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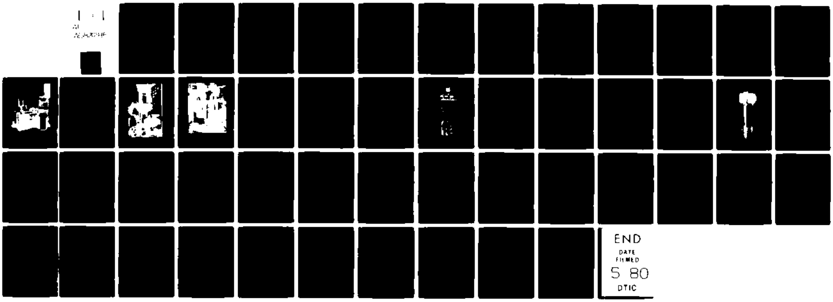

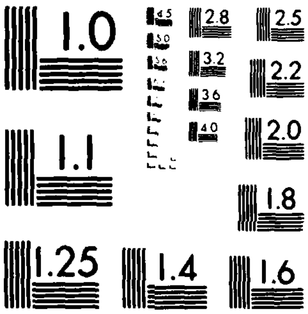

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INCOHERENT DETECTION OF ULTRASONICS USING THIN FILM AMORPHOUS SEMICONDUCTORS

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NOVEMBER 1979

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ROGER D. GRISWOLD
Project Engineer

FOR THE COMMANDER

D. M. FORNEY, Jr., Chief
Nondestructive Evaluation Branch
Metals and Ceramics Division

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20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

Thin film ultrasonic detectors have been fabricated from amorphous germanium. The detectors are insensitive to phase and function as sensitive power detectors for ultrasonic waves. Due to the mode of operation of the detectors, their usefulness is limited to the temperature range 1.5-77°K. The dependence of the sensitivity of the devices upon the structural and electrical characteristics of the a-Ge material has been investigated experimentally. It was found that useful performance is obtained only when electrical conduction is by a variable range hopping mechanism. Evidently, the variable range hopping behavior

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is strongly perturbed by the elastic wave distortion.

PREFACE

This program was initiated on 4/1/76 and completed on 6/1/79. The project was entitled "Incoherent Detection of Ultrasonics Using Thin Film Amorphous Semiconductors" and was funded under Contract Number F33615-76-C-5240. The work was performed entirely in the Department of Chemistry at the University of Michigan, Ann Arbor, Michigan, and was monitored by Dr. R. Panos and Mr. R. Griswold of the U. S. Air Force Materials Laboratory, Wright Patterson Air Force Base, Dayton, Ohio.

The research described in this report was carried out by the following graduate research assistants and postdoctoral research associate: Dr. Harriet Parker and Mr. Harry Hadjidemetriou (thin film preparations) and Professor K. W. Hipps (device characterization). Their assistance is gratefully acknowledged.

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SECTION I

Introduction

Piezoelectric crystals have been employed for the detection of ultrasonic elastic waves in a wide variety of situations. Piezoelectric detection offers the advantage of high sensitivity and relative ease of operation. Additionally, the response time of piezoelectric devices is in the microsecond region. All piezoelectric detectors derive their output from a stress generated voltage produced in the detector perpendicular to the applied stress whose magnitude is linearly related to the applied stress. This mode of operation is at once both the major strength and weakness of the piezoelectric detection scheme for ultrasonic elastic waves. The detector requires a well defined or coherent wavefront at the substrate-detector interface for the generation of a piezoelectric voltage, therefore, randomly phased (incoherent) elastic waves produced thermally as well as other incoherent signals are largely rejected by the detector.

The requirement of a well defined wavefront, however, makes the bonding of the detector to the substrate extremely critical. Lack of parallelism at the detector-substrate interface may lead to partial or complete cancellation of the piezoelectric voltage produced by the detector.[1] As the frequency of the elastic wave becomes higher, the quality and parallelism of the detector-interface bond becomes increasingly important. In addition to phase cancellation effects leading to partial loss of signal, lack of parallelism may also produce spurious signals or signals which can not be quantitatively or qualitatively interpreted.

From the latter point-of-view then, it would be useful to develop a detector which was insensitive to the nature of the detector-substrate interface and many schemes have been proposed over the past decade to accomplish this task. Such devices are generally termed incoherent detectors. The most promising incoherent devices depend upon the interaction of the elastic wave with relatively localized charge carriers. The coupling of acoustic waves in each instance results in a change in the electric or magnetic properties of the detector which may be sensed and related to the acoustic power. In general, the sensitivity of the acoustic devices based on incoherent processes may be comparable to that of piezoelectric devices and the response time is comparable or faster.

Detectors insensitive to phase have been developed for ultrasonic waves using thermocouples, thermistors and other bolometers. In general these lack the sensitivity and response time of the phase sensitive piezoelectric detector. More recently, ultrasonic detectors have been developed utilizing the acousto-voltaic effect in single crystals of cadmium sulfide. Since the acousto-voltaic signal is independent of phase relationships, these devices are true incoherent detectors.

Unfortunately, the majority of incoherent detectors require considerable peripheral equipment for their operation and may, additionally, have certain operating conditions which are incompatible with applications to nondestructive evaluation.

For example, some devices require cryogenic temperatures for proper operation or, conversely, must be operated at elevated temperatures.

The purpose of the contracted research was to investigate the use of certain semiconducting materials as ultrasonic detectors in the MHz and GHz frequency domain. In particular, it was hoped that the properties of semiconducting materials in the amorphous state could be employed to advantage in the detection of ultrasonic elastic waves.

SECTION II

Experimental

The major experimental equipment utilized in the research to be reported consisted of a variable temperature liquid helium cryostat and a high vacuum thin film evaporation system. Additionally, several specialized pieces of electrical apparatus were employed for measurements used to characterize the amorphous germanium films and to generate high frequency ultrasonics.

1. Evaporation System

The evaporator shown in Figure (1) is of a conventional design and consisted of a glass bell jar which could be evacuated to about 10^{-7} torr with a liquid nitrogen trapped 4 inch diameter oil diffusion pump. Although liquid nitrogen trapping is not necessary to achieve the high vacuum levels necessary for preparation

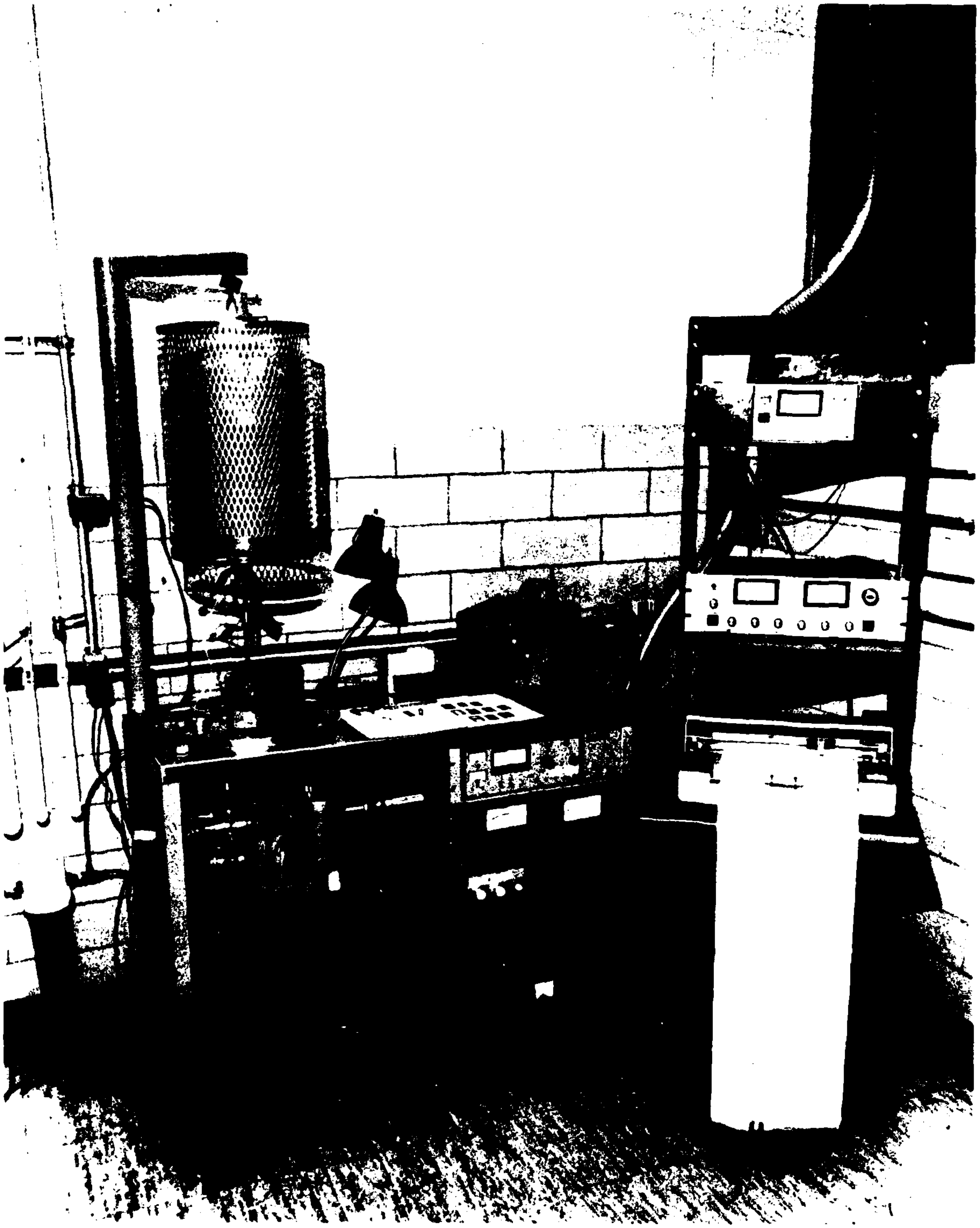

Figure (1) Overview of the evaporation system used to prepare a-Ge thin film acoustic devices.

of semiconductor films, it was essential to prevent oil contamination from reaching the bell jar working volume. The bell jar base plate was equipped with a variety of electrical and mechanical motion feedthroughs (Fig. (2)) to permit resistively heated evaporation of low melting semiconducting materials and manipulation of the substrate during evaporation.

Although a large number of semiconducting materials were studied, the majority of experimental measurements were conducted on thin films of germanium and the preparation of these films will, therefore, be described in greater detail.

2. Cryostat

The cryostat shown in Figure (3) and used for all experimental measurements was designed to accurately and automatically maintain the substrate temperature to within 0.1 °K within the temperature range 300-2 °K. The transducer substrates were cooled by a flow of helium gas at 1 atm. pressure. The cooling gas was generated by vaporizing liquid helium from a 4.2 °K bath in a resistively heated vaporizer assembly. The temperature of a cooling gas flow was controlled by regulation of the vaporizer assembly temperature to within 0.1 °K.

3. Film Preparation

The material used for evaporation was lump silicon and germanium of 99.99% purity. The material was placed in resistively heated alumina coated tungsten boats and fused at 10^{-7}

Figure (2) Detail of the evaporation system showing: (a) substrate heater, (b) substrate holder, (c) multiple source slag shield, (d) several of the masks used in device fabrication and (e) positioning rod.

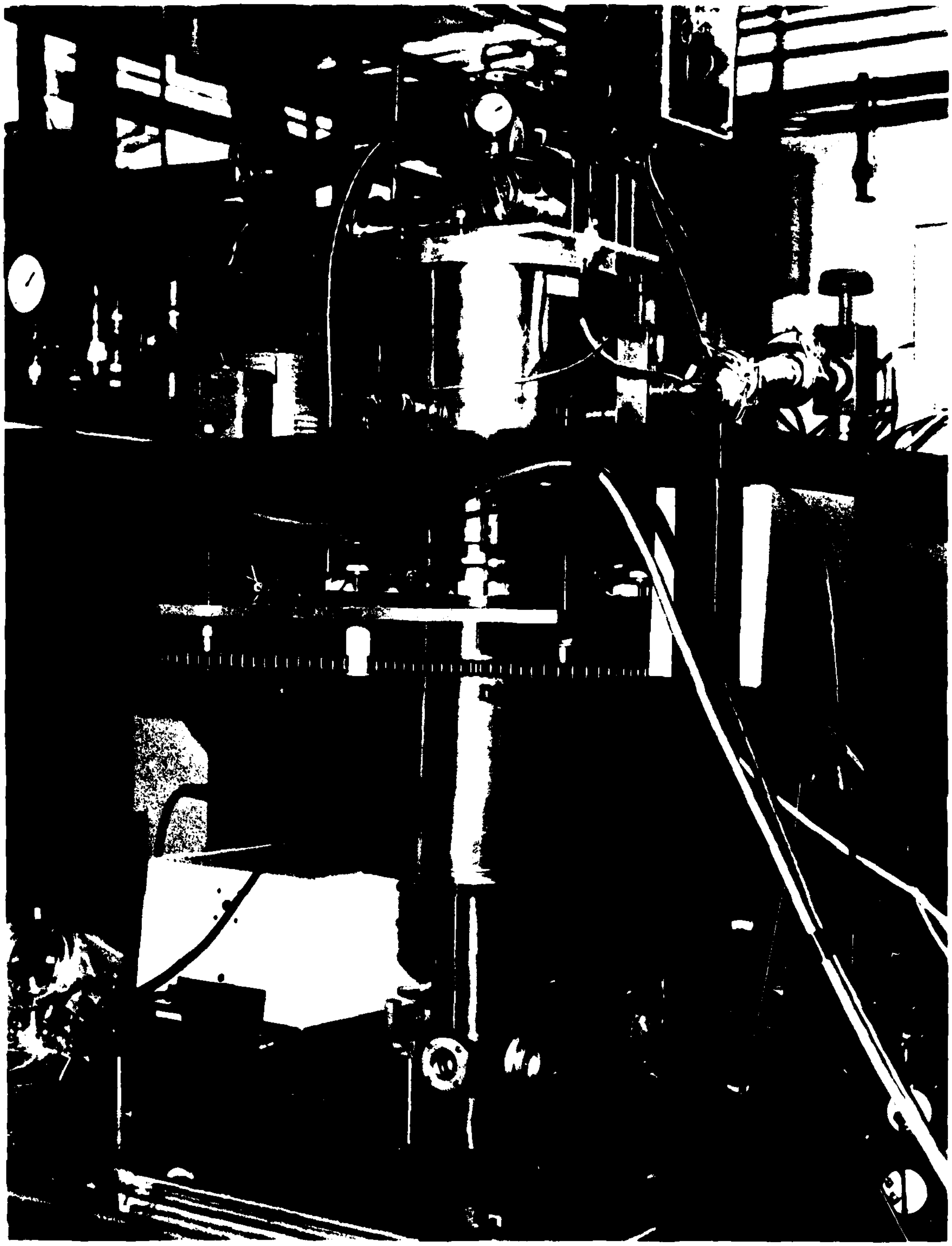

Figure (3) Variable temperature cryostat used to measure temperature dependence of device parameters.

torr to remove dissolved and adsorbed gases and other volatile impurities. The substrates used were pyrex, fused silica and sapphire plates which were cleaned by washing in detergent, distilled water and alcohol sequentially. Prior to evaporation the substrates were cleaned by an argon ion polishing for several minutes in the evaporation system.

The structure and electrical properties of the semiconductor films were found to be extremely sensitive to a variety of experimental parameters associated with evaporation. The evaporation parameters investigated included deposition rate, source-substrate distance and substrate temperature.

A variety of evaporation configurations were investigated in order to obtain a procedure by which amorphous films could be prepared with relatively reproducible electrical and mechanical properties. The substrates were mounted in a resistively heated copper block attached to the central positioning rod of the evaporation system. The positioning rod could be used to remotely vary the distance between the vapor source and the substrate. The temperature of the copper block was monitored with a copper/constantan thermocouple. During evaporation of the amorphous film, the pressure of the system rose to 10^{-6} torr from a base pressure of 10^{-7} torr.

Deposition rate was measured by a quartz microbalance whose measuring element was positioned at the height of the substrate but displaced 30° from the source-substrate vertical axis. Relatively reproducible films were obtained with the substrate placed 20 cm above the source and with deposition rates of 50-100 Å/sec. At higher deposition rates, the electrical properties varied dramatically with deposition rate. Additionally, film adhesion and general physical appearance were considerably altered. At smaller source-substrate separations, extremely non-uniform deposition was obtained both in thickness and electrical properties. The electrical properties of the films were strongly effected by in situ annealing during evaporation by radiative heating from the tungsten crucible. Source-substrate distances greater than 20 cm. were impractical due to lowered deposition rates and waste of source material. Film thicknesses were determined by weight/area measurement and interferometrically.

4. Electrical Measurements

We have measured the DC conductivity and Seebeck coefficient of evaporated amorphous germanium films. These measurements were conducted over an extended temperature range from 2-500 °K and were carried out on samples prepared by a variety of evaporation procedures and subjected to a variety of post-evaporation treatments. Post-evaporation treatments included oxidation/reduction cycling, annealing, and ion polishing.

Conductivity measurements were made using a-Ge evaporated on pyrex substrates. The cleaned substrates were placed, together with the appropriate mask in the evaporator and further cleaned by argon ion polishing. The a-Ge films were then evaporated as described in section 3. Subsequent to evaporation of the a-Ge films, gold contacts were evaporated during the same pump-down cycle. Due to the high resistance of the a-Ge films, particularly at cryogenic temperatures, close spaced electrodes were required for the electrical measurements. To achieve the necessary spacing, #36 or #40 copper wire was used as a mask during evaporation of the gold contacts.

The prepared substrates were mounted on the resistance probe illustrated in Figure (4). For accurate temperature control, this probe has been fitted with a second temperature regulation circuit. The ambient temperature of the probe and mounted substrate were determined as described in paragraph 2 by the regulated temperature of the flowing helium cooling gas. To achieve additional temperature stability at the substrate, the temperature of the brass substrate mount was regulated to within ±0.1 °K. Conductivity measurements were made using a four-lead circuit. Two leads were employed to pass a regulated 10 microampere excitation current through the a-Ge film and two of the leads were employed to measure the voltage drop across the film using a high impedance electrometer.

The sapphire substrate for Seebeck coefficient measurements was prepared with three evaporated germanium bolometers equally spaced along its length. Additionally, a nichrome resistive

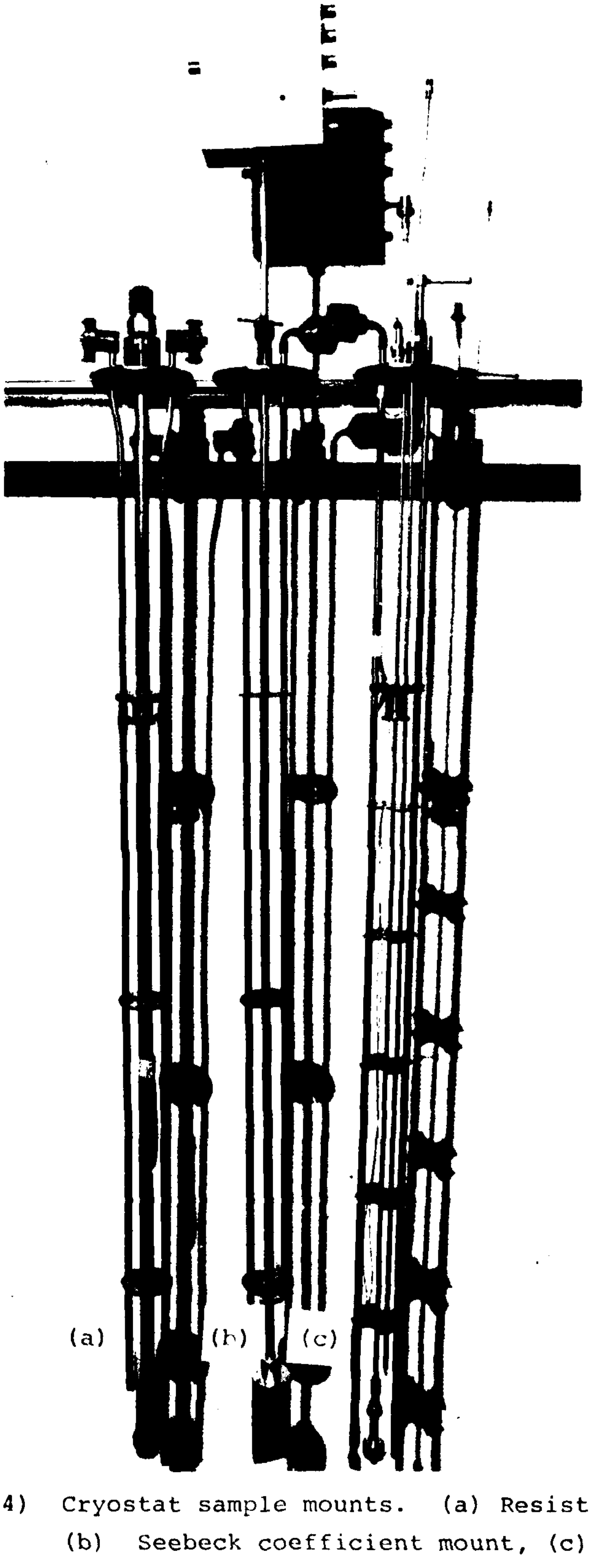

Figure (4) Cryostat sample mounts. (a) Resistance mount, (b) Seebeck coefficient mount, (c) Ultrasonic mount.

heater was evaporated along one edge of the sapphire substrate. The Seebeck coefficient measurements were made on a-Ge strips 3 cm. in length and approximately 0.5 cm wide which were evaporated onto the sapphire substrates. The final assembly is illustrated in Figure (5).

The sapphire substrates were placed in the probe assembly illustrated in Figure (4) and mounted in the cryostat. The ambient temperature of the substrate was regulated by the temperature of the cooling gas as described in section 2.2 above. Using the resistive heater evaporated onto the sapphire substrate a temperature gradient of 10-50 °K was established along the sapphire substrate. The steady state temperature gradient along the substrate was determined from the resistance of the germanium bolometers. Resistance measurements were made in a manner similar to that described in section 3. The thermoelectric potential developed between junctions was then measured using a Keithley high impedance electrometer ($Z \sim 10^{13}$ ohm).

5. Ultrasonic Measurements

Experimental measurements were conducted on the apparatus illustrated in Figure (6). Substrates were prepared from optical glass and single crystal sapphire and were cut either in the form of rectangular parallelopipeds with approximate dimensions 20mm x 10mm x 10mm or in the form of cylinders 3mm in diameter and 20mm in length as illustrated.

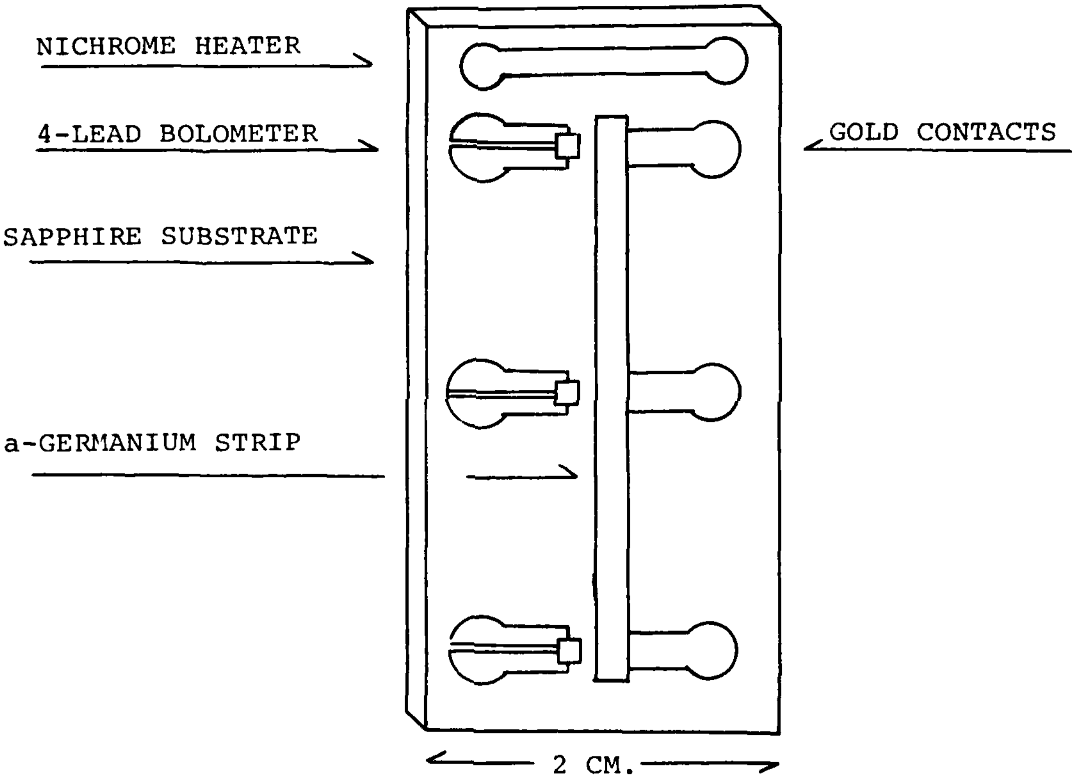

Figure (5) Seebeck coefficient substrate. Illustration of the placement of the nichrome heater, gold electrical contacts, a-germanium film and germanium bolometers on the sapphire substrate.

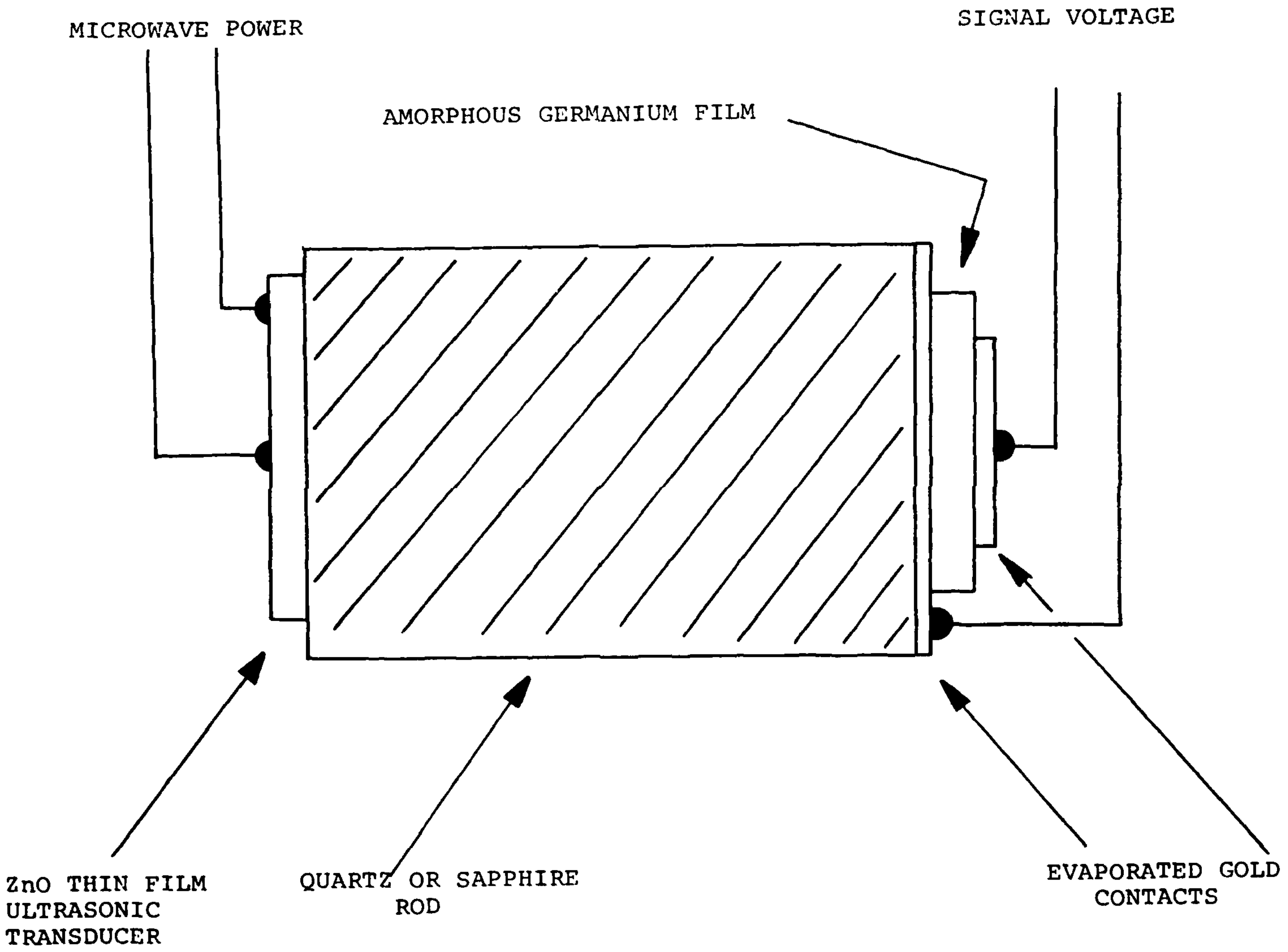

Figure (6) Ultrasonic substrate showing position of attachment of ultrasonic transducer and a-Ge detector.

The cylinder faces and opposing faces of the parallelopipeds were polished to 1/4 wave flatness at 5000 Å. Additionally, the sapphire substrates were oriented such that the crystallographic c-axis was parallel to the cylinder axis.

High frequency ultrasonic longitudinal waves were generated in the substrates using thin film ZnO piezoelectric transducers either bonded to the substrate with silicone oil or prepared directly on the substrate by reactive sputtering of Zn. The transducers were attached to one end-face of the substrate in order to launch longitudinal ultrasonic waves parallel to the long axis of the substrates. Acoustic transducers of a-Ge were attached to the opposing end-face by either direct evaporation or by bonding with silicone oil. The substrate-transducer assembly was attached to the end of a coaxial transmission line in the LHe cryostat. The assembled ultrasonic probe is shown in Figure (4c) and the detail of the transducer assembly in Figure (7). Ultrasonic waves in the frequency range 1-4 GHz were generated by driving by ZnO piezoelectric transducer with up to 100 mw of power from an H/P 8900 sweep oscillator gated through a pin diode.

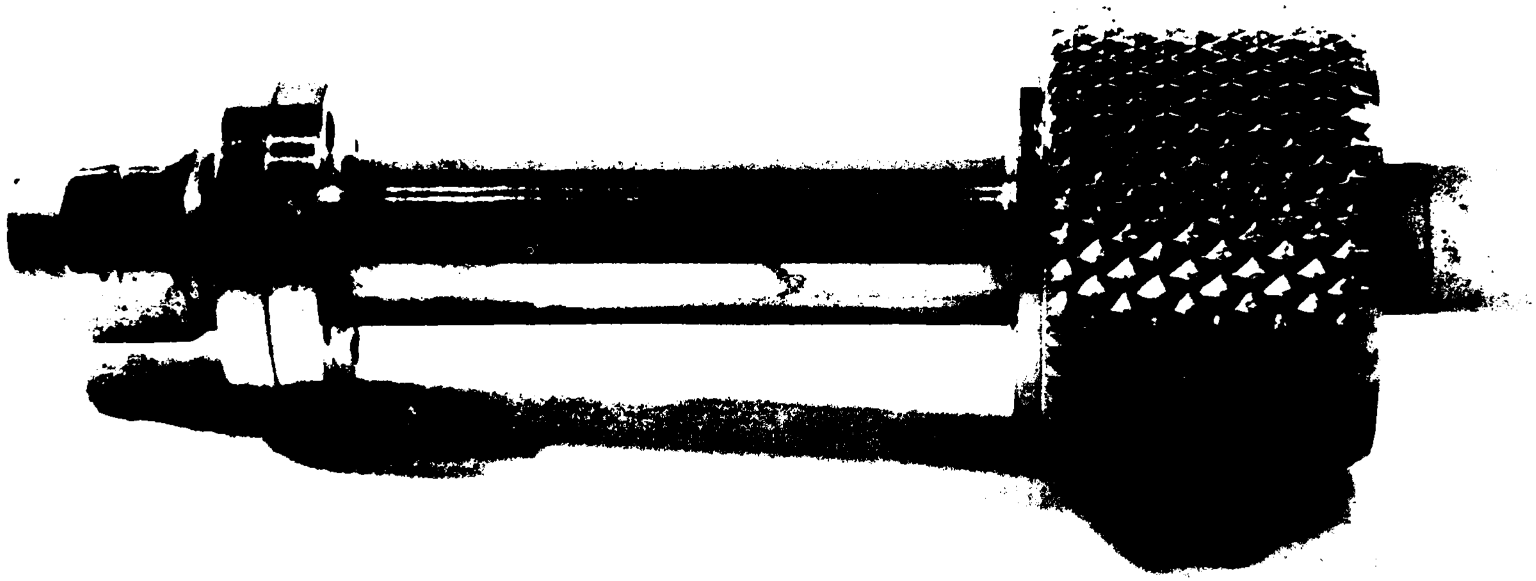

Figure (7) Detail of ultrasonic transducer mount.

6. Other Materials Studied

Initially, a variety of semiconducting materials were selected for investigation as possible materials for fabrication of an incoherent ultrasonic detector. The materials were chosen principally from semiconducting materials which had band gaps less than about 2 eV. Cadmium sulfide was later added to this list due to an interest in this material as a possible acousto-voltaic incoherent ultrasonic detector. The materials investigated are listed in TABLE (1). Of these materials, only Ge, Si and InSb could be conveniently evaporated using resistive heating techniques with reproducible results with regard to film structure and chemical composition. Direct evaporation of PbS and CdS produced films with variable chemical composition and structural character.

The behaviour of PbSe films depended dramatically and erratically upon whether the film had been exposed to visible light. Exposure to visible light irreversibly decreased the sensitivity and altered the response time of the film substantially. Cadmium sulfide films could not be evaporated with reproducible stoiciometry and as a result their structural and electrical characteristics were not reproducible. The several CdS devices prepared had a high dark resistivity, characteristic of a photoconductive material. In order to use the CdS films for the detection of incoherent ultrasonics, it was necessary to illuminate the films to provide a reasonable density of free charge carriers. Under these circumstances, the CdS films exhibited a sensitivity to ultrasonics comparable to that of the a-germanium films discussed above. However, the circumstances of the measurement are sufficiently different as to make direct comparison of the sensitivity of the two devices difficult. Moreover, the physical processes by which elastic waves interact with charge carriers in the two materials is probably distinctly different.

Germanium was selected for the majority of experimental measurements because of all materials investigated, its properties were found to be the most reproducible when produced in thin amorphous films. Additionally, its sensitivity was equal to or greater than that obtained with any of the other materials in our studies. Germanium films, after a short aging period of approximately 24 hrs. were stable indefinitely at or below room temperature. Films of all other materials, with the exception of silicon, exhibited aging effects for a period of months. The aging behaviour consisted of a general decrease in the resistivity of the material.

Functioning ultrasonic detectors were constructed from several of these materials and for these the general characteristics of the detector are indicated in TABLE 1. In some instances, the parameters are based on observations on no more than a single device. In other instances several devices were made and the measurements were more extensive. TABLE (1) is provided here only as a coarse indication of the relative merits of the materials investigated with respect to sensitivity and response time. The sensitivity and response time are critically dependent upon the structural and

TABLE I

Material*	Band Gap eV	NEP Watts	Response Time μsec.	Frequency Response Hz
CdS (2)		10^{-9}	.01	10 MHz-4 GHz
a-Si (4)	1.17	10^{-7}	.01	10 MHz-4 GHz
a-Ge (43)	0.74	10^{-9}	.01	10 MHz-4 GHz
PbS (1)	0.29	10^{-6}	.1	10 MHz
PbSe (5)	0.17	10^{-6}	.1	10 MHz

*Note: Number in brackets after material type indicates the number of devices of each type investigated.

chemical composition of the film, as has been noted above for the case of germanium.

The noise equivalent power (NEP) for the various detectors reported in TABLE (1) was determined by the thermal method described in SECTION III. All detectors have a broad band frequency response which is flat between approximately 10 MHz, the lowest frequency used in our measurements and 4 GHz, the highest frequency employed. Response times were determined from the time resolved decay of the detector response to pulsed ultrasonic power. These measurements were conducted in the temperature range 4-10 K using 1 GHz ultrasonics.

SECTION III

Discussion

Several years ago experiments in our laboratory indicated that films of amorphous germanium or silicon could be used with great sensitivity as incoherent detectors for ultrasonic waves at cryogenic temperatures. The experiments described in this report were undertaken to discover the useful temperature range of ultrasonic transducers using changes in the resistivity/ conductivity of amorphous semiconductors films. Additionally, it was hoped to discover some details of the physics of the interaction between ultrasonic waves and charge carriers in amorphous semiconductors.

Due to the extreme variability of the properties of amorphous materials, we wish to comment in the following discussion on several aspects of the preparation and properties of the a-Ge films prepared in our laboratory.

1. Preparation

It has long been established that the properties of semiconductor films depended strongly on the method of evaporation[3] (i.e., resistive heating, electron beam heating, sputtering, glow discharge or thermal decomposition). Additionally, the details of the evaporation procedure are also known to influence the film electrical and mechanical properties.[3] Therefore, our intention was to standardize our procedures sufficiently to be able to prepare films in a reproducible fashion using only one evaporation technique. Then we attempted to determine the relationship between the electrical properties of the material and the structural characteristics of the film as the evaporation procedures were varied.

We have chosen resistive evaporation from an alumina coated tungsten source as the method of preparation for a-Ge films, because of the relative simplicity of the technique and the extensive literature on the subject of a-Ge films prepared by this method. However, due to the variability of the properties of evaporated films as reported in the literature, it was necessary to carefully characterize the properties of material prepared in our laboratory. We have chosen two methods of characterization of the amorphous germanium films: Measurement of the DC conductivity and of the Seebeck coefficient. These measurements proved sufficient to establish the properties of our a-Ge material in relation to that prepared in other laboratories. The temperature dependence of these measurements has provided some limited insight into the physics of the interaction between ultrasonic waves and charge carriers in a-Ge films.

2. Electrical Properties

Amorphous semiconductors as a class have a wide range of electrical characteristics and several different theoretical models have been advanced to describe the electrical properties of individual amorphous semiconductors. The Mott-CFO[4] model has been employed with considerable success to the electrical properties of amorphous silicon and germanium and it is the model which we shall employ in the following discussion of our experimental results. The model is based upon the assumption of an ideal random covalent bonding network. The randomness of the crystal potential may be shown to produce localized states which lie within the gap between the valence and conduction bands of the crystalline material. It is important to emphasize that these states are not associated with a specific impurity or localized imperfection but rather result from the randomness of the crystal potential. The density of localized states and their distribution varies strongly with the extent of the randomness and amplitude of the crystal potential fluctuations. The character of the crystal wavefunctions therefore changes abruptly from localized states between the conduction (E_C) and valence (E_V) band edges to extended states above E_c and below E_V. Electron and hole mobility for states within the band gap is low and described by a phonon-assisted tunnelling process.

We may distinguish three principal contributions to the DC conductivity using the MOTT-CFO model.

1) For electrons with $E > E_c$ (or holes with $E < E_V$) the conductivity is described by:

$$\sigma = \sigma_1 \exp[-(E_c-E_F)/kT]$$

2) For electrons with $E_c > E > E_V$, the DC conductivity is dominated by thermally assisted tunnelling from jumps between

unoccupied levels of nearest neighbor centers. Since nearest neighbor states are unlikely to have identical energies, this process involves the emission or absorption of a phonon of energy W. In additon to the hopping energy W, the process involves the activation energy which raises the energy of the electron to the initial localized state $E - E_F$. The conductivity is described by the following equation:

$$\sigma = \sigma_2 \exp[-(E-E_F) + W)/kT]$$

As the temperature is lowered the number and energy of phonons available for adsorption decreases so that tunnelling is restricted to seek centers which are not nearest neighbors but which instead lie energetically closer and within the range kT. For this so-called variable range hopping process, Mott derived the relation:

$$\sigma_{(T)} = A\ e^{-[T_o/T]^{1/4}}$$

The prefactor (A) depends on the electron phonon coupling.

For all films prepared by the technique described in paragraph 2.3, the temperature dependence of the conductivity could be closely fit to a $T^{-1/4}$ dependence over the low temperature portion of the 500-2 °K temperature range investigated. The conductivity of films which had been annealed at 300 °K could generally be fit to a $T^{-1/4}$ curve over the broadest temperature range, from 77-2 °K as illustrated in Figure (8).

The temperature dependence of the conductivity illustrated in Figure (8) is characteristic of electrical conduction in amorphous materials and is in substantial agreement with previously published data for a-Ge films. Therefore, these measurements confirm the amorphous character of the a-Ge films prepared by the procedures described in paragraph 2.3.

As illustrated in Figure (9), the effect of increased annealing temperature (T_A) on the conductivity of a-Ge is to reduce the conductivity of a-Ge films. The higher annealing temperature increases the crystallinity of the film and reduces the density of states in the band gap. The decrease in conductivity with higher annealing temperatures is consistent with this behavior. [The sensitivity of the a-Ge films as acoustic transducers was generally decreased by annealing, and we conclude that the acoustic transducers rely upon the high density of localized states within the band gap for ultrasonic stimulated conduction.]

The Seebeck coefficient is given by:

$$S = -\frac{k}{e} \int_{0}^{\infty} \frac{(E-E_F)}{kT} \frac{\sigma}{\sigma}(E) \; dE$$

The magnitude and temperature dependence of S provides detailed insight into the behavior of charge carriers in a-Ge. Each charge carrier contributes to the magnitude of the Seebeck coefficient in proportion to the displacement of its state from the Fermi energy in units of kT. Additionally, each charge

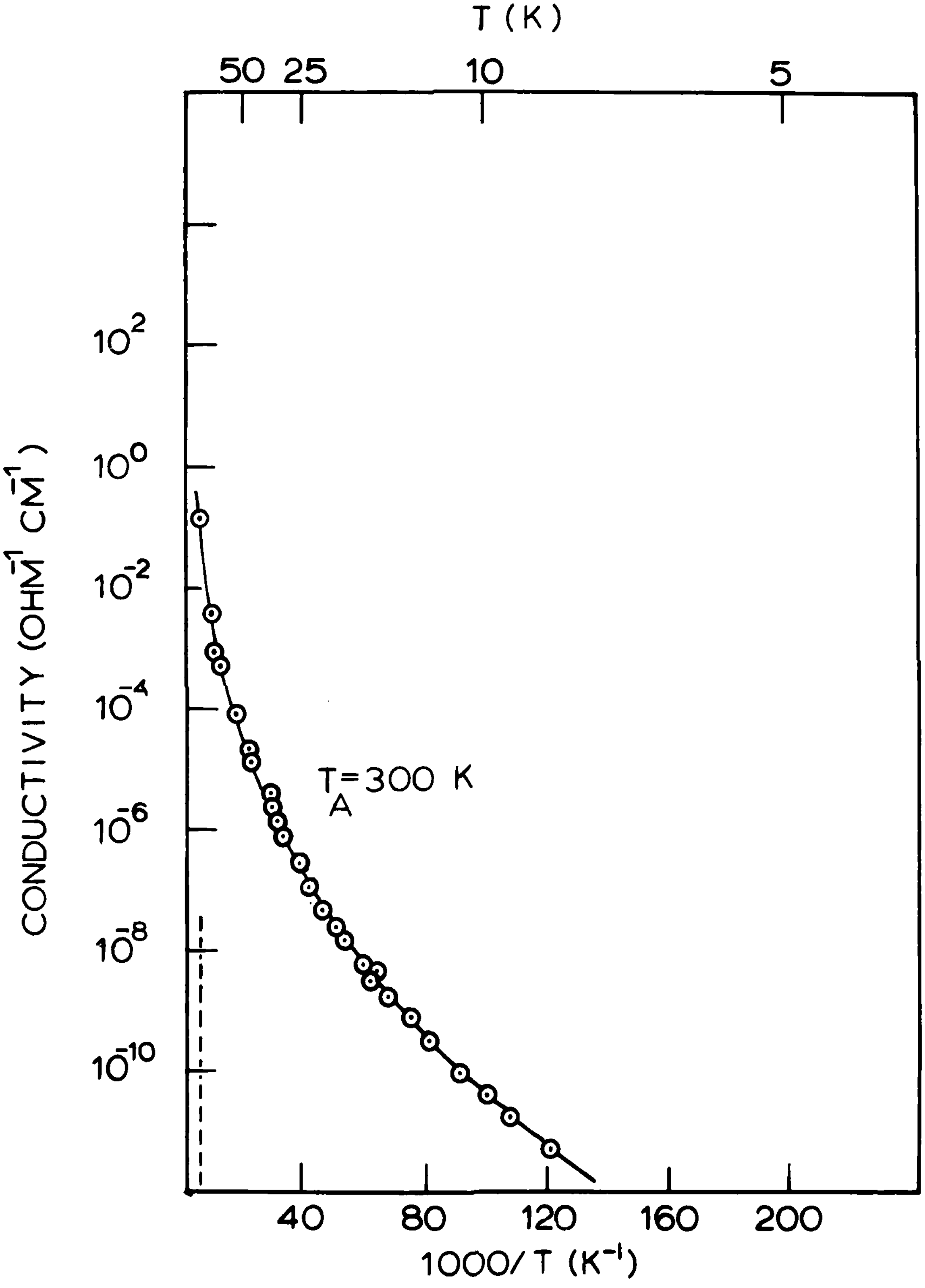

Figure (8) Temperature dependence of the conductivity of an a-Ge film annealed at $T_A=300$ °K. Solid curve is theoretical $T^{-1/4}$ dependence.

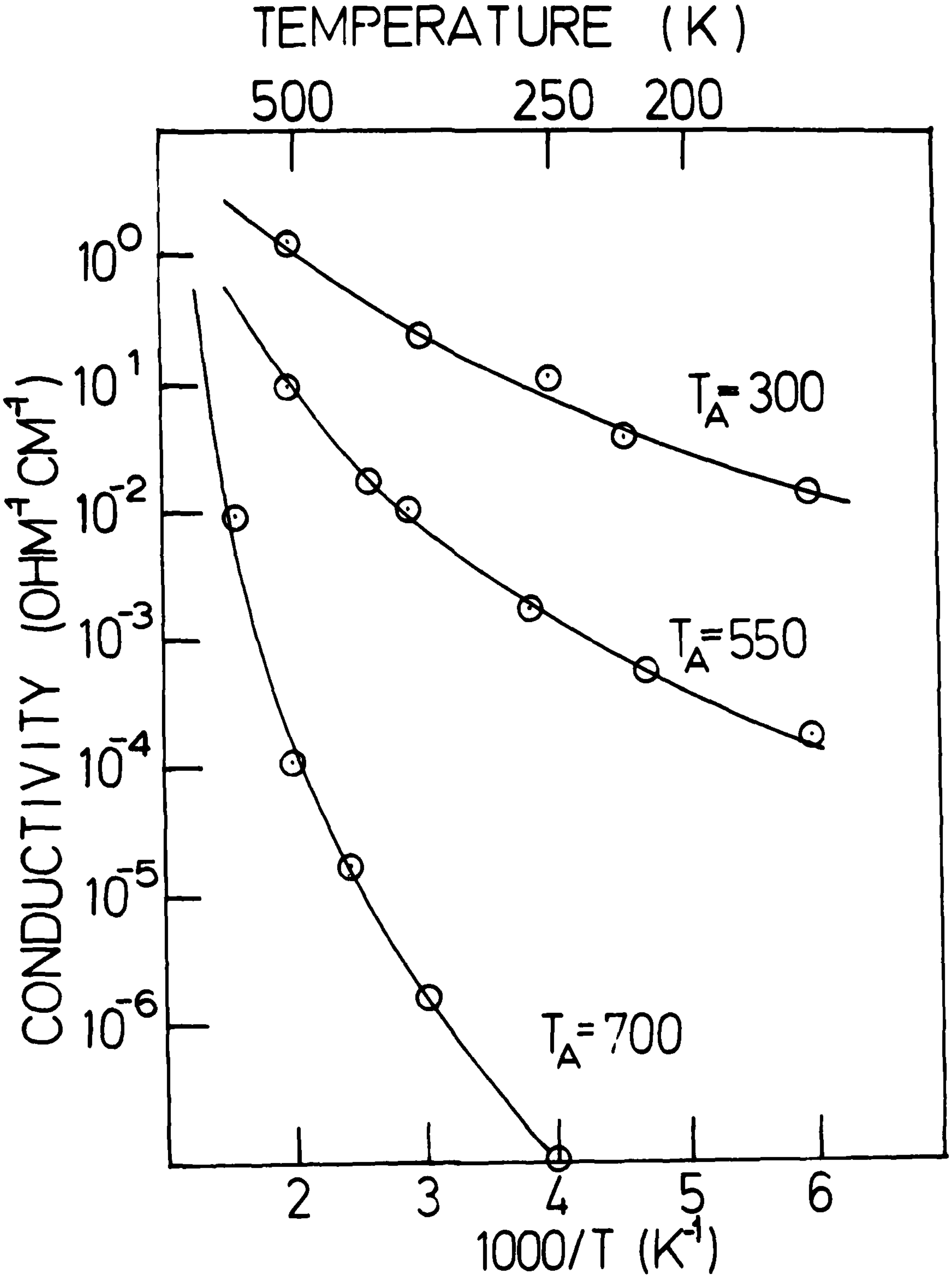

Figure (9) Effect of annealing of the conductivity of a-Ge films.

carrier contributes to S in proportion to its contribution to the total conductivity $\sigma(E)/\sigma$. The sign convention is such that $S < 0$ for electrons with $E > E_F$. One therefore expects the sign of the Seebeck coefficient to depend on whether conduction takes place predominately above or below the Fermi level. Thus, the sign and magnitude of the Seebeck coefficient provides information concerning the nature of the charge carriers and the density of states about E_F. The results of the Seebeck coefficient measurements are shown in Figure (10B). The behavior shown is typical of that observed for a-Ge films prepared by the procedures described in paragraph 2 above and are also generally representative of the results from similar measurements reported in the literature.

The magnitude of the Seebeck coefficient is a decreasing function of temperature between 450 and 300 °K. In this temperature range, the charge carriers are largely electrons in thermally populated extended states well above the Fermi level. Below about 300 °K the magnitude of the Seebeck coefficient is small and nearly independent of temperature. Therefore, between 300 and 2°K, the conduction process is dominated by thermally assisted tunnelling of electrons in states close to the Fermi level. The effect of annealing is also illustrated in Figure (10B). The reduction of localized states in the band gap which accompanies an increase in crystallinity upon annealing causes a more rapid decrease in the Seebeck coefficient with temperature.

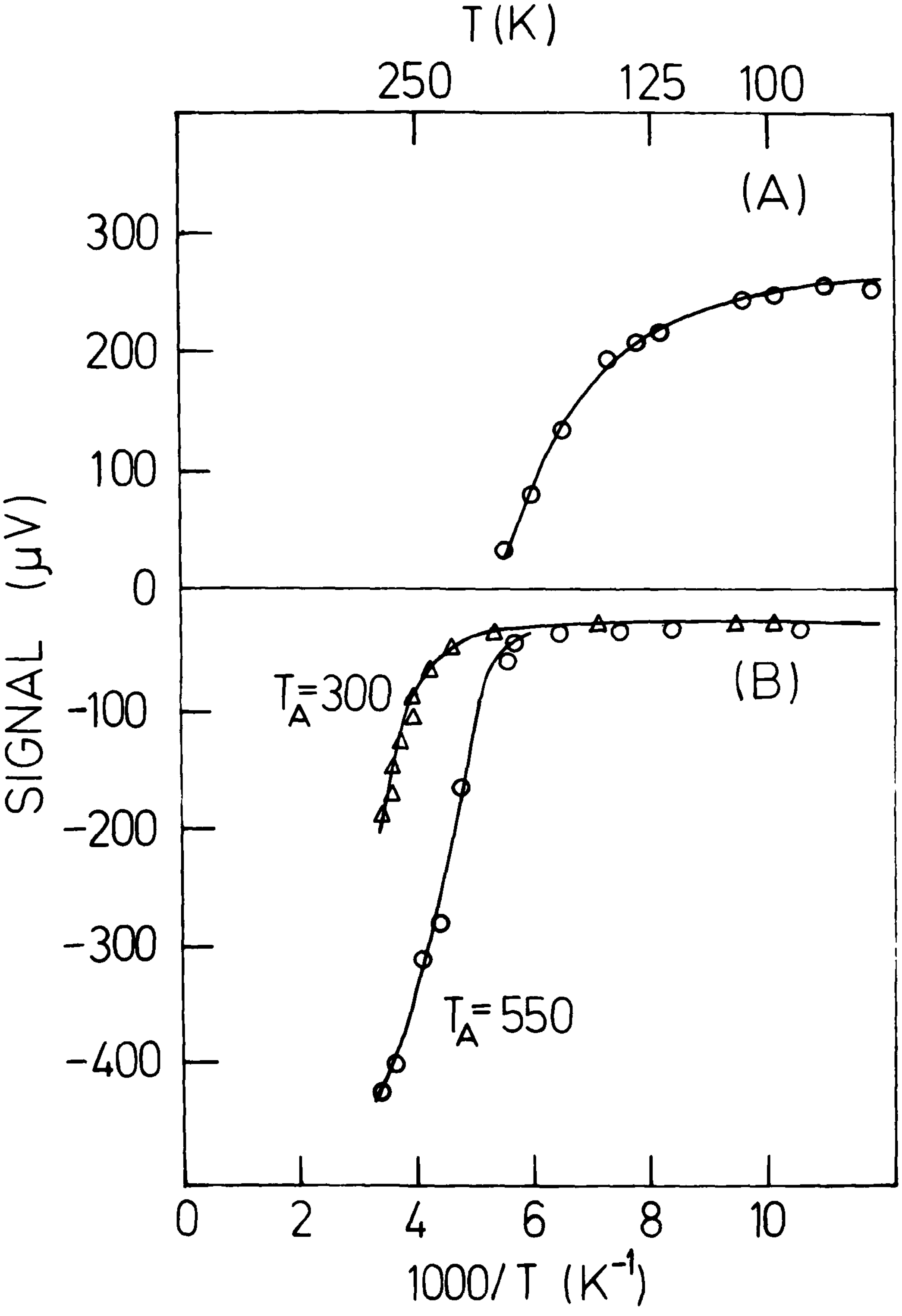

Figure (10) (A) Temperature variation of ultrasonic transducer signal voltage.

(B) Temperature variation of the Seebeck coefficient of two a-Ge films annealed at T_A=300 K and T_A=550 K.

3. Ultrasonic Detectors

The effect of ultrasonic elastic waves on the electrical properties of amorphous semiconductors at low temperatures is quite dramatic. The DC conductivity of the films was observed to change by up to two orders of magnitude. Both CW and pulse-echo measurements were conducted using the electronic circuit diagrammed in Figure (11). In the CW experiments an a-Ge transducer which had been evaporated onto a pyrex substrate was bonded to the end-face of a sapphire transducer assembly. The variation in resistivity of the a-Ge film was determined as a function of ultrasonic frequency and absolute temperature. The results of the frequency swept measurements are illustrated in Figure (12). The response of the transducer is relatively independent of frequency over the range investigated (1-4 GHz). The apparent variations in amplitude are due to the variations in ultrasonic power transmitted by the end-face bonded to the a-Ge transducer and correspond to ultrasonic frequencies which produce standing waves within the sapphire substrate.

The temperature variation of the signal amplitude is illustrated in Figure 10A for comparison with the temperature variation of the Seebeck coefficient. In order to make some direct comparisons of the a-Ge device and a conventional piezoelectric detector, we have recorded pulse amplitudes in the following manner using both devices. A film of amorphous germanium was evaporated on one end of a 20mm long sapphire rod.

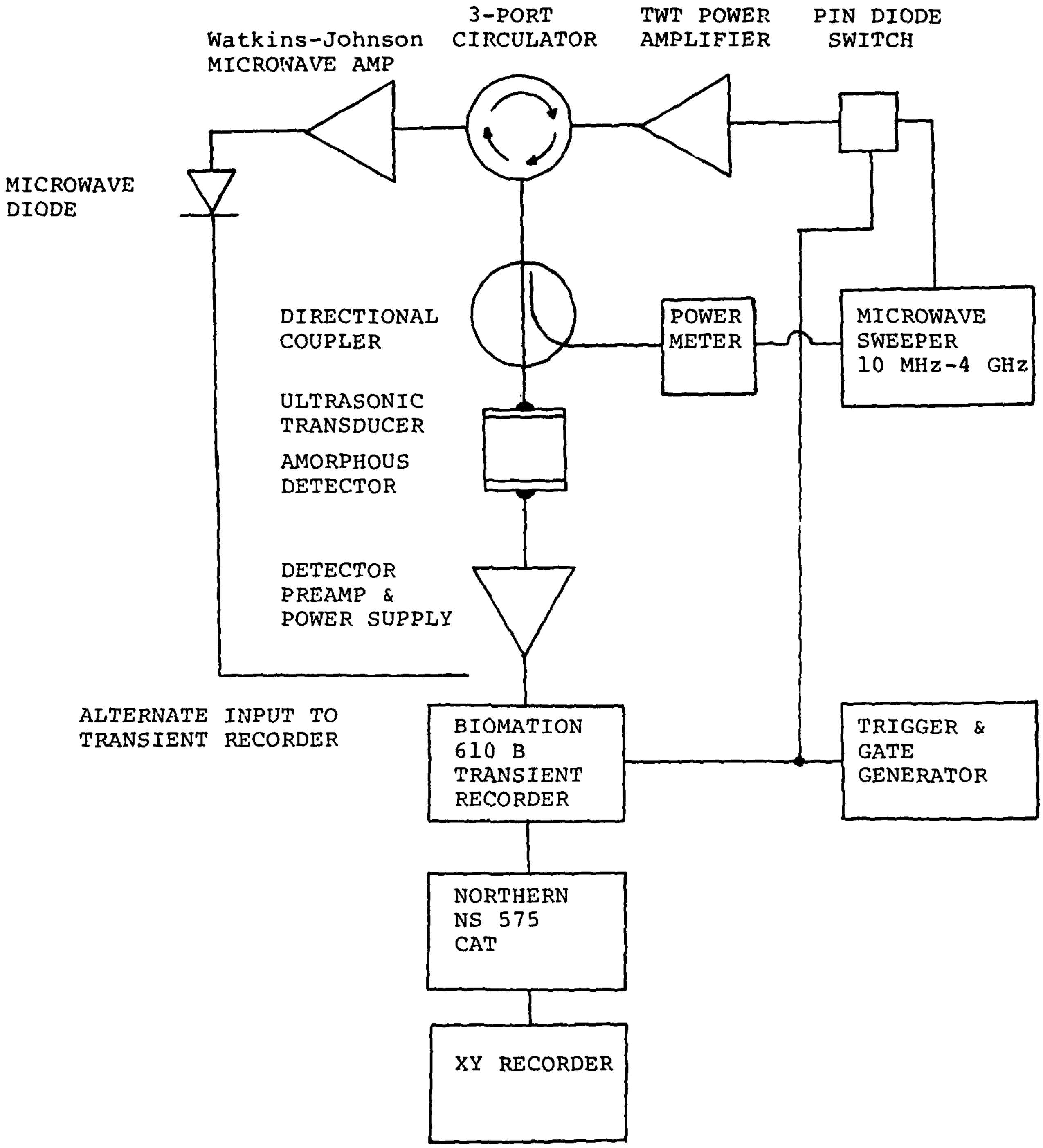

Figure (11) Circuit used for ultrasonic pulse-echo and CW frequency swept measurements.

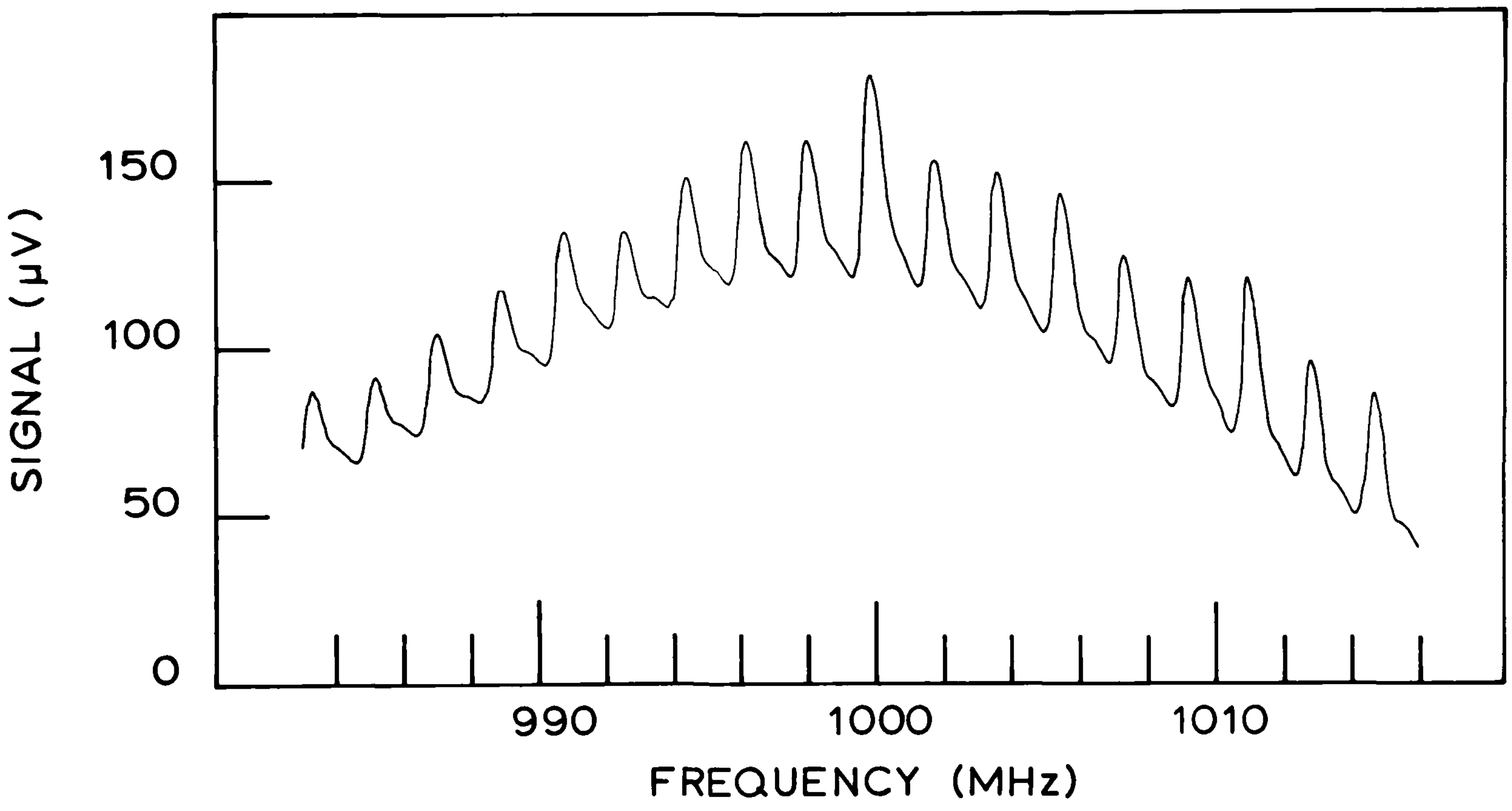

Figure (12) Output of a-Ge transducer as a function of ultrasonic frequency.

A thin film ZnO piezoelectric transducer was evaporated on the other end. Using the piezoelectric transducer in the pulse-echo circuit illustrated in Figure (11), the amplitude of a multiply reflected 1 GHz pulse launched from the transducer was measured using both the piezoelectric and the acousto-conductive device. An x-y recorder display of the data recorded is shown in Figure (13).

Figure (13A) illustrates the echo decay of a 0.1 microsecond ultrasonic pulse at 1 GHz. The decay envelope is very nearly exponential, although a weak low frequency modulation of the envelope is evident. This modulation may be due to a slight lack of parallism between the end faces of the sapphire rod substrate. Figure (13B) illustrates the echo decay of a 0.1 microsecond ultrasonic pulse at 1 GHz propagating in a sapphire rod with nonparallel end-faces. For this experiment, a 2 cm sapphire rod was lapped in such a fashion as to introduce slight nonparallelism between the end-faces. The final substrate was somewhat shorter than 2 cm in length. The distinctly non-exponential decay of the multiply reflected pulse as detected with the piezoelectric ZnO thin film transducer is the result of phase cancellations at the detector substrate interface. Figure (13C) was obtained using the thin film a-Ge detector evaporated onto the opposing end-face of the substrate used to obtain the decay illustrated in Figure (13B). The decay envelope, although not exactly exponential, does not manifest any phase cancellation effects.

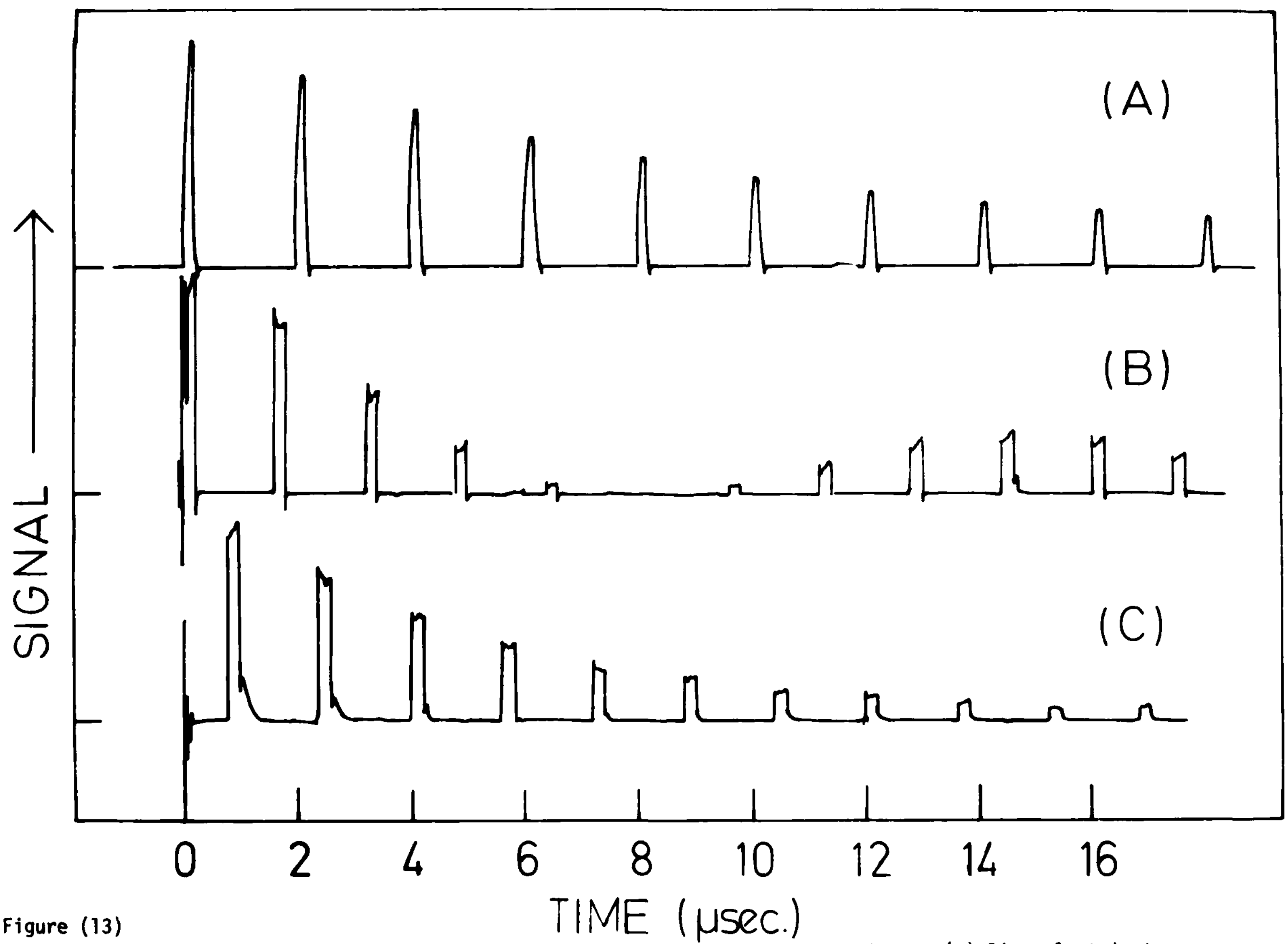

Figure (13)

Comparison of piezoelectric and a-Ge transducer response in a pulse-echo experiment. (a) Piezoelectric transducer echo decay, (b) Piezoelectric decay showing effect of nonparallism, (c) a-Ge echo decay.

Additionally, the envelope decay rate obtained with the a-Ge detector is approximately twice that obtained with the ZnO piezoelectric detector. This behavior results from the fact that the output of the a-Ge detector is proportional to the acoustic power dissipated in the device, which is, in turn, proportional to the square of the amplitude of the ultrasonic wave. The output of the piezoelectric device, on the other hand, is proportional directly to the amplitude. Measurement of the absolute sensitivity of the a-Ge detector is extremely difficult since it involves estimates of the absolute acoustic power propagating in the sapphire substrate. The sensitivity of the detector may be estimated by measuring its response to a known heat input. Then, assuming a flat frequency response for the device, the sensitivity may be computed. Alternatively, the conversion efficiency for the piezoelectric transducer may be used to estimate the amplitude of the ultrasonic power. Invariably, when this method of computation was employed, sensitivities greater by an order of magnitude than to those computed from the temperature rise technique were obtained.

SECTION IV

Conclusions

The effect of ultrasonic power on the conductivity of a-Ge films is most pronounced when the films are in a highly disordered state. The effect of annealing, which increases the crystalline character of the a-Ge film, is to reduce the sensitivity of the conductivity to ultrasonic waves. The most sensitive devices fabricated were those whose DC conductivity and Seebeck coefficients indicated the greatest amount of structural disorder.

The sensitivity of the DC conductivity of a-Ge films to ultrasonic power is observed only over the limited temperature range 77-1.5 °K. The temperature dependence of the signal voltage obtained in the ultrasonic experiments approximates the temperature dependence of the Seebeck coefficient as illustrated in Figure (10). Since the behavior of the Seebeck coefficient of a-Ge films in this temperature range is determined by the change from conduction in extended states to a variable range hopping process, we conclude that the sensitivity of the conductivity to ultrasonic power is due to a perturbation of the variable range hopping process by the ultrasonic waves. Experiments to explore more completely the microscopic physics of this interaction are at present incomplete. However, we may speculate on several possible reasons for the demonstrated sensitivity of the DC conductivity to the presence of ultrasonic elastic waves.

The acoustic waves may play a role similar to the statistical fluctuations of the local potential of the amorphous material. The compressions and rarefactions of the acoustic wave may produce fluctuations which modify the density of states within the energy gap and by that means alter the concentration of free carriers.

Alternatively, the conductivity changes in the presence of ultrasonic waves could be due entirely to a thermoelastic effect. The thermoelastic effect arises from the fact that when a material is subjected to a stress, the resulting strain is, in general, accompanied by a change in temperature. Since the DC conductivity is a rapidly varying function of temperature, changes in the conductivity in the presence of ultrasonic waves could be anticipated. Indeed, the a-Ge devices have also been used as sensitive bolometers. The absorption of ultrasonic power and its degradation to heat causes a power dissipation in the detector $p_s(t)$. In addition to the signal power, the electrical circuit dissipates a power in the detector p_e, so that the total power dissipated in the device is p_e+p_s. Letting C and G represent the heat capacity of the detector and the thermal conductance between the detector and the bath, respectively, the heat balance equation for the device may be written:

$$C\frac{dT}{dt} = p_e+p_s - G\Delta T$$

where ΔT is the temperature rise above ambient. For the case of interest, ultrasonic power was modulated at circular frequency ω, so that we may write:

$$p_s(t) = p_s^o\ (1-\cos\omega t)/2$$

Since the resistance of the detector is a rapidly varying function of temperature, the electrical power dissipated in the detector will vary with signal power. For the time dependent electrical power it may be shown that:

$$p_e(t) = \alpha p_e(R_L-R)\Delta T(t)/R_L+R$$

where we have introduced the detector sensitivity α defined as:

$$\alpha = \frac{1}{R}\frac{dR}{dt}$$

In terms of the above parameters, the thermal response time of the detector is

$$\tau_D = C/G - \alpha p_e(R_L-R)/(R_L+R)$$

Where e_D is the voltage across the detector. The heat capacity (C) and thermal conductance (G) for several devices have been determined. Using the known values of the load and detector resistance and the appropriate value of α determined from the temperature dependence of the detector conductivity, the thermal time constant of the device was computed to be on the order of 10^{-6} seconds. This is at least an order of magnitude slower than the time constant observed in ultrasonic pulse-echo experiments. It therefore appears that the thermoelastic effect is not responsible for the major portion of the detector signal.

In conclusion, ultrasonic detectors fabricated from thin films of a-Ge have been shown to be useful as power detectors, insensitive to phase, in the temperature range 77-1.5°K. The detection scheme utilizes the sensitivity of the DC conductivity of a-Ge films to ultrasonic power. Thin film ultrasonic detectors fabricated from amorphous germanium function efficiently in the MHz and GHz frequency range at temperatures below about 77 K. At or below this temperature they compare favorably in sensitivity and response time with conventional piezoelectric detectors, without the disadvantage of sensitivity to bonding, alignment, etc. Several of these devices are currently in use for ultrasonic power measurements in experimental applications where measurements are to be made at cryogenic temperatures. They have proven to be essentially perfect power detectors with complete insensitivity to bond parallelism and bonding characteristics over the frequency range studied (10 MHz - 4GHz). The methods developed for the production of these devices and covered in this report will yield devices with reproducible characteristics on substrates of quartz, pyrex or sapphire. Other substrate materials require a modification of fabrication techniques.

At temperatures significantly above 77 K, the performance of the thin film amorphous germanium detectors is rapidly degraded. The devices are not sufficiently sensitive at temperatures above approximately 77 K to be useful as ultrasonic detectors in any but the most high power applications. The restriction of the devices to operation below about 77 K, while not significant for many basic research applications, is a formidable problem for routine ultrasonic testing applications. The principal difficulty in testing applications is the requirement that the detector temperature be maintained below 77 K, while the work piece is, in most instances, at room temperature. Although small metal pieces might be easily cooled to the operating temperature of the detector, this would prove costly and difficult with larger pieces. It might be possible to utilize a plastic or glass coupling rod to connect a room temperature test piece with a liquid nitrogen cooled detector, if the ultrasonic frequencies were restricted to the MHz frequency range. We have not experimented with glass and plastic coupling rods for this purpose, however.

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