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THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF COLLECTIVE MICROWAVE PHENOMENA IN SOLIDS

under the direction of

G. S. Kino

Semi-Annual Status Report No. 7

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ABSTRACT

I. MICROWAVE AMPLIFICATION IN HIGH RESISTIVITY GaAs

The velocity field characteristic curve for electrons in GaAs above the Gunn threshold was measured by a new direct method involving probe measurements on the surface of a GaAs amplifier.

Experimental terminal gain vs frequency curves show the effect of small transverse dimension in lowering the gain at low frequencies.

Some initial results of a computer simulation of the GaAs amplifier are presented.

II. GUNN OSCILLATOR STUDIES

The work on GaAs growth has continued with a considerable improvement in the homogeneity and quality of the material obtained from the horizontal growth system. We have obtained material with a carrier concentration of $2 \times 10^{13}/\text{cm}^3$ and a mobility of $9300\ \text{cm}^2/\text{Vsec}$. We are fabricating devices with the current flow along the epitaxial layer but have not yet overcome the problem of surface breakdown. The work on the computer model continues with an investigation of two devices in series and the harmonic content of a single device.

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 Studies

The Responsible Investigator for this Grant is G. S. Kino.

MICROWAVE AMPLIFICATION IN HIGH RESISTIVITY GaAs

(G. S. Kino and B. Fay)

INTRODUCTION

The objective of this work is to realize a two port unilateral space charge wave amplifier based on the Gunn effect and to check the theory of wave propagation in finite semiconductors.

The active medium consists of a GaAs diode biased between the negative differential conductance threshold and the threshold for current oscillations, the latter being a function of the diode $n\ell$ product as well as of its thickness and dielectric environment.

PRESENT STATUS

A. Velocity-Field Characteristic Curve of GaAs

A new direct measurement of the velocity-field characteristic of electrons in GaAs was performed using the amplifier probe setup already described in the previous report and reproduced in Fig. 1.

The insert in Fig. 1 shows the configuration of the amplifier with the GaAs diode clamped between two grounded metal plates spaced roughly 0.5 mm apart. The input rf signal applied to the cathode contact sets up a decaying rf field into the diode which interacts with the drifting electrons and excites a space charge wave at the signal frequency.

The velocity-field data is obtained from a combination of rf and dc probe measurements on the amplifier for different values of the bias voltage. Figure 2 shows the rf and dc potential profiles obtained on

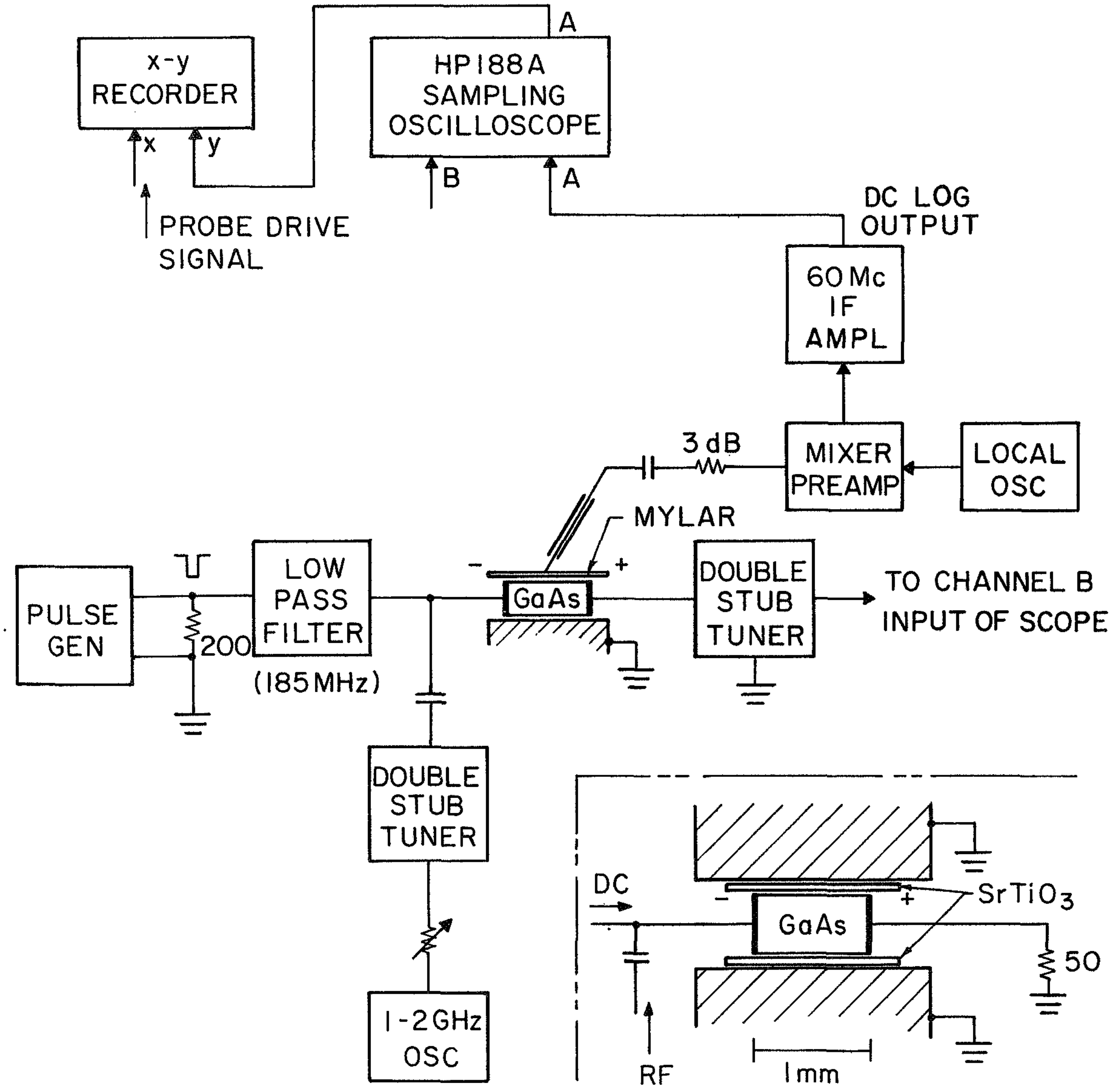

FIG. 1--Amplifier and rf probe circuits.

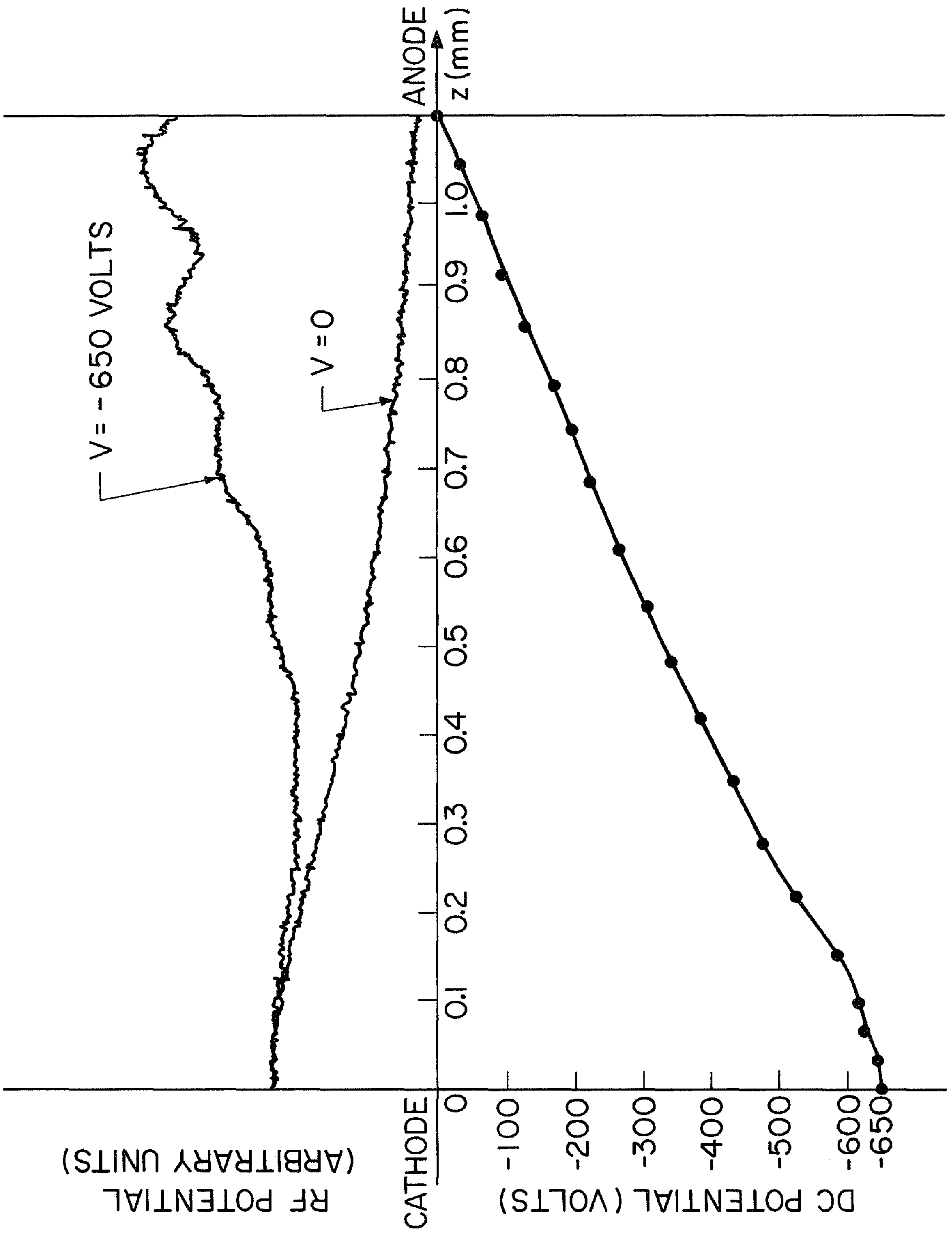

FIG. 2--Result of probe measurements.

one sample 1.1 mm long for a bias voltage of 650 V and a signal frequency of 1 GHz.

The ripple in the rf profile is caused by an interference effect between the "slow" space charge wave and a "fast" electromagnetic cutoff mode excited from the anode contact. The product of the ripple period and the frequency yields the phase velocity of the space charge wave, which for frequencies well below the diffusion cutoff frequency is virtually equal to the electron drift velocity.[1]

DC probing is carried out by a direct point contact method using a high impedance FET probe input stage and allows determination of the value of the dc field in the region where the space charge wavelength is measured.

Figure 3 shows the experimental points of the velocity field curve obtained by this method on two samples of resistivities 495 and 940 Ω-cm. Two other experimental curves obtained by Ruch and Kino[2] by a different method on insulating GaAs are also shown for comparison and it is seen that the agreement between the various curves is excellent.

It is interesting to note that of the Ruch-Kino results, only the curve they obtained from IBM material is the result of an absolute measurement, the other being the result of an indirect measurement, because the trapping time in their Monsanto material was too short to allow a transit time measurement. On the other hand, the curve obtained by our space charge wave method is an absolute measurement that does not

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[1] Microwave Laboratory Report No. 1789, September 1969, Stanford University.

[2] Microwave Laboratory Report No. 1600, December 1967, Stanford University.

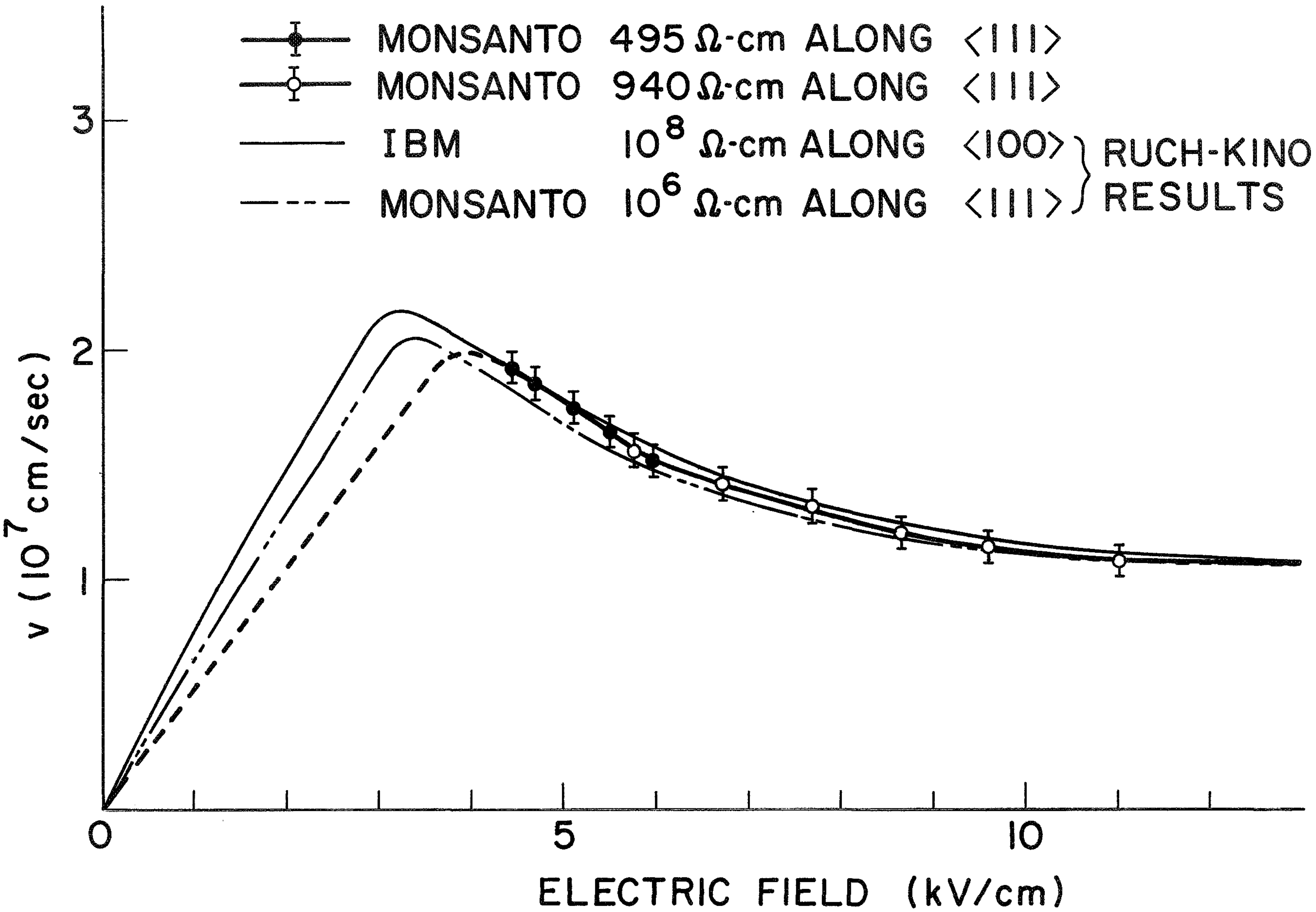

FIG. 3--Velocity-field curve of electrons in GaAs.

require a very pure, long trapping time material.

B. Two-Port Amplifier

As mentioned in the previous report the gain of the amplifier is limited at high frequencies by carrier diffusion and at low frequencies by finite transverse dimension effects.

A direct rf probe measurement of the variation of space charge wave growth rate with frequency can only be made if the decay rate of the cut-off modes is much greater than the length of the sample, which implies a length to thickness ratio of the order of 10. Our method of mounting these samples does not at the present time permit probe measurements to be made.

An indirect way of observing this effect is to measure the variation of tuned terminal gain with frequency. Figure 4 shows the gain frequency curves for 2 samples of same length (1.1 mm) but different thickness and resistivity, namely 0.265 mm and 400 ohm-cm for sample #1 , 0.635 mm and 780 ohm-cm for sample #2 . The theoretical gain-frequency curves are arrived at by solving two independent dispersion equations for the frequency dependence of the gain constant and combining the results into a simple frequency dependent gain constant.

The first dispersion equation corresponds to a one dimensional space charge wave allowing for carrier diffusion effects and accounts for the high frequency gain falloff.

The second dispersion equation corresponds to a two dimensional space charge wave[3] for a symmetrical metal-dielectric-semiconductor-dielectric-metal sandwich structure, neglecting carrier diffusion, and

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[3] G. S. Kino and R. N. Robson, "The Effect of Small Transverse Dimensions in the Operation of Gunn Devices," Proc. IEEE, 56, 2056-57 (1968).

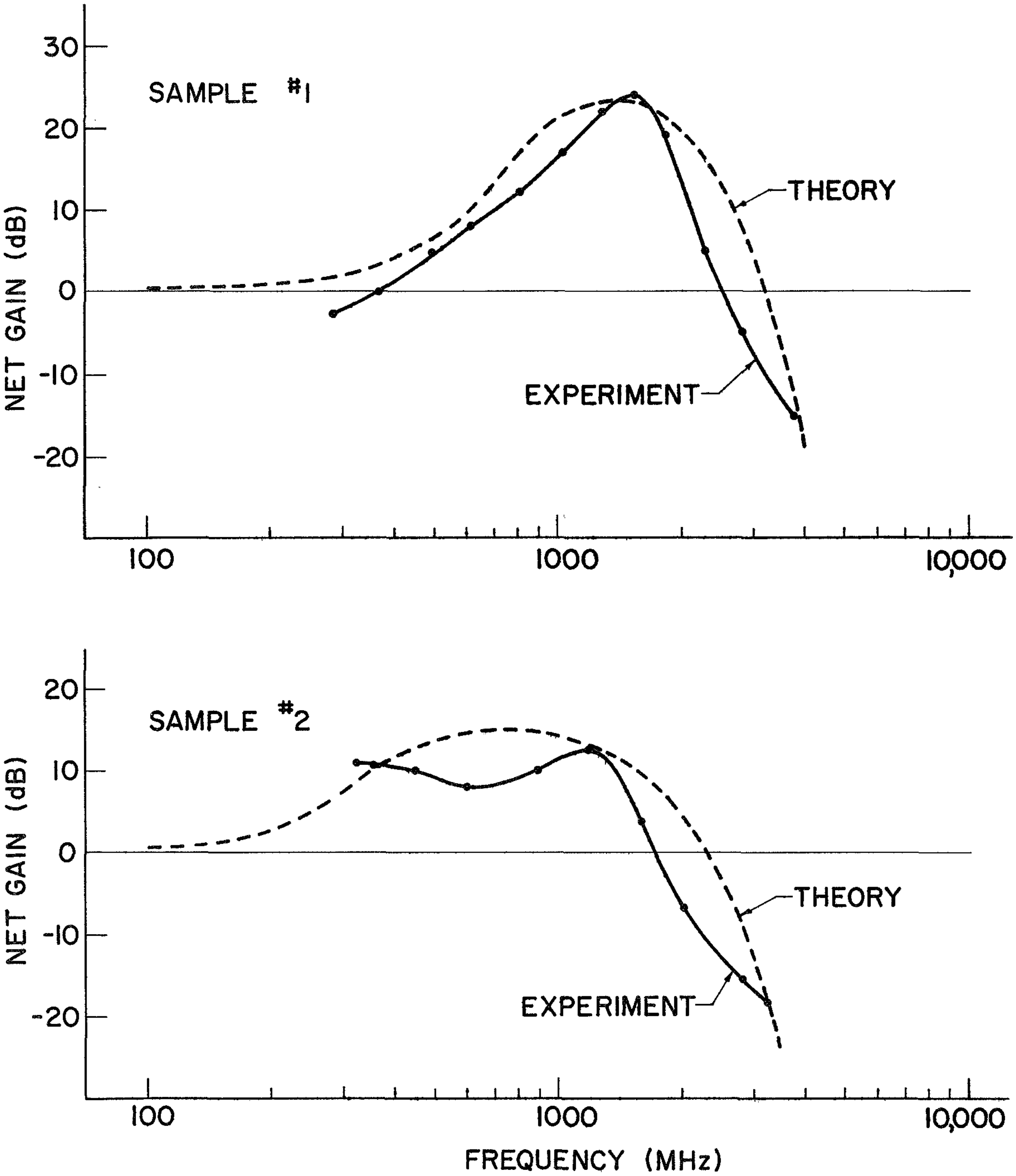


FIG. 4--Tuned terminal gain vs frequency.

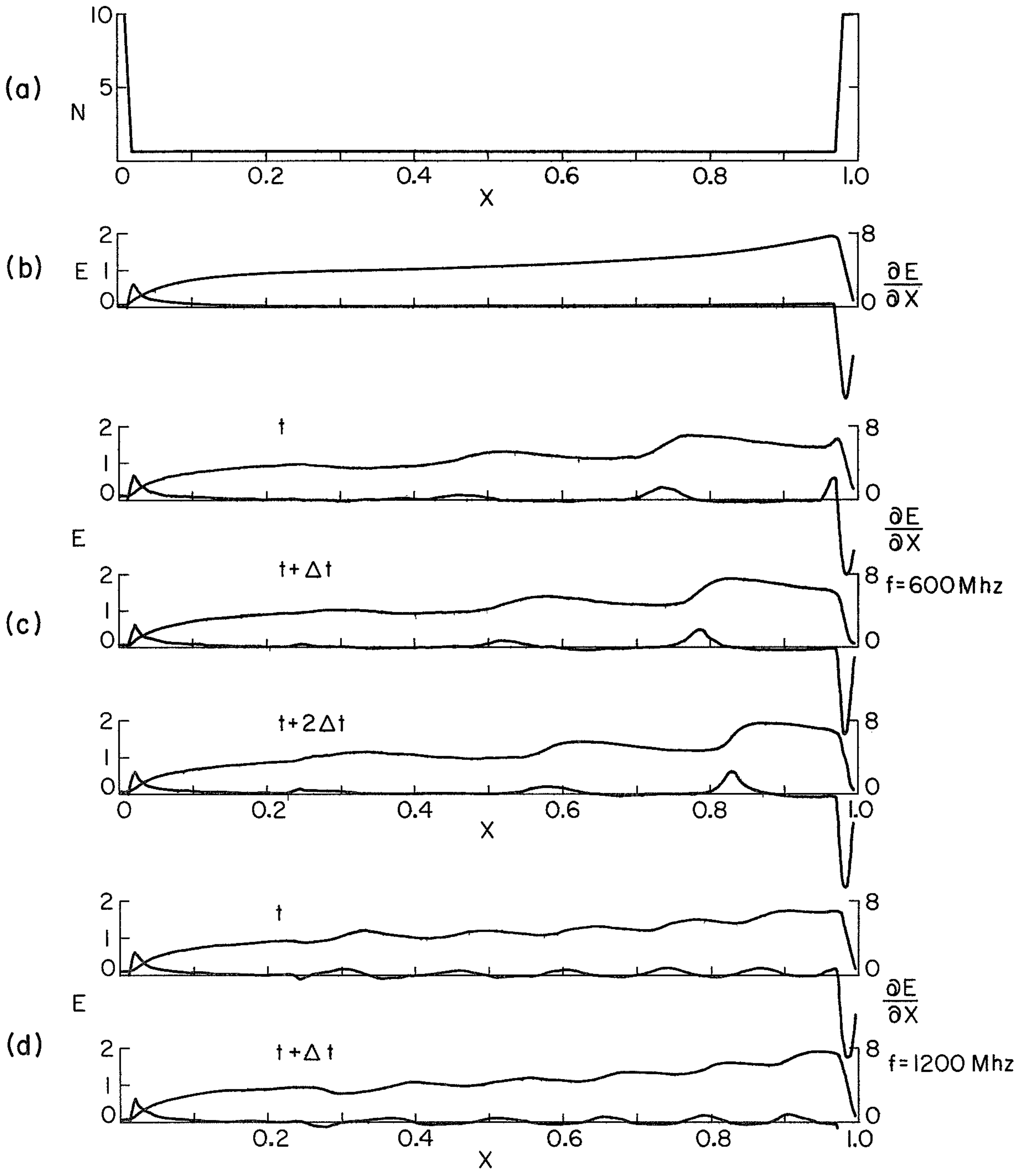


FIG. 5--Space charge wave field and charge distribution.

GUNN OSCILLATOR STUDIES

(C.F. Quate, G.S. Kino and J.A. Higgins)

INTRODUCTION

As in previous reports the following indicates the progress achieved in three areas of activity which come under the above heading. These are:

(a) growth of high purity GaAs

(b) fabrication of long cw oscillators

(c) computer studies of GaAs devices

PRESENT STATUS

A. GaAs Growth

At this stage we have achieved considerable improvement in the homogeneity and quality of material grown in the horizontal tipping system. Typical figures that are now obtainable from this system under carefully controlled conditions are:

$$\left.\begin{array}{rl} N_D - N_A & \simeq 2 \times 10^{13}/\mathrm{cm}^3 \\ \mu & \simeq 9300\ \mathrm{cm}^2/\mathrm{Vsec} \end{array}\right\} \quad 300^\circ\mathrm{K}$$

$$\left.\begin{array}{rl} N_D - N_A & \simeq 2 \times 10^{13}/\mathrm{cm}^3 \\ N_D - N_A & \simeq 100{,}000\ \mathrm{cm}^2/\mathrm{Vsec} \end{array}\right\} \quad 77^\circ\mathrm{K}$$

$$N_D + N_A \gtrsim 10^{15}/\mathrm{cm}^3$$

The path to the state of knowledge which enables us to achieve these figures has been the realization that the source was not the major contributor of impurities. This came about as second generation crystals consistently turned out to have lower liquid nitrogen mobilities than first generation. This meant essentially that some other source of impurity dominated in the system. Attention was paid to giving the gallium extra cleaning by high temperature hydrogen. This produced dramatic improvement in homogeneity of the crystals grown, as well as in their purity. Even crystals grown at moderately high temperatures showed good homogeneity. At this stage heat treatment of the boat in vacuum was tried and found to be only moderately effective. Leaching a boat with gallium for many hours in hydrogen greater than 800°C was found to be much more effective, indicating that we would be well advised to abandon graphite crucibles altogether. We are awaiting special quartz with this in mind. One final factor which brought about a slight improvement in resistivity was a method of evacuating and purging the reaction system of all impure gases which entered during loading - with particular emphasis on oxygen.

Uniformity of the most recently grown crystals is typified by the following figures:

thickness of growth, 4×10^{-3} inches

$N_D - N_A$ at 1×10^{-3} inches above seed $= 4.5 \times 10^{13}/\text{cm}^3$

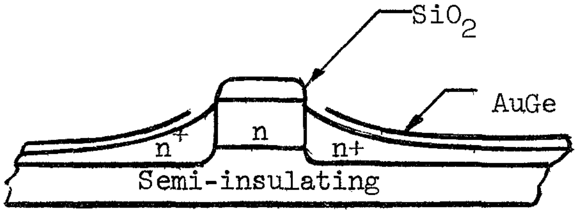
$N_D - N_A$ at 4×10^{-3} inches above interface $\simeq 2 \times 10^{13}/\text{cm}^3$

Variation between cannot be said to have been measured in detail; however, it is linearly interpolative.

Our vertical system growth has not been as successful: $10^{15}/cm^3$ is the best we can achieve, in spite of employing all the methods which worked so well in the horizontal system. We have, however, employed the constant temperature system mentioned in a previous report and found that it works well in that thin layers may be deposited at a constant temperature.

B. Fabrication of Devices

We are making devices aimed at pulsed and possibly cw operations. The devices are planar as indicated in the following sketch:



The steps used in making this device are complex and involve silicon dioxide deposition and etching, regrowth of n+ , AuGe deposition, dicing, surface preparation and bonding to a heat sink. All of these functions have been the subject of work over the last period, and each apparatus involved in each stage is now in working order.

The surface preparation referred to above is critical. Recently we have been experiencing breakdown along the surface when the voltage on a device is allowed to exceed twice threshold. This problem is overcome to a major extent by etching the subject surfaces with 50:1 methanol bromine.

Devices measured successfully to date have shown peak-to-valley current ratios as high as 2:1. Some of the higher resistivity crystals have yet to be used successfully, as even regrowth of n+ seems to be uncertain in achieving good contact to this material.

C. Computation Studies

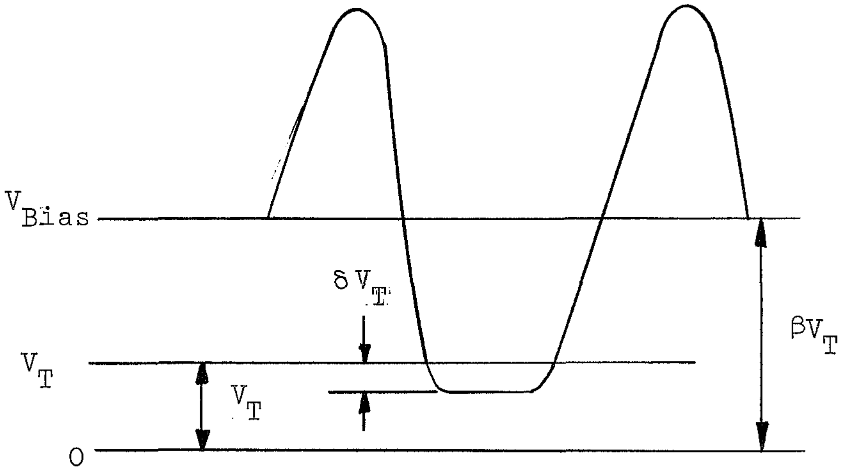
We have investigated a number of aspects of GaAs bulk oscillation, which we explain briefly here.

Device length is a parameter which can ensure dipole excess charge patterns for the ideal device without any glitches or random doping. The product $n_0\ell$ for two cases studied was 2×10^{12} and 8×10^{12}. In the former case the ideal perturbationless diode will produce for a constant voltage across it only accumulation layers. In the latter case dipole layers form very quickly at the cathode. The reasons for this may be seen quite easily from theory. Again, device length plays an important part in the ease of attaining LSA operation. Excess dipole charge layers are harder to quench, and one can see that rf voltage swings must be higher proportionally for long diodes than for short diodes, to achieve negative resistance from quenching effects. This appears, then, to put a limitation on the PZf^2 products available from operation in the LSA mode.

We have investigated putting devices in series and encountered the problem that any little mismatch between sections results in (for low rf signals and devices where $n_0\ell > 2 \times 10^{12}$) the device with the higher resistance taking on all the dc voltage, with resulting high E field values and avalanche breakdown. At high rf voltages this does not happen.

A proposal has been made by Kino and Kuru[1] that the harmonics of an oscillating signal may be used to improve efficiency. That proposal was made specifically with respect to domain operation where $f_0 \ell < 10^7$. More recently Copeland has proposed the same use of harmonics to increase the efficiency of the LSA mode.[2] The proposal suggests adding a second harmonic component in such a phase relation as to clip the trough of voltage at just the threshold level, thus allowing larger components of fundamental voltage. In the absence of the second harmonic large fundamental signals give rise to short periods of resistive current flow and this causes rapid decrease in efficiency.

The computer model shows, with the aid of the accompanying sketch, the following results for values of $\beta \simeq 3$:



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[1] G. S. Kino and I. Kuru, "High Efficiency Operation of a Gunn Oscillator in the Domain Mode," IEEE Trans. Elec. Devices, <u>ED-16</u>, p.735 (September 1969).

[2] J. A. Copeland, to be published in J. Appl. Phys.

(a) With $n_0 \ell \simeq 10^{12}$, δV_T may be quite small as described by references 1 and 2.

(b) When $n_0 \ell > 10^{12}$ then for the case where $f_0 \ell >> 10^7$ the value of δV_T must rise to make the quenching adequate for the LSA mode. For very long diodes δV_T must approach 0.5 V_T .

(c) If the δV_T does not increase with length the efficiency decreases due to the presence of the second harmonic because of incomplete quenching. This is accompanied by a situation giving high fields in the region of the positive contact. If δV_T does rise sufficiently, the improvement is restored.