THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF COLLECTIVE MICROWAVE PHENOMENA IN SOLIDS

under the direction of
M. Chodorow

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ABSTRACT

I. MICROWAVE AMPLIFICATION IN HIGH RESISTIVITY GaAs

The work on two-port unilateral amplifiers in the frequency range from 500 to 2000 MHz using GaAs samples with nl products in the 10^{11} cm^{-2} region has been continued.

RF probe measurements of the rf potential both in the longitudinal and transverse directions when a space charge wave is excited through an ohmic strip contact placed near the cathode indicate that:

(1) the growth of the rf signal toward the anode is accompanied by a strong modulation, the origin of which is yet to be ascertained;

(2) the wave penetrates transversely to some appreciable extent into the semiconductor.

A new amplifier configuration in which the rf signal is injected and extracted through the cathode and anode contacts respectively has been tried and appears to be more practical than the previous configuration.

II. GUNN OSCILLATOR NOISE STUDIES

Theoretical equations governing the Gunn effect have been used to investigate behavior of gallium arsenide oscillators. The experimentally observed effect of asymmetry in bulk devices may be explained by use of results from the computer program developed. Circuitry has been added to the mathematical model and as a result of computational work done a more complete picture of the modes of operation of such devices is beginning to emerge.

A low temperature system for growing GaAs from the liquid solution in gallium has been assembled and samples are now being made. The system will be made of ultra pure components and is to be used to grow high

resistivity trap free material for use in GaAs oscillators. Growths obtained so far have a resistivity less than 3 Ω cm.

Contact behavior and fabrication of good contacts to GaAs has been the subject of much investigation. The outcome of this work is as yet not very definite except to affirm that n^+ regrowth contacts seem the best from both fabrication and noise points of view.

INTRODUCTION

The work under this Grant is generally concerned with communication and information processing in space satellites and more particularly concerned with exploring new devices, particularly solid-state and optical devices, suitable for generation and modulation of electromagnetic waves in the microwave range and upward through the millimeter and optical frequency ranges. Two projects were active under this Grant during the reporting period:

I. Microwave Amplification in High Resistivity GaAs
II. Gunn Oscillator Noise Studies

The Responsible Investigator for this Grant is M. Chodorow.

PRESENT STATUS

I. MICROWAVE AMPLIFICATION IN HIGH RESISTIVITY GaAs

(G. S. Kino, J. Ruch, and B. Fay)

INTRODUCTION

The objective of this investigation is to determine the conditions of feasibility of a unilateral two-port microwave amplifier, exploiting the negative conductance property of GaAs biased beyond a threshold field of approximately 3000 volts per cm.

The preliminary work has consisted mainly of verifying the static behavior of high resistivity GaAs diodes above threshold by means of current-voltage characteristic curves and direct potential probing with a traveling capacitive probe.

PRESENT STATUS

A critical parameter for all GaAs devices is the doping × density product or nl product which is a measure of the rate of growth with distance of space charge disturbances. The transition between stable and an unstable (Gunn oscillation) mode of operation of GaAs devices occurs around the value $nl = 10^{12}\ \text{cm}^{-2}$.

For our purpose the desirable range of nl product values lies between 1 and $5 \times 10^{11}\ \text{cm}^{-2}$ for which the theoretical gain can be as high as 90 dB for a 1 mm long diode with a resistivity of 200 ohm-cm.

RF Probe Measurements

In the amplifier experiments previously reported, the coupling to and from the space charge wave was achieved by means of a pair of ohmic strip contacts deposited on one face of the diode as shown in Fig. 1. Using the same excitation scheme, we have investigated the longitudinal

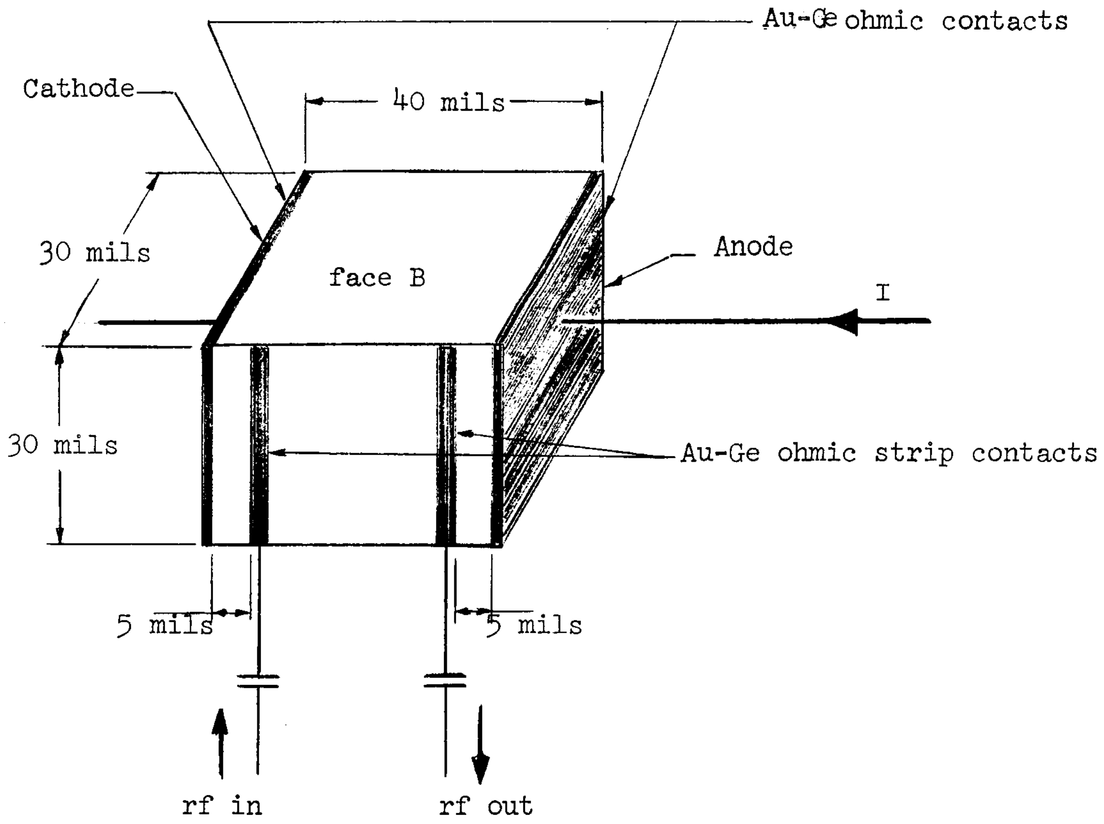

FIG. 1--Typical GaAs sample with ohmic strip contacts.

and transverse variation of the rf signal by means of an rf probe that could be positioned at various places over a face adjacent to the one carrying the strip contacts (face B in Fig. 1).

Two types of rf probes were employed. One consisted of a shielded 5 mil diameter tungsten wire capacitatively coupled to the GaAs surface through a 1 mil thick Mylar sheet. The other was a point-contact type probe and consisted of a shielded 15 mil diameter wire with its extremity etched down to a 0.5 mil point (12 microns). Figure 2 illustrates a typical rf potential profile for various bias currents observed with the capacitative probe at a frequency of 780 MHz on a 35 mil long diode ($nl = 9 \times 10^{11}$ cm^{-2}). In this case the transverse position of the probe was fixed and slightly inside the edge of the excited surface. Figure 3 shows the transverse variation of the rf potential at a fixed longitudinal position near the anode, measured with the point contact probe.

The modulation effect is stronger than what we would expect from a simple beating phenomenon between the slow space charge wave and the fast ohmic wave associated with the total current through the device. It may be that more than one space charge wave is excited and we are presently working on a two-dimensional analysis of the excitation process which should be more appropriate than the one-dimensional approach considered thus far.

Two-Port Amplifier

We have recently adopted the amplifier configuration depicted in Fig. 4. It has the advantages of greater output power capability, easier tuning, and also the fact that the gap spacings can be mechanically adjusted.

Some preliminary measurements on a 40 mil long diode ($nl = 2 \times 10^{11}$ cm^{-2}) have enabled us to observe a net terminal gain of up to 6 dB over narrow frequency bands spaced roughly 150 MHz apart from 500 to 1700 MHz. Maximum gain was observed at 1250 MHz where the saturation power level was - 10 dBm. (The drift field was pulsed with a 600 nsec pulse duration at a 100 pps repitition rate.) Detailed measurements will be reported later.

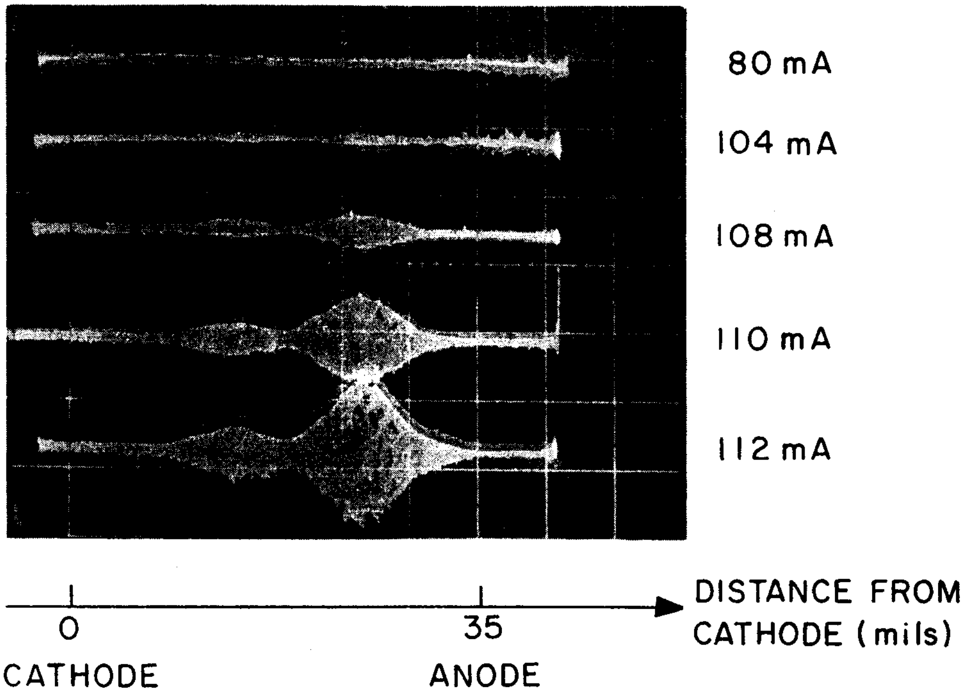

FIG. 2--Profile of rf potential for various bias current values (f = 780 MHz) (vertical sensitivity: 50 mV/cm).

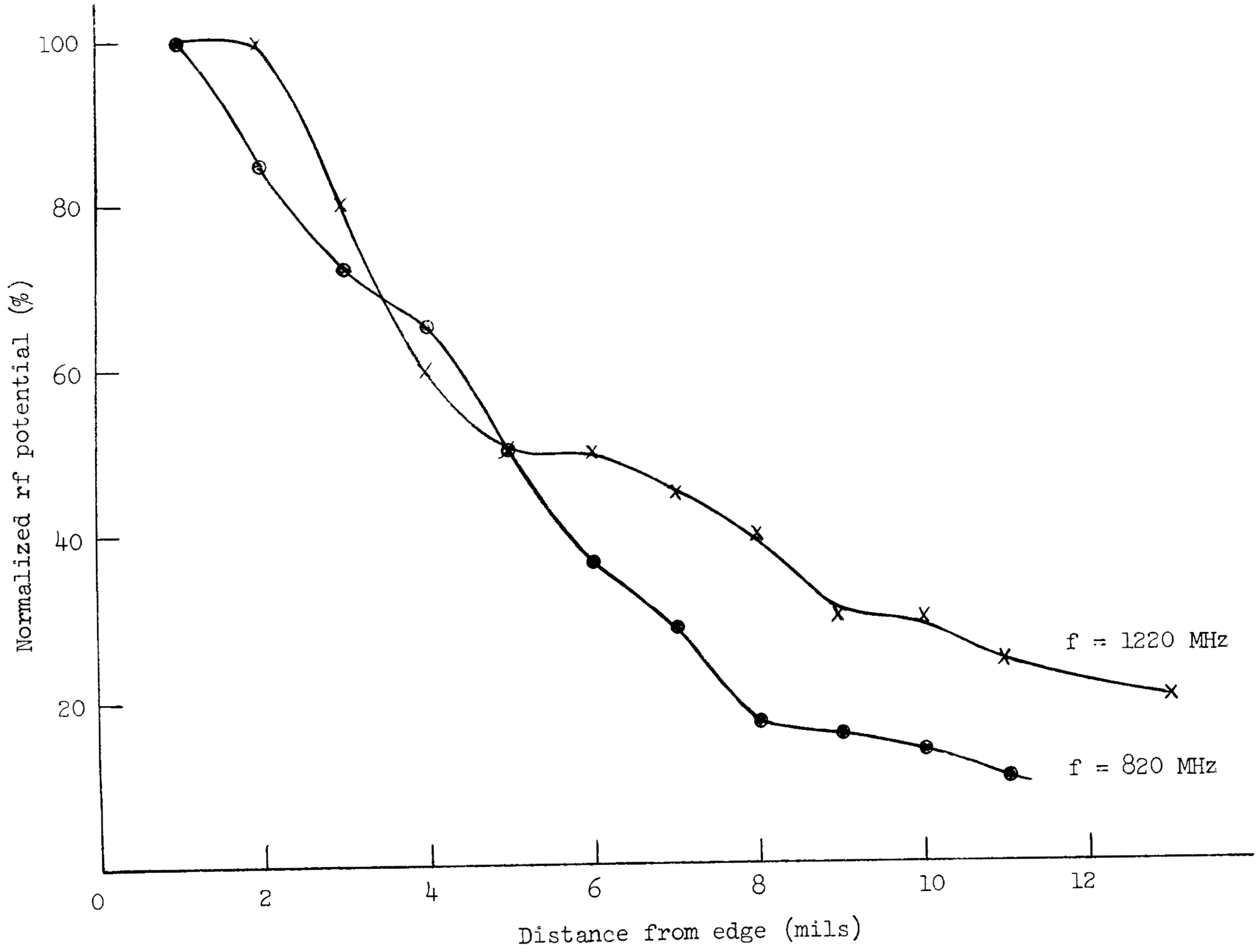

FIG. 3--Transverse variation of rf potential - 14 mils from the anode.

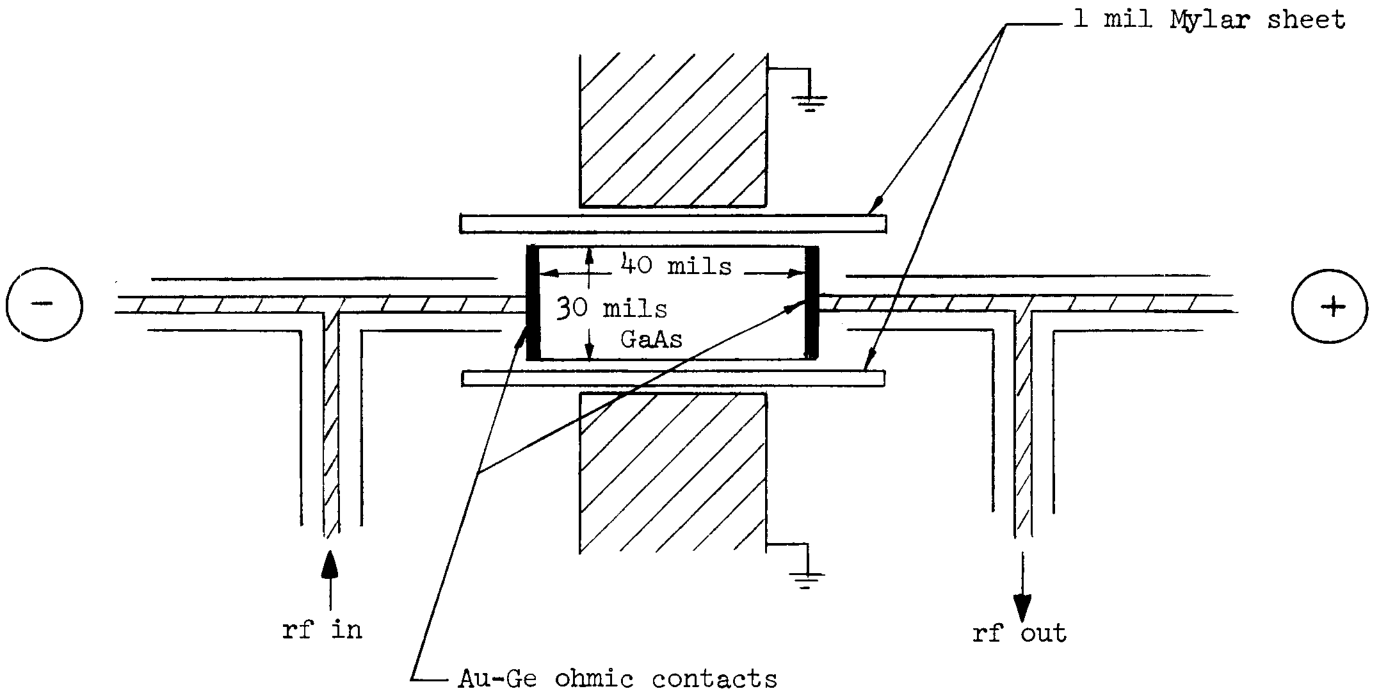

FIG. 4--New amplifier configuration.

We are still faced with the problem of obtaining samples with the right nl product (1 to 5 × 10^{11} cm^{-2}) as the commercially available material in the 500 Ω-cm resistivity range proves to be very inhomogeneous.

It appears that the new amplifier configuration is superior to the previous one and we will continue our efforts in this direction. The new mode of excitation seems well suited for epitaxial material and cw operation and we plan to try this in the near future.

II. GUNN OSCILLATOR STUDIES AND GROWTH OF EPITAXIAL GaAs

(C. F. Quate, J. A. Higgins)

INTRODUCTION

This work has two parts: (a) an investigation, using a digital computer, of the behavior of and the modes of operation of bulk oscillators; and (b) the growth of epitaxial GaAs of maximum purity and the fabrication of bulk oscillators, using n^+ contacts, from this material.

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Computer Simulations of Bulk Effect

An investigation of bulk effect phenomena has been initiated and some results achieved. The basic program on the bulk effect is based on the concept of taking numerical solutions for sufficiently small one dimensional segments of the equations which determine the bulk effect. These are the relationships of electron velocity to field, the total current equation, and Poisson equation. This approach is not new, having been successfully used by Harker[1] and Thim[2] under different conditions. Simplification by the assumption of convenient physical characteristics has been kept to a minimum for as close a simulation to the real thing as possible. To this end the relationship between velocity and field is taken from the experimental results Ruch and Kino[3] and

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[1] K. J. Harker, "Gunn Effect Theory," Microwave Laboratory Report No. 1588, Stanford University (October 1967).

[2] H. Thim, "Computer Study of Bulk GaAs Devices with Random One Dimensional Doping Fluctuations," to be published in J. Appl. Phys.

[3] J. Ruch and G. S. Kino, to be published.

from these are derived values of the mean mobility, mean electron temperature and mean electron diffusion coefficients for GaAs. The diffusion coefficients and velocity are shown in Fig. 5 as functions of the field. The low field value of mobility is 7000 $\mathrm{cm}^2/\mathrm{sec}$ in these calculations.

The computer work performed and to be performed has three main divisions: (1) The investigation of some aspects of the bulk effect device when not accompanied by any other circuitry. These aspects are the nucleation of dipole layers, the effects of doping gradients and variations, the effects of temperature profiles which may not be uniform, contacts and the effects of changing the velocity field characteristic. (2) The investigation of the starting behavior of bulk effect devices in series with a parallel tuned circuit as in Fig. 6. The effort here was to obtain theoretical derivation of some of the phenomena seen in the practical world. (3) The ultimate aim of the computer work is to produce a well founded study and chart of the modes of operation in cw and efficiencies of operation over a large range of circuit Q values, device bias values, frequencies, and doping profiles.

a. Bulk Effect Devices

A large amount of this initial work was done on two samples one 15 μM long, hereafter referred to as the "long" sample, and 7.5 μM, the "short." Both had doping profiles of some $7 \times 10^{14}/\mathrm{cm}^3$, making them have $\mu_0 \ell$ products of $\approx 1 \times 10^{12}$ and 0.5×10^{12}, respectively. Mobilities of 9000 $\mathrm{cm}^2/\mathrm{sec}$ V or 7000 $\mathrm{cm}^2/\mathrm{sec}$ V were accorded to the devices and the contact doping was given as 10 times the background doping n_0.

1. The difference between the long and the short is the readiness with which the dipole pattern may build up in the device when the device is biased above threshold. The shorter devices proved altogether harder to induce dipole modes into, preferring to show accumulation modes.

2. The short devices would show dipole modes if a resistive notch (i.e., a section of low carrier concentration were placed near the cathode) (end nearer 0) and if this notch were of sufficient width. If the notch were placed at the anode end then only accumulation modes would result. These would of course lead to break down as high fields would be at the anode at all times, causing a severe heat problem (see Fig. 7).

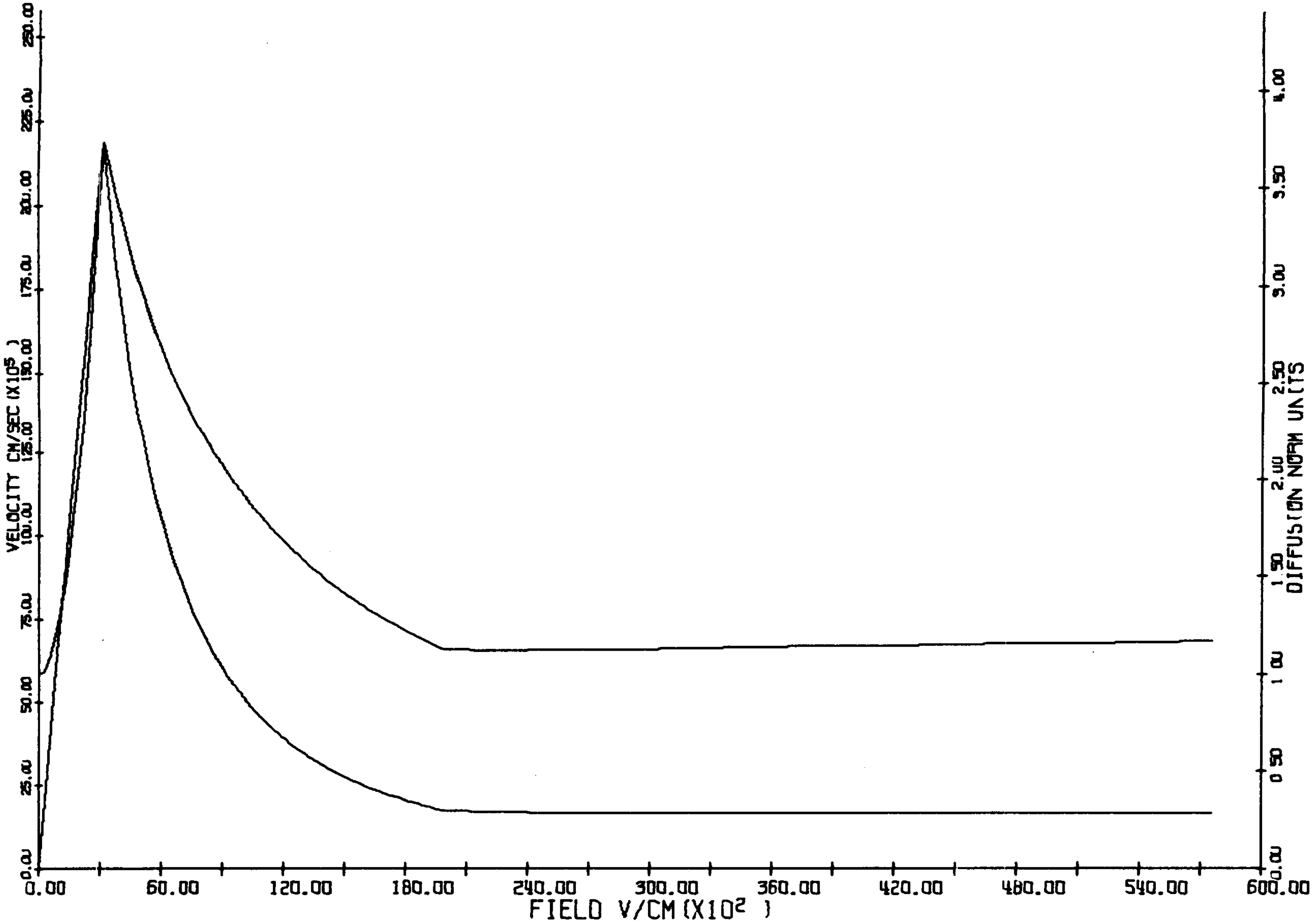

FIGURE 5

FIG. 5--Values of velocity and diffusion coefficient plotted against E field. Normal diffusion coefficient = 200 cm^2/sec.

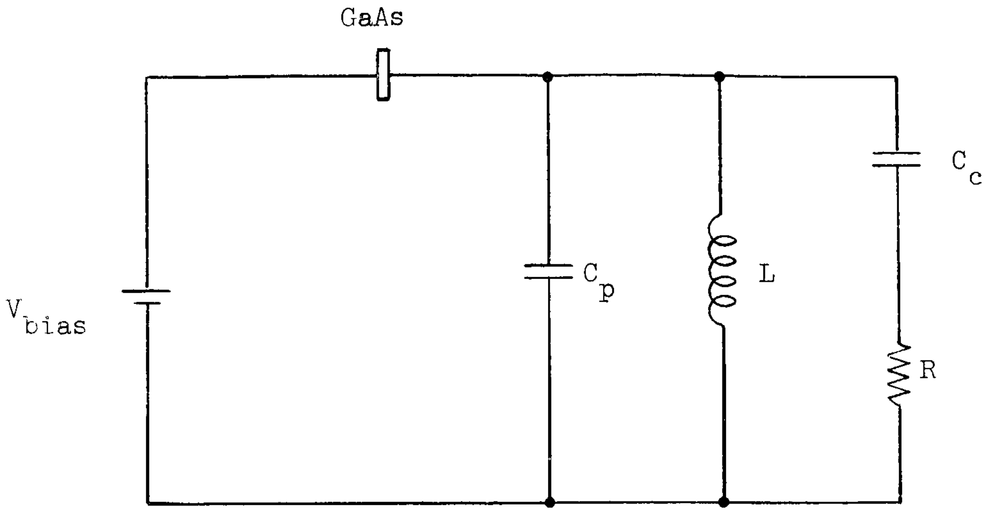

FIG. 6--Circuit configuration.

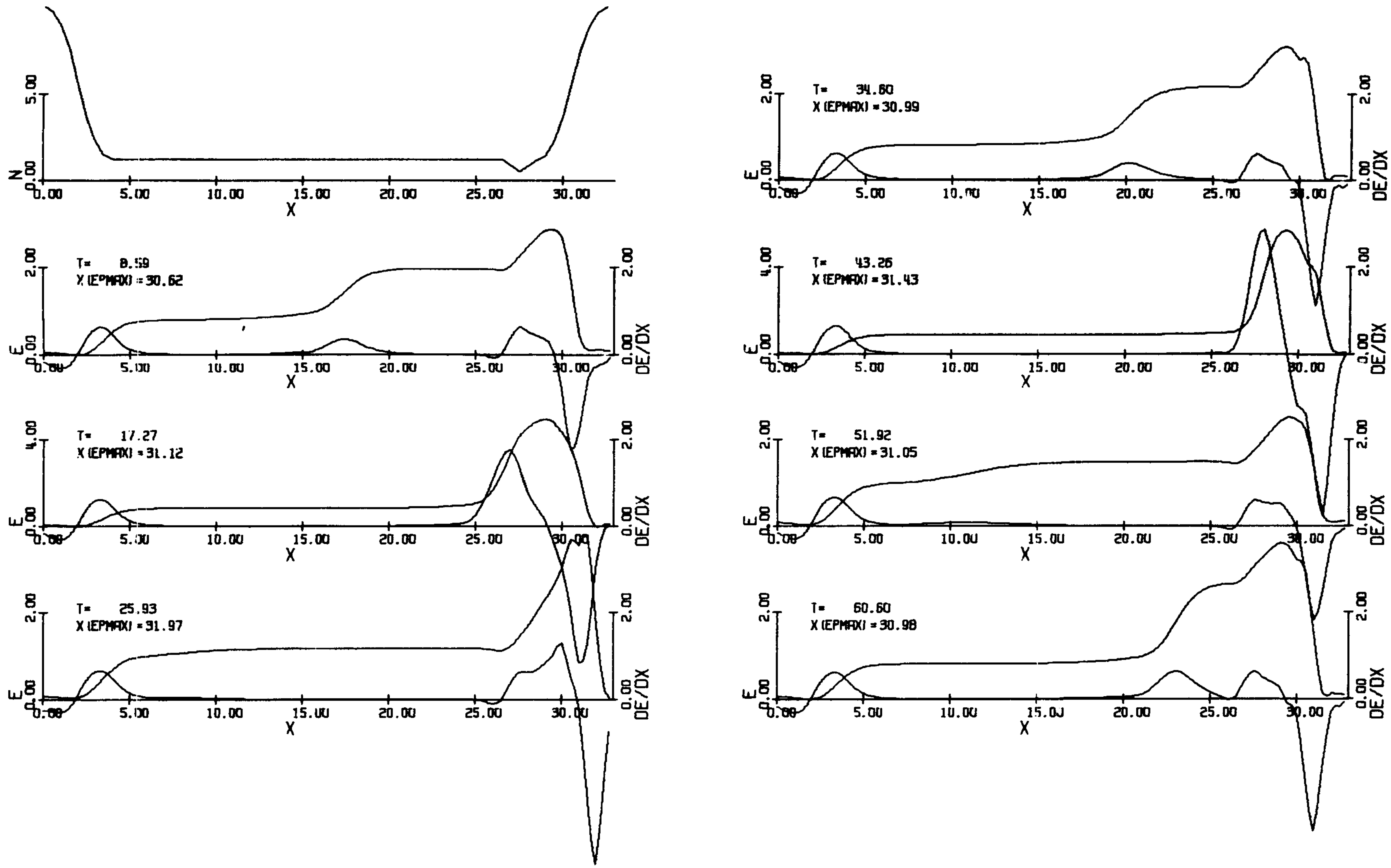

FIG. 7--Effect of a resistive notch at the anode end short sample.

3. In the long diodes the position of the resistive notch will have the same results. A difference is noticeable in the clarity with which the dipole forms in this case. The rate of growth conforms to a negative differential mobility of one sixth the low field mobility, which is the correct value.

4. While Fig. 7 shows the results of placing the notch in the anode of a short device, Fig. 8 shows the results of placing the notch in the cathode of a long device and Fig. 9 shows the current resulting. If one takes a bulk device and makes it perfectly symmetrical but with random variations (smooth) of doping (± 5%) within the body, the results are that neucleation takes place at the point(s) where slope of the conductivity is such as to induce fields similar to a dipole domain, i.e., with conductivity increasing toward the anode. Figure 10 shows this on a short sample where the slope is quite steep and takes up the whole length of the device. Slope of conductivity the other way will induce accumulation modes and avalanching at the anode.

5. The effects of a temperature change are taken to be (a) that density of carriers is unaffected but (b) the mobility is inversely proportional to the absolute temperature or some power thereof. In Fig. 11 the cathode has been made 20% hotter than the anode (in terms of absolute temperature). Here normal dipoles forming up quickly, propagate across the entire length. But if as in Fig. 12 the anode is made hotter, then this apparently symmetrical diode, which has randomized fluctuation in doping level, goes into the accumulation mode with its attendant probability of avalanche at the anode.

6. The speed of propagation of the dipole based on the long sample with sharp boundary contacts appears to be 1.4×10^7 cm/sec. For the long sample with mature domain the depletion layer is about 3 μM long and the accumulation layer about 1 μ long.

7. Figure 13 shows how drastically the E field, velocity, current, and accumulation layers fall off if the velocity field curve changes from Ruch-Kino to some other curve. The "other" curve used in this case is one

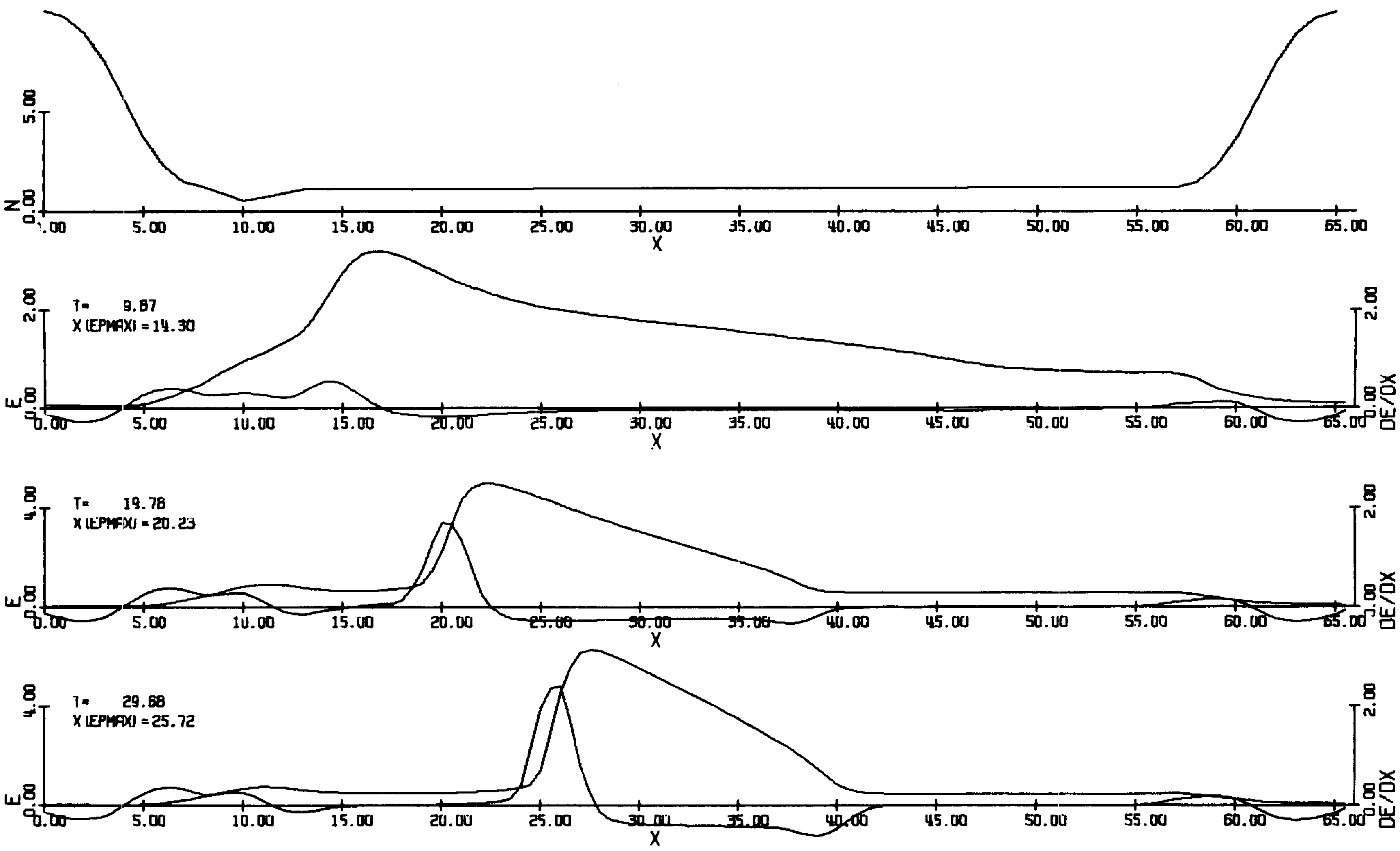

FIG. 8--Long sample with a resistive notch at the cathode.

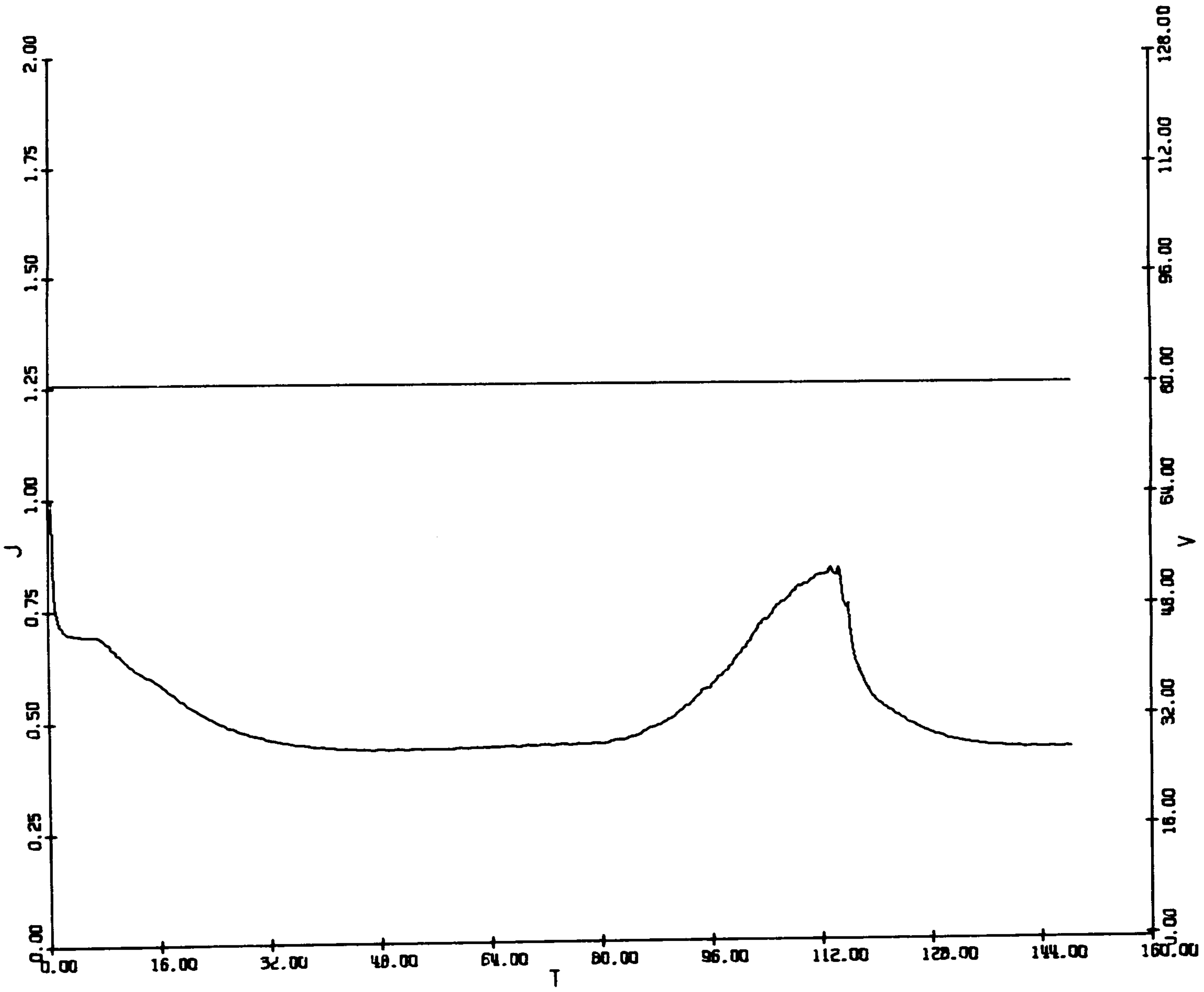

FIG. 9--Current in a long sample as of Fig. 4 with a mature dipole.

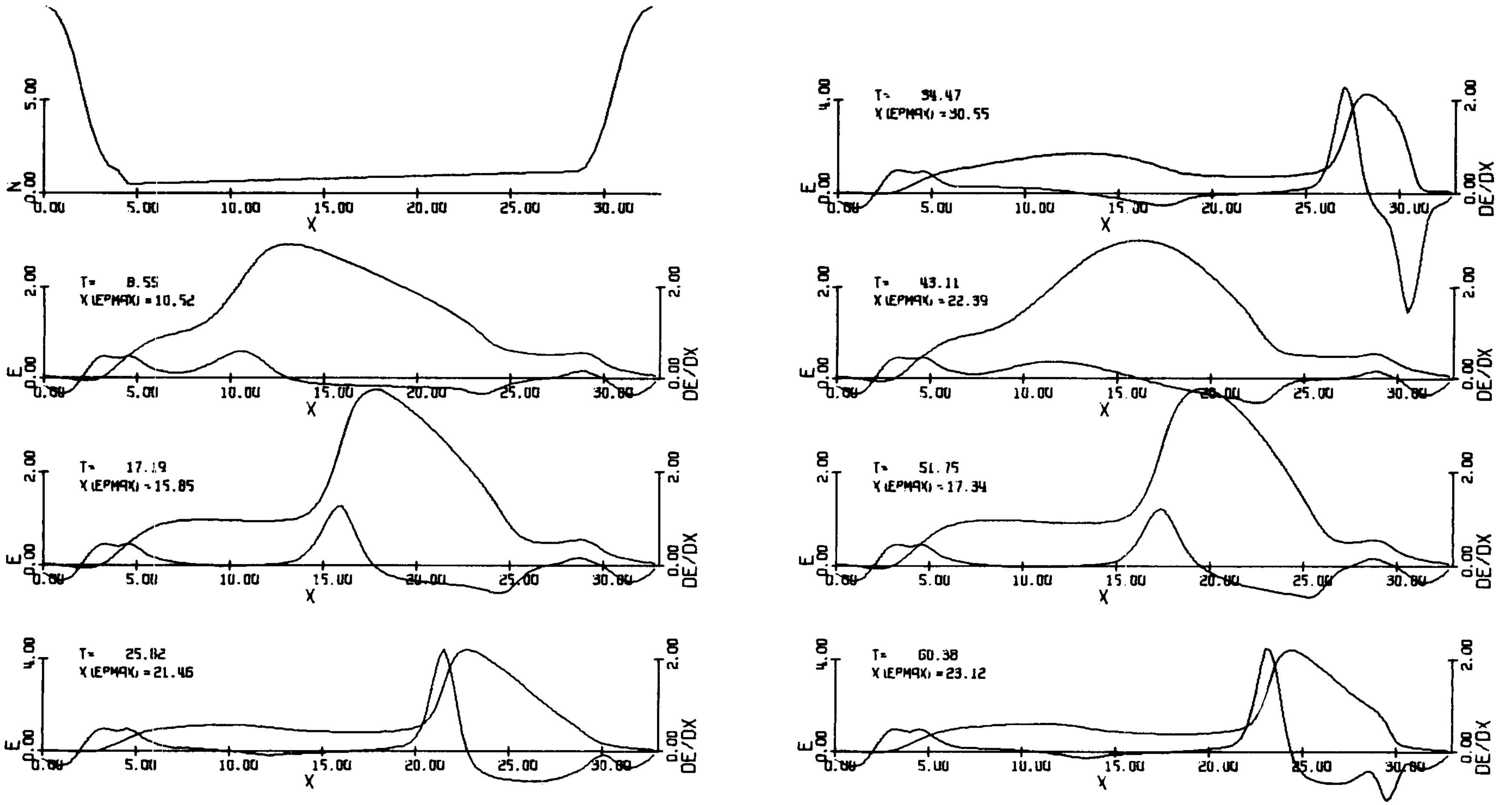

FIG. 10--Effects of a conductivity slope in a short sample.

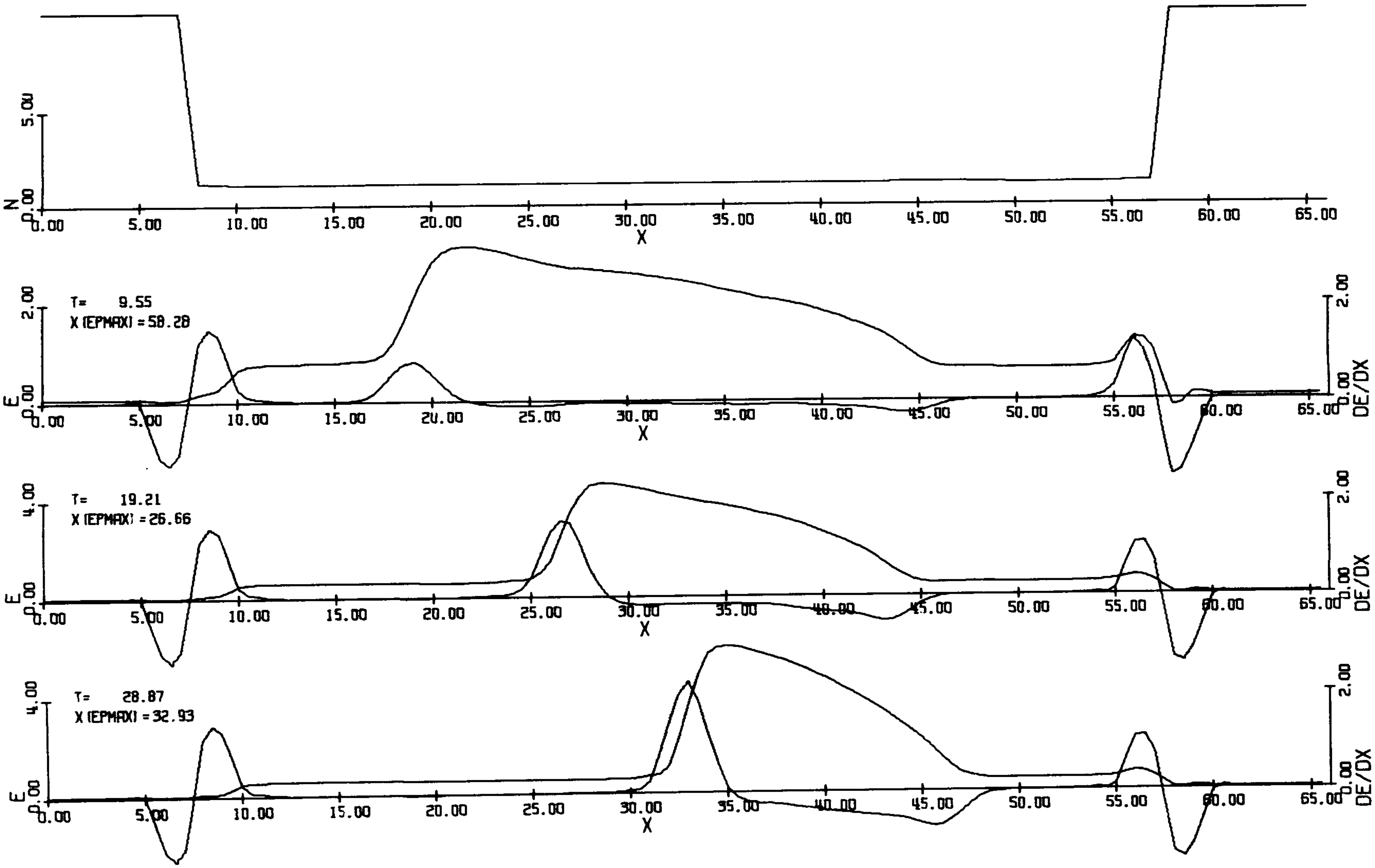

FIG. 11--A long sample with the cathode 20% "hotter" than the anode. There is a ± 5% variation of doping along the lengths of the device.

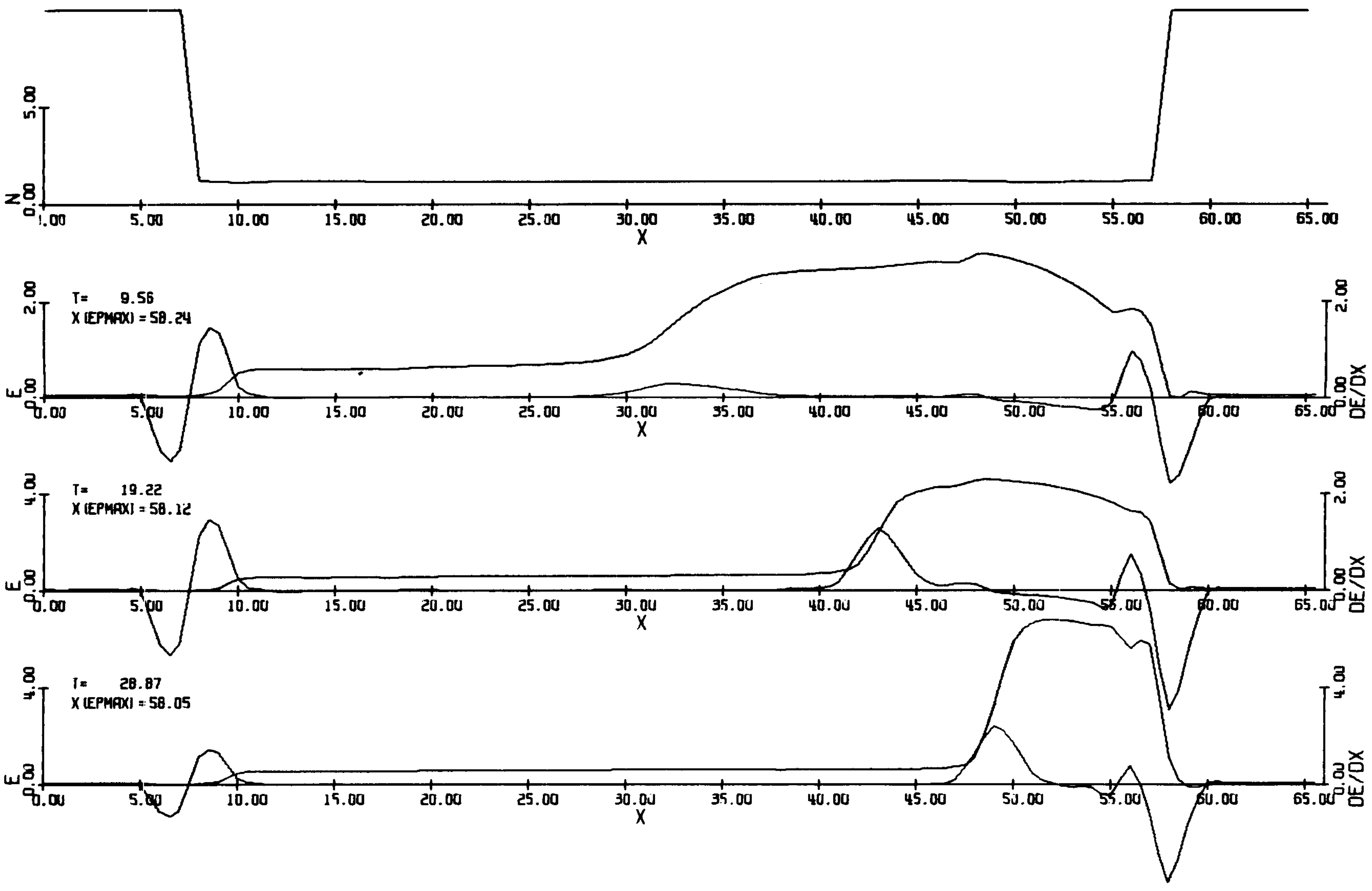

FIG. 12--A long sample with the anode 20% "hotter" than the cathode. There is a ± 5% variation in doping level along the device.

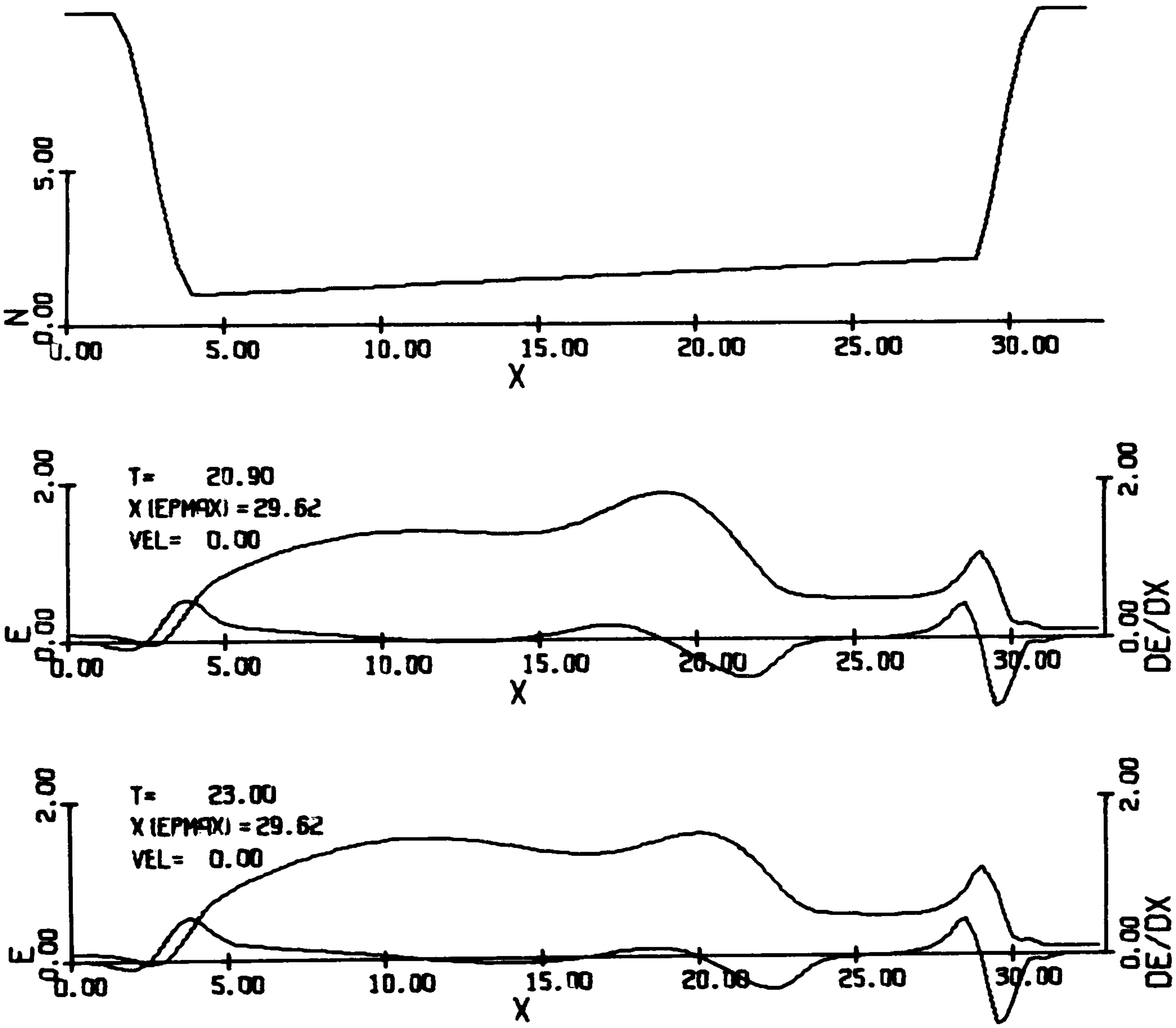

FIG. 13--Effects on the diode of a change of v-E characteristic. Changes are relative to Fig. 10.

calculated from the complete model of McCumber and Chynoweth[4] with a very low negative conductivity and a peak velocity of 1.6×10^7 cm/sec at threshold. This change in velocity/field is representative of the aging process thought to go on here. This figure must be compared with Fig. 10 which is the same diode under Ruch-Kino conditions.

8. The resistive notch at the cathode is thought to be quite probably due to the fact that the cathode is invariably small and dot-like in form, giving rise to surface state effects in its vicinity.

b. Circuit Oscillations Starting Problems

The second part of the study concerns the starting behavior of oscillation arising from the bulk effect when constrained by a circuit as in Fig. 6. The value of the load resistance for the initial studies was held high at 60 times the device resistance so that high values of Q could be studied. The Q of the circuit is given by the relationship $\omega C_p R$ which when the normalization is considered reduces to the simple expression,

$$Q = \frac{R}{\sqrt{L/C}} \quad .$$

The parameters of the device as taken for this investigation were the following:

doping level $\simeq$ 2.4×10^{15}
length = 10 μM
voltage = 2.6 threshold voltage
Q = 100 .

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[4] D. McCumber, A. Chynoweth, "Theory of Negative Conductance Amplification and Gunn Instabilities in Two Valley Semiconductors," IEEE Trans. Elect. Dev. ED-13, 4-21 (January 1966).

The circuit frequency was taken for the cases discussed below to be twice the Gunn frequency which then corresponds to a frequency of approximately 28 GHz. The doping level is such as to not require conductivity notches to start dipoles propagating.

In the above conditions the following significant values appear:

$$n_0\ell = 2.4 \times 10^{12}$$

$$n_0/f \simeq 0.9 \times 10^{5}$$

$$f_0\ell = 2.8 \times 10^{7} \quad .$$

This places the point of operation well in the middle of the LSA region in Copeland's chart of modes.[5] As a result of this, in spite of the fact that the frequency is only twice the Gunn frequency, it might be expected that a transition to a high power oscillation would occur. This does not happen, however. Oscillation builds up to a point where the voltage does not swing below threshold. The steady state is determined by the fact that when a fully formed dipole (accumulation layer and depletion layer of charge) is present in the device, the negative resistivity at the terminals is lost and becomes positive. This is seen in the phase relationship of current through the device to the voltage across the device. It must be concluded that this is due to the doping level being lower than required for quick collapse of the accumulation and depletion layers. This is best illustrated by the diagrams below, where

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[5] J. A. Copeland, "LSA Oscillator Diode Theory," Appl. Phys. 38, 3096-3101 (July 1967).

V is the rf peak voltage across the device and V_d is the rf voltage developed across the dipole. Here I is the current through the device, excluding inert capacitive current and I_d is the dipole charging current. The angle Θ is less than $\pi/2$ as long as the angle ϕ is large and ϕ becomes larger for lower doping level. At the instant when a dipole is exciting (and entering) the device, negative resistivity at the terminals will return due to the low dipole voltages at these times. This effect can give rise to modulation effects in the output voltage. Based on pertinent computer calculations, a behavior as depicted by Fig. 14 is expected, where Area 2 indicates that area where modulation is occurring at frequencies other than the Gunn frequency. Area 1 is the area of Gunn frequency modulation and Area 3 is an area of very little modulation. The idea that terminal resistivity will be positive in the presence of a dipole is contrary to Copeland's predictions[5,6] but in accordance with the results of Thim.[2]

From the above it may be expected that raising the doping level will decrease the phase lag of dipole voltage, i.e., angle ϕ , and cause Θ to be greater than $\pi/2$ for a greater part of one transit time. This is indeed the case. When the doping was made 4.5×10^{15} and $n_0/f \simeq 2 \times 10^5$ the amplitude of the oscillations was increased greatly and now went below threshold, giving conditions that lead to a quasi-LSA state. We may expect that the n_0/f bounds for LSA are higher than have been predicted, also Θ is now approximately 135°, in agreement with Thim.[2]

Another point of interest is in the notch expected in conductivity at a cathode contact. The addition of these notches (of halfing background carrier concentration at the cathode) lead as Thim has already pointed out to decaying rf oscillations because they cause large dipoles to exist for most of one transit time and enlarge the angle ϕ . The apparent result will be lower power outputs from devices. The difficulty of discharging through a large dipole may be responsible for the build up of an E field at the anode observed in some of the calculations involving low conductivity material. This build up of charge works like a large

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[6] J. A. Copeland, "Stable Space Charge Layers in Two Valley Semiconductors," J. Appl. Phys. 37, 3602-3609 (August 1966).

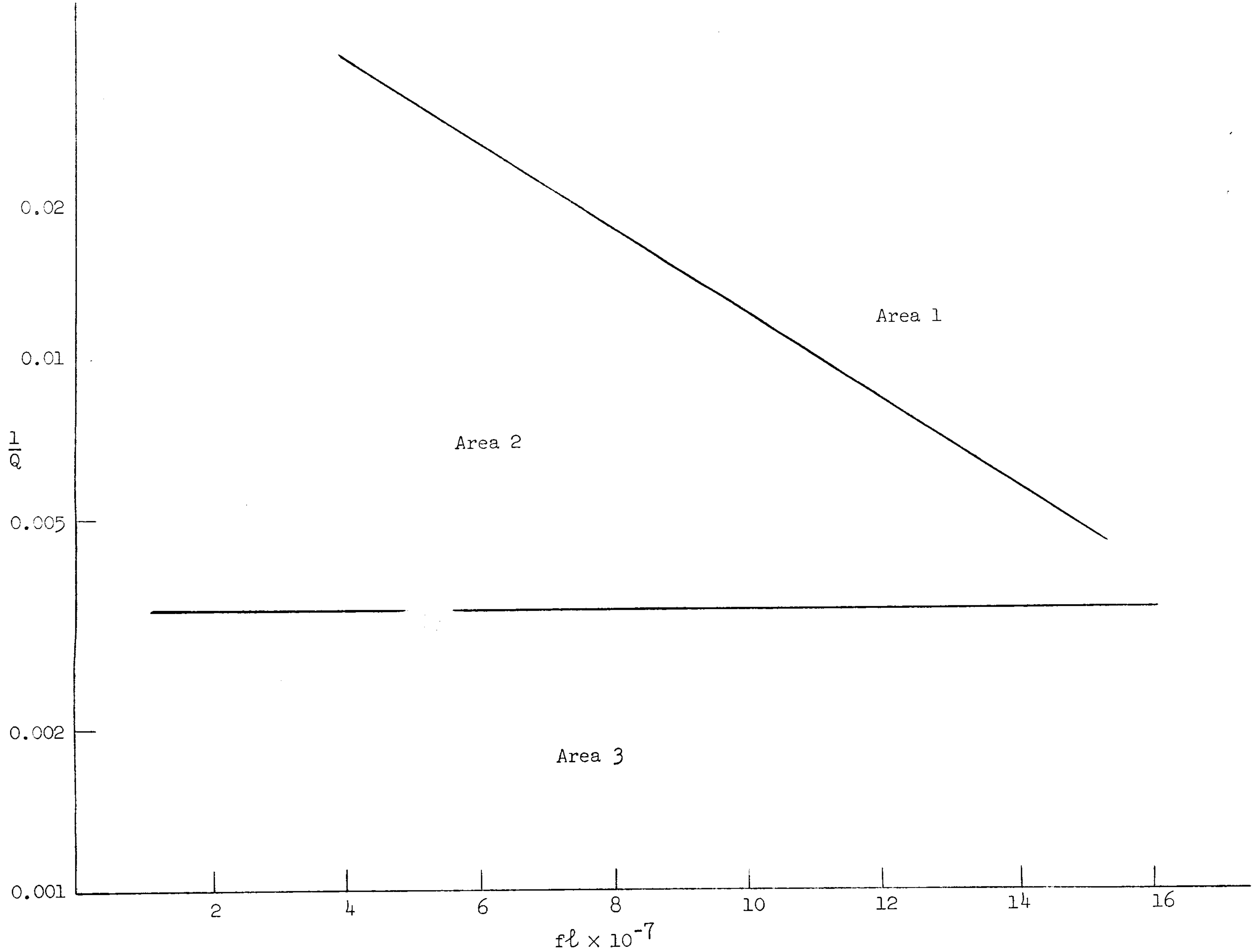

FIG. 14--Chart of the variation of output volts with Q and $f\ell$.

Extensive efforts were made to make good ohmic contact to this pure epitaxial GaAs. It was found that although putting contacts onto material of resistivity less than 0.5 ohm/cm presented no great problem, great care had to be exercised. With higher resistivity material the amphoteric nature of germanium in GaAs gives rise to trouble as acceptors become as prevalent in the germanium sites as donors. It is better to switch to Sn or use silver germanium indium as proposed by Texas Instruments. In any event it was found that with germanium even for the low resistivity samples, too long an alloying time (greater than 3 min.) or too high an alloying temperature (greater than 480°C) gives trouble from the amphoteric nature of germanium. But Sn alloyed at 500°C for up to and beyond 5 minutes rarely gives trouble of this nature.

A new liquid epitaxial system has been set up for continuing the work or try to grow purer material (GaAs). This system is now in operation.

Noise

Some measurements have been made on 1/f noise spectra of diodes obtained from Hewlett Packard Co. The investigation is centered around the fact that it was discovered that this noise is quite sensitive to storage at high temperatures and to surface conditions of the bonding of the diode to the heat sink. Previous theories on 1/f noise are adaptable to this case, but it is of more immediate interest to find what happens during this high temperature storage and how it relates to operating conditions and 1/f noise at the contacts.

To this end the equipment has been procured to measure noise of this nature in the laboratory.

GaAs Probing Set Up

A set up for making probing measurements (sub-threshold) on GaAs is made. The purpose is to measure doping profiles and their distortion near threshold.

extra dipole to cause the phase angle Θ to be less than $\pi/2$ for a major portion of the transit time.

The calculation of efficiency and power output against frequency is progressing in accordance with the following plan: a new characterization of the device in terms of impedance as a function of voltage, frequency, relaxation time and time will first be obtained and then used in a nonlinear iterative analysis.

Crystal Growth

A program is underway to grow very pure GaAs of carrier density $\simeq 10^{13}$ from the solution in gallium. This technique has been used to grow, over the last six months, some doped crystals of GaAs. The dopant used hitherto has been tin, with quite good results. Carrier densities can be predicted to a fair accuracy merely by controlling the amount of Sn in the melt. Two sets of three crystals were grown on insulating GaAs, one set with a resistivity of approximately 4 ohm cm and the other set with resistivities of approximately 0.3 ohm cm. Growth of these crystals was controlled by a slow automatic adjustment of temperature of the solution downwards over a long time period. With $\langle 111 \rangle$ orientation crystals this procedure gives a fairly tolerable and flat surface with only little steps on it.

Van de Pauw measurements were performed on the lower resistivity crystals giving the following results:

T	n density	Resistivity	μ cm^2/V sec
300°K	3.4×10^{15}	0.31	5980
260°K	3.4	0.26	7150
226°K	3.	0.216	8600
190°K	3.3	0.185	10200
154°K	3.2	0.153	12800
120°K	3.05	0.129	16100
77°K	2.9	0.098	22000

Schottky barrier measurements indicated a flat profile.