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FOR

SOLID-STATE MICROWAVE RESEARCH

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ABSTRACT

A brief discussion is given on the parametric interactions expected in vanadium doped cadmium sulfide. Recent experimental work by Nill suggests that these effects will be much larger than those observed in MgO.

Extensive experimental work on observing radiation from GaAs samples is reported for both n-type and p-type units of various doping concentrations. Small area samples have been studied and the radiation appears to be concentrated in the 4-40 micron wavelength range. New samples are being studied and considerable attention is being directed to the contact problem.

The theory of deformation potential phonon-wave amplifiers is outlined and discussed. Different coupling mechanisms are considered, and the effects of drift fields and frequency are considered. A spin-wave transducer program has been initiated and the use of thin CdS films, such as microwave coupling transducers, is outlined.

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Scientific and Engineering Personnel		Time Worked in Man Months*
J. Rowe	Professors	.56
C. Yeh		.70
W. Rensel	Assistant Research Engineer	.46
D. Hanson	Research Assistants	2.27
A. Heath		.27
J. King		1.53
R. Maire		.27
Service Personnel		6.40

* Time Worked is based on 172 hours per month.

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1. General Introduction (J. E. Rowe)

The purpose of this research study is to investigate the general characteristics of high-frequency (microwave) interactions in bulk semiconductors. The program is a general one concerned with the generation, amplification and detection of coherent electromagnetic energy in the centimeter through optical regions of the electromagnetic spectrum.

Although the general areas of study under this program cover a wide range of topics, the initial studies have been specialized to the following areas:

a. Phonon interactions in solid-state materials.

b. Generation in and radiation from solids.

c. Acoustic-wave interactions, including both longitudinal and shear mode excitations.

As each of the investigations progress it is planned that specific experiments will be designed to check the theoretical results. Each of the above topics is discussed in detail in the following sections of this report.

2. Phonon Interaction in Solids (J. E. King)

2.1 Introduction. The first half of the quarter was spent revising the spectrometer and obtaining performance characteristics of the system. Consistent results have been obtained for the cavity outside the dewar. By placing the cavity in the dewar, considerable loss of signal is obtained mainly due to eddy current losses in the metal dewar.

During the second half, work was stopped while Mr. King was on leave.

A literature search was conducted for nonlinear acoustic effects in CdS. The most interesting article is reviewed below.

2.2 Literature Review. Nill[1] points out several interesting effects associated with piezoelectric semiconductors such as CdS. Phonon-phonon nonlinear effects are not only due to anharmonic lattice effects, but can also be caused by bunching of the electrons by the high-power acoustic-wave interactions through the piezoelectric constant. This causes interaction with a second acoustic wave of different frequency in the usual parametric sense.

This particular effect should be important for parametric amplification in CdS:V. This means that, as Nill points out, there is an observable phonon-phonon scattering. This interaction is a consequence of the nonhomogeneous elastic constant resulting from the presence of space charge and takes place with perfectly harmonic lattice forces. For photoconducting CdS, it is possible to alter the space charge by changing light intensity. This means that it might be possible to control the nonlinear phonon-phonon interaction with light.

The second conclusion is that it is possible to achieve nonlinear interactions even with harmonic lattice forces. This means that the proposed parametric amplifier should work and be considerably better than the effects reported by Shiren[2].

1. Nill, K. W., "Piezoelectric Coupling Between Ultrasonic Waves and Free Electrons in Cadmium Sulfide", Tech. Report 181, Laboratory for Insulation Research, Massachusetts Institute of Technology, ASTIA No. AD 414 853; July, 1963.

2. Shiren, N. S., "Ultrasonic Traveling-Wave Parametric Amplification in MgO[1]", Appl. Phys. Letters, vol. 4, No. 4, pp. 82-85; February 15, 1964.

2.3 Spectrometer. Most of the circuits of the laboratory-built spectrometer have been revised. In addition the signal generator has been repaired and the audio oscillator replaced. Gain-frequency plots of the amplifiers have been obtained. The performance characteristics of the detector have been measured. The signal level has been plotted as a function of modulating field amplitude and also as a function of modulating frequency. The latter plot indicates the effect of eddy losses in the metal dewar. Further revision of the squarer circuit in the phase sensitive detector is planned.

The X-band cavity is very sensitive to vibrations and in particular tends to resonate with the modulating field at various frequencies. To eliminate this, the cavity will be rebuilt. This will considerably reduce the noise present in the system.

2.4 Program for the Next Quarter. The squarer circuit will be revised. In addition, the cavity will be rebuilt. Further work will be done on the spectrometer and acoustic parametric interaction will be attempted.

3. Radiation from Solids (D. C. Hanson)

3.1 Introduction. During the previous quarterly reporting period, data were presented showing the existence of far infrared radiation measured with a Perkin Elmer Model 301 grating spectrometer. A threshold for radiation was detected at 90 amps/cm^2 with a linear variation of power output with applied current density. Tentative conclusions from reststrahlen filter measurements indicated that the radiation was concentrated in the region between 100 μ - 1000 μ.

During this reporting period this radiation spectrum has been investigated with two other infrared spectrometers with a higher degree of spectral purity. These tests, along with transmission filter tests, have determined that the radiation is concentrated in the 4 μ - 40 μ region.

During this quarter additional GaAs structures of both n-type and p-type doping concentrations have been received and an investigation has been initiated with smaller area structures. This will allow the higher current density pulses and electric fields required for the observation of microwave radiation without destroying the GaAs structure.

3.2 Far Infrared Spectrometer and Filter Measurement with Golay Cell Detector. In order to investigate the far infrared region where water vapor absorption is predominant, a vacuum spectrometer is required. Such an instrument was designed by Randall[1] in the late 1930's. This instrument is still in use and has recently been improved with a better far infrared spectral purification system. Since transmission and reststrahlen materials with good band characteristics have not been found in the region beyond 100 μ, this instrument uses three gratings in zeroth order with alternating polarity to eliminate shorter wavelength radiation.

With this instrument set to eliminate radiation shorter than 100 μ, it was determined that with current densities up to 715 amps/cm^2 (the highest investigated in the previous Perkin Elmer Model 301 spectrometer data) no radiation could be detected beyond 100 μ. Subsequent tests

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1. Randall, H. M., "The Spectroscopy of the Far Infrared", Rev. of Mod. Phys., vol. 10, pp. 72-85; January, 1938.

established that the observed radiation is concentrated in the region between 4 μ and 40 μ. These included the following transmission filter tests:

a. The reference condition was established by transmitting directly into a Golay cell with a diamond window. Diamond has a flat transmission characteristic[2] for wavelengths longer than 1 μ, except for a sharp absorption band at 5 μ, thus its reference output will be considered 100 percent.

b. A glass slide (which transmits[2] wavelengths shorter than 2.6 μ) reduced the relative output of the diamond window Golay cell to the point where it could not be detected, indicating that the majority of the radiation is longer than 2.6 μ.

c. A quartz window (which has an absorption band between 4.5 μ and 44 μ) reduced the relative output of the diamond window Golay cell to about 5 percent of full scale.

d. A potassium iodide window (which has a flat 80 percent transmission characteristic[2] between 0.25 μ - 35 μ) reduced the relative output of the diamond window Golay cell to 72 percent of full scale.

Thus it is apparent that the majority of the radiation is between 4 μ and 40 μ.

The tentative conclusions previously deduced from the radiation date with variation in the grating angle and reststrahlen filter absorption must thus be re-evaluated. It is apparent that specular reflection from the grating blaze angle occurred for radiation in the 4 μ - 40 μ region, which is shorter a wavelength than that normally studied with the Model 301 spectrometer. The reduction in the radiation intensity

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2. Smith, R. A., Jones, F. E. and Chasmar, R. P., Detection and Measurement of Infrared Radiation, Oxford Press, London; 1957.

using reststrahlen filters of KRS-5 and CsBr, as shown in Fig. 3.3 of Interim Scientific Report No. 3, has the correct relative absorption to indicate radiation longer than 150 μ (where these filters are used in this instrument). But in addition the same relative absorption occurs[3] in the region from 4 μ to 40 μ, where these filters are not normally used due to considerably higher absolute absorption. In the region from 40 μ - 150 μ the CsBr reststrahlen filter is normally used.

Another factor which led to the tentative conclusion of the previous quarterly report was the data in Fig. 3.5 of that report which shows the linear detected output power variation with current density. Since it now appears that the majority of the radiation is between 4 μ and 40 μ, it might be immediately concluded that the detected radiation must be thermally generated. However, this is contrary to the Wien thermal radiation law which states that the power at the maximum is proportional to T^5. Since the thermal power is proportional to I^2, as the current density is increased from 200 amps/cm^2 to 283 amps/cm^2, the thermal power at the maximum should increase by a factor of 32. Figure 3.5 showed that the detected radiated power increased linearly with current and only by a factor of 1.75.

Since the measured variation of power output vs. current density appears to be significant, it was measured again with a different Golay cell which also had a diamond window. A different GaAs structure was used with 66 percent of the surface area of the structure used in the previous experiment. The output peak-to-peak voltage of the amplified Golay cell signal was measured directly on an oscilloscope. Again a

3. Mitsuishi, A., Yamada, Y. and Yoshinaga, H., "Reflection Measurements on Reststrahlen Crystals in the Far-Infrared Region", Jour. of Soc. of Am., vol. 52, pp. 14-16; January, 1962.

linear variation of power output with current density was detected with the curve being asymptotic to 85 amps/cm^2 at the threshold.

3.3 Perkin Elmer Prism Spectrometer Experiment. Results presented in the previous section established that the detected infrared radiation was concentrated in the region between 4 μ and 40 μ. Because of the linear variation of detected infrared power output with applied current density, it was desired to examine the 4 μ - 40 μ region in detail. An available Perkin Elmer 12C prism spectrometer was located for this purpose. Such a prism device is advantageous since it eliminates the problems associated with higher-order mode rejection if a prism with sufficient dispersion is available in the region of interest. To cover the region from 4 μ to 20 μ, a NaCl prism is available in this instrument.

Considerable preliminary work was required to investigate and synchronize this spectrometer with the pulsed GaAs source; however, when this was completed no infrared signal could be detected with the internal thermocouple detector even when the optical dispersion path through the prism was eliminated with a plane mirror reflector. Thus, subsequent tests included removing the remote thermocouple detector and mounting a Golay cell detector. This established that the instrument was working correctly; however, as the separation between the source mount and Golay cell was increased, the detected signal dropped off rapidly due to the solid angle subtended by the source radiation. It is concluded that to use this instrument a converging reflector of lens is required; however, since neither was immediately available, this experiment was discontinued temporarily due to the receipt of additional GaAs structures form Texas Instruments. This interesting experiment will be returned to at a later date.

3.4 Development of Small Area GaAs Structures. Work has continued to improve the technique for making smaller area GaAs structures. After several attempts using a grinder and ultrasonic cutter gave negative results, a lathe-type jig was designed and built. This apparatus allows a concentric pin to be locked in place with uniform pressure on the gold contact above the crystal. Gears drive the concentric pressure pin and heat sink at the same angular rate. With this arrangement good structures 0.020 inch on a side have been made and it appears that structures 0.015 inch on a side can be made.

By the jig arrangement described above it is possible to produce mounted structures with about 3×10^{-4} inch^2 cross-sectional area. However, mechanical grinding or filing damaged the crystal structure when attempts were made to reduce the area further. For this reason it was decided to try to cleave structures of the desired size before mounting in order to eliminate any further mechanical operations and still expose a clean surface for radiation studies.

The procedure involves initial scribing and cleaving (breaking along the scribed line with the structure held between glass slides) of the 0.080 inch x 0.080 inch structures into four 0.040 inch x 0.040 inch structures. One of the 0.040 inch square structures is then scribed again approximately 0.008 inch from one edge to form a slab approximately 0.008 inch x 0.040 inch from which 0.008 inch x 0.008 inch final structures can be cleaved. This small area GaAs square is then carefully placed on a coaxial square stud (with approximately the same area) of the heat sink and a 0.001 inch x 0.008 inch x 0.008 inch gold contract is positioned above. The entire unit is soldered together at 125°C with moderate pressure.

3.5 New Group of GaAs Structures and Initial Pulse Experiments. During the middle part of this reporting period, four groups of six GaAs structures each were received. They are 0.080 inch squares covered on their large area, rhodium plated, surface with approximately 0.003 inch of indium-tin solder to form ohmic contacts. These structures have characteristics as shown in Table 3.1.

Table 3.1

GaAs Structures

No.	Material Type	Carrier Concentration	Dopant	Resistivity (Ω-cm)
1	n-type	$5 \times 10^{16}/cm^3$	not doped	0.10
2	n-type	$1 \times 10^{18}/cm^3$	tellurium	0.0008
3	p-type	$1 \times 10^{17}/cm^3$	zinc	0.05
4	p-type	$1 \times 10^{18}/cm^3$	zinc	0.027

The lower carrier concentration in each material type represents the lowest uncompensated material available from Texas Instruments in the stated configuration. For lower carrier concentration, and thus higher resistivity, it is necessary to compensate the material. This has the limitation of not being able to isolate the type of scattering (attractive or repulsive) occurring from impurity centers. However, it has the advantage that small area structures with total resistances near the normal 50 ohm generator impedance can be constructed.

Small area structures of the undoped n-type GaAs material ($n = 5 \times 10^{16}/cm^3$) have been mounted. The measured pulse resistance of these structures is approximately 4.25 ohms. Using the data of the previous table, the calculated area is $(0.061)^2$ inch^2 for this total resistance, assuming negligible contact resistance.

Pulse studies using these mounted structures have begun. Previously reported experiments, with structures formed by different methods, have indicated that current densities of approximately 7500 amps/cm^2 at an electric field of 3000 v/cm are required to observe microwave oscillations, thus a pulse source with high pulse current capability is required.

The experimental circuit is completely in N-type coax in order to minimize mismatch problems. A special component has been made to facilitate positioning resistors in series and shunt with the radiation mount along the center conductor of N-type coax. This is necessary since the pulse sources prefer to work into at least 50 ohms rather than the less than 5 ohm resistance of the GaAs structure and possible shunting resistor. Two different pulse generators have been used in the initial experiments to observe an oscillation threshold. The first, a Clegg Laboratories pulse amplifier, is capable of producing pulses of 250 V into 50 ohms. The second, a Narda Model 10010 pulse generator, is capable of delivering up to 16 amperes of pulse current at 20,000 volts in 250 n sec pulses and is normally used for magnetron and klystron studies.

Using a Tektronix Model 661 sampling oscilloscope, a threshold condition was observed during initial pulsing. This occurred when the structure resistance was considerably higher than 5 ohms and nonlinear, i.e., before good linear ohmic contacts were formed and the final structure resistance reduced to 4.25 ohms. Subsequent tests included varying the external shunt resistance, but threshold instabilities have not been observed to date after the 4.25 ohm linear structure resistance was formed even though the current density and applied electric field exceed that reported elsewhere[4] for the onset of bulk instabilities. This may be due to the fact that with these GaAs structures the ohmic contacts are not diffused into the material as reported elsewhere[4] but rather are obtained by plating the GaAs surface with rhodium. This allows the formation of an ohmic contact between a layer of indium-tin solder and the rhodium-plated crystal surface but the boundary condition between the contact and the crystal will undoubtedly be different in this case than with diffused contacts.

3.6 Program for the Next Quarter. Work will continue to investigate small area GaAs structures of both n-type and p-type doping for the consistent observation of a microwave radiation threshold. Contracts and surfaces will be investigated to try to eliminate nonlinear contact conditions and the possibility of surface conduction.

4. Traveling-Wave Phonon Interaction (J. E. Rowe, C. Yeh)

4.1 Introduction. The research during this period has progressed along two specific lines. In the theoretical phase, the discussion of traveling-wave phonon interaction has been extended to include a new approach advanced by Spector[1]. His approach is based upon the degenerate statistics of the semiconductor carriers and the Boltzmann transport equation. It seems to be somewhat more general than other approaches on two accounts. First, in the coupling mechanism between the phonon wave and the drifting electrons, he assumes the presence of a deformation

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4. Gunn, J. B., "Instabilities of Current in III-IV Semiconductors", IBM Jour., vol. 8, pp. 141-159; April, 1964.

1. Spector, H. N., "Amplification of Acoustic Wave Through Interaction with Conduction Electrons", Phys. Rev., vol. 127, No. 4, pp. 1084-1090; August 15, 1962.

potential. However, his theory can easily be extended to cover the other coupling mechanism, i.e., the piezoelectric coupling mechanism, by simply adding a new term to that effect. Second, his treatment is applicable to higher frequencies at which the acoustic wavelength in the crystal is comparable or even shorter than the mean free path of the carriers. In this report, Spector's results will be converted to a form consistent with the notations used in our research.

In the experimental phase of this investigation a transducer research program has been initiated. It is well known that one of the principle limitations to acoustic-wave amplifier performance is the very high coupling loss associated with the usual $\lambda/2$ X-cut quartz transducers which are in general glued to the piezoelectric material. In addition to high coupling loss such transducers are generally limited to the frequency region below 1 Gc. The preparation of CdS thin film transducers and methods for evaluating the transducer coupling losses are discussed in this report.

4.2 Gain Equations for the Phonon-Wave Amplifier-Transverse-Wave Mode. For materials with large piezoelectric constants compared to the deformation potential the piezoelectric effect can be used to advantage in phonon-wave amplifiers. For example, the piezoelectric constant of CdS at frequencies up to 10^{13} cps is several orders of magnitude larger than its corresponding deformation potential. Spector carried out the derivation of this case for a transverse-wave mode. These equations are presented below in converted form for piezoelectric effect devices.

For low frequencies such that $\lambda > \ell$, i.e., for the acoustic wavelength greater than the mean free path of the carrier, [or $q\ell < 1$]*,

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* Notations in the square brackets are those used by Spector.

and for the condition that the piezoelectric effect is greater than the deformation potential and that $(\omega/\omega_c)(e_{xz}/\epsilon_o E) > 1$, [or $ed_{xz} > qC_{xz}$, $(\omega/\omega_p^2)(ed_{xz}/mv_s) > 1$], Spector's equation for α is just that derived by Hutson, et al.[2]. (See the detailed reduction in the Monthly Progress Report for 15 May 1964.) However, for high frequencies, $\lambda < \ell$, [or $q\ell > 1$, $(\omega/\omega_p^2)(ed_{xz}/mv_s) > 1$],

$$[\alpha] = \frac{\gamma(1-\gamma)^2 \dfrac{\omega^2}{\omega_c\ \omega_D}}{\left[1 + (1-\gamma)^2 \dfrac{\omega^2}{\omega_c\ \omega_D}\right]^2}\ , \qquad (4.1)$$

where $[\alpha]$ is the normalized gain (or attenuation) factor defined previously. Of course the piezoelectric constant and the elastic constants used for the normalization are those corresponding to the transverse-wave mode. Equation 4.1 differs from Spector's original equation by a factor γ. If straightforward conversion were made, the numerator of Eq. 4.1 would contain a term γ^2. It is believed that the original equation has a misprint. Since $\gamma = 1 - u_o/v$, $[\alpha]$ becomes negative (amplification) only when $u_o > v$. Having a γ^2 term as a multiplier in the numerator destroys this property and $[\alpha]$ will always be positive, i.e., amplification is impossible. Using $\omega_d \triangleq (v/u_o)^2\omega_D$ as previously, Eq. 4.1 can be rewritten as

$$[\alpha] = \frac{\dfrac{\gamma\omega^2}{\omega_c\ \omega_d}}{\left[1 + \dfrac{\omega^2}{\omega_c\ \omega_d}\right]^2}\ . \qquad (4.2)$$

2. Hutson, J. H., McFee and White, D. L., "Ultrasonic Amplification in CdS", Phys. Rev. Letters, vol. 7, pp. 237-239; September 15, 1961.

$[\alpha]$ has a maximum at $\omega^2 = \omega_c \omega_d$. It decreases very rapidly toward both the high and low frequency ends, at frequencies for which $\omega^2/\omega_c\omega_d > 1$, $[\alpha] \propto \omega_c\omega_d/\omega^2$; in other words, the gain is inversely proportional to the square of the frequency at a fixed product of $\omega_c\omega_d$. This is in disagreement with the prediction from our previous equation and represents a more realistic one as indicated by most experimental results. (See Eq. 4.12b, Monthly Progress Report of 15 May 1964.) This is to be expected since our previous equation is not expected to be valid at frequencies such that $\lambda < \ell$.

4.3 Gain Equations for the Phonon-Wave Amplifier Using the Deformation Potential as a Coupling Mechanism. As phonon waves propagate within the crystal, the momentary change in compression (in a longitudinal wave) produces local variations in the size and shape of the unit cell. The changes in lattice constant will thus change the energy-band structure in the crystal. The change in energy-band boundaries may be seen to be substantially equivalent to the introduction of a varying potential for an electron which is referred to here as the deformation potential. This effect is in general quite small in most crystals. Particularly for piezoelectric materials, the effect of deformation potential may be negligible in comparison with the corresponding piezoelectric effect. However, certain semiconductors which may be chosen for the phonon-wave amplifier due to their high carrier mobility may not have the desired piezoelectric effect, while the effect due to the deformation potential may be significant. A typical material of this kind is a very pure n-type InSb. It has a mobility of 5×10^5 cm^2/volt-sec and the deformation potential constant C is about 10 ev.

Spector's equations for [α] for the longitudinal and transverse waves using deformation potentials are rewritten in terms of our present notation as follows (the details of conversion are omitted):

a. For the longitudinal wave (Equation 3.5b in Spector's paper) for $\lambda > \ell$, $(\omega/\omega_c)(kC/qE) > 1$,

$$\alpha = \frac{N_o qE}{3c_z} \frac{\gamma\left(\frac{\omega}{\omega_c}\right)^2 \frac{k^2 C_{zz}^2}{q^2 E^2}}{\left(\gamma \frac{\omega}{\omega_c}\right)^2 + \left[1 + \frac{\omega^2}{\omega_c \omega_D}(1-\gamma)^2\right]^2} , \qquad (4.3)$$

where C_{zz} is the deformation potential constant in the z-direction and c_{zz} is the elastic constant in the same direction. E is the drift field in the same direction.

For $\lambda < \ell$,

$$\alpha = \frac{\pi N_o qE}{2c_{zz}} \frac{\gamma(1-\gamma)^2 \frac{\omega}{\omega_D}\left[1 + \frac{\omega}{\omega_c} \frac{kC_{zz}}{qE}\right]^2}{\left[1 + \frac{\omega^2}{\omega_c \omega_D}(1-\gamma)^2\right]^2} . \qquad (4.4)$$

b. For the transverse wave for $\lambda > \ell$, $(\omega/\omega_c)(kC_{xz}/qE) > 1$,

$$\alpha = \frac{N_o qE}{c_{xz}} \frac{k^2 C_{xz}^2}{q^2 E^2} \frac{\gamma\left(\frac{\omega}{\omega_c}\right)^2}{\left(\gamma \frac{\omega}{\omega_c}\right)^2 + \left[1 + \frac{\omega^2}{\omega_c \omega_D}(1-\gamma)^2\right]^2} . \qquad (4.5)$$

For $\ell > \lambda$, $(\omega/\omega_c)(kC_{xz}/qE) > 1$,

$$\alpha = \frac{\pi N_o qE}{2c_{xz}} \frac{k^2 C_{xz}^2}{q^2 E^2} \frac{\gamma(1-\gamma)^2 \frac{\omega}{\omega_D}\left(\frac{\omega}{\omega_c}\right)^2}{\left[1 + \frac{\omega^2}{\omega_c \omega_D}(1-\gamma)^2\right]^2} . \qquad (4.6)$$

The physical significance of these equations will be discussed in the next report.

4.4 Discussion of Gain Equations-Deformation Potential. A detailed analysis of the equations in the preceding sections is still in progress, however, a few pertinent points of interest can be observed directly. It is observed that the effect of the deformation potential on the gain equation resembles that of the piezoelectric effect in that the gain is proportional to either the square of the piezoelectric coefficient "e" or to the square of the deformation potential "C". Furthermore, the gain equations for the longitudinal mode differ from those for the transverse mode only by the proper choice of the elements of the deformation potential matrix and the elastic constant matrix respectively. Analysis of the gain equations for this drift and frequency dependence is complicated by the fact that the E field and ω appear in many places both in the numerators and denominators and a universal chart cannot be constructed. Further rearrangement of the terms is necessary in order to have a better picture of these effects.

4.5 Microwave Aspect of the Traveling-Wave Phonon Interaction. The question of extending the theory of traveling-wave phonon interaction to microwave frequencies has been a subject of intensive discussion in recent years. In fact, many authors have revealed their optimistic views about this extension. Spector[1], by introducing the deformation potential in computing the gain of a traveling-wave phonon interaction, has given hope to use materials other than CdS whose mobility is too low to be used at microwave frequencies. For successive operation, in order to reduce the acoustic attenuation within the crystal at microwave frequencies, the crystal has to operate at a reduced temperature, say below 20°K. At this temperature, the mobility of the carriers in the crystal is greatly reduced and thus requires a high electric field to achieve the critical drift velocity needed for proper interaction. High electric field gives rise to higher dissipation which in turn heats up the crystal and produces other undesirable nonlinear effects. Materials such as GaAs and InSb have mobility of the carriers many thousand times larger than that of CdS and are therefore better materials to use at microwave frequencies. The lack of a piezoelectric effect in InDb in comparison to CdS is compensated by the deformation potential developed in the crystal when it is subjected to strain. Pauwels[3] has computed the gain/cm of InSb using Spector's formula and found a gain of $\alpha = 5$ db/cm under an electric field of $E = 8$ volts/cm at $f = 10$ Gc/sec. Higher gain is obtained by using GaAs. In fact, in GaAs, the piezoelectric effect is several times larger than the deformation effect and can therefore be used promisingly at microwave frequencies. However, experimental evidences to substantiate these claims are still lacking. In fact, Conwell[4], in a paper published just recently, argued that the extimation of gain at microwave frequencies using the low-field parameters of the crystal may lend to very optimistic

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3. Pauwels, H. J., "Possibilities of Amplification of Sound Waves at Microwave Frequencies", Proc. IEEE, vol. 52, No. 3, p. 300; March, 1964.

4. Conwell, E. M., "Amplification of Acoustic Waves at Microwave Frequencies", Proc. IEEE, vol. 52, No. 8, pp. 964-965; August, 1964.

results. Power dissipated in the crystal heats the carriers. The increase of electron temperature effects its mobility which in turn changes the diffusion frequency ω_D. The effect is to reduce the gain. Conservative calculations, taking into account the increase of electron temperature due to power dissipation, fix the decrease in gain by a factor as large as 10-50 depending upon the materials used.

4.6 Phonon-Wave Amplifier Transducers. During the past month a CdS rod has been equipped with thin film diffused copper layer transducers and is mounted in a coaxial line structure. Such a transducer should operate at high frequencies although no specific experimental data is yet available. Measurements below 100 mc indicate strong echoes and suggest good coupling efficiency compared to the quartz transducers.

A more promising approach appears to be the utilization of thin insulating CdS films as transducers. The films are to be deposited by vacuum evaporation and the thickness for fundamental resonance is $t = \lambda/2$. The necessary film thickness is shown vs. frequency in Table 4.1 assuming that the compressional velocity along the c-axis of CdS is 4.4×10^5 cm/sec.

Table 4.1

CdS Film Thickness vs. Frequency

$v = 4.4 \times 10^5$ cm/sec

f(Gc)	Thickness $t = \lambda/2$
1	2.2 microns
3	0.72 microns
10	0.22 microns
30	720 Å

50	440 Å
100	220 Å
1000	22 Å

There appears to be no reason why these transducers could not work to 1000 Gc. It is planned to investigate this type of transducer in conjunction with deformation potential devices for the microwave region.

4.7 Measurement of Coupling Loss. A successful transducer program depends greatly upon a sound measurement technique to determine the coupling loss. Ordinary microwave insertion loss technique to measure the coupling loss is not directly applicable. This is because the phonon attenuation in the solid to which the transducers are attached is also included in the measurement and must be deduced from it to get the actual transducer loss. This means that acoustic loss in the solid should be determined and invariably pulse techniques need to be used.

Several papers have been written on the measurement technique of the phonon-wave attenuation of solids at lower frequencies in the order of 100 mc and lower. Roderick and Truell[5] described a pulse technique to measure the attenuation in solids over a frequency range from 5 to 50 mc. A paper by Gobreicht and Bartschat[6] described a similar experiment. Instrumentation more directly applicable to the measurement of ultrasonic attenuation is described in a paper by Chick, et al.[7] The instrument

5. Roderick, R. L. and Truell, R., "The Measurement of Ultrasonic Attenuation in Solids by the Pulse Technique and Some Results in Steel", Jour. Appl. Phys., vol. 23, pp. 267-279; February, 1952.

6. Gobreicht, H. and Bartschat, A., "Über die Optischen und Elektrischen Eigenschatten vom Cadmium Solfid-Einkristallen", J. Physik, vol. 136, p. 224; 1953.

7. Chick, B., Anerson, G. and Truell, R., "Ultrasonic Attenuation Unit and Its Use in Measuring Attenuation in Alkali Halides", J.A.S.A., vol. 32, pp. 186-193; February, 1960.

measures the attenuation and velocity in the frequency range from 5-200 mc. Circuits for a pulse r-f oscillator, superheterodyne receiver, exponential wave-form generator, precision time delay generator, CRT display and appropriate synchronization are described in detail. In order to adapt these measurement techniques to the present problem, proper redesigning of these circuitry is necessary so that the frequency range can be extended to over 1 Gc and higher.

For the measurement of coupling loss of the transducer, a substitution method is preferred. For this purpose, two equal transducers are deposited on each side of the phonon-wave solid of the proper orientation and the total insertion loss measured by substitution. The insertion loss of the phonon-wave solid is determined by the modified Chick's method. It is modified to work into a higher frequency range and also to work on the principle of transmission stead of by a reflection method. The net insertion loss per coupler is then one half of the total insertion loss minus the insertion loss of its solid, assuming two equal transducers.

4.8 Program for the Next Quarter. The theoretical analysis of the deformation potential amplifier will be continued, particularly in the direction of evaluating the precise effects of drift field and frequency. Experiments with CdS thin film transducers and the evaluation of its coupling loss will be carried out at microwave frequencies.

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