Quarterly Progress Report 4

INVESTIGATION OF SOLID STATE TRAVELING-WAVE-AMPLIFIER TECHNIQUES FOR FUTURE SATELLITE APPLICATIONS

(1 March 1965 - 30 June 1965)
Contract No. NAS 5-3972

prepared by

National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland

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Microwave Electronics Corporation

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July 1965

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The program objective is to investigate solid-state traveling-wave-amplifier techniques, with emphasis on those problem areas critical to using these techniques in satellite application. Specific tasks include developing improved transducers, eliminating spurious oscillation, evaluating and selecting optimum semiconductor materials, and investigating and evaluating properties of the solid-state traveling-wave amplifier process.

The main program efforts during the period covered by this report were devoted to developing and improving the techniques for fabricating and testing acoustic amplifier crystals. An important aspect of the tests was the observation of amplification in a CdS crystal.

A computer was programmed to give theoretical data on the gain and efficiency characteristics for several acoustic amplifier crystals of interest to this program. These data are being used to guide design considerations.

For the first time in this research, transducers of acceptable characteristics were evaporated onto an acoustic-amplifier crystal. This has made the authors very optimistic about the amplifier-fabrication techniques presently being used.

The present state-of-the-art techniques now available to this program establish a definite base for acquiring considerable experimental data on acoustic-amplifier properties. Author

I. TECHNICAL DISCUSSION

A. Introduction

1. Objective

The program objective is to investigate solid-state traveling-wave amplifier techniques, with emphasis on those problem areas critical to future use of these techniques in satellite applications. Particular tasks include developing improved transducers, eliminating spurious oscillation, evaluating and selecting optimum semiconductor materials, and investigating and evaluating properties of the solid-state traveling-wave-amplifier process. An ultimate objective is a conclusive over-all evaluation of the solid-state traveling-wave amplifier with the unique advantages of the solid state. These key potential advantages important to satellite applications include inherent simplicity, ultralight weight, unusually small size, broad bandwidth characteristics, long life, radiation resistance, and high reliability under the arduous space environment from launch through orbit.

2. Program Plan

The program objectives are to be achieved by performing the following coordinated set of tasks:

TASK 1: Developing Improved Transducers

This phase involves studying, fabricating and evaluating materials and processes for improved microwave-frequency acoustic-wave transducers. Major emphasis will be placed on developing ferromagnetic and piezoelectric thin-film transducers and associated thin-film impedance-matching layers. This topic will be investigated in considerable depth, since development of improved transducers is critical to subsequent phases of the investigation.

TASK 2: Eliminating Oscillation

This phase involves testing and proving the effectiveness of proposed techniques for suppressing spontaneous oscillation in the amplification process. These techniques include suppressing oscillation due to reflected waves and eliminating oscillation due to external feedback.

TASK 3: Investigating Optimum Materials

Using the improved transducers and tested techniques for eliminating oscillation of the first and second tasks, the most promising acoustic-amplification materials will be evaluated. Particular emphasis will be placed on choosing the material offering the highest possible operating efficiency as a microwave amplifier.

TASK 4: Evaluating the Solid-State Amplifier

Results of the previous tasks will be combined in the design, development and fabrication of a model solid-state traveling-wave amplifier, suitable for determining many performance characteristics of the amplification technique. This investigation will provide initial data on size, weight, gain, efficiency, bandwidth, frequency range, noise performance, life and reliability.

3. Progress Summary

Major effort during the period covered by this report was devoted to fabricating ohmic contacts onto the acoustic amplifier crystals. Considerable time was consumed searching for a method of making the necessary ohmic contacts while maintaining an extremely flat and smooth surfact for the acoustic transducer. The results of this search have been very worthwhile and now appear complete.

A program was written, following the theory presented in the Second Quarterly Progress Report, and run on a Burroughs B5500 computer to give theoretical gain and efficiency characteristics of various crystal materials. These data are being used to guide design considerations. At least a portion of the data are included in this report.

Transducer studies have developed to a point where one can get good acoustic transducers with reasonable regularity on highly polished and plated acoustic materials. These are the type of crystals used for testing transducers or used as buffer crystals for acoustic amplifiers. Recently, this transducer development added the ability to evaporate what appear to be good acoustic transducers on amplifier wafers. Because of the high acoustic attenuation in CdS crystals, these transducers must be tested at the same time as the entire amplification process. Great optimism is involved in these measurements because of the excellent physical appearance and good low-frequency characteristics of these films.

After overcoming several fabrication problems, an experimental amplifier model was realized with some of the necessary properties required for testing. Even though this unit was far from optimum in design and configuration, some very encouraging results were observed before it was destroyed during testing. The problem responsible for the voltage breakdown that destroyed the sample was the result of reworking required because of the previous fabrication problems.

Because of the effects of current saturation and oscillation associated with the amplifier crystal, time was expended in studying the parameters associated with nonohmic behavior of CdS and CdSe. These studies are an important part of understanding the acoustic-amplification process and will be continued beyond the level reported herein.

Results achieved thus far in developing transducers, investigating amplifier processes, materials, and noise-measurement considerations -- as well as the various fabrication and processing techniques -- form a firm base for accomplishing this program in accordance with the three-month time extension that has been received for this program. At the end of this period there will still be questions unanswered concerning the final application of the acoustic amplifier for satellite communications. To obtain acceptable answers to these questions will require an additional six months research and development program beyond the scope of the present program.

B. Amplifier Materials

Theoretical analysis of several materials operating in shear and longitudinal acoustic modes was conducted during the period covered by this report. A Burroughs B5500 computer was programmed to calculate the theoretical gain and efficiency characteristics of various crystal materials. The materials considered to date by this approach are CdS, CdSe, and ZnO. The data presented herein represent only a sampling of that obtained, but do give typical data of what can be expected from the various materials. The computer was not programmed to calculate maximum gain or efficiency but rather to give the gain characteristics and frequency response over reasonable ranges of the various parameters. Quarterly Progress Report 2 defined the parameters in question, formulated the necessary gain and efficiency equations and described the optimum operating characteristics as far as oscillation-free amplification is concerned. The curves picked for presentation in this report were calculated using the equations derived in the above report.

Typical gain characteristics are shown in Fig. 1 through 6, where data are presented at a conductivity of 5×10^{-3} per ohm-cm and frequencies of 0.5, 1.0 and 2.0 Gc. For a given crystal and frequency, the conductivity that yields the highest gain is that which satisfies the equation

$$f^2 = f_c f_d$$

where f_c and f_d are the conduction and diffusion frequencies, respectively. The conductivity value was chosen as an average value, certainly representative of what one should expect. It was also chosen because of crystal availability. The frequencies are representative of these of immediate interest to this project.

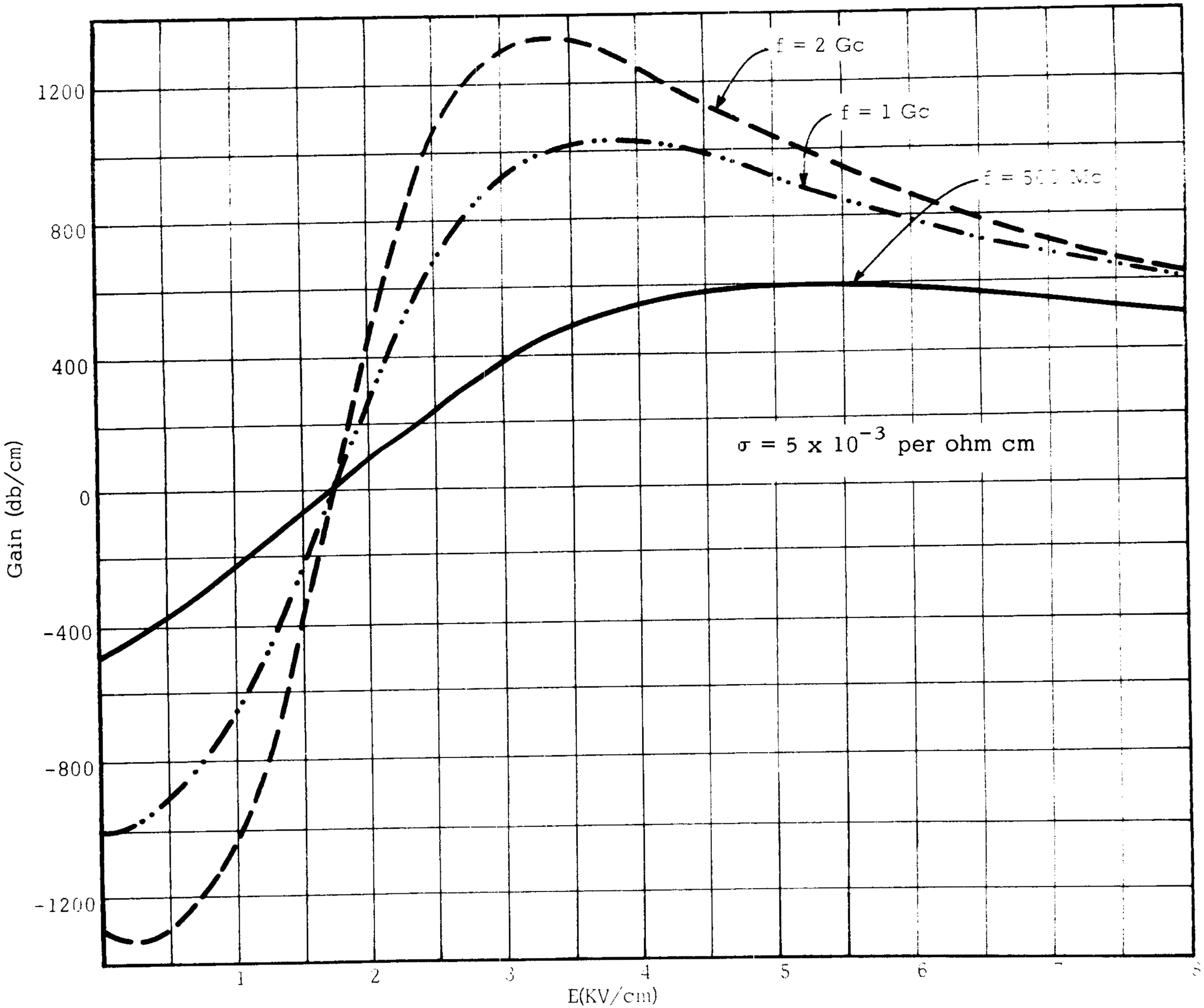

Fig. 1. Gain characteristic for CdS operating in a longitudinal mode.

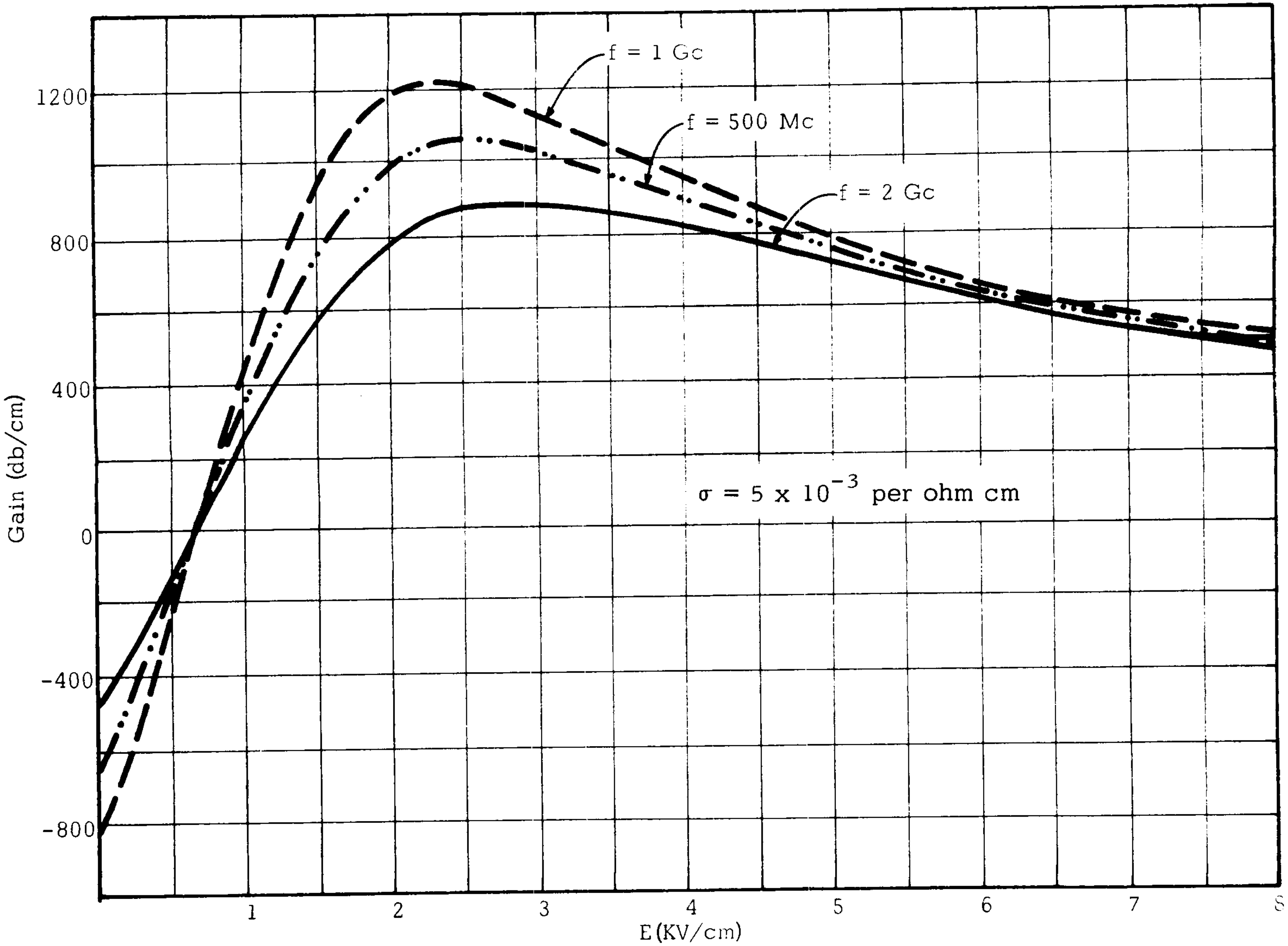

Fig. 2. Gain characteristic for CdS operating in a shear mode.

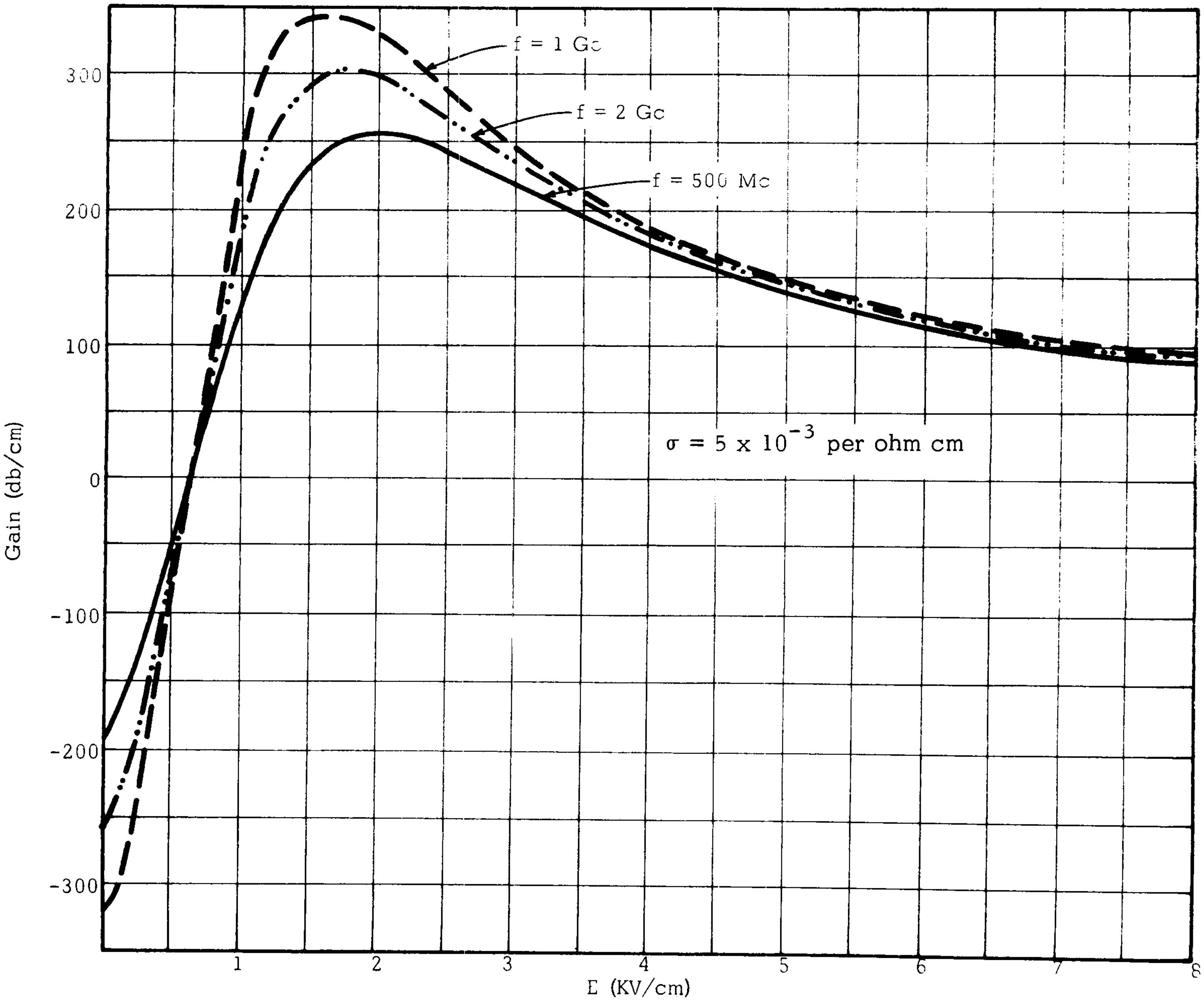

Fig. 3. Gain characteristic for CdSe operating in a longitudinal mode.

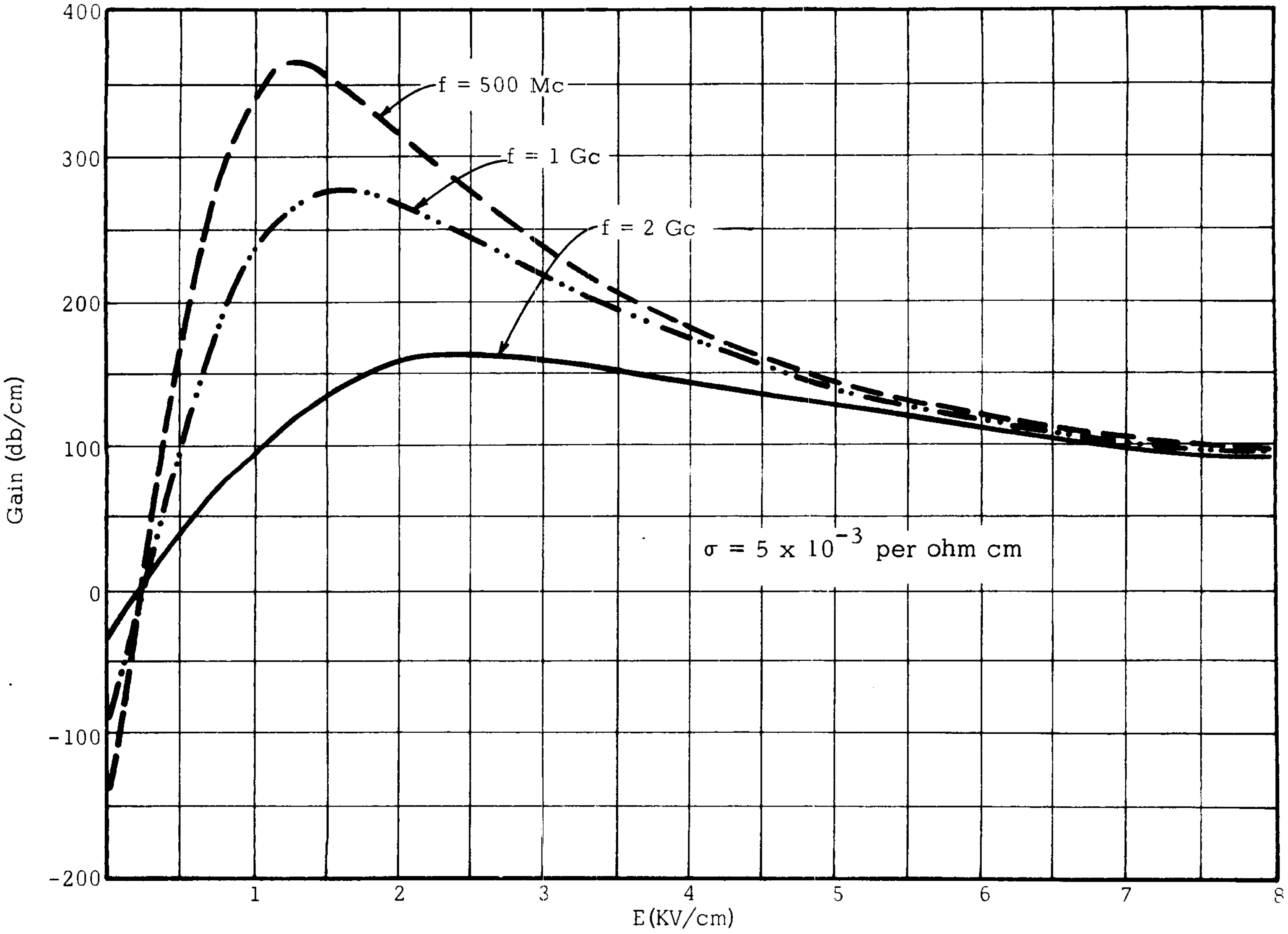

Fig. 4. Gain characteristic for CdSe operating in a shear mode.

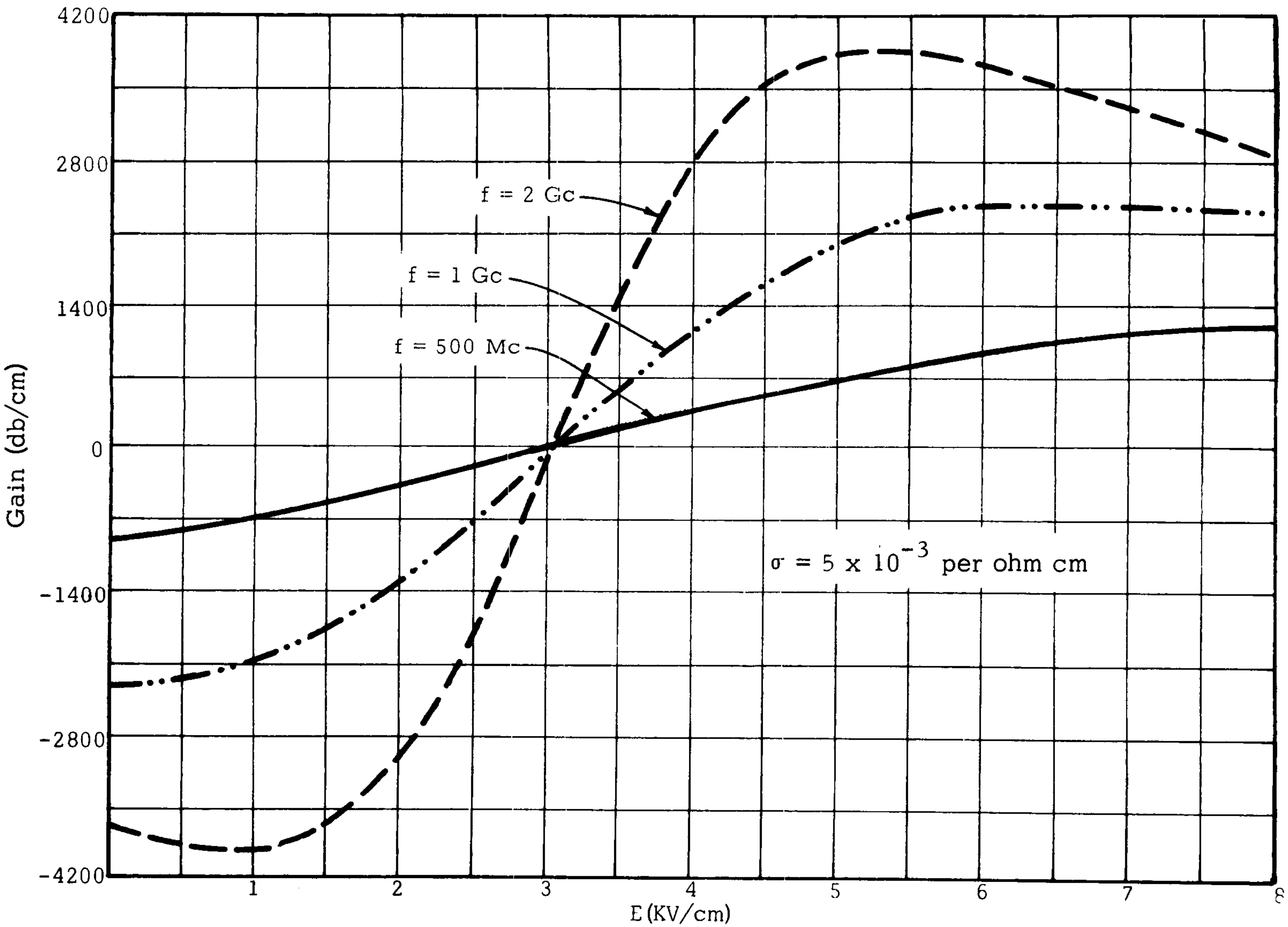

Fig. 5. Gain characteristic for Z_nO operating in a longitudinal mode.

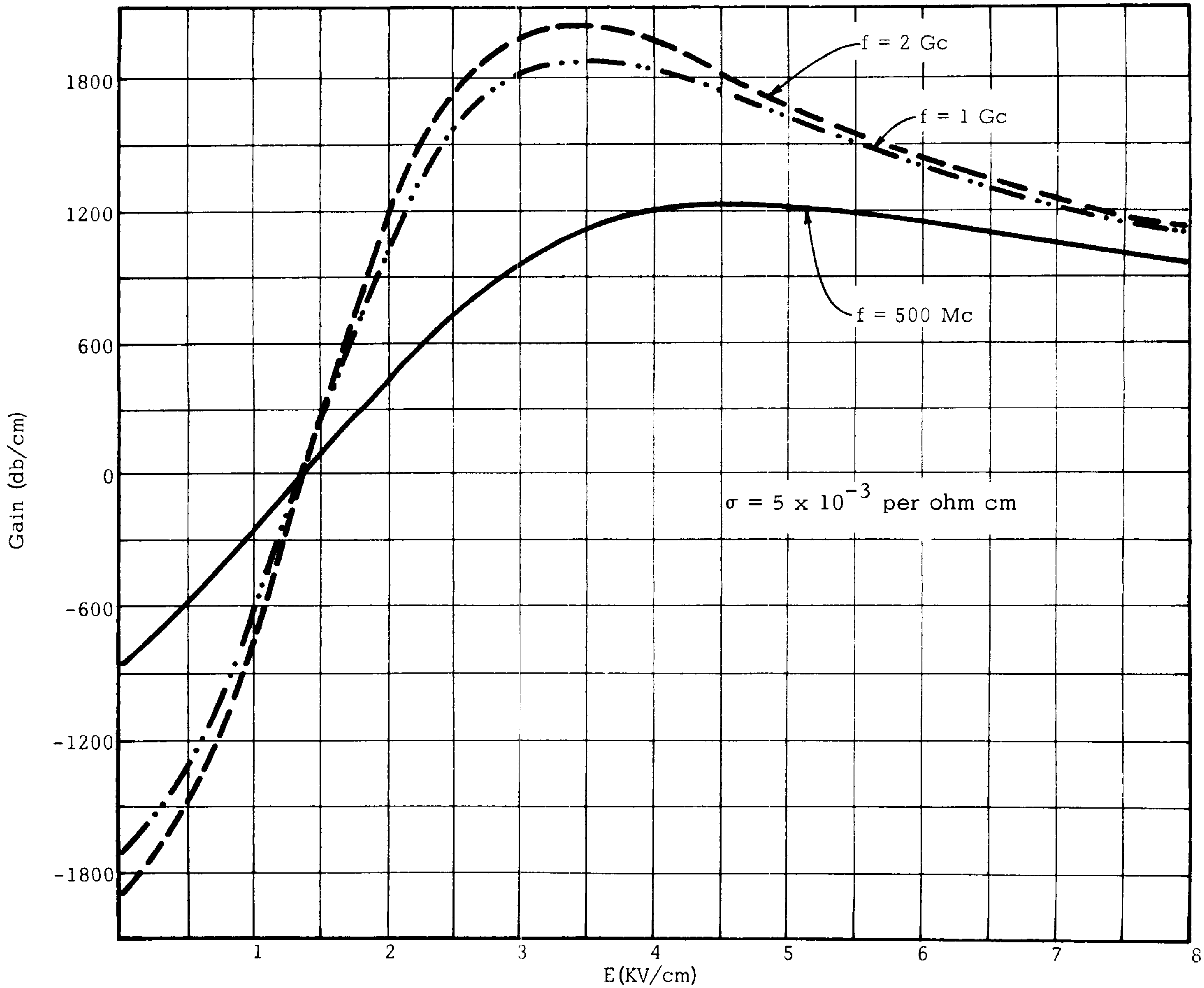

Fig. 6. Gain characteristic for Z_nO operating in a shear mode.

Typical response data are shown in Figs. 7 through 12, where gain is presented as a function of frequency for conductivities of 0.5, 1 and 5×10^{-3} per ohm-cm. In each case the electric field chosen was that giving the highest gain response among the calculated values. Points were taken by the computer program in 500 volt/cm steps so the value listed is that nearest the optimum value.

These data give good insight into amplifier-design criteria and will prove very helpful in carrying out the experimental tests of interest to this program. A more complete study of these data will be included in the final program report.

C. Semiconductor Contact and Resistivity Research

Effort was expended during this period to test various methods of making ohmic contacts to CdS and CdSe crystals. The contacts on each of the previously prepared amplifier crystals were made using evaporated indium films. This presents a fabrication difficulty because indium has a relatively low melting point--156°C--and properly oriented, efficient transducers require a deposition temperature exceeding 175°C. The result is that indium diffuses or, in some cases, actually bubbles into the transducer material even though a thin indium film is used and a heavy layer of gold is placed over the indium. Once indium is present in the piezoelectric-transducer medium, it becomes highly conductive and unusable as an acoustic transducer. To overcome indium diffusion into the transducer, layers of platinum, gold, and even MgF_2 have been deposited on the indium film in preparation for the transducer deposition. However, each time the indium melted and formed small bubbles because of the necessary heating during transducer deposition. The result is that indium cannot be used for ohmic contacts unless a buffer crystal is used in the system.

Though not ohmic, reasonably good contacts can be made to the amplifier crystals by using evaporated gold films if the surfaces are properly prepared. This requires careful chemical cleaning followed by ion bombardment in the

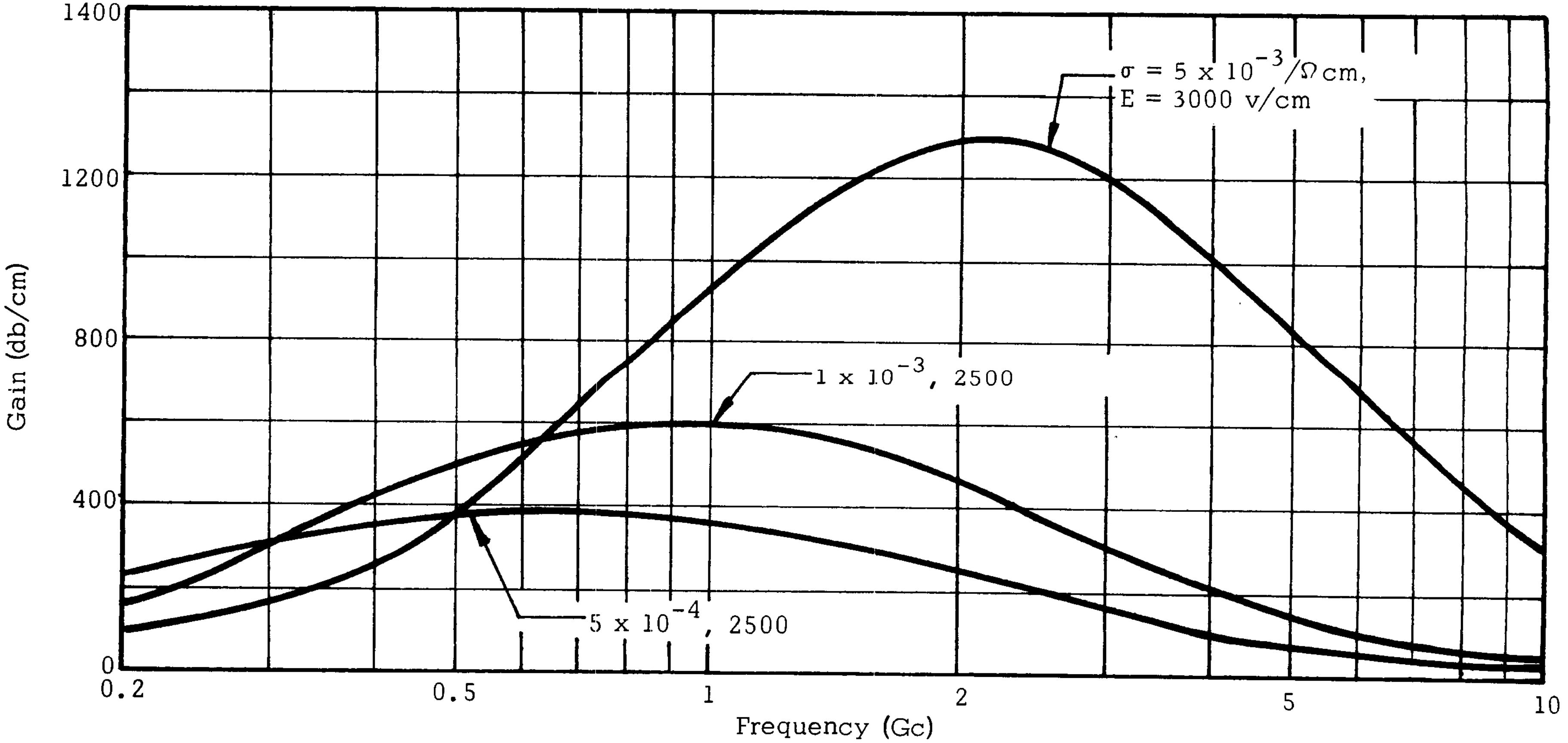

Fig. 7. Frequency response for CdS operating in a longitudinal mode.

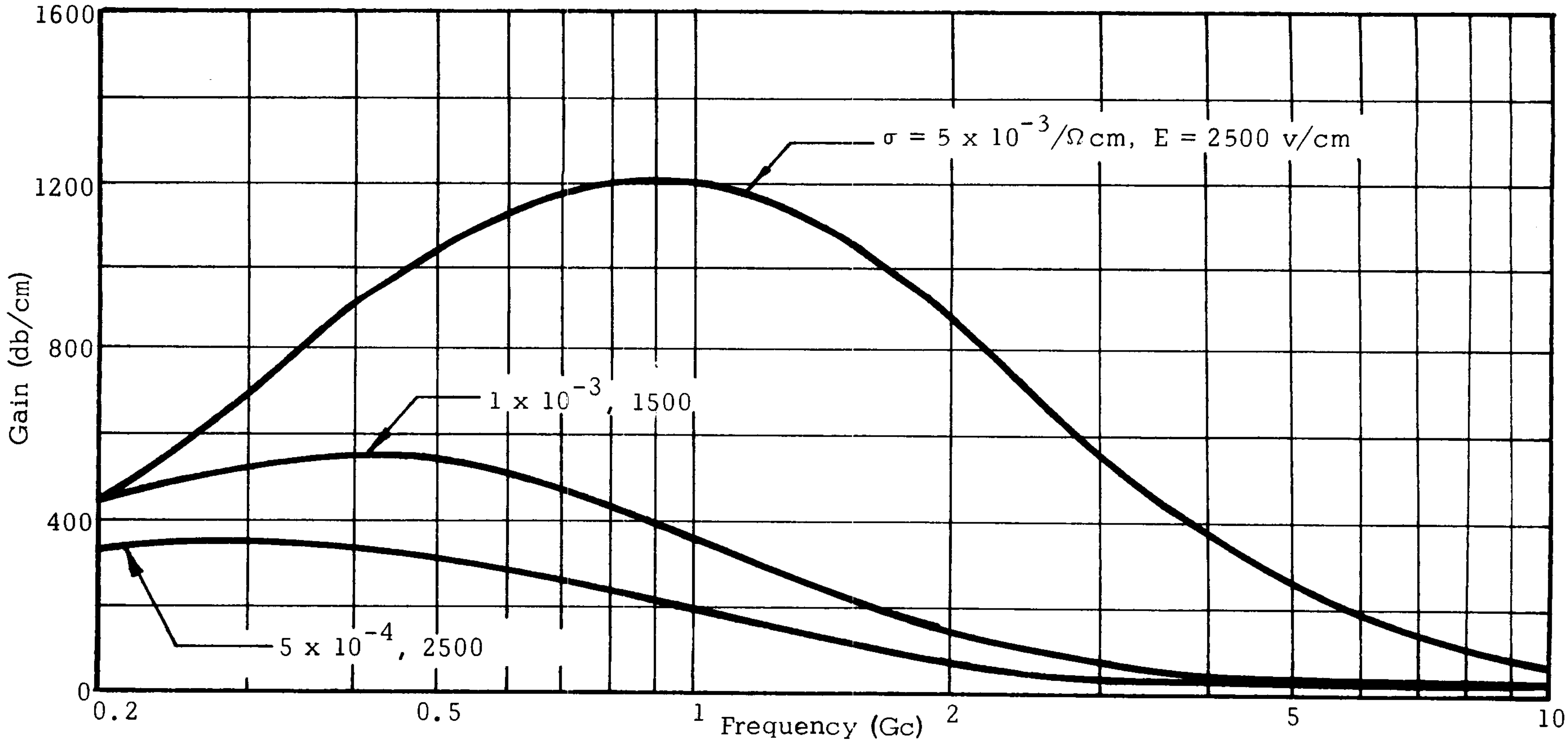

Fig. 8. Frequency response for CdS operating in a shear mode.

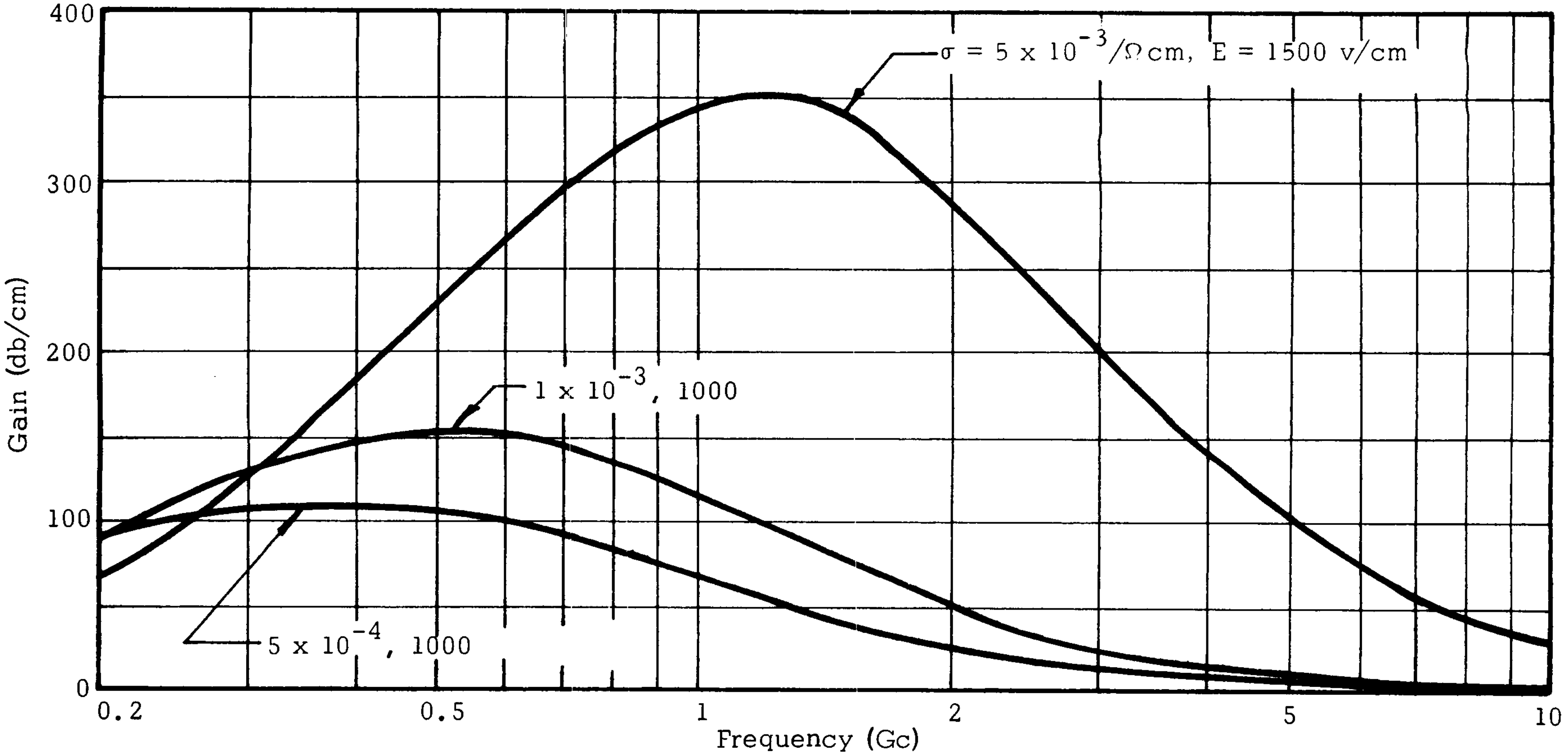

Fig. 9. Frequency response for CdSe operating in a longitudinal mode.

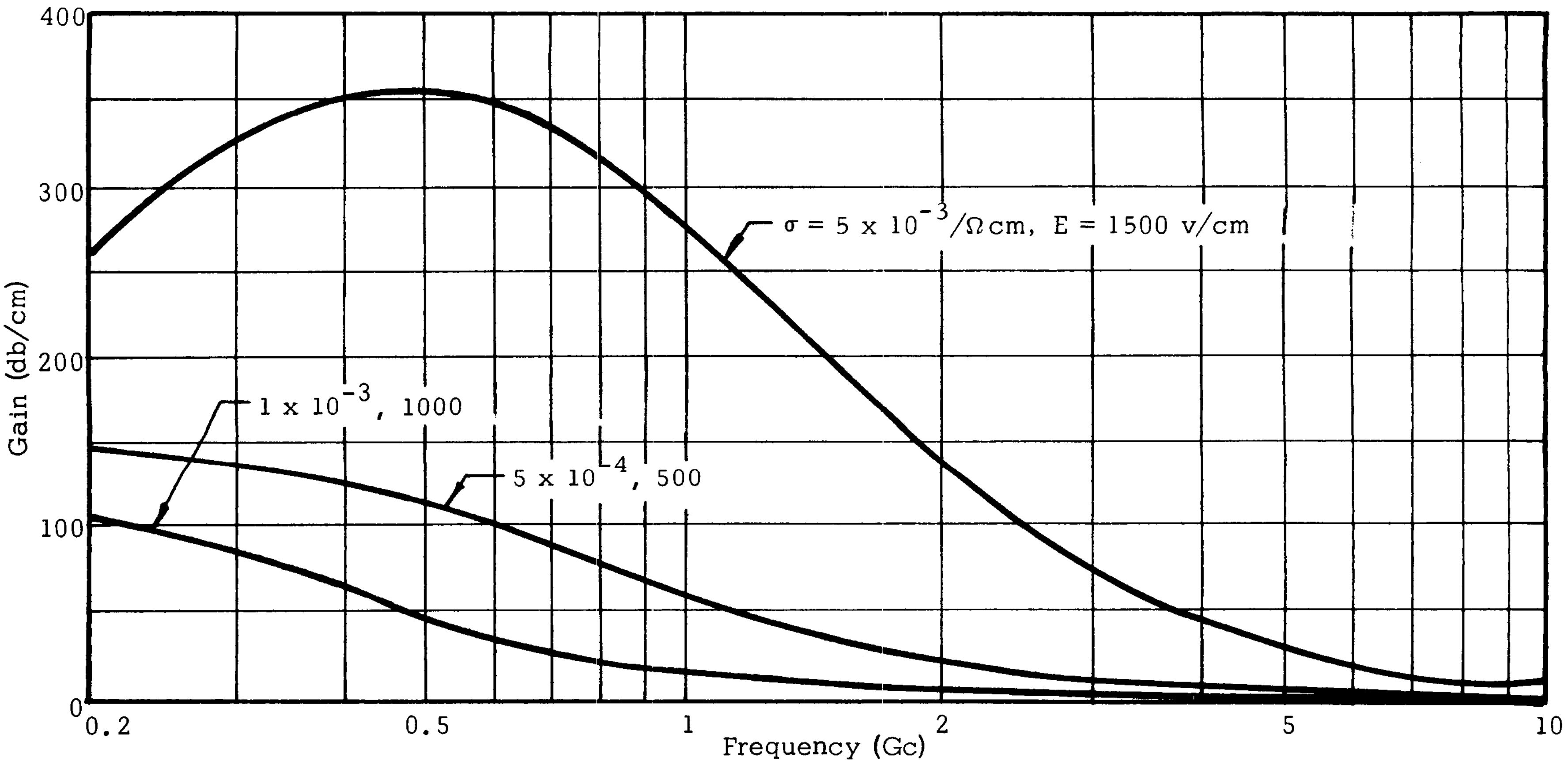

Fig. 10. Frequency response for CdSe operating in a shear mode.

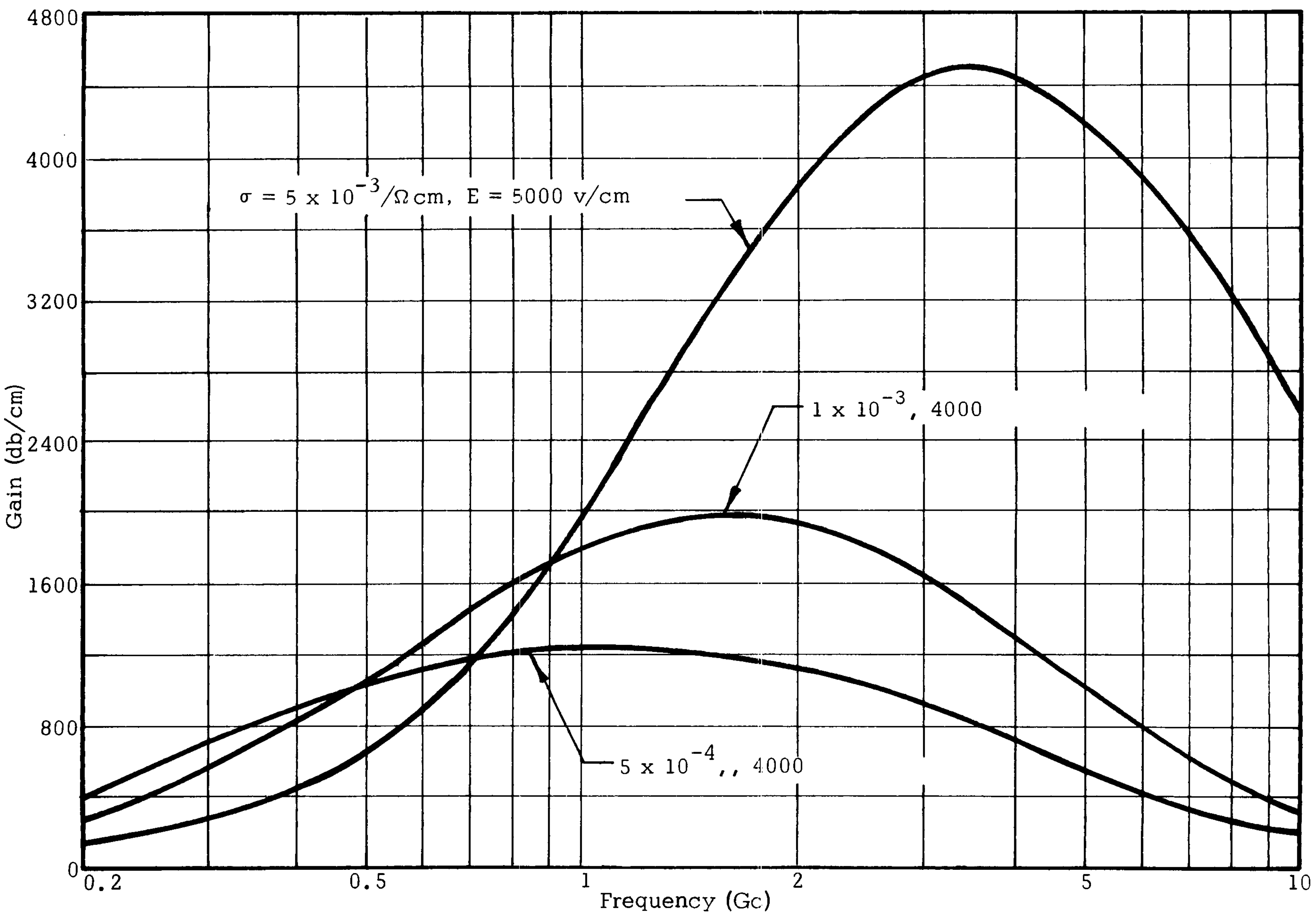

Fig. 11. Frequency response for ZnO operating in a longitudinal mode.

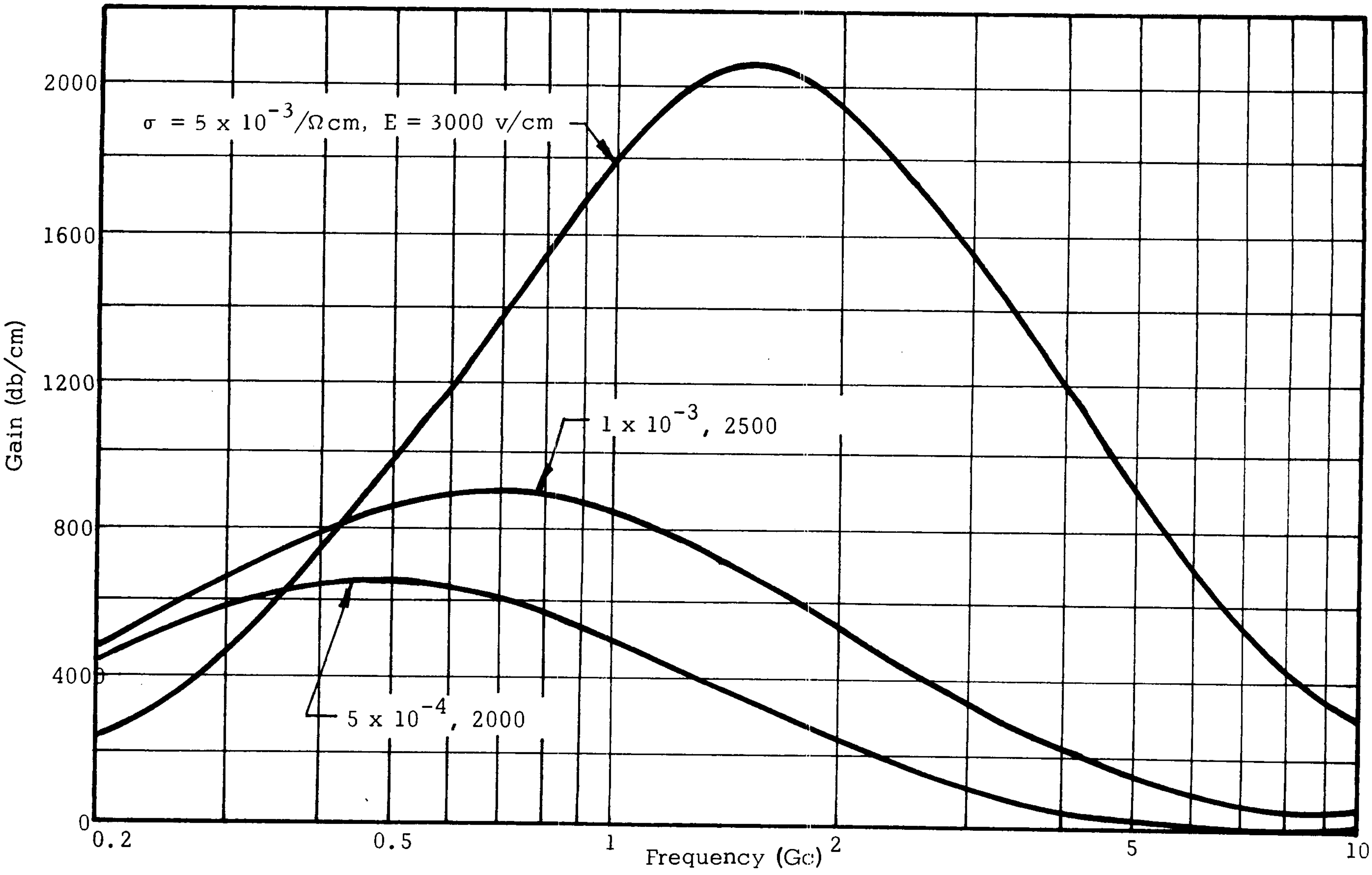

Fig. 12. Frequency response for ZnO operating in a shear mode.

vacuum station just before the gold is evaporated. A wafer was prepared using this technique and incorporating 1.5-Gc transducers. The resulting transducers proved to have less than optimum characteristics when tested; however, the sample was tested, as mentioned later in this report. The results were encouraging but erratic, so this method of making ohmic contacts was abandoned in favor of some more promising methods.

A careful study was carried out using electroless-nickel plating on the semiconductor crystals in question. Studies show this to be an excellent way of obtaining ohmic contacts on both CdS and CdSe as described below.

Following is an outline of the process resulting from the experimental tests conducted:

- Ultrasonically clean and rinse the sample.
- Etch for approximately 10 seconds in a solution of:

Hydrochloric acid	50 cc
Nitric acid	155 cc
Acetic acid	60 cc
Water	525 cc

- Sensitize in a stannous-chloride solution at 80°F (70 g/l stannous chloride and 40 g/l hydrochloric acid) for about 10 minutes.
- Rinse very thoroughly in deionized or distilled water.
- Immerse for 3 minutes in cold palladium chloride (1g/l) containing 1 ml. of concentrated hydrochloric acid.

- Place in a heated solution of No. 24, Anomet electroless-nickel plating solution.[1] The temperature of this solution is very critical and best results were obtained at about 95°C or slightly higher. Below this temperature, the plastic material in which the CdS or CdSe crystal is encapsulated will be plated but not the crystal itself.

Each sample was tested on a curve tracer to test the contacts for nonohmic behavior. Typical results are as shown in Fig. 13 for a CdSe sample. This shows the contacts to be very ohmic and thus acceptable for use in the acoustic amplifier.

Considerable time was spent attempting to deposit these films with as smooth a plating as possible. However, in all cases the films tended to have slightly textured surfaces. This effect is undesirable, because the transducers to be evaporated onto these films demand a very smooth, flat backing surface.

The next step was to find a means of evaporative rather than chemical plating. Disregarding a previous attempt using an evaporated nickel plating for ohmic contacts, a method was devised that gave excellent results. This consisted of cleaning and etching the sample as suggested in Steps 1 and 2 of the previously described method of electroless-nickel plating. The sample was next cleaned in trichloroethylene, acetone and alcohol, respectively, prior to evaporation. During evaporation, the substrate was held at 150 to 180°C for 30 minutes before actual evaporation took place. Thicknesses of about 2000 Å proved adequate; care must be taken to cover the nickel film with gold or some other material to keep the surface from discoloring. Typical results are similar to that shown in Fig. 13, which was for electroless-nickel plating.

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1. Anomet Inc., Hawthorne, California.

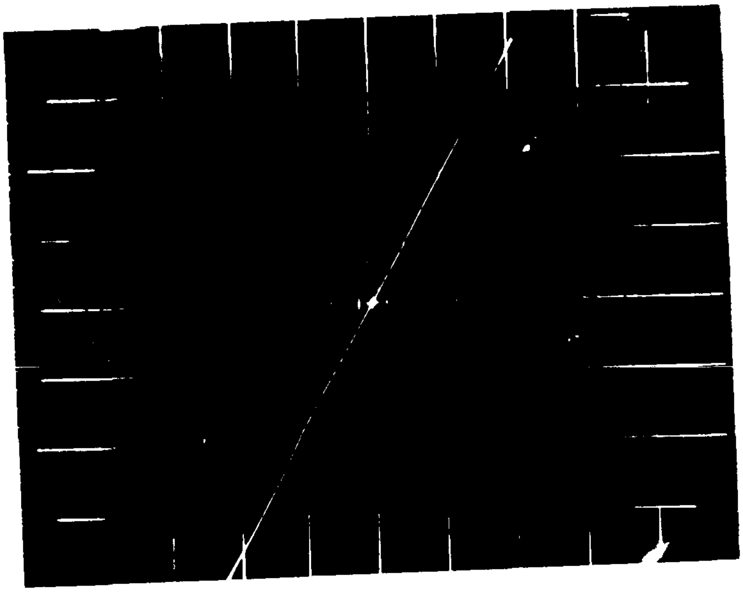

Fig. 13. V-I characteristics of electroless-nickel contacts on CdSe. Scale: Vertical scale 2 ma/cm, and horizontal scale 50 mV/cm.

The over-all result is a very ohmic contact that is relatively easy to obtain and gives excellent surfaces for the transducers. This is the method to be used on future work.

It was anticipated to sputter platinum films for the ohmic contacts but results of the above nickel plating prove this to be unnecessary at present. Once ohmic contacts were available, the crystals were tested for resistivity, a very important parameter in the amplification process.

Measurements obtained from crystal samples plated with nickel have yielded resistivities of 20 to 10^6 ohm-centimeters for CdSe and 300 to 10^6 ohm-centimeters for CdS. Both were obtained using photoconductive crystals obtained from Clevite Corporation. These are excellent resistivity ranges for amplification in the microwave region and are the only ones known to reach this low resistivity value using a highly photoconductive crystal. Previous researchers have been limited to resistivities below 10 or greater than 10^4 ohm-centimeters.

D. Transducer Studies

During this project, the methods for evaporating thin-film transducers onto the amplifier wafers has changed considerably and become more dependable and, of course, more sophisticated. The present method is described in the cross-sectional view of the evaporating station as shown in Fig. 14. This consists basically of an evaporating boat positioned just below a hole in an otherwise closed chamber in the vacuum envelope. This chamber is enclosed in a heater unit and has several thermocouples placed for careful temperature control. The sample requiring transducer evaporation is positioned in this chamber by an appropriately masked holder. This description leaves out several aspects of the station that are not pertinent to the discussion herein and are thus omitted for clarity and conciseness.

Excellent results have been obtained using this evaporating scheme on rods of various low-loss crystals, but considerable difficulty has been experienced in obtaining good transducers on the amplifier crystals used on this project.

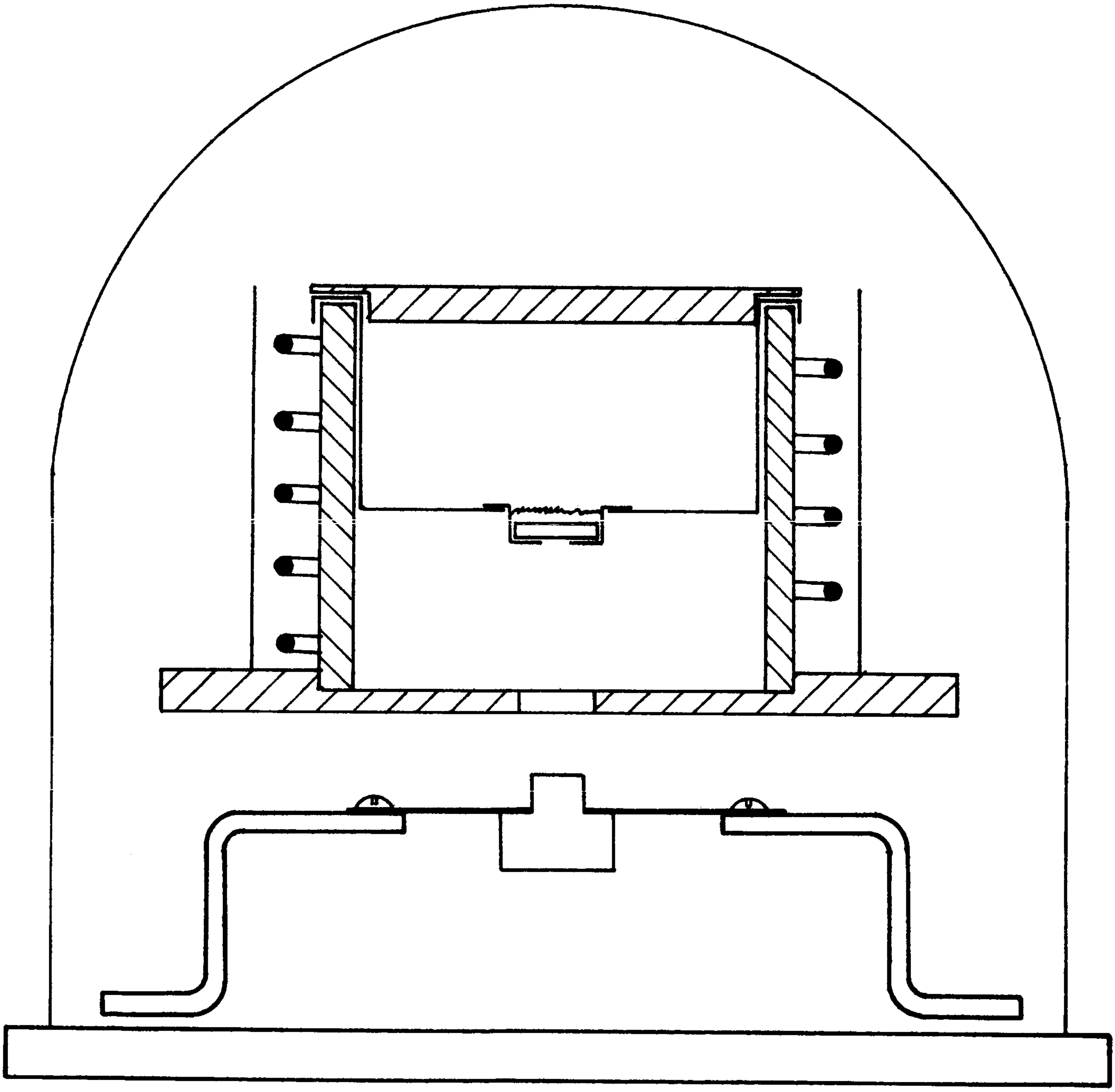

Fig. 14. Basic components of the thin-film transducer evaporating station.

As of the writing of this report, these problems appear to be overcome. Difficulties experienced included highly conducting films due to indium diffusing through and into the film. When the cause of this problem was discovered and no way could be found to compensate for it, electroless nickel replaced the indium. Due to the rough surfaces resulting from this chemical process, good acoustic transducers could not be fabricated. The first evaporations onto samples incorporating the previously mentioned evaporated nickel contacts were not usable because of a problem with substrate temperature during transducer evaporation. The result was a very thin transducer with uncontrollable thickness. This was not, of course, permissible. The films presently being evaporated appear in color, texture, and thickness to be very good and they will be tested early in the next period for acoustic-generation properties.

E. Experimental Amplifier Tests

A new testing structure has been designed and constructed. This structure offers much smaller size, as well as promising superior operating characteristics and assembly ease. The photographs of Fig. 15 show exploded and assembled views of this device. Included in the design is the latest in spring-loaded center conductors.

The only experimental-amplifier model available during this period with good thin-film transducers was not of optimum configuration or design. Several fabrication difficulties were encountered but the sample was reworked to a point where it was suitable for testing. Contacts to the piezoelectric-semiconductor crystals were obtained using a special cleaning process and evaporated gold films. As mentioned previously, these were nonohmic contacts, but sifficed for this experiment. Figure 16 shows a rough drawing of the results obtained at 1 Gc; Fig. 17 is a schematic representation of the test setup required; and Fig. 18 shows a photograph of the experimental setup used. During these tests, voltage breakdown occurred at the output transducer because of reworking this transducer. For this reason, no photos

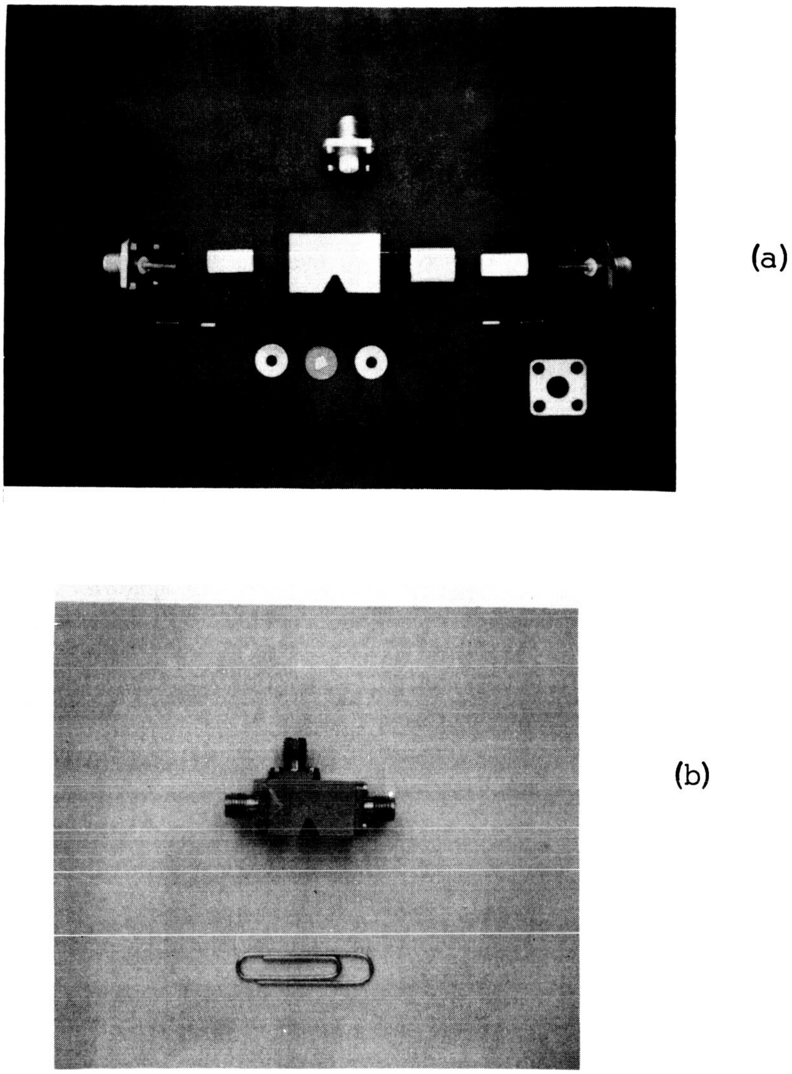

Fig. 15. Amplifier test structure: (a) exploded view, and (b) assembled view.

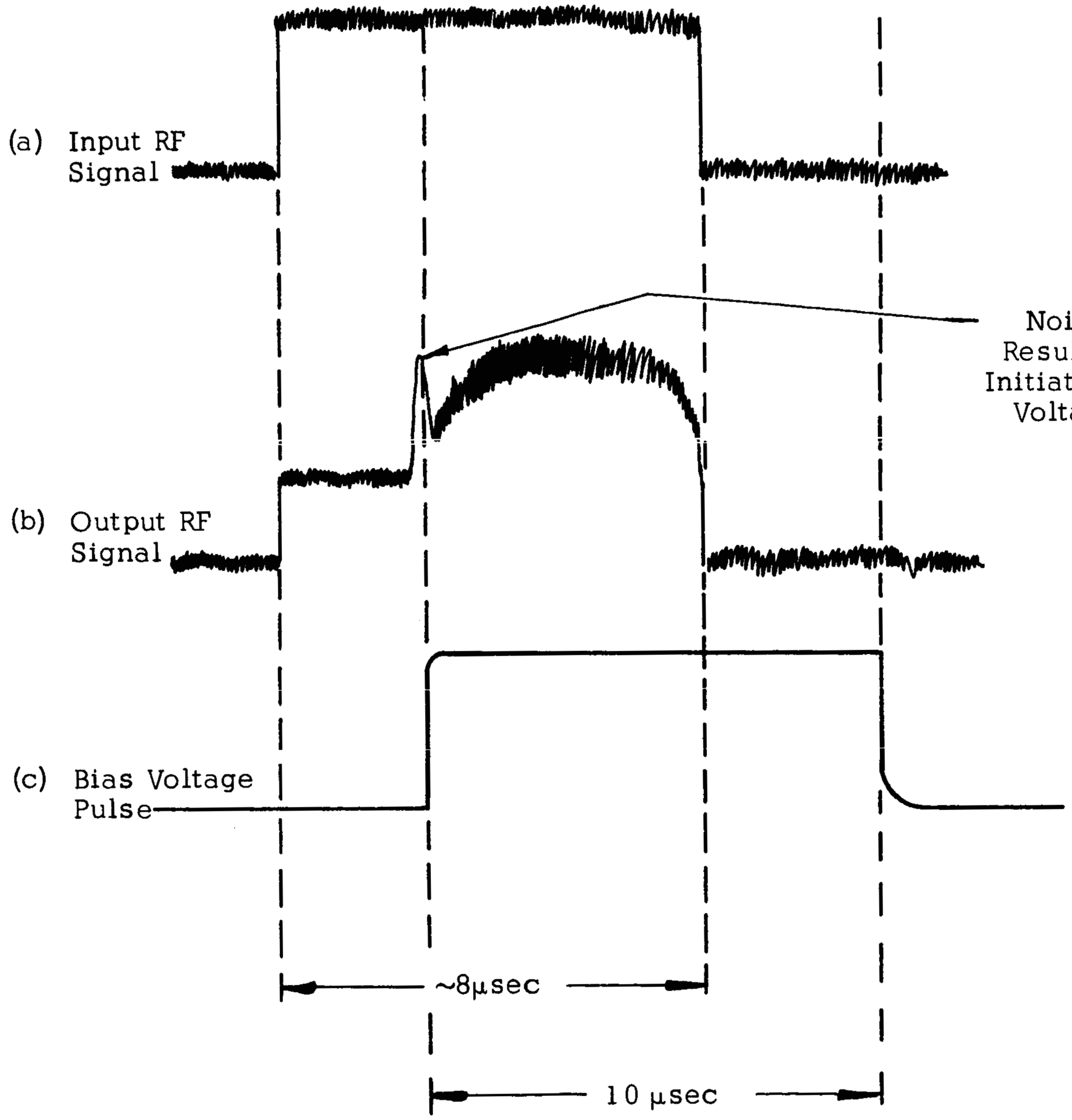

Fig. 16. Wave forms of (a) input rf pulse, (b) output rf pulse, and (c) bias voltage pulse.

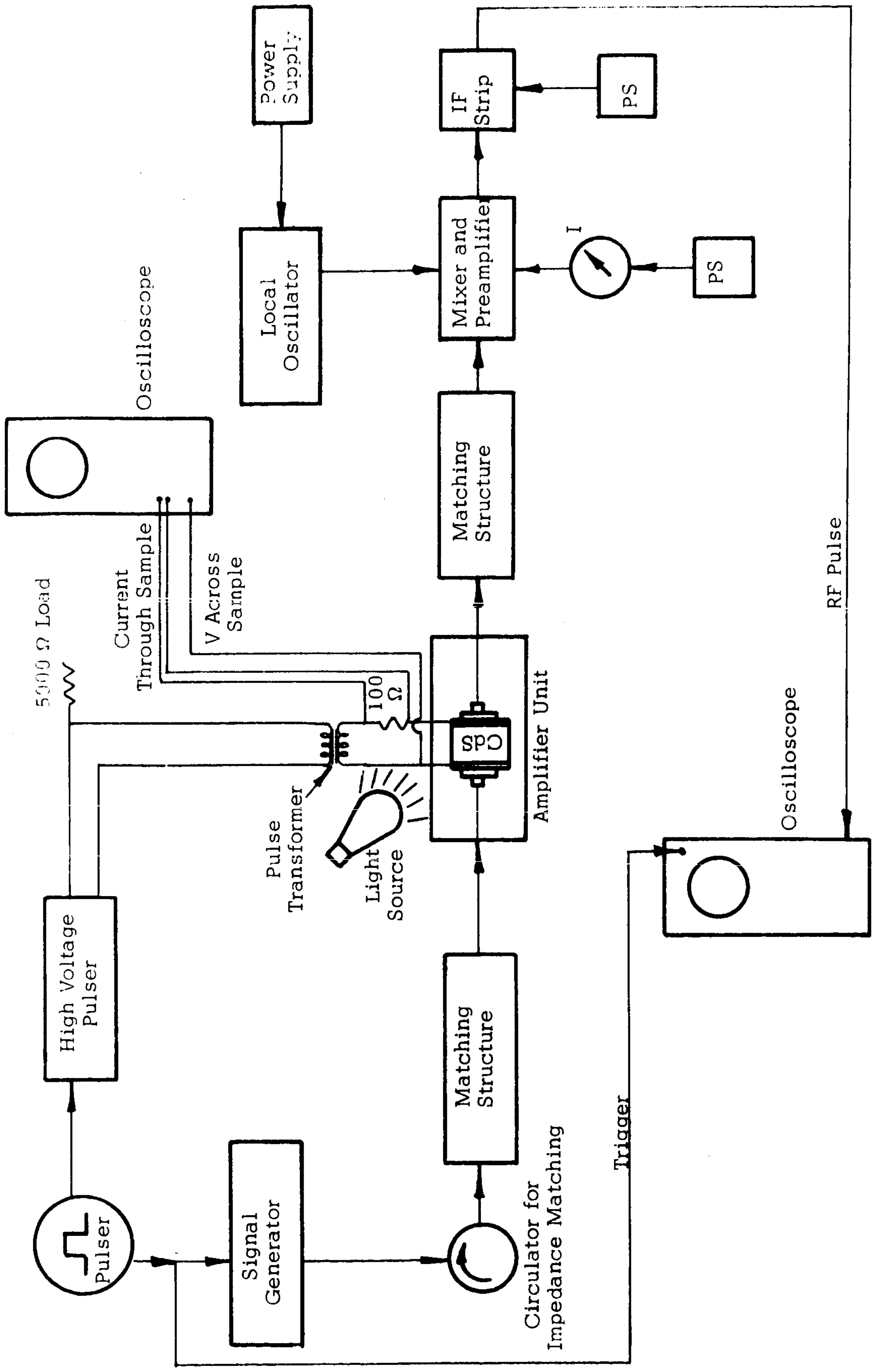

Fig. 17. Amplifier testing schematic.

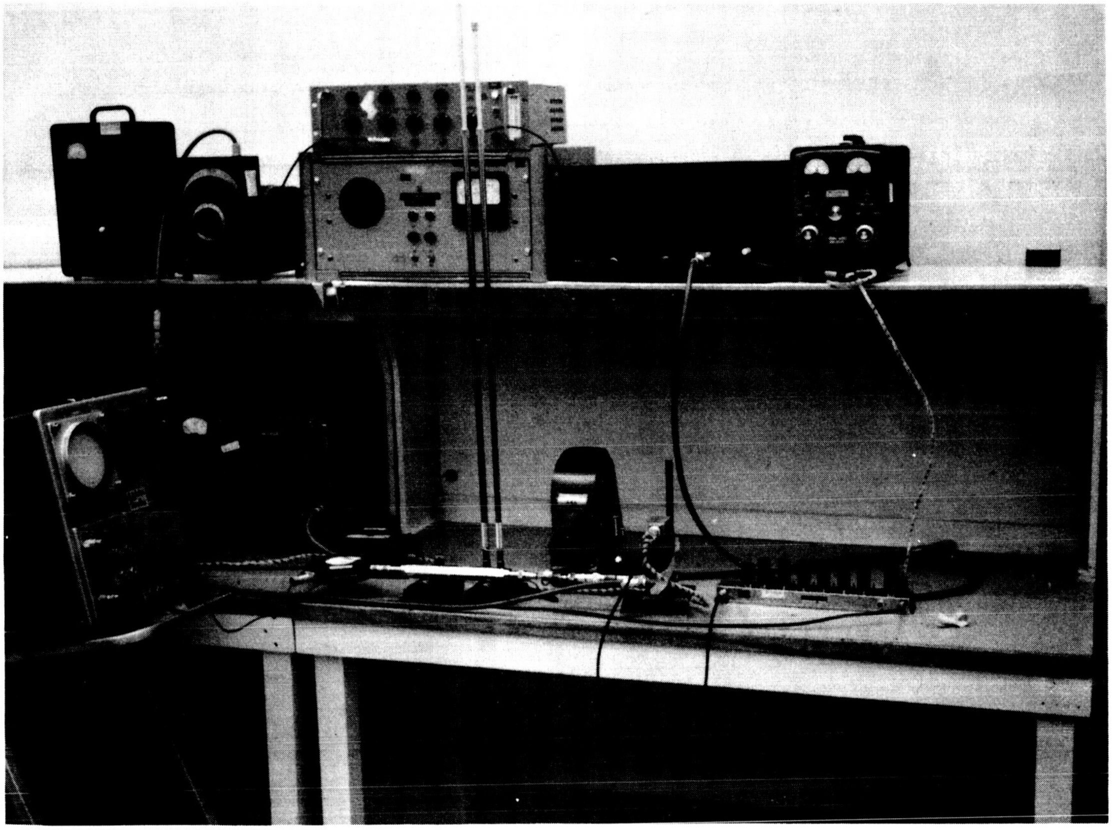

Fig. 18. Photograph of test equipment.

were taken of the wave forms shown in Fig. 16. The noteworthy and very significant result from these data is the increase in detected output-pulse level immediately after applying the bias-voltage pulse. Unless this was associated with breakdown at the output transducer, which is extremely unlikely, the observed increase in output signal resulted from acoustic amplification at 1 Gc. Actual measurements of the exact amount of amplification were not available from this test because the output-transducer breakdown precluded further measurements.

It is felt that the transducer-fabrication difficulties have been corrected, and it is predicted that amplifier tests will be continued shortly. The wafers presently being processed have evaporated nickel films on the amplifier crystals and a gold film on the nickel. The acoustic transducer is placed on the gold film. This is repeated on both sides of the amplifier crystal.

F. Current Oscillation and Saturation Studies

It is known that, for operation in the 50-Mc region, crystals with high acoustic-amplification values are also characterized by oscillation and current saturation in the amplifying crystals. This has been observed using fairly large crystal samples for testing. Using these factors, and the need for further knowledge of the amplifying process and associated noise mechanisms, studies have been carried out to test crystals for possible bulk effects causing nonohmic behavior. Research into the literature has invoked the distinct possibility that oscillation should not be observed in samples smaller than 2 mm long. It has also been suggested[2] that such oscillation is associated with a mechanism that is related to but not entirely dependent on the acoustic flux. This in turn results in saturation of the crystal's acoustic-amplification characteristics. Previous theories have assumed the opposite, namely that the oscillation results from acoustic amplification.

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[2] W. H. Haydl and C. F. Quate, W. W. Hansen Laboratories, Stanford University, Microwave Lab. Report No. 1334, June 1965.

If the present theory is correct, then relatively thin amplifier crystals--the size being used on this project--will be excellently suited to oscillation-free acoustic amplification, whereas larger samples will not.

Besides the oscillation mentioned above, research has shown there is a definite current saturation that occurs in most piezoelectric semiconducting crystals. This saturation appears to be directly associated with the current oscillation, however, the exact correlation is not presently understood.

Samples have been tested for oscillation and saturation using the experimental arrangement suggested in Fig. 19. Oscillation was not observed during this reporting period but had been observed as of the writing of this report and will thus be described in the next project report. The current-saturation phenomena can be described by the I-V curve shown in Fig. 20, and the photograph shown in Fig. 21. The data presented in Fig. 20 and 21 were taken for a CdS crystal obtained from Clevite Corporation. It was 0.134-inch thick and had 0.039-square-inch cross section. The sample was highly photoconductive and the data presented on this particular sample were taken under strong light-illumination conditions. As shown in Fig. 20, the sample was very ohmic for voltages up to 850 volts. The current began to saturate at this point and the curve deviated more and more from ohmic behavior for increasingly higher voltages. Shown in Fig. 21 are photographs of the current and voltage pulses as observed during saturation. As can be seen, the voltage pulse is quite flat across the top, where the current pulse increases to a high value (approximately the ohmic level) then saturates to a somewhat lower level. It is this level that is plotted in Fig. 20. There is a slight oscillation in the current pulse and this has been observed to a greater extent than shown in the figure; however, it is felt that this oscillation is due to some ringing in the circuitry and is not the result of a bulk effect in the sample. Although the pulses shown were about 4 microseconds wide, longer pulses were also used to see if there would be a buildup time for oscillation. No additional information was obtained using pulses up to

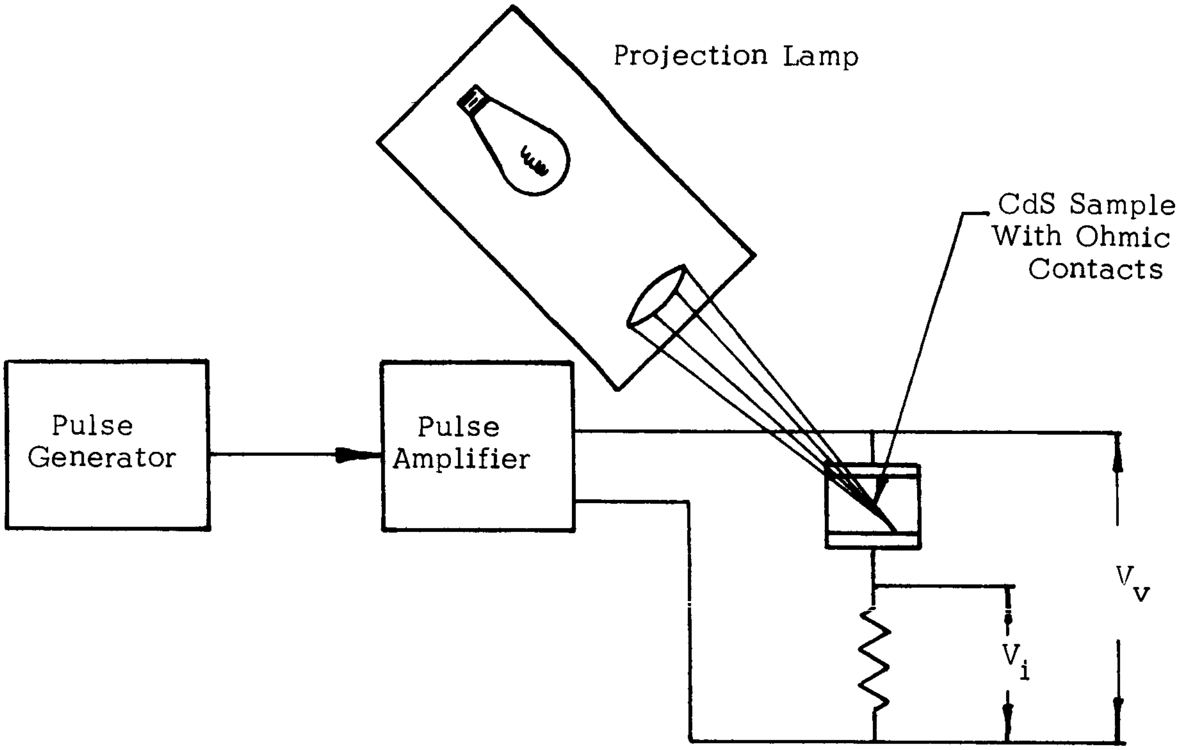

Fig. 19. Schematic of equipment used for observing oscillation and current saturations.

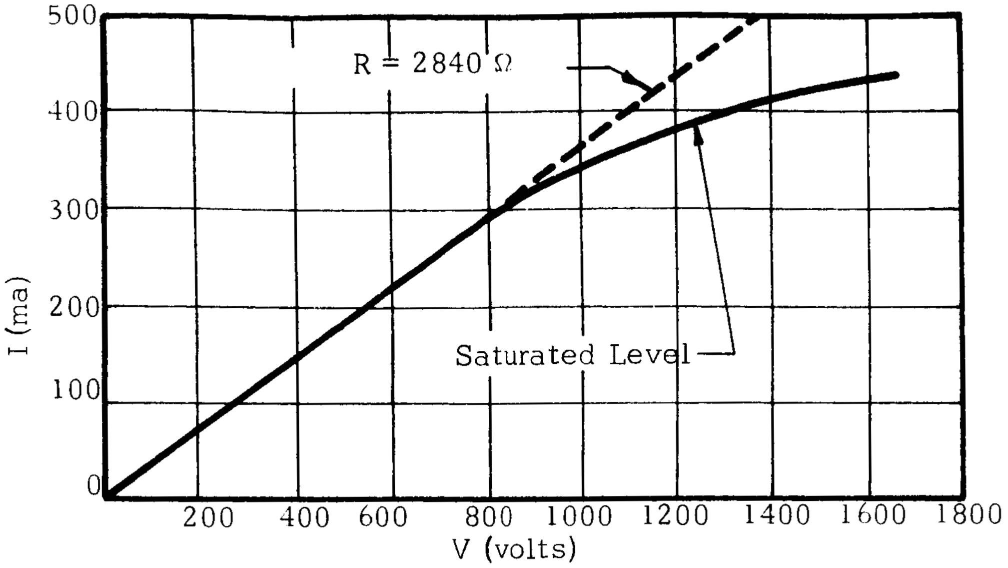

Fig. 20. V-I curve for a CdS sample showing current saturation.

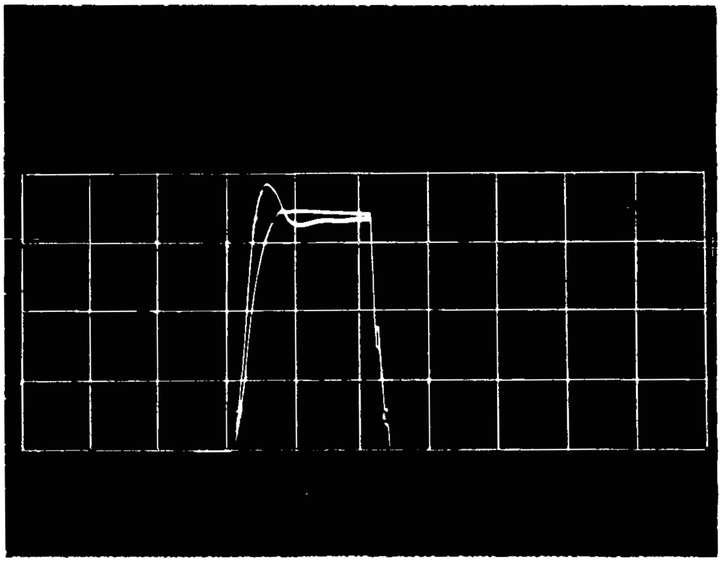

Fig. 21. Photograph of current and voltage pulses showing current saturation. The sweep time was 2 μ sec/cm.

20 microseconds long. Tests were made at liquid-nitrogen temperature but the crystal has a very high resistivity at this temperature and no saturation effects were observed.

Because of the importance of these oscillation and saturation effects in the acoustic-amplification process, further study is planned to investigate these effects.

II. PROGRAM FOR NEXT REPORTING PERIOD

Theoretical analyses of transducer techniques, oscillation-suppression mechanisms, noise-reduction techniques and material properties will continue. Experimental portions of the program will emphasize further improvement of microwave-acoustic amplifier models with special considerations given to oscillation-free amplification. Specific tasks will include:

- Continued design, fabrication and testing of advanced experimental-amplifier models,
- Advanced development of longitudinal- and shear-wave piezoelectric thin-film transducers,
- Continued studies of the oscillation and current-saturation properties of CdS and CdSe and their effects on the amplification process, and
- Measurement and comparison of the amplification properties of CdS and CdSe.

These tasks are directed toward demonstrating and evaluating solid-state traveling-wave-amplifier techniques for future satellite applications.

III. CONCLUSIONS AND RECOMMENDATIONS

From the material presented herein it can be concluded that the techniques necessary for fabricating an operable acoustic amplifier are being developed rapidly. These developments, coupled with theoretical understanding of the optimum materials and configurations, form the necessary techniques for accomplishing the program objectives.

The project is presently in a position to fabricate acoustic amplifiers using an evaporated-nickel plating for ohmic contact to the piezoelectric semiconductor crystal. This plating is such as to offer an excellent surface for the evaporation of thin-film acoustic transducers. Techniques for encapsulation, lapping, and structure mounting of the samples are complete. The necessary materials have been, or are now being, tested and the transducer coupling structures have been developed for easy assembly and optimum operation.

Using the design curves obtained by a computer study during this period a good theoretical foundation is established for experimental guidance. According to the theoretical information the crystals that have been tested have conductivities excellently applicable to microwave amplification. Resistivity measurements obtained from crystal samples have yielded resistivities of 20 to 10^6 ohm-centimeters for CdSe and 300 to 10^6 ohm-centimeters for CdS. These are excellent resistivity ranges for amplification in the microwave region and are the only ones known to reach this low resistivity value using a highly photoconductive crystal.

A necessary beginning was made during this period dealing with the nonohmic saturation and oscillation effects associated with the crystal materials used. This must be continued to give a better insight into the oscillation processes and problems associated with acoustic amplification.

Early amplifier tests have proven somewhat erratic, as mentioned earlier in this report, but acoustic amplification has been observed in a modified amplifier wafer. This is very promising and is, of course, being pursued with optimism.

The results achieved thus far on investigating transducers, amplifier processes, noise-measurement techniques and materials, and the development of various fabrication and processing techniques and amplifier configurations, form a firm base for accomplishing this program in accordance with the revised time schedule. This, in turn, has opened new avenues for advanced development beyond the scope of the present contract. This involves determining the future of acoustic amplifiers as applied to use in satellite communications. A further program of research and development is suggested to answer this question conclusively.