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INTERIM SCIENTIFIC REPORT NO. 2

FOR

SOLID-STATE MICROWAVE RESEARCH

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ABSTRACT

Various electron paramagnetic resonance experiments are reviewed in an effort to determine those materials most appropriate for parametric phonon interactions. One of the most promising materials is $CdS:V^{3+}$ since the nuclear spin of 7/2 associated with the V^{51} isotope splits each fine line into eight lines. This results in a linewidth for absorption of approximately 700 gauss which is a 10 percent bandwidth at X-band.

The use of X-cut longitudinal quartz transducers resonant in the 5-40 mc region has allowed the observation of echoes up to 577 mc at room temperature. Similar results have been obtained up to 400 mc at liquid nitrogen temperature.

The theory of stimulated Bremsstrahlung radiation from solids is developed further with particular emphasis on ionized impurity scattering. Experimental observation of significant powers at microwave frequencies can possibly be explained as a result of Raman scattering by optical phonon vibrational modes due to coupling with the previously postulated radiation and subsequent down conversion to microwave frequencies.

Acoustic gain and velocity characteristics have been calculated for longitudinal mode excitation as a function of the velocity parameter u_o/v. Furthermore a general ω-k relation is derived. Possible Alfvén wave interactions in semiconductors are investigated.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

PERSONNEl

Scientific and Engineering Personnel		Time Worked in Man Months*
G. Haddad	Assistant Professor of Electrical Engineering	.30
M. Miller	Associate Professor of Electrical Engineering	.25
W. Rensel	Assistant Research Engineer	.37
D. Hanson	Research Assistants	1.09
J. King		1.39
R. Maire		.23
Service Personnel		4.35

* 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. In addition the excitation and propagation of Alfvén waves in solids is discussed.

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

2.1 Introduction. In Interim Scientific Report No. 1, phonon paramagnetic resonance was summarized and the absorption coefficients for various configurations were presented. In this quarter the electron paramagnetic resonance of these configurations was reviewed. In addition the frequency of phonon propagation was extended through use of a resonant transducer.

2.2 Review of Electron Paramagnetic Experiments. From Table 2.2, page 23, of Interim Scientific Report No. 1, the absorption coefficients for the configurations with an even number of electrons is seen to be much higher than for the configurations with an odd number. This could have been anticipated from the general results of electron paramagnetic resonance where the even configurations have a very short spin-lattice relaxation time, implying a strong coupling between the lattice and the spin of the electrons. It is because of this extremely short relaxation time that very little is known about the paramagnetic resonance spectra for the even electron configurations.

At present the even configurations have been examined mainly in cubic crystals where the spin Hamiltonian is much simpler. The original experimental work in this area was done by W. Low[1] on $Ni^{2+}(3d^8)$ and $Fe^{2+}(3d^6)$ in MgO. Fe^{2+} was also investigated in cubic ZnS but the spectra could not be interpreted.

For the $Ni^{2+}(3d^8)$ in MgO, one broad line at $g = 2.23$ was found. This again was substantiated by Walsh[2]. The linewidth is very large indicating a large dipole-dipole interaction. For the $Fe^{2+}(3d^6)$ in MgO, three lines are observed, a very narrow and a very broad line at $g = 3.427$ and a line with high-field cutoff at $g = 6.33$. The high g line is due to a forbidden transition $\Delta M = \pm 2$ and the high field cutoff is attributed to

1. Low, W., "The Paramagnetic Resonance and Optical Spectra of Some Ions in Cubic Crystalline Fields", Annals of the New York Academy of Sciences, vol. 72, Article 2, pp. 69-126; March 17, 1958.

2. Walsh, W. M., "Effects of Hydrostatic Pressure on the Paramagnetic Spectra of Several Iron Group Ions in Cubic Crystals", Phys. Rev., vol. 122, pp. 762-771; May 1, 1961.

an asymmetrical distribution of strains. These lines were only observable at liquid helium temperature (4.2°K) indicating an extremely short spin-lattice relaxation time. Recently the same type of spectra for $Fe^{2+}(3d^6)$ has been observed in CaO[3].

No results have been obtained on the $3d^4$ configuration although several people have been investigating the effect of electron trapping by $Cr^{2+}(3d^4)$ to become $Cr^{+}(3d^5)$ in ZnS[4]. The trapping occurs under stimulation by 365mμ light. It is very probable that the relaxation time is so short that electron paramagnetic resonance is not observed. This effect also has been observed in ZnSe and ZnTe[5].

The $3d^2$ configuration of V^{3+} has been investigated in several substances. It has been observed in ZnS and ZnTe cubic crystals and CdS which is a hexagonal crystal. Strain broadened transitions were observed for the $\Delta M = \pm 1$ transition and a rather sharp line for the forbidden transition $\Delta M = \pm 2$ was observed for V^{3+} in ZnS[6]. These transitions were observed at 1.3°K indicating possible short relaxation times. The $3d^2$ configuration has also been observed in hexagonal CdS[7].

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3. Shuskus, A. J., "Paramagnetic Resonance of Divalent Iron in Calcium Oxide", Jour Chem. Phys., vol. 46, pp. 1602-1604; 15 March 1964.

4. Kallmann, H., "Progress Report 20 on Paramagnetic Resonance in the Solid State", New York University; August, 1963.

5. Title, R. S., "Paramagnetic-Resonance Spectra of the $3d^5$ Configuration of Chromium in ZnSe and ZnTe", Phys. Rev., vol. 133, pp. A1613-A1616; 16 March 1964.

6. Holton, W. C., Schneider, J. and Estle, T. L., "Electron Paramagnetic Resonance of Photosensitive Iron Transition Group Impurities in ZnS and ZnO", Phys. Rev., vol. 133, pp. A1638-A1641; 16 March 1964.

7. Ludwig, G. N., and Woodbury, H. H., "Electron Spin Resonance in Semiconductors", Solid State Physics, vol. 13, p. 299, New York; 1962.

These were observed at 10°K. The nuclear spin of 7/2 associated with the V^{51} isotope (99.7 percent prevalent) splits each fine line into 8 lines. This causes a large range over which absorption would occur. The line-width is about 700 gauss which corresponds roughly to 1000 mc at 10,000 mc. In addition the zero field splitting is about 7000 mc so that two allowed lines are observed for frequencies over 7000 mc.

2.3 Material Selections. Based on the results of paramagnetic resonance and on the availability of various crystals, it is felt that $CdS:V^{3+}$ is the best material. Cadmium sulfide is readily available on the market. However, doping with Vanadium is somewhat complicated. Most investigators have tried to diffuse Vanadium in by heating the crystal for a long period of time, usually a few days. It is hoped that this crystal can be obtained commercially thus eliminating a long period of crystal processing. Several inquiries have been made regarding this material.

2.4 Experimental Results. Recently a trial package of transducers was obtained from Valpey Corporation. These transducers are gold plated X-cut longitudinal quartz units and resonant at various frequencies from 5 mc to 40 mc. A 17.5 mc transducer was selected which had electrical connections to both sides on the front surface. This transducer was bonded with Duco Cement to the ruby rod. Using this experimental setup echoes have been observed as high as 577 mc at room temperature. Phonon paramagnetic resonance was looked for at room temperature with no success. Cooling to liquid nitrogen was attempted very recently to improve the mechanical bond between the transducer and the ruby rod. The electrical connections came loose, so that an improved method of attaching leads was necessary. The leads were soldered on with Indium reasonably successfully and at the same time vacuum grease was used as a bonding agent. When cooled to liquid nitrogen this worked up to 400 mc, but with a considerable reduction in the number of echoes. Some deterioration of gold plating has been noticed and its cause will be investigated.

2.5 Program for the Next Quarter. Further studies of the even configurations of electrons of the transition metals will be made. Attempts will be made to secure a sample of CdS:V^{3+}. Extension of the frequency will be attempted and operation of liquid nitrogen temperatures will be investigated further. Also bonding materials will be investigated to find better coupling between transducer and crystal sample.

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

3.1 Introduction. In the intervening period since Interim Scientific Report No. 1 was issued, effort has been directed toward expanding and developing the background theory of Bremsstrahlung radiation which was proposed in that report as being responsible for the radiation phenomenon observed by Gunn[1]. In the first report it was shown that, based on the theory due to Marcuse[2,3], one can calculate that approximately one watt of power should be available at 1000 Gc from a small GaAs specimen with a minimum of 10^{12} impurities/cm^3 and an applied electric field of 2000-4000 volts/cm.

In addition, a preliminary investigation of a nonlinear interaction and frequency conversion mechanism based on stimulated Raman scattering has been initiated to account for the observation of approximately one watt of microwave radiation[1].

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1. Gunn, J. B., "Microwave Oscillations of Current in III-V Semiconductors", Solid State Communications, vol. 1, pp. 88-91, Pergamon Press Inc.; 1963.

2. Marcuse, D., "Stimulated Emission of Bremsstrahlung", B.S.T.J., vol. XLI, No. 5, pp. 1557-1571; September, 1962.

3. Marcuse, D., "A Further Discussion of Stimulated Emission of Bremsstrahlung", B.S.T.J., vol. XLII, No. 2, p. 426; March, 1963.

3.2 Stimulated Emission of Bremsstrahlung Radiation.

3.2.1 Scattering Mechanism. A recent paper by Muska and Yoshida[4] is apparently the first generally available publication to recognize the significance of Marcuse's theory[2,3]. This paper points out the conflict of theories as to whether radiation can be generated by ionized impurity scattering and notes the significance of scattering parallel with the applied electric field for stimulated emission of radiation. Isotropic scattering will always absorb radiation.

By expanding the theory to a Maxwellian distribution of velocities along the applied electric field and by considering the net conductivity of the scattering region, Musha and Yoshida[4] show that the region develops a negative conductance (i.e., radiates power) if the ratio of the average drift velocity to the thermal spread in velocities is greater than 0.8, for the parameter values considered. For "hot electron" conduction in a semiconductor where a scattering limited drift velocity occurs (as pointed out in the original work by Ryder[5]) this condition should be satisfied with saturated drift velocities in the range of 10^7 cm/sec. It is pointed out further that this effect is due to electron scattering from ions and is not due to two-stream instabilities or space-charge effects.

A recent report of observation of negative resistance in irradiated gas diodes[6] is interesting and relevant in two respects. First, the observed negative resistance only occurs for those gases which have a

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4. Musha, T. and Yoshida, F., "Negative Absorption Due to Coulomb Scattering of an Electron Stream", Phys. Rev., vol. 133, No. 5A, pp. 1303-1307; March 2, 1964.

5. Ryder, E. J., "Mobility of Holes and Electrons in High Electric Fields", Phys. Rev., vol. 90, pp. 766-769; June 1, 1953.

6. Forman, R., "Theory of Negative Resistance Characteristics in Irradiated Gas Thermionic Diodes", Phys. Rev., vol. 128, pp. 1487-1492; Nov. 15, 1962.

Ramsauer minimum in their electron scattering cross-section as a function of electron energy (i.e., a maximum in their mean path length). This implies that at this minimum in the scattering cross-section the electrons are selectively scattered in the forward direction, thus satisfying the conditions of Marcuse's[2,3] theory of radiation. Second, the reported characteristic dip in the current as the Ramsauer scattering minimum is encountered is synonomous with the dip in current at the onset of radiations as reported by Gunn[1].

3.2.2 Scattering Effects Observed in Semiconductors. It is apparent from a search of the literature that mobility calculation and measurement has been the predominant method of determining the validity of any scattering theory in semiconductors. The theory which has evolved from mobility studies can be utilized, however, to gain insight into the generation of radiation through scattering since the mobility depends inversely on the scattering cross-section; the same parameters as utilized by Marcuse[2] to develop his theory of radiation will be used.

It is necessary to consider scattering both from the lattice (i.e., phonon scattering) and impurity scattering. Depending on the relative purity of the specimen, the temperature range and the applied electric field, either mechanism may predominate. In relatively pure specimens of III-V semiconductor compounds, mobility theory is well correlated with experiment[7]. It has been determined that in the range above 200°K, the mobility of relatively pure GaAs is accounted for by polar lattice scattering[7].

Impurity dominated scattering is not well understood[7]; especially at temperatures above 300°K and with high electric fields ("hot electron

7. Ehrenreich, H., "Band Structure and Transport Properties of Some III-V Compounds", Jour. Appl. Phys., Sup. to vol. 32, pp. 2155-2166; October, 1961.

scattering"). Considerable discrepancies from impurity scattering mobility theory have been reported. In the initial report[8] of high-field impurity scattering in germanium, experiments justify theory only if the rate of energy loss was taken as being several times higher than that of the assumed model. More recently, it has been reported[9] that large variations in mobility occur in III-V semiconductors with the same carrier concentration and temperatures above 300°K due to an unexplained impurity scattering mechanism, although the fit is good at 78°K. A very recent calculation[10] of the high frequency resistivity in degenerate semiconductors indicates that the resistivity due to electron-phonon interaction is less than 20 percent of that due to electron-ion collisions for electron energies up to the Fermi energy. The cross-over in the effectiveness of phonon and impurity scattering occurs for electron energy about six times the Fermi energy.

Sclar[11] has reported an analysis of ionized impurity scattering in which he considers the effects of attractive, repulsive, and in a companion paper, neutral impurities. Although his results are only valid at relatively low temperatures and low fields, they are enlightening because they show that resonances in the scattering cross-section occur for attractive impurity scattering but not for repulsive impurity potentials. Predominately attractive scattering occurs with electrons as majority carriers and ohmic contacts in the n-type GaAs specimens used for

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8. Conwell, E. M., "High Field Mobility in Ge with Impurity Scattering Dominant", Phys. Rev., vol. 90, pp. 769-772; June 1, 1953.

9. Weisberg, L. R. and Blanc, J., "Evidence for a Mobility Killer in GaAs, InAs, and InP", Bull. of Am. Phys. Soc., p. 62; January 27, 1960.

10. Tzoar, N., "High-Frequency Resistivity of Degenerate Semiconductors", Phys. Rev., vol. 133, pp. 1213-1214; February 17, 1964.

11. Sclar, N., "Ionized Impurity Scattering in Nondegenerate Semiconductors", Phys. Rev., vol. 104, pp. 1548-1561; December, 15, 1956.

the Gunn experiment[1]. The significance of this calculated attractive impurity scattering resonance becomes more meaningful when coupled with the previously discussed significance of a Ramsauer minimum[6] in the scattering cross-section for observation of negative resistance due to scattering in an ionized plasma diode.

This discussion indicates that impurity scattering theory should be extended to temperatures above 300°K with high electric fields and should be coupled with Marcuse's theory of generation of radiation during scattering. It is necessary that this theory consider possible correlation effects between scattering events since Marcuse[2,3] considered a single scattering event and generalized directly to N scattering events. It is quite possible that observed discrepancies[7,8,9] in impurity scattering mobility will become apparent in this analysis as being due to generation or absorption of radiation.

3.3 Nonlinear Frequency Conversion. In order to justify the observation of microwave radiation, although the above theory indicates that power on the order of one watt will only become available at frequencies near 1000 Gc (due to the strong f^5 power dependence[3]), an investigation of the Raman scattering, frequency conversion mechanism has been initiated. No data is presently available for the exact Raman vibrational spectrum in III-V semiconductors such as GaAs, however, it will be pointed out in the following discussion that the required characteristics for strong frequency conversion coupling appear to exist.

The required condition for Raman scattering by optical phonon vibrational modes is that the mean or individual ion polarizabilities change due to coupling with radiation. This will certainly be the case in III-V semiconductors due to alternate planes of oppositely charged neuclei in a perfect crystal. Raman frequency conversion has been observed in diamond[12] which does not have this polar character and has been attributed to impurity modes which introduce a local polar character to the crystal. Similarly, it is predicted[12] that the lowest infrared absorption lines in germanium and silicon are due to impurity bands and that the Raman vibrational, optical phonon modes are within 4 percent of the observed absorption frequencies.

The infrared absorption spectrum of GaAs has been reported[13] along with the actual frequencies of the individual vibrational modes from neutron spectrometry[14]. It is significant that the phonon wave vibrational modes occur in the range from 2×10^{12} to 8×10^{12} cycles/sec. This is in the range where theory[2,3] predicts that substantial Bremsstrahlung radiation will be available. Thus it appears that the conditions for energy and momentum conservation in an interaction process can be satisfied.

It has recently[15] been reported that the coupling between electrons and polar optical-phonon vibrational modes in GaAs is very strong at 77°K. It should follow that coupling to electromagnetic radiation in the same frequency range will be strong.

3.4 Program for the Next Quarter. In the next quarter, a theoretical analysis will be initiated incorporating the radiation model and background theory presented in this report. Additional theory and observation relevant to the reported interaction mechanism will be sought.

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12. Lax, M. and Burstein, E., "Infrared Lattice Absorption in Ionic and Homopolar Crystal", Phys. Rev., vol. 97, pp. 39-52; Jan. 1, 1955.

13. Cochran, W., Fray, S. J., et. al., "Lattice Absorption in GaAs", Jour. of Appl. Phys., Supp. to vol. 32, pp. 2102-2106; October, 1961.

14. Waugh, J. L. T. and Dolling, G., "Crystal Dynamics in GaAs", Phys. Rev., vol. 132, pp. 2410-2412; December 15, 1963.

15. Ikoma, H., Kuru, I. and Hataya, K., "Optical Phonon Effects in GaAs", Jour. of Phys. Soc. of Japan, vol. 19, pp. 141-142; January, 1964.

An experimental mount similar to that proposed in Report No. 1 has been constructed with certain additional features. An experimental program, to evaluate the radiation mechanism proposed in Report No. 1 and expanded in this report, will be initiated when semiconductor specimens are received.

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

4.1 Introduction. In the previous report a detailed analysis of traveling-wave phonon interactions in bulk semiconductors was carried out with particular attention on the interaction of drifting charge carriers with longitudinal acoustic vibrations. Acoustic gain results when the carrier drift velocity exceeds the acoustic-wave velocity. Normalized gain and acoustic velocity have been calculated vs. frequency. The gain mechanism is further explored in this report and a normalized velocity [v] vs. u_o/v diagram is developed. In addition possible Alfvén wave propagation in solid-state magnetoplasmas is analyzed.

4.2 Gain Calculations. The acoustic gain parameter (negative attenuation constant) has been derived as

$$\alpha = \frac{\omega}{v} c^{1/2} I_m(c'^{-1/2})$$

$$= \frac{\omega}{v_o} \frac{e^2}{2c\epsilon} \frac{\omega_c/\gamma\omega}{1 + \left(\frac{\omega_c}{\gamma\omega}\right)^2 \left[(1-\gamma)^2 \frac{\omega^2}{\omega_c\omega_D} - 1\right]^2} , \qquad (4.1)$$

where $\gamma = 1 - \frac{u_o}{v}$,

$u_o = \sqrt{c/\rho_m}$ = the unperturbed acoustic velocity.

In Eq. 4.1 it is noticed that α is a function of many parameters. A thorough knowledge of α can help in selecting the material most useful for acoustic-wave amplifiers. It is therefore worthwhile to discuss these parameters and the effect of their variation on α. Let it be assumed that a certain piezoelectric crystal has been chosen so that the mass density ρ_m, the piezoelectric coefficient e, the elastic constant c and the dielectric constant ϵ are all fixed. There still remains to be determined such parameters as the frequency ω, the conductivity σ which is incorporated in the conduction frequency $\omega_c = \sigma/\epsilon$, the electric field E, and the mobility μ which appears both in the drift velocity u_o and the diffusion frequency $\omega_d = u_o^2/D$. Also assume that the acoustic velocity remains essentially constant within the range of operation so that the effect of these parameters on the attenuation constant α can be discussed as follows. Rewrite Eq. 4.1 as

$$[\alpha] = \frac{\alpha v_o}{\omega}\left(\frac{e^2}{2c\epsilon}\right) = \frac{\left(1 - \frac{u_o}{v}\right)\left(\frac{\omega_c}{\omega}\right)}{\left(1 - \frac{u_o}{v}\right)^2 + \left[\frac{\omega}{\omega_d} + \frac{\omega_c}{\omega}\right]^2} \quad . \ (4.2)$$

Here $\omega_d = (v^2/u_o^2)\ \omega_D$ has been redefined to remove the effect of μ and E on ω_D. $[\alpha]$ is denoted as the normalized α.

In Eq. 4.2, u_o/v appears as a discrete parameter and can be treated as a single variable. Since $u_o = \mu E_o$, and if v remains unchanged, the variation in u_o/v can be considered as either the variation of the drift field E_o for constant μ or the variation of mobility μ for constant E_o. Constant v is considered a reasonable approximation. In fact ω_c/ω and ω/ω_d are chosen so as to make v approximately constant.

The variation of $[\alpha]$ in response to the change of u_o/v can be seen from the two plots in Figs. 4.1 and 4.2. In Fig. 4.1, $[\alpha]$ is plotted as a function of u_o/v for various values of ω_c/ω while maintaining ω/ω_d constant. In Fig. 4.2, $[\alpha]$ vs. u_o/v is presented using ω/ω_d as a

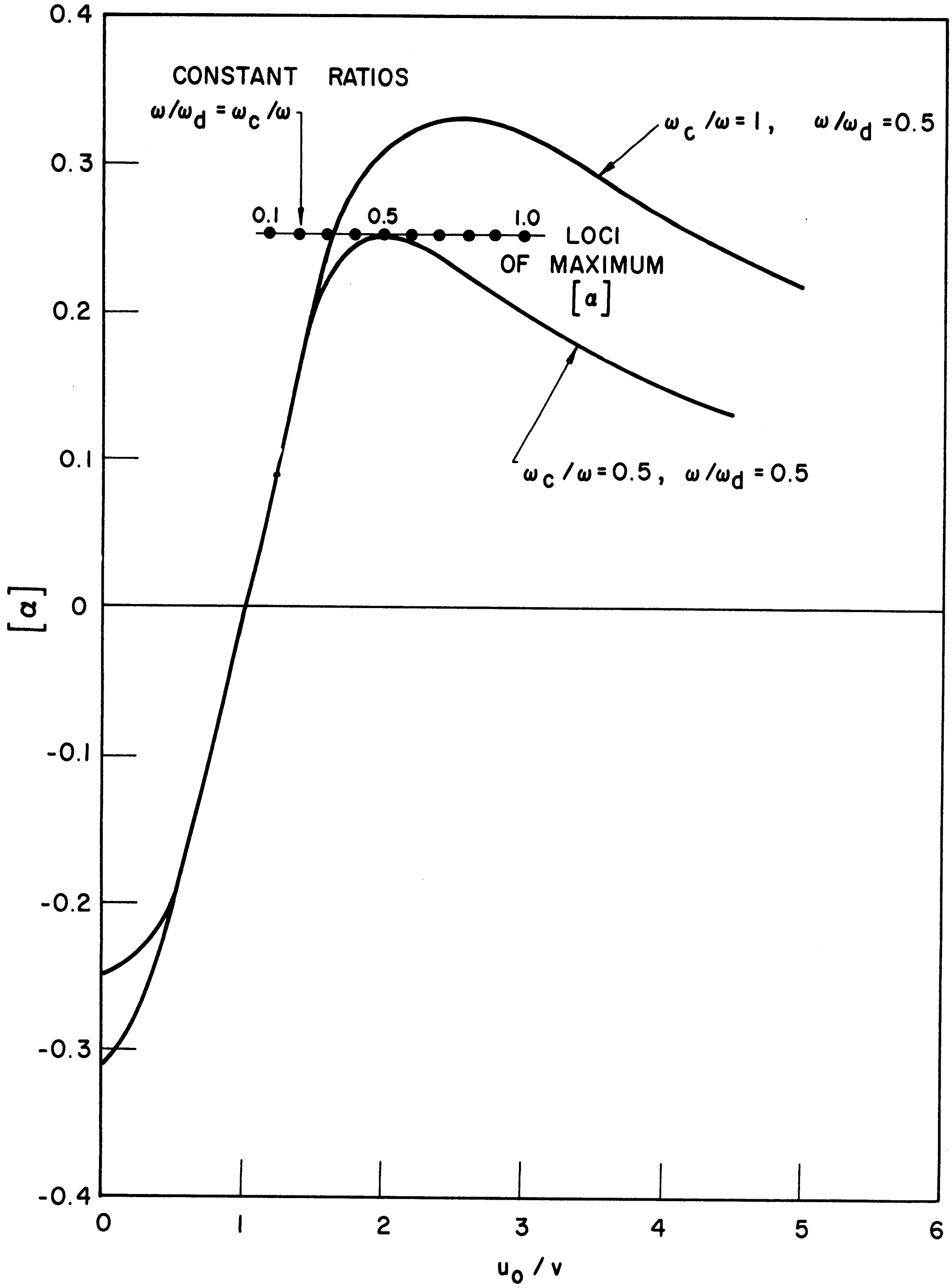

FIG. 4.1 NORMALIZED GAIN VS. THE VELOCITY PARAMETER.

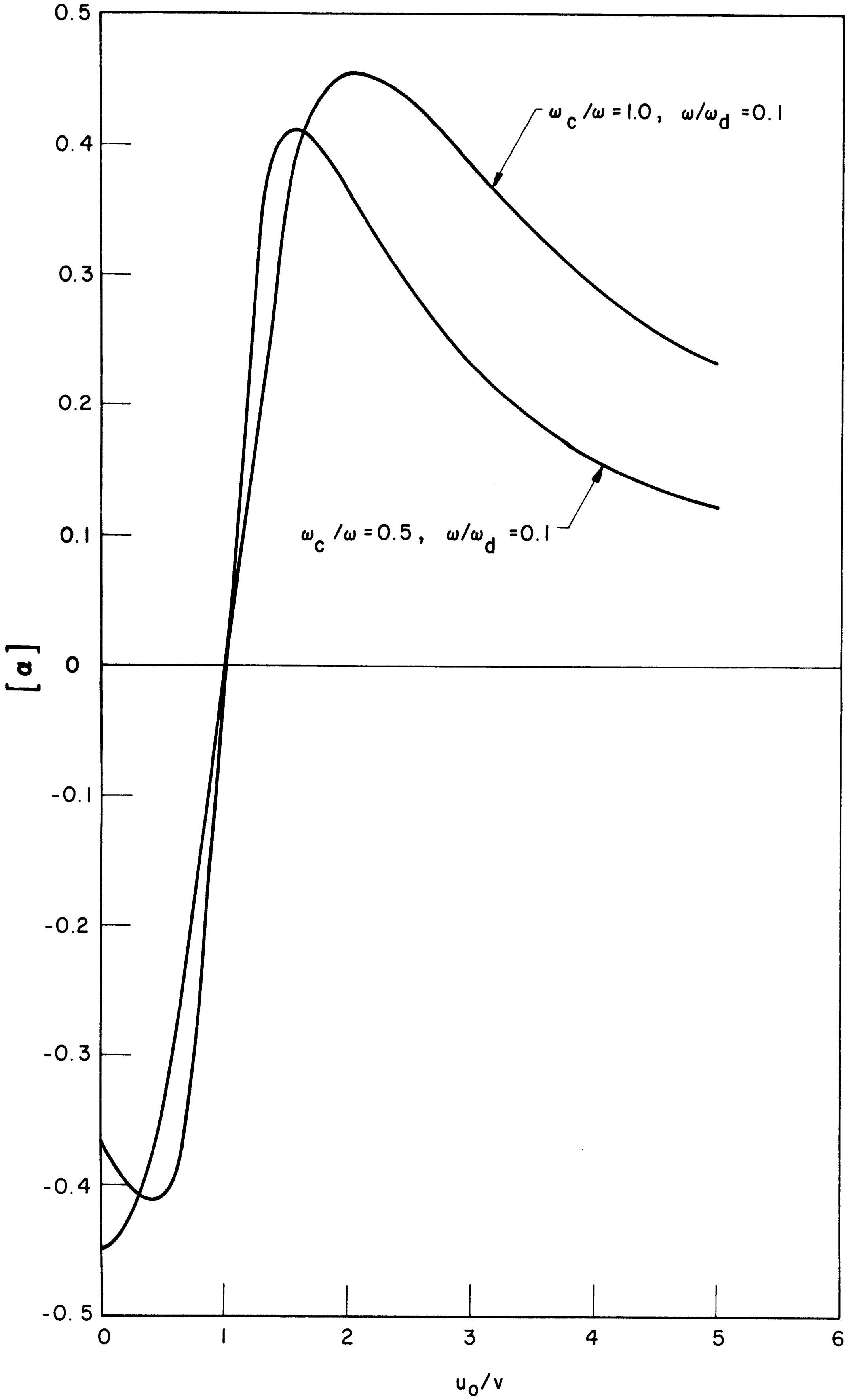

FIG. 4.2 NORMALIZED GAIN VS. THE VELOCITY PARAMETER.

parameter and keeping ω_c/ω fixed. The shapes of these curves are quite similar. The curves start to show amplification (positive $[\alpha]$)as soon as u_o/v becomes slightly greater unity. It reaches a maximum at $u_o/v = 1 + (\omega_c/\omega + \omega/\omega_d)$* and decreases monotonically thereafter for increasing u_o/v. The maximum value of the maximum $[\alpha]$ is

$$[\alpha]_m = \frac{\frac{\omega_c}{\omega}}{2\left(\frac{\omega}{\omega_d} + \frac{\omega_c}{\omega}\right)} \quad . \qquad (4.3)$$

In general, it is desirable to have the maximum gain occur at a value of u_o/v as close to unity as possible. This would mean either a lower drift field E or a lower mobility μ or both. This is possible if both ω/ω_d and ω_c/ω are less than unity, and as small as possible.

One interesting case exists if $\omega/\omega_d = \omega_c/\omega$. Under this condition $[\alpha]_m = 1/4$ and remains unchanged. This occurs at $\omega = \sqrt{\omega_c\omega_d}$, which is also the frequency at which maximum gain can be obtained if ω alone is varied. The horizontal dotted line in Fig. 4.1 with points indicating the various values of $\omega/\omega_d = \omega_c/\omega$ depicts this special case.

The maximum gain as a function of ω/ω_d for various values of ω_c/ω is plotted in Fig. 4.3. It is obvious that the maximum gain decreases as ω_c/ω is decreased. For high frequency operation, for a given crystal, the combination of lowering ω_c/ω and increasing ω/ω_d is therefore responsible for the rapid decrease in gain.

Figure 4.3 might lead one to believe that a larger ω_c, or a higher material conductivity, might be helpful in order to maintain a high

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* Note that in discussing the amplification of the device, one is only interested in that portion of the solution where $[\alpha] > 0$.

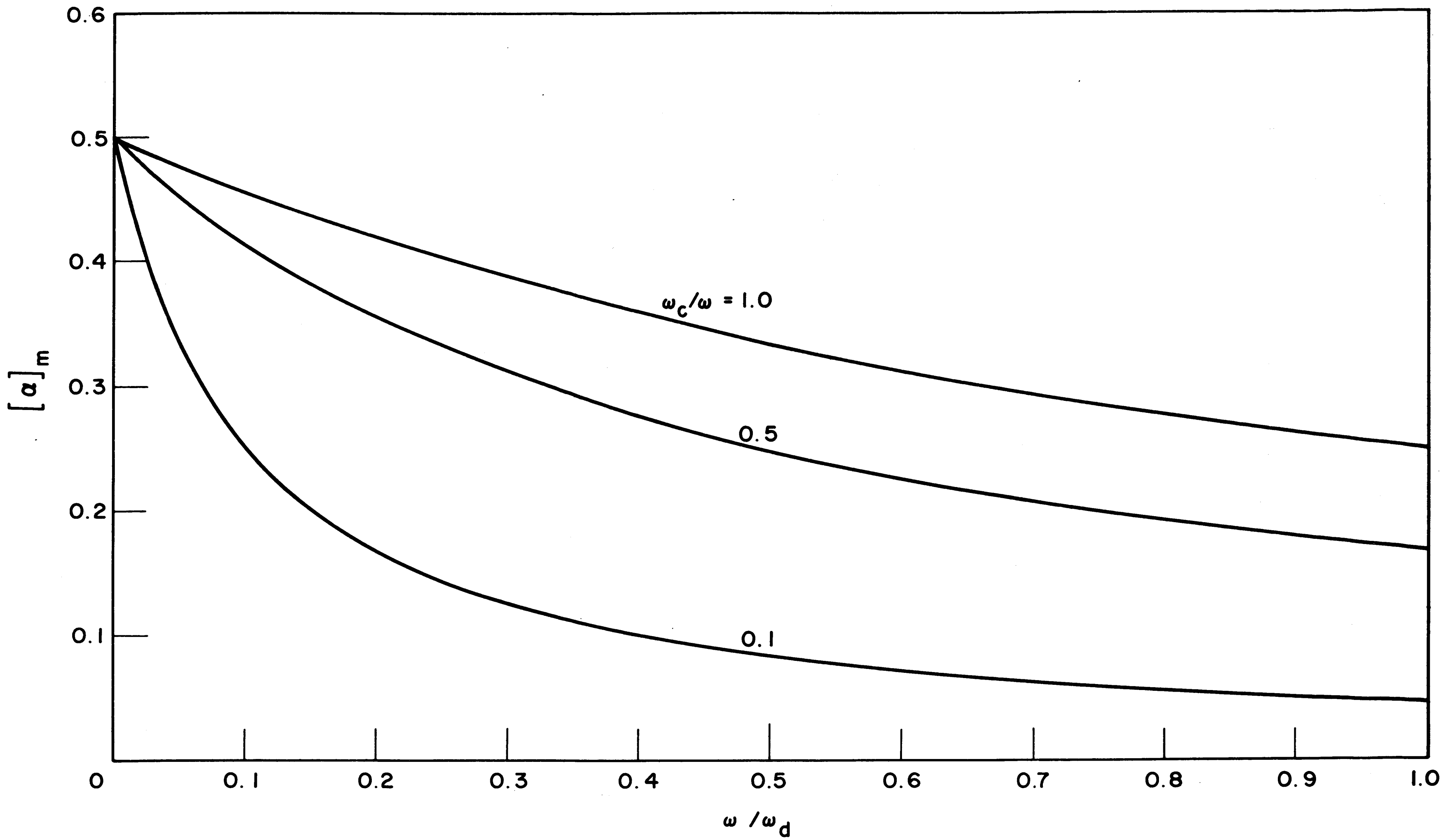

FIG. 4.3 MAXIMUM GAIN VS. FREQUENCY.

ω_c/ω ratio at high frequencies. Unfortunately this criterion cannot be used without bound. For materials with high conductivity, it is difficult to maintain a d-c field of the proper magnitude for adequate operation, i.e., to maintain a drift velocity higher than the acoustic velocity in the medium. Also if such a field could be maintained, the drift current due to this field would be so excessive as to overheat the crystal and thus change its properties. In practice therefore, a limit is set on the conduction carrier density of the material whose mobility is μ ($\sigma = Ne\mu$). In fact, ω_c/ω is usually considered to be less than unity. Also, ω/ω_d is considered to be less than unity. In other words, both conduction and diffusion currents are small in comparison with the displacement current.

The mobility μ of the material is important in determining the critical d-c field required for proper operation, i.e., $u_o = v_s$. As $u_o = \mu E$, high mobility is advantageous since it reduces the critical field required to match the acoustic velocity. This leads also to the criterion that the carrier density should not be too high. Spector[1] estimates the upper limit of this density as $N = 10^{18}$ cm^{-3}.
The acoustic velocity is written in terms of normalized parameters as follows:

$$v = v_o \left\{ 1 + \frac{e^2}{2c\epsilon} \frac{1 + \left(\frac{1-\gamma}{\gamma}\right)^2 \frac{\omega_c}{\omega_D}\left[(1-\gamma)^2 \frac{\omega}{\omega_c\omega_D} - 1\right]}{1 + \left(\frac{\omega_c}{\gamma\omega}\right)^2 \left[(1-\gamma)^2 \frac{\omega^2}{\omega_c\omega_D} - 1\right]^2} \right\}. \qquad (4.4)$$

1. Spector, H. N. "Amplification of Acoustic Waves Through Interaction with Conduction Electrons", Phys. Rev., vol. 127, pp. 1084-1090, August 15, 1962.

The interpretation of this expression in terms of actual parameters is difficult. One useful form for the interpretation is to find the ω-k diagram. This can be accomplished by solving Eq. 4.4 in terms of ω and k, noticing that $v = \omega/k$. A third-order equation in ω is obtained. This is

$$\omega^3 - \left[2u_o + v_o\left(1 + \frac{e^2}{2c\epsilon}\right)\right] k\omega^2 + \left[\omega_c^2 + u_o k^2 \left\{u_o\left(1 + 2\frac{\omega_c}{\omega_D}\right) + v_o \frac{e^2}{c\epsilon}\right\}\right.$$

$$\left. + \frac{u_o^4}{\omega_D^2} k^4\right] \omega - \frac{e^2}{2c\epsilon} v_o u_o^2 \left[\left(1 + \frac{\omega_c}{\omega_D}\right) k^3 - \frac{u_o^2}{\omega_D^2} k^5\right] = 0 \quad . \tag{4.5}$$

Roots of this equation are being computed for various values of the parameters. However, a much simplified version of this dispersion equation can be obtained by taking advantage of the fact that for maximum amplification,

$$\frac{u_o}{v} = 1 + \frac{\omega_c}{\omega} + \frac{\omega}{\omega_d} \quad . \tag{4.6}$$

Again using $v = \omega/k$ in the above equation, one obtains

$$\omega^2 + \omega_d \omega + \omega_d(\omega_c - k\, u_o) = 0 \tag{4.7}$$

or

$$\omega = -\frac{\omega_d}{2} \pm \frac{\omega_d}{2}\sqrt{1 + 4\left(k\frac{u_o}{\omega_d} - \frac{\omega_c}{\omega_d}\right)}$$

$$\simeq (k\, u_o - \omega_c) \quad . \tag{4.8}$$

Thus, the ω-k diagram is a straight line whose slope is u_o and the origin is shifted downward to ω_c.

Another method of interpreting Eq. 4.4 is to rewrite it in the form

$$[v] = \frac{v - v_o}{\frac{e^2}{2c\epsilon}} = \frac{\left(1 - \frac{u_o}{v}\right)^2 + \frac{\omega}{\omega_d}\left(\frac{\omega_c}{\omega} + \frac{\omega}{\omega_d}\right)}{\left(1 - \frac{u_o}{v}\right)^2 + \left(\frac{\omega_c}{\omega} + \frac{\omega}{\omega_d}\right)^2} \tag{4.9}$$

and write the right-hand side of this equation as

$$[v] = \frac{u_o/(u_o/v) - v_o}{e^2/2c\epsilon} = \frac{u_o}{\frac{e^2}{2c\epsilon}}\left[\frac{v}{u_o} - \frac{v_o}{u_o}\right] . \tag{4.10}$$

A few sample calculations of the curves for [v] vs. u_o/v from Eq. 4.9 for various parameters ω_c/ω and ω/ω_d are plotted as solid lines and [v] vs. u_o/v from Eq. 4.10 for constant A, v_o and u_o are plotted as dotted lines in Fig. 4.4. The intersection of the two sets of curves represents the acoustic velocity for the proper combination of these parameters. As one can see, the process of finding v with so many parameters is rather involved.

4.3 Waves in Solid-State Plasmas. In the past a great many investigations have been carried out on wave propagation in gaseous plasmas and possible ensuing interactions with drifting electron streams. Gaseous plasmas are characterized by the presence of a relatively high density 10^{10} - 10^{16} per cm^3 of quite mobile electrons and ions. The plasma may be assumed to be macroscopically neutral and prefectly conducting. Much less attention has been given to magnetoplasma waves in metals and semiconductors. The nature of the plasma in a metal or a semiconductor is somewhat different than in the gaseous system since in

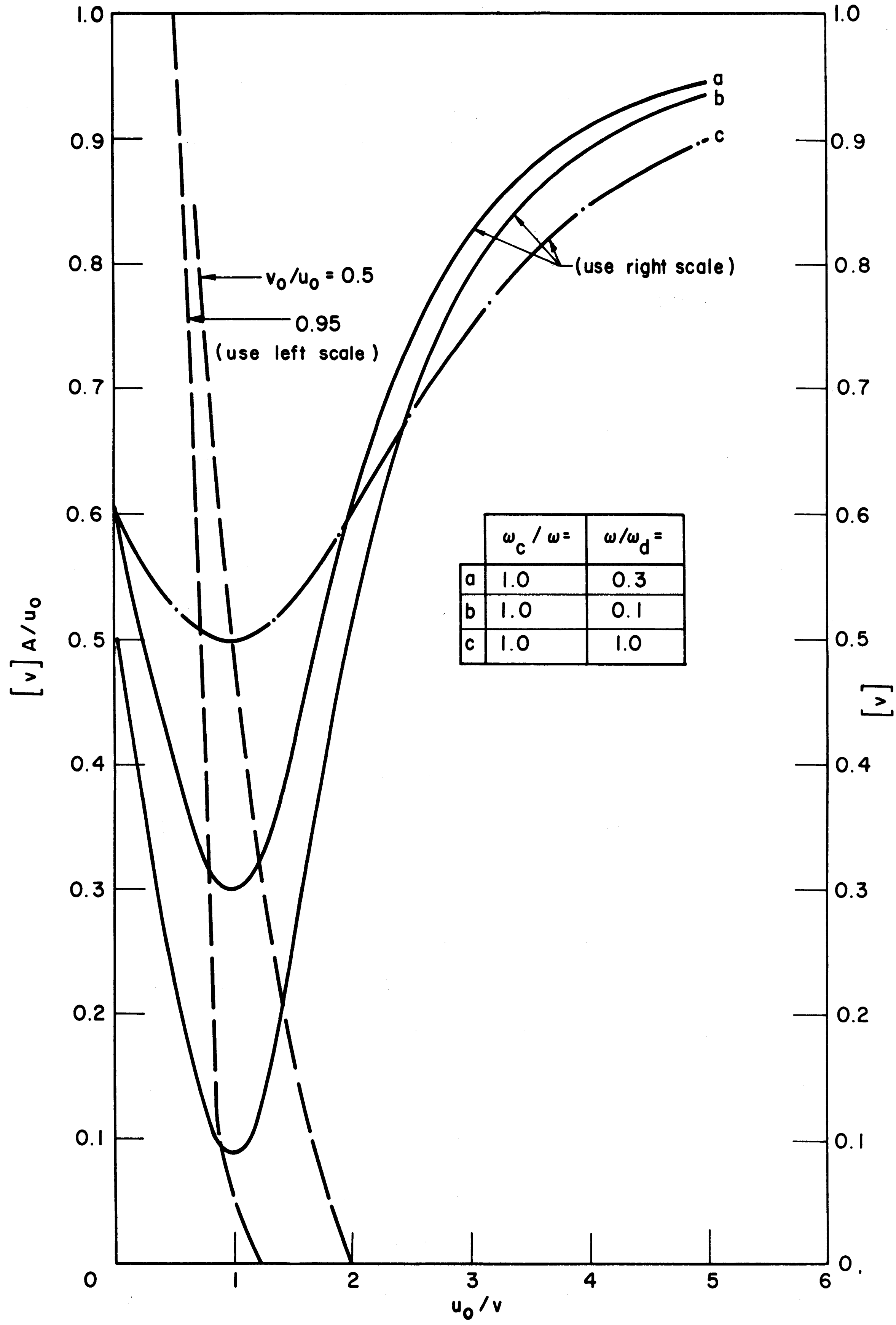

FIG. 4.4 NORMALIZED VELOCITY VS. u_o/v.

metals the carrier electrons are highly mobile and the ions are locked in the crystal lattice and in semiconductors the mobile carriers are electrons and positive holes with no vastly different mobilities.

Some very pure metals exhibit very high mobilities at low temperature due to a reduction of the thermal vibrations of the atoms in the crystal lattice. For semiconductors in thermal equilibrium the composition of the thermal plasma is dependent upon the injection level and hence can be made intrinsic, n-type or p-type. In studying instabilities in semiconductor magnetoplasmas both the injection plasma and the thermal background plasma must be considered.

The two types of magnetoplasma waves which invite study in solids and low temperature semi-metals are "whistlers" and "Alfvén" waves. Whistlers have been observed in the electron gas of a metal at liquid helium temperatures and are characterized by a frequency which is inversely proportional to the square of the wavelength so that the velocity increases as frequency increases. Alfvén waves result from the interaction between magnetic and kinetic energies in a system (plasma-medium) and are characterized by a frequency which is inversely proportional to the wavelength so that the velocity is constant. If the plasma moves in the direction of the static magnetic field pure Alfvén waves result and if the motion is normal to the static magnetic field compressional waves result. Some work on Alfvén waves in liquid metals has yielded interesting results although due to low conductivities the waves are rapidly damped. Further studies have been made in bismuth where both electrons and holes are mobile and the velocity is less than the electromagnetic wave velocity and is proportional to the magnetic field strength. An analysis of these hydromagnetic waves is given here with the suggestion that they be further investigated in appropriate solids (semiconductors) and semi-metals.

The starting point for plasma phenomena is the Boltzmann equation

$$\frac{\partial f}{\partial t} + \sum_i \frac{\partial f}{\partial x_i}\frac{\partial x_i}{\partial t} + \sum_i \frac{\partial f}{\partial w_i}\frac{dw_i}{dt} = \left.\frac{\partial f}{\partial t}\right|_{coll.} , \qquad (4.11)$$

where f = the particle (carrier) distribution function,

w_i = the velocity component along the ith coordinate and

x_i = the displacement in the ith direction.

Various hydrodynamic equations are obtained by taking moments of Eq. 4.11. Collision effects are temporarily neglected. The global (macroscopic) momentum equation obtained in this way is

$$\rho_m \frac{\partial V}{\partial t} = \sigma E + jxB - \nabla_r p - \rho_m \nabla_r \Phi , \qquad (4.12)$$

where $\rho_m = n_e m_e + n_h m_h$, the mass density,

$$V = J/\rho_m = \frac{n_e m_e \bar{v}_e + n_h m_h \bar{v}_h}{n_e m_e + n_h m_h} ,$$

σ = conductivity ,

p = pressure ,

Φ = gravitational potential.

Also a generalized Ohms law obtained in this manner is

$$\frac{m}{nq^2}\frac{\partial j}{\partial t} = E + \left(V + \frac{j}{nq}\right) xB - \frac{1}{nq}\nabla p - \eta j . \qquad (4.13)$$

All dissipation phenomena (collisions) are neglected so that the processes are adiabatic. The Alfvén waves are transverse and are associated with minute electromagnetic disturbances. Assume that the magnetoplasma has a time average velocity along the static B field lines as suggested in Fig. 4.5. Possible current, velocity, magnetic field and electric field directions are illustrated assuming symmetry about the z-axis. The microscopic Lorentz equation is

$$\frac{d\vec{v}}{dt} = \eta\,[\vec{E} + \vec{v} \times \vec{B}] \quad , \tag{4.14}$$

which for the assumed one-dimensional system becomes

$$\left(\frac{\partial v_x}{\partial t} + u_o \frac{\partial v_x}{\partial z} \right) = \frac{J_y B_o}{\rho_m} \quad . \tag{4.15}$$

The Maxwell field equations are

$$(\nabla \times \bar{E})_x = - \left(\frac{\partial \bar{B}}{\partial t} \right)_x$$

or

$$\frac{\partial E_y}{\partial z} = \frac{\partial B_x}{\partial t} \quad , \tag{4.16}$$

and

$$(\nabla \times \vec{H})_y = (\vec{J})_y$$

or

$$\frac{\partial B_x}{\partial z} = \mu_o J_y \quad . \tag{4.17}$$

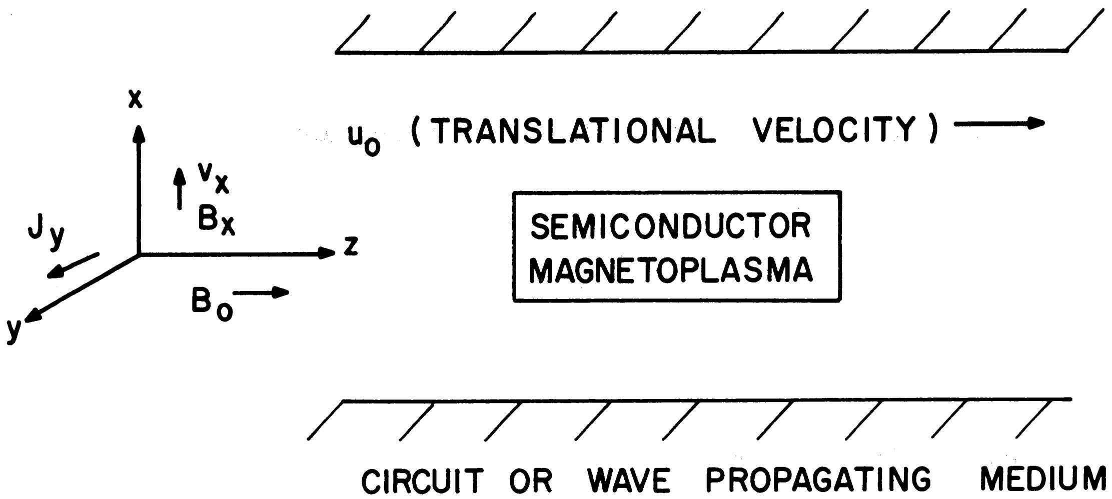

FIG. 4.5 SOLID-STATE PLASMA CONFIGURATION.

At this stage in the theory it is convenient to assume a perfectly conducting magnetoplasma so that Ohms Law becomes

$$E_y = -(u_o B_x - v_x B_o) \quad . \tag{4.18}$$

The above equations are combined to give the following after some manipulation:

$$\left(\frac{\partial}{\partial t} + u_o \frac{\partial}{\partial z}\right)^2 v_x = V_A^2 \frac{\partial^2 v_x}{\partial z^2} \quad , \tag{4.19}$$

where $V_A^2 \triangleq B_o^2/\mu_o\rho_m$, the Alfvén velocity.

For an ansatz of the form $e^{j(\omega t - kz)}$ Eq. 4.19 reduces to

$$(\omega - u_o k)^2 = k^2 V_A^2 \quad . \tag{4.20}$$

It is noted that Haus[1] has obtained a similar result in his study of a-c generation with moving conducting fluids. The quadratic nature of Eq. 4.20 suggests two waves with phase constants

$$\beta_{1,2} = \frac{\omega}{u_o \pm V_A} \quad . \tag{4.21}$$

For $V_A < u_o$ both waves are forward and the group velocity is

$$v_g = u_o \pm V_A \quad . \tag{4.22}$$

The propagation of a wave along the circuit (z-direction) surrounding the semiconductor may be described in terms of the usual transmission-line circuit and voltage equation:

$$(\beta^2 - \beta_o^2)\, V = -\,\alpha\beta B_x \quad , \tag{4.23}$$

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1. Haus, H., "Alternating-Current Generation with Moving Conducting Fluids", Jour. Appl. Phy., vol. 33, No. 7, pp. 2161-2172; July 1962.

where $\beta_o^2 = \omega^2 LC$,

L,C = inductance and capacitance per unit length along the circuit,

V = $(\beta/\omega C)$ I, Circuit voltage.

The combined magnetoplasma and circuit equations yield the system determinantal equation

$$(\omega - u_o\beta)^2 = \left[1 + \frac{\frac{\mu_o}{L}\beta_o^2}{(\beta_o^2 - \beta^2)}\right] V_A^2\, \beta^2 \quad . \qquad (4,24)$$

It can be shown that complex β arises when $u_o > V_A$, i.e., when the carrier drift velocity exceeds the medium Alfvén velocity and thus energy may be transferred to the circuit wave. This phenomenon is worthy of further studies relative to semiconductors and semi-metals.

4.4 Conclusions. Gain variations and conditions for maximum gains in acoustic-wave amplifiers have been explored for longitudinal wave systems and provide a basis for material selection. In addition a specialized set of [v] vs. u_o/v diagrams has been calculated to give some indications of the overall characteristics.

It has been suggested that Alfvén wave propagation may be important in both semiconductors and semi-metals and should be explored further from the standpoint of device applications.

4.5 Program for the Next Quarter. It is planned to investigate further the ω-k characteristics for longitudinal acoustic-wave amplifiers and to explore the characteristics of shear-wave devices. Also Alfvén wave investigations will be continued along with the study of possible instabilities in semiconductor magnetoplasmas.

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Various electron paramagnetic resonance experiments are reviewed in an effort to determine those materials most appropriate for parametric phonon interactions. One of the most promising materials is $CdS:V^{3+}$ since the nuclear spin of 7/2 associated with the V^{51} isotope splits each fine line into eight lines. This results in a linewidth for absorption of approximately 700 gauss which is a 10 percent bandwidth at x-band. The use of x-cut longitudinal quartz transducers resonant in the 5-40 mc region has allowed the observation of echoes up to 577 mc at room temperature. Similar results have been obtained up to 400 mc at liquid nitrogen temperature. The theory of stimulated Bremsstrahlung radiation from solids is developed further with particular emphasis on ionized impurity scattering. Experimental observations of significant powers at microwave frequencies can possibly be explained as a result of Raman scattering by optical phonon vibrational modes due to coupling with the previously postulated radiation and subsequent down conversion to microwave frequencies. Acoustic gain and velocity characteristics have been calculated for longitudinal mode excitation as a function of the velocity parameter u_0/v. Furthermore a general ω-k relation is derived. Possible Alfvén wave interactions in semiconductors are investigated.

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