

THEORETICAL AND EXPERIMENTAL INVESTIGATIONS
OF COLLECTIVE MICROWAVE PHENOMENA IN SOLIDS

under the direction of
M. Chodorow

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ABSTRACT

I. MICROWAVE OSCILLATORS AND AMPLIFIERS BASED ON THE GUNN EFFECT

In the first part of this report we describe some experiments designed to investigate the steady state and transient behavior of freely propagating, high field dipole domains in n-type GaAs. By using comparatively long (≈ 1 mm) specimens of low resistivity material ($\rho \approx 2 \Omega \text{ cm}$), the domain transit time is sufficient to allow the current response, following a variable step function in terminal voltage, to be measured. Some preliminary results showing the variation of domain voltage and charge as a function of field external to the domain are presented.

The second part of the report discusses experiments currently being set up to measure the propagation constant and growth rate of small signal space charge waves in high resistivity GaAs, where domain formation is impossible.

II. MICROWAVE AMPLIFIERS UTILIZING ELECTROACOUSTIC MECHANISMS

The electroacoustic amplifier is in some ways a solid state counterpart of the traveling wave tube which uses an electron beam in a vacuum. The electroacoustic amplifier uses a semiconducting material and the electron beam is replaced by electrons flowing in the semiconductor under the influence of an applied field of the order of 1000 volts/cm. The electromagnetic slow wave circuit of the ordinary traveling tube is replaced by a column of coherent acoustic waves which are introduced into the semiconducting material by means of transducers which convert an electromagnetic signal to an acoustic signal. In the electroacoustic amplifier the material is semiconducting as well as piezoelectric so that the acoustic waves in the material create an electric field having the same frequency and wavelength as the acoustic waves themselves. Since acoustic waves are characteristically very slow waves, it is a simple matter to adjust the velocity of the electrons in the material to be approximately synchronous with that of the acoustic waves.

Our interest has been in electroacoustic amplifiers to operate in the microwave frequency ranges. Earlier work under other contracts here has demonstrated that large values of gain can be observed in devices of this kind. The earlier work also showed that the principal problem encountered was concerned with unwanted oscillations in the device, and succeeded in tracing the causes of these oscillations and prescribing means for overcoming them. Under the present contract we have developed techniques for fabricating amplifiers in the form of miniature sandwich type structures in which the various layers of the sandwich consist of electroacoustic transducers, thin film electrical contacts, and the active amplifier material, as described in the body of the report below. The materials and dimensions have been designed to optimize the gain in the frequency range of interest while avoiding instabilities and oscillations. Experimentation on these new designs is now in an early stage under the present contract, and will be continuing for the future period.

The designs which we have been led to as a result of the earlier experiments are extremely small, leading to miniature solid state amplifiers. Consideration of the applied voltages and material resistivities for proper operation shows that relatively high values of power density are involved so that one can anticipate, as an end result, microwave solid state amplifiers of moderate power capability. Heat dissipation problems are important in any such device. The thin sandwich structures now being explored have favorable geometries for application of cooling measures and are presently being given consideration under the project.

III. ACOUSTO-OPTICAL DEVICES

In Part III we summarize the results of analysis and calculations which have been carried out on the problem of electronic deflection of the direction of a laser beam. The schemes which are proposed there utilize the Brillouin scattering process, in which a laser beam is scattered from a coherent acoustic column in a transparent crystal.

The parameter which is to be used to control the optical beam direction is the frequency of the acoustic wave which is excited in the crystal. By operating with acoustic waves in the microwave frequency range, we can consider large frequency variations, which lead to large scan angles, without requiring excessive system bandwidth. In the work described in Section III we have concentrated on the problem of producing this scanning by purely electronic means, that is, without any simultaneous requirement for rotation of the crystal. This requires some new departures from the usual forms of Brillouin scattering, and several new schemes are proposed there which are designed to accomplish this end. They offer the possibility of extremely rapid, extremely precise scanning over a large number of resolvable spot diameters. Experimental work on this problem will be undertaken in the coming period.

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 microwave range upward through the millimeter and optical frequencies. At present, the projects under this Grant are grouped into three general categories:

1. The use of semiconductors to produce oscillations at microwave frequencies in devices related to the Gunn effect.
2. The investigation of acoustic amplification at microwave frequencies by the interaction of acoustic waves with drifting carriers in piezoelectric smiconductors.
3. Parametric optical acoustic interaction in which one could use the coupling between an acoustic beam and, by Bragg diffraction, shift its frequency.

In the following sections we will briefly review the status of the projects in these three areas.

PRESENT STATUS

I. MICROWAVE OSCILLATORS AND AMPLIFIERS BASED ON THE GUNN EFFECT

A. INTRODUCTION

Two general modes of operation of Gunn effect devices can be distinguished depending on whether the product nL is approximately greater or less than 10^{11} , where n is the donor density (per cc) and L the specimen length in cms. For $nL > 10^{11}$, completely formed, or partially formed, dipole domains are observed and specimens satisfying this inequality are commonly used for oscillation purposes. The majority of the previously published work has been concerned with the steady state behavior of fully formed, freely propagating, dipole domains in such material. When a Gunn specimen is placed in a resonant circuit, the terminal voltage is no longer constant during the time a domain is propagating, and it is important therefore to be able to predict its transient response. Such understanding is necessary, for example, in order to design the optimum circuitry for high efficiency operation. Part of the work done under this contract during the reporting period has been concerned with measuring the transient and steady state response of freely propagating domains in long specimens of GaAs.

If the nL product is less than 10^{11} , the specimen is found to be stable against domain formation, and such a device can exhibit one port reflection gain over a limited frequency range if suitably loaded. Implicit in analyses of this type of amplification is the assumption of small signal space charge wave growth with distance along the specimen from the cathode contact. The existence of such waves has not yet been verified directly, however. We are currently attempting, using a traveling wave capacitance probe, to observe the growth rate and wavelength of such waves in long specimens of relatively high resistivity GaAs. These measurements should be capable of providing information on the

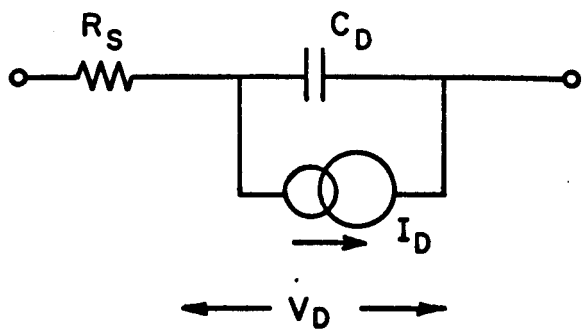
shape of the velocity-field characteristic and also the significance of fast trapping effects in the high resistivity material being used. We are ultimately interested in the possibility of using these growing waves in a distributed two port microwave amplifier.

B. TRANSIENT BEHAVIOR OF FREELY PROPAGATING DOMAINS

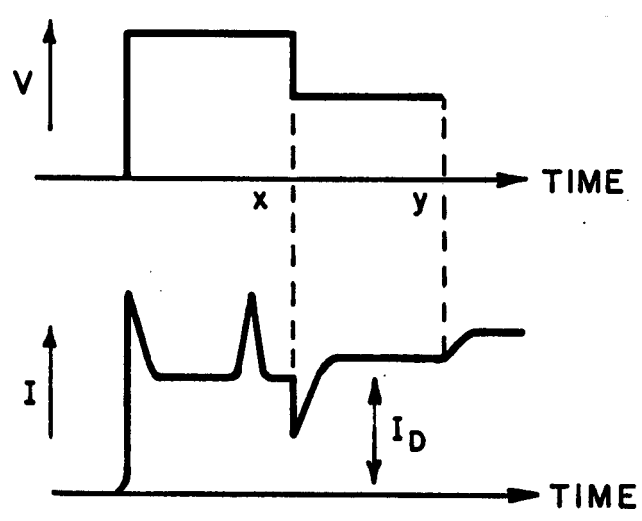
The equivalent circuit shown in Fig. 1a is considered to be capable of representing the terminal behavior of a Gunn specimen during the time a domain is in transit. The resistance R_s is the low field resistance of the diode; the charge stored on the dipole domain is represented by the capacitor C_D and the current I_D is induced by domain drift. Both the charge stored on the domain Q_D and the current I_D are considered to be instantaneous functions of the domain voltage V_D in this approximation.

We have started to measure the above parameters in the following way, using long samples with a transit time > 10 nsecs. A voltage pulse shaped as shown in Fig. 1b is applied to the device. The initial part of the pulse is at a potential greater than threshold and thus the device oscillates. There is a step at X which is timed to occur with a domain in transit and the height of the step can readily be altered. The transient effect, associated with the domain discharging, eventually dies away and the current reaches an equilibrium value. This current persists until the domain reaches the anode contact (Y). So far our work has been largely concerned with the equilibrium current which is just I_D of Fig. 1a. Since the terminal voltage and R_s are known, V_D as a function of I_D can be determined. Examples of some results for samples of different resistivities are shown in Fig. 2 and are compared with a theory due to Butcher and Fawcett. In Fig. 2, the field external to the domain is plotted rather than I_D , but I_D is linearly related to this field through the low field conductivity. As will be seen, the qualitative behavior is in agreement; the quantitative agreement, however, is not so good. We believe that the reasons are:

- (1) the velocity-field characteristics used in the theory are not



(a)



(b)

FIG. 1a--Equivalent circuit of Gunn diode with domain in transit.
 1b--Voltage step waveform applied to diode and resulting current response.

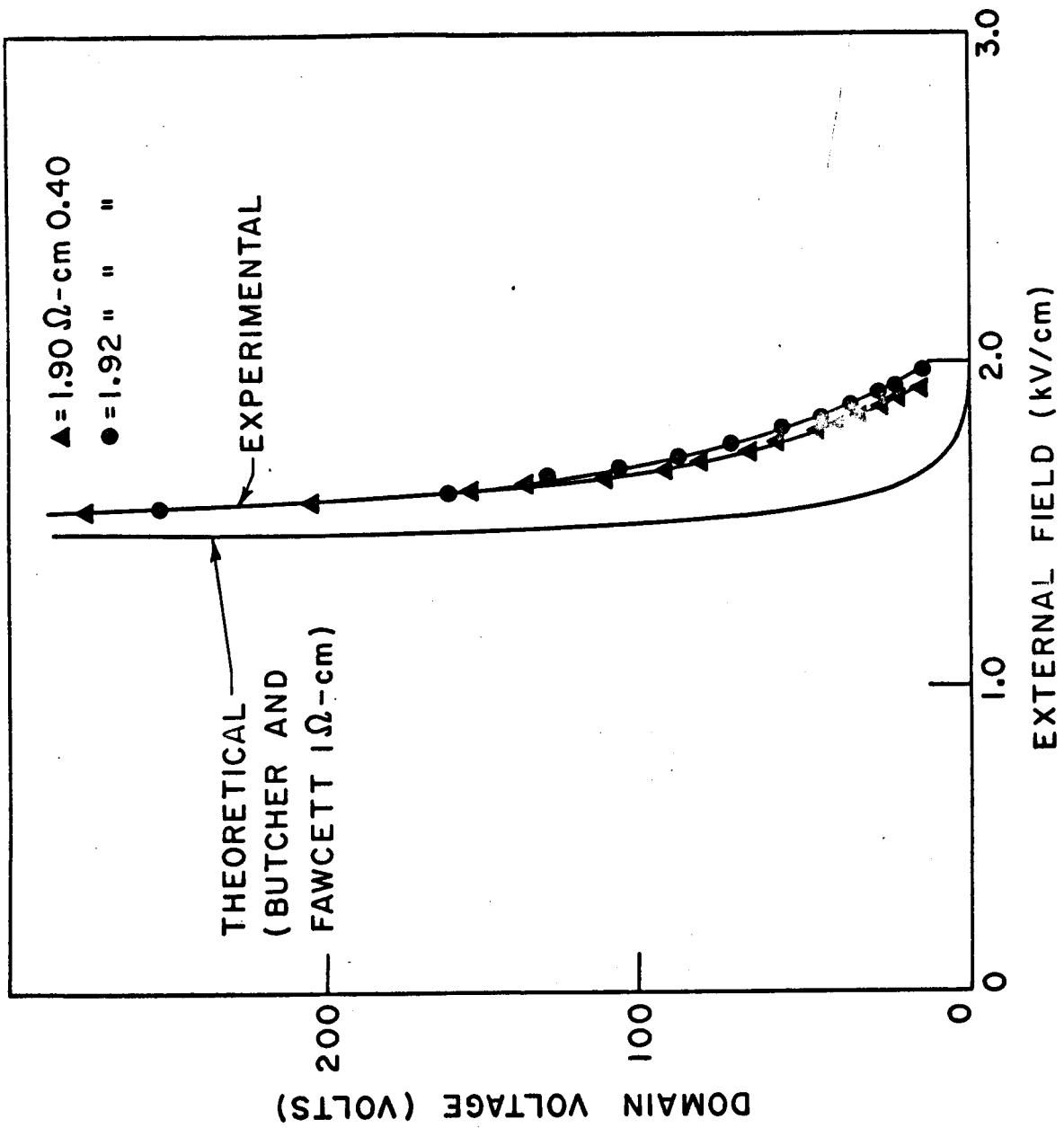


FIG. 2--Domain voltage versus external field. Domain current is proportional to external field.

accurately known, (2) in the theory the diffusion rate as a function of field is not taken properly into account, and (3) the samples are not as uniform as would be desirable. We intend to compare these results with a modified theory we are carrying out in which the field dependence of the diffusion constant is taken into account.

The domain differential capacity $C_D = \partial Q_D / \partial V_D$ is a nonlinear function of the domain voltage. Its value is readily calculable when delta function accumulation on the trailing edge of the domain (and uniform depletion on the leading portion) is assumed. These conditions in general do not pertain exactly. The transient measurements described, however, allow the charge stored on the domain, as a function of the domain voltage, to be measured and this information in turn allows the charge distribution through the domain to be inferred approximately. Some initial measurements have already been made and the results are shown in Fig. 3. They are compared with a theoretical curve which assumes uniform depletion and a thin accumulation layer.

We hope in the forthcoming period to extend these results to cover a wider range of resistivity material than presently considered. We also intend to study experimentally the time dynamics associated with domain nucleation and eventually to subject the specimens to large signal ac voltages and study the current response.

C. MEASUREMENT OF SPACE CHARGE WAVE GROWTH IN HIGH RESISTIVITY MATERIAL

In order that the nL product be less than 10^{11} , we are working with GaAs of typically $3000 \Omega \text{ cm}$, from which specimens approximately 1 mm long are prepared. A traveling probe and probe carriage have been constructed, enabling the voltage distribution along the specimen to be determined. Initially we are currently studying the steady state field distribution along the specimen since theoretically, in trap free material, this should not be uniform at high field strengths. A bias voltage pulse some 1 μsec long is applied to the specimen for these measurements. Later we intend to apply an rf signal in the frequency range 100 Mc/s-1Gc/s across the specimen also and probe the rf voltage distribution, measuring both the phase of the forward slow space charge wave and its growth rate.

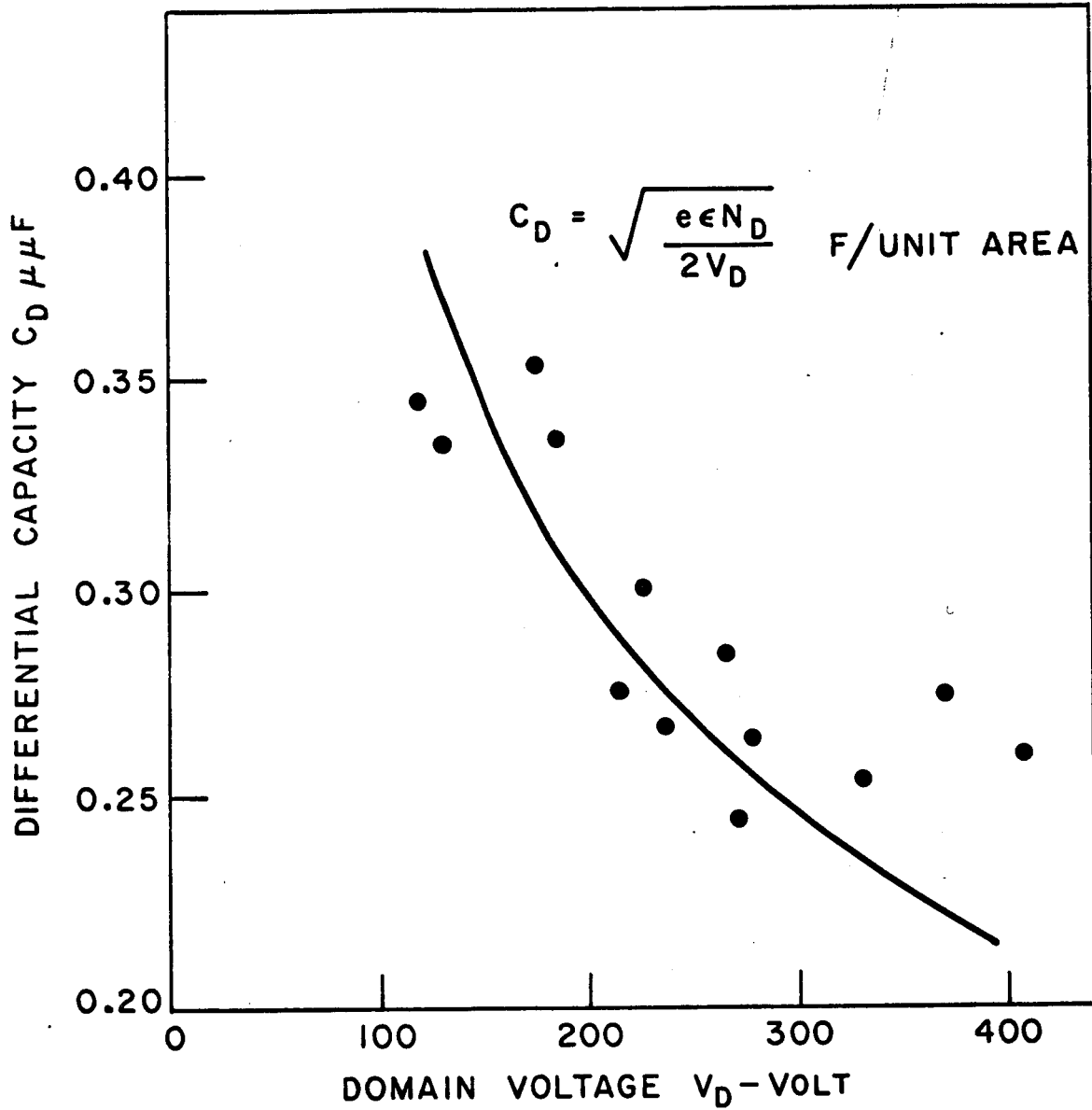


FIG. 3--Domain differential capacity versus domain voltage. ● = Exptl. results. Solid line is a theoretical curve assuming complete depletion within domain. Material $\rho = 4 \Omega \text{ cm}$.

By adopting certain modulation techniques, we hope to be able to provide considerable rejection against the fast, undamped wave which is also present.

A computer program has also been written to enable both the static and rf field distributions to be calculated from any assumed drift velocity-electric field characteristic.

II. MICROWAVE AMPLIFIERS UTILIZING ELECTROACOUSTIC MECHANISMS

At the beginning of this program we had demonstrated that photoconducting CdS crystals could produce acoustic gains at 800 Mc which were in reasonable agreement with the one-dimensional theory. The initial experiments pointed up the problems which had to be overcome if the phenomenon was to be reduced to a useful device. These were two - first, the couplers had to be improved and pushed to higher frequencies - second, the instabilities which were observed in the crystal had to be understood and methods devised for overcoming them. The work on these two problems has proceeded on other contracts and there have been advances in both areas. The insertion loss at 800 Mc has been reduced to a value below 8 dB and at 1600 Mc to a value less than 15 dB. This has been accomplished with thin films of piezoelectric material such as CdS and ZnO. The oscillation problem is now fairly well understood, and a model has been developed which is in satisfactory agreement with the experimental observations. The study has served to define the range of crystal parameters where oscillations will not occur.

Under the present program we have concentrated on the problem of extending the amplifiers to higher frequencies. We have been successful in developing a process which allows us to incorporate thin film CdS transducers in a sandwich structure which includes a CdS wafer which serves as an integrated amplifier. The schematic diagram of Fig. 4 indicates the final configuration. The CdS wafer is a semiconducting material with a resistivity of approximately 10 ohm-cm. On each side of the CdS wafer we have placed ohmic contacts to cover the central area, and the remaining area was coated with SiO to form an oxide barrier layer. We followed this with a deposition of gold and CdS film which serves as the transducer symmetrical to both sides of the layer. With this structure we have been able to study the transmission properties

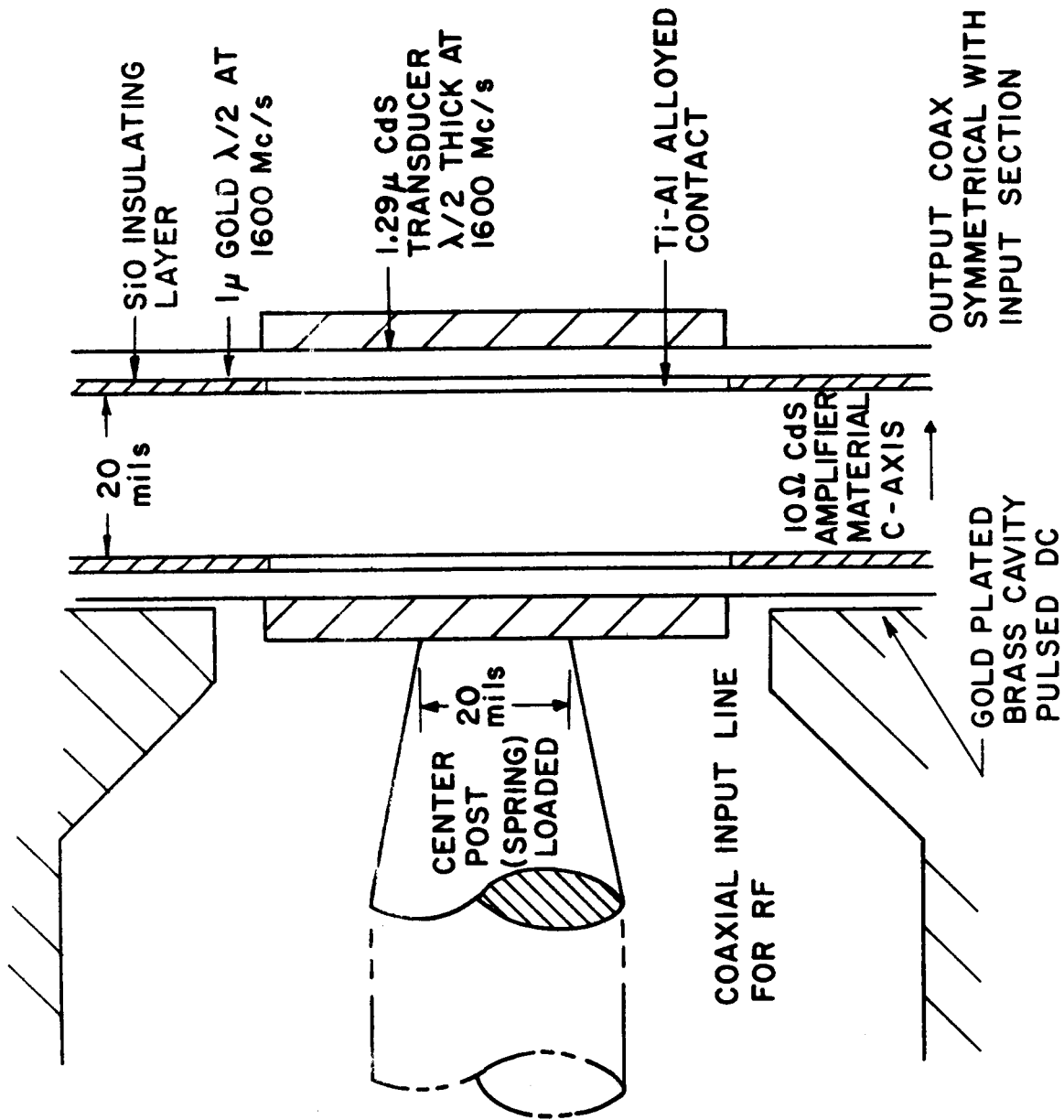


FIG. 4--CdS Acoustic amplifier.

of the sandwich as a function of frequency over the range of 500 Mc to 3000 Mc. We find a minimum insertion loss at 800 Mc of 30 dB at zero drift field which is consistent with the thickness of the evaporated CdS films being equal to one-quarter wavelength. We have measured the acoustic gain at 2400 Mc and find a value in excess of 20 dB.

This study has uncovered several difficulties. First, the crystal is too long and exhibits acoustic oscillations. As mentioned above, the problem of oscillations has been studied on another contract. In essence, we have found that the acoustic instabilities which are observed come from excessive acoustic gain at a frequency much higher than the operating frequency. We have further found that we can eliminate this instability by reducing the length of the crystal well below the one-half millimeter of length used here. Our calculations indicate that with the shorter length we should be able to achieve acoustic gains of 30 dB if we adjust the resistivity of the crystal to the point where it gives maximum gain at the operating frequency. This is determined by the relation $\omega_m = \sqrt{\omega_c \omega_D}$. Here ω_m is the radian frequency for maximum gain, $\omega_c = \sigma/\epsilon$ is the conduction frequency and $\omega_D = v_s^2/D$ is the diffusion frequency. For a given value of ω_m we see that the parameter to be varied in a given crystal is the conductivity, σ_0 .

The second difficulty with the structure of Fig. 4 is one of inadequate thermal dissipation. It is now clear that we must use a heat sink for proper thermal dissipation, and therefore the structure will have to be mounted on a crystal of good thermal characteristics.

The third problem is one of confining the active area and the crystal to a small portion of the crystal area. Our acoustic beams are typically 1/2 mm in diameter and it is inefficient to use an active semiconducting crystal with an area that is in excess of this. Since it is desirable to work with semiconducting wafers which have rather large diameters, it behooves us to find a method of evaporating an ohmic contact over a small central area of the wafer and surrounding this with an insulating layer of some sort. This problem of using insulating layers in semiconducting devices is not uncommon, and we should be able to use the experience of other laboratories in developing a solution. We are considering the

question of depositing the active layer directly upon an appropriate substrate, discussed below.

Turning now to future activities, we propose to further pursue the investigation of acoustic amplification in the microwave range. We will continue the work on cadmium sulphide and, as the time permits, extend our studies into other materials such as CdSe and ZnO. Thin deposited films of Te, or Se, may also be investigated, since the acoustic coupling is extraordinarily high in these two materials.

In this program we have in mind two alternate approaches to the problem of device fabrication. One is to construct devices from bulk crystals which are properly oriented and mounted with ohmic contacts. The second would be to study deposited films with a thickness in the range of 50-100 microns. It is now known that films of the II-VI compounds deposit rather easily with the c-axis normal to the substrate which is proper for amplification of longitudinal waves. In those materials such as ZnO, which have relatively high electromechanical coupling constants, this thickness range should be sufficient to provide 25-30 dB of gain.

In the first system we still face problems of fabricating samples from bulk crystals with ohmic contacts over part of the crystal area and a non-ohmic overlay that will form a suitable base for the thin film transducer. At present we surround the central ohmic contact with a layer of SiO₂, but it is rather unsatisfactory since it appears to break down under high electric fields. As mentioned above, we are devoting considerable effort to thin film piezoelectric transducers and have now reached the point where they are efficient and have considerable bandwidth. We are currently incorporating the results of this work into the amplifier program. It will be necessary to mount the crystals by means of an acoustic bond to a second crystalline medium, which will serve as both a heat sink and a transmission medium for the sound waves.

In the second approach which consists of depositing films to a thickness of 50-100 microns we plan to concentrate on the problem of obtaining uniform films of high quality. We have had experience with insulating films of ZnO and CdS up to 5 microns, but beyond that we

experience problems of cracking and surface roughness. We believe it is a question of controlling the deposition rates and substrate temperature. We must also control the resistivity so that it lies in the range above 10 ohm-cm. The films must be deposited on a metallic film which will provide ohmic contact to the material. We will cover the film with a second metallic layer which will serve the dual purpose of contacting the active film and provide a base of the insulating piezoelectric film which will serve as an electromechanical transducer.

It should be pointed out that the alternative approaches to electro-acoustic amplifiers probably require a more extensive effort than can be pursued simultaneously on the NASA program, and we expect to concentrate our efforts on that approach which seems to have the most bearing on NASA interests. It is likely that some other phases of this problem will be investigated under other auspices.

With these prototype amplifiers we plan to investigate the important characteristics which are predicted from the theoretical analysis. Very little is known about the noise figure. There is good reason to believe that the noise figure should be as good as other semiconductor amplifiers in the lower frequency range and, therefore, it is worthwhile to pursue the study of noise properties both theoretically and experimentally. The saturation characteristics will also come under study in order that we may come to understand the limits on the efficiency of such a device. It has long been clear that the dc power density is very high in the bulk semiconducting material, and if a reasonable fraction of this can be converted to a useful rf output it could prove to be a most useful solid state amplifier. The question of parallel operation will also be considered, although it is not clear at the present writing how this might be accomplished.

The upper frequency limit is another question which must be investigated. We believe that this will be eventually determined by the lattice loss, since this increases with frequency faster than the electronic gain. In CdS our best estimate is that the limit is somewhere above 5 Gc. The material ZnO is much harder than CdS and exhibits less acoustic loss. This combined with the higher electromechanical coupling constant should

allow one to work at much higher frequencies in ZnO than in CdS. We think that it should be possible to work at frequencies above X-band in ZnO.

We plan to continue with the investigation of the problem of acoustic interactions with carriers drifting normal to both the electric and magnetic fields. In this system with intrinsic material containing equal numbers of holes and electrons the positive and negative particles travel in the same direction, and, therefore, the space charge does not accumulate as the particles are bunched. Again, this allows for certain flexibility in the amplifier design in that the coupling increases as the density of carriers is increased. With extrinsic materials with a single type of carrier it would appear that there are advantages to the crossed field case which could overcome the disadvantage of the addition of the magnetic field. It would appear that a material such as InSb and InAs would be proper candidates since the acoustic gain at low temperatures has been measured by workers in France. It turns out that the electromechanical coupling constant for the material is moderate and almost as strong as GaAs. Here again, we believe that it is worthwhile to study the interaction with waves propagating in films.

III. ACOUSTO-OPTICAL DEVICES

The purpose of the current activities in this area is to investigate methods for the rapid and precise electronic scanning of the direction of a light beam. During this period we have studied the possible application of Brillouin scattering of laser light by coherent microwave acoustic waves as a means of achieving this objective. The Brillouin scattering or Bragg diffraction process in principle allows the direction of a light beam to be varied by varying the frequency of the acoustic wave. The use of microwave frequencies as distinguished from lower ultrasonic frequencies may allow wide angle scan without exceeding reasonable bandwidth requirements. During the reporting period, we have made basic studies of the Brillouin scattering process, and have analyzed several approaches to applying this process to flying spot scanning.

An important consideration in the application of microwave Brillouin scattering to practical application is the diffraction efficiency, which expresses the ratio of diffracted light to incident light intensity. In this connection, we have examined the photoelastic properties of a number of crystals which are suitable for Bragg diffraction of light from a microwave acoustic column. The properties of KRS-5, crystalline thallium bromide, have been examined at 500 MHz. This follows the work of Korpel at Zenith Corporation, where he found that the diffracting power of KRS-5 at 30 MHz exceeded that of quartz by some 15 dB, i.e., the acoustic power required to scatter a given fraction of the incident light was 15 dB below that required in quartz. Our measurements have shown a similar reduction at 500 megacycles. KRS-5 is a relatively soft material, and we have found the acoustic attenuation at 500 MHz to be 5 dB/cm. This is a rather high value and would render the crystal unsuitable for acoustic frequencies above 1000 MHz. We have also examined crystalline MnF_2 and found it to offer a slight improvement over quartz. The crystal CdTe is also being tested. It is found to have high diffracting power but as yet no quantitative data have been obtained. Crystalline LiNbO_3 and AsS_3 will also be studied in connection with the present objectives.

As stated in the introductory remarks we have carried out some analysis of the problem of continuous scanning of the laser beam without mechanical motion. In scattering of light from an acoustic column, the axis of the diffracted light beam is deflected from that of the incident light beam by an angle equal to twice the Bragg angle θ_B . The latter is given by $\sin \theta_B = f\lambda/2v$ where λ is the optical wavelength and v and f are the velocity and frequency of the acoustic waves. This provides a mechanism for varying the deflection of the light beam, by varying the frequency of the acoustic waves. Since frequency can be controlled with extreme precision, very accurate control and positioning of the light beam should be possible. In the straightforward implementation of this process, a problem arises from the fact that, in principle, both the incident and deflected light beams must intersect the normal to the acoustic beam axis at angle θ_B which means that the proper direction of the incident light must change as the acoustic frequency is varied. To satisfy this condition would require rotation of the crystal in step with the variation of the acoustic frequency, if the incident light angle is to satisfy the Bragg condition at all frequencies of concern. For plane waves of broad extent, this proves to be a severe requirement, in which the total angle that can be scanned without mechanical tracking of the crystal can be reduced to unusable limits. As a result, we have studied modifications and extensions of the usual Bragg scattering procedures which are designed to overcome this limitation.

A direct approach at overcoming this limitation is that of decreasing the diameter of the acoustic column below the values employed in present Brillouin scattering experiments. If this diameter is sufficiently reduced, the acoustic column can be regarded as a line grating. In the line-grating limit, the requirements on the direction of the incident light beam disappear and the diffraction process produces a total deflection angle of $2\theta_B$ between the diffracted beam from the incident beam regardless of the direction of the incident beam. In this case, both the incident beam and the crystal may be fixed in space and the diffracted beam direction may be controlled by varying only the acoustic frequency as desired. We know that present techniques will allow a substantial

decrease in the acoustic column diameter and a corresponding decrease in the relevant optical beam dimension. In this case the optical beam would be in the form of a flat ribbon whose thickness would be comparable to the diameter of the acoustic column. As the acoustic column diameter is decreased, the diffraction efficiency could be maintained, for a given total acoustic power, by allowing the acoustic power density to increase correspondingly. The extent to which this approach can be carried will be determined by the limiting acoustic power densities which can be handled in the more highly diffracting crystals, and this question will be investigated.

A second approach to optical deflection by Brillouin scattering without rotation of the crystal involves the use of an input light beam in the form of a two-dimensional wedge of convergent ray paths, converging upon a point P_1 in space. If this beam is passed through a suitable acoustic column in a transparent crystal ahead of the point P_1 , a portion of this beam will be coherently scattered into a diffracted beam which appears to diverge from a conjugate point, P_2 , which is the mirror image of point P_1 with respect to the axis of the acoustic column. At a given acoustic frequency, the diffracted wedge will subtend at point P_2 an angle $\Delta\theta$ which can be chosen to be a fraction of the wedge angle θ of the incident beam at P_1 . As the acoustic frequency is varied, this diffracted beam can be continuously scanned in direction throughout a total angle equal to the angle θ of the incident wedge, while the crystal remains fixed in space. If the acoustic frequency is in the microwave range, relatively large angular deflection could result without the requirement of large system bandwidth. This system could serve as a frequency-controlled beam positioner or flying-spot scanner, and could also perform as a non-scanning spectrum analyzer with optical readout.

The above schemes for optical beam steering involve first-order Brillouin scattering processes. We have also devised second-order processes which offer controlled optical beam deflection without mechanical rotation of the crystal. For these schemes we plan to investigate the light scattering from an acoustic column generated in a nonlinear

medium by two crossed acoustic beams. The nonlinearity of the medium can be exploited to produce an acoustic beam which is equal to the vector product of the two incident acoustic beams. We denote the wave propagation vector of the first beam by \vec{k}_1 and the second beam by \vec{k}_2 . The directions of \vec{k}_1 and \vec{k}_2 are fixed but the magnitudes can be varied by changing the acoustic frequencies. The product wave, as generated in the presence of the nonlinearity, will have a wave vector \vec{k}_3 given by $\vec{k}_3 = \vec{k}_1 + \vec{k}_2$. In this equation we see that it is possible to vary both the magnitude and direction of \vec{k}_3 by varying only the magnitudes of \vec{k}_1 and \vec{k}_2 . Thus, varying the magnitude of \vec{k}_3 is equivalent to varying the acoustic frequency of a single beam and varying the direction of \vec{k}_3 is equivalent to varying the direction of propagation of a single beam through mechanical rotation of the crystal. It therefore follows that one can achieve an acoustic wave vector that varies both in magnitude and amplitude. Light scattering from such a wave will give a deflected beam of constant intensity whose angle can be continuously varied without mechanical rotation. Here, the disadvantage comes from the required values of the acoustic power in the two crossed beams. The product wave is a second-order effect and therefore rather weak. However, we have made a preliminary investigation of some materials by measuring the second harmonic acoustic power generated by a single beam. These numbers give us reason to believe that the mechanism could be made to work as a practical system. In addition, we note that workers at Bell Telephone Laboratories at Murray Hill have also studied second harmonic sound generation in CdS and have found that carriers drifting at the velocity of sound enhance the effective elastic nonlinearity to the point where the second harmonic sound can be an appreciable fraction of the primary power. It is our opinion that this could be exploited to produce a product acoustic wave with a wave vector equal to the sum of the two primary beams which is of sufficient amplitude to produce an optical intensity in the deflected beam that would be of practical value. If we then place the scattering crystal within the optical cavity of a laser, the output beam might be comparable to that emerging from the partially transmitting end mirrors.

The theory of second order Bragg scattering has been worked out as a parametric process which involves the successive scattering of a light beam from two acoustic columns. The work is to be described in a forthcoming paper. As a preliminary effort to the experimental program in this area we have begun to measure acoustic nonlinearities in a few selected crystals. We are obtaining this information by studying the growth of second harmonic sound energy as generated by an intense acoustic beam propagating down an acoustic axis. We believe that a number of interesting schemes for light deflection and modulation may come from this study if we can uncover a material with a strong nonlinearity.

Experimental studies of optical beam deflection by coherent microwave Brillouin scattering will be undertaken during the coming period. Also, the considerations involved in the schemes just discussed emphasize the need for continuing materials study as outlined in the beginning of this section, and this type of activity will remain active during the coming period.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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