frac{2}{N} \sum_{r=0}^{N-1} X(r \cdot \frac{\pi}{N}) - x \right]$$

$$\hat{i}_1 = \frac{I_s}{x} \left[\alpha \hat{V}_p - \frac{2}{N} \sum_{r=0}^{N-1} X(r \cdot \frac{\pi}{N}) \cdot \cos(r \cdot \frac{\pi}{N}) \right]$$

$$\hat{i}_2 = \frac{I_s}{x} \left[-\frac{2}{N} \sum_{r=0}^{N-1} X(r \cdot \frac{\pi}{N}) \cos 2(r \cdot \frac{\pi}{N}) \right] \qquad (5.45)$$

$$\vdots$$

$$\hat{i}_K = \frac{I_s}{x} \left[-\frac{2}{N} \sum_{r=0}^{N-1} X(r \cdot \frac{\pi}{N}) \cos K(r \cdot \frac{\pi}{N}) \right] \quad \text{for } K \geqslant 2$$

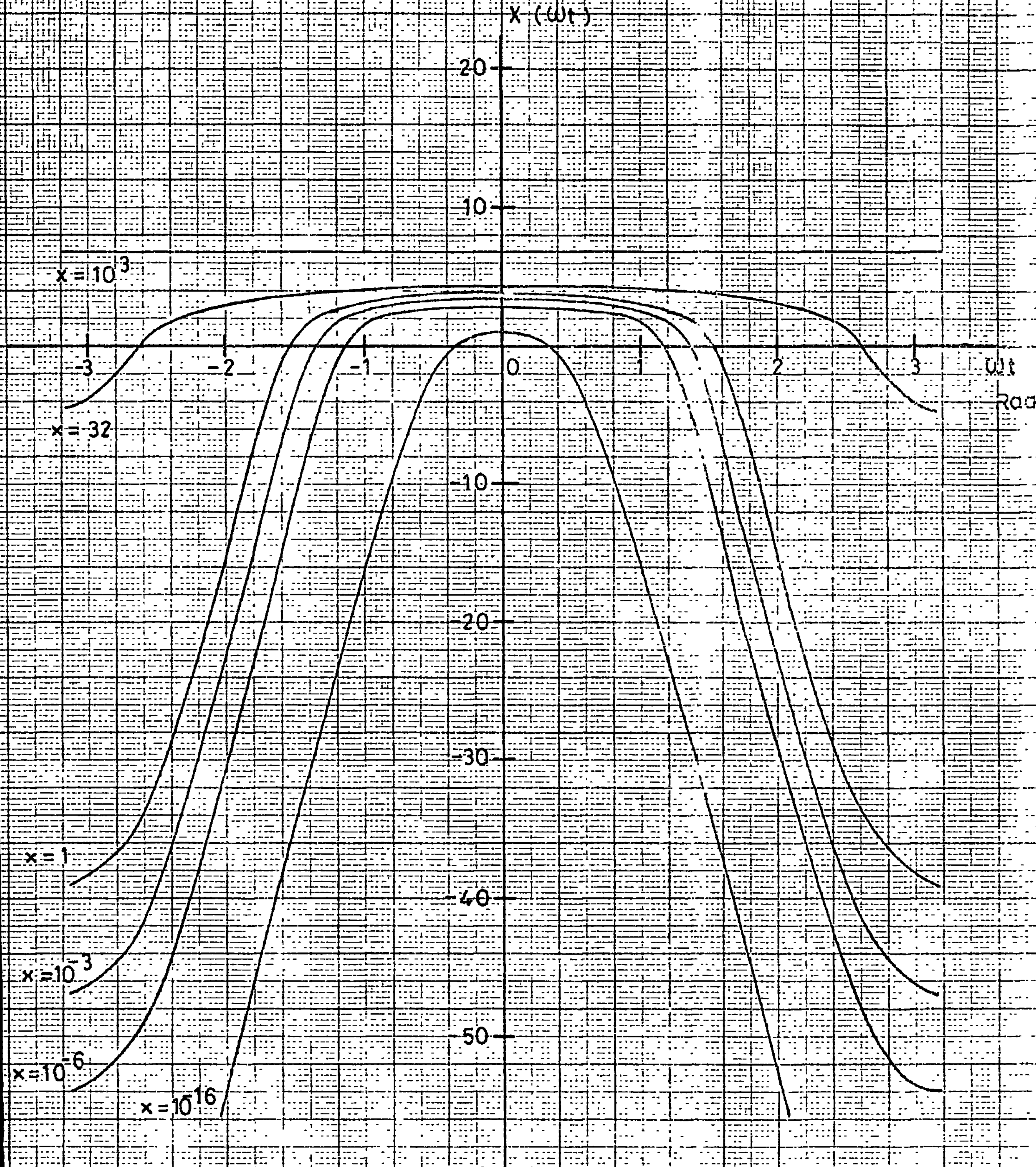


FIG 5.2 X(ωt) Vs ωt

or from equation (5.42)

$$i_K = \frac{2}{N} \sum_{r=0}^{N-1} i\,(r\,.\,\frac{\pi}{N})\,.\cos K\,(r\,.\,\frac{\pi}{N}) \qquad \ldots \qquad \ldots \qquad (5.46)$$

where

$$i\,(r\,.\,\frac{\pi}{N}) = \frac{I_s}{x}\,(e^{X(r.\frac{\pi}{N})} - x) \qquad \ldots \qquad \ldots \qquad (5.47)$$

The error of these approximations diminishes as N increases.

5.6 An Alternative Approximate Solution

In Section 5.5 the waveforms of $X(\omega_p t)$ were plotted (Figure 5.2) numerically, using the auxiliary indicial equation

$$Z(\omega_p t) = X(\omega_p t) + e^{X(\omega_p t)} \qquad \ldots \qquad \ldots \qquad (5.48)$$

where $Z(\omega_p t) = \alpha \hat{V}_p \cos \omega_p t + \ell nx + x$. For a constant applied voltage $\hat{V}_p$, it is clear that the amplitude and the width of $X(\omega_p t)$ are proportional to $x = \alpha I_s R_T$ and hence to the total series resistance R_T. The positive going waveform may be represented by a pulse train of duration τ, repetitive in the period 2π, and with amplitude $|X(0)|$. Since $T = 2\pi$ there is no loss of generality to consider X as a function of t, e.g. X(t).

It is also noticed that X(t) is less than Z(t) for all positive waveforms. Therefore, it is thought that X(t) may be expressed as an explicit function of Z(t) if equation (5.48) is expanded in terms of X(t)/Z(t) and the terms of powers greater than two are neglected. That is to say

$$X = \ell n\ (Z - X)$$

$$X = \ell n Z + \ell n \left(1 - \frac{X}{Z}\right)$$

$$X \simeq \ell n Z - \frac{X}{Z} - \frac{1}{2}\left(\frac{X}{Z}\right)^2 \quad \ldots \quad \ldots \quad \ldots \quad (5.49)$$

Solving the resultant quadratic equation, for X_+, yields

$$X(t) \approx \left[Z^2(t) + Z(t)\right] \left[\sqrt{\frac{2\ell n\, Z(t)}{1 + Z(t)^2} + 1} - 1\right] \quad \ldots \quad (5.50)$$

This equation is valid over the positive waveform interval which ranges from zero to $\tau/2$. Since $X(\tau/2) = 0$, it follows from equation (4.48) that

$$\alpha \hat{V}_p \cos \tau/2 + \ell n x + x = 1$$

and

$$\tau/2 = \cos^{-1}\left[\frac{1 - \ell n\, x - x}{\alpha \hat{V}_p}\right] \quad \ldots \quad \ldots \quad \ldots \quad (5.51)$$

It is found that equation (5.50) is accurate within 0.03% over the interval

$$\cos^{-1}\left[\frac{1 - \ell n\, x - x}{\alpha \hat{V}_p}\right] \geqslant t \geqslant 0 \quad \ldots \quad \ldots \quad \ldots \quad (5.52)$$

From equation (5.51), the value of x and hence R_T may be limited such that $1 \geqslant \frac{1 - \ell n\, x - x}{\alpha \hat{V}_p} \geqslant - 1$. Therefore, the maximum and minimum values of x are given respectively by

$$\ell n\ x + x = \alpha \hat{V}_p + 1 \quad \ldots \quad \ldots \quad \ldots \quad (5.53)$$

$$\ell n\ x + x = -(\alpha \hat{V}_p - 1) \quad \ldots \quad \ldots \quad \ldots \quad (5.54)$$

Thus, when x and α are known it is interesting to predict from equation (5.54) the maximum value of the peak applied voltage, $\hat{V}_p = \frac{1 - \ln x - x}{\alpha}$, such that the maximum (∞) number of harmonic currents may be extracted for a practical diode.

For a very small portion of the negative waveform $|X(t)|$ is very small. Therefore, equation (5.48) can be expanded as

$$Z(t) \simeq X(t) + 1 + \frac{X(t)}{1!} + \frac{X^2(t)}{2!} \qquad \ldots \qquad \ldots \qquad (5.55)$$

Solving for X(t) gives

$$X(t) \simeq 2\left[\sqrt{\frac{Z+1}{2}} - 1\right] \qquad \ldots \qquad \ldots \qquad \ldots \qquad (5.56)$$

This expression is valid for $1 \geqslant \frac{Z+1}{2} > 0$ or

$$\cos^{-1}\left[\frac{-1 - \ln x - x}{\alpha \hat{V}_p}\right] > t \geqslant \cos^{-1}\left[\frac{1 - \ln x - x}{\alpha \hat{V}_p}\right] \qquad (5.57)$$

The corresponding relation of X(t) over the rest of the interval may be approximated by

$$X(t) \simeq Z(t) \qquad \ldots \qquad \ldots \qquad \ldots \qquad (5.58)$$

where

$$\pi \geqslant t \geqslant \cos^{-1}\left[\frac{-1 - \ln x - x}{\alpha \hat{V}_p}\right] \qquad \ldots \qquad \ldots \qquad (5.59)$$

It is shown in Section 5.5 that the current is given by equation (5.42) as

$$i(t) = \frac{I_s}{x}\left[e^{X(t)} - x\right] \qquad \ldots \qquad \ldots \qquad (5.60)$$

Substituting equations (5.50), (5.56) and (5.58) into equation (5.60) gives

$$i(t) \simeq \begin{cases} \frac{I_s}{x}\left[\exp\left\{\left(Z^2(t)+Z(t)\right)\left(\sqrt{\frac{2\ell n Z(t)}{1+Z(t)^2}+1}-1\right)\right\}-x\right] & \cos^{-1}\left[\frac{1-\ell nx-x}{\alpha\hat{V}_p}\right] \geqslant t \geqslant 0 \\ \frac{I_s}{x}\left[\exp\left\{2\left(\sqrt{\frac{Z(t)+1}{2}}-1\right)\right\}-x\right] & \cos^{-1}\left[\frac{-1-\ell nx-x}{\alpha\hat{V}_p}\right] > t \geqslant \cos^{-1}\left[\frac{1-\ell nx-x}{\alpha\hat{V}_p}\right] \\ \frac{I_s}{x}\left[\exp\left(Z(t)\right) - x\right] & \pi \geqslant t \geqslant \cos^{-1}\left[\frac{-1-\ell nx-x}{\alpha\hat{V}_p}\right] \end{cases} \quad \ldots \quad (5.61)$$

One half of the period is considered only since the waveform of X(t) is symmetrical about the origin. The amplitudes of the harmonic currents may be given by equation (5.46) as

$$i_K = \frac{2}{N}\sum_{r=0}^{N=1} i\left(r\cdot\frac{\pi}{N}\right)\cdot\cos K\left(r\cdot\frac{\pi}{N}\right) \quad \ldots \quad \ldots \quad (5.62)$$

where N is the number of ordinates taken in the interval 0 to π and $i(r\cdot\frac{\pi}{N})$ is the value of current evaluated from equation (5.61) over the assigned intervals at $(r\cdot\frac{\pi}{N})$ and

$$Z\left(r\cdot\frac{\pi}{N}\right) = \alpha\hat{V}_p\cos\left(r\cdot\frac{\pi}{N}\right) + \ell nx + x\ .$$

To calculate the forward current I_f as a function of the applied forward voltage V_f, the limits of equation (5.61) are given respectively as

$$V_f \geqslant \left(\frac{1-\ell nx-x}{\alpha}\right) \ldots \quad \ldots \quad (5.63)$$

$$\left(\frac{1-\ell nx-x}{\alpha}\right) > V_f > \left(\frac{-1-\ell nx-x}{\alpha}\right) \ldots \quad \ldots \quad (5.63)$$

$$\left(\frac{-1-\ell nx\,1\,x}{\alpha}\right) \geqslant V_f \quad \ldots \quad \ldots \quad (5.64)$$

CHAPTER 6

EXPERIMENTAL RESULTS

6.1 Introduction

The aim of this chapter is to present and examine the experimental aspects of the exponential law in the same comprehensive way that the theoretical principles were analysed in the previous chapters. Considerable attention was given to select the most practical methods which required the minimum of equipment and which were least likely to introduce large errors.

Initially the validity of the exponential law for hot-carrier diodes was investigated. This was done by calculating the three constants commonly encountered in such laws, I_s, α, and r_s, from the measurements of currents and voltages. Then the measured currents in each case, together with the calculated constants, had been put back into the exponential law and the forward voltages determined. The results, including the percentage errors, have been tabulated for three different types of diodes.

This was followed by measuring the amplitudes of the first ten harmonic currents including the dc component. Twelve diodes, four of each of the three types, were tested in the same way to prove the methods of analysis. The calculated harmonic currents have been plotted against the applied voltages with the experimental points superimposed.

Finally the static curve for each diode was compared with the dynamic one. The former was plotted using equation (3.10). The latter was obtained experimentally by taking the algebraic summation of all the measured harmonic currents plus the dc component for each applied voltage. The polarities of the measured harmonic currents were deduced from the calculated results.

The diodes were grouped and allocated the symbols An, Bn and Cn which stand for the diode type 5082-2800, 5082-2811 and 5082-2833 respectively where n indicated the number of the diode in the group.

6.2 Methods and Basic Circuits

The circuit shown in Figure 6.1 was used to measure the dc current-voltage characteristics. The voltage across the diode and the 50 Ω resistor (V_{d+50}) was measured using a high quality vacuum-tube voltmeter type HP 412. The current was deduced from the voltage drop across the 50 Ω resistor to avoid the errors possibly introduced by the series resistance of the ammeter. The series resistance of the diode was considered as the combination of (r_s + 50) Ω. The 1 MΩ resistor in series with the 1 KΩ potentiometer, across the input voltage was used to ensure that the characteristic of the diode would not change by varying the applied voltage.

Apart from the dc characteristics, the other measurements which have been made were those of harmonic currents. The experimental verification of the calculated harmonics was carried out using the arrangement shown in Figure 6.2. The applied voltage was measured on the oscilloscope and then the harmonic currents were calculated from the voltage drop, across the 75 Ω load, measured on the wave analyzer at the required harmonic. The wave analyzer was initially calibrated by means of the oscillator at the reference voltage of 100 mV peak. The attenuators of the wave analyzer were adjusted so that the output indication produced zero reading at the fundamental frequency. Then the deviation of the harmonic components had been taken in ± dBs which were subtracted from or added to the measured harmonics accordingly.

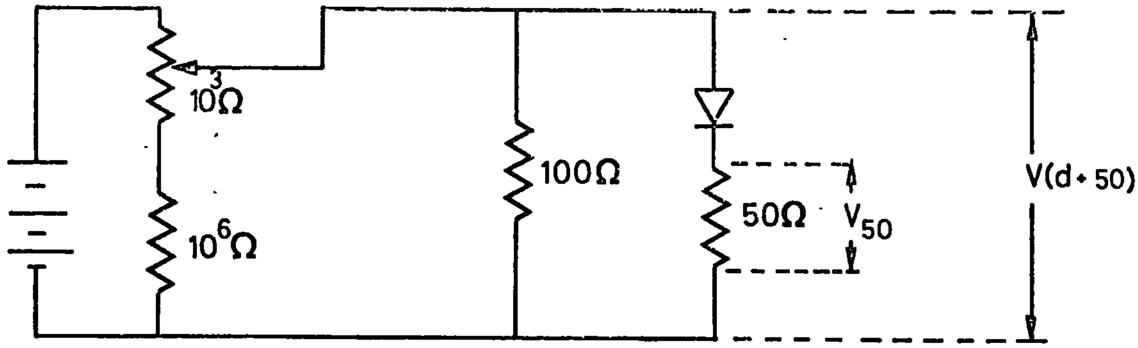
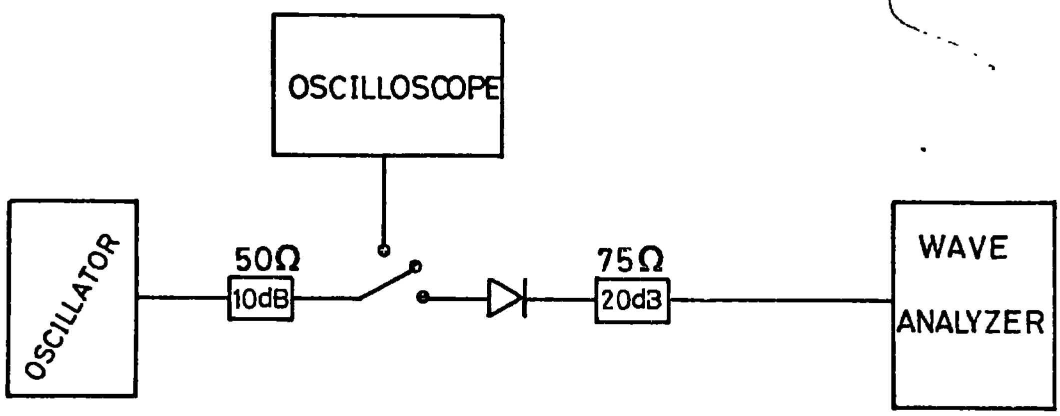


FIG. 6·1 D.C. CURRENT — VOLTAGE MEASUREMENTS.



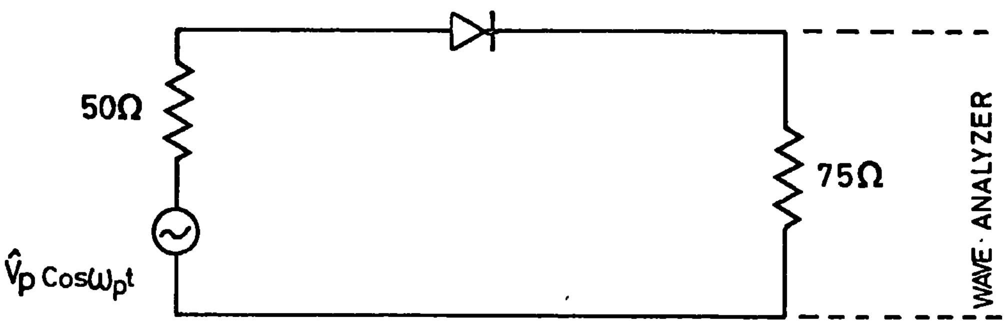


FIG. 6·2 HARMONIC CURRENT MEASUREMENTS

6.3 D.C. Characteristics

The characteristics of three different types of hot-carrier diodes are presented with the dual purpose of providing useful data and of showing the validity of the exponential law. The data obtained in the circuit of Figure 6.1 are shown in Table 6.1 for diode type 5082-2800. The low current range is represented by the straight line of Figure 6.3 where equation (3.9) is predominant. From the slope ($\ell n\ i_f/V_f$) of such a straight line, the constant α was determined. Figure 6.4 is a plot of $\ell n \left[i_f/e^{\alpha V_f} \right]$ vs. i_f for the high current range. Using the value of α which had been calculated from Figure 6.3, the constants r_s and I_s were evaluated as demonstrated previously in equation 3.12. The same procedures were used to calculate the constants for the diode types 5082-2811 and 5082-2833 and the figures are self-explanatory. The calculated constants for each diode were fitted to the modified exponential law, i.e. Equation (3.10), and the agreement was better than expected. The average errors were within $\pm 2\%$ when the measured data had been compared with the computed results as shown in Tables 6.2, 6.4 and 6.6 in Appendix 5.

6.4 Harmonic Currents

Twelve hot-carrier diodes, four of each type, were tested at a pumping frequency of 50 kHz. Such low frequency was thought appropriate in order to reduce both the effect of diode parasitics and the noise. The pump voltage used ranged from 0.3 volt to 2 volts. Voltages less than 0.3 volt had been considered as small signals and the effect of the diode series resistance was therefore insignificant.

The theoretical calculations with the experimental results superimposed are compared in Figure 6.9 to Figure 6.20. The 'circles'

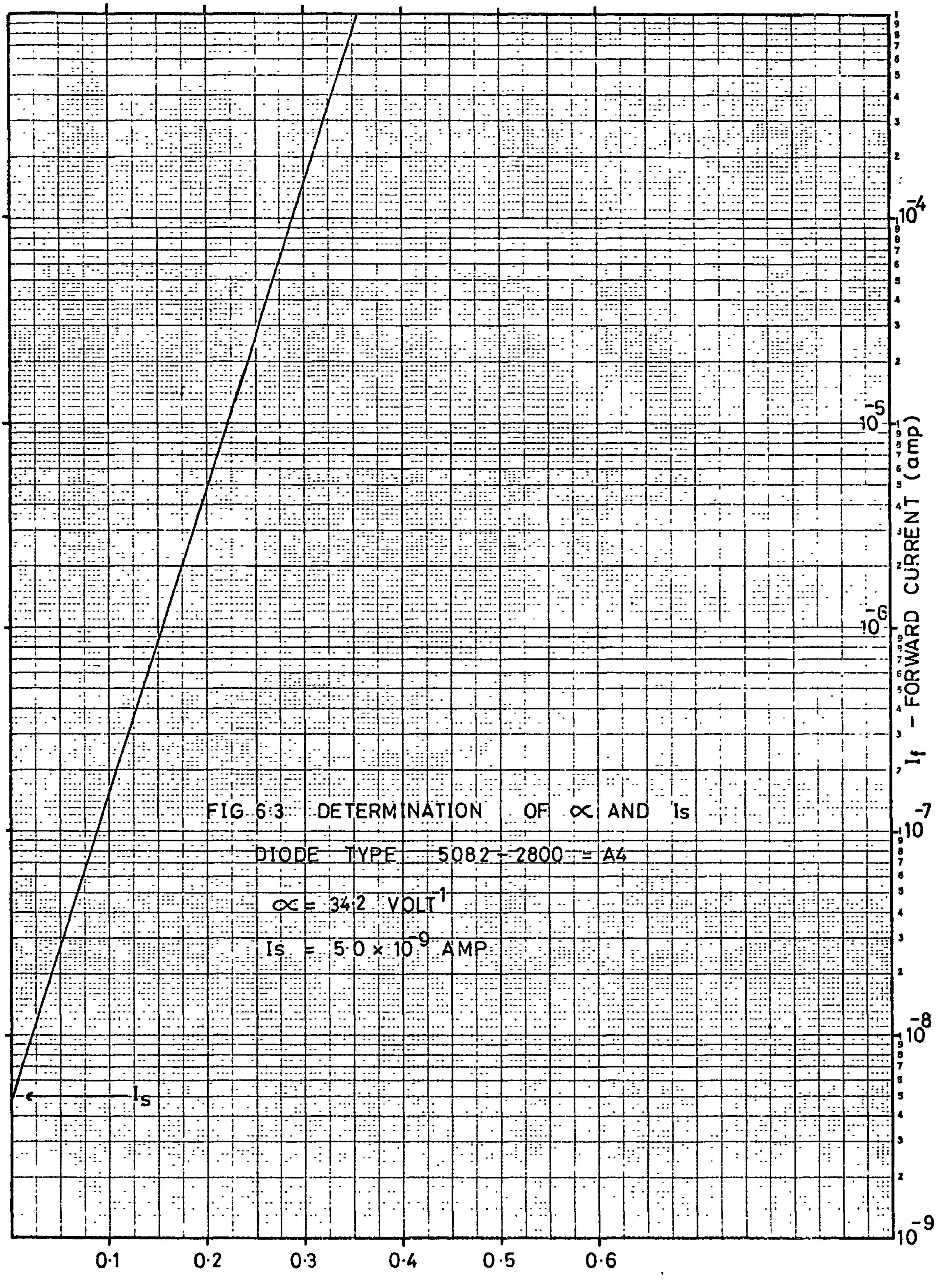


FIG 6·3 DETERMINATION OF α AND Is

DIODE TYPE 5082 – 2800 = A4

α = 34·2 VOLT^{-1}

Is = 5·0 × 10^{-9} AMP

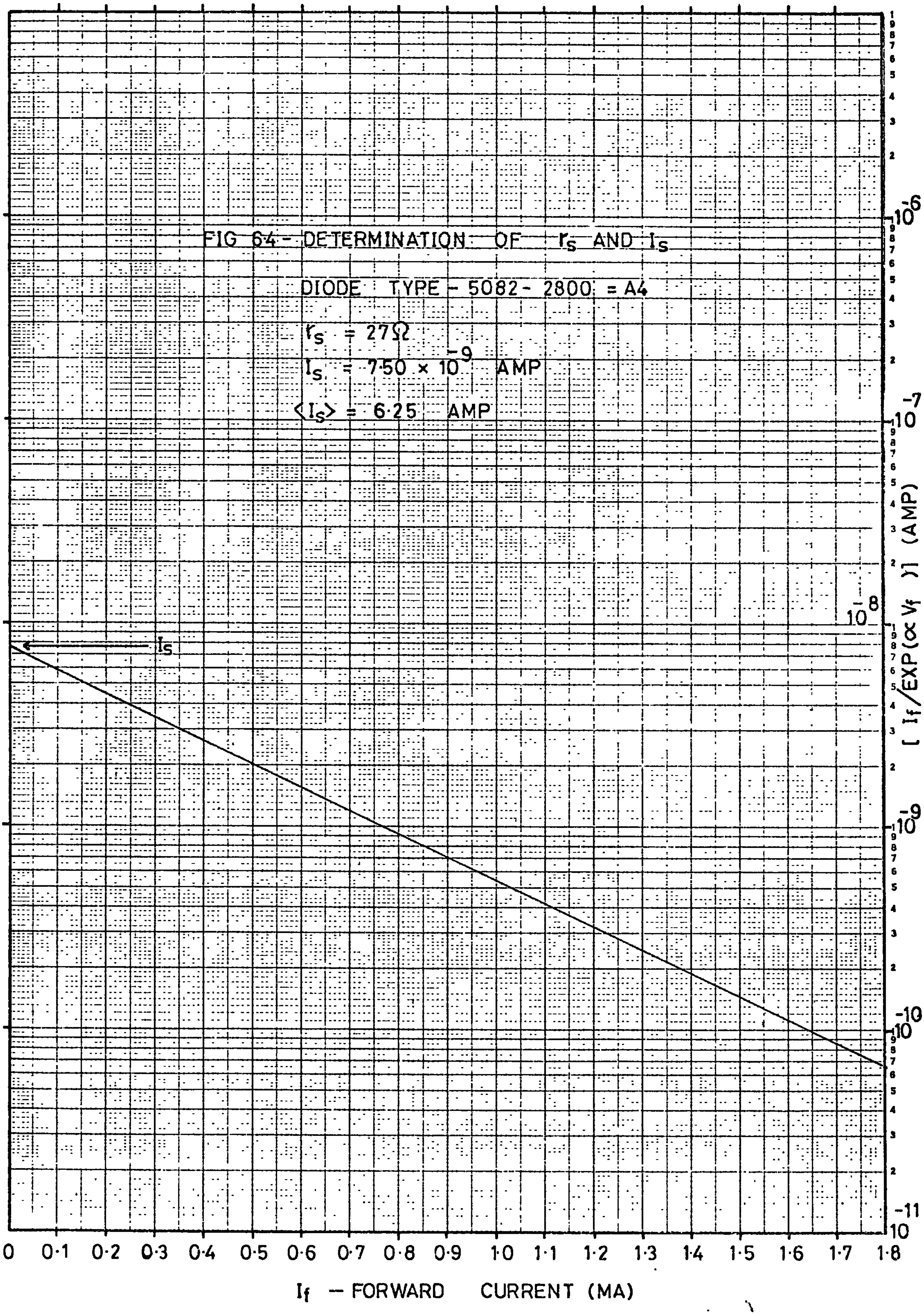


FIG 6·4 - DETERMINATION OF r_s AND I_s

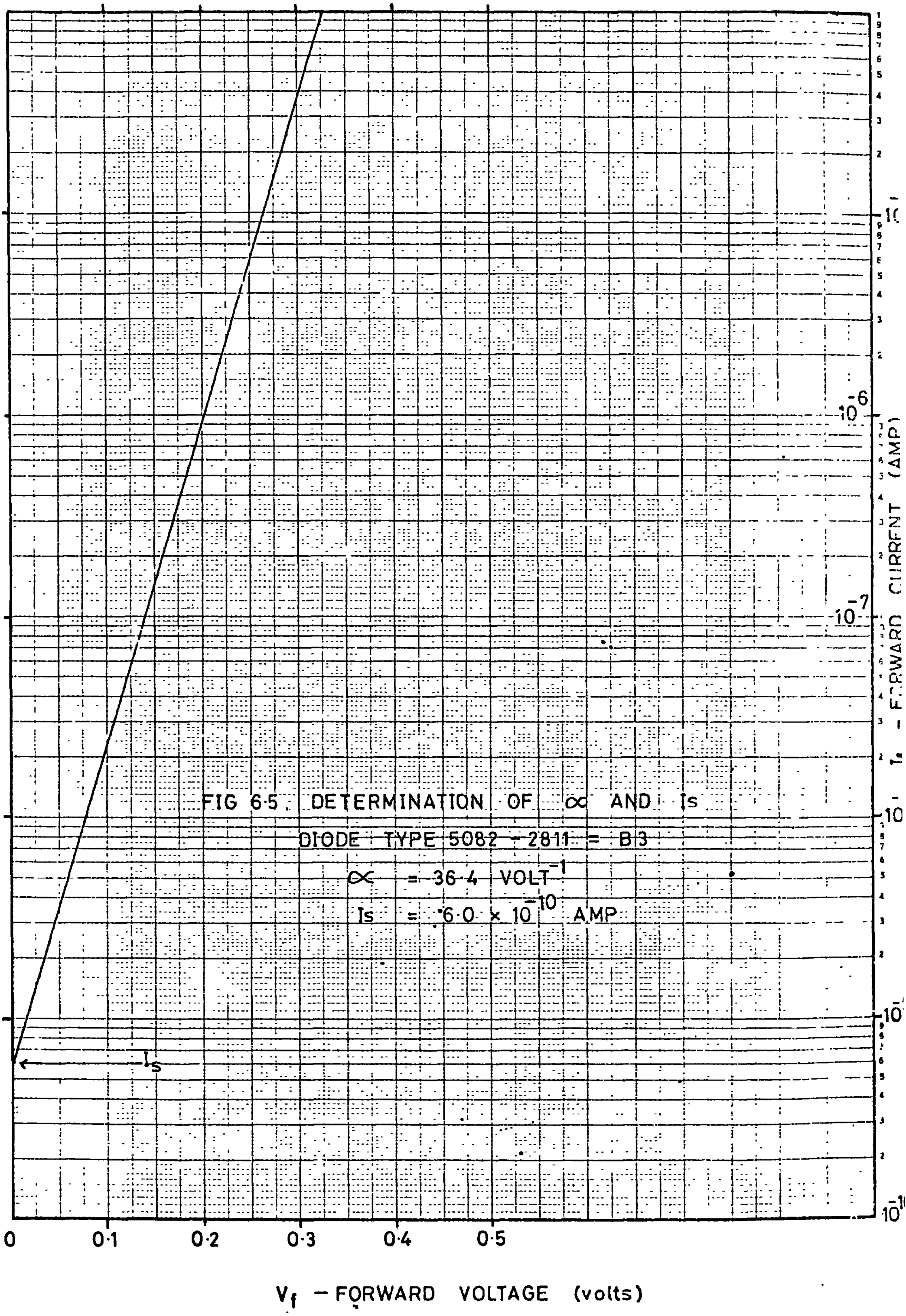


FIG 6·5. DETERMINATION OF $\propto$ AND Is

DIODE TYPE 5082 – 2811 = B3

$\propto$ = 36·4 $VOLT^{-1}$

Is = 6·0 × 10^{-10} AMP

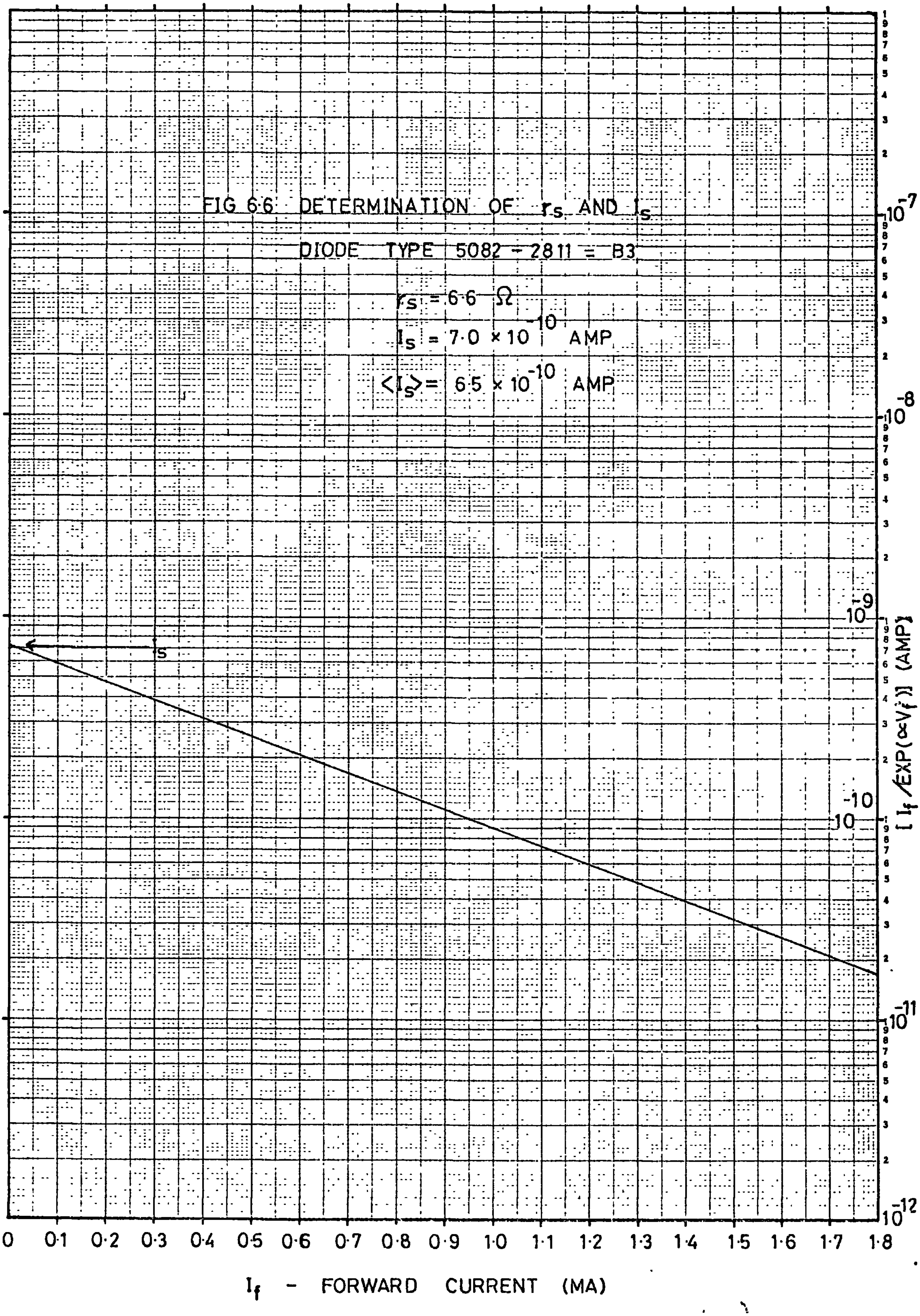


FIG 6·6 DETERMINATION OF r_s AND I_s

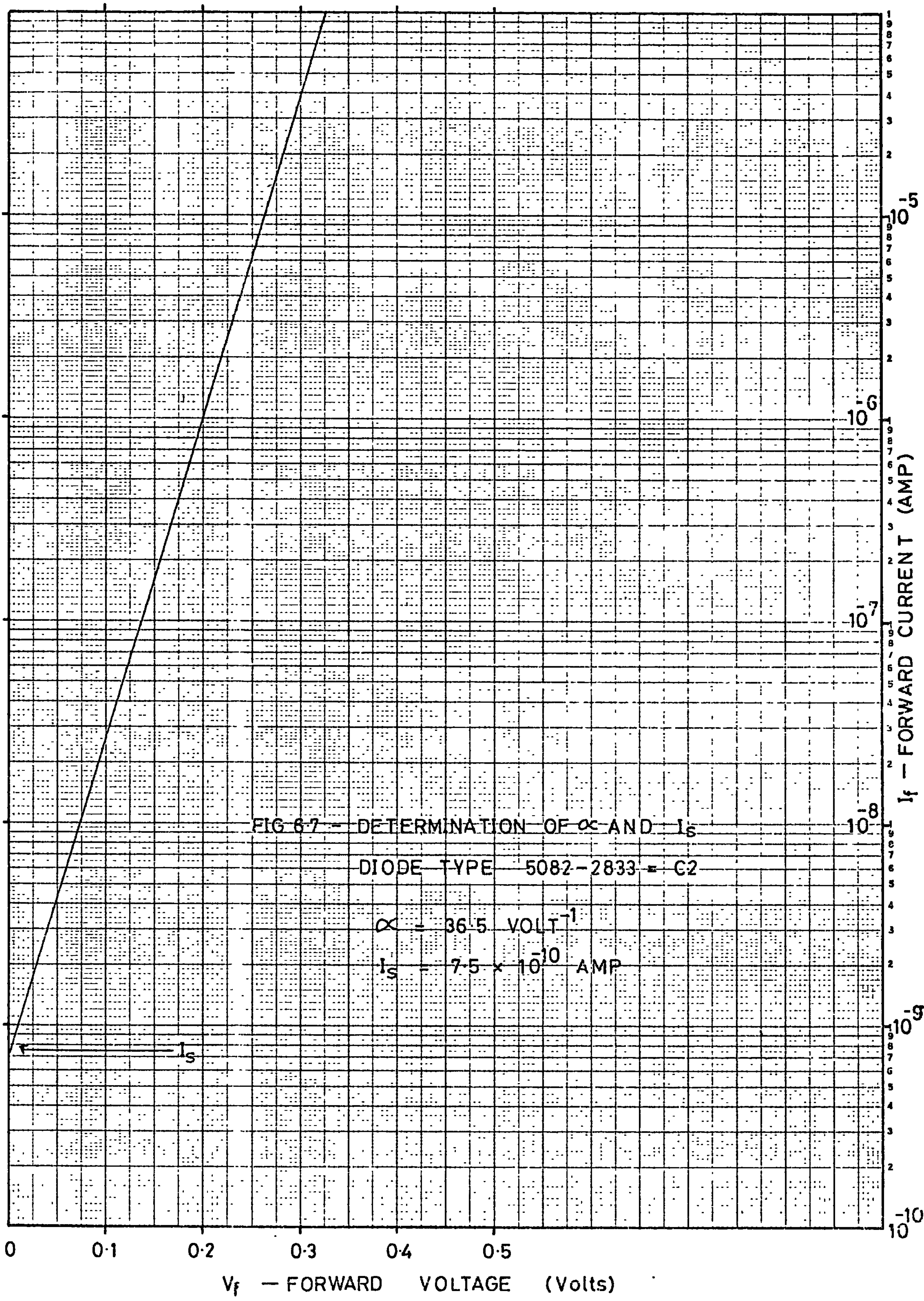


FIG 6·7 — DETERMINATION OF α AND I_s

DIODE TYPE 5082-2833 = C2

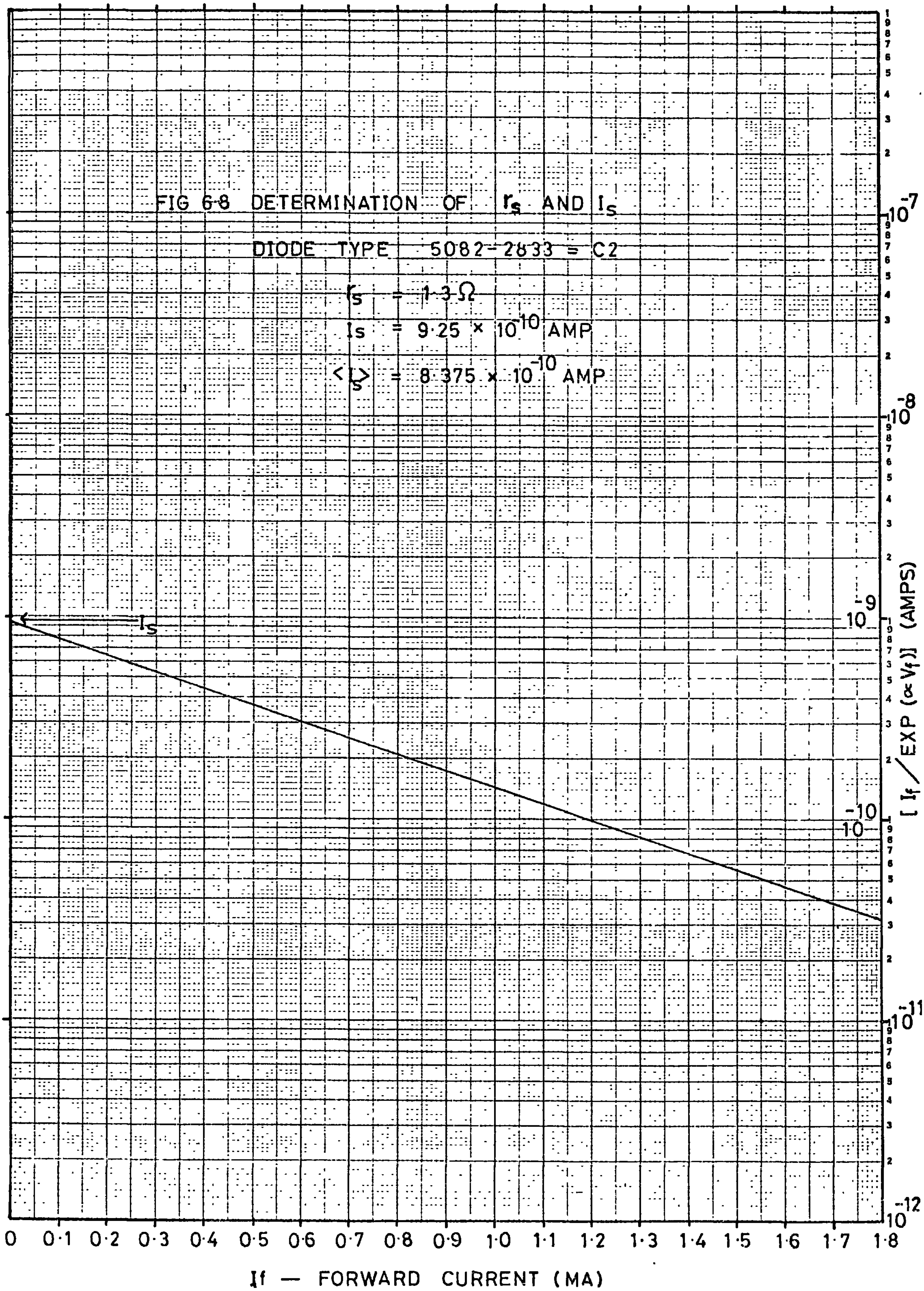


FIG 6·8 DETERMINATION OF r_s AND I_s

DIODE TYPE 5082-2833 = C2

r_s = 1·3 Ω

I_s = 9·25 × 10^{-10} AMP

$\langle I_s \rangle$ = 8·375 × 10^{-10} AMP and the 'solid lines' indicate the theoretical dc and harmonic components, respectively. The dots are used for the measured dc currents and the 'crosses' are used for the measured harmonic currents.

On referring to the theoretical values, there is a reasonable correlation with the measurements carried out on the diodes. The deviation from the predicted values may have been caused by the noise at very low levels. Other errors may have resulted from the oscilloscope readings over the wide range of 0.3 to 2 volts.

In general, the harmonic spectrum has shown resemblance to $\frac{\sin\theta}{\theta}$ function with unsymmetrical effective pulse width over the alternating lobes. This can be seen from the theoretically tabulated harmonic spectrum. However, it is noteworthy that the negative spectrum occurred after the first minima had been reached. The polarities of the spectrum continued to change after each minima. The range between two successive minima or the position of the first minimum proved to be a function of $x = \alpha R_T I_s$ which varied from diode to diode even within the same group.

6.5 Comparison of Static and Dynamic Characteristics

Since the actual wave analyzer could not detect phase, its display does not show polarity of the spectrum. Study of the theoretical harmonic curves has provided the means of determining the polarities of the measured amplitudes. The comparison between the static and the dynamic characteristics provided an additional verification of the exponential law. The former (solid lines) were obtained by plotting the peak currents against the peak voltages from the modified exponential law, e.g. equation 3.10. The latter (squares) were superimposed and obtained from the algebraic summation of the first ten measured

FIG.6.9

DIODE TYPE 5082 - 2800 - A1

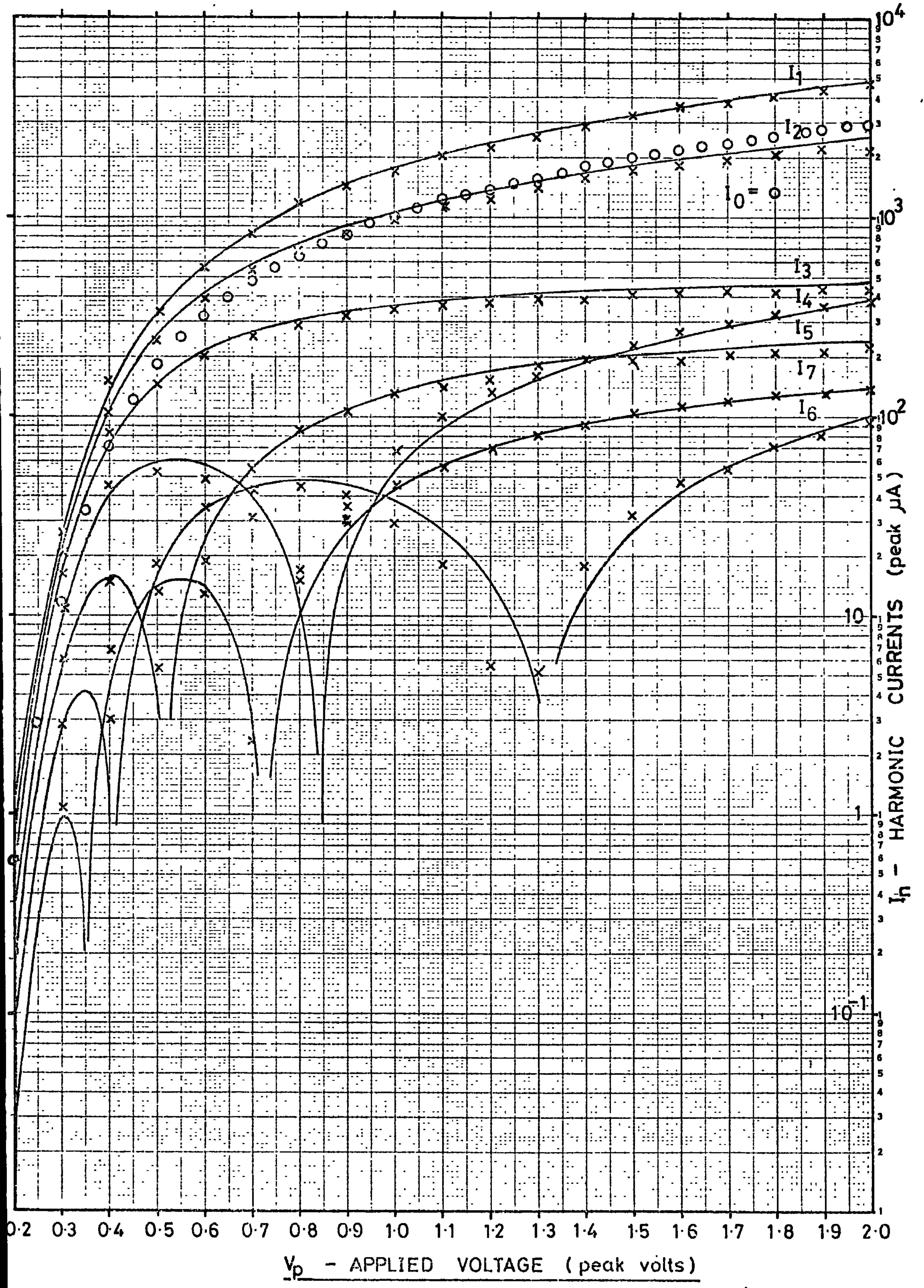


FIG.6.10 DIODE TYPE 5082-2800 A2

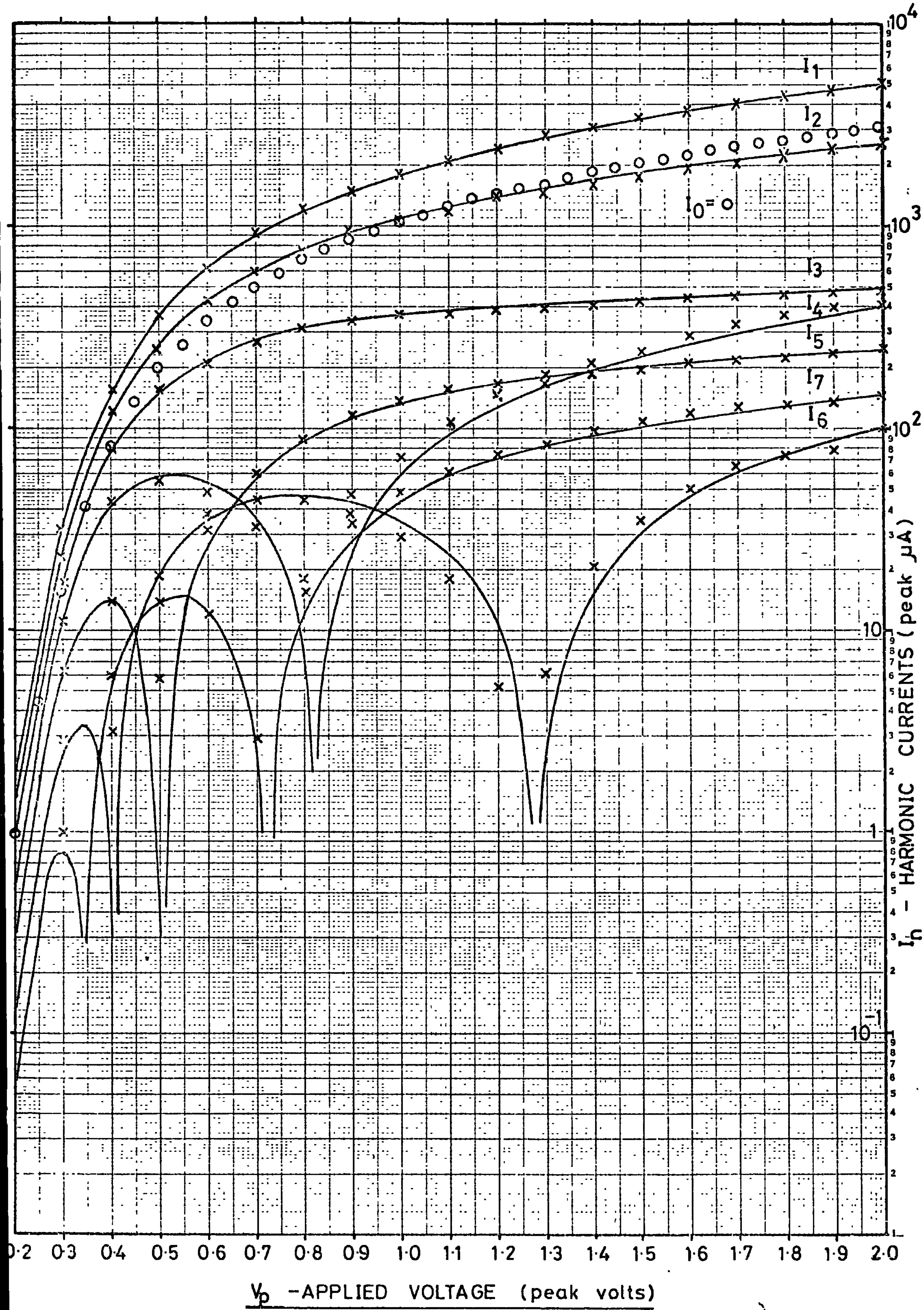


FIG.6.11 DIODE TYPE 5082-2800-A3

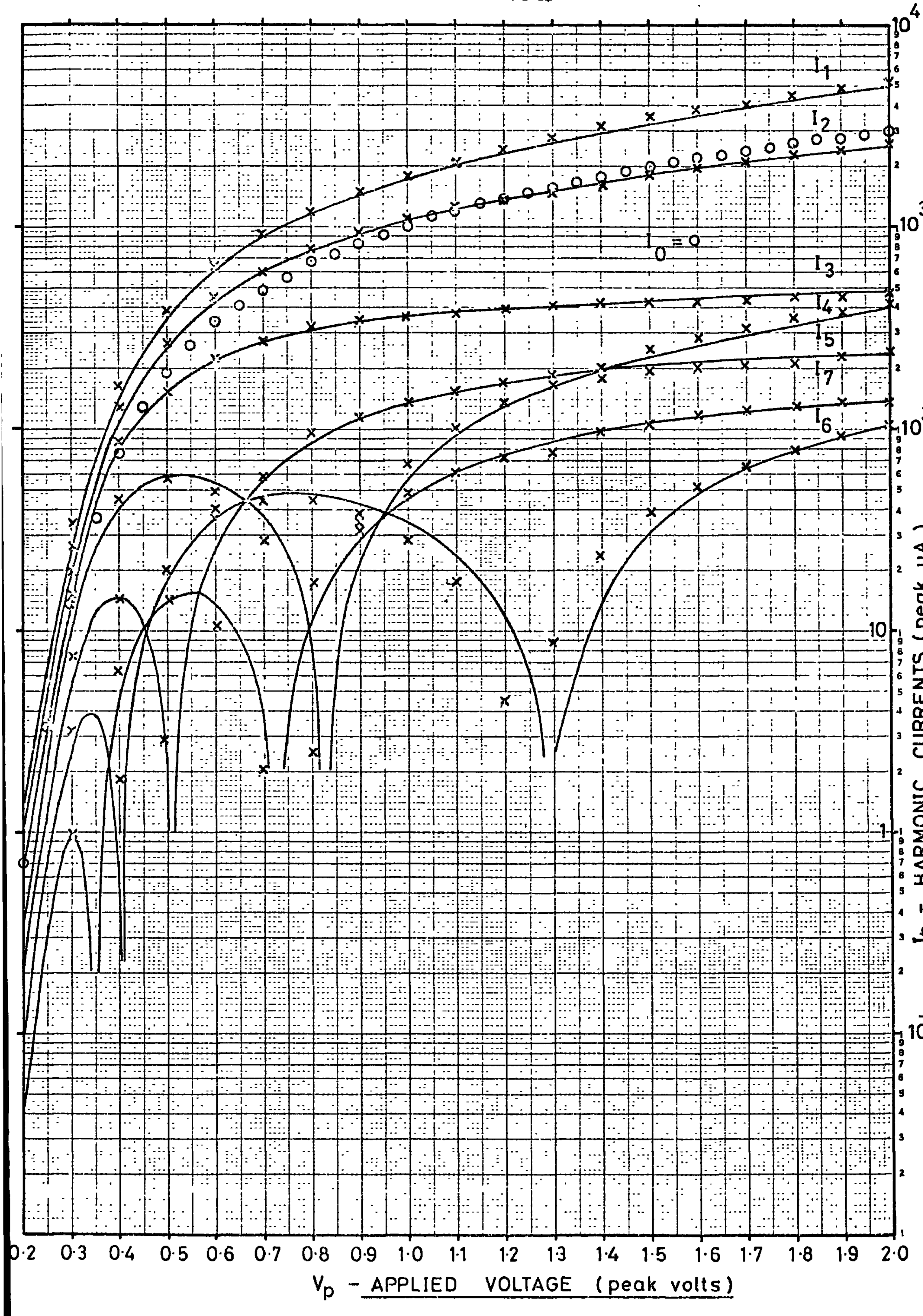


FIG.6.12 DIODE TYPE 5082 - 2800 - A4

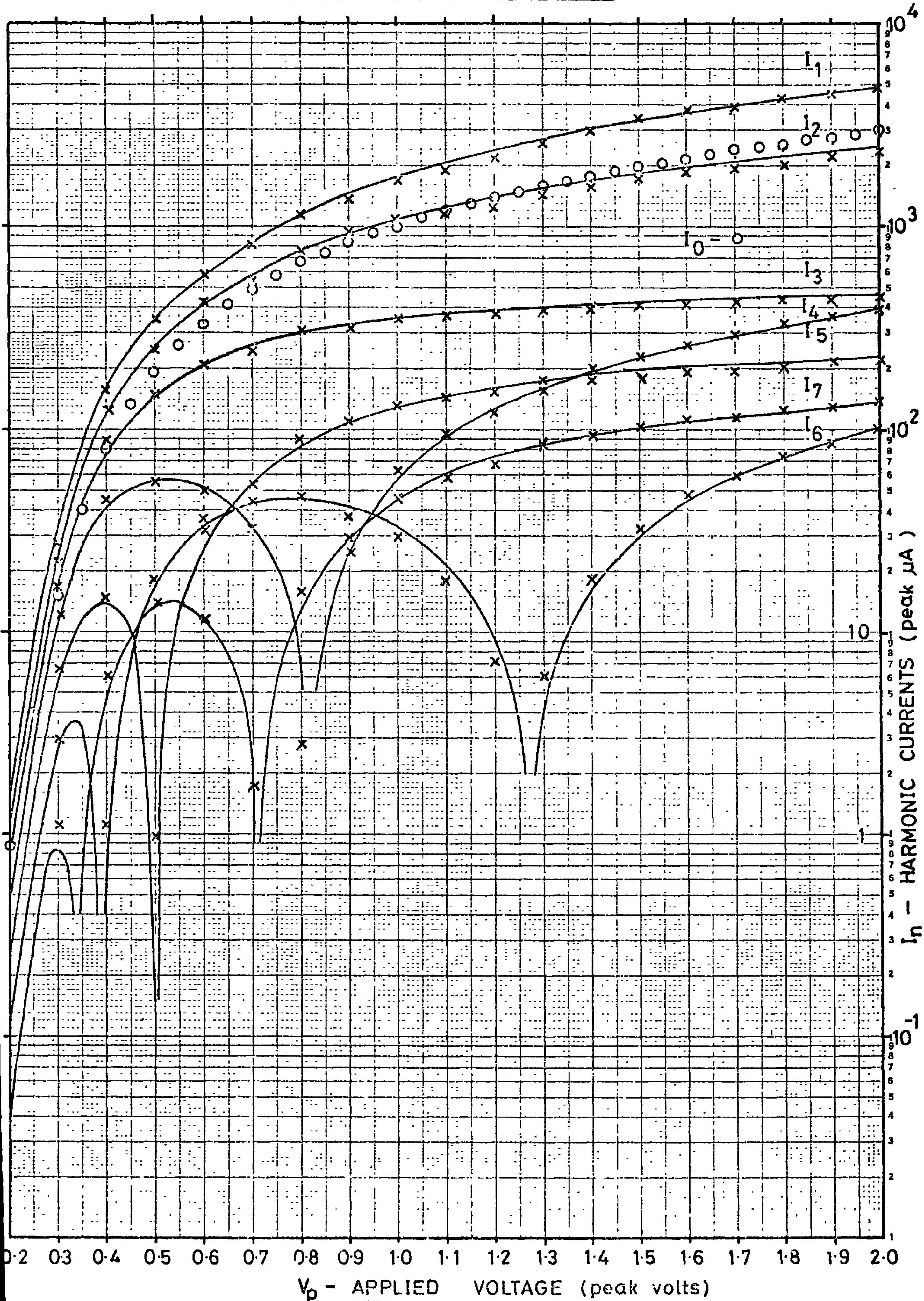


FIG.6.13 DIODE TYPE 5082 - 2811 - B1

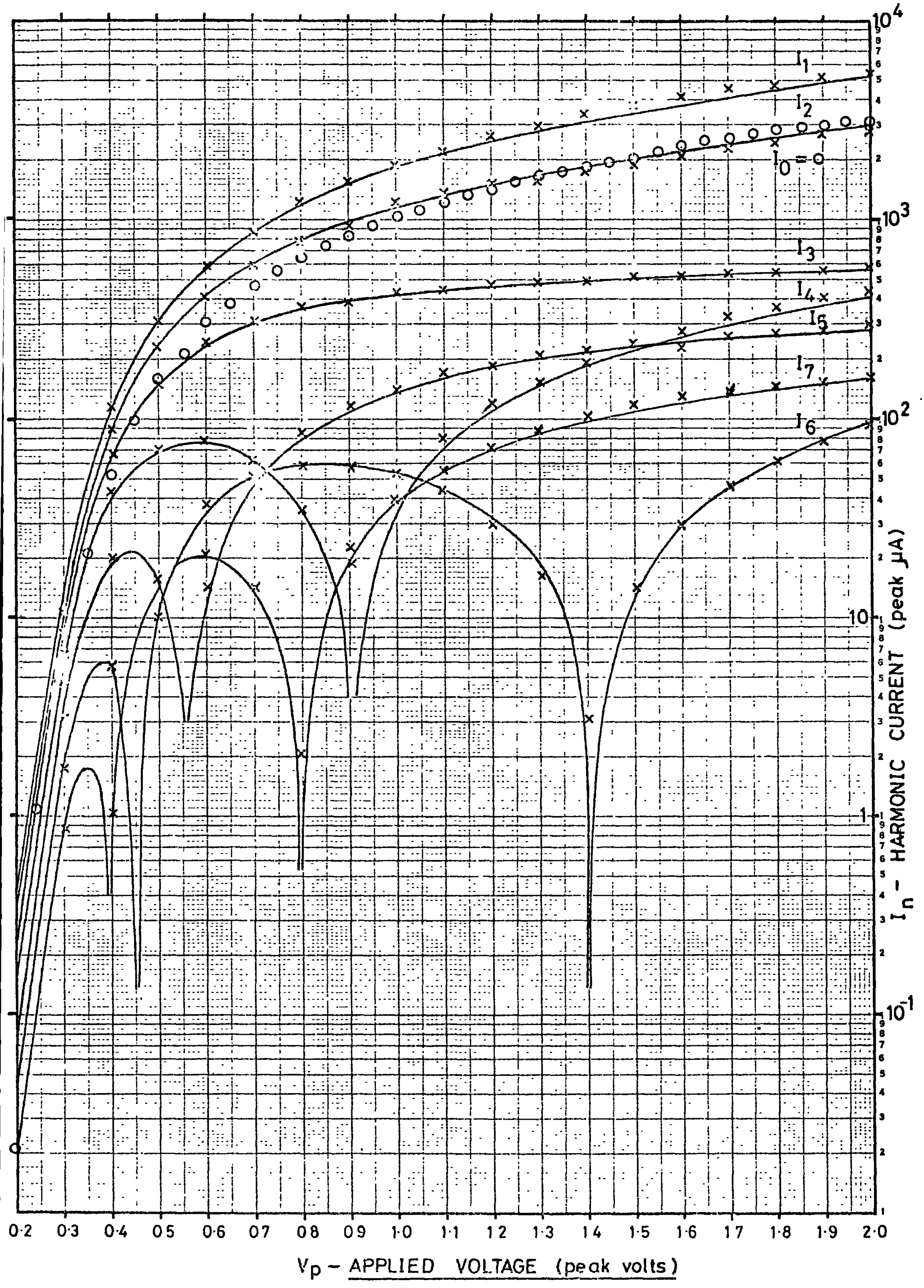


FIG.6.14 DIODE TYPE 5082-2811- B2

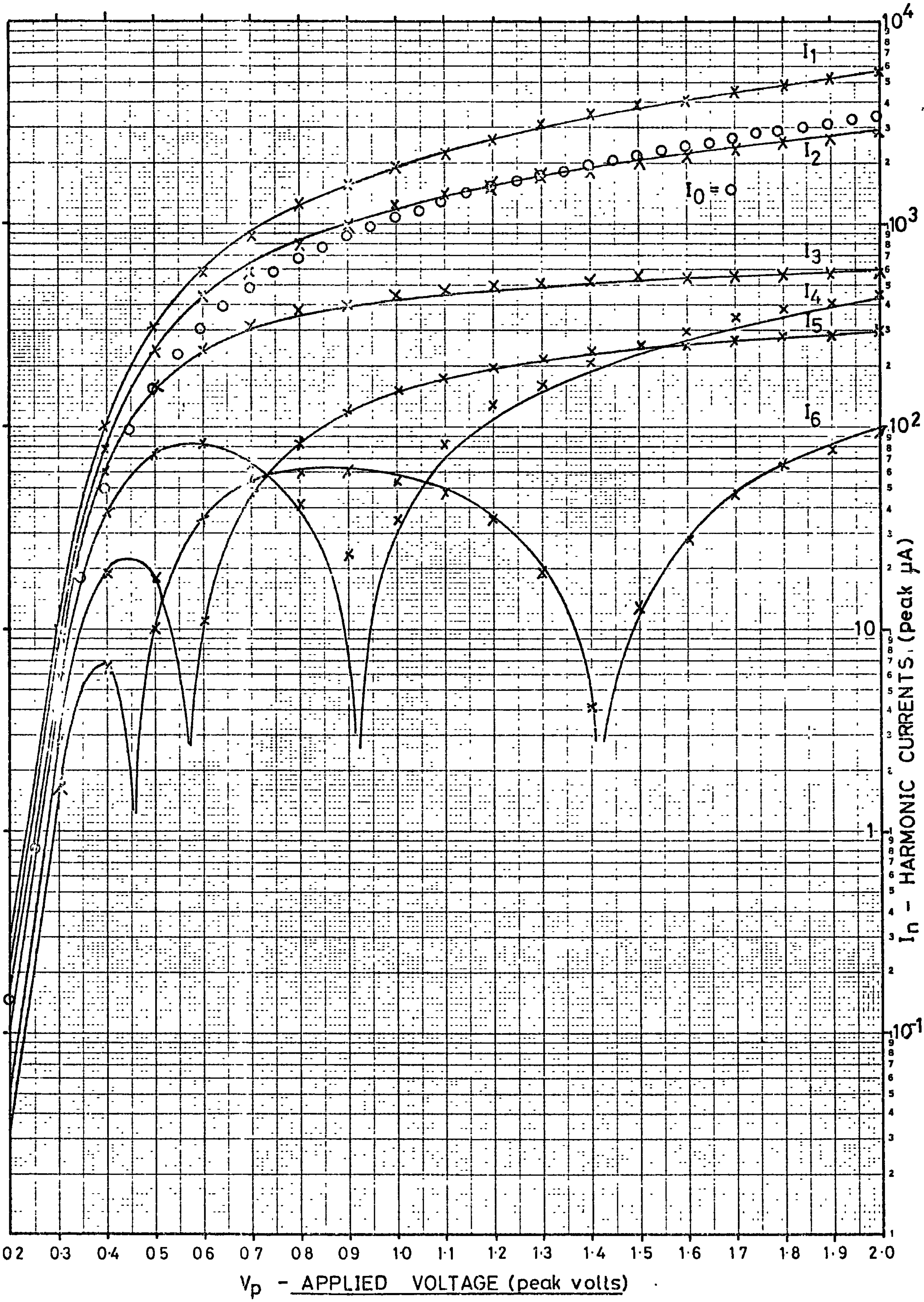


FIG.6.15 DIODE TYPE 5082-2811 - B3

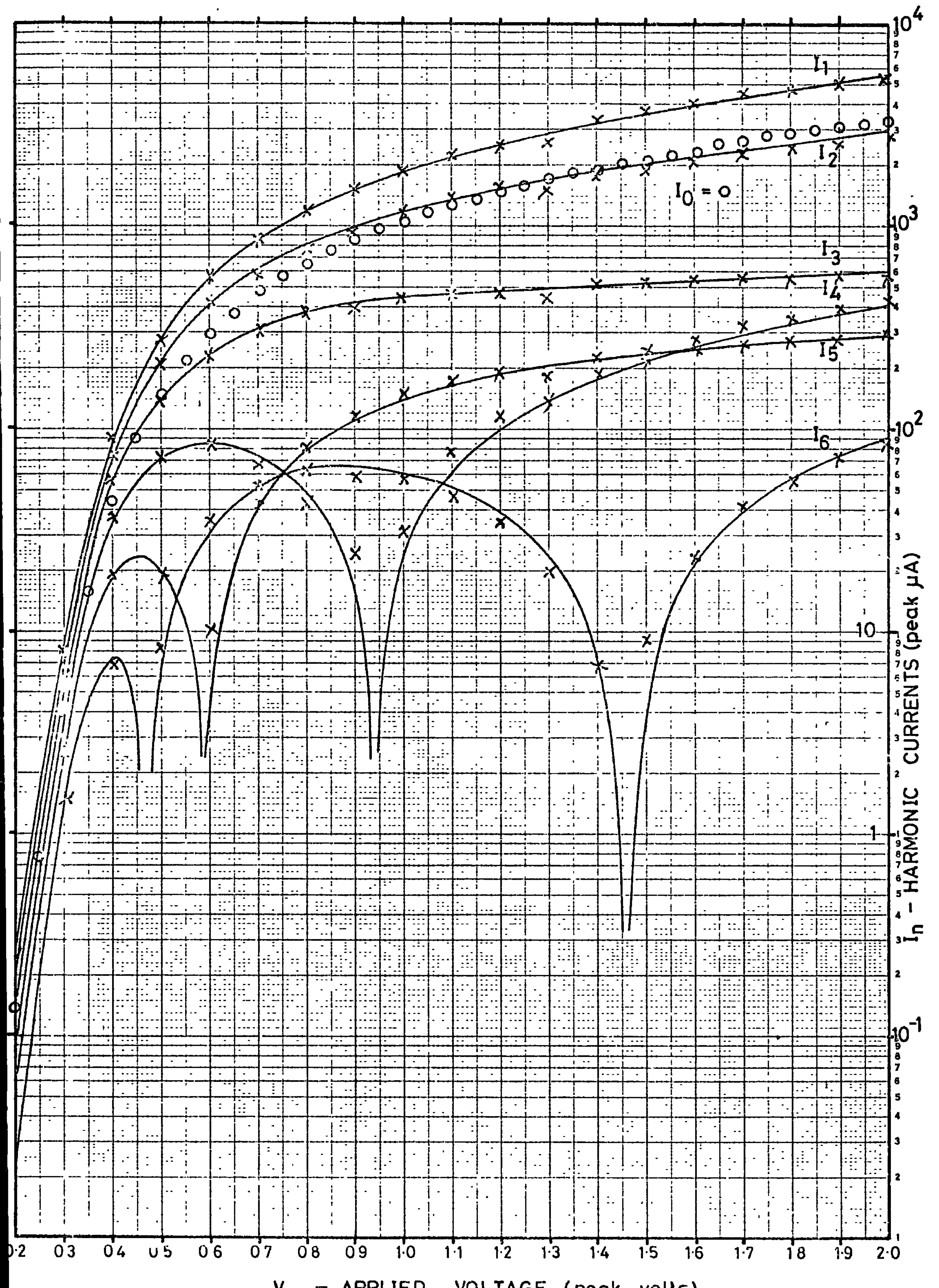


FIG.6.16 DIODE TYPE 5082 - 2811 - B4

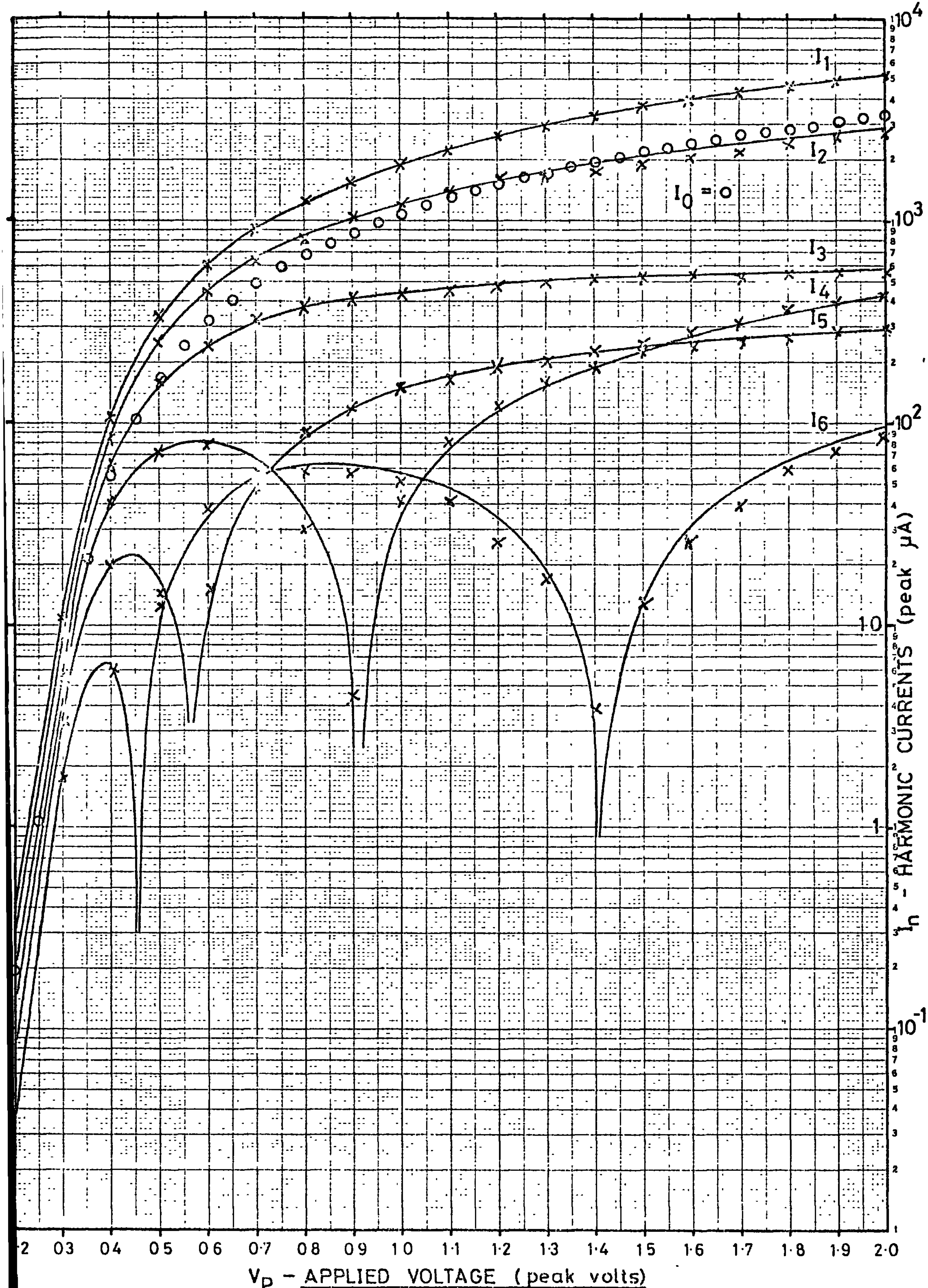


FIG.6.17 DIODE TYPE 5082 - 2833 - C1

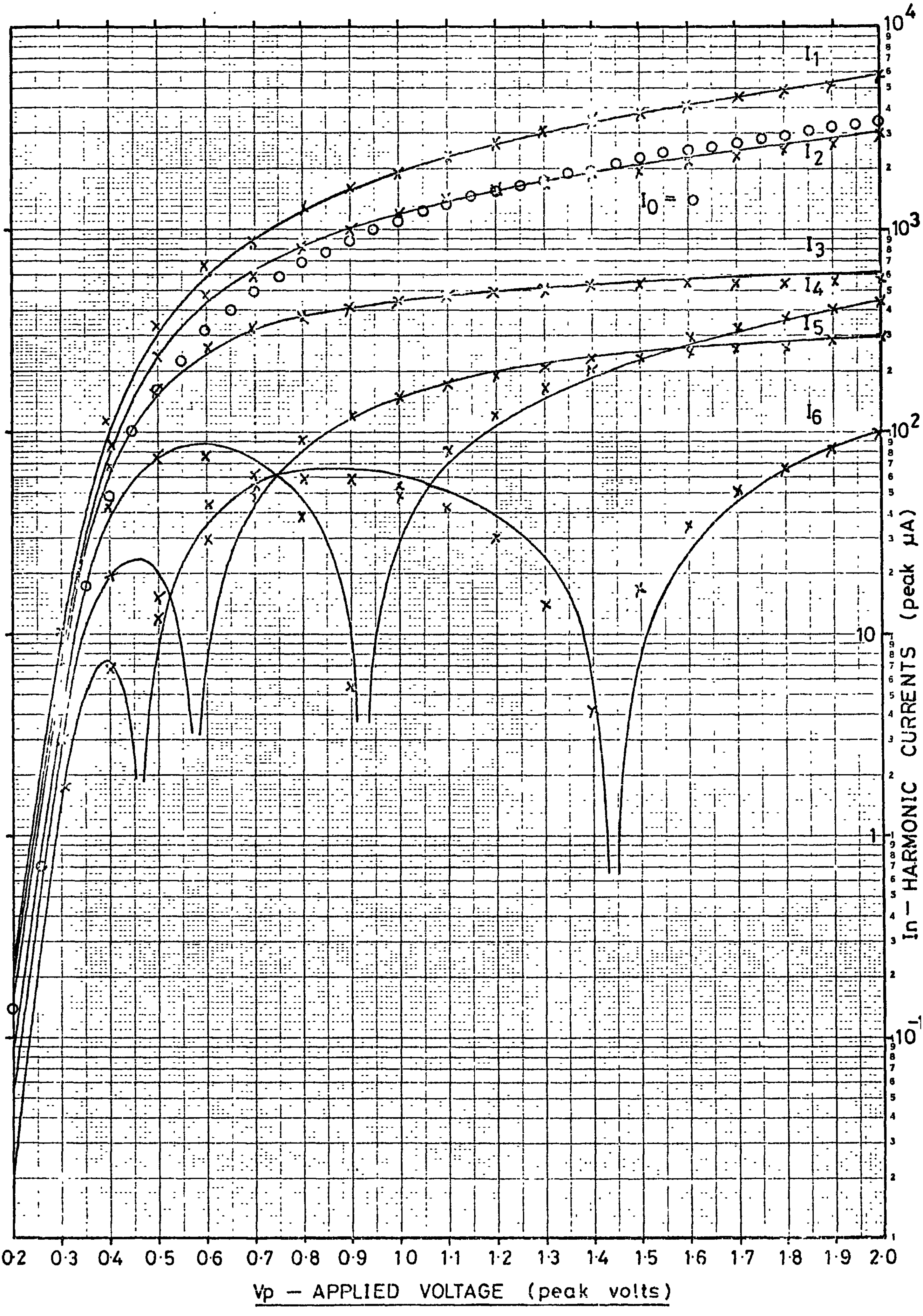


FIG.6.18 DIODE TYPE 5082 — 2883 — C2

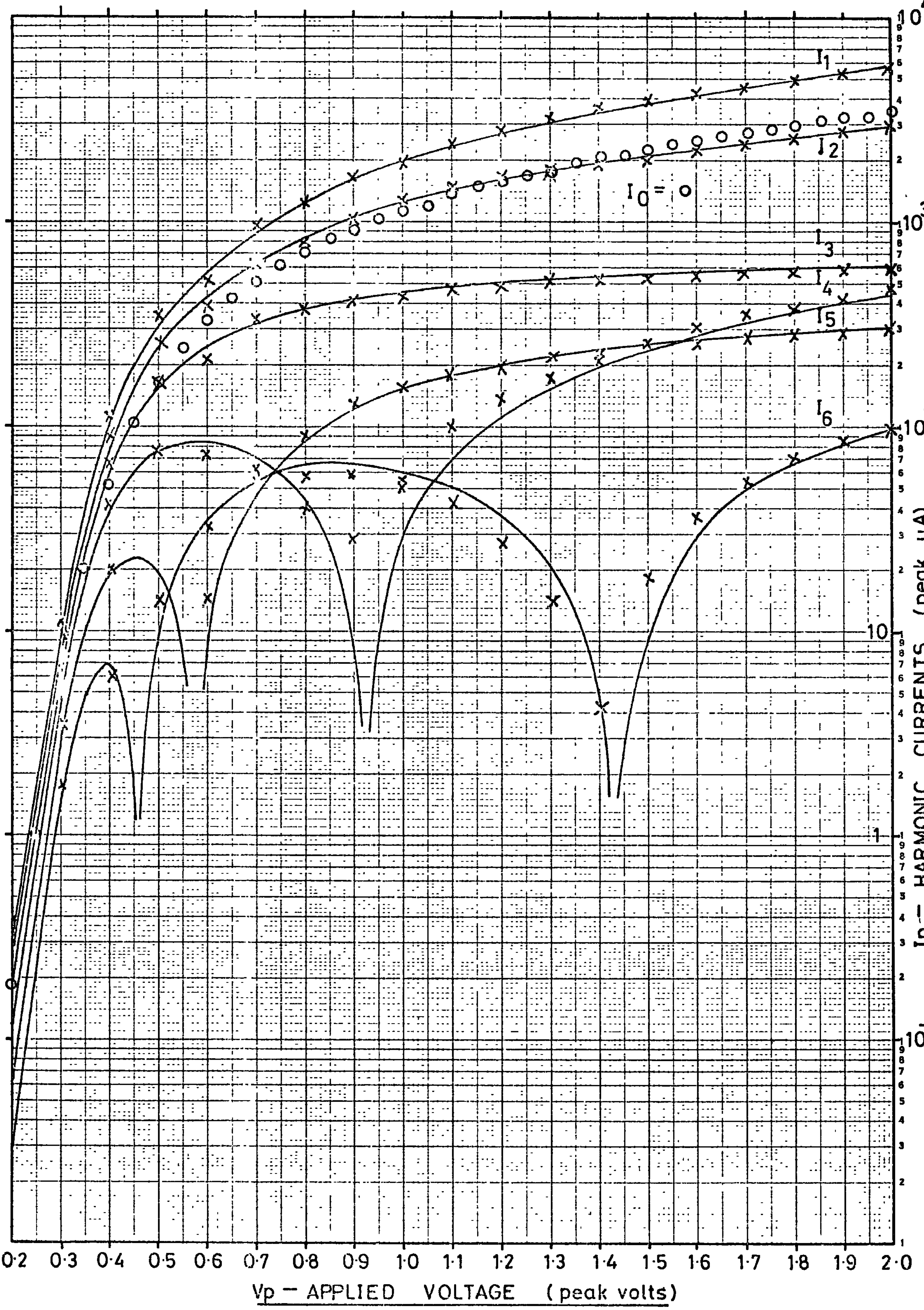


FIG.6.19 DIODE TYPE 5082 – 2833 – C3

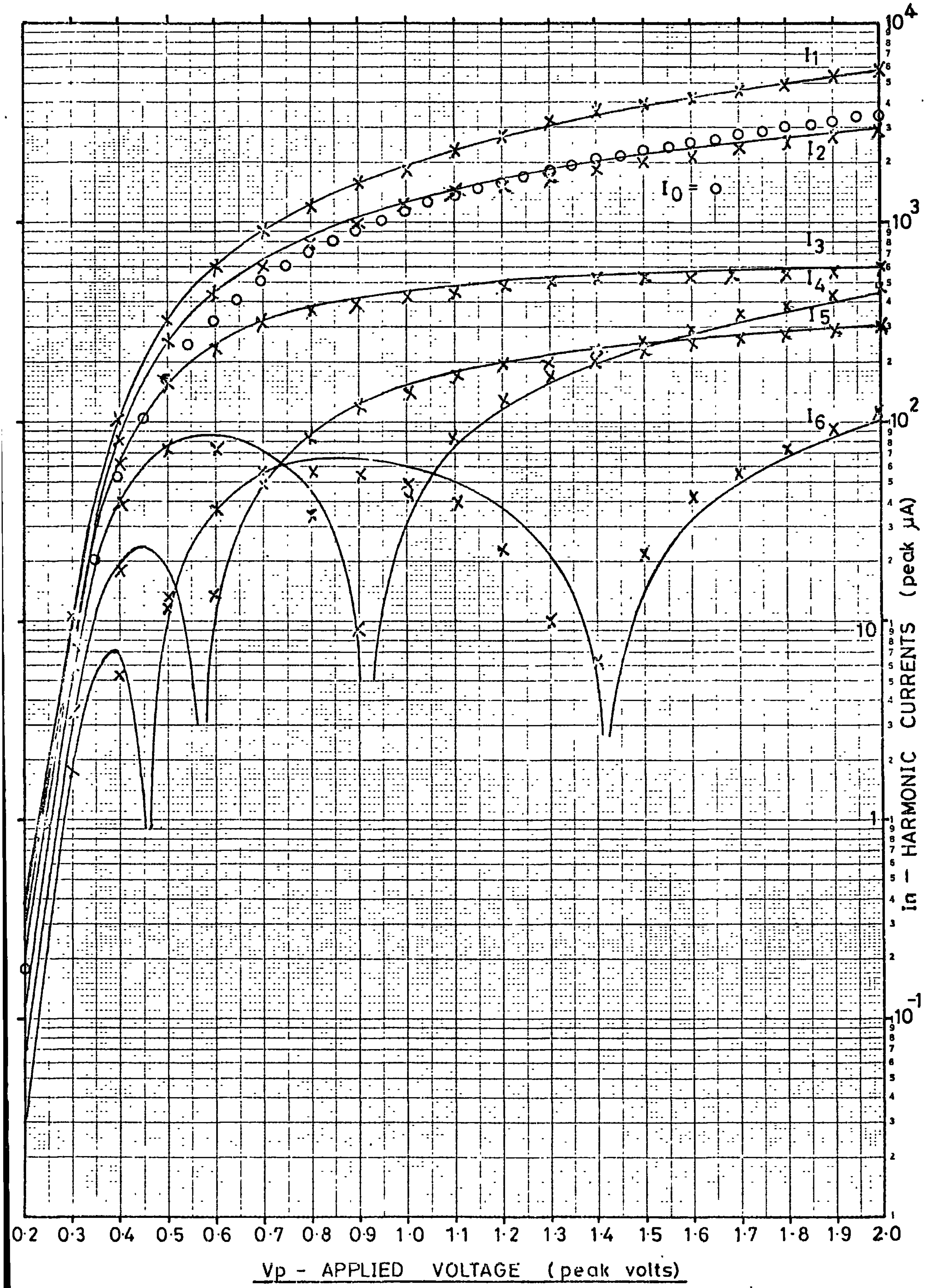
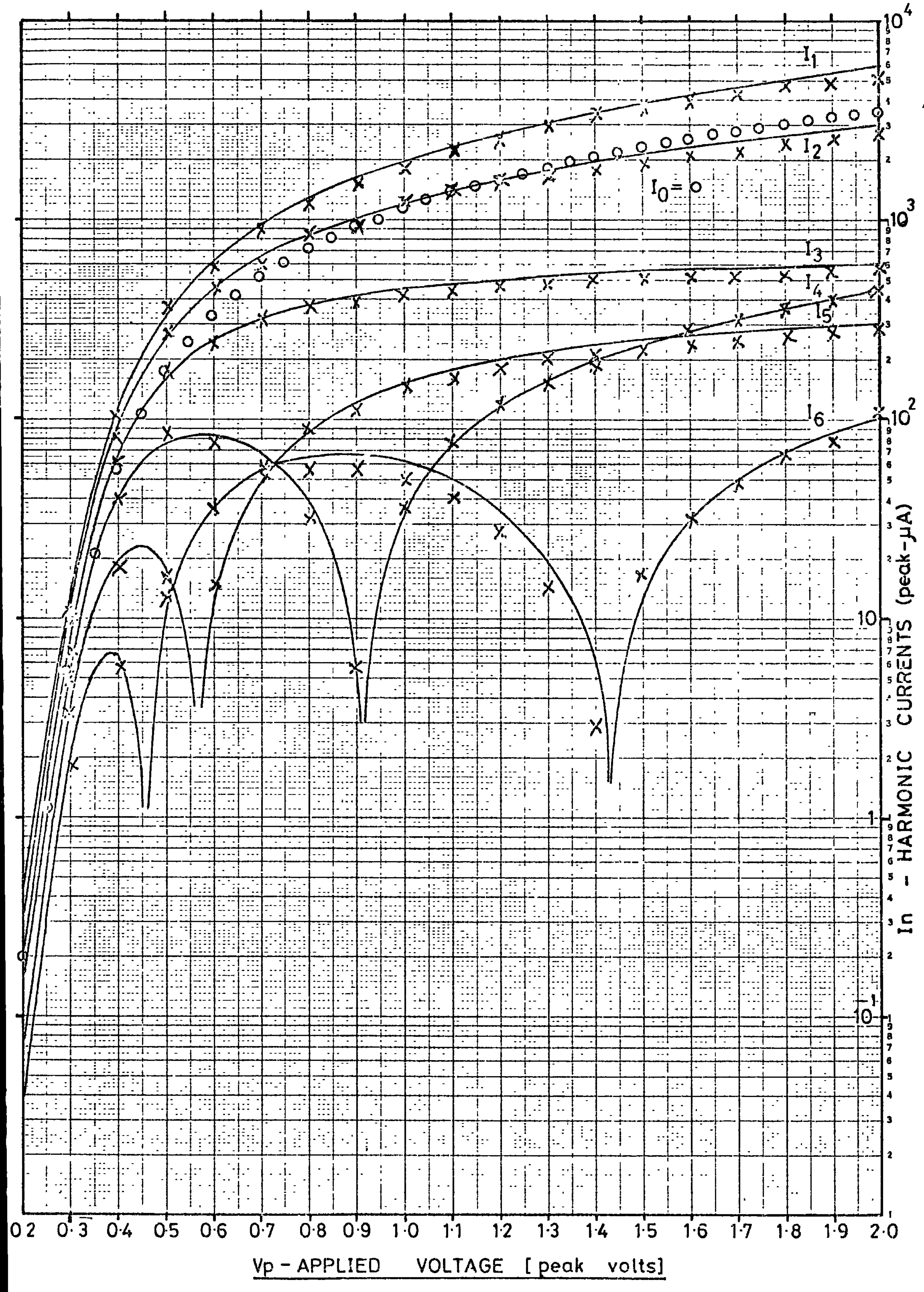


FIG.6.20 DIODE TYPE 5082-2883 - C4



harmonics plus the dc component against the corresponding peak voltages. The appropriate data and plots are shown in Tables 6.31-6.33 and Figures 6.21-6.23 respectively. The deviation of the dynamic from the static curves was due to the fact that more than ten harmonic currents had to be taken into account. The reasonable agreement of the static with the dynamic curves has proved the assumption made before that the diode equivalent circuit was purely resistive at the chosen frequency

6.6 Discussion and Comments

In proposing the use of a hot-carrier diode in either a detector or a mixer circuit one should normally know the i-v characteristic of the diode. This is because the i-v relationship can be represented by a Taylor expansion whose terms contain the component of the modulating signal or the intermediate frequency, respectively, in addition to many other beat and harmonic frequencies. If the law accurately describes the i-v curve of the diode in situ then the amplitude of the required frequency can be predicted theoretically.

An attempt, therefore, has been made to give a simple and useful picture of the electrical performance of hot-carrier diodes which may reveal a wealth of information necessary for their applications. The electrical properties of such diodes, based on the modified exponential law, have been verified experimentally. The calculated and measured results have illustrated the general effects of the various parameters. It was found that the theoretical and experimental results had proved to be adequate in satisfying the modified exponential law.

The theoretical curves of the harmonic currents have been explored over a wide range of applied voltages (0.3 to 2 volts) which served as a guide to experimental optimization of pump and harmonic

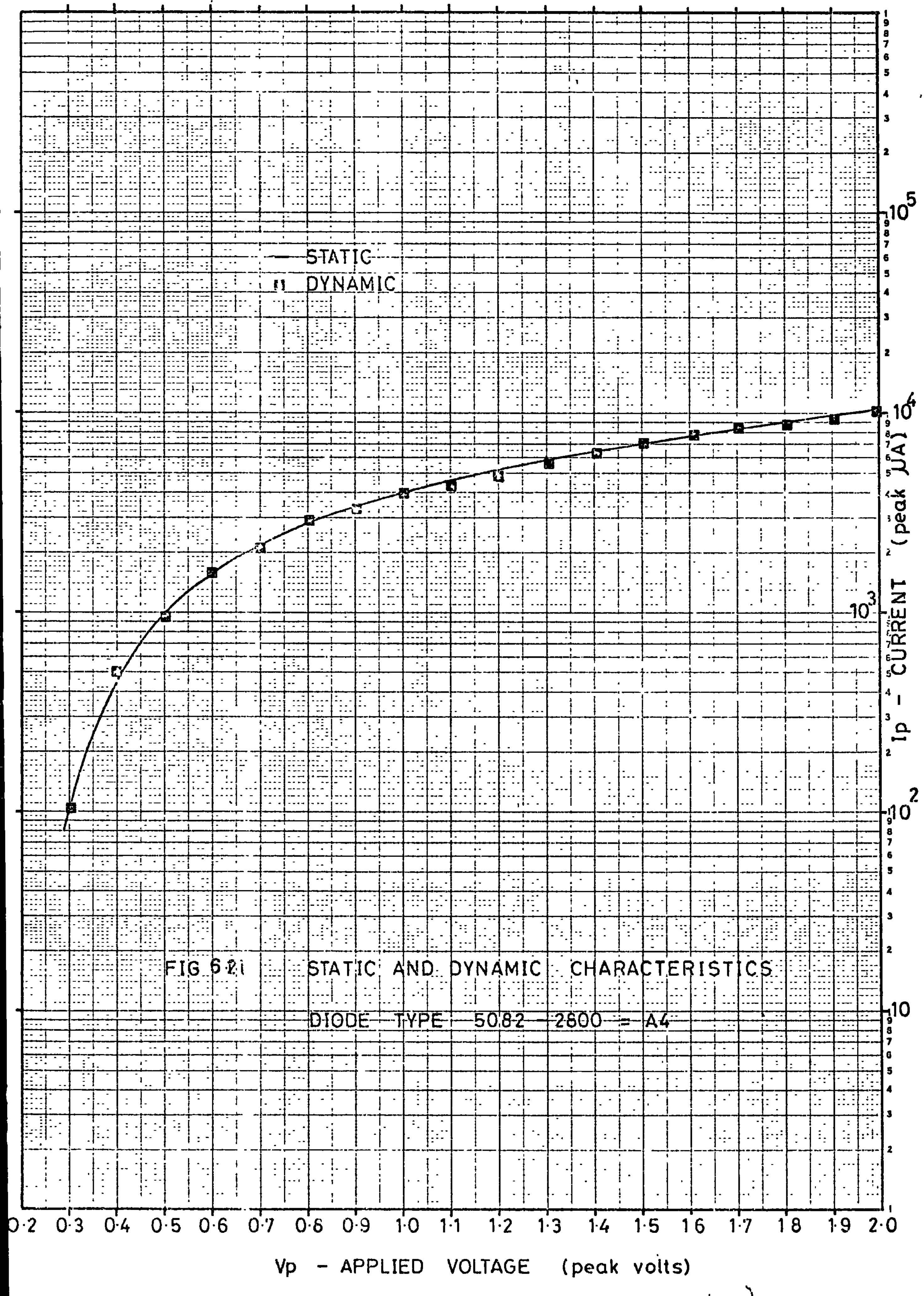


FIG 6·2i STATIC AND DYNAMIC CHARACTERISTICS

DIODE TYPE 5082 - 2800 = A4

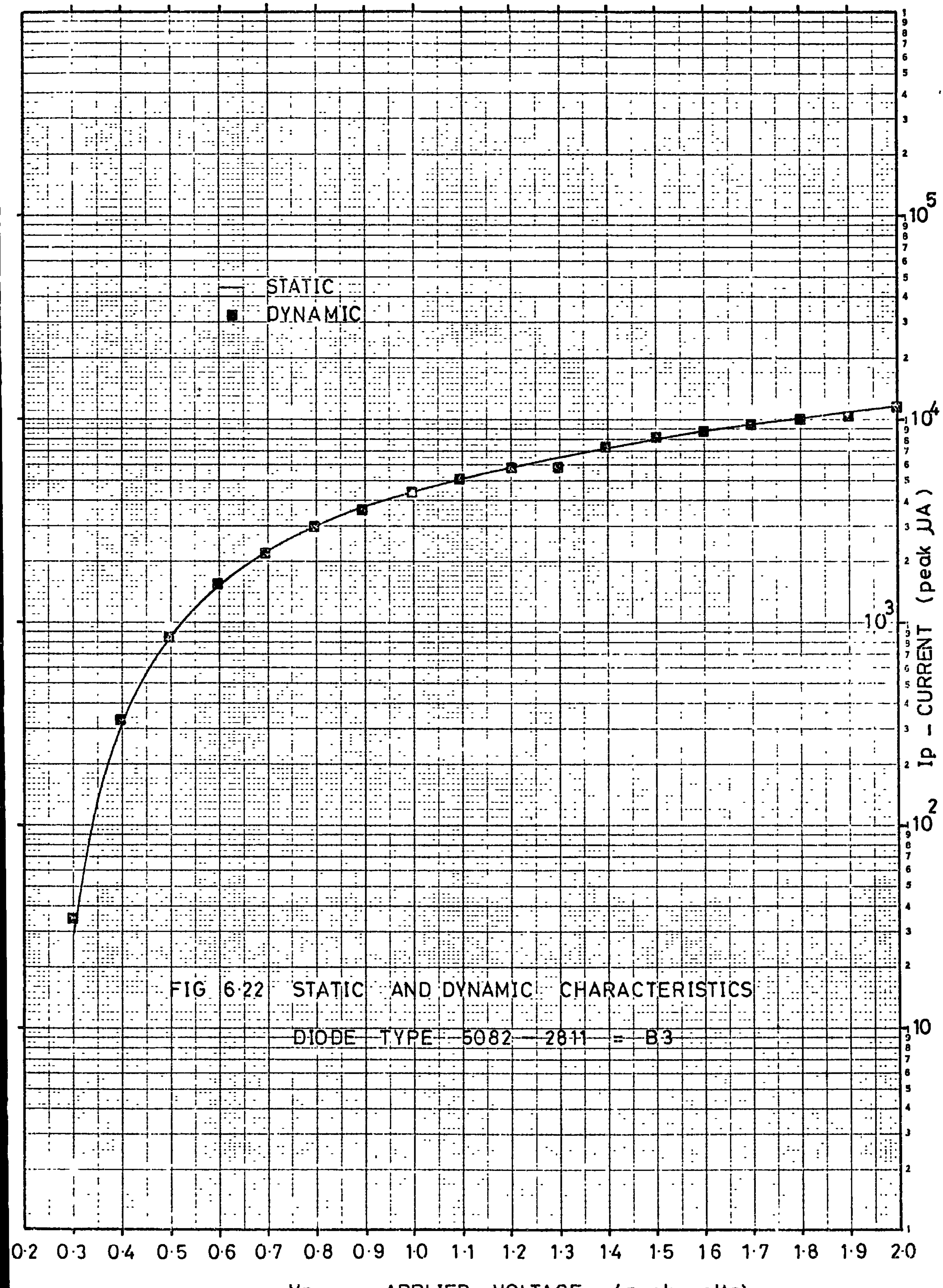
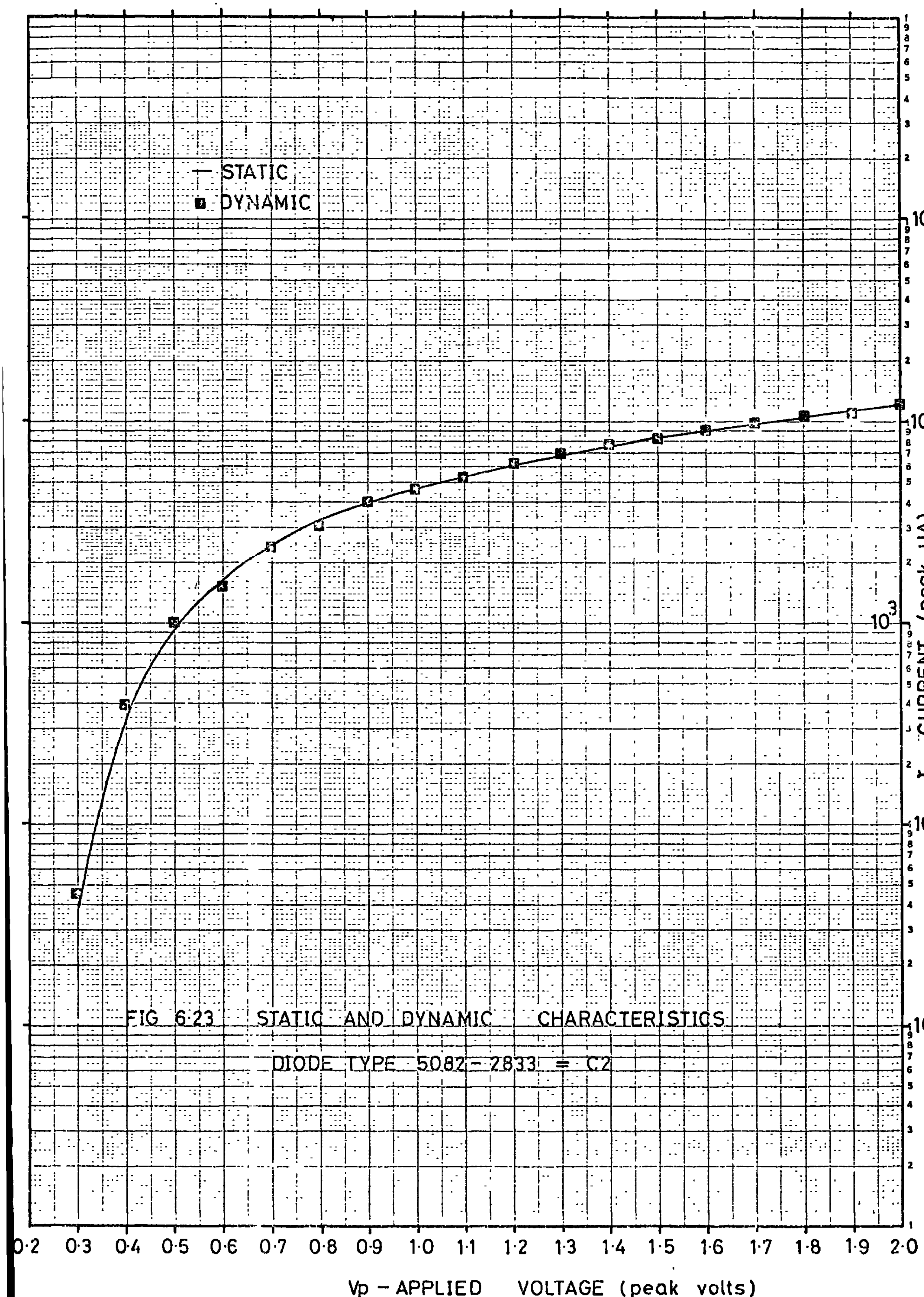


FIG 6·22 STATIC AND DYNAMIC CHARACTERISTICS



— STATIC
▪ DYNAMIC
FIG 6·23 STATIC AND DYNAMIC CHARACTERISTICS
DIODE TYPE 5082 - 2833 = C2
Ip CURRENT (peak μA)
10^5
10^4
10^3
10^2
10
0·2
0·3
0·4
0·5
0·6
0·7
0·8
0·9
1·0
1·1
1·2
1·3
1·4
1·5
1·6
1·7
1·8
1·9
2·0
Vp - APPLIED VOLTAGE (peak volts)

amplitudes, phase, and the parameter x. For example, the position of the maximum and minimum harmonics, along the axis of the applied voltage, are proportional to the reciprocal value of x and hence they may be shifted, relatively, as a function of x. This type of information is particularly important for higher harmonic applications and hence for detecting and mixing processes to improve their conversion efficiencies. By proper choice of the parameter x and the pump level one may ensure that the intermediate frequency, e.g. in a mixing process, produced by beating of the image and the sidebands with the pump and its harmonics add in phase to the direct product of the beat between the pump and the signal.

This area of investigation has received little attention in the past, partly because the theoretical difficulties are so severe and partly because of the limited amount of experimental verification of the exponential law. Hot-carrier diodes have provided excellent means for studying such a law. Thus, it is probable that the understanding of other nonlinear devices, such as varactor diodes, may be greatly increased from the insight gained during the investigations of hot-carrier diodes carried out here.

CHAPTER 7

CONCLUSIONS

The qualitative discussion of nonlinear elements in Chapter 2 was necessary to the analysis of the electrical properties of hot-carrier diodes. It was deduced that the essential process of a nonlinear element is to generate harmonic spectrum and no frequency conversion can take place without the existence of harmonic sources.

In practice, a pure nonlinear element cannot be achieved. The need for an equivalent circuit of the actual hot-carrier diode produced the physical representation discussed in Chapter 3. This led to the general conclusion that, at microwave frequencies, the values of junction capacitance, lead inductance, and package capacitance, in addition to the junction and series resistances, should normally be taken into account. At frequencies less than 30 MHz, the equivalent circuit of hot carrier diodes may be taken as a nonlinear junction resistance in series with the substrate resistance.

In Chapter 4, the pumping problems of voltage and current driven hot-carrier diodes were treated together with the measurement difficulties of harmonic voltages that will be encountered in the latter case. In the voltage driven circuit, the diode employed was assumed to have the modified exponential curve, shown in Figure 4.4c, to avoid the Fourier voltage drive. Such modification cannot be easily considered in the current-driven circuit since an ideal current source is difficult to achieve. The measurements of the harmonic currents are easy to obtain selectively, while the measurements of harmonic voltages across a high impedance are very difficult in practice. Therefore, the analysis of a voltage-driven diode was considered for easier experimental verification.

The amplitudes of the harmonic spectrum were given in terms of an arbitrary power series coefficient $\bar{a}_m$ by the equations (4.10) and (4.11). Then the harmonic chord and incremental conductances were obtained as functions of the harmonic currents for further consideration.

The analysis of a single frequency, voltage-driven hot-carrier diode, given in Chapter 5, consisted of two main parts: infinite series and numeric solutions for the harmonic current. In the first part, the amplitudes of the harmonic currents were derived from the power series expansion of the modified exponential law in terms of the applied voltage. The coefficient in the power series were obtained by successive differentiation of the current w.r.t. V evaluated about $V = 0$. The auxiliary coefficient $A_m(x)$, given by the quotient of two polynomials, was expanded into an infinite power series in terms of x. Using the Stirling numbers of the second kind, the general formula for $A_m(x)$ was deduced as a power series expansion in terms of xe^x. This formula proved to be a powerful expression in computing the n^{th} coefficient or the derivative of the exponential law independently.

Apart from substituting the coefficient $A_m(x)$ into the power series expansion of the current in terms of the driving voltage $V = V_p \cos \omega_p t$, the term $(\cos \omega_p t)^m$ was evaluated in terms of its harmonic components using the trigonometric expansion given in equation (5.20).

Thus, terms had been rearranged and the amplitudes of the harmonic currents were extracted, finally, in terms of the modified Bessel functions of the K^{th} kind of order zero and n, where K is the power of xe^x in the power series expansion of the n^{th} harmonic current $(\hat{i}_n)$ as given by equations (5.28) and (5.29).

Unfortunately, such elegrant expressions for the amplitude of the n^{th} harmonic current do not converge quickly enough for increasing values of the applied voltages to be of practical value for numerical evaluations. Therefore, a method for obtaining a closed form expression was proposed to provide the fastest and most easily programmable solution.

In the second part, the diode power series solution of the current as a function of the applied voltage had been expanded in terms of $\left(x\ e^{\alpha v}+x\right)^K$ and rearranged until the current was put in a closed form satisfying the auxiliary indicial equation given by equation (5.41). This relation was used to calculate, numerically, the values of $X(\omega_p t)$ over the period 2π of the applied voltage $v_p \cos \omega_p t$. Then the amplitudes of the harmonic currents were determined from equation (5.42) by subroutine C06AAF of the finite Fourier transform. (App. 2)

The waveform of $X(\omega_p t)$ vs. $\omega_p t$ has led to the approximate analytic solution given by equation (5.61) over the three assigned intervals. The calculation of harmonics by integrating over the first interval is very difficult to achieve. The representation over the second interval may be integrated by applying Fourier series technique to the power series expansion of the function. The contribution of the function over the third interval to the harmonic currents may be represented by a modified Bessel function. However, the function $X(z)$ was expressed in a form useful for calculating the dc characteristics of hot-carrier diodes; it was also helpful in reducing the complexity and time of the computer programme.

Thus, the graph of $X(\omega_p t)$, shown in Figure (5.2) for different values of $x = \alpha I_S R_T$, indicated that each positive waveform may be represented by a pulse train of width τ which is proportional to x and the pumping voltage. The width of the pulse was obtained as a function of x and V_p and hence the number of harmonics $\left(\frac{2\pi}{\tau}\right)$ could be calculated and the zero frequencies $\left(\frac{1}{\tau}, \frac{2}{\tau}, \ldots\right)$ might be located in the frequency domain. Consequently, one may select the pump voltage and the total series resistance R_T to find the required polarities and number $(n-1)$ of the harmonic spectrum in $\frac{1}{\tau}$ from the relation

$$V_p = \frac{1 - \ell nx - x}{\alpha \cos\left(\frac{\pi}{n}\right)}$$

where $n > 2$.

The optimum peak applied voltage $\hat{V}_p$ for infinite positive harmonic spectrum (e.g. $\frac{1}{\tau} = \infty$) can be found from the relation

$$\hat{V}_p = \frac{1 - \ell nx - x}{\alpha} .$$

From the fact that the peak current generated at such optimum peak voltage is equal to $\frac{1}{\alpha R_T}$ amp, one may use it as a figure of merit to compare the capabilities of hot-carrier diodes.

In summary, the waveforms of Figure (5.2) showed that the effect of the series resistance is to give rise to wave-like pulse of positive $X(\omega_p t)$. This was proved by calculating the minimum values of x and the optimum peak applied voltage for infinite positive spectrum. The peak value X(0) tends to zero as x approaches its minimum and as V reaches it optimum values. It can also be seen that any further decrease in x, from its minimum value, will shift $X(\omega_p t)$ to the negative side at which $Z(\omega_p t) \simeq X(\omega_p t)$ and consequently the ideal exponential law is reached.

Experimental results were presented, in Chapter 6, to support the theory of the analysis. Starting with the dc characteristics, the three constants α, r_s, and I_s were calculated. By substituting the calculated constants together with the measured currents back into the modified exponential law the forward voltages had been obtained within an average error of 2% compared to the measured values. This so far proved the validity of the modified exponential law and provided useful data for the analysis.

The amplitudes of the harmonic currents were then measured selectively for a wide range of applied voltages at the fundamental frequency of 50 KHz. The results obtained for twelve difference diodes compared well with the theoretically calculated harmonics.

It is felt that the conclusions of the analysis have been substantiated by the experiments with the equivalent circuit of the actual diode represented by the combination of nonlinear and series resistances at the proposed frequency. The resultant expressions from the analysis should, therefore, apply generally to the practical hot-carrier diodes.

From the foregoing investigations, one may conclude that a large amount of useful information was obtained about the harmonic generating properties of practical hot-carrier diodes used as non-linear resistances. This information and the approach presented in the analysis should help in the selection of diodes for the best performance in a number of applications. In a mixing process, for example, the pump conductance waveform can be accurately predicted from equations (4.21) and (4.22) which were given in terms of the pump voltage and the harmonic currents calculated in Chapter 5. The pump power and the conductance offered to the pump may also be obtained by considering the driving voltage and the fundamental current. The small signal conductance waveform can be calculated from equations (4.27) and (4.28). With the help of the matrix form, of a specific mixing circuit, the conversion power loss and source and output conductances may be deduced.

Further mathematical study might lead to more elegant closed form solutions for numerical evaluation of the harmonic amplitudes. As a result, the problem of analytic calculation of the conductance waveform may be solved and the basic mechanism of harmonic generation more fully understood.

There are a variety of aspects which deserve further investigations. The reported results on the calculation of the harmonic amplitudes have been very encouraging, but the effect of various circuit and diode parameters such as junction, capacitance and series inductance at microwave frequencies have not been treated and are sufficiently important to warrant further research.

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APPENDIX A1

CALCULATED DATA FOR FIGURE 5.2

FOR DIFFERENT VALUES OF x.

```
C       M.KATIB   APPL.  PHYS.
C       DIODE B2
        IMPLICIT REAL*8(A-H,O-Z)
        DIMENSION X(6000),Z(6000),Y(300),PZ(300),SMIN(300),
       1X1(400),A(300),B(300),AD(300),BD(300),C(300),D(300),
       2ILST(300),VOLT(300),HARM(300)
        X(1)=0.0D0
        DO 1 K=2,500
        X(K)=X(K-1)+0.01D0
      1 CONTINUE
        X(501)=-0.01D0
        DO 2 K=502,1500
        X(K)=X(K-1)-0.01D0
      2 CONTINUE
        S=4.0D0*DATAN(1.0D0)
        Y(1)=0.0D0
        DO 3 K=2,33
        Y(K)=Y(K-1)+S/32.0D0
      3 CONTINUE
        DO 4 I=1,1500
        Z(I)=X(I)+DEXP(X(I))
      4 CONTINUE
        ARCS=10.0D0**(-16)
        BIA=DLOG(ARCS)
        DO 5 J=1,33
        RZ(J)=40.0D0*DCOS(Y(J))+BIA+ARCS
      5 CONTINUE
        DO 8 K=1,33
        RVAL=RZ(K)
        IF(RZ(K).LE.-9.99995) GO TO 22
        ZRMIN=DABS(RVAL-Z(1))
        DO 9 J=2,1500
        ZRVAL=DABS(RVAL-Z(J))
        IF(ZRVAL.LT.ZRMIN)ZRMIN=ZRVAL
      9 CONTINUE
        SMIN(K)=ZRMIN
      8 CONTINUE
     22 CONTINUE
        DO 11 K=1,33
        IF(RZ(K).LE.-9.99995) GO TO 33
        DO 12 J=1,1500
        IF(DABS(RZ(K)-Z(J)).NE.SMIN(K)) GO TO 12
        X1(K)=X(J)
     12 CONTINUE
     11 CONTINUE
     33 CONTINUE
        DO 55 I=K,33
     55 X1(I)=RZ(I)
        WRITE(6,100)
    100 FORMAT(5H1LIST,1X,9HVAL.OF X1,4X,5HANGLE,4X,9HVAL.OF.RZ)
        WRITE(6,350)(K,X1(K),Y(K),RZ(K),K=1,33)
    350 FORMAT(I5,3F10.5)
        STOP
        END
```

$\hat{V}_p$ 1·0 VOLT

LIST	ANGLE	X = 1000 VAL OF X1	X = 1000 VAL OF RZ	X = 1 VAL OF X1	X = 1 VAL OF RZ	X = 10^{-3} VAL OF XI	X = 10^{-3} VAL OF RZ	X = 10^{-6} VAL OF X1	X = 10^{-6} VAL OF RZ	X = 10^{-16} VAL OF X1	X = 10^{-16} VAL OF RZ
				- - -	- - -						
1	0.0	6.95000	1046.90776	3.62000	41.00000	3.39000	33.09324	3.14000	26.18449	0.84000	3.15864
2	0.09817	6.95000	1046.71514	3.62000	40.80739	3.38000	32.90063	3.13000	25.99188	0.78000	2.96603
3	0.19635	6.95000	1046.13917	3.60000	40.23141	3.37000	32.32466	3.11000	25.41590	0.59000	2.39005
4	0.29452	6.95000	1045.18537	3.58000	39.27761	3.33000	31.37086	3.06000	24.46210	0.21000	1.43625
5	0.39270	6.94000	1043.86294	3.54000	37.95518	3.29000	30.04843	3.00000	23.13967	-0.50000	0.11382
6	0.49087	6.94000	1042.18461	3.49000	36.27685	3.22000	28.37010	2.92000	21.46134	-1.74000	-1.56451
7	0.58905	6.94000	1040.16654	3.43000	34.25878	3.14000	26.35203	2.81000	19.44327	-3.61000	-3.58258
8	0.68722	6.94000	1037.82817	3.35000	31.92042	3.04000	24.01366	2.67000	17.10491	-5.92000	-5.92094
9	0.78540	6.94000	1035.19203	3.26000	29.28427	2.92000	21.37752	2.48000	14.46876	-8.56000	-8.55709
10	0.88357	6.93000	1032.28349	3.15000	26.37573	2.75000	18.46898	2.23000	11.56022	-11.46563	-11.46563
11	0.98175	6.93000	1029.13056	3.01000	23.22281	2.55000	15.31605	1.88000	8.40730	-14.61855	-14.61855
12	1.07992	6.93000	1025.76362	2.83000	19.85597	2.27000	11.94911	1.32000	5.04036	-17.98549	-17.98549
13	1.17810	6.92000	1022.21509	2.62000	16.30734	1.88000	8.40058	0.23000	1.49183	-21.53402	-21.53402
14	1.27627	6.92000	1018.51914	2.33000	12.61139	1.24000	4.70463	-2.30000	-2.20412	-25.22997	-25.22997
15	1.37445	6.92000	1014.71137	1.93000	8.80361	-0.05000	0.89686	-6.01000	-6.01190	-29.03775	-29.03775
16	1.47262	6.91000	1010.82844	1.29000	4.92069	-3.03000	-2.98607	-9.89000	-9.89482	-32.92068	-32.92068
17	1.57080	6.91000	1006.90776	0.0	1.00000	-6.91000	-6.90676	-13.81551	-13.81551	-36.84136	-36.84136
18	1.66897	6.90000	1002.98707	-2.97000	-2.92069	-10.82744	-10.82744	-17.73620	-17.73620	-40.76205	-40.76205
19	1.76715	6.90000	999.10414	-6.80000	-6.80361	-14.71037	-14.71037	-21.61912	-21.61912	-44.64497	-44.64497
20	1.86532	6.90000	995.29637	-10.61139	-10.61139	-18.51814	-18.51814	-25.42690	-25.42690	-48.45275	-48.45275
21	1.96350	6.89000	991.60042	-14.30734	-14.30734	-22.21409	-22.21409	-29.12285	-29.12285	-52.14870	-52.14870
22	2.06167	6.89000	988.05189	-17.85587	-17.85587	-25.76262	-25.76262	-32.67138	-32.67138	-55.69723	-55.69723
23	2.15984	6.89000	984.68495	-21.22281	-21.22281	-29.12956	-29.12956	-36.03832	-36.03832	-59.06417	-59.06417
24	2.25802	6.88000	981.53202	-24.37573	-24.37573	-32.28249	-32.28249	-39.19124	-39.19124	-62.21709	-62.21709
25	2.35619	6.88000	978.62348	-27.28427	-27.28427	-35.19103	-35.19103	-42.09978	-42.09978	-65.12563	-65.12563
26	2.45437	6.88000	975.98734	-29.92042	-29.92042	-37.82717	-37.82717	-44.73593	-44.73593	-67.76178	-67.76178
27	2.55254	6.87000	973.64897	-32.25878	-32.25878	-40.16554	-40.16554	-47.07429	-47.07429	-70.10015	-70.10015
28	2.65072	6.87000	971.63090	-34.27685	-34.27685	-42.18361	-42.18361	-49.09236	-49.09236	-72.11821	-72.11821
29	2.74889	6.87000	969.95257	-35.95518	-35.95518	-43.86194	-43.86194	-50.77069	-50.77069	-73.79654	-73.79654
30	2.84707	6.87000	968.63014	-37.27761	-37.27761	-45.18437	-45.18437	-52.09312	-52.09312	-75.11897	-75.11897
31	2.94524	6.87000	967.67634	-38.23141	-38.23141	-46.13817	-46.13817	-53.04692	-53.04692	-76.07277	-76.07277
32	3.04342	6.87000	967.10037	-38.80739	-38.80739	-46.71414	-46.71414	-53.62290	-53.62290	-76.64875	-76.64875
33	3.14159			-39.00000	-39.00000	-46.90676	-46.90676	-53.81551	-53.81551	-76.84136	-76.84136

APPENDIX A2

THEORETICAL DATA FOR FIGURES 6.9 - 6.20 ;

DIODES A1, A2, A3, A4, B1, B2, B3, B4,

C1, C2, C3, C4 .

```
C       M.KATIB   APPL.  PHYS.
C       DIODE A1
        IMPLICIT REAL*8(A-H,O-Z)
        DIMENSION X(6000),Z(6000),Y(300),RZ(300),SMIN(300),
       1X1(400),A(300),B(300),AD(300),BD(300),C(300),D(300),
       2ILST(300),VOLT(300),HARM(300),HCUR(50,50)
        X(1)=0.01D0
        DO 1 K=1,500
        X(K)=X(K-1)+0.01D0
      1 CONTINUE
        X(501)=-0.01D0
        DO 2 K=502,1500
        X(K)=X(K-1)-0.01D0
      2 CONTINUE
        S=4.0D0*DATAN(1.0D0)
        Y(1)=0.0D0
        DO 3 K=2,33
        Y(K)=Y(K-1)+S/32.0D0
      3 CONTINUE
        DO 4 I=1,1500
        Z(I)=X(I)+DEXP(X(I))
      4 CONTINUE
        ALPH=35.0D0
        RS=151.5D0
        CIS=3.5D0*(10.0D0**(-9))
        ARCS=ALPH*RS*CIS
        BIA=DLOG(ARCS)
        READ(6,119)NST,MVOLT
    119 FORMAT(2I4)
        DO 44 L=NST,MVOLT
        VOLT(L)=FLOAT(L)*0.05D0
        DO 5 J=1,33
        RZ(J)=ALPH*VOLT(L)*DCOS(Y(J))+BIA+ARCS
      5 CONTINUE
        DO 8 K=1,33
        RVAL=RZ(K)
        IF(RZ(K).LE.-9.99995) GO TO 22
        ZRMIN=DABS(RVAL-Z(1))
        DO 9 J=2,1500
        ZRVAL=DABS(RVAL-Z(J))
        IF(ZRVAL.LT.ZRMIN)ZRMIN=ZRVAL
      9 CONTINUE
        SMIN(K)=ZRMIN
      8 CONTINUE
     22 CONTINUE
        DO 11 K=1,33
        IF(RZ(K).LE.-9.99995) GO TO 33
        DO 12 J=1,1500
        IF(DABS(RZ(K)-Z(J)).NE.SMIN(K)) GO TO 12
        X1(K)=X(J)
     12 CONTINUE
     11 CONTINUE
     33 CONTINUE
        DO 55 I=K,33
     55 X1(I)=RZ(I)
```

```
      N=32
      DO 13 I=1,N
      K=N-I+2
      A(I)=(CIS/ARCS)*DEXP(X1(I))-CIS
      B(I)=(CIS/ARCS)*DEXP(X1(K))-CIS
      AD(I)=A(I)
      BD(I)=B(I)
   13 CONTINUE
      N1=N+1
      M1=12
      CALL C06AAF(A,B,N1,.FALSE.,M1,ILST)
      DO 14 I=1,N1
      C(I)=A(I)
      D(I)=B(I)
   14 HCUR(L,I)=C(I)*(10.0D0**6)
      CALL C06AAF(A,B,N1,.TRUE.,M1,ILST)
      HARM(1)=C(1)/2.0D0
      HCUR(L,1)=HARM(1)*(10.0D0**6)
   44 CONTINUE
      WRITE (6,666)
  666 FORMAT (1H1,34X,23HDIODE TYPE 5082-2800=A1///
     14X,4HVOLT,3X,4HI(0),4X,4HI(1),4X,4HI(2),4X,4HI(3)
     2,4X,4HI(4),4X,4HI(5),4X,4HI(6),4X,4HI(7),4X,4HI(8),4X,
     34HI(9),4X,5HI(10)//)
      WRITE (6,444)(VOLT(L),(HCUR(L,I),I=1,11),L=1,40)
  444 FORMAT(12F8.2)
      STOP
      END
```

```
   TOTAL MEMORY REQUIREMENTS 02479A BYTES
EXECUTION TERMINATED


$R -LOAD#+*NAG
EXECUTION BEGINS
```

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.05	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.02	0.04	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.15	0.12	0.21	0.16	0.09	0.05	0.02	0.01	0.00	0.00	0.00	0.00
0.20	0.58	1.08	0.85	0.58	0.35	0.18	0.08	0.03	0.01	0.00	0.00
0.25	2.80	5.26	4.36	3.19	2.07	1.19	0.61	0.27	0.10	0.03	0.01
0.30	11.49	21.69	18.20	13.54	8.89	5.08	2.45	0.92	0.18	-0.09	-0.14
0.35	33.55	63.06	52.19	37.69	23.28	11.71	4.15	0.26	-1.06	-1.04	-0.59
0.40	70.92	132.13	106.23	72.32	39.74	15.25	1.17	-4.08	-4.01	-2.03	-0.30
0.45	121.08	223.40	173.92	110.77	52.85	12.90	-6.17	-9.47	-5.25	-0.32	2.09
0.50	180.18	329.22	248.09	147.29	59.36	4.28	-16.23	-13.94	-4.12	2.82	3.95
0.55	247.34	447.92	327.51	181.71	60.57	-8.09	-26.27	-15.68	-0.11	7.20	5.54
0.60	319.53	573.93	408.04	212.03	56.72	-22.61	-34.83	-14.58	5.19	10.25	4.26
0.65	395.03	704.26	487.94	238.24	49.29	-37.07	-39.90	-9.34	12.78	13.42	2.54
0.70	476.42	843.85	571.48	263.44	39.75	-52.10	-44.13	-3.69	19.28	14.90	0.26
0.75	557.56	981.46	650.25	282.83	26.45	-67.50	-46.96	2.40	24.02	13.59	-3.89
0.80	642.82	1125.47	731.52	302.02	13.02	-81.49	-47.76	9.33	27.91	10.80	-8.97
0.85	730.40	1272.62	812.91	319.63	-1.12	-94.24	-46.54	17.27	31.39	7.28	-13.98
0.90	820.10	1422.47	893.86	334.86	-17.19	-107.40	-45.11	25.02	34.73	5.17	-15.43
0.95	908.21	1568.63	970.56	346.88	-33.78	-118.63	-41.29	33.67	37.22	1.38	-18.78
1.00	1002.31	1724.59	1052.30	360.17	-50.08	-128.91	-36.46	42.15	38.16	-4.50	-24.05
1.05	1091.43	1871.27	1126.94	369.68	-67.01	-138.42	-31.40	50.00	39.08	-8.11	-24.67
1.10	1186.21	2027.67	1207.74	382.21	-82.55	-147.44	-26.94	56.16	37.92	-13.86	-28.34
1.15	1278.96	2179.18	1282.25	388.55	-102.27	-158.38	-23.68	60.47	34.60	-20.44	-30.20
1.20	1375.48	2337.88	1363.34	401.07	-116.13	-164.25	-16.66	67.39	33.40	-25.16	-31.14
1.25	1470.73	2493.21	1439.78	409.43	-131.67	-169.54	-8.95	73.44	30.39	-30.71	-30.91
1.30	1567.04	2649.66	1514.84	413.49	-153.68	-181.72	-6.46	77.40	28.07	-35.02	-31.27
1.35	1662.93	2805.59	1591.10	422.76	-165.53	-181.09	7.24	88.05	28.30	-38.39	-30.42
1.40	1759.65	2962.70	1666.98	428.89	-183.92	-189.52	11.85	92.38	26.14	-41.44	-28.75
1.45	1854.04	3114.31	1736.13	428.84	-205.85	-198.83	16.21	95.14	20.88	-47.99	-29.88
1.50	1954.13	3276.66	1814.90	438.22	-217.70	-198.07	28.93	103.55	18.95	-52.77	-30.74
1.55	2048.97	3428.78	1883.80	437.43	-240.72	-209.00	31.52	105.89	16.15	-54.03	-25.56
1.60	2150.17	3593.39	1964.88	448.80	-251.78	-209.31	42.15	113.34	15.74	-55.97	-24.95
1.65	2251.28	3756.32	2041.55	454.88	-266.49	-211.60	49.61	113.59	4.30	-69.11	-30.95
1.70	2349.55	3914.59	2115.30	458.26	-285.65	-219.58	54.12	118.29	5.90	-64.58	-21.10
1.75	2445.18	4067.17	2182.79	455.73	-309.25	-230.25	57.04	121.50	5.04	-64.62	-18.75
1.80	2543.70	4225.86	2258.30	465.61	-315.30	-221.49	75.16	131.04	1.85	-71.01	-21.07
1.85	2644.93	4387.33	2330.20	464.94	-337.10	-231.21	75.19	126.89	-7.29	-75.54	-17.75
1.90	2746.71	4550.30	2404.39	467.25	-354.89	-234.64	84.76	134.36	-5.93	-73.74	-12.90
1.95	2845.35	4708.95	2478.79	473.68	-368.16	-237.18	89.57	132.27	-16.20	-82.34	-13.73
2.00	2942.86	4863.89	2546.54	471.89	-388.22	-242.60	96.48	137.22	-15.78	-79.77	-7.89

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.05	0.01	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.04	0.08	0.05	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00
0.15	0.21	0.39	0.28	0.16	0.08	0.03	0.01	0.00	0.00	0.00	0.00
0.20	0.96	1.78	1.39	0.93	0.54	0.27	0.12	0.05	0.02	0.01	0.00
0.25	4.18	7.83	6.40	4.58	2.88	1.59	0.76	0.32	0.11	0.03	0.00
0.30	15.18	28.52	23.57	17.08	10.77	5.79	2.54	0.78	0.04	-0.16	-0.13
0.35	40.24	75.24	61.26	42.95	25.24	11.62	3.27	-0.55	-1.45	-1.04	-0.37
0.40	80.20	148.71	117.77	77.93	40.67	13.81	-0.55	-4.98	-3.99	-1.53	0.24
0.45	132.36	243.13	186.62	115.57	52.04	10.02	-8.40	-10.11	-4.82	0.24	2.26
0.50	193.53	352.18	261.91	151.26	57.00	0.42	-18.39	-13.87	-3.05	3.56	3.92
0.55	261.54	471.87	340.78	184.10	56.90	-12.04	-27.43	-14.47	1.39	7.59	4.93
0.60	335.07	599.83	421.70	213.68	52.28	-26.61	-35.53	-13.14	6.31	9.94	3.29
0.65	413.27	734.63	503.97	240.49	44.91	-40.75	-40.18	-7.99	13.11	12.18	1.19
0.70	494.35	873.04	585.31	263.12	33.58	-56.30	-44.21	-2.33	19.02	12.69	-2.13
0.75	577.71	1014.42	666.50	284.18	22.21	-69.28	-44.96	4.49	23.00	9.87	-7.71
0.80	664.84	1161.21	748.37	302.12	7.00	-84.48	-45.99	12.16	28.61	9.68	-9.80
0.85	753.02	1308.85	828.95	318.46	-7.58	-96.48	-43.73	20.46	31.76	6.02	-14.05
0.90	842.94	1459.11	910.33	334.39	-22.73	-109.14	-42.86	26.63	33.25	2.40	-16.82
0.95	932.34	1607.03	987.15	345.49	-40.13	-120.61	-39.20	34.66	34.73	-2.31	-20.79
1.00	1025.95	1761.86	1067.61	357.80	-56.82	-131.03	-34.70	42.90	36.48	-5.64	-22.12
1.05	1119.25	1915.56	1146.34	368.99	-72.92	-139.79	-29.50	49.47	34.73	-12.60	-26.20
1.10	1212.50	2069.00	1224.41	379.08	-90.77	-151.07	-26.88	55.06	35.01	-14.97	-25.34
1.15	1309.25	2227.76	1304.80	390.69	-104.66	-155.52	-17.59	63.62	33.64	-21.60	-28.68
1.20	1402.20	2378.83	1377.68	396.03	-122.84	-162.59	-10.05	71.29	33.07	-25.31	-27.97
1.25	1497.93	2535.27	1455.49	405.59	-138.01	-168.45	-2.93	78.15	32.65	-27.99	-26.93
1.30	1597.56	2697.87	1535.85	414.85	-154.20	-174.68	4.09	83.91	29.34	-34.99	-30.41
1.35	1694.67	2855.25	1610.96	419.51	-173.82	-183.32	9.70	90.18	29.71	-35.14	-25.52
1.40	1795.96	3019.87	1690.94	427.43	-190.47	-189.39	15.74	93.01	22.71	-45.03	-30.90
1.45	1893.20	3177.14	1765.56	432.21	-208.99	-197.32	19.90	95.66	19.22	-47.31	-26.26
1.50	1988.80	3330.72	1836.08	433.93	-227.95	-202.82	28.02	101.91	17.42	-50.90	-26.18
1.55	2091.50	3496.66	1914.73	439.82	-244.71	-206.30	38.63	110.85	17.99	-52.91	-25.51
1.60	2192.18	3659.84	1993.83	449.33	-257.57	-209.92	42.78	109.28	9.18	-58.98	-22.99
1.65	2292.77	3821.03	2066.98	450.10	-277.97	-215.75	51.55	116.93	9.79	-59.43	-20.41
1.70	2390.42	3978.41	2141.29	456.54	-292.04	-219.34	56.38	116.42	1.92	-66.05	-21.30
1.75	2493.40	4144.96	2221.40	465.87	-304.24	-220.53	64.30	118.95	-3.53	-70.66	-19.92
1.80	2592.34	4302.39	2289.98	461.72	-329.75	-232.21	66.28	120.13	-7.08	-71.90	-14.92
1.85	2694.41	4465.70	2364.75	466.78	-341.14	-226.55	84.44	132.43	-6.20	-75.44	-18.33
1.90	2796.51	4629.16	2438.83	467.68	-362.22	-235.32	86.82	131.28	-13.85	-80.72	-15.36
1.95	2895.87	4787.82	2510.58	470.55	-377.22	-236.45	96.09	136.67	-13.92	-79.00	-11.28
2.00	2998.19	4951.34	2584.69	473.28	-393.80	-239.82	101.94	136.10	-22.88	-86.95	-13.46

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.05	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.03	0.05	0.03	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00
0.15	0.14	0.26	0.19	0.12	0.06	0.03	0.01	0.00	0.00	0.00	0.00
0.20	0.71	1.31	1.04	0.71	0.42	0.22	0.10	0.04	0.01	0.00	0.00
0.25	3.37	6.34	5.24	3.82	2.46	1.40	0.70	0.31	0.11	0.03	0.00
0.30	13.38	25.22	21.08	15.57	10.10	5.66	2.64	0.91	0.11	-0.15	-0.16
0.35	37.35	70.05	57.60	41.10	24.84	12.00	3.81	-0.18	-1.35	-1.12	-0.51
0.40	76.51	142.23	113.56	76.27	40.84	14.69	0.15	-4.80	-4.22	-1.89	-2.05
0.45	128.18	235.94	182.28	114.25	52.60	10.98	-7.99	-10.37	-5.35	-0.16	2.09
0.50	188.93	344.45	257.72	150.67	58.42	1.98	-17.65	-13.82	-3.01	4.02	4.74
0.55	256.49	463.49	336.43	183.65	58.37	-10.75	-27.17	-14.80	1.20	7.72	5.00
0.60	329.72	590.93	416.92	212.69	52.87	-26.47	-36.34	-14.10	6.06	10.46	3.99
0.65	407.54	725.18	499.14	239.71	45.59	-40.81	-41.30	-9.15	12.68	12.19	0.78
0.70	486.41	859.86	578.39	262.07	35.17	-55.15	-44.50	-3.35	18.17	12.22	-2.38
0.75	570.76	1003.09	660.95	283.58	23.29	-69.02	-45.57	4.31	23.95	11.35	-6.56
0.80	656.05	1146.63	740.61	300.39	7.57	-84.72	-47.61	10.26	27.25	8.74	-10.66
0.85	743.20	1292.82	821.03	317.64	-5.72	-95.44	-43.90	20.42	32.46	6.60	-14.62
0.90	831.86	1440.71	900.49	332.28	-21.41	-107.80	-42.05	27.80	34.93	3.78	-16.23
0.95	920.64	1587.87	977.60	344.49	-37.53	-118.27	-37.67	36.48	37.04	-0.45	-19.98
1.00	1015.10	1744.48	1059.99	358.77	-52.47	-127.49	-32.92	43.66	36.43	-6.97	-24.64
1.05	1104.58	1891.07	1132.68	364.69	-73.51	-140.52	-30.16	50.47	37.12	-10.92	-26.66
1.10	1200.20	2048.65	1213.76	377.28	-88.15	-147.47	-23.30	58.21	36.35	-16.56	-26.94
1.15	1293.85	2201.99	1290.08	385.11	-107.21	-158.87	-21.01	62.55	35.49	-18.25	-25.36
1.20	1386.95	2353.54	1363.81	391.46	-124.41	-164.86	-12.12	71.40	34.83	-24.46	-29.79
1.25	1486.30	2515.95	1444.37	400.19	-142.90	-174.92	-9.26	73.62	28.90	-32.68	-32.61
1.30	1579.66	2667.96	1519.13	409.67	-154.42	-174.57	4.32	85.61	32.40	-31.82	-27.62
1.35	1675.77	2824.64	1596.31	418.32	-170.63	-182.74	6.44	84.90	23.62	-41.74	-31.89
1.40	1773.84	2983.08	1670.82	421.73	-190.04	-190.67	12.73	90.74	22.62	-43.25	-28.04
1.45	1872.59	3143.52	1748.84	429.99	-205.65	-194.78	21.12	97.25	21.10	-46.89	-28.24
1.50	1970.01	3300.44	1822.02	433.78	-222.75	-198.34	31.33	105.78	21.97	-47.08	-23.92
1.55	2069.42	3461.20	1898.58	439.94	-239.39	-204.34	35.94	106.41	14.16	-55.45	-26.58
1.60	2164.20	3613.18	1968.09	442.16	-256.29	-207.76	44.28	110.58	9.39	-60.74	-25.28
1.65	2263.76	3772.46	2039.86	442.45	-276.33	-213.02	53.14	117.81	9.64	-61.05	-22.36
1.70	2362.09	3931.16	2115.34	450.08	-288.54	-213.38	62.24	121.07	3.71	-66.98	-21.60
1.75	2464.74	4096.12	2191.62	453.38	-307.66	-220.39	67.17	123.98	0.73	-70.03	-22.70
1.80	2565.18	4256.67	2263.84	453.74	-327.99	-227.36	71.95	125.32	-4.78	-73.92	-19.69
1.85	2661.43	4411.43	2336.36	460.12	-340.43	-228.65	79.30	128.70	-6.16	-72.46	-13.98
1.90	2760.66	4569.47	2406.56	460.52	-357.86	-231.30	86.92	129.46	-15.16	-80.67	-14.26
1.95	2865.82	4739.65	2488.90	471.47	-367.81	-228.67	101.44	140.86	-11.14	-80.10	-16.50
2.00	2962.17	4893.32	2558.00	473.63	-383.15	-231.47	106.26	139.89	-18.47	-82.28	-9.85

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.05	0.01	0.02	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.04	0.07	0.04	0.02	0.01	0.00	0.00	0.00	0.00	-0.00	-0.00
0.15	0.18	0.34	0.25	0.15	0.07	0.03	0.01	0.00	0.00	0.00	0.00
0.20	0.88	1.64	1.29	0.88	0.51	0.26	0.12	0.05	0.02	0.00	0.00
0.25	4.03	7.55	6.20	4.48	2.84	1.58	0.77	0.32	0.11	0.03	-0.09
0.30	15.02	28.25	23.44	17.10	10.87	5.91	2.62	0.82	0.03	-0.19	-0.17
0.35	40.30	75.41	61.55	43.31	25.58	11.83	3.31	-0.63	-1.61	-1.21	-0.52
0.40	80.40	149.16	118.31	78.49	41.12	14.10	-0.40	-4.87	-3.84	-1.32	0.47
0.45	131.99	242.46	186.10	115.17	51.71	9.74	-8.55	-10.07	-4.60	0.53	2.45
0.50	193.20	351.58	261.44	150.94	56.81	0.40	-18.16	-13.40	-2.44	4.13	4.34
0.55	261.08	470.91	339.75	183.01	55.93	-12.64	-27.46	-13.98	2.09	8.09	5.00
0.60	333.91	597.60	419.71	212.13	51.43	-26.57	-34.63	-11.73	7.68	10.79	3.50
0.65	410.33	728.95	498.89	236.25	41.71	-42.81	-41.17	-8.22	13.19	12.14	0.88
0.70	491.44	867.83	581.75	261.76	34.32	-54.08	-41.48	-0.05	20.26	12.91	-2.45
0.75	573.70	1007.09	662.89	280.65	20.53	-69.55	-44.17	6.11	25.27	12.57	-4.83
0.80	659.24	1150.94	740.67	297.89	6.14	-83.05	-43.89	13.52	28.70	9.00	-10.26
0.85	746.75	1297.37	820.21	313.07	-10.03	-96.96	-43.27	21.11	32.20	6.10	-14.34
0.90	834.48	1443.42	898.16	327.31	-24.44	-106.72	-38.69	30.11	34.77	2.28	-17.34
0.95	924.15	1592.31	976.73	340.25	-41.14	-119.34	-37.52	35.84	35.57	-1.16	-18.91
1.00	1016.25	1745.32	1058.20	356.28	-52.98	-125.73	-31.07	43.66	34.96	-8.09	-24.42
1.05	1107.85	1894.79	1133.79	359.75	-76.84	-140.38	-28.61	50.69	35.81	-11.78	-25.63
1.10	1201.28	2049.26	1211.71	374.94	-88.03	-145.22	-21.78	57.23	34.29	-17.15	-27.55
1.15	1295.47	2203.17	1287.59	381.71	-107.85	-156.43	-18.54	62.48	33.53	-19.68	-25.08
1.20	1388.34	2354.48	1361.51	388.52	-124.77	-162.66	-10.21	71.05	33.23	-25.22	-29.28
1.25	1486.07	2513.81	1439.66	396.16	-142.71	-171.00	-5.29	75.31	29.62	-30.64	-26.83
1.30	1580.59	2667.48	1514.46	403.92	-157.08	-173.76	5.28	83.92	28.59	-35.34	-29.56
1.35	1677.71	2826.08	1593.36	414.22	-171.53	-180.03	9.42	85.16	21.61	-43.58	-32.13
1.40	1775.18	2983.76	1668.16	418.82	-190.39	-187.90	14.43	89.53	20.38	-43.79	-26.68
1.45	1871.87	3139.25	1739.74	420.38	-210.27	-193.92	23.21	97.09	19.35	-47.46	-25.49
1.50	1967.30	3292.64	1810.75	422.23	-230.52	-202.23	28.19	101.39	17.38	-49.97	-24.82
1.55	2067.89	3456.20	1890.66	433.74	-239.92	-200.35	39.48	106.46	12.01	-57.32	-28.19
1.60	2165.93	3614.99	1964.73	438.48	-255.99	-204.28	46.43	109.11	6.59	-61.49	-23.66
1.65	2264.04	3772.12	2038.31	441.51	-275.51	-211.79	52.92	116.53	9.27	-60.01	-21.54
1.70	2361.95	3928.78	2109.74	444.91	-292.09	-213.06	60.30	116.09	-0.91	-68.67	-21.97
1.75	2463.95	4093.79	2189.05	453.64	-303.31	-215.44	67.82	119.66	-4.38	-71.79	-20.90
1.80	2550.92	4248.30	2256.96	450.58	-327.43	-226.51	69.61	120.26	-8.83	-74.22	-16.60
1.85	2660.18	4407.72	2331.70	458.58	-336.12	-221.26	84.31	129.15	-8.03	-74.27	-16.24
1.90	2761.02	4569.28	2404.67	459.35	-356.87	-229.75	86.70	127.89	-15.68	-79.43	-13.19
1.95	2856.09	4719.67	2469.64	456.92	-375.96	-234.12	93.54	131.88	-15.87	-76.49	-6.68
2.00	2959.43	4885.52	2549.44	456.06	-387.91	-235.33	104.59	131.00	-23.24	-84.87	-12.19

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.15	0.04	0.08	0.06	0.03	0.02	0.01	0.00	0.00	0.00	0.00	0.00
0.20	0.22	0.41	0.33	0.23	0.14	0.07	0.04	0.02	0.01	0.00	0.00
0.25	1.18	2.23	1.86	1.39	0.92	0.55	0.30	0.14	0.06	0.02	0.01
0.30	5.79	10.99	9.40	7.23	5.01	3.12	1.73	0.84	0.35	0.12	0.02
0.35	21.38	40.54	34.51	26.25	17.67	10.32	4.99	1.73	0.12	-0.44	-0.47
0.40	53.88	101.43	84.33	61.21	37.79	18.62	5.86	-0.68	-2.71	-2.32	-1.19
0.45	102.28	190.72	153.66	104.75	57.26	21.18	0.35	-7.17	-6.49	-2.88	0.17
0.50	162.89	300.65	234.19	148.90	70.14	15.50	-10.47	-14.37	-7.63	-0.07	3.52
0.55	232.75	425.56	321.25	190.93	76.34	3.91	-23.20	-19.76	-5.90	4.09	5.90
0.60	308.83	559.90	410.47	228.70	76.50	-10.65	-34.03	-20.29	0.23	9.95	7.54
0.65	390.97	703.00	501.41	261.92	70.49	-28.54	-44.33	-18.71	6.99	13.86	5.91
0.70	477.80	853.15	594.02	292.80	62.12	-45.76	-51.09	-13.31	15.67	17.88	4.39
0.75	567.31	1006.27	684.51	318.02	48.55	-65.02	-57.48	-8.30	21.92	17.91	-0.31
0.80	660.61	1165.02	776.57	342.24	34.74	-81.94	-60.03	0.30	29.35	18.53	-3.27
0.85	755.13	1324.78	866.92	363.70	19.90	-97.23	-60.15	9.15	34.42	15.06	-10.42
0.90	853.76	1490.88	959.67	384.87	4.95	-110.93	-57.83	19.77	40.58	13.40	-13.93
0.95	953.36	1657.32	1049.47	401.10	-14.39	-127.41	-57.81	27.16	42.81	8.79	-18.26
1.00	1052.41	1821.90	1136.48	415.68	-31.98	-138.97	-52.46	37.45	44.93	2.52	-24.37
1.05	1153.72	1989.59	1223.72	428.59	-51.02	-150.68	-46.39	48.83	48.92	-0.50	-26.39
1.10	1258.10	2162.45	1314.22	443.68	-67.91	-160.61	-40.40	57.38	48.12	-8.66	-32.90
1.15	1362.74	2333.31	1403.66	456.99	-86.79	-172.72	-36.75	64.37	48.05	-13.10	-33.73
1.20	1465.53	2503.19	1485.90	462.85	-110.74	-187.13	-34.50	69.27	45.78	-18.31	-33.72
1.25	1571.05	2676.05	1572.43	473.16	-129.36	-195.96	-27.96	76.16	43.36	-25.14	-36.48
1.30	1677.04	2843.67	1655.59	480.82	-149.05	-201.11	-15.48	88.67	44.72	-29.78	-37.31
1.35	1785.70	3026.43	1745.09	490.94	-167.64	-211.41	-11.27	93.06	41.23	-35.61	-38.39
1.40	1891.95	3198.93	1828.39	498.50	-184.56	-214.06	2.03	103.92	39.96	-42.18	-40.81
1.45	2001.54	3377.16	1914.88	505.83	-205.52	-224.13	7.00	109.52	39.67	-42.05	-35.01
1.50	2107.40	3548.09	1994.93	508.65	-228.37	-234.08	11.91	112.30	32.45	-51.72	-38.14
1.55	2220.65	3732.07	2084.34	518.14	-245.19	-237.82	22.69	120.54	31.26	-54.14	-33.94
1.60	2327.57	3905.33	2167.33	524.51	-265.02	-247.04	25.90	121.59	25.06	-60.29	-34.77
1.65	2436.93	4080.21	2245.64	523.61	-288.11	-252.43	37.01	129.14	21.34	-65.97	-33.17
1.70	2544.14	4253.44	2329.20	531.50	-302.80	-254.18	46.88	134.23	17.03	-71.12	-33.12
1.75	2658.47	4438.16	2415.52	537.04	-323.90	-262.01	54.25	141.07	17.26	-71.10	-28.93
1.80	2771.68	4621.40	2503.39	545.27	-341.79	-268.72	59.02	142.33	10.92	-77.41	-30.85
1.85	2874.20	4783.91	2573.84	543.88	-358.82	-260.61	74.06	149.58	5.08	-85.89	-33.80
1.90	2991.37	4973.35	2664.46	552.79	-375.56	-270.71	82.03	153.75	1.92	-87.61	-29.73
1.95	3101.58	5150.24	2745.92	556.48	-395.36	-278.39	85.10	153.70	-2.28	-87.03	-21.91
2.00	3209.30	5321.99	2822.55	556.77	-415.69	-283.54	91.30	154.06	-10.61	-93.32	-19.55

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.15	0.03	0.05	0.04	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00
0.20	0.15	0.28	0.22	0.16	0.10	0.05	0.03	0.01	0.00	0.00	0.00
0.25	0.85	1.50	1.35	1.02	0.69	0.42	0.23	0.11	0.05	0.02	0.01
0.30	4.52	8.60	7.41	5.78	4.08	2.60	1.50	0.77	0.34	0.13	0.03
0.35	18.37	34.95	30.04	23.26	16.11	9.82	5.11	2.08	0.45	-0.23	-0.38
0.40	49.44	93.38	78.41	57.97	35.89	19.18	6.93	0.22	-2.25	-2.26	-1.33
0.45	97.66	182.65	148.58	103.15	58.28	23.26	2.12	-6.38	-6.59	-3.36	-0.19
0.50	158.60	293.57	230.83	149.50	73.10	18.56	-8.88	-14.52	-6.74	-1.08	3.23
0.55	229.57	420.87	320.50	193.97	81.00	7.63	-21.73	-23.12	-6.72	3.93	6.59
0.60	307.60	558.93	413.08	234.03	81.84	-7.79	-34.20	-21.99	-0.98	10.26	8.89
0.65	392.07	706.62	507.90	269.87	76.77	-26.17	-45.43	-20.76	6.52	15.70	8.96
0.70	481.47	861.71	604.77	303.82	69.98	-43.11	-52.67	-16.19	13.97	17.80	4.78
0.75	573.09	1018.62	697.81	329.74	55.29	-64.47	-60.88	-11.53	20.69	18.64	0.54
0.80	668.80	1181.75	793.05	355.50	41.55	-82.00	-63.87	-3.25	27.98	18.23	-4.61
0.85	767.92	1349.67	888.75	378.86	25.99	-98.67	-64.04	7.74	36.87	19.08	-7.75
0.90	868.48	1518.94	982.95	399.54	9.23	-114.67	-64.21	15.29	38.81	12.26	-15.19
0.95	969.97	1688.55	1074.52	416.34	-9.64	-129.49	-60.76	27.27	45.49	10.87	-18.93
1.00	1073.27	1861.04	1167.61	433.96	-27.65	-144.05	-59.32	34.20	45.26	2.93	-26.32
1.05	1178.47	2035.28	1258.32	446.94	-48.82	-158.30	-55.00	44.55	48.24	-1.32	-29.15
1.10	1283.99	2209.51	1347.92	458.84	-69.86	-171.41	-49.84	54.89	51.22	-4.52	-30.18
1.15	1389.13	2382.59	1436.25	471.12	-87.39	-178.85	-39.60	66.85	52.48	-11.06	-34.58
1.20	1498.26	2562.65	1529.14	485.24	-105.87	-190.31	-36.57	71.20	48.39	-18.89	-37.12
1.25	1605.53	2738.06	1615.94	493.59	-127.24	-200.80	-29.62	80.13	48.39	-23.85	-38.61
1.30	1719.12	2923.43	1706.92	501.70	-149.61	-210.82	-21.22	94.05	48.65	-25.23	-38.32
1.35	1827.23	3099.89	1793.76	509.98	-171.06	-223.39	-20.51	89.29	39.26	-38.83	-41.55
1.40	1939.31	3282.46	1883.43	520.54	-186.13	-223.12	-2.45	105.66	42.56	-42.90	-43.35
1.45	2051.09	3463.97	1971.03	527.93	-205.66	-229.80	6.37	112.60	39.53	-47.96	-41.68
1.50	2161.75	3642.95	2054.97	529.52	-233.88	-245.88	7.60	116.30	37.54	-50.94	-40.47
1.55	2273.24	3824.15	2143.46	540.16	-243.39	-247.87	18.04	121.71	31.96	-57.86	-40.25
1.60	2383.94	4002.95	2228.07	546.50	-265.71	-250.13	30.22	129.31	27.62	-64.97	-40.94
1.65	2497.40	4185.47	2311.91	547.07	-292.03	-261.41	36.65	136.21	26.76	-67.63	-39.50
1.70	2608.78	4365.80	2398.57	555.83	-308.18	-266.07	42.49	135.72	19.23	-71.92	-33.41
1.75	2723.37	4551.05	2487.02	564.37	-324.01	-268.14	53.08	142.41	14.76	-77.64	-33.68
1.80	2840.91	4741.06	2577.28	571.00	-344.86	-276.46	58.46	145.43	9.81	-83.49	-35.63
1.85	2948.18	4911.30	2651.02	567.98	-355.56	-279.05	71.20	153.52	7.20	-87.82	-35.08
1.90	3058.39	5105.27	2743.10	576.81	-382.46	-285.81	81.30	157.76	1.87	-92.57	-33.27
1.95	3182.44	5288.35	2827.25	579.54	-404.89	-293.31	84.36	153.59	-1.68	-91.26	-23.54
2.00	3297.65	5473.31	2912.77	584.45	-423.09	-293.94	93.28	162.91	-6.23	-95.83	-25.92

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.15	0.03	0.05	0.04	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00
0.20	0.14	0.26	0.21	0.15	0.09	0.05	0.02	0.01	0.00	0.00	0.00
0.25	0.76	1.44	1.21	0.91	0.61	0.36	0.20	0.10	0.04	0.02	0.01
0.30	3.95	7.51	6.46	5.01	3.52	2.23	1.28	0.65	0.29	0.11	0.03
0.35	16.09	30.61	26.33	20.41	14.17	8.71	4.61	1.97	0.54	-0.08	-0.24
0.40	44.80	84.71	71.41	53.21	34.40	18.49	7.34	1.05	-1.47	-1.75	-1.09
0.45	90.42	169.36	138.44	97.06	55.92	23.44	3.35	-5.23	-6.08	-3.50	-0.67
0.50	149.63	277.47	219.45	143.90	72.34	20.45	-6.60	-13.25	-8.75	-1.87	2.36
0.55	219.33	402.82	308.64	189.29	81.68	10.43	-19.58	-19.79	-7.75	2.71	6.05
0.60	295.73	538.35	400.39	230.13	83.94	-4.02	-32.06	-22.43	-2.97	8.27	7.80
0.65	379.39	685.08	495.67	267.51	80.39	-21.86	-43.84	-22.13	4.00	13.81	8.15
0.70	467.77	838.49	591.57	302.76	72.43	-40.60	-52.79	-18.02	12.83	18.68	7.05
0.75	558.77	995.07	686.35	330.27	61.93	-58.36	-58.33	-11.29	21.41	21.22	4.03
0.80	654.19	1158.10	782.41	357.37	49.27	-75.38	-61.00	-2.41	29.46	20.95	-2.19
0.85	751.44	1322.85	876.21	379.63	32.28	-94.76	-65.27	3.69	33.43	17.44	-8.91
0.90	851.23	1491.22	970.79	401.48	16.53	-110.09	-64.25	13.86	39.40	14.97	-13.69
0.95	950.55	1657.39	1060.84	418.00	-2.86	-126.52	-63.19	23.53	44.17	11.79	-18.27
1.00	1055.65	1832.63	1154.57	434.22	-22.87	-141.65	-59.53	35.16	49.54	8.71	-22.25
1.05	1160.25	2007.00	1248.25	452.13	-39.57	-154.25	-57.23	40.57	46.17	-1.74	-29.89
1.10	1266.66	2183.02	1339.47	464.93	-60.82	-168.12	-52.27	52.01	51.42	-2.29	-28.27
1.15	1372.57	2358.07	1430.31	479.18	-78.09	-176.82	-43.60	63.57	52.75	-9.77	-35.80
1.20	1480.67	2535.02	1517.70	485.84	-103.71	-192.48	-40.50	70.61	51.69	-15.84	-37.63
1.25	1589.33	2714.25	1610.55	501.88	-117.70	-197.78	-31.38	79.10	49.78	-22.89	-40.41
1.30	1698.56	2892.57	1698.00	508.95	-141.29	-211.00	-27.89	83.98	46.24	-29.45	-41.11
1.35	1811.82	3077.78	1790.10	519.69	-167.10	-217.54	-16.72	96.06	48.43	-32.35	-40.52
1.40	1916.40	3247.77	1872.45	526.85	-178.54	-223.40	-7.03	104.84	47.69	-36.32	-39.78
1.45	2031.52	3434.75	1962.13	531.80	-204.41	-237.18	-3.14	110.54	46.26	-39.04	-35.45
1.50	2143.96	3617.58	2050.89	539.90	-224.12	-244.48	4.74	116.38	41.67	-46.93	-39.38
1.55	2253.78	3795.13	2134.83	544.81	-244.77	-251.34	12.72	121.04	35.21	-55.95	-41.60
1.60	2366.43	3978.15	2224.21	555.90	-258.49	-251.86	25.31	129.56	34.22	-57.11	-36.07
1.65	2484.18	4169.47	2316.92	564.44	-278.69	-259.05	33.87	135.96	29.12	-67.55	-43.26
1.70	2595.38	4348.93	2401.95	571.78	-294.74	-261.68	42.30	138.77	23.37	-74.53	-37.38
1.75	2710.49	4533.83	2486.74	573.67	-317.72	-268.67	51.58	144.94	18.59	-74.57	-41.15
1.80	2820.77	4711.34	2569.20	577.43	-339.41	-277.47	55.95	146.60	12.97	-82.86	-37.97
1.85	2937.67	4898.83	2654.78	578.99	-361.51	-282.10	68.61	157.79	15.34	-82.16	-32.95
1.90	3054.04	5085.67	2740.39	580.49	-387.46	-295.33	67.76	153.94	5.75	-87.83	-30.27
1.95	3165.16	5264.94	2825.85	590.42	-397.89	-291.29	83.73	164.47	5.80	-91.35	-33.30
2.00	3281.39	5451.15	2911.27	594.72	-416.49	-296.28	89.32	161.42	-3.98	-93.63	-22.01

DIODE TYPE 5082-2811=04

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	-0.00	-0.00
0.15	0.03	0.06	0.05	0.03	0.02	0.01	0.00	0.00	0.00	0.00	-0.00
0.20	0.19	0.35	0.28	0.20	0.12	0.07	0.03	0.01	0.01	0.00	0.00
0.25	1.06	2.00	1.68	1.26	0.85	0.52	0.28	0.14	0.06	0.03	0.01
0.30	5.48	10.41	8.95	6.94	4.87	3.07	1.74	0.87	0.37	0.13	0.02
0.35	21.16	40.18	34.37	26.38	18.00	10.73	5.37	2.02	0.30	-0.34	-0.42
0.40	54.63	102.99	85.95	62.81	39.19	19.64	6.44	-0.47	-2.73	-2.40	-1.22
0.45	105.01	195.99	158.35	108.47	59.72	22.33	0.44	-7.69	-7.13	-3.32	0.05
0.50	167.62	309.61	241.76	154.40	73.30	16.59	-10.70	-15.03	-8.04	0.06	4.07
0.55	240.24	439.62	332.75	198.84	80.56	5.23	-23.43	-20.23	-5.85	4.71	6.65
0.60	320.92	582.08	427.61	239.08	80.52	-10.97	-36.07	-21.94	-0.16	10.57	8.39
0.65	405.38	730.33	522.31	274.40	75.21	-28.98	-46.74	-20.72	6.28	14.14	6.44
0.70	496.51	887.60	618.89	306.37	65.97	-47.54	-54.15	-14.98	15.84	18.91	5.21
0.75	589.39	1045.95	712.70	332.49	52.09	-66.92	-59.80	-8.45	22.89	18.67	-0.74
0.80	685.96	1210.24	807.95	357.60	38.09	-83.70	-61.32	1.31	31.31	19.34	-4.37
0.85	785.79	1378.88	902.92	379.22	20.77	-101.75	-63.09	9.64	36.38	15.99	-11.10
0.90	887.12	1549.49	998.12	400.87	5.37	-115.92	-61.15	19.42	40.72	11.77	-17.11
0.95	990.00	1721.10	1089.99	416.49	-15.34	-132.74	-59.93	28.88	45.07	8.96	-19.91
1.00	1095.08	1896.23	1183.78	433.68	-33.18	-145.48	-55.36	39.14	47.58	3.13	-25.70
1.05	1198.46	2067.22	1272.21	445.42	-55.09	-160.71	-52.55	48.00	49.85	-1.05	-28.72
1.10	1308.00	2249.14	1369.01	464.67	-68.31	-165.74	-43.28	58.01	46.82	-9.45	-33.79
1.15	1415.95	2426.01	1456.68	471.45	-94.59	-183.71	-41.31	64.91	46.49	-14.87	-35.84
1.20	1523.76	2602.96	1545.76	482.19	-114.26	-193.19	-33.28	75.49	50.44	-18.20	-36.30
1.25	1633.19	2782.01	1634.62	491.04	-136.27	-205.26	-28.79	81.61	48.51	-22.98	-35.13
1.30	1744.59	2964.37	1725.90	502.87	-153.23	-210.58	-17.97	91.63	47.36	-29.74	-38.22
1.35	1856.31	3145.93	1813.14	507.73	-176.70	-224.81	-15.81	94.04	40.63	-39.79	-43.08
1.40	1966.50	3329.09	1904.41	520.95	-191.07	-223.57	0.48	107.06	41.77	-42.68	-41.14
1.45	2079.48	3508.84	1989.73	525.26	-214.74	-234.63	5.44	111.74	38.83	-45.34	-35.29
1.50	2193.58	3693.52	2077.25	529.90	-238.92	-244.19	12.41	117.41	34.33	-54.20	-40.12
1.55	2305.68	3374.56	2162.79	536.14	-255.31	-244.97	28.13	130.06	34.93	-57.30	-38.88
1.60	2418.43	4058.27	2253.54	547.90	-279.91	-250.54	33.71	131.34	26.98	-65.74	-40.86
1.65	2533.06	4242.55	2338.12	548.94	-296.31	-260.61	40.26	137.16	24.59	-69.35	-39.24
1.70	2645.90	4125.27	2425.96	557.81	-312.79	-265.65	46.23	137.90	17.12	-73.85	-33.40
1.75	2763.24	4614.05	2514.08	564.06	-329.51	-266.10	59.05	144.03	10.99	-81.46	-33.90
1.80	2878.17	4799.37	2601.07	569.11	-350.98	-275.23	63.40	147.50	10.03	-79.72	-27.19
1.85	2988.54	4974.30	2676.12	564.65	-374.10	-276.27	81.39	162.33	11.86	-84.54	-31.76
1.90	3111.77	5174.27	2774.06	578.71	-386.83	-278.99	85.52	157.27	-2.37	-94.58	-31.05
1.95	3220.22	5348.03	2853.62	582.19	-404.62	-281.80	96.23	166.40	1.99	-88.11	-21.18
2.00	3339.50	5539.07	2947.13	582.34	-432.08	-297.22	92.76	168.05	-9.28	-95.15	-20.01

DIODE TYPE 5082-2835-C1

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	-0.00	-0.00
0.15	0.02	0.04	0.03	0.02	0.01	0.01	0.00	0.00	0.00	0.00	-0.00
0.20	0.14	0.25	0.20	0.14	0.09	0.05	0.02	0.01	0.00	0.00	0.00
0.25	0.78	1.48	1.25	0.94	0.64	0.39	0.22	0.11	0.05	0.02	0.01
0.30	4.25	8.08	6.98	5.46	3.87	2.48	1.43	0.74	0.33	0.12	0.03
0.35	17.70	33.70	29.05	22.59	15.75	9.71	5.15	2.18	0.56	-0.13	-0.31
0.40	48.92	92.50	77.94	57.98	37.29	19.77	7.49	0.60	-2.09	-2.26	-1.41
0.45	97.87	183.23	149.55	104.48	59.72	24.48	2.86	-6.15	-6.73	-3.66	-0.46
0.50	160.63	297.67	234.95	153.34	76.20	20.51	-8.19	-14.83	-9.57	-1.96	2.60
0.55	233.66	428.79	327.58	199.52	84.47	8.89	-22.19	-21.38	-7.85	3.45	6.74
0.60	314.75	572.45	424.37	241.96	85.94	-7.12	-35.80	-24.42	-3.12	8.86	8.14
0.65	401.37	724.18	522.55	280.28	82.58	-24.20	-45.77	-21.79	5.75	15.31	8.56
0.70	493.30	883.46	621.36	313.46	72.97	-44.55	-55.41	-17.62	14.86	20.36	7.58
0.75	587.71	1045.45	718.20	341.75	59.65	-64.95	-62.77	-12.38	21.50	20.31	1.92
0.80	685.49	1212.02	815.13	367.43	44.96	-83.05	-65.18	-2.50	30.56	20.97	-3.13
0.85	788.57	1387.04	915.93	393.52	30.15	-100.34	-66.97	6.00	36.39	18.89	-8.12
0.90	893.08	1562.85	1013.32	413.83	10.91	-118.81	-68.04	14.47	40.27	13.89	-15.69
0.95	998.92	1740.29	1110.57	433.84	-6.59	-133.23	-64.67	25.89	45.76	10.95	-19.50
1.00	1104.21	1915.52	1203.55	448.85	-27.79	-149.55	-62.77	34.81	47.70	4.30	-26.89
1.05	1211.75	2094.01	1297.35	463.61	-48.31	-163.99	-59.25	44.12	49.97	0.21	-28.67
1.10	1324.88	2281.82	1396.63	481.17	-66.02	-174.27	-51.11	56.80	53.46	-4.80	-33.29
1.15	1436.54	2465.77	1490.53	493.32	-87.40	-186.52	-45.09	65.94	52.97	-11.81	-36.17
1.20	1542.21	2638.51	1575.72	500.86	-109.23	-197.27	-38.34	74.11	51.02	-19.39	-39.32
1.25	1658.21	2829.30	1672.97	514.69	-128.25	-206.80	-31.13	82.78	50.81	-23.74	-39.26
1.30	1770.41	3012.56	1763.18	522.72	-151.33	-218.83	-25.56	90.07	49.02	-30.40	-42.73
1.35	1885.40	3200.47	1856.53	534.08	-169.26	-224.94	-16.32	97.03	44.61	-38.11	-43.03
1.40	1998.25	3383.45	1943.75	538.95	-191.94	-231.60	-2.01	113.75	51.05	-38.81	-43.27
1.45	2115.75	3574.74	2037.07	547.54	-214.01	-242.87	1.14	115.33	44.81	-43.53	-37.74
1.50	2232.99	3765.13	2128.98	555.43	-234.55	-250.01	9.71	121.30	39.65	-51.91	-40.60
1.55	2346.44	3948.84	2216.68	562.08	-254.53	-257.08	16.37	124.21	32.55	-59.62	-40.73
1.60	2462.08	4135.55	2304.28	565.93	-277.71	-264.93	26.28	133.49	31.70	-64.79	-43.10
1.65	2582.12	4330.09	2398.00	575.43	-294.88	-268.08	36.87	139.22	26.74	-69.94	-39.75
1.70	2699.85	4519.40	2485.42	578.58	-316.66	-272.78	48.97	148.09	24.27	-75.20	-39.30
1.75	2814.15	4703.99	2572.68	584.37	-337.86	-282.88	50.54	146.73	16.98	-79.95	-38.16
1.80	2931.02	4891.31	2658.00	586.29	-359.67	-287.24	63.03	157.42	19.16	-78.83	-32.59
1.85	3055.20	5092.42	2754.73	595.91	-378.42	-293.53	68.99	158.23	10.05	-88.15	-35.03
1.90	3166.25	5269.57	2834.15	597.83	-395.51	-292.55	82.84	164.55	4.04	-95.60	-36.27
1.95	3289.22	5468.01	2928.51	607.23	-411.61	-295.02	92.01	168.93	1.80	-93.56	-25.21
2.00	3402.85	5650.53	3013.55	614.01	-426.53	-295.88	101.20	170.93	-6.16	-101.99	-29.81

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.00
0.15	0.03	0.36	0.05	0.03	0.02	0.01	0.00	0.00	0.00	0.00	0.00
0.20	0.18	0.34	0.28	0.19	0.12	0.06	0.03	0.01	0.00	0.00	0.00
0.25	1.00	1.90	1.59	1.19	0.80	0.48	0.26	0.13	0.06	0.02	0.01
0.30	5.10	9.69	8.31	6.43	4.49	2.83	1.60	0.80	0.35	0.13	0.03
0.35	19.91	37.83	32.39	24.90	17.05	10.24	5.20	2.02	0.37	-0.29	-0.40
0.40	52.62	90.29	83.13	61.14	38.61	19.85	7.01	0.10	-2.37	-2.31	-1.34
0.45	102.57	191.66	155.42	107.28	64.01	23.42	1.59	-5.96	-6.99	-3.63	-0.46
0.50	166.68	308.33	241.96	155.12	75.84	18.88	-9.49	-15.13	-9.36	-1.24	3.02
0.55	243.44	444.57	334.94	202.04	83.75	7.28	-23.02	-21.09	-7.05	4.04	6.88
0.60	322.15	585.04	431.56	243.45	83.99	-9.51	-36.71	-23.71	-1.72	10.05	8.84
0.65	409.69	738.20	530.25	281.50	80.13	-26.97	-47.10	-22.01	5.40	14.06	6.65
0.70	502.01	897.94	628.92	314.27	72.50	-46.59	-55.56	-16.84	14.86	18.90	5.35
0.75	599.36	1065.30	729.96	345.79	62.09	-63.92	-59.83	-9.03	23.13	19.51	-2.40
0.80	699.64	1236.31	829.94	372.80	45.10	-83.71	-64.87	-1.96	30.29	20.05	-3.66
0.85	809.76	1406.96	925.54	393.53	26.03	-103.34	-67.33	6.58	35.83	16.85	-10.53
0.90	923.60	1579.02	1021.40	413.97	8.19	-120.05	-67.04	15.96	40.84	13.82	-15.45
0.95	1010.52	1753.90	1119.13	433.64	-9.61	-134.09	-62.69	28.37	46.72	10.37	-20.54
1.00	1119.90	1941.42	1216.97	451.16	-29.84	-150.27	-61.16	36.74	48.72	5.33	-24.54
1.05	1227.57	2119.78	1310.06	465.32	-49.69	-162.20	-53.88	49.72	53.18	1.21	-28.36
1.10	1338.62	2304.17	1407.62	482.69	-67.40	-173.90	-49.28	57.55	52.26	-6.38	-33.55
1.15	1451.99	2490.78	1502.47	494.19	-90.17	-187.47	-43.91	67.12	53.36	-11.29	-35.23
1.20	1565.26	2678.32	1595.67	504.77	-112.62	-199.69	-37.87	75.54	52.14	-18.27	-38.31
1.25	1677.15	2859.65	1686.51	513.96	-133.63	-209.40	-30.09	84.77	52.25	-22.30	-37.59
1.30	1789.07	3042.33	1776.53	523.12	-153.79	-217.81	-22.38	91.14	46.93	-32.88	-43.02
1.35	1906.89	3235.48	1873.82	536.32	-171.91	-224.61	-12.07	102.19	48.57	-35.40	-41.26
1.40	2022.33	3422.52	1962.50	540.14	-197.77	-237.09	-6.58	107.78	45.69	-39.44	-37.77
1.45	2138.31	3610.94	2053.52	547.57	-218.97	-244.53	3.14	117.59	45.80	-42.82	-35.85
1.50	2254.62	3802.42	2146.80	558.76	-236.10	-250.22	10.50	120.89	38.42	-51.95	-39.24
1.55	2370.47	3987.56	2234.80	563.08	-258.84	-258.24	18.74	126.65	33.29	-60.06	-41.80
1.60	2489.60	4180.76	2328.16	572.96	-271.99	-259.04	33.64	137.95	33.13	-62.93	-38.88
1.65	2607.64	4371.54	2417.78	577.25	-293.55	-263.63	39.46	141.13	25.29	-71.63	-41.20
1.70	2726.12	4561.84	2505.93	581.58	-318.74	-272.56	50.28	147.44	22.49	-75.27	-37.49
1.75	2845.52	4755.58	2599.93	591.89	-336.02	-277.53	58.81	153.55	20.80	-77.64	-36.00
1.80	2962.43	4938.14	2679.00	587.34	-363.00	-285.94	66.53	157.63	15.95	-81.08	-31.38
1.85	3085.91	5141.21	2776.40	596.78	-381.91	-292.04	72.70	158.34	6.56	-90.55	-33.73
1.90	3199.04	5323.09	2860.80	601.08	-402.13	-299.18	78.18	161.31	3.52	-92.04	-30.28
1.95	3327.02	5529.32	2958.45	611.23	-416.34	-297.14	92.44	168.12	-0.74	-96.58	-29.94
2.00	3440.72	5710.42	3438.62	610.63	-439.27	-301.70	132.43	174.73	-1.83	-97.20	-26.40

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	-0.00	-0.00	0.00
0.15	0.03	0.06	0.04	0.03	0.01	0.01	0.00	0.00	0.00	0.00	0.00
0.20	0.18	0.23	0.26	0.19	0.11	0.06	0.03	0.01	0.00	0.00	0.00
0.25	0.98	1.85	1.56	1.17	0.79	0.48	0.26	0.13	0.06	0.02	0.01
0.30	5.08	9.66	8.30	6.45	4.53	2.87	1.63	0.82	0.36	0.13	0.03
0.35	20.12	38.24	32.79	25.26	17.36	10.47	5.34	2.10	0.39	-0.29	-0.41
0.40	53.24	100.47	84.14	61.89	39.06	20.01	6.97	-0.04	-2.51	-2.38	-1.30
0.45	103.94	194.23	157.56	108.83	67.93	23.85	1.75	-6.94	-6.74	-3.18	0.16
0.50	168.27	311.32	244.39	157.83	76.82	19.33	-9.32	-14.98	-8.83	-0.93	3.36
0.55	242.65	444.58	337.90	203.70	84.30	7.19	-23.24	-21.14	-6.90	4.23	6.94
0.60	325.06	590.29	435.35	245.47	84.58	-9.66	-36.96	-23.75	-1.59	10.14	8.77
0.65	413.34	744.75	534.90	283.91	80.76	-27.22	-47.44	-22.10	5.49	14.12	6.59
0.70	506.52	905.95	634.40	316.87	70.98	-46.98	-55.88	-16.82	15.02	18.91	5.21
0.75	603.86	1073.20	735.12	347.88	60.03	-64.66	-60.07	-8.37	24.45	21.04	1.09
0.80	704.76	1244.81	834.22	372.59	42.13	-87.18	-67.49	-3.74	28.58	17.84	-6.27
0.85	806.08	1416.06	930.99	395.35	26.05	-103.01	-65.65	9.27	38.59	19.02	-9.07
0.90	911.85	1594.17	1030.19	417.05	7.83	-121.01	-67.09	16.60	41.21	13.44	-16.15
0.95	1019.01	1773.40	1127.40	435.66	-11.17	-136.25	-64.09	27.39	45.43	8.71	-22.04
1.00	1127.01	1953.37	1223.55	452.42	-31.36	-151.84	-61.70	36.61	47.96	3.46	-26.59
1.05	1236.00	2134.21	1318.63	467.67	-51.33	-165.21	-56.92	46.63	49.83	-1.93	-30.35
1.10	1346.88	2317.07	1412.20	479.67	-73.40	-178.52	-51.15	57.31	52.49	-5.49	-31.15
1.15	1459.68	2503.54	1509.08	494.99	-92.11	-189.18	-44.54	66.66	52.13	-13.06	-36.57
1.20	1572.46	2689.46	1601.80	505.71	-112.81	-198.80	-36.18	76.21	50.73	-20.81	-39.96
1.25	1685.13	2872.56	1692.57	514.09	-135.35	-209.60	-28.65	85.63	50.63	-26.11	-41.51
1.30	1802.81	3065.27	1788.84	525.18	-156.70	-220.14	-21.79	93.86	50.20	-29.62	-39.44
1.35	1916.76	3251.02	1879.56	532.67	-180.34	-233.43	-19.88	94.61	40.89	-41.87	-44.72
1.40	2033.84	3441.79	1973.60	544.64	-194.89	-232.68	-1.98	110.01	43.54	-44.95	-44.41
1.45	2150.57	3631.76	2066.11	553.21	-215.65	-240.55	6.69	117.70	41.24	-50.05	-43.38
1.50	2267.08	3819.77	2153.40	553.98	-244.98	-256.50	8.62	121.15	38.18	-53.46	-41.40
1.55	2381.59	4005.23	2242.56	563.11	-260.15	-256.55	23.11	131.27	37.17	-56.14	-37.57
1.60	2501.65	4199.16	2334.06	568.94	-280.99	-261.51	34.09	137.51	29.65	-68.42	-44.59
1.65	2618.66	4288.27	2423.19	573.04	-305.81	-273.37	38.44	142.13	27.70	-70.44	-40.83
1.70	2735.49	4577.36	2513.93	582.14	-322.67	-278.14	44.54	142.54	19.77	-74.84	-34.36
1.75	2855.63	4771.58	2606.67	591.08	-339.30	-280.31	55.68	148.53	15.04	-80.88	-34.61
1.80	2978.91	4970.82	2701.21	597.95	-361.09	-288.93	61.31	151.59	9.81	-86.93	-36.58
1.85	3091.45	5149.33	2778.41	594.70	-383.77	-291.53	74.66	159.95	7.03	-91.38	-35.92
1.90	3215.22	5350.05	2876.24	607.88	-397.12	-292.94	82.94	161.15	-0.75	-96.26	-31.53
1.95	3333.82	5538.49	2958.17	604.07	-423.86	-300.51	93.17	171.22	4.35	-89.57	-18.89
2.00	3455.08	5731.93	3044.46	603.95	-448.24	-309.36	96.19	167.45	-8.94	-99.91	-22.00

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.10	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.15	0.04	0.07	0.05	0.03	0.02	0.01	0.00	0.00	0.00	0.00	-0.00
0.20	0.20	0.38	0.31	0.21	0.13	0.07	0.03	0.01	0.01	[illegible]	0.00
0.25	1.11	2.09	1.76	1.31	0.88	0.53	0.29	0.14	0.06	0.03	0.01
0.30	5.57	10.58	9.07	7.01	4.89	3.07	1.72	0.85	0.36	0.11	0.01
0.35	21.27	40.39	34.51	26.43	17.99	10.70	5.35	2.02	0.31	-0.33	-0.41
0.40	54.88	103.45	86.35	63.14	39.49	19.94	6.73	-0.21	-2.53	-2.29	-1.19
0.45	105.70	197.31	159.53	109.48	60.59	23.09	1.08	-7.20	-6.84	-3.23	-0.03
0.50	170.05	314.28	245.87	157.69	75.67	16.02	-10.16	-15.25	-8.79	-0.98	3.02
0.55	244.36	447.25	338.75	202.70	82.34	5.41	-24.15	-21.18	-6.53	4.53	7.01
0.60	326.38	592.22	435.70	244.47	83.30	-10.13	-36.28	-22.36	-0.23	11.01	9.19
0.65	413.79	744.80	533.04	280.48	77.18	-29.57	-48.13	-21.64	6.26	14.72	7.05
0.70	505.31	904.02	631.46	313.56	68.55	-47.76	-55.33	-15.95	15.43	18.65	5.21
0.75	602.19	1069.40	730.58	343.45	57.03	-65.65	-59.75	-8.06	23.97	19.97	0.11
0.80	701.56	1238.40	825.20	368.01	30.94	-87.14	-66.58	-3.43	27.87	16.97	-6.14
0.85	803.28	1410.61	926.28	392.39	25.45	-101.84	-64.24	9.59	37.75	18.00	-9.28
0.90	907.79	1586.11	1022.77	411.50	5.16	-121.16	-66.27	16.91	40.75	13.64	-15.66
0.95	1013.00	1761.87	1117.55	428.92	-14.11	-136.22	-63.04	27.82	44.94	8.09	-22.12
1.00	1122.11	1943.91	1215.53	447.40	-32.41	-149.60	-58.16	39.68	50.08	5.26	-25.23
1.05	1230.33	2123.79	1311.06	464.69	-49.64	-161.04	-53.50	47.36	48.35	-3.86	-31.58
1.10	1339.78	2304.06	1402.42	473.94	-75.99	-180.05	-53.40	54.11	49.41	-7.50	-32.31
1.15	1449.63	2484.67	1494.08	486.14	-94.50	-187.65	-42.86	66.24	50.21	-14.58	-36.79
1.20	1564.50	2674.13	1591.83	501.48	-112.13	-195.77	-33.27	78.37	53.11	-17.54	-36.55
1.25	1678.42	2860.58	1684.49	511.00	-134.54	-207.70	-28.09	84.58	49.55	-25.91	-40.47
1.30	1793.04	3047.73	1775.79	520.35	-155.59	-216.93	-20.33	92.26	46.81	-33.28	-43.32
1.35	1902.77	3226.71	1864.86	529.67	-174.23	-223.68	-11.12	101.14	46.29	-37.28	-42.93
1.40	2020.75	3417.97	1955.71	533.49	-201.41	-237.82	-7.61	104.43	39.67	-46.49	-44.54
1.45	2135.30	3623.81	2045.22	541.50	-219.70	-241.38	4.85	113.55	36.32	-54.04	-46.41
1.50	2252.41	3795.28	2141.17	555.66	-234.23	-244.96	14.35	119.51	31.85	-60.76	-47.19
1.55	2369.79	3985.28	2231.66	562.05	-255.22	-251.24	25.11	129.77	34.05	-59.26	-40.08
1.60	2485.72	4171.49	2316.64	562.29	-281.60	-262.22	30.49	133.00	28.08	-65.45	-38.50
1.65	2602.57	4361.17	2409.05	573.72	-295.67	-263.01	42.26	139.47	23.81	-70.82	-37.64
1.70	2722.44	4554.43	2499.61	578.79	-317.39	-270.21	49.63	143.26	18.05	-77.02	-37.09
1.75	2839.32	4744.01	2589.39	585.55	-336.93	-276.39	56.79	146.44	11.32	-85.76	-41.51
1.80	2953.46	4925.46	2670.72	586.34	-357.47	-279.35	68.06	152.53	7.50	-89.12	-37.99
1.85	3071.66	5116.87	2762.76	595.47	-375.37	-285.02	75.81	159.03	8.93	-85.32	-28.42
1.90	3195.11	5313.87	2850.23	593.32	-403.95	-297.45	77.98	157.02	-1.56	-93.58	-27.76
1.95	3312.38	5502.22	2938.04	601.11	-416.33	-291.74	97.17	169.00	-3.09	-99.85	-32.07
2.00	3431.46	5691.05	3022.35	601.15	-438.59	-296.47	106.79	175.33	-2.22	-94.03	-18.08

APPENDIX A3

EXPERIMENTAL DATA FOR FIGURES 6.9 - 6.20;

DIODES A1, A2, A3, A4, B1, B2, B3, B4,

C1, C2, C3, C4.

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FORTRAN IV G COMPILER          MAIN               09-17-75          10:22:24

              C      M.KATIB   APPL.  PHYS.
 0001               DIMENSION FUND(20,20),DB(20,20),VOLT(20),CDC(20)
 0002               READ(6,1)(CDC(M),FUND(M,1),(DB(M,N),N=2,10),M=1,18)
 0003             1 FORMAT (2F8.2,9F5.2)
 0004               DO 3 M=1,18
 0005               VOLT(M)=0.1*FLOAT(M)+0.2
 0006               DO 3 N=1,10
 0007               FUND(M,N+1)=FUND(M,1)/(10.0**(DB(M,N+1)/20.0))
 0008             3 CONTINUE
 0009               WRITE (6,666)
 0010           666 FORMAT (1H1,34X,23HDIODE TYPE 5082-2800=A2///
                   14X,4HVOLT,4X,4HI(0),4X,4HI(1),4X,4HI(2),4X,4HI(3)
                   2,4X,4HI(4),4X,4HI(5),4X,4HI(6),4X,4HI(7),4X,4HI(8),4X,
                   34HI(9),4X,5HI(10)//)
 0011               WRITE(6,55)
 0012            55 FORMAT(22X,36HTHE HARMONICS ARE IN DBS RELATIVE TO
                  1 11H THE FUNDS.//)
 0013               WRITE(6,2)(VOLT(M),CDC(M),FUND(M,1),(DB(M,N),N=2,10),
                   1M=1,18)
 0014             2 FORMAT(12F8.2)
 0015               WRITE(6,666)
 0016               WRITE(6,4)(VOLT(M),CDC(M),(FUND(M,N),N=1,10),M=1,18)
 0017             4 FORMAT(12F8.2)
 0018               STOP
 0019               DEBUG SUBCHK
 0020               END

  TOTAL MEMORY REQUIREMENTS 001404 BYTES
XECUTION TERMINATED


R -LOAD#
XECUTION BEGINS
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DIODE TYPE 5082-28[illegible]=A1

THE HARMONICS ARE IN DBS RELATIVE TO THE FUNDS.

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	14.27	26.00	1.82	3.90	7.23	12.52	18.79	26.90	37.15	38.33	40.33
0.40	82.35	156.75	1.90	5.28	10.80	2[illegible].50	34.36	27.28	29.5[illegible]	39.15	47.00
0.50	180.00	345.00	3.05	7.50	16.25	36.00	25.55	28.25	43.60	37.55	37.40
0.60	324.00	543.00	2.85	8.83	21.10	25.65	23.76	32.73	36.30	33.35	43.3[illegible]
0.70	453.00	840.[illegible]	3.85	10.50	28.75	23.65	26.15	51.15	32.80	37.25	47.60
0.80	660.00	1135.00	4.60	11.84	36.25	22.35	27.91	37.03	31.10	42.95	38.98
0.90	786.00	1395.00	4.55	12.80	30.65	22.15	31.85	33.15	32.2[illegible]	58.65	37.[illegible]
1.00	1017.[illegible]	166[illegible].[illegible]	4.45	13.53	27.40	21.90	35.16	31.03	32.65	43.70	36.00
1.10	1120.00	1905.00	4.55	14.50	25.15	22.45	40.55	30.55	34.80	40.85	36.40
1.20	13[illegible].[illegible]	2185.[illegible]	4.55	15.3[illegible]	24.[illegible]5	23.[illegible]	51.65	30.00	37.00	37.35	37.10
1.30	1440.00	2485.00	4.95	16.20	23.65	23.45	53.45	29.65	39.50	36.45	38.20
1.40	1625.00	2855.00	5.25	17.10	23.35	24.05	43.85	29.85	43.[illegible]	35.85	39.7[illegible]
1.50	1800.[illegible]0	3245.00	5.55	17.80	22.95	24.75	39.95	29.75	47.20	35.65	41.70
1.60	1970.00	3600.00	6.05	18.60	22.55	25.45	37.65	30.05	54.80	35.85	44.00
1.70	216[illegible].00	375[illegible].[illegible]	5.95	19.[illegible]	22.[illegible]5	25.45	36.35	3[illegible].[illegible]	59.7[illegible]	35.15	45.80
1.80	2350.00	4080.00	5.95	19.60	21.75	25.95	35.25	30.05	52.10	34.85	48.50
1.90	2505.00	4310.00	6.05	19.90	21.55	26.25	34.55	30.35	48.20	34.85	51.3[illegible]
2.00	2730.00	4630.00	6.25	20.50	21.55	26.55	33.75	3[illegible].55	45.1[illegible]	34.55	56.8[illegible]

DIODE TYPE 5082-2800=A1

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	14.27	26.00	21.08	16.59	11.31	6.15	2.99	1.17	0.36	0.32	0.25
0.40	82.35	156.75	125.95	85.35	45.21	14.8[illegible]	3.[illegible]	6.78	5.25	1.73	0.70
0.50	180.00	345.00	242.84	145.49	53.13	5.47	18.21	13.35	2.28	4.57	4.65
0.60	324.00	543.00	391.11	196.47	47.84	28.33	35.22	12.54	8.31	11.68	3.71
0.70	453.00	840.00	539.24	250.77	30.67	55.18	41.38	2.33	19.24	11.53	3.50
0.80	660.00	1135.00	668.34	290.40	17.48	86.60	45.66	15.98	31.62	8.08	12.76
0.90	786.00	1395.00	826.18	319.58	40.93	108.91	35.65	30.70	34.24	1.63	19.70
1.00	1017.00	1660.00	994.51	349.63	70.81	133.39	28.98	46.62	38.69	10.84	26.31
1.10	1120.00	1905.00	1128.22	358.84	105.29	143.68	17.88	56.55	34.67	17.27	28.83
1.20	1300.00	2185.00	1294.05	375.36	137.07	154.69	5.71	69.10	30.86	29.65	30.51
1.30	1440.00	2485.00	1405.49	384.88	163.24	167.04	5.28	81.81	26.32	37.40	30.57
1.40	1625.00	2855.00	1559.93	398.66	194.14	179.10	18.33	91.86	20.21	46.04	29.55
1.50	1800.00	3245.00	1712.83	418.04	231.06	187.81	32.64	105.61	14.16	53.54	26.68
1.60	1970.00	3600.00	1793.92	422.96	268.41	192.22	47.18	113.19	6.55	58.05	22.71
1.70	2160.00	3750.00	1890.30	420.76	296.16	200.23	57.09	118.59	3.88	65.54	19.23
1.80	2350.00	4080.00	2056.65	427.23	333.55	205.67	70.50	128.28	10.13	73.82	15.33
1.90	2595.00	4310.00	2147.72	435.99	360.56	209.88	80.72	130.91	16.77	77.98	11.73
2.00	2730.00	4630.00	2254.66	437.10	387.33	217.81	95.08	137.43	25.74	86.71	6.69

STOP 0
EXECUTICN TERMINATED

$SIG

DIODE TYPE 5082-2800=A2

THE HARMONICS ARE IN DBS RELATIVE TO THE FUNDS.

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	14.65	31.50	2.65	5.00	8.50	14.00	21.00	29.35	38.70	39.45	41.50
0.40	83.50	158.00	2.05	5.60	11.25	21.2[illegible]	34.15	28.15	3[illegible].60	40.35	47.10
0.50	184.00	359.00	3.35	7.60	16.25	35.65	25.65	28.05	42.9[illegible]	38.65	37.7[illegible]
0.60	334.00	601.00	2.95	9.10	21.75	25.25	24.25	34.15	35.80	34.05	45.10
0.70	480.00	894.00	3.75	10.60	28.95	23.35	26.05	45.75	32.60	37.00	46.85
0.80	655.00	1215.00	4.55	12.[illegible]	36.25	22.55	28.75	37.25	31.90	44.25	39.30
0.90	840.00	1515.00	4.65	12.90	30.35	22.05	32.10	32.75	32.40	55.75	37.10
1.00	1000.00	1760.00	4.45	13.70	27.55	22.25	35.75	31.15	33.4[illegible]	44.45	36.50
1.10	1185.00	2040.00	4.35	14.60	25.05	22.55	41.15	30.35	35.00	39.95	36.30
1.20	1350.00	2400.00	4.75	15.70	24.35	23.15	53.15	30.05	37.30	37.35	37.30
1.30	1535.00	2725.00	5.05	16.70	23.95	23.85	52.70	30.15	40.30	36.85	39.00
1.40	1710.00	3080.00	5.50	17.55	23.40	24.30	43.40	30.00	43.95	36.10	40.15
1.50	1910.00	3440.00	5.85	18.20	22.95	24.90	39.85	29.85	48.1[illegible]	35.85	42.[illegible]
1.60	2100.00	3815.00	6.05	19.00	22.35	25.35	37.55	30.00	56.20	35.45	44.10
1.70	2280.00	4000.00	5.85	19.10	21.65	25.35	36.05	29.75	60.40	34.95	45.80
1.80	2470.00	4320.00	6.05	19.70	21.55	25.85	35.35	30.15	52.60	34.95	48.60
1.90	2730.00	4685.00	5.95	20.00	21.65	26.15	35.75	30.65	50.10	35.25	51.00
2.00	2940.00	5015.00	6.00	20.70	21.55	26.45	33.65	31.00	46.40	34.95	55.7[illegible]

DIODE TYPE 5082-2800=A2

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	14.65	31.50	23.22	17.71	11.84	6.29	2.81	1.07	0.37	-0.34	-0.27
0.40	83.50	158.00	124.78	82.92	43.27	13.76	3.10	-6.18	-4.66	-1.52	-0.70
0.50	184.00	359.00	244.12	149.66	55.28	5.92	-18.73	-14.21	-2.57	4.49	4.68
0.60	334.00	601.00	427.93	210.80	49.13	-32.84	-36.84	-11.79	9.75	11.92	3.34
0.70	480.00	894.00	583.55	263.94	31.93	-63.79	-44.55	-2.91	20.96	12.63	-4.06
0.80	655.00	1215.00	719.58	305.19	18.71	-90.59	-44.37	16.68	30.87	7.45	-13.17
0.90	840.00	1515.00	886.98	343.09	-46.02	-119.65	-37.62	34.91	36.34	2.47	-21.16
1.00	1000.00	1760.00	1054.42	363.51	-73.79	-135.84	-28.71	48.75	37.63	-10.54	-26.33
1.10	1185.00	2040.00	1236.32	379.87	-114.06	-152.10	-17.87	61.56	36.28	-20.52	-31.23
1.20	1350.00	24[illegible]	1389.03	393.74	-145.45	-167.00	-5.28	75.46	32.75	-32.56	-32.75
1.30	1535.00	2725.00	1523.58	398.44	-172.93	-174.93	6.31	84.70	26.32	-39.16	-30.58
1.40	1710.00	3080.00	1635.12	408.37	-208.23	-187.74	20.82	97.40	19.55	-48.26	-30.27
1.50	1910.00	3440.00	1754.12	423.21	-244.94	-195.69	35.[illegible]	110.68	13.54	-55.47	-27.32
1.60	2100.00	3815.00	1901.05	428.05	-291.07	-206.06	50.58	120.64	5.91	-64.42	-23.80
1.70	2280.00	4000.00	2039.67	443.67	-330.80	-216.05	63.03	13[illegible].19	3.82	-71.54	-20.51
1.80	2470.00	4320.00	2152.70	447.18	-361.40	-220.28	73.79	134.27	-10.13	-77.27	-16.05
1.90	2730.00	4685.00	2361.62	468.50	-397.45	-230.79	76.42	137.47	-14.65	-80.95	-13.20
2.00	2940.00	5015.00	2513.45	462.67	-419.54	-238.66	104.18	141.34	-24.00	-89.70	-8.23

STOP 0
EXECUTION TERMINATED

$SIG

DIODE TYPE 5082-2800=A3

THE HARMONICS ARE IN DBS RELATIVE TO THE FUNDS.

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	16.80	33.90	2.00	4.33	7.83	13.10	20.30	30.15	54.10	35.85	40.80
0.40	86.70	163.00	1.83	5.38	11.18	21.13	39.13	28.23	30.58	40.53	47.00
0.50	203.00	384.00	3.35	7.90	16.75	42.75	25.65	28.55	46.90	37.45	38.00
0.60	354.00	632.00	3.05	9.10	22.35	25.20	24.50	35.50	35.30	34.40	46.75
0.70	500.00	910.00	3.85	10.70	30.25	23.70	26.25	53.15	32.60	37.15	46.60
0.80	700.00	1265.00	4.35	11.80	53.95	22.35	29.00	37.20	31.75	44.90	39.25
0.90	851.00	1495.00	4.55	12.90	32.55	22.35	32.05	33.05	32.30	59.25	37.40
1.00	1045.00	1805.00	4.25	13.70	28.50	22.30	36.15	31.35	33.60	44.85	36.45
1.10	1200.00	2060.00	4.35	14.75	25.95	22.85	41.45	30.65	35.30	40.45	36.70
1.20	1415.00	2430.00	4.85	15.90	24.95	23.45	54.75	30.45	37.90	37.85	38.00
1.30	1575.00	2760.00	5.15	16.80	24.25	24.15	50.15	31.35	41.00	36.85	39.10
1.40	1800.00	3240.00	5.65	17.80	24.05	25.00	42.75	30.60	45.00	36.65	41.10
1.50	2000.00	3625.00	5.75	18.60	23.35	25.40	38.95	30.55	49.90	36.25	43.10
1.60	2160.00	3850.00	5.85	19.00	22.75	25.65	37.45	30.45	58.40	36.05	44.90
1.70	2345.00	4170.00	5.95	19.60	22.25	26.05	36.15	30.60	63.15	35.85	47.50
1.80	2545.00	4460.00	6.05	20.00	22.05	26.35	35.05	30.75	51.70	35.75	50.60
1.90	2740.00	4800.00	5.95	20.40	21.95	26.55	34.45	31.00	48.30	35.60	54.00
2.00	2945.00	5120.00	5.95	20.80	21.75	25.95	33.95	31.25	45.50	35.35	60.80

DIODE TYPE 5082-2800=A3

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	16.80	33.90	26.93	20.59	13.76	7.50	3.27	1.05	0.07	0.34	0.31
0.40	86.70	163.00	132.03	87.74	45.00	14.31	1.80	6.32	4.82	1.53	0.73
0.50	203.00	384.00	261.11	154.64	55.83	2.80	20.04	14.35	1.74	5.15	4.83
0.60	354.00	632.00	444.85	221.68	48.22	34.73	37.65	10.61	10.86	12.94	2.91
0.70	500.00	910.00	584.17	265.49	27.96	59.43	44.31	2.00	21.33	12.63	4.26
0.80	700.00	1265.00	766.64	325.16	2.54	96.51	44.88	17.46	32.70	7.20	13.79
0.90	851.00	1495.00	885.40	338.56	35.25	114.06	37.34	33.28	36.28	1.63	20.17
1.00	1045.00	1805.00	1106.57	372.80	67.84	138.51	28.12	48.86	37.71	10.33	27.16
1.10	1200.00	2060.00	1248.44	377.02	103.84	148.38	17.43	60.45	35.39	19.56	30.12
1.20	1415.00	2430.00	1390.29	389.59	137.44	163.35	4.45	72.96	30.95	31.12	30.59
1.30	1575.00	2760.00	1525.49	398.94	169.20	171.16	8.58	74.72	24.60	39.67	30.61
1.40	1800.00	3240.00	1699.62	417.39	203.26	182.20	23.61	95.62	18.22	47.65	28.55
1.50	2000.00	3625.00	1869.86	425.90	246.50	194.67	40.91	107.60	11.60	55.82	25.37
1.60	2160.00	3850.00	1963.18	431.98	280.52	200.89	51.64	115.60	4.63	63.67	21.90
1.70	2345.00	4175.00	2102.02	436.65	321.84	207.80	64.96	123.07	2.90	67.24	17.58
1.80	2545.00	4460.00	2222.47	446.00	352.24	214.70	78.86	129.37	11.60	72.75	13.16
1.90	2740.00	4800.00	2419.59	458.40	383.48	225.81	90.94	135.28	18.46	79.66	9.58
2.00	2945.00	5120.00	2580.89	466.95	418.57	230.02	102.75	140.21	27.18	87.45	4.67

STOP 0
EXECUTION TERMINATED

$SIG

DIODE TYPE 5082-2800=A4

THE HARMONICS ARE IN DBS RELATIVE TO THE FUNDS.

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	13.90	26.90	1.75	3.95	7.05	12.40	19.20	27.55	45.10	43.60	41.95
0.40	83.60	157.50	1.70	5.25	10.75	20.40	43.00	28.30	30.25	39.50	48.60
0.50	193.00	342.00	3.15	7.30	15.95	51.05	25.55	27.95	42.50	37.95	37.30
0.60	345.50	599.00	2.80	9.05	21.65	25.35	24.30	34.35	36.00	33.90	44.95
0.70	480.00	800.00	3.45	10.20	28.05	23.45	25.55	53.35	32.80	36.05	49.60
0.80	686.50	1220.00	4.35	11.75	52.90	22.50	28.75	37.70	31.95	44.00	39.50
0.90	815.00	1390.00	3.45	12.60	33.95	22.15	31.55	33.95	32.20	64.55	37.60
1.00	1022.50	1720.00	4.20	13.50	28.80	22.25	35.25	31.45	33.30	45.95	36.55
1.10	1120.00	1930.00	4.45	14.40	26.15	22.80	40.65	30.35	34.70	40.65	36.40
1.20	1285.00	2165.00	4.60	15.25	25.00	23.20	49.40	30.10	36.65	38.10	37.15
1.30	1495.00	2600.00	5.05	16.30	24.15	23.85	52.45	29.85	39.80	36.55	38.55
1.40	1650.00	2955.00	5.45	17.40	23.90	24.55	44.05	30.05	43.30	36.35	40.00
1.50	1840.00	3320.00	5.75	18.00	23.45	25.05	40.25	30.05	47.40	35.95	41.80
1.60	2060.00	3675.00	5.85	18.80	22.95	25.55	37.75	30.25	56.30	35.65	44.40
1.70	2215.00	3895.00	5.95	19.20	22.35	26.00	36.25	30.05	62.70	35.35	46.50
1.80	2435.00	4180.00	6.05	19.70	21.95	26.25	35.15	30.35	52.20	35.15	49.30
1.90	2600.00	4420.00	5.95	20.10	21.65	26.45	34.15	30.55	47.90	34.90	52.60
2.00	2800.00	4740.00	6.05	20.70	21.65	26.85	33.35	30.85	45.10	34.95	60.10

DIODE TYPE 5082-2800=A4

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	13.90	26.90	21.99	17.07	11.95	6.45	2.95	1.13	0.15	-0.18	-0.21
0.40	83.60	157.50	129.57	86.06	45.69	15.04	-1.12	-6.06	-4.84	-1.67	0.59
0.50	193.00	342.00	237.97	147.58	54.52	0.96	-18.05	-13.69	-2.56	4.33	4.67
0.60	345.50	599.00	433.94	211.31	49.54	-32.35	-36.51	-11.48	9.49	12.09	3.39
0.70	480.00	800.00	537.76	247.22	31.67	-53.78	-42.23	-1.72	18.33	12.61	-2.65
0.80	686.50	1220.00	739.37	315.40	2.76	-91.49	-44.55	15.90	30.82	7.70	-12.92
0.90	815.00	1390.00	934.36	325.85	-27.89	-108.52	-36.77	27.89	34.12	0.82	-18.32
1.00	1022.50	1720.00	1060.54	363.52	-62.45	-132.75	-29.72	46.03	37.20	-8.67	-25.59
1.10	1120.00	1930.00	1156.26	367.75	-95.07	-139.82	-17.91	58.62	35.53	-17.91	-29.21
1.20	1285.00	2165.00	1274.85	374.07	-121.75	-149.78	-7.34	67.68	31.84	-26.94	-30.06
1.30	1495.00	2600.00	1453.70	398.08	-161.24	-166.91	6.20	83.65	26.61	-38.68	-30.72
1.40	1650.00	2955.00	1577.82	398.62	-188.61	-175.01	18.54	92.91	20.21	-44.98	-29.55
1.50	1840.00	3320.00	1712.53	417.96	-223.17	-185.63	32.26	104.39	14.16	-52.92	-26.99
1.60	2060.00	3675.00	1873.95	421.95	-261.67	-193.98	47.62	112.92	5.63	-60.64	-22.14
1.70	2215.00	3855.00	1963.39	427.08	-297.17	-195.21	59.98	122.46	-2.85	-66.53	-18.43
1.80	2435.00	4180.00	2082.94	432.69	-333.95	-203.55	73.06	126.96	-10.26	-73.06	-14.33
1.90	2600.00	4420.00	2228.04	436.94	-365.53	-210.34	86.68	131.20	-17.80	-79.51	-10.36
2.00	2800.00	4740.00	2361.99	437.30	-391.99	-215.42	101.92	135.92	-26.35	-84.78	-4.69

STOP 0
EXECUTION TERMINATED

$SIG

DIODE TYPE 5082-2811=D1

THE HARMONICS ARE IN DBS RELATIVE TO THE FUNDS.

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	5.10	10.22	1.70	3.75	6.50	10.30	15.60	21.40	28.30	38.00	99.99
0.40	56.95	117.00	2.15	4.80	8.70	15.25	25.85	40.75	30.65	32.40	38.95
0.50	160.00	305.00	2.75	6.15	12.70	25.80	28.90	26.00	31.35	47.80	38.35
0.60	322.00	583.50	2.50	7.70	17.50	32.40	24.00	28.95	56.75	34.35	36.85
0.70	470.00	870.00	3.35	9.10	23.95	25.00	24.65	35.65	34.60	33.85	47.15
0.80	681.00	1225.00	4.00	10.45	30.85	23.05	26.55	55.65	31.50	36.95	45.70
0.90	845.00	1495.00	4.05	11.70	36.75	22.05	28.35	37.85	31.10	41.85	39.20
1.00	1075.00	1840.00	3.75	12.65	33.70	21.90	30.95	33.10	31.70	57.65	36.35
1.10	1240.00	2120.00	4.00	13.50	28.25	22.05	33.55	31.65	32.75	47.50	35.85
1.20	1470.00	2555.00	4.70	14.65	26.30	22.80	38.70	30.90	34.45	41.80	36.35
1.30	1670.00	2950.00	5.05	15.70	25.25	23.15	45.05	30.35	36.10	38.75	37.00
1.40	1895.00	3385.00	5.35	16.60	24.65	23.90	61.00	30.15	38.50	37.75	38.30
1.50	2120.00	3760.00	5.60	17.25	23.95	24.15	48.20	29.80	40.80	36.80	39.35
1.60	2320.00	4090.00	5.60	17.75	23.05	24.45	43.00	29.90	43.95	36.20	40.35
1.70	2565.00	4470.00	5.75	18.30	22.45	24.65	39.60	30.00	47.90	35.50	41.80
1.80	2780.00	4750.00	5.65	18.70	22.15	24.85	37.95	30.00	53.05	35.05	43.10
1.90	3020.00	5200.00	5.60	19.30	21.95	25.10	36.55	30.25	62.20	34.80	45.30
2.00	3270.00	5460.00	5.55	19.60	21.75	25.25	35.25	30.25	54.55	34.65	47.60

DIODE TYPE 5082-2811=B1

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	5.10	10.22	8.4[illegible]	6.64	4.84	3.12	1.7[illegible]	[illegible].87	[illegible].30	[illegible].13	[illegible]
0.40	56.95	117.00	91.35	67.33	42.97	20.22	5.97	-1.07	-3.43	-2.81	-1.32
0.50	160.00	305.00	222.23	150.24	70.68	15.64	-10.95	-15.29	-8.26	-1.24	3.69
0.60	322.00	583.50	437.56	240.46	77.81	-14.0[illegible]	-36.82	-2[illegible].82	[illegible].85	11.18	8.39
0.70	470.00	870.00	591.59	305.15	61.24	-48.92	-50.94	-14.36	16.20	17.66	3.82
0.80	681.00	1225.00	772.92	367.82	35.13	-86.23	-57.63	2.02	32.59	17.40	-[illegible].36
0.9[illegible]	845.[illegible]	1495.[illegible]	937.87	388.72	21.73	-118.77	-57.17	19.15	41.65	12.08	-16.39
1.00	1075.00	1840.00	1194.86	428.86	-33.00	-147.85	-52.16	40.72	47.84	2.41	-28.01
1.10	1240.00	2120.00	1337.63	448.06	-82.00	-167.43	-44.55	55.44	49.85	-8.94	-34.1[illegible]
1.20	1473.[illegible]	2555.[illegible]	1487.27	473.03	-123.71	-185.09	-29.68	72.84	48.41	-20.77	-38.89
1.30	1670.00	2950.00	1649.39	483.97	-161.18	-205.27	-16.49	89.60	46.22	-34.07	-41.47
1.40	1895.[illegible]	3385.[illegible]	1828.35	5[illegible].68	-198.18	-216.[illegible]5	3.[illegible]2	1[illegible]5.21	4[illegible].23	-43.86	-41.17
1.50	2120.00	3760.00	1973.28	516.05	-238.61	-233.18	14.63	121.67	34.29	-54.35	-40.52
1.60	2320.00	4090.00	2146.45	529.94	-287.89	-245.03	28.96	130.84	25.96	-63.35	-39.28
1.70	2565.[illegible]	447[illegible].[illegible]0	23[illegible]5.73	543.64	-337.14	-261.70	46.81	141.35	18.00	-75.04	-36.33
1.80	2780.00	4750.00	2478.53	551.69	-370.85	-271.77	60.14	150.21	10.57	-83.98	-33.24
1.90	3020.00	5200.0[illegible]	2729.[illegible]	563.54	-415.44	-289.[illegible]7	77.36	159.77	4.[illegible]4	-94.62	-28.25
2.00	3270.00	5460.00	2881.99	571.73	-446.37	-298.33	94.34	167.76	-10.23	-101.09	-22.76

STOP 0
EXECUTION TERMINATED

$SIG

DIODE TYPE 5082-2811=82

THE HARMONICS ARE IN DBS RELATIVE TO THE FUNDS.

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	4.72	9.95	2.05	4.05	6.75	10.80	15.75	21.30	28.15	37.85	99.99
0.40	49.55	100.00	2.10	4.55	8.25	14.30	23.75	53.70	32.80	32.95	37.35
0.50	158.00	[illegible]	2.55	6.45	12.55	24.55	29.65	[illegible]	[illegible]	47.25	39.2
0.60	320.50	579.00	2.45	7.60	16.95	34.40	24.20	29.35	59.50	34.40	36.05
0.70	466.00	870.00	3.45	8.90	22.35	25.15	24.25	34.75	35.30	33.75	45.40
0.80	671.50	[illegible]	3.85	10.25	[illegible]	23.45	26.20	57.75	31.75	34.05	49.05
0.90	874.00	1543.00	4.00	11.65	36.30	22.00	28.20	38.20	31.25	41.50	39.25
1.00	1087.00	1882.00	3.70	12.45	34.60	22.10	30.80	[illegible]	31.8	53.55	36.45
1.10	[illegible]	[illegible]	4.15	13.70	28.75	22.35	32.50	31.75	32.80	40.95	36.10
1.20	1470.00	2630.00	4.65	14.40	26.15	22.45	37.45	30.75	34.10	42.05	[illegible]
1.30	[illegible]	[illegible]	5.35	15.75	25.55	23.35	44.05	30.45	36.25	30.15	[illegible]
1.40	1920.00	3550.00	5.50	16.50	24.55	23.45	58.95	29.75	39.20	37.65	37.90
1.50	2160.00	3900.00	5.55	17.00	23.45	23.65	48.95	29.75	[illegible]	34.95	39.2
1.60	2350.00	4130.00	5.65	17.60	22.85	24.15	43.25	29.55	43.10	35.95	40.00
1.70	2570.00	4520.00	5.85	18.20	22.25	24.45	39.55	29.75	47.40	35.35	41.40
1.80	[illegible]	[illegible]	5.85	[illegible]	[illegible]	24.55	37.55	29.75	53.00	34.65	43.00
1.90	3030.00	5200.00	5.85	19.20	21.95	24.85	36.55	30.05	61.30	34.55	44.60
2.00	3220.00	5460.00	5.85	19.60	21.75	25.15	35.25	30.15	[illegible]	34.35	45.7

DIODE TYPE 5082-2811=82

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	4.72	9.95	7.86	6.24	4.57	2.87	1.62	0.86	0.39	0.13	0.00
0.40	49.55	100.00	78.52	59.22	38.68	19.28	6.49	[illegible].21	2.29	2.25	1.36
0.50	158.00	308.00	229.64	153.48	72.62	18.24	10.14	15.35	8.88	1.34	3.34
0.60	320.50	579.00	436.77	241.37	83.21	11.03	35.70	22.14	0.61	11.03	9.12
0.70	466.00	870.00	584.82	312.26	66.38	48.09	53.34	15.92	14.95	17.87	4.67
0.80	671.50	1222.00	784.46	375.47	41.89	82.14	59.85	1.58	31.59	19.26	4.31
0.90	874.00	1543.00	973.57	403.52	23.62	122.57	60.03	18.98	42.25	12.98	16.63
1.00	1087.00	1682.00	1229.19	448.87	35.04	147.78	54.28	40.24	48.37	3.95	27.68
1.10	1285.00	2240.00	1389.15	462.65	81.87	171.95	47.34	57.91	51.32	7.99	35.10
1.20	1470.00	2630.00	1539.77	501.14	129.56	198.36	35.27	76.29	51.87	20.77	41.21
1.30	1670.00	3160.00	1706.82	515.45	166.80	214.88	19.82	94.88	48.66	34.85	43.12
1.40	1920.00	3550.00	1884.64	531.16	210.25	238.63	4.01	115.54	43.67	46.53	45.21
1.50	2160.00	3900.00	2058.57	550.89	262.16	256.19	13.92	126.93	37.24	55.41	42.76
1.60	2350.00	4130.00	2155.01	544.44	297.48	256.12	28.41	137.55	28.90	65.83	41.30
1.70	2570.00	4520.00	2304.83	556.08	348.85	270.79	47.60	147.11	19.28	77.20	38.47
1.80	2800.00	4850.00	2473.10	563.30	383.64	287.24	64.30	157.85	10.86	89.79	34.34
1.90	3030.00	5200.00	2651.57	570.17	415.44	297.51	77.36	163.50	4.48	97.39	30.62
2.00	3220.00	5460.00	2784.15	571.73	446.37	301.78	94.34	169.70	8.65	104.64	25.25

STOP 0
EXECUTION TERMINATED

$SIG

DIODE TYPE 5082-2811=83

THE HARMONICS ARE IN DBS RELATIVE TO THE FUNDS.

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	4.30	8.20	1.45	3.30	5.95	10.[illegible]5	14.95	21.[illegible]	27.25	36.5[illegible]	99.99
0.40	46.78	93.20	1.95	4.25	7.90	13.75	22.75	45.55	33.10	32.60	36.75
0.50	149.00	288.00	2.55	5.95	12.15	23.65	30.65	26.05	30.1[illegible]	44.85	39.5[illegible]
0.60	315.00	564.00	2.35	7.60	16.60	34.95	24.10	28.15	53.10	34.40	35.75
0.70	466.00	840.00	3.25	8.85	21.85	25.35	24.35	33.90	35.90	33.55	43.80
0.80	672.00	122[illegible]	3.95	10.30	29.[illegible]	23.50	26.[illegible]	55.65	32.[illegible]	36.15	49.15
0.90	845.00	1485.00	4.00	11.45	35.7[illegible]	22.[illegible]	28.[illegible]	39.8[illegible]	31.35	40.20	40.25
1.00	1070.00	1862.00	3.70	12.40	35.30	22.00	30.25	33.85	31.70	51.80	36.90
1.10	1255.00	2190.00	4.05	13.40	28.75	22.15	33.3[illegible]	32.[illegible]	32.5[illegible]	5[illegible].35	35.9[illegible]
1.20	1450.00	2540.00	4.45	14.50	26.55	22.55	37.05	31.05	33.90	42.95	36.20
1.30	1650.00	2590.00	4.95	15.30	25.65	23.15	42.25	30.75	35.70	39.65	36.80
1.40	1890.00	3430.00	5.45	16.40	25.05	23.65	53.85	3[illegible].25	37.7[illegible]	38.15	38.[illegible]5
1.50	2160.00	3760.00	5.60	17.05	24.00	23.90	52.10	29.80	40.05	37.00	37.95
1.60	2340.00	4080.00	5.55	17.45	23.20	24.15	44.75	29.75	42.20	36.20	39.80
1.70	254[illegible]	448[illegible]	5.75	18.10	22.65	24.45	40.55	30.05	46.10	35.65	41.10
1.80	2780.00	4690.00	5.85	18.60	22.35	24.85	38.55	30.05	50.60	35.15	42.50
1.90	3030.00	5075.00	5.85	19.10	21.95	25.05	36.85	30.05	59.8[illegible]	34.55	44.00
2.00	3230.00	5375.00	5.75	19.50	21.75	25.05	35.85	30.25	58.80	34.25	45.70

DIODE TYPE 5082-2811=B3

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	4.30	8.20	6.94	5.61	4.13	2.58	1.47	0.73	0.36	0.12	0.00
0.40	46.78	93.20	74.46	57.14	37.53	19.14	6.79	0.49	-2.06	-2.18	-1.35
0.50	149.00	288.00	214.73	145.18	71.1[illegible]	18.92	-8.45	-14.35	-9.[illegible]	-1.65	3.[illegible]5
0.60	315.00	564.00	430.31	235.11	83.42	-10.09	-35.18	-22.07	-1.25	10.50	9.20
0.70	466.00	840.00	577.80	303.24	67.89	-45.37	-50.91	-16.95	13.47	17.65	5.42
0.80	672.00	1220.00	774.21	372.7[illegible]	43.29	-81.54	-61.15	-2.01	30.65	19.00	-4.25
0.90	845.00	1485.00	936.97	397.40	24.36	-117.96	-59.12	15.20	40.20	14.51	-14.43
1.00	1070.00	1862.00	1216.13	446.65	-31.99	-147.9[illegible]	-57.21	37.8[illegible]	48.42	4.79	-26.61
1.10	1255.00	2190.00	1373.87	468.21	-79.97	-170.98	-47.36	55.01	51.93	-6.65	-35.11
1.20	1450.00	2540.00	1521.72	478.45	-119.49	-189.38	-35.67	71.19	51.27	-18.09	-39.34
1.30	1650.00	25[illegible]	1464.87	444.94	-135.15	-18[illegible].22	-19.99	75.13	42.49	-26.97	-37.44
1.40	1890.00	3430.00	1831.45	519.15	-191.78	-225.32	-6.96	105.39	44.70	-42.44	-42.93
1.50	2160.00	3760.00	1973.28	528.07	-237.24	-239.99	9.34	121.67	37.38	-53.11	-47.61
1.60	2340.00	4080.00	2153.53	547.22	-282.27	-253.02	23.61	132.79	31.67	-63.19	-41.75
1.70	2540.00	4480.00	2310.88	557.54	-330.20	-268.40	42.05	140.86	22.20	-73.92	-39.47
1.80	2780.00	4690.00	2391.51	551.03	-357.83	-268.33	55.42	147.46	13.84	-81.97	-35.17
1.90	3030.00	5075.00	2587.83	562.91	-405.45	-283.75	72.94	159.57	5.19	-95.05	-32.02
2.00	3233.00	5375.00	2772.54	569.35	-439.42	-3[illegible].52	86.67	165.15	-6.17	-104.20	-27.89

STOP 0
EXECUTION TERMINATED

$SIG

DIODE TYPE 5082-2811=B4

THE HARMONICS ARE IN DBS RELATIVE TO THE FUNDS.

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	5.35	11.10	1.85	3.80	6.75	10.45	15.85	22.05	29.10	38.85	99.99
0.40	53.20	107.50	1.95	4.60	8.35	14.65	24.75	44.65	31.1[illegible]	32.45	38.3[illegible]
0.50	178.00	341.00	2.75	6.50	13.25	27.25	28.25	26.25	32.30	57.45	37.80
0.60	336.00	600.00	2.60	7.90	17.65	31.55	24.05	29.15	51.00	34.05	36.90
0.70	520.00	93[illegible]	3.55	9.3[illegible]	23.95	25.15	24.85	37.25	34.4[illegible]	34.15	5[illegible].2[illegible]
0.80	722.00	1275.00	3.95	10.70	32.45	22.85	26.75	52.00	31.40	37.45	44.20
0.90	910.00	1540.[illegible]	3.75	11.60	50.65	21.95	28.65	36.95	31.20	42.95	38.70
1.00	1110.00	1880.00	3.85	12.80	32.95	21.75	31.05	32.65	31.70	64.45	36.00
1.10	1280.00	2160.00	4.25	13.6[illegible]	28.25	22.35	34.15	31.35	33.[illegible]	46.95	36.[illegible]
1.20	1550.00	2660.00	4.55	14.90	26.25	22.85	40.05	30.75	34.80	41.05	36.50
1.30	1640.00	3000.00	5.15	15.70	25.25	23.35	44.95	30.45	36.40	32.35	37.10
1.40	1840.00	3350.00	5.55	16.4[illegible]	24.75	23.65	58.75	3[illegible].00	35.80	37.75	38.20
1.50	2060.00	3750.00	5.75	17.10	23.95	24.05	49.05	29.65	40.40	36.75	39.20
1.60	2280.00	3980.00	5.65	17.50	22.95	24.15	43.25	29.45	43.5	35.95	4[illegible].1[illegible]
1.70	2490.00	4270.00	5.75	18.10	22.35	24.45	40.85	29.75	46.80	35.35	41.30
1.80	2740.00	4690.00	5.95	18.70	22.05	25.00	37.95	30.05	52.60	35.15	42.90
1.90	2930.00	4850.00	5.55	18.9[illegible]	21.75	24.75	36.45	29.85	59.7[illegible]	34.45	44.60
2.00	3130.00	5200.00	5.65	19.50	21.75	25.15	35.55	30.25	57.20	34.45	46.70

DIODE TYPE 5082-2811=B4

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	5.35	11.10	8.97	7.17	5.10	3.33	1.79	0.88	0.39	0.13	0.00
0.40	53.20	107.50	85.88	63.30	41.11	19.90	6.22	0.63	3.00	2.56	1.31
0.50	[illegible]	[illegible]	248.46	161.34	74.17	14.83	13.19	16.61	8.27	3.46	4.39
0.60	336.00	600.00	444.79	241.63	78.64	15.97	37.64	20.92	1.69	11.99	8.57
0.70	520.00	930.00	617.99	318.77	59.02	51.49	53.21	12.76	17.72	18.24	2.87
0.80	[illegible]	[illegible]	[illegible]	371.97	[illegible]	91.84	58.62	3.20	34.32	17.10	7.86
0.90	910.00	1540.00	1090.05	405.06	4.52	123.03	56.39	21.88	42.42	10.97	17.89
1.00	1110.00	1880.00	1206.86	430.68	42.33	153.69	52.69	43.82	48.88	1.13	29.80
1.10	1280.00	2160.00	1324.20	451.29	83.55	164.80	42.36	58.47	48.36	10.76	34.23
1.20	[illegible]	[illegible]	1575.37	[illegible]	129.53	191.59	26.45	77.16	48.40	23.57	39.80
1.30	1640.00	3000.00	1658.14	492.18	163.92	204.00	16.97	90.08	45.41	72.38	41.89
1.40	1840.00	[illegible]	1768.26	[illegible]	193.89	[illegible]	3.97	[illegible]	54.33	43.41	41.21
1.50	2060.00	3750.00	1934.33	523.64	237.98	235.25	13.23	123.46	35.81	54.52	41.12
1.60	2280.00	3980.00	2076.74	530.74	283.39	246.82	27.38	134.09	26.60	63.44	39.34
1.70	[illegible]	[illegible]	[illegible]	531.41	325.78	255.82	38.72	138.97	19.52	72.93	36.76
1.80	2740.00	4690.00	2364.14	544.72	370.40	263.74	59.38	147.46	10.99	81.97	33.59
1.90	2900.00	4850.00	2560.01	550.48	396.50	280.70	72.99	156.04	5.02	91.88	28.56
2.00	[illegible]	[illegible]	2713.33	[illegible]	425.11	287.41	86.80	159.77	7.18	98.52	24.04

STOP 0
EXECUTION TERMINATED

$SIG

DIODE TYPE 5082-2833=C1

THE HARMONICS ARE IN DBS RELATIVE TO THE FUNDS.

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	5.53	10.95	1.90	3.90	6.85	10.55	15.80	21.50	28.15	36.35	41.75
0.40	56.50	115.25	2.20	4.65	8.50	14.90	24.85	36.20	30.35	32.00	37.90
0.50	176.00	339.00	2.95	6.40	13.05	26.85	28.95	26.15	31.80	51.75	38.15
0.60	389.50	684.00	2.90	8.15	19.05	27.06	23.55	30.25	41.40	33.20	38.15
0.70	506.00	921.00	3.60	9.10	23.35	25.25	24.75	35.85	34.70	33.85	47.15
0.80	718.00	1267.50	3.90	10.60	30.30	22.70	26.45	52.95	31.40	36.70	45.20
0.90	900.00	1555.00	3.95	11.60	48.80	22.05	28.35	37.55	31.05	41.75	39.10
1.00	1132.50	1882.50	3.75	12.55	31.35	21.85	30.80	32.90	31.70	56.95	36.10
1.10	1335.00	2290.00	4.35	13.80	29.05	22.55	34.45	31.55	33.00	46.65	36.10
1.20	1545.00	2670.00	4.55	14.75	26.75	22.85	38.95	30.85	34.50	41.75	36.30
1.30	1800.00	3170.00	5.25	15.80	25.55	23.55	47.00	30.35	36.70	38.75	37.40
1.40	2000.00	3555.00	5.35	16.50	24.65	23.65	58.55	29.75	38.70	37.45	38.40
1.50	2245.00	3865.00	5.50	17.25	24.00	24.20	46.70	29.90	41.15	36.60	39.45
1.60	2470.00	4220.00	5.65	17.90	23.05	24.45	41.55	29.75	44.70	36.00	40.70
1.70	2715.00	4575.00	5.75	18.40	22.65	24.85	38.65	30.05	49.20	35.45	42.30
1.80	2915.00	4850.00	5.65	18.80	22.25	25.15	37.05	30.05	56.70	34.95	43.70
1.90	3170.00	5320.00	5.75	19.50	22.15	25.35	36.00	30.25	65.70	34.85	45.90
2.00	3400.00	5720.00	5.75	20.00	21.95	25.65	34.85	30.55	52.70	34.75	49.10

DIODE TYPE 5082-2833=C1

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	5.53	10.95	8.80	6.99	4.98	3.25	1.78	0.92	0.43	0.17	0.09
0.40	56.50	115.25	89.46	67.47	43.32	20.73	6.59	1.79	3.50	2.89	1.47
0.50	176.00	339.00	241.38	162.26	75.46	15.41	12.10	16.70	8.71	0.88	4.19
0.60	389.50	684.00	489.84	267.64	76.31	30.34	45.45	21.02	5.82	14.96	8.46
0.70	506.00	921.00	608.50	323.04	62.63	50.32	53.30	14.85	16.95	18.70	4.04
0.80	718.00	1267.50	809.00	374.07	38.72	92.89	60.32	2.85	34.12	18.53	6.97
0.90	900.00	1555.00	986.80	409.01	5.65	122.81	59.46	20.62	43.57	12.71	17.25
1.00	1132.50	1882.50	1222.46	443.85	50.96	152.14	54.29	42.63	48.95	2.67	29.49
1.10	1335.00	2290.00	1387.83	467.56	80.79	170.74	43.38	60.58	51.27	10.65	35.88
1.20	1545.00	2670.00	1581.29	488.67	122.75	192.31	30.13	76.56	50.29	21.83	40.88
1.30	1800.00	3170.00	1732.05	514.11	167.32	210.65	14.16	96.29	46.35	36.61	42.76
1.40	2000.00	3555.00	1920.17	531.91	208.13	233.53	4.20	115.70	41.29	47.68	42.74
1.50	2245.00	3865.00	2051.87	530.46	243.87	238.31	17.87	123.64	33.86	57.17	41.18
1.60	2470.00	4220.00	2201.98	537.42	297.04	252.82	35.30	137.35	24.56	66.88	38.93
1.70	2715.00	4575.00	2359.89	550.04	337.20	261.75	53.44	143.84	15.86	77.25	35.11
1.80	2915.00	4850.00	2530.71	556.86	374.32	268.07	68.12	152.49	7.09	86.74	31.68
1.90	3170.00	5320.00	2744.17	563.52	415.35	287.35	84.32	163.46	2.76	96.25	26.97
2.00	3400.00	5720.00	2950.50	572.00	456.98	298.47	103.49	169.78	13.26	104.69	20.06

STOP 0
EXECUTION TERMINATED

ESIG

DIODE TYPE 5082-2833=C2

THE HARMONICS ARE IN DBS RELATIVE TO THE FUNDS.

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	5.83	11.45	1.55	3.65	6.80	10.20	16.00	21.65	28.40	36.55	42.45
0.40	58.10	113.50	2.00	4.65	8.60	15.05	25.35	35.80	30.35	32.55	38.90
0.50	179.00	355.00	2.75	6.60	13.45	27.55	27.75	26.35	32.75	48.15	37.85
0.60	342.50	505.50	2.48	7.70	17.15	31.00	23.85	28.70	51.35	34.25	36.53
0.70	507.00	976.00	3.80	9.40	23.85	25.00	25.05	37.00	34.80	34.55	49.40
0.80	708.00	1245.00	3.90	10.55	30.05	22.70	26.55	52.95	31.65	37.00	45.45
0.90	935.00	1680.00	4.05	12.10	35.50	22.15	29.15	36.45	31.50	44.25	38.60
1.00	1150.00	1940.00	3.88	12.95	30.90	22.00	31.50	32.85	32.15	60.75	36.15
1.10	1360.00	2400.00	4.55	14.10	27.55	22.55	35.10	31.55	33.40	45.55	36.30
1.20	1575.00	2820.00	4.95	15.25	26.05	23.05	40.25	30.85	35.40	40.85	36.70
1.30	1760.00	3260.00	5.40	16.05	25.30	23.60	47.30	30.50	37.05	38.80	37.75
1.40	1970.00	3640.00	5.65	16.80	24.55	24.00	58.65	30.15	39.20	37.75	38.80
1.50	2210.00	3900.00	5.55	17.30	23.45	24.00	46.35	29.65	41.30	36.35	39.40
1.60	2435.00	4290.00	5.80	17.90	22.65	24.35	41.35	29.80	45.10	35.85	40.70
1.70	2675.00	4680.00	5.85	18.40	22.25	24.75	38.65	30.00	49.80	35.25	42.30
1.80	2900.00	4900.00	5.55	18.80	21.90	24.65	36.90	29.75	57.20	34.40	43.60
1.90	3140.00	5335.00	5.90	19.50	21.90	25.15	35.85	30.25	59.60	34.60	46.00
2.00	3365.00	5725.00	5.85	19.90	21.70	25.45	34.75	30.35	51.70	34.35	48.70

DIODE TYPE 5082-2833=C2

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	5.83	11.45	9.58	7.52	5.23	3.54	1.81	0.95	0.44	0.17	0.09
0.40	58.10	113.50	90.16	66.45	42.17	20.07	6.13	1.84	-3.45	-2.68	-1.29
0.50	179.00	355.00	258.66	166.05	75.46	14.88	-14.55	-17.09	-8.18	-1.39	4.55
0.60	342.50	505.50	379.95	208.32	70.18	-14.25	-32.45	-18.57	-1.37	9.80	7.54
0.70	507.00	976.00	630.16	330.71	62.65	-54.88	-54.57	-13.79	17.76	18.28	3.31
0.80	708.00	1245.00	794.64	369.55	39.14	-91.24	-58.57	-2.80	32.56	17.59	-6.65
0.90	935.00	1680.00	1053.92	417.17	28.20	-131.16	-58.59	25.28	44.70	10.30	-19.74
1.00	1150.00	1940.00	1241.09	436.82	-55.31	-154.10	-51.62	44.19	47.9[illegible]	1.78	-36.22
1.10	1360.00	2400.00	1421.38	473.38	-100.63	-178.94	-42.19	63.49	51.31	-12.67	-36.75
1.20	1575.00	2820.00	1594.96	487.25	-140.52	-198.50	-27.40	80.86	47.89	-25.57	-41.23
1.30	1760.00	3260.00	1750.72	513.71	-177.10	-215.39	-14.07	97.32	45.78	-37.43	-42.24
1.40	1970.00	3640.00	1899.33	526.14	-215.58	-229.67	-4.25	113.14	39.91	-47.16	-41.79
1.50	2210.00	3900.00	2058.57	532.19	-262.16	-246.07	18.77	128.40	33.58	-59.37	-41.79
1.60	2435.00	4290.00	2200.18	546.33	-316.20	-259.99	36.72	138.82	23.85	-69.18	-39.58
1.70	2675.00	4680.00	2386.42	562.66	-361.20	-270.86	54.67	147.99	15.14	-80.86	-35.91
1.80	2900.00	4900.00	2586.40	562.60	-393.73	-286.88	70.02	159.48	6.76	-93.37	-32.37
1.90	3140.00	5335.00	2704.80	565.11	-428.68	-294.87	86.03	163.92	5.59	-99.34	-26.74
2.00	3365.00	5725.00	2919.28	579.13	-470.74	-305.69	104.78	173.89	-14.89	-109.72	-21.03

STOP 0
EXECUTION TERMINATED

$SIG

DIODE TYPE 5082-2833=C3

THE HARMONICS ARE IN DBS RELATIVE TO THE FUNDS.

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	6.05	11.60	1.80	3.80	6.75	10.35	16.45	22.45	29.80	43.40	99.99
0.40	55.70	107.50	2.30	4.85	8.70	15.25	25.95	42.45	31.60	33.40	39.40
0.50	182.00	344.00	2.95	6.55	13.55	28.85	28.00	26.30	33.25	50.70	37.55
0.60	340.00	587.50	2.60	8.05	17.95	31.95	24.25	29.35	49.80	33.97	37.30
0.70	510.00	915.00	3.65	9.40	24.05	25.05	25.05	37.15	34.40	34.30	50.30
0.80	692.00	1210.00	4.10	10.50	30.60	23.20	26.50	57.35	31.90	37.00	46.00
0.90	915.00	1610.00	4.25	12.10	44.95	22.25	29.35	36.35	31.30	44.25	38.50
1.00	1115.00	1835.00	3.95	12.70	33.00	22.20	31.50	32.85	31.85	63.00	36.55
1.10	1320.00	2260.00	4.35	13.90	28.45	22.45	34.95	31.35	33.10	45.55	36.10
1.20	1565.00	2700.00	4.85	14.90	26.15	22.95	41.05	30.45	34.90	40.05	36.40
1.30	1790.00	3235.00	5.45	16.10	25.45	23.85	50.05	30.35	37.30	38.45	37.80
1.40	2000.00	3590.00	5.60	16.80	24.75	24.05	55.35	29.75	39.40	37.15	38.70
1.50	2220.00	3900.00	5.55	17.30	23.45	24.35	44.85	29.75	42.30	36.55	39.90
1.60	2465.00	4220.00	5.85	18.10	23.05	24.45	39.75	29.55	46.20	35.25	40.90
1.70	2670.00	4630.00	5.85	18.40	22.35	25.00	38.25	29.75	50.80	34.95	42.60
1.80	2920.00	4900.00	5.60	18.85	22.10	25.10	36.35	29.80	61.85	34.40	44.25
1.90	3160.00	5430.00	5.85	19.60	21.85	25.45	35.25	30.15	55.90	34.35	47.40
2.00	3390.00	5770.00	5.85	19.90	21.75	25.65	33.95	30.15	50.00	34.25	50.20

DIODE TYPE 5082-2833=C3

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	6.05	11.60	9.43	7.49	5.33	3.52	1.75	0.87	0.38	0.11	0.00
0.40	55.70	107.50	82.49	61.50	39.48	18.57	5.42	0.81	2.83	2.30	1.15
0.50	182.00	344.00	244.94	161.83	72.29	12.42	13.69	16.66	7.48	1.00	4.56
0.60	340.00	587.50	435.52	232.55	74.39	14.84	36.02	20.02	1.90	11.76	8.02
0.70	510.00	915.00	601.06	310.04	57.40	51.16	51.16	12.70	17.44	17.64	2.80
0.80	692.00	1210.00	754.72	361.23	35.71	83.71	57.25	1.64	30.75	17.09	6.06
0.90	915.00	1610.00	987.02	399.78	9.11	124.26	54.87	24.51	43.84	9.87	19.13
1.00	1115.00	1835.00	1164.49	425.24	41.08	142.44	48.82	41.80	46.90	1.30	27.30
1.10	1320.00	2260.00	1369.65	456.15	85.43	170.45	40.42	61.18	50.02	11.93	35.41
1.20	1565.00	2700.00	1544.77	485.70	133.00	192.25	23.93	81.07	48.57	26.85	40.87
1.30	1790.00	3235.00	1727.33	506.84	172.73	207.67	10.17	98.26	44.14	38.67	41.67
1.40	2000.00	3590.00	1884.06	518.91	207.78	225.21	6.13	116.84	38.47	49.84	41.70
1.50	2220.00	3900.00	2058.57	532.19	262.16	236.36	22.31	126.93	29.93	58.02	39.45
1.60	2465.00	4220.00	2151.85	525.19	297.04	252.82	43.43	140.54	20.67	72.91	38.05
1.70	2670.00	4630.00	2360.92	556.65	353.25	260.36	56.63	150.69	13.35	82.81	34.32
1.80	2920.00	4900.00	2571.56	559.37	384.77	272.39	74.59	158.56	3.96	93.37	30.04
1.90	3160.00	5430.00	2768.85	568.59	438.83	289.94	93.82	168.77	8.71	104.06	23.16
2.00	3390.00	5770.00	2942.23	583.68	471.71	301.08	115.79	179.34	18.25	111.86	17.83

STOP 0
EXECUTION TERMINATED

$SIG

DIODE TYPE 5082-2833=C4

THE HARMONICS ARE IN DBS RELATIVE TO THE FUNDS.

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)
0.30	5.60	11.10	0.15	3.60	6.65	10.25	16.05	22.15	29.40	39.15	99.99
0.40	54.00	105.50	2.15	4.60	8.45	14.95	25.25	45.95	31.80	33.15	38.90
0.50	173.00	370.00	2.55	6.30	12.65	26.85	28.65	26.55	32.30	60.85	38.00
0.60	336.00	582.00	2.45	7.80	17.55	31.60	24.05	28.95	50.90	34.05	37.00
0.70	536.00	910.00	3.60	9.05	23.70	25.00	24.90	36.70	34.65	34.10	49.05
0.80	714.00	1245.00	4.05	10.50	31.65	22.45	26.75	49.35	31.40	37.35	45.90
0.90	880.00	1485.00	3.85	11.50	48.25	22.05	28.25	38.35	31.20	41.45	39.60
1.00	1090.00	1830.00	3.85	12.50	33.75	21.85	31.15	32.85	31.80	59.25	36.40
1.10	1275.00	2170.00	4.00	13.55	28.80	22.40	34.30	31.30	33.05	46.20	36.05
1.20	1605.00	2510.00	4.55	14.60	26.45	22.65	39.05	30.55	34.50	41.35	36.30
1.30	1700.00	2960.00	4.95	15.70	25.55	23.35	46.05	30.35	36.40	38.65	37.30
1.40	1935.00	3390.00	5.35	16.40	24.65	24.05	61.75	29.75	38.80	37.55	38.40
1.50	2130.00	3740.00	5.65	17.10	23.90	24.15	46.85	29.55	40.90	36.55	39.10
1.60	2350.00	4000.00	5.55	17.60	23.05	24.35	41.65	29.35	44.20	35.55	40.30
1.70	2720.00	4270.00	5.75	18.10	22.35	24.55	38.85	29.55	48.30	34.95	41.70
1.80	2800.00	4670.00	5.85	18.80	22.05	25.05	36.95	29.65	57.80	34.65	43.50
1.90	2980.00	4870.00	5.70	19.00	21.80	25.10	35.80	29.70	68.95	34.10	45.10
2.00	3240.00	5340.00	5.85	19.50	21.65	25.45	34.45	30.15	52.20	34.05	48.40

CIODE TYPE 5082-2833=C4

VOLT	I(0)	I(1)	I(2)	I(3)	I(4)	I(5)	I(6)	I(7)	I(8)	I(9)	I(10)	$I=\sum_{0}^{10} i_n$ µA	I·
0.30	5.60	11.10	10.90	7.33	5.16	3.41	1.75	0.87	0.38	0.12	0.00	46.62	
0.40	54.00	105.50	82.37	62.12	39.88	18.87	5.76	-0.53	-2.71	-2.32	-1.20	361.74	3
0.50	173.00	370.00	275.87	179.14	86.24	16.82	-13.67	-17.41	-8.98	-0.34	4.66	1065.33	9
0.60	336.00	582.00	438.96	237.10	77.17	-15.31	-36.51	-20.77	-1.66	11.55	8.22	1616.75	16
0.70	506.00	910.00	601.23	321.03	59.43	-51.17	-51.77	-13.31	16.85	17.95	3.21	2319.45	23
0.80	714.00	1245.00	781.03	371.68	32.56	-93.90	-57.24	-4.24	33.51	16.89	-6.31	3032.98	30
0.90	880.00	1485.00	953.29	395.12	5.74	-117.28	-57.44	17.96	40.90	12.57	-15.55	3600.31	33
1.00	1090.00	1830.00	1174.77	433.96	-37.58	-147.89	-50.69	41.68	47.04	2.00	-27.70	4355.59	47
1.10	1275.00	2170.00	1369.18	455.99	-78.79	-164.61	-41.83	59.08	48.30	-10.63	-34.19	5047.5	52
1.20	1605.00	2510.00	1486.53	467.38	-119.45	-185.00	-28.00	74.50	47.28	-21.49	-38.43	5798.32	60
1.30	1700.00	2960.00	1674.14	485.61	-156.24	-201.28	-14.75	89.91	44.80	-34.58	-40.39	6507.22	67
1.40	1935.00	3390.00	1831.05	513.10	-198.47	-212.67	-2.77	110.33	38.92	-44.95	-40.76	7318.78	75
1.50	2130.00	3740.00	1951.51	522.24	-238.71	-231.94	17.00	124.56	33.72	-55.64	-41.48	7951.26	[illegible]
1.60	2350.00	4000.00	2111.35	527.30	-281.55	-242.42	33.08	136.32	24.66	-66.77	-38.64	8553.33	90
1.70	2720.00	4270.00	2202.56	531.41	-325.78	-252.89	48.74	142.21	16.42	-76.37	-35.11	9241.13	99
1.80	2800.00	4670.00	2381.32	536.19	-368.82	-261.11	66.35	153.75	6.02	-86.46	-31.21	9856.03	106
1.90	2980.00	4870.00	2526.56	546.42	-395.85	-270.73	78.98	159.42	-1.74	-96.06	-27.07	10369.93	114
2.00	3240.00	5340.00	2722.96	565.64	-441.61	-285.13	101.17	165.97	-13.11	-105.94	-2[illegible].30	11269.65	1.22

STOP 0
EXECUTION TERMINATED

$SIG

APPENDIX A4

CALCULATED DATA FOR FIGURES 6.21 - 6.23

DIODES A4, B3, C2.

Diode Type 5082 - 2800 = A4

Static and Dynamic Characteristics

V_p volts	$I_p - I_s\left[e^{\alpha(V_p - RI_p)} - 1\right]$ µa	$I_p \approx \sum_{o}^{10} \hat{i}_n$ µa
0.3	103.47	102.1
0.4	473.14	504.29
0.5	991.68	950.73
0.6	1555.26	1583.92
0.7	2163.32	2027.21
0.8	2750.13	2869.49
0.9	3392.77	3336.54
1.0	4021.47	3990.6
1.1	4625.79	4368.24
1.2	5267.98	4862.57
1.3	5880.54	5665.69
1.4	6564.32	6274.95
1.5	7182.51	6952.59
1.6	7858.91	7658.64
1.7	8428.75	8102.72
1.8	9130.76	8695.50
1.9	9792.81	9219.32
2.0	10398.4	9853.9

$\alpha = 34.2\ V^{-1}$

$R_s = V_s + 50 + 75 = 152\ \Omega$

$I_s = 6.25 \times 10^{-9}$ Amp.

$r_s = 27\ \Omega$

Diode Type 5082 - 2811 = B3

Static and Dynamic Characteristics

V_p volts	$I_p = I_s\left[e^{\alpha(V_p - RI_p)} - 1\right]$ μa	$I_p \simeq \sum_{o}^{10} \hat{I}_n$ μa
0.3	30.91	34.44
0.4	311.43	328.94
0.5	855.06	856.53
0.6	1496.93	1578.95
0.7	2188.94	2178.24
0.8	2896.26	2982.90
0.9	3608.96	3567.13
1.0	4320.71	4422.09
1.1	5070.40	5053.95
1.2	5774.31	5710.65
1.3	6510.52	5867.66
1.4	7267.55	7311.26
1.5	7951.97	8011.79
1.6	8700.84	8668.64
1.7	9520.23	9381.54
1.8	10210.5	9885.96
1.9	10950.9	10677.17
2.0	11744.9	11320.51

$\alpha = 36.4\ V^{-1}$

$R_s = V_s + 50 + 75 = 131.6\ \Omega$

$I_s = 6.5 \times 10^{-10}$ Amp.

$r_s = 6.6\ \Omega$

Diode Type 5082 - 2833 = C2

Static and Dynamic Characteristics

V_p volts	$I_p = I_s \left[e^{\alpha(V_p - RI_p)} - 1\right]$ µà	$I_p \approx \sum_{o}^{10} \hat{i}_n$ µa
0.3	39.6	46.61
0.4	354.1	391
0.5	934.1	1012.39
0.6	1618.96	1457.15
0.7	2320.5	2422.6
0.8	3070.32	3047.09
0.9	3787.79	3985.08
1.0	4534.81	4570.53
1.1	5321.65	5398.38
1.2	6060.44	6172.70
1.3	6833.13	6941.3
1.4	7627.67	7650.07
1.5	8346.00	8272.12
1.6	9131.98	8985.95
1.7	9892.56	9773.05
1.8	10716.5	10378.91
1.9	11493.5	11150.82
2.0	12204.2	11945.01

$\alpha = 36.5\ V^{-1}$

$R_s = V_s + 50 + 75 = 126.3\ \Omega$

$I_s = 8.375 \times 10^{-10}$ Amp.

$r_s = 1.3\ \Omega$

APPENDIX A5

COMPARISON BETWEEN CALCULATED AND MEASURED DC CHARACTERISTICS FOR DIODES A4, B3 AND C2.

Table 6.1: Diode Type 5082 - 2800 = A4

DC Characteristics

$V_{(d+50)}$ volt	V_{50} mV	I_f μA	$\alpha V_{(d+50)}$	$\exp[\alpha V_{(d+50)}]$	$I_f/\exp \alpha V_{(d+50)}$ Amp
0.20	0.2275	4.55	6.84	8.98×10^{2}	5.08×10^{-9}
0.22	0.49	9.8	7.5	1.808×10^{3}	5.42×10^{-9}
0.24	1.025	20.6	8.2	3.64×10^{3}	5.68×10^{-9}
0.26	2.05	41.0	8.9	7.331×10^{3}	5.6×10^{-9}
0.28	3.89	77.7	9.6	1.476×10^{4}	5.28×10^{-9}
0.30	6.9	138	10.2	2.73×10^{4}	5.06×10^{-9}
0.32	11.3	226	10.9	5.42×10^{4}	4.18×10^{-9}
0.34	16.75	335	11.6	1.08×10^{5}	3.10×10^{-9}
0.26	23.85	476	12.3	2.21×10^{5}	2.16×10^{-9}
0.38	31.65	635	13.0	4.42×10^{5}	1.44×10^{-9}
0.40	40.1	804	13.7	8.9×10^{5}	9.05×10^{-10}
0.42	49.1	983	14.4	1.79 xx 10^{6}	5.5×10^{-10}
0.44	58.65	1170	15.0	3.269×10^{6}	3.58×10^{-10}
0.46	68.8	1375	15.7	6.58×10^{6}	2.10×10^{-10}
0.48	78.65	1575	16.4	1.33×10^{7}	1.18×10^{-10}
0.50	88.75	1775	17.1	2.66×10^{7}	6.65×10^{-11}
0.60	142.5	2850			
0.70	198.0	3960			
0.80	256.5	5130			
0.90	316.0	6320			
1.0	374.5	7490			

Therefore

$\alpha = 34.2 \ V^{-1}$

Therefore

$r_s = 27.0 \ \Omega$ and $I_s = 6.25 \times 10^{-9}$ Amp.

Table 6.2: Diode Type 5082 - 2800 = A4

Experimental		Calculated	%
V_f volts	I_f μA	V_f	Error
0.20	4.55	0.193	- 3.578
0.22	9.8	0.216	- 1.895
0.24	20.6	0.238	- 0.649
0.26	41.0	0.260	+ 0.055
0.28	77.7	0.282	+ 0.589
0.30	138	0.303	+ 1.022
0.32	226	0.324	+ 1.325
0.34	335	0.344	+ 1.220
0.36	476	0.365	+ 1.458
0.38	635	0.386	+ 1.554
0.40	804	0.406	+ 1.456
0.42	983	0.426	+ 1.309
0.44	1170	0.445	+ 1.137
0.46	1375	0.466	+ 1.196
0.48	1575	0.485	+ 1.018
0.50	1775	0.504	+ 0.761
0.60	2850	0.600	+ 0.076
0.70	3960	0.696	- 0.641
0.80	5130	0.793	- 0.857
0.90	6320	0.891	- 1.018
1.0	7490	0.986	- 1.421

$\alpha = 34.2\ V^{-1}$

$R_s = V_s + 50 = 77\ \Omega$

$I_s = 6.25 \times 10^{-9}$ Amp

$r_s = 27\ \Omega$

Table 6.3: Diode Type 5082 - 2811 = B3

DC Characteristics

$V_{(d+50)}$ volt	V_{50} mV	I_f μA	$\alpha V_{(d+50)}$	$\exp[\alpha V_{(d+50)}]$	$I_f/\exp[\alpha V_{(d+50)}]$
0.20	0.0415	0.83	7.25	1.4×10^{3}	5.95×10^{-10}
0.22	0.0855	1.75	8.00	2.98×10^{3}	5.90×10^{-10}
0.24	0.182	3.64	8.75	6.3×10^{3}	5.78×10^{-10}
0.26	0.379	7.6	9.45	1.24×10^{4}	6.1×10^{-10}
0.28	0.8055	16.1	10.2	2.68×10^{4}	6.1×10^{-10}
0.30	1.62	32.4	10.9	5.4×10^{4}	6.0×10^{-10}
0.32	3.24	64.9	11.6	1.08×10^{5}	6.0×10^{-10}
0.34	6.16	123	12.4	2.43×10^{5}	5.06×10^{-10}
0.36	10.65	213	13.1	4.85×10^{5}	4.4×10^{-10}
0.38	17.0	340	13.8	9.8×10^{5}	3.46×10^{-10}
0.40	25.15	502	14.5	1.98×10^{6}	2.54×10^{-10}
0.42	35.2	705	15.25	4.23×10^{6}	1.67×10^{-10}
0.44	46.0	920	16.0	8.89×10^{6}	1.04×10^{-10}
0.46	58.05	1160	16.7	1.8×10^{7}	6.45×10^{-11}
0.48	70.75	1410	17.4	3.6×10^{7}	3.93×10^{-11}
0.50	83.75	1670	18.15	7.6×10^{7}	2.2×10^{-11}
0.60	156.0	3120			
0.70	234.0	4680			
0.80	314.5	6290			
0.90	398	7960			
1.0	480	9600			

Therefore

$\alpha = 36.4 \ V^{-1}$

Therefore

$r_s = 6.6 \ \Omega$ and $I_s = 6.5 \times 10^{-10}$ Amp.

Table 6.4: Diode Type 5082 - 2811 = B3

Experimental		Calculated	%
V_f volts	I_f μA	V_f volts	Error
0.20	0.83	0.197	- 1.751
0.22	1.75	0.217	- 1.339
0.24	3.64	0.237	- 1.132
0.26	7.6	0.258	- 0.869
0.28	16.1	0.279	- 0.471
0.30	32.4	0.299	- 0.335
0.32	64.9	0.320	- 0.024
0.34	123	0.341	+ 0.227
0.36	213	0.361	+ 0.264
0.38	340	0.381	+ 0.260
0.40	502	0.401	+ 0.216
0.42	705	0.422	+ 0.399
0.44	920	0.441	+ 0.264
0.46	1160	0.461	+ 0.242
0.48	1410	0.481	+ 0.131
0.50	1670	0.499	- 0.011
0.60	3120	0.599	- 0.128
0.70	4680	0.699	- 0.190
0.80	6290	0.798	- 0.261
0.90	7960	0.899	- 0.121
1.0	9600	0.997	- 0.313

$\alpha = 36.4\ V^{-1}$

$R_s = V_s + 50 = 56.5\ \Omega$

$I_s = 6.5 \times 10^{-10}$ Amp.

$r_s = 6.6\ \Omega$

Table 6.5: Diode Type 5082 - 2833 = C2

DC Characteristics

$V_{(d+50)}$ volt	V_{50} mV	I_f μA	$V_{(d+50)}$	$\exp[\alpha V_{(d+50)}]$	$I_f/\exp \alpha V_{(d+50)}$ Amp
0.20	0.0575	1.15	7.3	1.48×10^3	7.78×10^{-10}
0.22	0.1165	2.33	8.03	3.07×10^3	7.60×10^{-10}
0.24	0.2475	4.95	8.76	6.35×10^3	7.8×10^{-10}
0.26	0.5315	10.6	9.49	1.32×10^4	8.05×10^{-10}
0.28	1.105	22.2	10.22	2.74×10^4	8.15×10^{-10}
0.30	2.25	45.0	10.35	5.70×10^4	7.88×10^{-10}
0.32	4.475	89.5	11.68	1.17×10^5	7.6×10^{-10}
0.34	8.13	163	12.41	2.46×10^5	6.61×10^{-10}
0.36	13.775	276	13.14	5.07×10^5	5.43×10^{-10}
0.38	21.7	435	13.87	1.06×10^6	4.10×10^{-10}
0.40	31.35	627	14.6	2.18×10^6	2.84×10^{-10}
0.42	42.7	834	15.33	4.54×10^6	1.84×10^{-10}
0.44	55.45	1110	16.06	9.40×10^6	1.18×10^{-10}
0.46	68.65	1375	16.79	1.95×10^7	7.05×10^{-11}
0.48	82.3	1650	17.52	4.05×10^7	4.07×10^{-11}
0.50	96.8	1940	18.25	8.40×10^7	2.31×10^{-11}
0.60	177	3540			
0.70	261	5220			
0.80	349	6980			
0.90	435.5	8710			
1.0	523.5	10470			

Therefore

$\alpha = 36.5 \ V^{-1}$

Therefore

$r_s = 1.3 \ \Omega$ and $I_s = 8.375 \times 10^{-10}$ Amp.

Table 6.6: Diode Type 5082 - 2833 = C2

Experimental		Calculated	%
V_f volts	I_f μA	V_f volts	error
0.20	1.15	0.198	- 0.999
0.22	2.33	0.217	- 1.188
0.24	4.95	0.238	- 0.759
0.26	10.60	0.259	- 0.254
0.28	22.20	0.280	+ 0.067
0.30	45.00	0.301	+ 0.238
0.32	89.50	0.322	+ 0.570
0.34	163.00	0.342	+ 0.594
0.36	276	0.362	+ 0.623
0.38	435	0.383	+ 0.752
0.40	627	0.403	+ 0.681
0.42	834	0.421	+ 0.280
0.44	1110	0.443	+ 0.715
0.46	1375	0.463	+ 0.569
0.48	1650	0.482	+ 0.360
0.50	1940	0.501	+ 0.209
0.60	3540	0.5996	- 0.066
0.70	5220	0.696	- 0.513
0.80	6980	0.795	- 0.670
0.90	8710	0.889	- 1.181
1.0	10470	0.985	- 1.541

% error = $\frac{V_{cd} - V_{EX}}{V_{cd}} \times 100$

$\alpha = 36.5\ V^{-1}$

$R_s = V_s + 50 = 51.3\ \Omega$

$I_s = 8.375 \times 10^{-10}$ Amp

$r_s = 1.3\ \Omega$