1. Classification *INPE-COM.10/PE* *CDU: 537.311.33*	2. Period	4. Distribution Criterion
3. Key Words (selected by the author) *SEMICONDUCTORS, PHOTOACOUSTIC EFFECT, TRANSPORT PHENOMENA IN SOLIDS.*		internal [ ] external [X]

5. Report No.	6. Date	7. Revised by
INPE-1193-PE/110	*December, 1977*	*Ivan C. da C. Lima*

8. Title and Sub-title	9. Authorized by
ON THE USE OF PHOTOACOUSTIC CELL FOR INVESTIGATING THE ELECTRON-PHONON INTERACTION IN SEMICONDUCTORS	*Nelson de J. Parada* *Director*

10. Sector *DEE* Code *400*	11. No. of Copies *12*
12. Authorship *C.C. Ghizoni* *M.A.A. Siqueira* *H. Vargas* *L.C.M. Miranda*	14. No. of Pages *15*
13. Signature of first author	15. Price

16. Summary/Notes

In this work we have demonstrated experimentally the usefulness of the photoacoustic cell for studying the transport properties of semiconductors. This technique allows us to separate the different sources of sound generation in a semiconductors. Specific application is made for the case of Si crystals submitted to rectangular voltage pulses.

17. Remarks *Paper submitted for publication in "Applied physics letters" - American Institute of Physics.*

"ON THE USE OF PHOTOACOUSTIC CELL FOR INVESTIGATING THE ELECTRON-PHONON INTERACTION IN SEMICONDUCTORS"

C.C. Ghizoni, M. A. A. Siqueira

Departamento de Engenharia Espacial

Conselho Nacional de Desenvolvimento Científico e Tecnológico

Instituto de Pesquisas Espaciais

12200 S.J.Campos, S.P., Brazil

H. Vargas and L. C. M. Miranda

Instituto de Física

Universidade Estadual de Campinas

13100 Campinas, S.P. Brazil

ABSTRACT

By exploring the simple periodic heat flow principle of the photoacoustic cell we demonstrate experimentally the usefulness of the acoustic cell for studying the transport properties of semiconductors. An interesting feature of this technique is that it allows us to separate the different sources of sound generation in a semiconductor. Specific application is made for the case of Si crystals submitted to rectangular voltage pulses.

Photoacoustic spectroscopy (PAS) has proved[1,2] to be an extremely useful tool for studying optical absorption spectra, not only of crystalline, powdered and amorphous solids but also of liquid and gases[3]. Its theory for solid samples was developed by Rosencwaig and Gersho[4]. According to these authors[4], the primary source of the accoustic signal arises from the periodic heat flow, from the sample to the surrounding gas, as the solid is cyclically heated by the absorption of chopped light. The periodic flow of this heat, into the gas cell, produces pressure fluctuations in it and this is how the sound originates. It is precisely the high sensitivity of the gas to temperature fluctuations in the cell, that is making the PAS a widely used alternative tool for optical studies.

Exploring this simple periodic heat flow principle, together with its high performance, one might therefore generalize the use of the cell in itself to investigate any phenomena involving the periodic heating of a solid. Amongst these phenomena, the simplest ones are related to the transport properties of a semiconductor, under the influence of a d.c. field[5-7]. Under a d.c. electric field, the free carriers of a semiconductor, gaining energy from the field, will ultimately establish a steady state when the energy gained from the field equals the energy lost to the lattice. This heat, dissipated by the carriers, is translated into excitation of mechanical vibrations (phonons) of the solid, via the electron-phonon interaction. Hence, by pulsing a d.c. voltage in a semiconductor, these phonons (excited by the heat dissipation), once transmitted through the crystal, can cause pressure fluctuations in the surrounding gas. Confining this surrounding gas in a cell (acoustic cell) one can, therefore, detect an acoustic signal at the d.c. pulse frequency similarly to the case of PAS.

The main purpose of the present work is to demonstrate the usefulness of the acoustic cell, for studying the transport properties of carriers in semiconductors. We present the experimental results for Si--crystals, subjected to a pulsed electric field, and a simple model to describe theoretically the phenomenon.

Our experimental apparatus consisted of a small volume aluminium cell. The sample to be studied was placed inside the cell containing a gas, such as air, and a miniature condenser microphone faced the sample. This is illustrated schematically in Fig. 1. The sample used was Si - single crystals sandwiched between Al-film electrodes. A pulsed d.c. voltage was applied between the $A\ell$ electrodes, producing a pulsed electric field in the semiconductor. The applied voltage was of a rectangular pulse type, of amplitude V_p, duration τ and period T. In Fig. 2 we present the acoustic signal as a function of the amplitude, V_p, for two different sample thickness d and different values of the pulse duration τ. In Fig.3 we show the variation of the acoustic signal, as a function of the pulse duration, for different values of the sample thickness and applied voltage. It follows from Fig. 2 that the acoustic signal grows initially with $(V_p/d)^2\,\tau$ (Joule heating), whereas, for relatively high fields, it exihibits an exponential growth with $(V_p/d)\ \tau$. The most important result comes, however, from the data displayed in Fig. 3. There is clearly a threshold value for the peak amplitude V_p, for which the acoustic signal will grow with the time duration τ. This well defined value of V_p allows the determination of semiconductor parameters with very good accuracy, as we will see. As we shall show, in the following, these features of the sound generated in the microphone are essentially due to two kinds of mechanisms, namely: the periodic Joule heating of the sample and the generation of phonons in the semiconductor due to the interaction of the phonons with the drifting carriers.

The kind of behaviour depicted in Figs. 2 and 3 may be understood by assuming a crude model whereby: (i) the acoustic signal, produced in the cell is proportional to the number of phonons, excited in the sample by the drifting carriers during a pulse duration; (ii) the phonons are described in terms of a kinetic equation involving stimulated emission of phonons by the carriers[5,7]; (iii) the electron distribution function is assumed to be of a heated displaced Maxwellian type[8,9], with a temperature T_e, different from the lattice temperature T_L. The distribution is centered at $\vec{v} = \vec{v}_d$, $\vec{v}_d$ being the drift velocity of the carriers.

Now, the energy delivered by the electric field to the electrons is dissipated, mainly, by emission of phonons, so that one assumes that the phonon population reaches an equilibrium in a very short time; from the energy balance, the electron energy loss rate to the phonons is $e\mu E^2$ where μ is the mobility and $\vec{E}$, the applied electric field. After the phonon population has reached its equilibrium in the presence of the applied field, the electron-phonon collision with absorption or emission of phonons becomes important. With an increasing electric field, the electron-phonon collision may eventually lead to a growth (amplification) of the phonon population[5-7]. The threshold for this sound amplification is, of course, reached when the phonon growth rate γ_q becomes larger than the inverse of the phonon relaxation time τ_q. The phonon growth rate depends upon the carriers' drift velocity, which depends on the applied electric field.

Within the classical linear theory of the acoustoelectric effect, the rate equation for the phonon population is given by

$$\frac{dN_q(t)}{dt} = - \frac{N_q(t) - \bar{N}_q}{\tau_q} + \gamma_q N_q(t) \qquad (1)$$

where τ_q is the phonon relaxation time assumed to be described by the Landau - Rumer loss[10] $\left[\tau_q^{-1} = \frac{\pi\gamma_G^2 C_v T_o \omega_q}{4\rho v_s^2}\right.$; C_v = lattice specific heat (Dulong-Petit); γ_G = Grüneisen constant; ρ = mass density; T_o = absolute temperature; ω_q = phonon frequency and v_s = velocity of sound$\left.\right]$; γ_q is the phonon growth rate due to the collision with the carriers[11-13] and $\bar{N}_q$ is the equilibrium population, which is obtained from the energy balance. We assume $\bar{N}_q = \alpha\,(\mu E)^2$, with α being a proportionality constant. The form of the expression for the growth rate γ_q depends on the situation being examined. In our case, with Si-crystals the sound wave propagates in the (111) direction also the direction of the applied electric field. From the expressions derived in Ref.11 we conclude that, in our case ($\omega_q = 2\pi \times 100$ rd/s) a longitudinal wave will be excited with a growth rate given by $\gamma_q = \frac{n_o e}{\rho v_s} (\frac{V}{d})$, n_o being the carrier concentration, and V(t) the instantaneous applied voltage. Equation (1) can be rewritten as

$$\frac{dN_q(t)}{dt} = \frac{\alpha}{\tau_q} [\frac{\mu V(t)}{d}]^2 - [\frac{1}{\tau_q} - \frac{n_o e}{\rho v_s d} V(t)] N_q(t) \qquad (2)$$

In the case of a rectangular voltage pulse of amplitude V_p, duration τ, and starting at t = 0, the solution for $N_q(t)$ is straighforward.
One gets, during a pulse duration,

$$N_q(\tau) = \frac{\alpha}{\tau_q} (\frac{\mu V_p}{d})^2 \frac{\exp [(\frac{n_o e V_p}{\rho v_s d} - \frac{1}{\tau_q}) \tau] - 1}{\frac{n_o e V_p}{\rho v_s d} - \frac{1}{\tau_q}} \qquad (3)$$

For weak fields, the situation $\frac{n_o e V_p}{\rho v_s d} - \frac{1}{\tau_q} < 0$ is always true, given the shortness of the phonon relaxation time, so that $N_q(\tau)$ varies with $(V_p/d)^2$ (Joule heating). On the other hand, for high enough values of (V_p/d), $n_o e V_p/\rho v_s d - 1/\tau_q$ may become positive (sound amplification) with the result that $N_q(\tau)$ may grow exponentially with the pulse duration τ.

Since the pressure fluctuation, in the closed cell, is proportional to the peak value of the phonon population, $N_q(\tau)$, the acoustic signal, Q, in the microphone is given by $Q = AN_q(\tau)$, where A is related to the conversion efficiency and involves the cell gas parameters. Equation (3) explains very closely the kind of behaviour depicted in Fig. 2. The acoustic signal grows exponentially with the peak voltage V_p, for sufficiently high values of V_p/d. However, by far the most significative results are those Fig. 3, where the acoustic signal was measured as a function of the pulse duration τ. For fields such that $n_o e V_p/\rho v_s d - 1/\tau_q < 0$, there is phonon generation by Joule - heating and, for a long enough pulse duration, a steady state situation is reached. When the electric field is such that $n_o e V_p/\rho v_s d - 1/\tau_q > 0$, the process of phonon stimulated emission dominates and the acoustic signal grows exponentially with the pulse duration, τ, indicating the presence of gain in the medium. The existence of a threshold value for the voltage amplitude, V_p, suggests a simple way to determine semiconductor parameters. We will use this simple experiment to determine, for example, the carrier concentration in a Silicon sample. It is important to observe that this determination does not depend on good ohmic contacts between the sample and the electrodes. From the data of Fig. 3 for d = 0.020 cm a threshold $V_p^{th} \cong 4.5$ volts is estimated. Using[14] $v_s = 9.37 \times 10^5$ cm/seg (longitudinal wave in |111| direction); $\rho = 2.33$ g/cm^3; $C_v = 1.61 \times 10^7$ ergs/cm^3 ^oC; $T_o = 300$ ^oK; $\omega_q = 2\pi \times 100$ rd/seg and $\gamma_G \cong 0.44$, we estimate the Landau - Rumer loss[15] $\tau_q^{-1} = 0.226$ sec^{-1} . We can then calculate the carrier concentration n_o from the threshold equation

$$n_o \, e \, V_p / \, \rho \, v_s d = 1/\tau_q \tag{4}$$

We obtained $n_o = 1.4 \times 10^{15}$ cm^{-3} which is in good agreement with experimental values. Alternatively, we could have also, knowing the mobility and conductivity, used equation (4) to estimate γ_G which, for some other materials may be a more interesting parameter to be obtained.

In conclusion, we should emphasize that our model contains a number of simplifying assumptions. Nevertheless, the good agreement between theory and experiment clearly indicates the usefulness of exploring the mechanism of the photoacoustic cell (periodic heating) for studying the transport properties of semiconductors. Furthermore the existence of a clear threshold makes possible to determine semiconductor parameters very easily.

REFERENCES

1. A. Rosencwaig, Opt. Commun. 7, 305 (1973)
2. A. Rosencwaig, Physics Today 28, 23 (1975)
3. C.K.N. Patel and R.J. Kert, App. Physics Letters 30, 578 (1977)
4. A. Rosencwaig and A. Gersho, J. Appl. Phys. 47, 64 (1976)
5. E.M. Conwell, in "Solid State Physics", Suppl. 9, edited by F. Seitz and F. Turnbull (Academic Press, New York, 1967)
6. H.N. Spector, in "Solid State Physics", vol. 19, edited by F. Seitz and F. Turnbull (Academic Press, New York, 1966)
7. B.R. Nag, Solid State Electronics, vol. 10, (1972)
8. H. Frohlich and B.V. Paranjape, Proc. Phys. Soc. B69, 21 (1956)
9. R. Stratton, Proc. Phys. Soc. A 246, 406 (1958)
10. L.D. Landau and G. Rumer, Physik Z. Sowjetunion 11, 18 (1937): T.O. Woodruff and H. Ehrenreich, Phys. Rev. 123, 1553 (1961)
11. D.L. White, J. Appl. Phys. 33, 2547 (1962)
12. H.N. Spector, Phys. Rev. 127, 1084 (1962)
13. H. Ozaki and N. Mikoshiba, J. Phys. Soc. Japan, 21, 2486 (1966)
14. H.F. Wolf, "Silicon Semiconductor Data" Pergamon Press (Oxford, 1969).
15. R.A. Smith, "Semiconductors", Cambridge University Press (Cambridge, U.K., 1964).

FIGURE CAPTIONS

Fig. 1: Acoustic cell used for investing the transport properties in semiconductors.

Fig. 2: Acoustic signal versus the applied peak voltage (V_p) for various pulse duration (τ). a) Sample thickness d = 0.6 mm; b) d = 0.2 mm.

Fig. 3: Acoustic signal versus pulse duration for different values of the amplitude V_p.

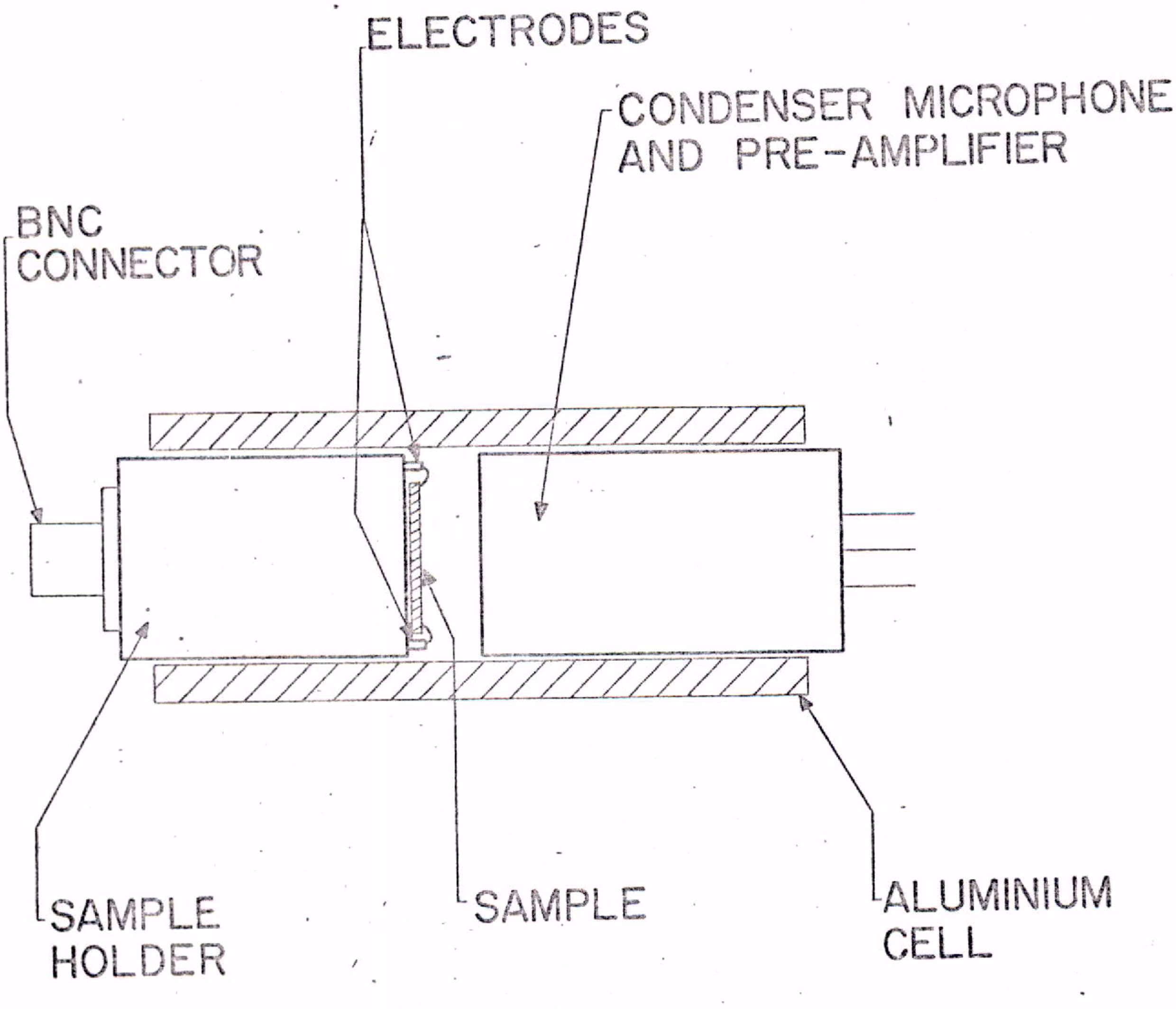
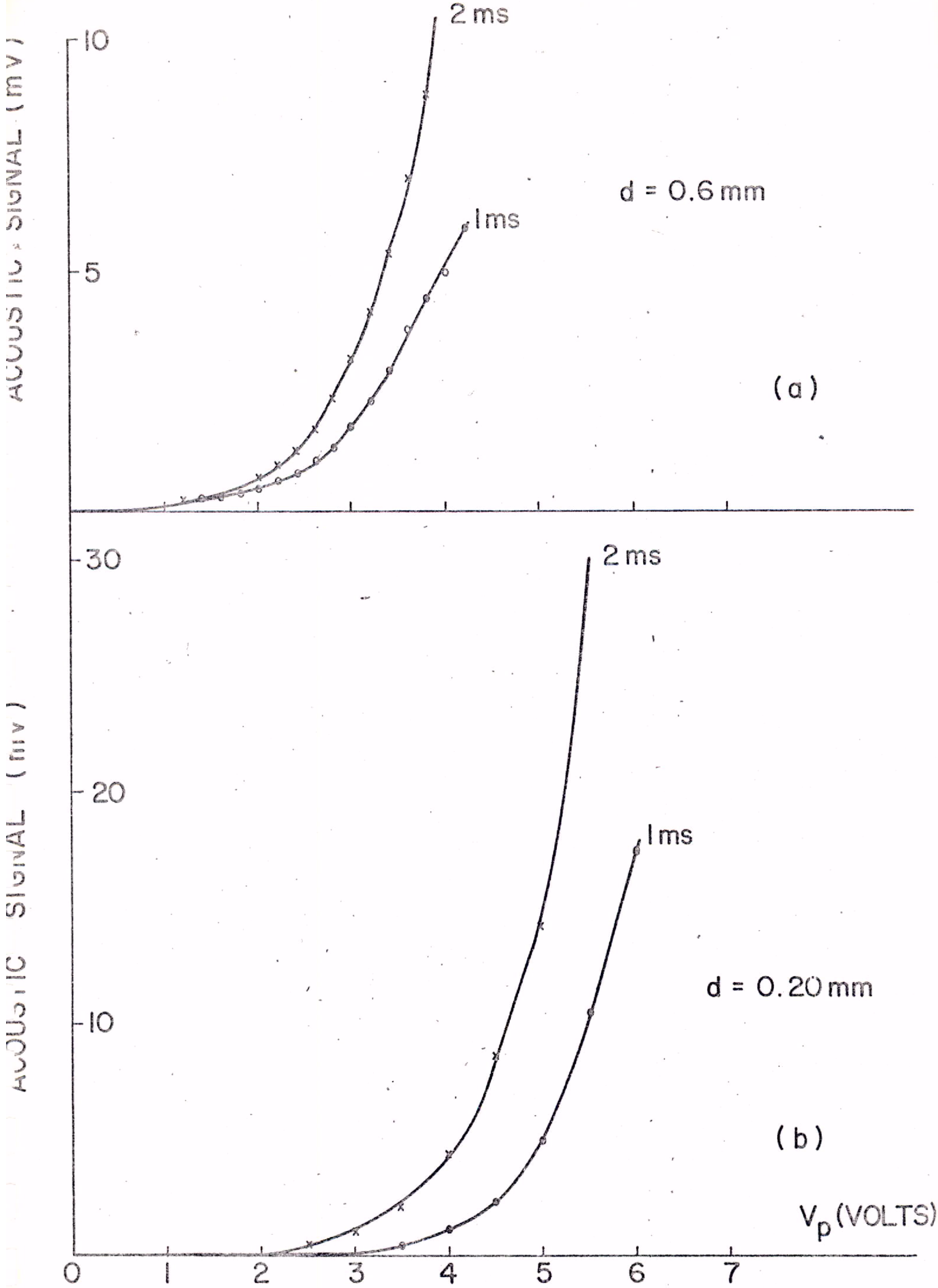

ELECTRODES
CONDENSER MICROPHONE
AND PRE-AMPLIFIER
BNC
CONNECTOR
SAMPLE
HOLDER
SAMPLE
ALUMINIUM
CELL

Fig. 1 -



ACOUSTIC SIGNAL (mV)
10
5
2 ms
1ms
d = 0.6 mm
(a)
ACOUSTIC SIGNAL (mV)
30
20
10
2 ms
1ms
d = 0.20 mm
(b)
V_p (VOLTS)
0
1
2
3
4
5
6
7

Fig. 2

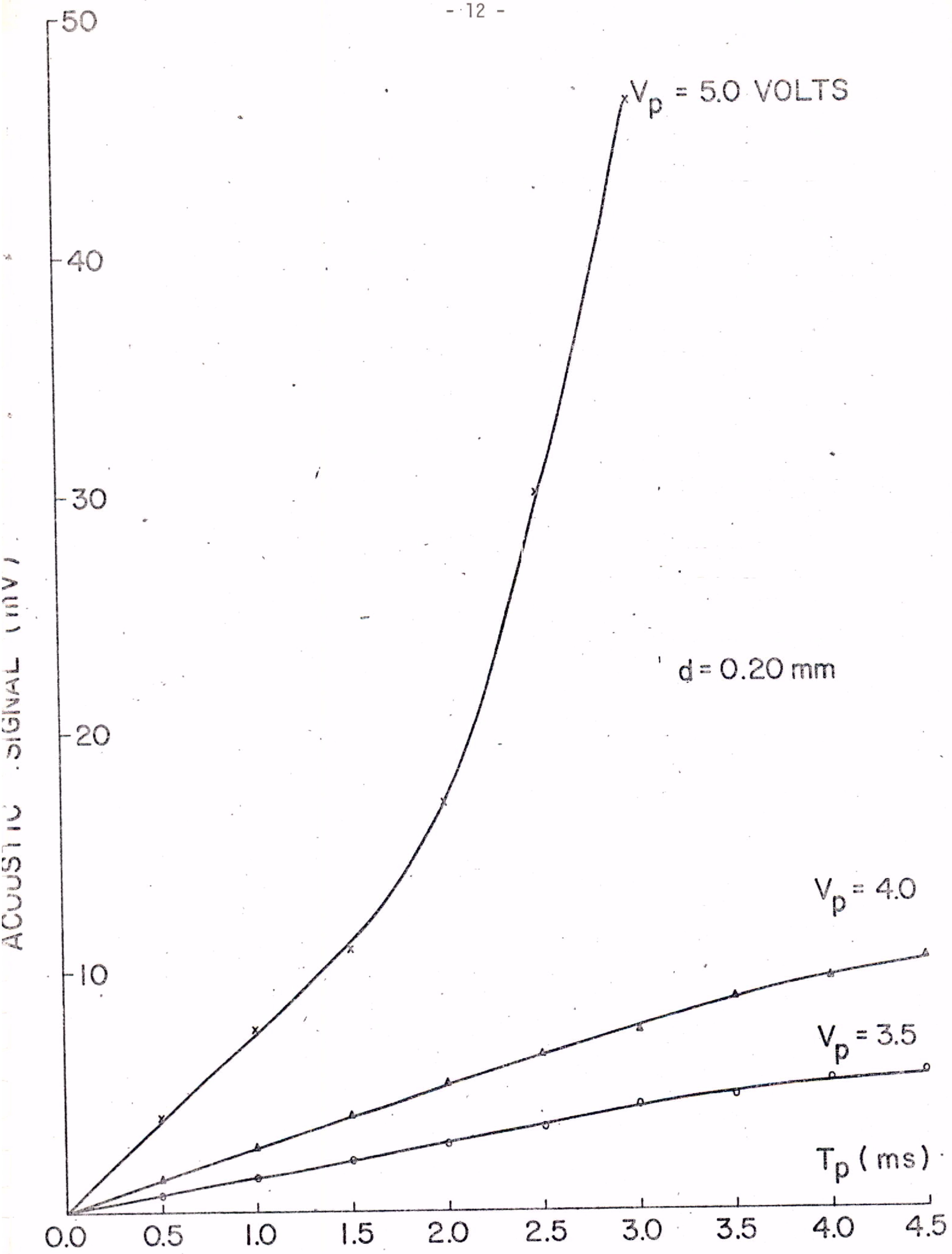

50
40
30
20
10
ACOUSTIC SIGNAL
V_p = 5.0 VOLTS
d = 0.20 mm
V_p = 4.0
V_p = 3.5
T_p (ms)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5

Fig 3 -