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DYNAMICAL ELECTROPHOTOCONDUCTIVITY IN

POLYCRYSTALLINE THIN FILMS

Final Report

to

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Stephen T. Kowel

Philipp G. Kornreich

Principal Investigators

Akbar Nouhi

Department of Electrical and Computer Engineering
Syracuse University
Syracuse, NY 13210

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ABSTRACT

Studies of the modulation of the photoconductivity of polycrystalline films of cadmium sulfide (CdS) by acoustically induced electric fields are presented. The CdS films were deposited on lithium niobate ($LiNbO_3$) substrates by vacuum evaporation which was followed by annealing to yield films of high photosensitivity. The change in photoconductivity of these films due to the penetration of electric fields associated with elastic waves propagating on their substates was demonstrated and studied. The origin of this phenomenom was established by investigating the light intensity and temperature dependences of the conductivity change. The elastic waves traveling on the piezoelectric substrate under the film were generated by interdigital transducers.

The relationship between the acoustic electric field and the induced change in film conductivity was found to be a nonlinear one. The fractional change in conductivity is strongly dependent on the light intensity and the film temperature, showing a prominent maximum as a function of these quantities. The largest recorded fractional change in conductivity was about 25% at electric fields of the order of 10^3 volts per centimeter.

A phenomenological model was developed based on the interaction between the space charge created by the electric field and the electron trapping states in the photoconductor. We have assumed the existence of a quasi-continuous distribution of impurity states in the forbidden gap which act either as traps of as recombination centers depending on the excitation intensity and the film temperature.

1. INTRODUCTION

The electric field-induced effects upon the charge carriers in a semiconductor have long been of considerable theoretical and practical interest to physicists and engineers. For instance, the application of an electric field to a crystal may change the concentration mobility, and/or the energy distribution function of the free carriers in the cyrstal. Numerous studies have been published dealing with these effects. They reveal much interesting information about the energy band structure in some materials while also being of great help in ilucidating the scattering of the carriers by the lattice, impurities and other defects in crystalline solids. A change in characteristics of the free carriers in a crystal usually results in a change in its electrical conductivity. And this has found many applications in solid state science and technology. In fact, many solid state electronic devices are either based on some effect of electric field on the charge carriers or necessarily involve this in their operation.

We here present experimental data and a theoretical model for the electric field induced modulation of the photoconductivity of polycrystalline films of CdS. The CdS films were vacuum deposited on a lithium niobate ($liNbO_3$) substrate followed by suitable heat treatment to increase their light sensitivity. In the films used, photoductivity was found to be a superlinear function of light intensity when the film was at room temperature, and becomes a sublinear function of the excitation intensity at relatively low film tempera-

duece electrical signals representative of the special Fourier components of the light pattern on the film. The electrical signals from the DEFT sensors can be processed for purposes of pattern recognition, motion detection, and electronic focusing in optical systems.

After carefully examining the existing theoretical models concerning the electric field-induced changes in the photoconductivity, we have found them unable to explain the large field modulation of the photoconductivity of our CdS film and its dependence on the various parameters that we have observed. In view of this, we have developed a new model whose predictions are in good agreement with our experimental observations. This model is based on the combined effect of electron trapping states and the space charge, induced by the space dependent acoustic-electric field, on concentration of free carriers in the conductions band.

We assumed a very fast electron exchange between some low laying localized electron trapping states and the conduction band. This means a rapid establishment of a quasi thermal equilibrium between some electron traps and the free electrons.

Franz[3] and Keldysh[4] have shown that the application of a strong electric field can alter the optical absorption coefficient of a crystal. The theory of this phenomenon, known as the Franz-Keldysh effect, has been further developed and studied by Callaway[5] and Dow and Redfield[6]. It has been shown that the optical absorption thresholds of semiconductors and insulators should shift toward the longer wavelengths in the presence of an electric field. Vavilou and Britsyn[7] carried out experiments studying the effect of strong electric fields on the optical absorption of single crystal of silicon.

They observed substantial increase in the optical absorption of these crystals in the wavelength region of 0.8 to 0.9 micrometers for applied electric fields of about 5 x 10^6 V/cm. Similar changes have been reported by French[8] for single crystals of GaAs for electric fields of about 10^5 V/cm. Electric field induced changes in optical absorption and photo-conductivity of single crystals of CdS also have been reported by Williams[9,10] for electric fields as big as 10^5 V/cm.

Unfortunately, we have not been able to reconcile our measurements with the Franz-Keldysh effect. The change in optical absorption of a crystal and the resultant change in its photoconductivity, due to and applied electric field, as predicted by this model, is independent of excitation intensity and temperature. However, our experimental observations do not support such predictions. In addition we have also recorded the electric field modulation of the dark conductivity in some of our films which indicates that some other mechanism is at work.

Another mechanism through which the electric field may change the conductivity of a crystal, is the Poole-Frankel[11] effect. This theory states that the appplication of a strong electric field to a solid increases the thermal excitation probability of the charge carriers from bound localized states by lowering the height of the binding potential of the bound electrons. In fact, the application of the electric field not only can ease the thermal ionization of trapped electrons, but can also decrease the capture cross section of the trapping centers. This, however, results in further increase in the density of free carriers. Indeed, the electric field-assisted changes in thermal emission and capture parameters of trapping centers in single crystals of CdS have been reported by Bube and Dussel[12].

The application of the Poole-Frankel model to our problem pre-dicts an increase in photoconductivity which is an exponentially increasing function of the applied electric field, indicating a non-linear relationship between the photocurrent and applied biasing drift voltage. However, the current-voltage characteristics of our films are linear over a large range of voltages. Moreover, this model predicts a fractional change in the photoconductivity which is independent of excitation intensity and monotonically increases with decreasing temperature, whereas our observations are quite different.

We also considered the "barrier model" which assumes the existance of potential barriers between the crystallite and intercrystallite regions in a polycrystalline film. This model, first proposed by Petritz[13], and used by other authors to explain field effect con-ductances in CdS film,[14] indicate that the I-V characteristics of the film, in which the potential barriers exist, ought to be strongly nonlinear. Such nonlinear behavior is absent in our CdS films.

Finally, we will show that the theory of the acousto-electric effect alone is not also capable of fitting our observations. This theory, based on the space charge creation due to the spatial gradiat of the electric field, has been successfully used by many authors to explain the harmonic generation and the acoustic amplification in structures such as separated and combined media convolvers.[15] We will demonstrate that the acousto-electric effect can only predict the bias independent signals in our films while the model developed here is compatible with the whole range of our experimental results.

2. CHARGE REDISTRIBUTION AND THE ELECTRON TRAPPING STATE

As in the acoustic-electric effect, the spatial equilibrium dis-
tribution of the charge carriers is perturbed when an acoustically
induced electric field penetrates into the CdS film. However, we
should also take into account the presence of the localized energy
states in the forbidden band gap. It is a well known fact that these
defect states play a very important role in the mechanism of the
photoconductivity. It is known that the existance of impurity states
in the band gap is essential to the explanation of many interesting
features of photoconductivity. In ordinary semiconductors the con-
ductivity, in the absence of any incident radiation or particle bom-
bardment, is basically due to the thermally freed charge carriers
that are in thermal equilibrium with the conduction band, valence
band and impurity states in the band gap. But, in the case of
photoconductivity the electrons are excited from the valence to the
conduction band by means of the photon absorption and not by thermal
emission. This means that in a photoconductor the conduction and
valence bands are not in thermal equilibrium any more. However,
after a steady state is established, the phot-generated electrons
will reach a quasi-thermal equilibrium state with some shallow
electron trapping states in the forbidden gap. Such an equilibrium,
which is provided by the fast scattering processes in a solid, re-
quires a very fast electron exchange between the conduction band
and the shallow electron trapping states[7,16]. Indeed, the time
needed for a change in the number of electrons in the conduction
band to be seen by the electron trapping states, or vice versa, is

of the order of scattering times in solid, about $\tau_e = 10^{-13}$ seconds.
For example, the photoelectrons generated in the initial stages of
illumination are captured by the electron trapping centers after
staying only about 10^{-13} seconds in the conduction band. Conversely,
these states also start to supply electrons to the conduction band
within about 10^{-13} seconds after the illumination is stopped.

On the other hand, the elctron lifetime which is a measure of
the speed of recombination processes through which the electron is
finally transferred from the conduction to the valence band, is about
$\tau_L = 10^{-3}$ seconds, much longer than the typical scattering times in
solid. Now, consider a disturbance in the steady state density of
the conduction electrons, such as an interuption in the illumination.
Let us assume that the duration of such a change induced in the steady
state density of free electrons be much shorter than τ_L but signifi-
cantly longer than τ_e. Now, it is quite reasonable to assume that a
change of this nature will not to be seen in the recombination channel
but change the occupancy of the electron trapping states.

Of course, what was said about the electrons is also true for holes.
Nevertheless, in our n-type CdS films the majority carriers are electrons
and the electrical conductivity due to the holes is neglegibly small.
Therefore, from now on we will consider only the contribution of the
electrons to the current.

Let us now consider a thin photoconducting CdS film acted on by a
space-varying electric field which also osscilates rapidly in time.
Such an electric field will push some of the free electrons out of
some regions of the film and accumulate them in some other regions.

This will produce a space-varying charge distribution through the film

as described by Coulomb's law

$$\nabla \cdot \vec{D} = q\delta n \qquad (2-1)$$

where $\vec{D}$ is the displacement vector, and δn is the excess or scarce

electrons per unit volume. Therefore, δn can be positive or negative

and in general osscilates with the frequency of osscillating acoustic

field. In our experiments, we used sinusoidal acoustic-electric fields

with the frequency range of several megaherts corresponding to time

periods of about 10^{-6} seconds. This means that when the space varying

electric field accumulates δn excess electrons in a region of the film

These electrons stay there for about 10^{-6} seconds which is much longer

than 10^{-13} seconds, the time scale for fast communication between the

trapping states and the conduction band electrons, so that some of

these electrons will be captured by the trapping centers. This will

leave less than $n_o + \delta n$ free electrons available for electrical transport,

where n_o is the concentration of free photogenerated electron in the

absence of the perturbation δn. On the other hand there will be more than

$n_o - \delta n$ electrons(per unit volume) available for conduction in the region

from which δn free electrons per unit volume have been taken away,

because some of the previously trapped electrons will be excited to

the conduction band.

Now, one may ask the following question: What is the actual

local density of free electrons available to conduction in the pre-

sence of such an osscillating electric fields? Therefore, in the following

we will attempt to calculate the electric field induced perturbation

in the local density of the free electrons by taking into consideration some of the concepts discussed here along with some of the mechanisms governing the phenomenon of photoconductivity. First, we will study the simple case of a photoconductor in which there is only one kind of electron trapping states in the band gap. Then, the mehtod of calculation developed for this simple case will be applied to the more general and realistic case of a photoconductor with a quasi-continuous distribution of electron trapping state in the forbidden gap.

3. A PHOTOCONDUCTOR WITH ONLY ONE TRAP LEVEL

Let us consider a photoconductor in which the shallow electron trapping centers of density N_t have only one energy level, E_t, as shown in Fig. 1. In the presence of light when the quasi-Fermi level has an energy E_{fn}, the density, n_o, of photo-generated electrons in the conduction band is given to a good approximation by

$$n_o = N_c \exp[-(E_c - E_{fn})/kT] \qquad (3-1)$$

where N_c is the effective density of states at the bottom of the conduction band

$$N_c = 2[m^* kT/2\pi h^2]^{3/2} \qquad (3-2)$$

Here m^* is the electrons effective mass. The average number n_t of electrons in the shallow electron trapping states of energy E_t are determined by the Fermi probability function and are given by

$$n_t = N_t f(E_t) = N_t/[1+\exp(E_t - E_{fn})/kT] \qquad (3-3)$$

The last expression for n_t can be put into a simpler form as follows

$$n_t = N_t/[1+\exp(E_t - E_c + E_c - E_{fn})/kT] \qquad (3-4)$$

where E_c is the lowest energy state in the conduction band. Subsitution for $\exp[(E_c - E_{fn})/KT]$ in Eqn. (3-3) from Eqn. (3-1) yields
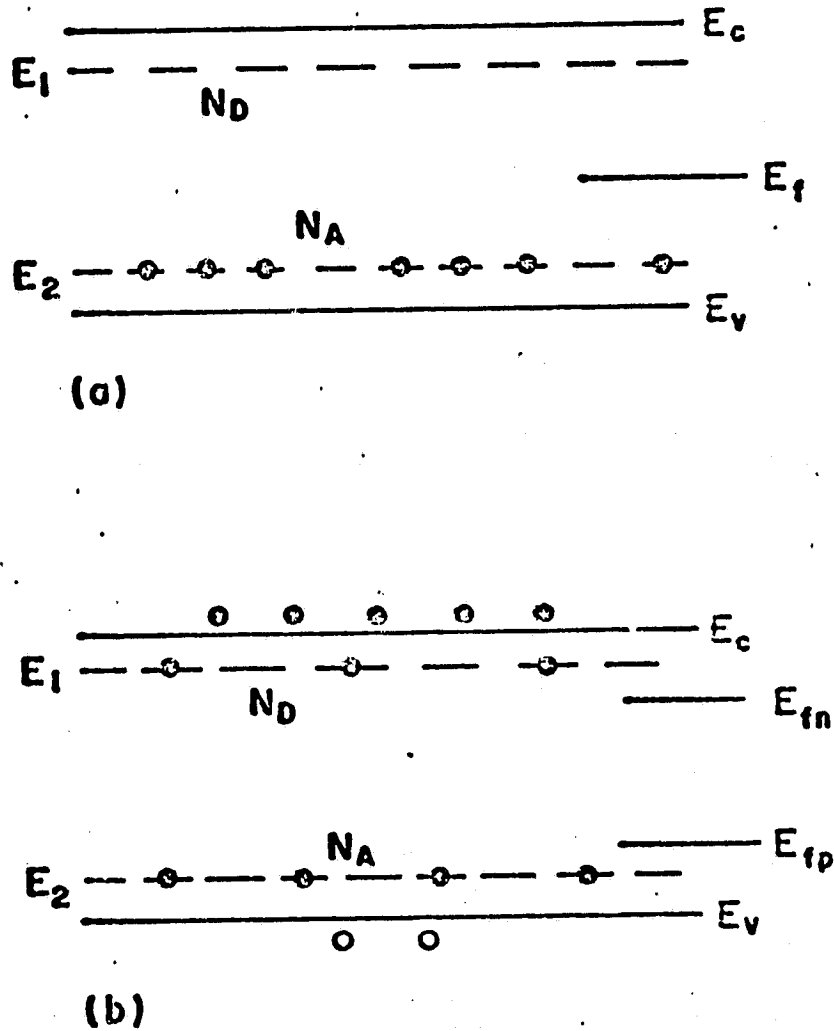
(a)

(b)

Figure 1 Schematic energy diagram for a photoconductor whose
electron trapping centers of density N_t have only
one energy level E_t: (a) situation in the dark
(b) at intermediate light level.

$$n_t = N_t / [1 + (N_c/N_o) \exp(E_t - E_c)kT]$$ (3-5)

on the other hand $N_c \exp(E_t - E_c)/kT$ is the density of electrons in the conduction band when the light intensity is such that the electron Fermi level associated with the shallow trap coincides with the trapping energy level F_t. Let us denote this constant quantity by n_f. i.e.

$$n_f \equiv N_c \exp[-(E_c - E_t)/KT]$$ (3-6)

Substitution of Eqn. (3-5) into Eqn. (3-4) results in the following simpler form for n_t:

$$n_t = n_o N_t / (n_o + n_f)$$ (3-7)

This equation, which relates the density of trapped electrons n_t to the steady-state concentration of free photogenerated electrons n_o, is a consequence of the assumption that there is always a quasi-thermal equilibrium between the electrons in the conduction band and the electron shallow trapping states in the band gap.

Now, let us consider the case in which some δn electrons are pushed away from one region and are accumulated in another region. Let these excess electrons be kept there for a very short period of time, much shorter than the time needed for recombination of electrons, before returning to original places. As we discussed earlier, during such a short period of time the probability for these excess electrons to drop to the valence band or to the recombination centers is negli-

giblly small. However, some of these accumulated electrons can still be captured by the shallow trapping states because of the fast communication between these states and the conduction band. Therefore, these extra electrons will be distributed only over the conduction band and the electron traps. If n and n_t' are the new local densities of free and trapped electrons respectively, then one can write the conservation of electron number density as

$$n + n_t' = n_o + n_t + \delta n \qquad (3\text{-}8)$$

Let the new electron Fermi level, after the perturbation δn is induced, be $E_{fn}' = E_{fn} + \Delta E_{fn}$, where ΔE_{fn} is a displacement in the position of electron Fermi level caused by the perturbation δn. Now, one can repeat the calculations previously presented for n_t to find a similar relationship between the new densities of trapped and free electrons.

$$n_t' = n\, N_t/(n + n_f) \qquad (3\text{-}9)$$

Substitution for n_t and n_t' from Eqns. (3-6) and (3-9) into Eqn. (3-8) results in

$$n^2 + n(n_f + N_t - A - \delta n) \equiv n_f \delta n + A n_f \qquad (3\text{-}10)$$

Where

$$A = n_o + n_o N_t/(n_o + n_f) \qquad (3\text{-}11)$$

It is clear form Eqn. (3-10) that n is a non-linear function of δn. Let us expand n in powers of δn around $\delta n = 0$. Note that $n = n_o$ when $\delta n = 0$. Therefore, one can write

$$n = n_o + \frac{dn}{d(\delta n)}\bigg|_{\delta n=0} \delta n + \frac{1}{2}\frac{d^2 n}{d(\delta n)^2}\bigg|_{\delta n=0} (\delta n)^2 + \dots \qquad (3\text{-}12)$$

We calculate the first two derivatives of n with respect to δn from equations (3-10). We obtain,

$$\frac{dn}{d\delta n}\bigg|_{\delta n=0} = (n_o + n_f)^2/[(n_o + n_f + N_f)(n_o + n_f) - n_o N_t] \qquad (3\text{-}13)$$

$$\frac{d^2 n}{d(\delta n)^2}\bigg|_{\delta n=0} = 2n_f N_t (n_o + n_f)/[(n_o + n_f)^2 + n_f N_t]^3 \qquad (3\text{-}14)$$

Suppose the photoconductor that we have discussed here is a thin film of CdS deposited on a piezoelectric substrate which is acted on by an electric field accompanying a surface acoustic wave traveling on the film's substrate. Then, as discussed earlier, the perturbation δn is exactly the space charge created in the film by the acousto-electric field and osscilates with the frequency of the acoustic wave. For a traveling acousto-electric field in the form of

$$\vec{E} = \vec{E}_1 \cos(\vec{k} \cdot \vec{r} - \omega t) \qquad (3\text{-}15)$$

the space charge density, δn, can be approximated by

$$\delta n = \alpha n_o E_1 \sin(\vec{k} \cdot \vec{r} - \omega t) \qquad (3\text{-}16)$$

where E_1 is the amplitude of the traveling electric field in the film and α is given to a good approximation by

$$\alpha = (\mu/v_o)\gamma/[\gamma^2 + (\omega/\omega_D)^3] \qquad (3\text{-}17)$$

where μ is the electron mobility, v_o and ω are respectively the velocity and frequency of the acoustic wave carrying the electric field and

$$\gamma = 1 + (v_d/v_o) \qquad (3\text{-}18)$$

in which v_d is the electron drift velocity induced by dc biasing voltage applied to the film through the contact lines. The electron drift velocity in our films is much smaller than the acoustic velocity because of the small electron mobility. Thus, γ is approximately equal to one. The electron diffusion frequency ω_D is given by

$$\omega_D = v_o^2/D_n \qquad (3\text{-}19)$$

where D_n is the electron diffusion coefficient. The dependecy of δn on E_1 and n_o, predicted by equation (3-16), has been justified by our experimental results. This will be discussed in detail in the next section. Now, let us substitute for δn into Eqn.(3-12) from Eqn. (3-16) to obtain

$$n = n_o + \frac{dn}{d(\delta n)}\bigg|_{\delta n=0} \alpha n_o E_1 \sin(\vec{k} \cdot \vec{r} - \omega t) +$$

$$\frac{1}{2}\frac{d^2 n}{d(\delta n)^2}\bigg|_{\delta n=0} (\alpha n_o E_1)^2 \sin^2(\vec{k} \cdot \vec{r} - \omega t) + \ldots \qquad (3\text{-}20)$$

Let us denote by, $\Delta n(E^2)$, the second order tem in the series of Eqn. (3-20) or Eqn. (3-12) and calculate the ratio $\Delta n(E^2)/n_o$. This ratio is will be referred to as the fractional change in photoconductivity. Therefore, substitution for $\left.\dfrac{d^2 n}{d(\delta n)^2}\right|_{\delta n=0}$ into Eqn. (3-20) from Eqn. (3-14) yields

$$\frac{\Delta\sigma}{\sigma_o} = \Delta n(E^2)/n_o = \alpha^2 E_1^2 \; <n_f N_t n_o \; \{(n_o+n_f)/[(n_o+n_f)^2+n_f N_t]\}^3 >\sin^2(\vec{k}\cdot\vec{r}-\omega t)$$

$$(3-21)$$

It is clear from Eqn. (3-21) that the fractional change in photoconductivity, $\dfrac{\Delta n(E^2)}{n_o}$, is a function of the light intensity through n_o. By setting the derivative with respect to n_o of the quantity inside the curly bracket in Eqn. (3-21) to zero, one can show that the fractional change in conductivity has a maximum at some value of n_o corresponding to a finite light intensity. In Fig. 2 we have plotted the ratio $\Delta n(E^2)/n_o$, given by Eqn. (3-21) versus n_o for three different reasonable values of n_f and N_t, while $\alpha E_1 = 0.7$ was assumed for all three curves.

All three curves indeed show a maximum at some finite light intensity as the density and the energy level of the electron trapping states change. The effect of concentration and energy level of the electron trapping centers on the maximum fractional change in photoconductivity will be discussed in detail in the next section.
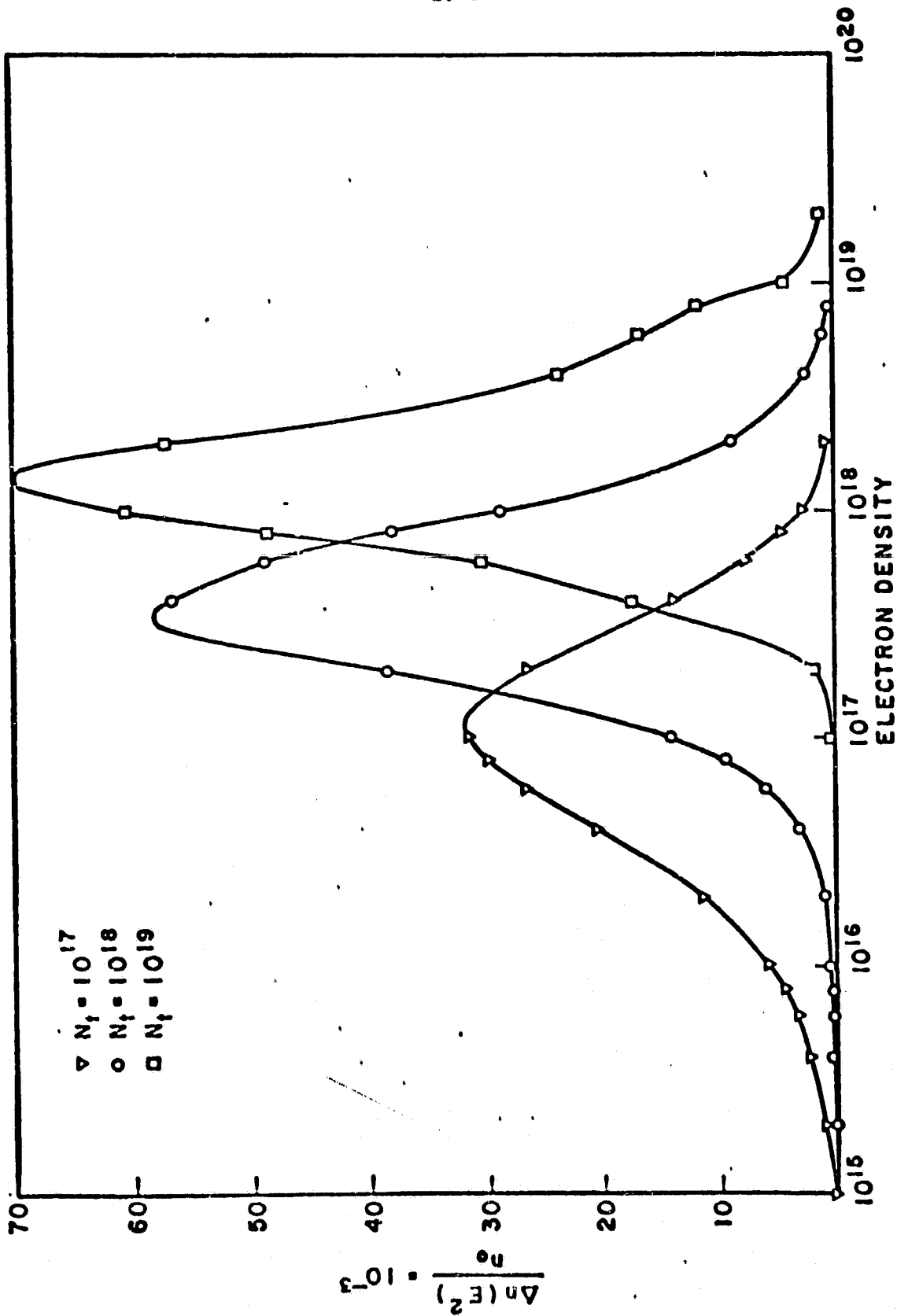
Figure 2 Fractional change in electron number density as a function of electron density for a simple photoconducting model in which all the electron traps have only one energy level at E_t

We previously discussed the mutual interaction between the bunched electrons and electron shallow traps in a photoconductor considering only a single level of electron trapping states. But in reality there is always a variety of impurity and defect states distributed in the band gap. The existance of such a distribution of states in photoconducting CdS films has already been reported by other authors[17,18]. A typical form of such an impurity state distribution is shown in Fig. 3. Let $g_t(E)$ be the number of impurity states per unit volume per unit energy interval at energy level E close to the conduction band. Let the density of free photo-generated electrons in the film be n_o and the electron quasi-Fermi level be at the energy level E_{fn} in the absence of any acoustic-electric field. Here n_t is given by

$$n_t = \int_{E_{fn}}^{E_c} g_t(E) f(E) dE \qquad (3-22)$$

where $f(E)$ is the quasi-Fermi distribution function associated with the shallow traps. According to the arguments in the previous section, after applying the acousto-electric fields to the film the density of free and trapped electrons will change to n and n_t'. Consequently, the electron Fermi level will shift to some other energy E_{fn}', such that

$$E_{fn}' = E_{fn} + \Delta E_{fn} \qquad (3-23)$$

where ΔE_{fn} is the amount of energy shift in position of the electron quasi-Fermi level caused by the electron bunching. If the change in

ENERGY ϵ

CONDUCTION BAND

ϵ_c

ϵ_{F0}

$g_1(\epsilon)$, IMPURITY DENSITY
OF STATES

ϵ_{Fh}

DENSITY OF STATES
$g(\epsilon)$
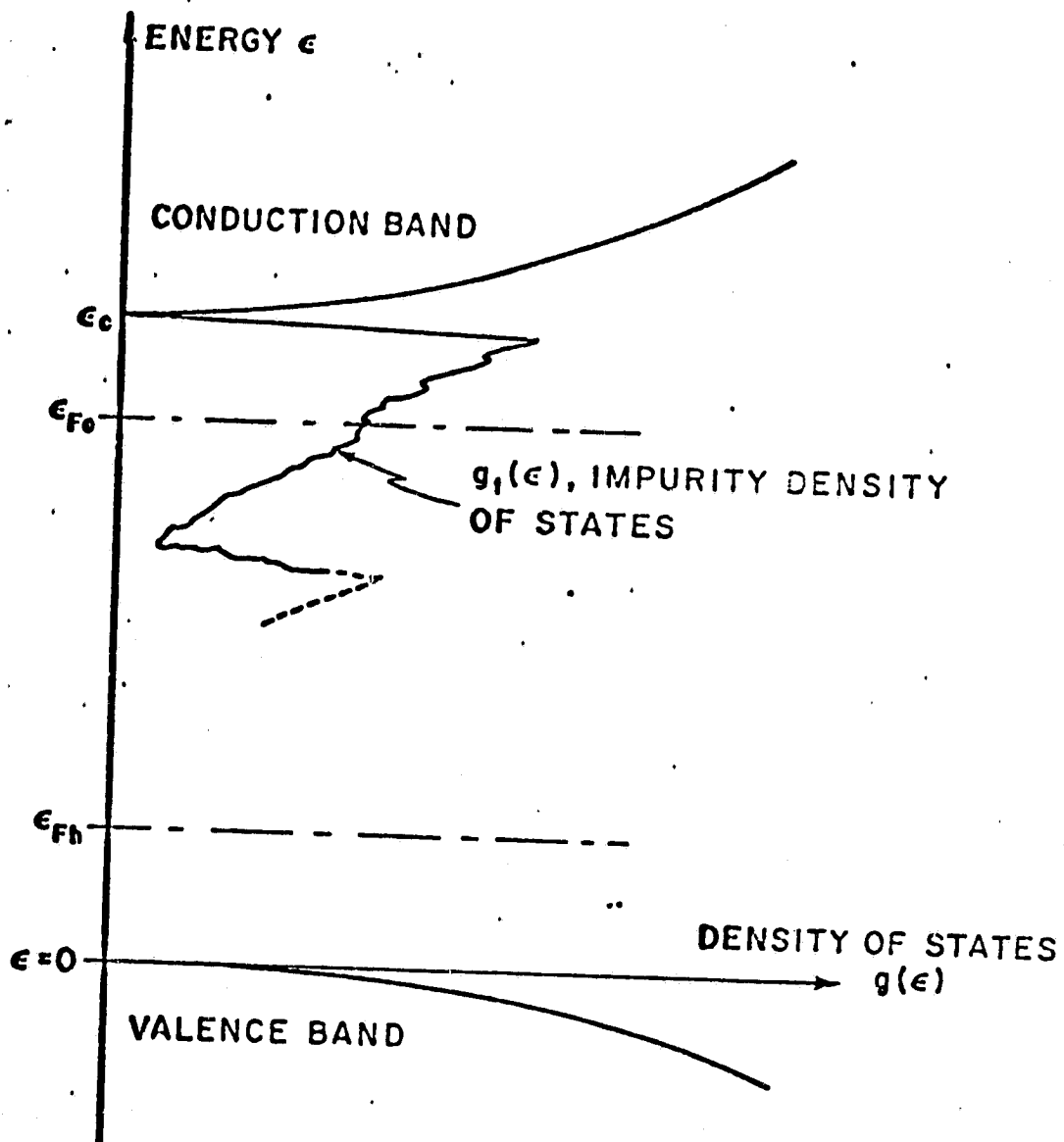
$\epsilon = 0$

VALENCE BAND

Figure 3   Typical density of states distribution of a CdS film showing impurity state distribution and quasi Fermi energies for electrons and holes.

local density of electrons by the acoustic-electric field is δn. Then, statement of the conservation of the electron number dneisty is

$$n + n_t' = n_o + n_t + \delta n \qquad . \qquad (3\text{-}24)$$

We intend to calculate n as a function of n_o and δ_n. Combination of the Eqns. (3-1) and (3-23) yields

$$n = N_c \exp -(E_c - E_{fn})/kT + \Delta E_{fn}/kT \qquad (3\text{-}25)$$

By combination Eqn. (3-1) and Eqn. (3-23) and taking the logarithm of the result we obtain

$$\Delta E_{fn} = KT \ln(n/n_o) \qquad (3\text{-}26)$$

The density of trapped electrons in the presence of space charge, induced by acoustic-electric field in the film, is given by an expression similar to Eqn. (3-22)

$$n_t' = \int_{E_{fn}}^{E_c} g_t(E) f'(E) dE \qquad (3\text{-}27)$$

where $f'(E - E_{fn}')$ is the new Fermi function. Let us expand $f'(E)$ in powers of $\Delta E_{fn} = E_{fn}' - E_{fn}$ at point $E_{fn}' = E_{fn}$. The mth dirvative of $f'(E)$ with respect to E_{fn}' is proportional to $(1/KT)^m$. Thus, the mth order term in the series will be proportional to $(\Delta F_{fn}'KT)^m$. For ΔE_{fn} much smaller than KT we will consider only the contribution of the first two terms of this series

$$f'(E) = f(E) + [\frac{\partial f'(E)}{\partial E_{fn}'}]_{E_{fn}} \Delta E_{fn} \qquad (3\text{-}28)$$

Substitution for $f'(E)$ into Eqn. (3-27)

$$n'_t = \int_{E_{fn}}^{E_c} g_t(E)[f(E) + R(E)\Delta E_{fn}]dE \qquad (3-29)$$

Where

$$R(E) = [\frac{\partial f'(E)}{\partial E_{fn}}]_{E_{fn}}$$

One can eliminate n_t and n'_t from Eqn. (3-21) using Eqns. (3-29) and (3-22) to obtain

$$n - n_o + \Delta E_{fn} \int_{E_{fn}}^{E_c} g_t(E)R(E)dE = \delta n \qquad (3-30)$$

We define

$$L \equiv \int_{E_{fn}}^{E_c} g_t(E)R(E)dE \qquad (3-31)$$

and substitute for ΔE_{fn} from Eqn.(3-26) into Eqn. (3-30) to obtain

$$\delta n = n - n_o + KTL \ln(n/n_o) \qquad (3-32)$$

We pointed out earlier that δn is linearly dependent on the space vary-ing acoustically induced electric field in a CdS film. Thus, it is clear from Eqn. (3-32) that n is a non-linear function of the acoustic-field. Now, let us expand n in powers of δn, around $\delta n=0$, as we did in the previous section,

$$n = n_o + [\frac{dn}{d(\delta n)}]_{\delta n=0} \delta n + \frac{1}{2}[\frac{d^2 n}{d(\delta n)^2}]_{\delta n=0} (\delta n)^2 + \ldots \qquad (3-33)$$

The first and the second derivatives of n with respect to δn are found by taking the corresponding derivatives of the both sides of the Eqn. (2-30). The results of such calculations are

$$n = n_o + n_o \delta n/(n_o + kTL) + [n_o KTL/2(n_o + KTL)^3](\delta n)^2 + \dots \qquad (3-34)$$

Let us use again the approximate value given for δn by Eqn. (3-16), and denote by $\Delta n(E^2)$, the term proportional to the second power of the electric field in the expansion for n in Eqn. (3-34). Then the fractional change in photoconductivity induced by the bunching of electrons with acoustic-electric field, $\Delta n(E^2)/n_o$, is given by

$$\Delta n(E^2)/n_o = 1/n_o \ [n_o KTL/2(n_o + KTL)^3] \ (\delta n)^2 \qquad (3-35)$$

Substitution for δn from Eqn. (3-16) yields

$$\Delta n(E^2)/n_o = (\alpha^2 E_1^2/2)[n_o KTL/2(n_o + KTL)^3]\sin^2(\vec{k}.\vec{r}-\omega t) \qquad (3-36)$$

Both n_o, the free electron concentration, and L given by Eqn. (3-31) are functions of the intensity of light incident on the film. n_o monotonically increases with increasing intensity of illumination. But the value of L and its light dependency is mainly determined by the shallow electron trapping states concentration throught the location of the electron Fermi level, E_{fn}, associated with these traps as can be seen in Eqn. (3-31). Consequently, the fractional change in free electron concentration is a function of light intensity through the quantity in square brackets in Eqn. (3-36). Its variations with light

light intensity is such that it stays close to its maximum value as long as the value of KTL is comparable to the steady state density of free photogenerated electrons n_o. Fractional change in density of photoelectrons falls much below its maximum value when KTL becomes much smaller (or much larger) than n_o. On the other hand, the value of KTL can roughly be approximated (See Eqn. (3-31)) by the density of electron trapping states at the location of electron Fermi level associated with the shallow traps, E_{fn}. Thus, one can conclude that the form of the impurity states distribution functions $g_t(E)$ determine the variation of the fractional change in concentration of the free electrons with light intensity.

The fractional change in density of free photo-generated electrons induced by the acoustic-electric field was calculated from Eqn. (3-34) for various values of n_o, equivalent to differnt illumination intensities on the film. In these calculations $g_t(E)$ given below was employed to represent the impurity state distribution in the film.

$$g_t(E) = g_o \exp[-(E_c - E)/\beta] \qquad (3-37)$$

The results of these calculations for several different values of β and g_o are shown in Fig. 4 and 5 as plots of fractional change in electron concentration versus steady state electron density n_o. We will show in the next section that the characteristics of these curves, representing the behavior of the fractional change in photoconductivity of a film by acoustic electric fields, are in fairly good quantitative agreement with our experimental observations of the electrophotoconductivity in CdS films.
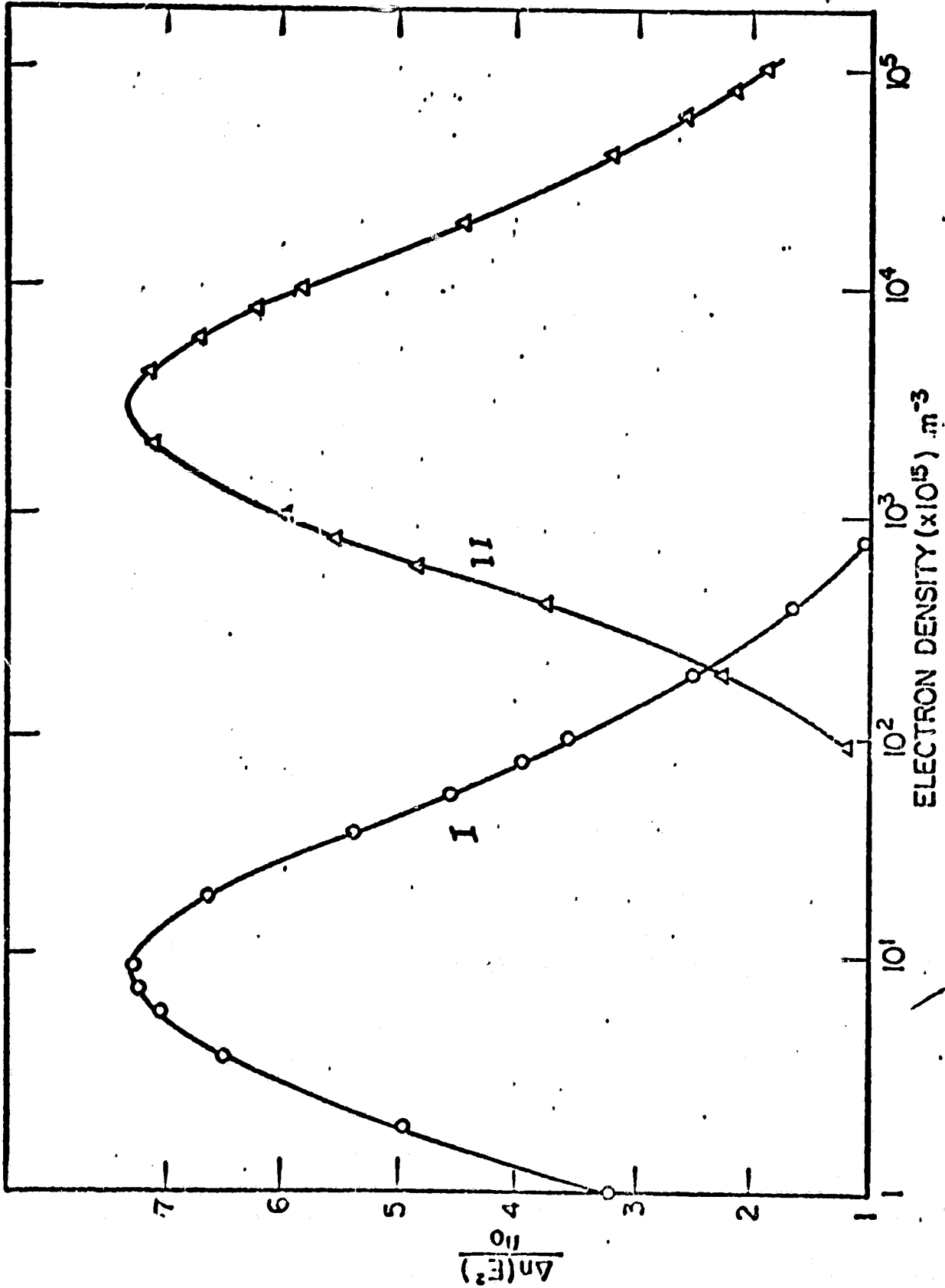
Figure 4 Calculated fractional change in conductivity versus electron concentration.
Curve I for $g_o = 10^{20}/m^3$, $\beta = 0.08$ ev and Curve II for $g_o = 5 \times 10^{21}/m^3$.
$\beta = 0.08$ ev.

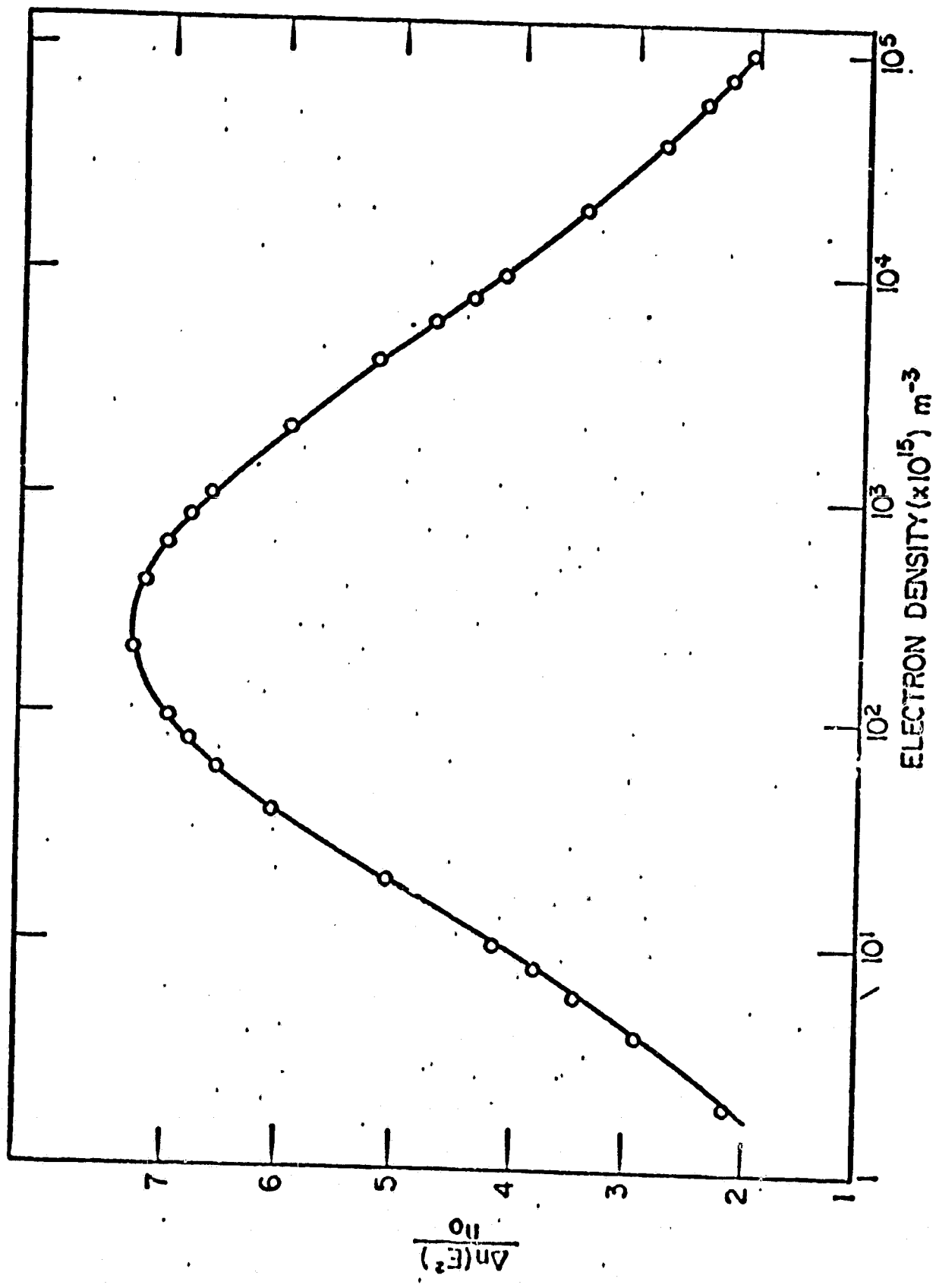Figure 5   Calculated fractional change in conductivity versus electron concentration for $g_0' = 5 \times 10^{22}/m^3$, $\beta = 0.042$ ev.

4. EXPERIMENTAL OBSERVATIONS

The CdS films used were fabricated by vapor deposition. These films exhibited a poor photosensitivity, slow responses and very small ratio of light conductivity to dark conductivity (hereafter will be referred to as light to dark ratio, L/D). The CdS films were subsequently heat treated. It is only after heat treatment in the presence of O_2, N_2, Cu and Cl that the film acquires high photoconductivity and fast response to the light. It turns out that these changes come about essentially from the introduction of imperfection states in the forbidden gap as a result of doping and also due to the crystallization effect of the high annealing temperature. What follows is a description of our experimental observations.

In all the experimental descriptions that follow the electrical currents were always measured between two interdigital metal electrodes on the film. These electrical contact patterns, were made by first evaporating a thin layer of indium onto the CdS film and then a layer of aluminum on top of the indium. Indium was used since it is believed to make a good Ohmic contact to the n-type CdS films. The separation between individual electrodes were about 60 micrometers, and there were 200 strips of CdS between the metal contact lines.

The spectral response of the photoconductivity of these films was the first to be studied. Monochromatic light was obtained from a white light source using a grating monochromator. Fig. 6 displays a typical spectral distribution of the photocurrent, normalized to equal numbers of incident photons, for a CdS film. It is seen that the photons of
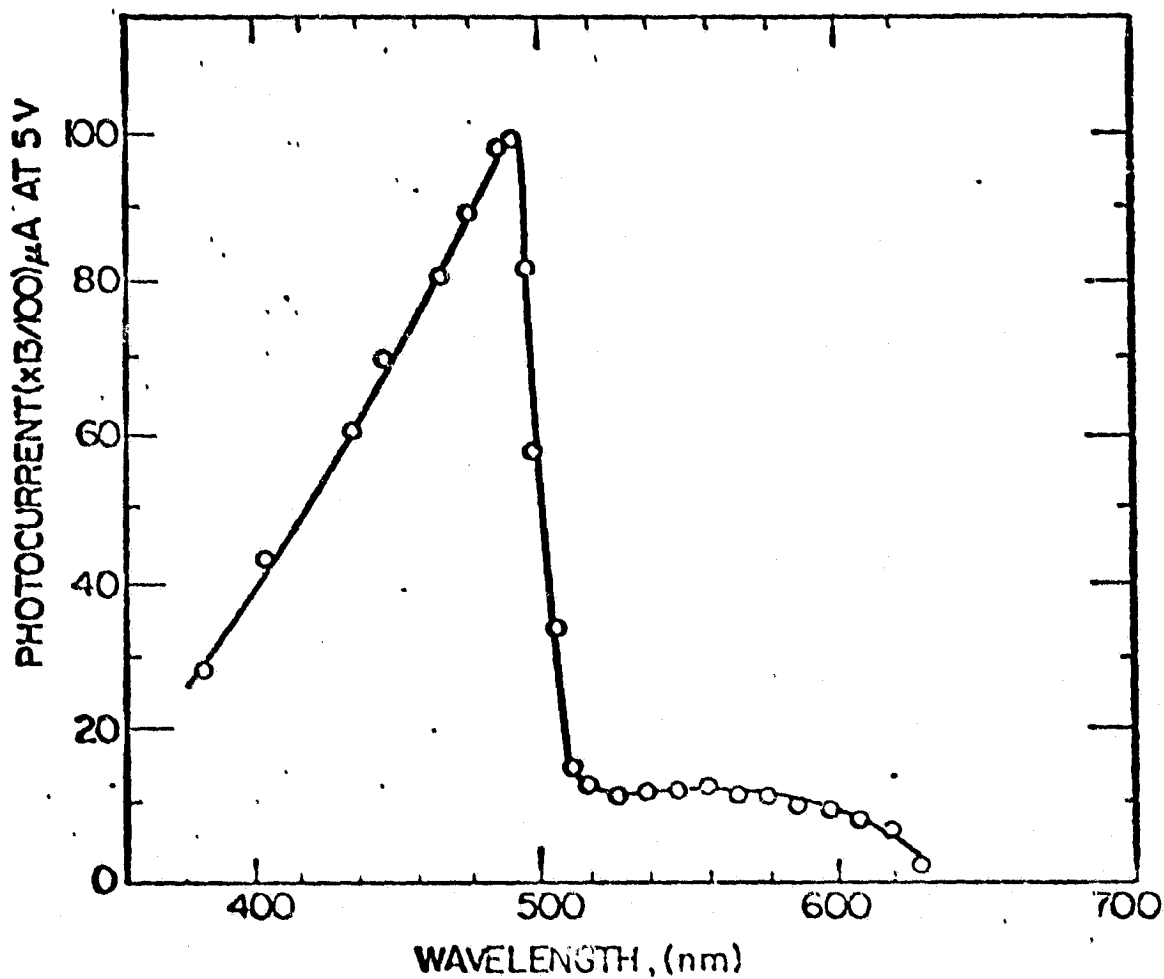
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**Figure 6   Spectral distribution of photocurrent at 24°C.
Normalized to equal numbers of incident photons.**

wavelengths of about 500 nm have the maximum efficiency for free carrier

generation corresponding to a band gap of $E_g = 2.47$ ev. A small amount

of photocurrent (about 12% of the maximum photocurrent at 500 nm) was

detected for photons having wavelengths in the range of 510 nm to 610 nm.

Clearly the photocurrent in this wavelength region, which is still

considerably larger than the dark current, arises from electrons excited

to the conduction band from impurity states at 2.03 electron volts (ev)

below the conduction band or 0.43 ev above the valence band. These states

which are negatively charged in the dark because they are occupied with

electrons, may act as hole traps in the presence of light. These states

are most probably introducted by Cu impurities.

Next we measured the rise time and decay time of the photocurrent

at various light intensities. Here we have defined the rise time as

the time it takes for the photocurrent to rise to 90% of its steady

state value from the moment the film is exposed to the light. Like-

wise, the decay time is the time needed for the photocurrent to drop

to 10% of its previous steady state value after the light is removed.

Fig. 7. shows the rise time for the photocurrent as a function of light

intensity (white light) for a CdS film deposited on a $LiNbO_3$ sub-

strate at room temperature. It is shown that the rise time of the

photocurrent decreases from about 0.5 second to 4 milliseconds as the

light intensity on the film increases from 2 foot candles to 150 foot

candles (the light meter that we used calibrated in terms of foot

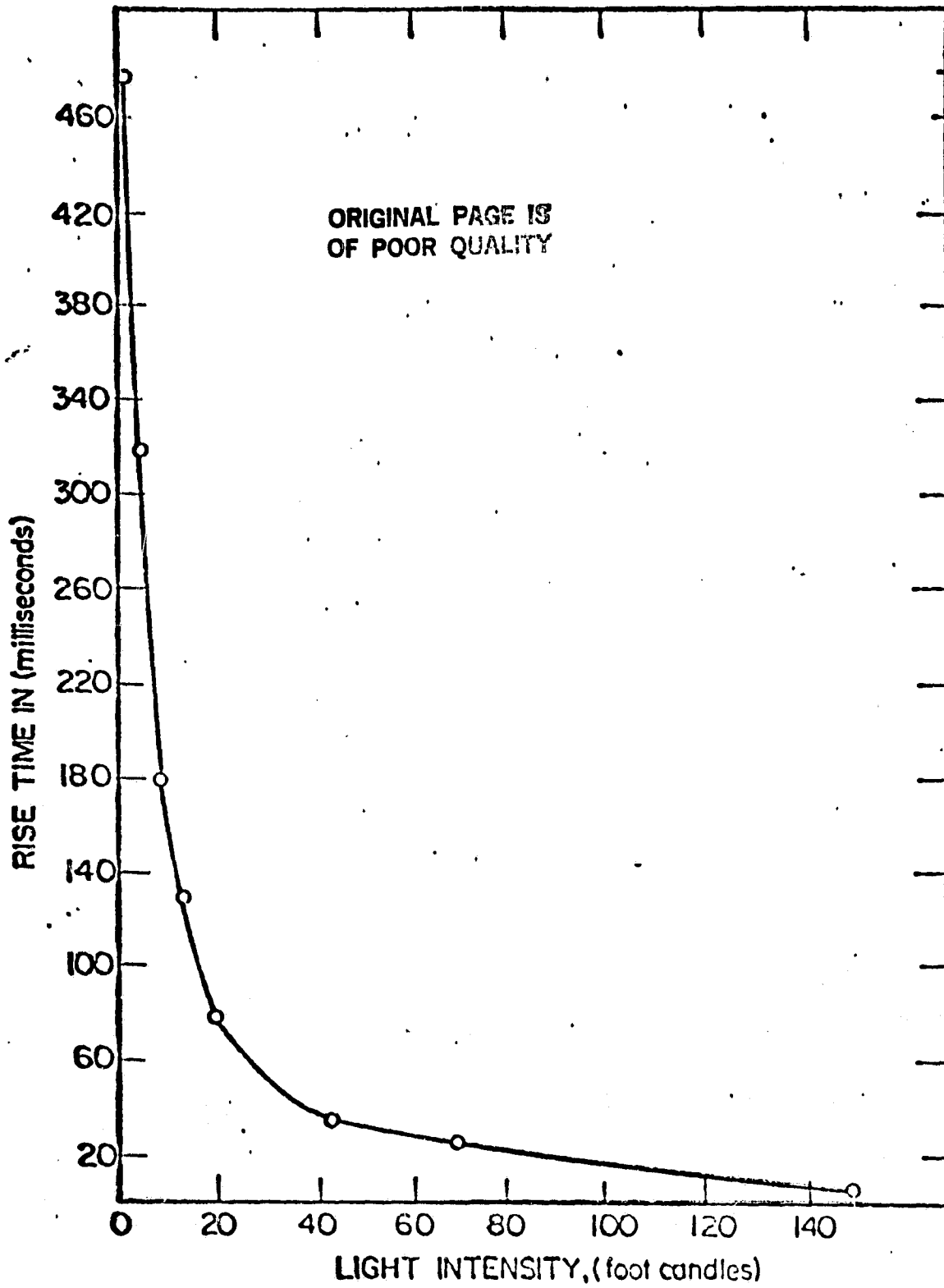candles where one foot candle is equivalent to 15.83 mW/m^2).

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Figure 7   Rise time of photocurrent as a function of light
            intensity at $24^{\circ}C$.

Such a light dependency for the rise time of the photoconductivity is an indication of the presence of electron trapping states in the band gap close to the conduction band. The steady state concentration of the photo-generated electrons in the conduction band is reached only after these electron trapping states are filled with electrons. On the other hand, the lower the excitation intensity the longer it takes to fill out the electron traps. Therefore, a longer rise time should be expected at lower excitation intensities if strong electron trapping states are present.

The decay time of the photocurrent in a typical CdS film is plotted in Fig. 8 as a function of light intensity. It is seen that the decay rate of the photocurrent after the illumination is terminated, decreases with increasing excitation intensity. For a photoconductor without electron trapping states the decay time of the photocurrent will be equal to the lifetime of the photogenerated electrons. However, the presence of the electron traps elongates the decay time, since the trapped electrons are gradually thermally excited back to the conduction band after the excitation is stoped. These electrons stay in the conduction band and maintain a conductivity higher than dark conductivity until being removed from the conduction band by recombination. This, of course, will continue until all the trapped electrons are recombined through their transfer to the conduction band.

Fig. 9 displays a plot of photocurrent versus applied voltage, for a typical CdS film fabricated on a $LiNbO_3$ substrate. During the experiment the light intensity on the film was kept constant and the photocurrent was measured for different values of the applied drift voltage.
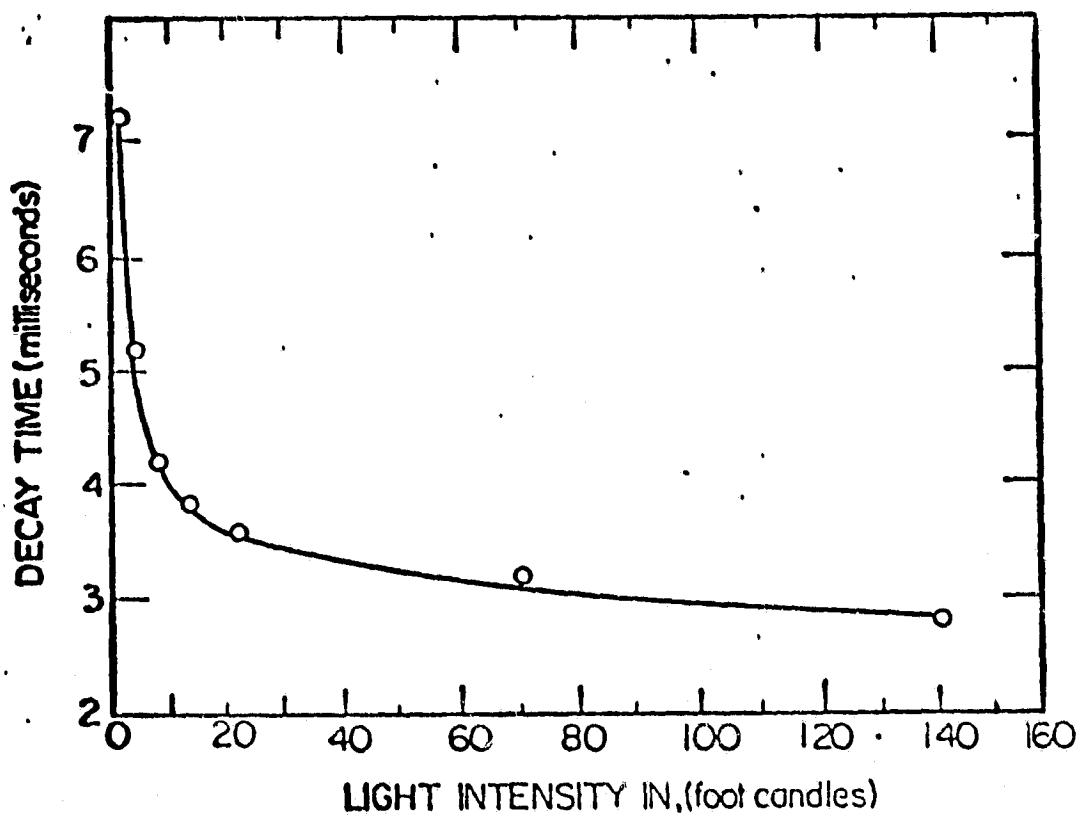
Figure 8   Decay time of photocurrent as a function of
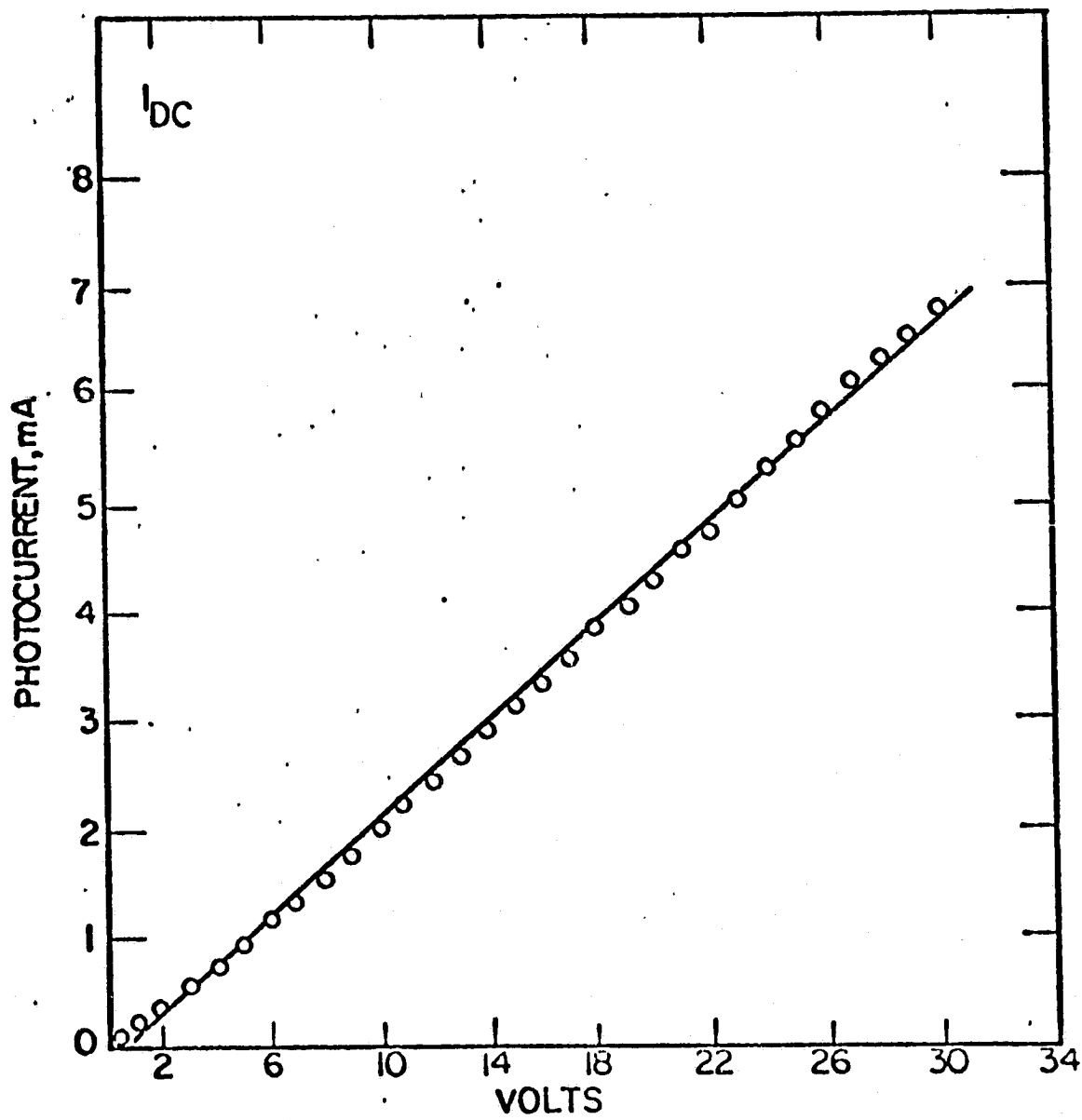light intensity at 24°C.

Figure 9. Current versus voltage applied to the electrodes on a photoconducting CdS film.

Such a linear I-V characteristic, as we discussed in Section 1, eliminates the possibility of potential barrier formation at crystalline boundaries in our polycrystalline CdS films.

Also studied was the dependency of the photoconductivity of the CdS films on the light intensity. This was done by measuring the photocurrent through the film at various excitation intensities. The result of such a measurement is shown in Fig. 10 as a plot of the photoconductance of the film as a function of light intensity for a typical CdS film at room temperature (about 24°C).

The photoconductivity of the CdS films was always found to be proportional to some power, γ, of the light intensity, I, on the film. Where it was found that $1 < \gamma < 2$ for photoconducting CdS films on LiNbO$_3$ substrate at room temperature. For example, we found $\gamma = 1.7$ for the film corresponding to the plot in Fig. 10. It was demonstrated that the photocurrent in these films increases superlinearly (i.e. $\gamma > 1$) with increasing light intensity when the film is at room temperature.

The effect of temperature on the photoconduction properties of the CdS film was also studied. In these measurements the sample was suitably mounted in a vacuum system in order to prevent water vapor from condensing on the sample when cooled and atmospheric oxygen being absorbed when it was heated. We studied the effect of the temperature on the photoconductivity of the CdS film by measuring its resistance at various temperatures while the intensity of light on the film was kept constant. In Fig. 11 we have shown plots of the photoconductance against the reciprocal of temperature for the same film that was used in measurements corresponding to Fig. 10. It is seen that, as the temperature of the film decreases,
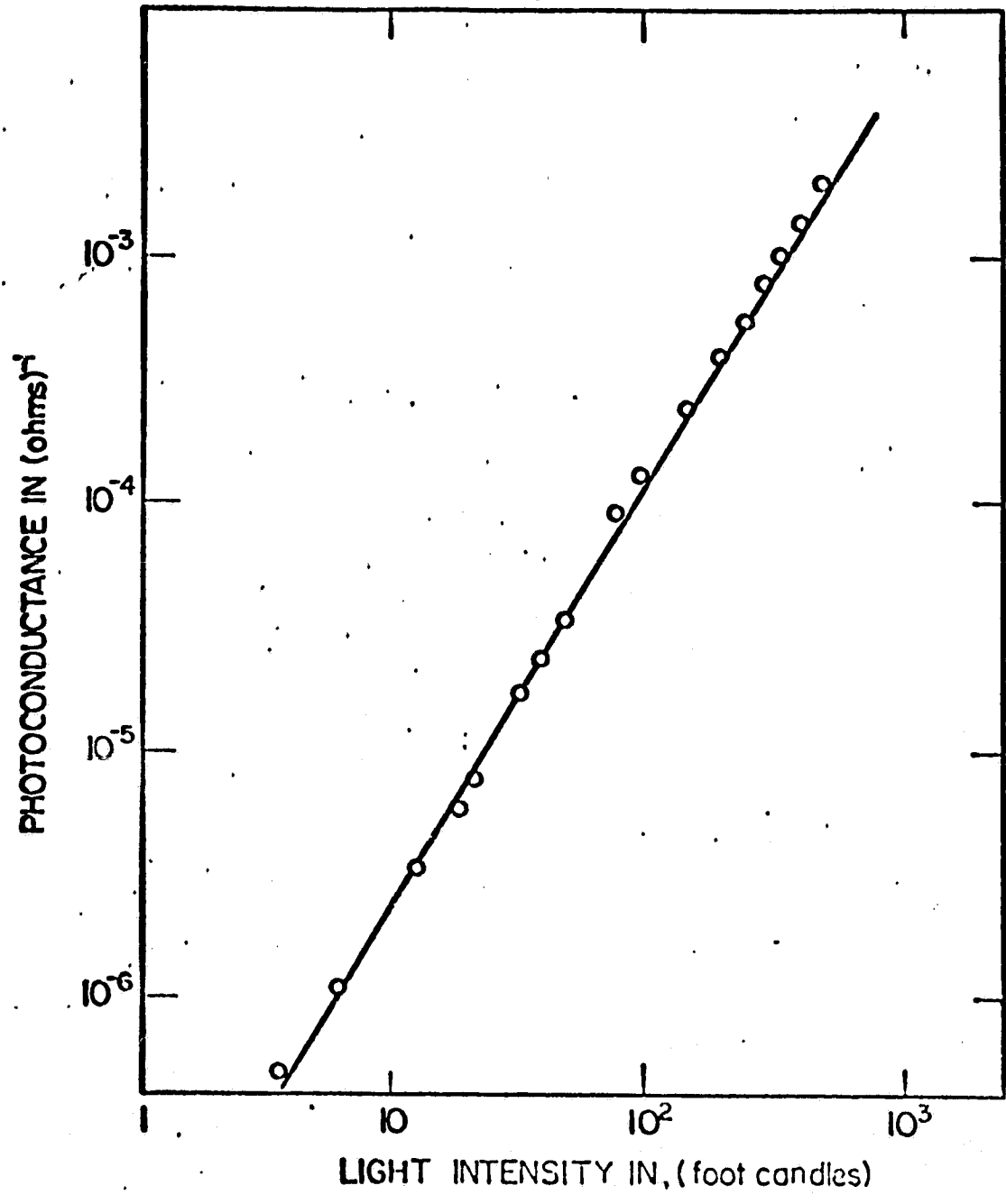
Figure 10   Photoconductance of a CdS film as a function of white light intensity at 24°C.
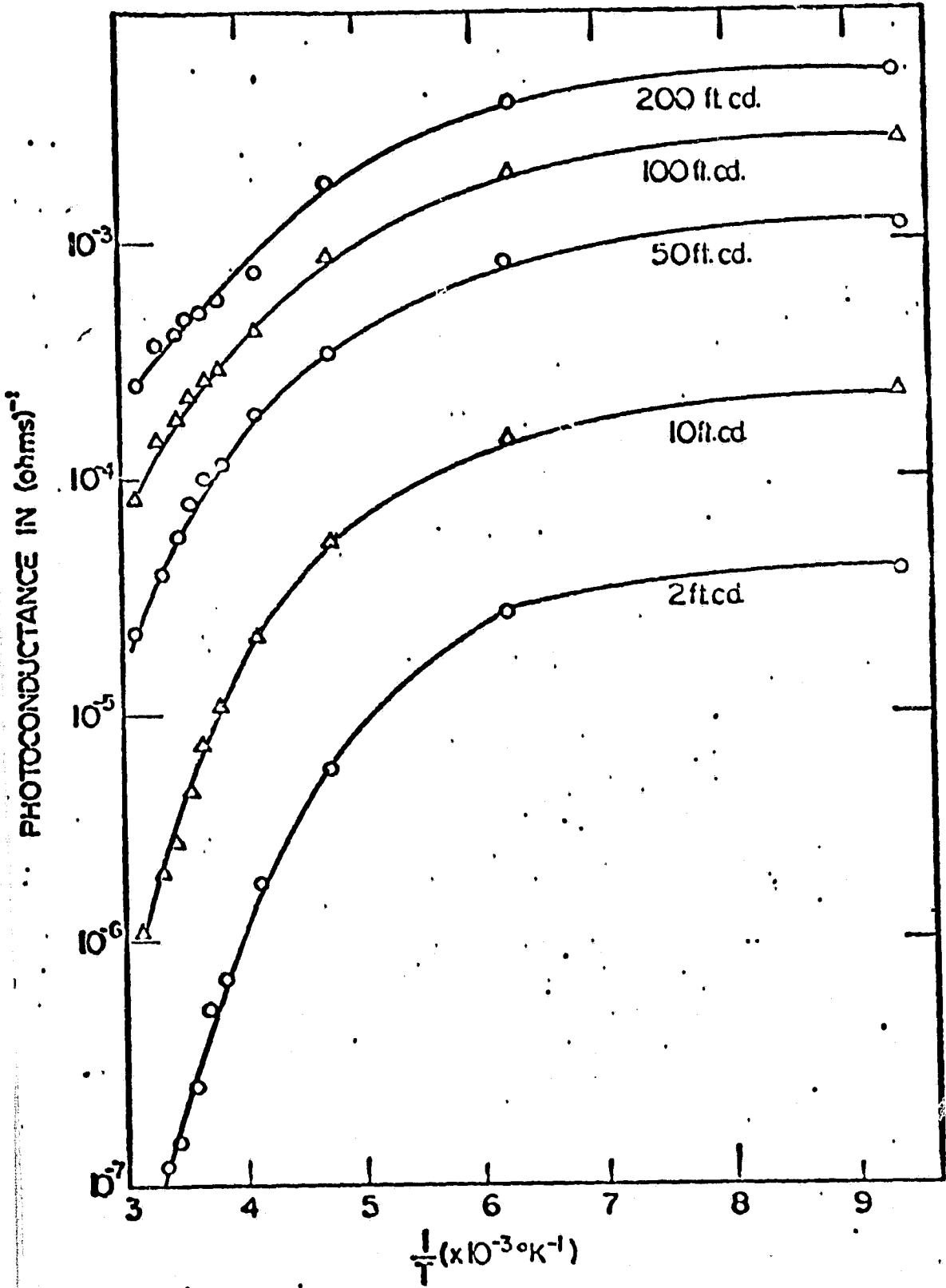
Figure 11   Photoconductance of a CdS film as a function of temperature at various light intensities.

its photoconductance increases and finally reaches a region, at relatively low temperature, in which it becomes almost insensitive to a further decrease in temperature. The rate of change of photoconductivity of the film with temperature decreases with increasing light intensity. For low level excitation the photoconductivity of the film increases by a factor of more than 10^2 as the temperature of the film drops from room temperature to about, -100°C. The electron mobility cannot change significantly over this temperature range [31]. Therefore, it is concluded that the density of conduction electrons rises as the temperature drops.

A CdS film with superlinear photoconductivity at room temperature (Fig. 15) was cooled down to -160°C, and then its phtoconductance at various light intensities was measured. The result of these measurements is plotted in Fig. 12. It is clear that the dependency of the photoconductivity, σ, of the film on the light intensity, I, has changed from $\alpha\sigma.I^{1.7}$ at troom temperature to $\alpha\sigma\ I^{0.9}$ at -160°C.

The experimental justification and studies of the modulation of photoconductivity by acoustically induced electric field in our CdS films were made possible through the measurement of electricl signal currents indicative of such changes. These are the signal currents produced by part of the photoconductivity modulation which is proportional to the square of the acoustic electric fields. These signals, expected from the anticipated non-linear relationship between the change in conductivity and the acoustic-electric field, can be calculated either by using the Eq. (3-34) or starting from the series expansion of the photoconductivity in terms of the electric fields. A complete discussion of this prescription is
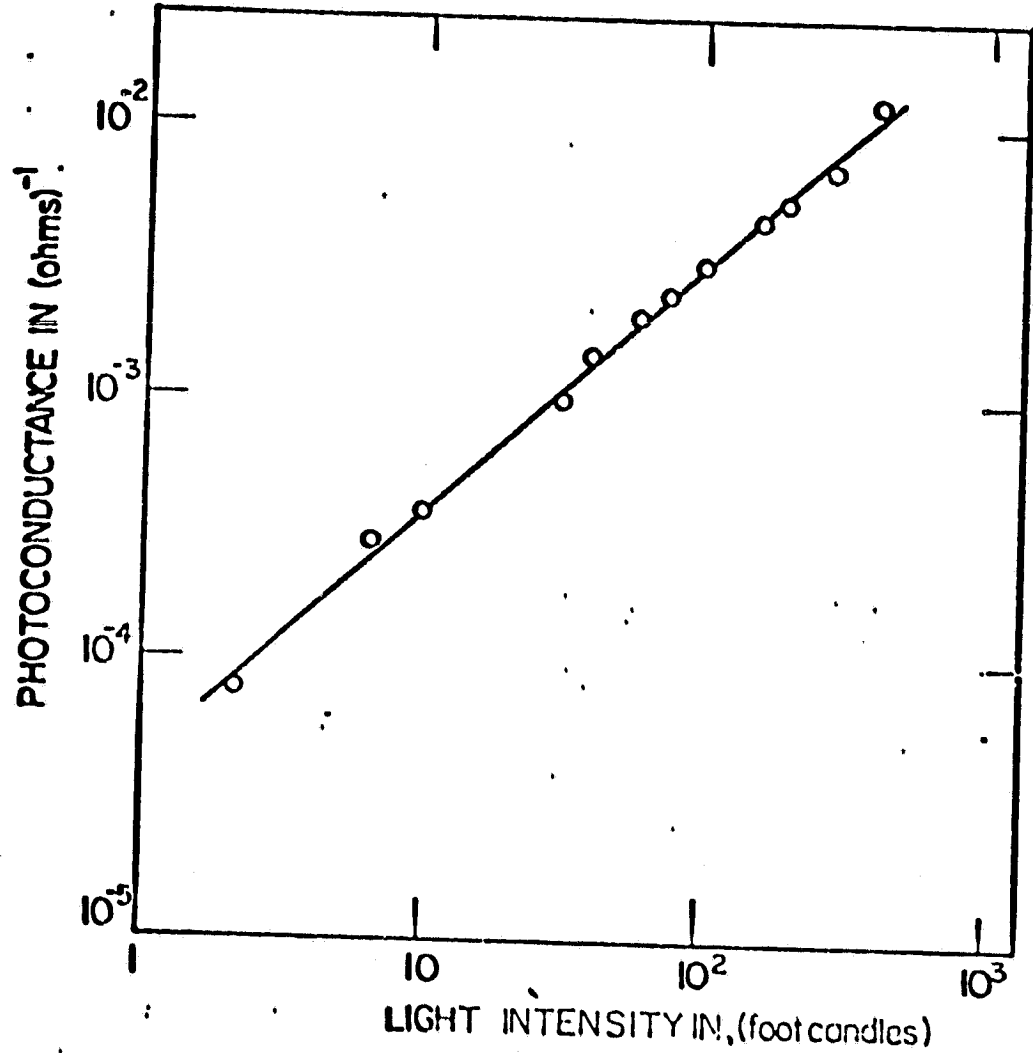
Figure 12   Photoconductance of a CdS film as a function
of white light intensity at -160°C.

presented elsewhere[1,2], therefore, only a brief review is given here.
To this end, we will start with considering the case of two surface
acoustic waves traveling in the same direction, x, on the substrate
under the film. We will assume, for simplicity, that the acoustic
loss is neglegible and that the electric field effects are uniform
through the thickness of the film. Consequently, for two piezoelectric
surface waves propagating in the x-direction, the associated electric
fields inside the film can be approximated by the following plane
waves.

$$E_x = E_1 \cos(k_1 x - \omega_1 t) + E_2 \cos(k_2 x - \omega_2 t) \qquad (4-1)$$

$$E_Y = 0 \qquad (4-2)$$

$$E_Z = E_1' \cos(k_1 x - \omega_1 t) + E_2' \cos(k_2 x - \omega_2 t) \qquad (4-3)$$

Due to the spatial gradient of these electric fields, a space charge is
created in the film. A linearized solution to problem will approximate
the density of bunched electrons, δn, also by a plane wave such as

$$\delta n = \alpha_1 E_1 n_o \sin(k_1 x - \omega_1 t) + \alpha_2 E_2 n_o (k_2 x - \omega_2 t) \qquad (4-4)$$

α_1 and α_2 are constants that we introduced in previous sections. Let
us assume that the electrical contacts to the film are provided by an
interdigital finger pattern whose lines are running parallel to x-direc-
tion on the plane of the film. Application of a CD voltage to these
contact electrodes will generate a DC biasing field E_d which will result
in an electrical current flowing in Y-direction. The current density
J at any point in the film is given by

$$J = \sigma E_d = q \mu n E_d \qquad (4-5)$$

where q and μ are respectively the electronic charge and mobility, and the free electron density n in a film under the influence of acoustic-electric fields is obtained from Eqn. (3-35) and (4-4). Substitution for n in Eqn. (4-5) revelas the fact that the current density contains components osscilating with frequencies of $\omega_1 - \omega_2$, ω_1, ω_2, $\omega_1 + \omega_2$ etc. We are interested only in the component of the current that osscilates with the difference frequency of the two acoustic waves, $\omega_1 - \omega_2$. This current, denoted by i_{ac}, will be referred to as the electrophotoconductance (EPC) signal. The EPC signal i_{ac} for the case which is presently discussed can easily be calculated to be

$$i_{ac} = \hat{u} j J(\omega_1 - \omega_2) dx dy = C E_d \int \frac{n_o^3 KTL}{(n_o + KTL)^3} \cos(kx - \omega t) dx dy \qquad (4\text{-}6)$$

where

$$C \equiv \frac{q\mu\alpha_1\alpha_2 E_1 E_2 h}{4}$$

$$k = k_1 - k_2$$

$$\omega = \omega_1 - \omega_2 \qquad (4\text{-}7)$$

h is the film thickness and integration in Eq. (4-6) is over the whole film area contributing to current. For a uniformly illuminated film the density of photogenerated electrons, n_o, is independent of X and Y coordinates and Eq. (4-6) can be simplified to:

$$i_{ac} = C' E_d \frac{n_o^3 KTL}{(n_o + KTL)^3} \int \cos(kx - \omega t) dx \qquad (4\text{-}8)$$

From Eqs. (4-6) and (4-8) it is expected that the EPC signals i_{ac} to be proportional to the biasing field E_d as well as being proportional to the Fourier components of the light distribution on the film when

it is illuminated by a uniform light or a periodic light-dark pattern. Both of these expectations were satisfied by our experimental observations. One can also calculate the total DC current through the film in the absence of any acoustic electric field to obtain:

$$i_{dc} = \int q\mu n_o E_d \, dxdy = q\mu E_d n_o h \int dxdy \qquad (4-9)$$

Dividing the Eq. (4-8) by Eq. (4-9) yields the following

$$\frac{i_{ac}}{i_{dc}} \propto \frac{n_o^2 \, KTL}{(n_o+KTL)^3} \propto \frac{\Delta n(E^2)}{n_o} \qquad (4-10)$$

The constants of proportionality in Eq. (4-10) are independent of n_o and KTL. Thus the light intensity and temperature dependency of the measured $\frac{i_{ac}}{i_{dc}}$ is expected to be the same as that of the calculated ratio $\frac{\Delta n(E^2)}{n_o}$.

So far we have shown that when two surface acoustic waves are propagating on the piezoelectric substrate of the film, an EPC signal oscillating at the difference frequency of the two waves will be detected at the metal contact lines on the film. These are the signal currents that we have measured in all the experiments to be described in the rest of this section.

The surface acoustic waves were created by interdigital transducers laid down on the $LiNbO_3$ substrate. Usually six transducers were fabricated, two on each of three sides of the CdS film/contact region. These transducers were made by vacuum evaporation of aluminum on the $LiNbO_3$ substrate, using the proper masks and photolithographic techniques. In most of our experimental measurements we used the

transducers that had center frequencies of about 30 MHz and a useable

bandwidth of about 4 MHz. The transducer terminals were simply con-

nected to the output of an rf signal generator. The driving voltage

was typically about 1 to 5 volts peak-to-peak. The efficiency of

the transducers could have been improved by compensating for its

capacitance using an inductor of approximately 1 micro henry.

A complete schematic diagram of the experimental arrangement used

to measure the EPC signals is shown in Fig.13 . Two surface acoustic

waves (SAW) traveling in the same direction on the $LiNbO_3$ substrate

were generated by exciting the two adjacent transducers on the same

side of the CdS film/contact region (the central square in Fig.13).

From all of the modulation product signals generated in the film

we wished to extract only the EPC signal at the difference frequency

of the two waves. Thus, a very selective low-pass filter was inserted

directly after the metal contacts. This filter, with 60 dB gain differ-

ence between 30 MHz and 1 MHz effectively eliminates the feed-through

and all of the high sum frequency signals. Thus, only the signals oscil-

lating at the difference frequency of the two acoustic waves, could pass

through the filter.

The signal was then fed into a current amplifier for detection.

This amplifier was designed to maintain a constant dc biasing photo-

current through the film, i_{dc}. This meant that the dc voltage applied

to the metal contacts would change with light intensity. For ac signals

the input impedance of the amplifier was very low, only about 11 ohms.

The low impedance implies that the amplifier was a "current amplifier".
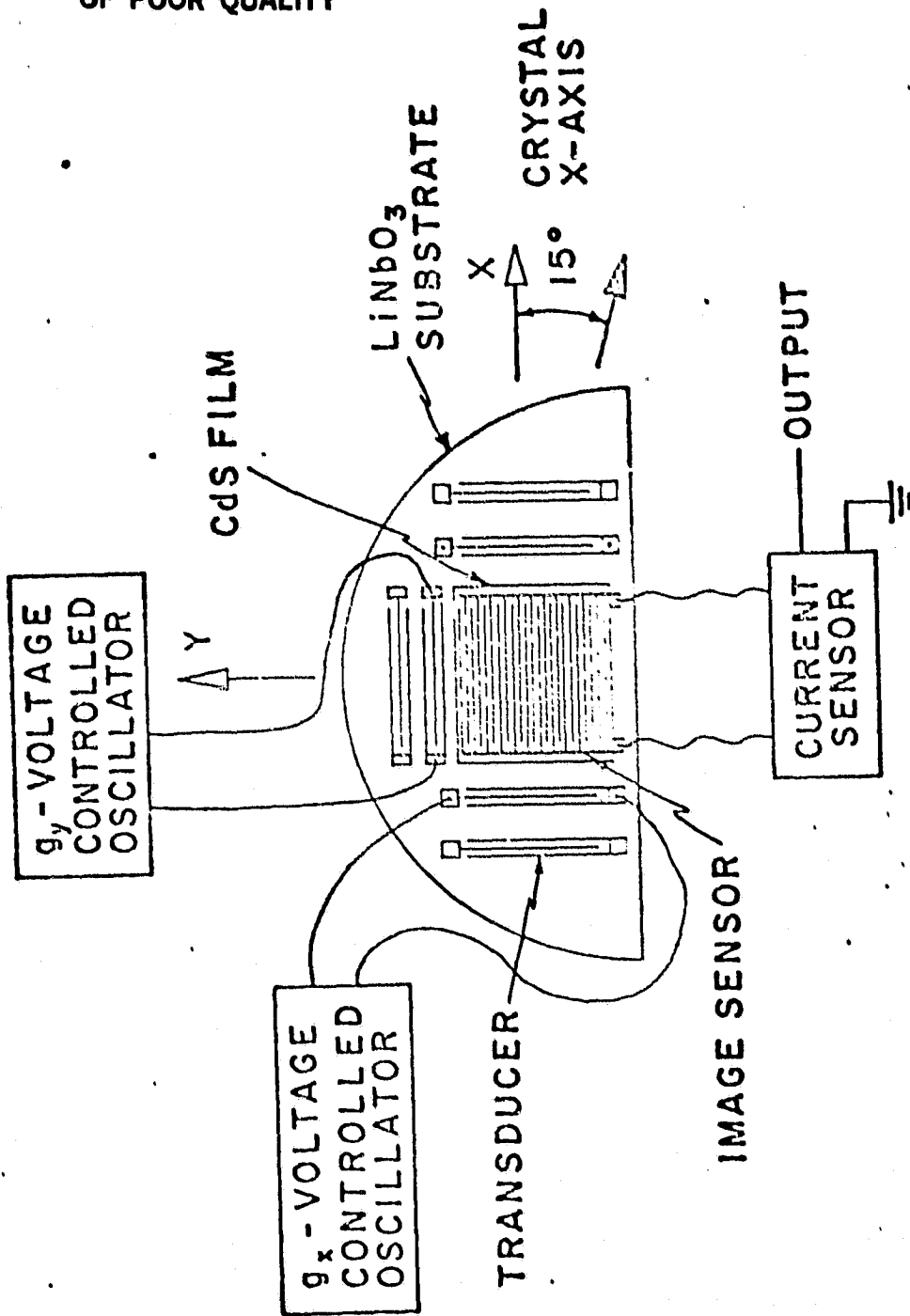
Figure 13   Schematic diagram of experimental arrangement for measuring electrophotoconductance signals

If the input current into a current amplifier is, i_{ac}, and if its output voltage is, V_{ac}, then the transresistance is defined as

$$R_T = V_{ac}/i_{ac} \qquad (4\text{-}11)$$

R_T can be determined by injecting a known ac current into the amplifier and measuring the output voltage. Once R_T is known, Eqn. (4-11) can be used to calculate i_{ac} from the observed values of the output voltage, V_{ac}. We used an amplifier with a transresistance of 160 kilo-ohms. The substrate, low pass filter, and the amplifier were all mounted in an aluminum box that was suitably designed to minimize the electromagnetic feed-through from the transducer drivers to the pick-up amplifier.

Usually, one transducer was driven by a signal generator at fixed frequency of about 30 MHz while the other transducer was excited by a generator sweeping from 25 MHz to 35 MHz. This way, all the EPC signals i_{ac}, representative of the spatial Fourier components of the image projected on the film, with frequencies of up to 5 MHz corresponding to spatial frequencies up to 13 cycles per centimeter, could be displayed on an oscilloscope screen for simultaneous comparison of their amplitudes. In all the experiments to be described here, we projected either a uniform light or a simple light-dark bar pattern onto the CdS film. For such simple light patterns, the amplitudes of the EPC signals at the difference frequencies of the two acoustic waves were found to be exactly proportional to the Fourier components of the light intensity distribution on the film.

We first studied the efect of the dc biasing current on an EPC signal This was done by measuring an EPC signal for various applied biasing currents while the intensity and the distribution of light on the film and the voltages applied to the transducers were all kept constant.

A typical result of such a measurement is displayed in Fig. 14 as the measured peak-to-peak value of a signal at 2 MHz is plotted against the biasing current. It is seen that the size of the signal is linearly proportional to the biasing current. This proportionality relationship between i_{ac} and i_{dc} justifies the existance of the proposed electric field modulation of the photoconductivity in our CdS films.

According to the model that we have developed for electrophotoconductivity, explained in detail in the last two sections, it is the local density of the conduction electrons in the CdS film which is altered by the acoustic electric fields. The modulated density of the free photo-generated electrons, n, is given by Eqn. (3-30).

All the quantities in Eqn. (3-36) have already been introduced previously. Let us define the new parameter, η, to be

$$\eta = KTL/n_o \qquad (4-12)$$

Substitution of Eqn. (4-12) in Eqn. (4-10) yields

$$i_{ac}/i_{dc} \propto \Delta n(E^2)/n_o \propto [\eta/(1 + \eta)^3] \qquad (4-13)$$

In the remaining part of this section we will describe the observed characteristics of the EPC signals, a measure of the electric field modulation of photoconductivity of the CdS films. This will be done in parallel with an attempt to demonstrate the consistancy of these experimentally observed characteristics with predictions of our theoretical models. Of course, we do not intend to investigate the exact quantitative match between the experimentally measured values of the EPC signals, i_{ac}, and their calculated values based on our theoretical model. This really re-
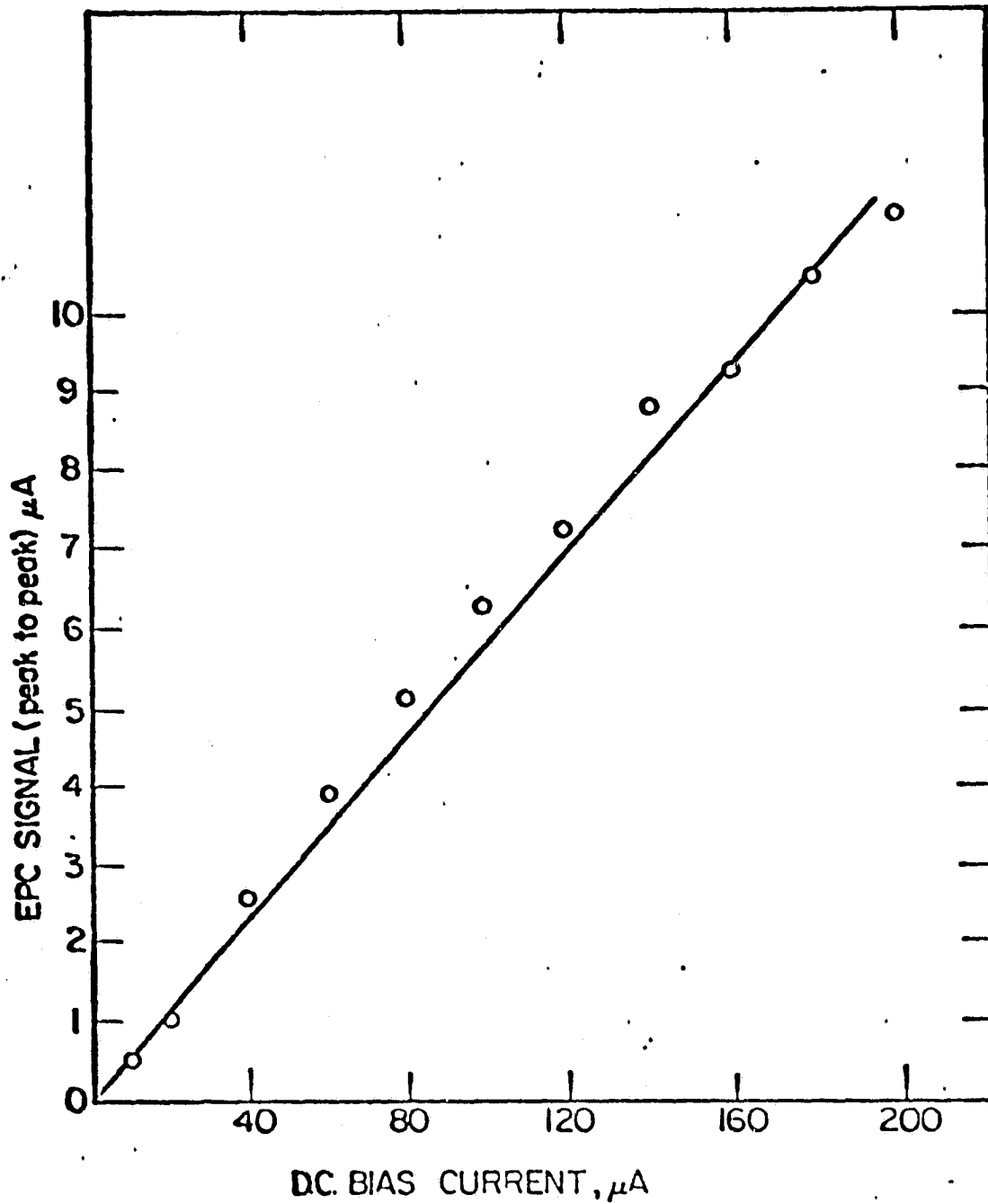
Figure 14   EPC signal, i_{ac}, as a function of DC biasing
current, i_{dc}.

quires a detailed knowledge of the distribution and concentration of the

impurity states just below the conduction band edge, the mobility of

electrons, and other such parameters. In addition, it also requires an

exact and complete solution to the problem of surface acoustic wave pro-

pagation in the presence of the photoconducting CdS film. Instead, we

will demonstrate a good qualitative agreement between the theory and

experiment, using reasonable approximations for the quantities involved.

We have demonstrated in Section 3 that the fractional change in

electron concentration, $\Delta n(E^2)/n_o$, is a function of the light intensity

on the film through the quantities n_o and L inside the square brackets

in Eqn. (3-34) . While n_o is proportional to the excitation intensity,

the value of L at any excitation level is mainly determined by the con-

centration of the impurity states close to the quasi-Fermi level, of the

electrons in rapid communication with the conduction electrons. As a

function of η, given by Eqn. (4-12), the quantity inside the square brackets

in Eqn. (4-13) stays close to its maximum value as long as the ratio η

remains close to η_{max}. Where η_{max} is the value of η for which the quan-

tity inside the square brackets in Eqn.(4-13) is at its maximum. It can

easily be shown that η_{max} = 0.5. Accordingly, the fractional change in

conductivity, $\Delta n(E^2)/n_o$, decreases from its maximum when η deviates appre-

cialby from η_{max}. This happens when n_o is much smaller or much bigger

than the value of KTL. Thus, it is the profile and size of the impurity

state distribution function, $g_t(E)$, which determines the light dependency

of $\Delta n(E^2)/n_o$. Impurity distributions having high concentrations at

energies close to the conduction band, and decaying toward the middle

of the band gap, have been reported for photoconducting CdS thin films similar to ours. Therefore, quite reasonably, the existence of such impurity states in our CdS films also was assumed and approximated by the distribution function $g_t(E)$ given in Eqn. (3-37). This distribution function was employed to calculate, L, from Eqn. (3-31), and then the dependence of $\Delta n(E^2)/n_o$ on the steady state electron density n_o, from Eqn. (3-36).

Some results of such calculations are shown in Fig. 3 and Fig. 4 in which the fractional change in n_o is plotted versus n_o. In these plots the parameters g_o and β, defined in Eqn. (3-33), are kept constant over each individual curve, but at least one of them changes from one curve to the other. It is clear that the electrically induced fractional change in free electron concentration becomes a maximum for some value of n_o, and that the position of this maximum is shifted as a result of a change in the profile and the magnitude of the impurity state distribution function, $g_t(E)$.

On the other hand, the dependency of i_{ac}/i_{dc} on the steady state concentration of electrons, n_o, should be the same as that of $\Delta n(E^2)/n_o$. Since n_o is proportional to the intensity of light on the film, therefore the light intensity dependency of i_{ac}/i_{dc} is expected to follow a pattern similar to the curves displayed in Fig. 3 and Fig. 4.

The experimental investigation of the effect of excitation intensity on the fractional change in photoconductivity of the CdS films was made possible by measurements of the EPC signals for various intensities of white light on the film. During these measurements the driving voltages

and frequencies of the transducers, the biasing current, the film temperature, and the light pattern projected on the film were all kept unchanged. Thus, the only varying element was the excitation intensity, which generates free carriers in the film. Similar measurements were repeated for several different CdS films. A typical result obtained from these experiments is shown in Fig. 15 in which the measured i_{ac}/i_{dc} is plotted against light intensity for two different CdS films. At each light level the free electron density in the film was calculated from its measured photoconductance. Curves in Fig. 15 are redrawn in Fig. 16 as a plot of i_{ac}/i_{dc} versus free electron density, n_o, in the film. Comparison of the curves in Fig. 16 and those in Fig. 3 shows a remarkable consistancy between theoretically predicted and experimentally observed modulation of photoconductivity in a CdS film. Fig. 15 reveals that, starting at very low light intensities, the normalized EPC signals, i_{ac}/i_{dc}, increases with increasing light intensity and reaches its maximum value, and then decreases. Such a behavior was found to be universal for all the heat-treated CdS films. However, the position of the maximum was found to differ from one film to another. This, can presumably be attributed to variations of the density of impurity states from film to film. Indeed, we are aware of the fact that our impurity diffusion and film curing technique does not produce identical CdS films. This can be shown by means of very simple film characterization techniques. Of course, a drastic difference between different CdS films is not expected either, as long as the same recipe is employed.
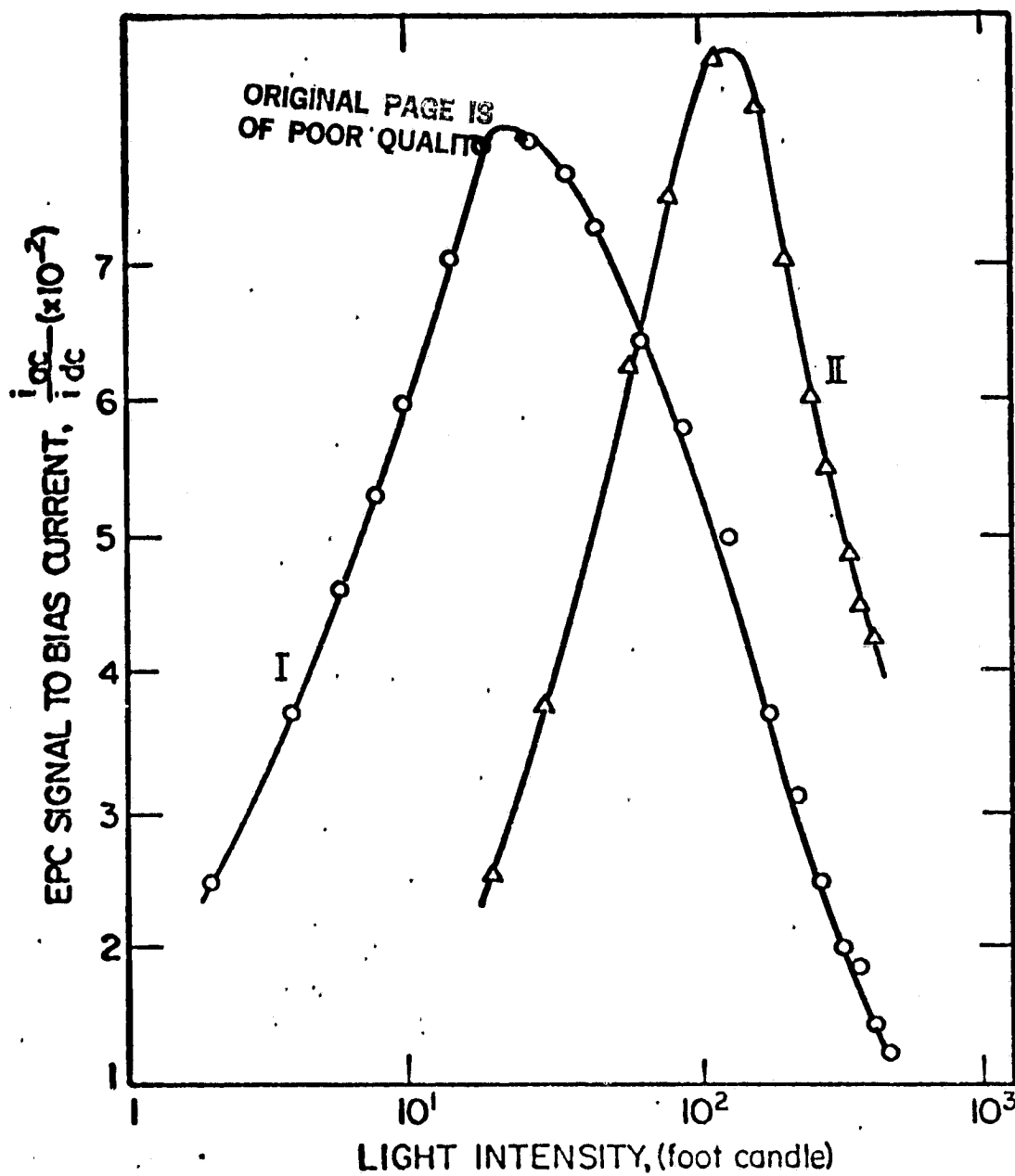
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Figure 15   Normalized signal current as a function of
            light intensity for two different CdS films at
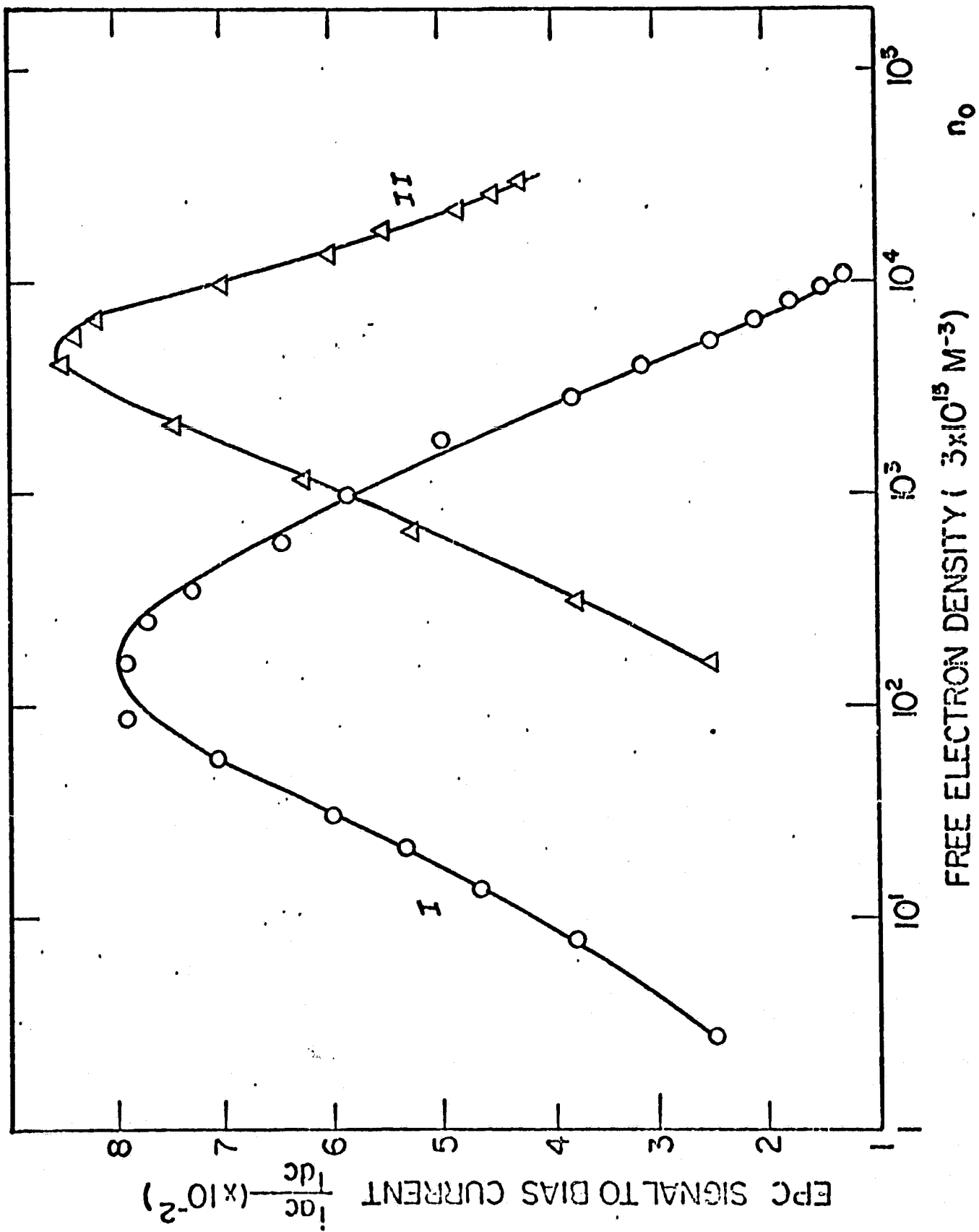   room temperature.

Figure 16 Measured fractional change in conductivity for two different CdS films.

In Fig. 17 the measured normalized signal current, i_{ac}/i_{dc}, is plotted as a function of excitation intensity for a CdS film that was subjected to a heat-treatment quite different than the usual one. The film was simply heated in the furnace at about $650^{o}C$ for about an hour in the absence of all the dopants that we use in our usual film annealing process.

This film had a clear yellowish color, unlike the ordinarily heat treated CdS films which have a dark brownish appearance. The density of the impurity states, at least in this film, is expected to be quite different from those described earlier. Therefore, according to the predictions of our previously discussed model, the light intensity dependency of the normalized signal current in this film is expected to be considerably different from those in the other films. This is clearly the case as is seen from the comparison of Fig. 15 with Fig. 17.

We explained earlier that the quantity inside the square brackets in Eqn. (4-13) is really a function of the ratio $\eta = KTL/n_o$, and has a maximum. Its maximum occurs when η becomes equal to $\eta_{max} = 0.5$.

On the other hand, it was pointed out that η itself is a function of the radiation level on the film through n_o and L. Any change in light intensity will also change the parameter η, but its dependency on light is mostly determined by $g_t(E)$. Therefore, i_{ac}/i_{dc} approaches its maximum when the light intensity is such that the electron density n_o becomes comparable to KTL so that η assumes a value close to η_{max}.

It might be more practical to identify the position of the maximum in i_{ac}/i_{dc} in terms of the corresponding values of n_o and L at this maximum rather than specifying it with the related light intensity.
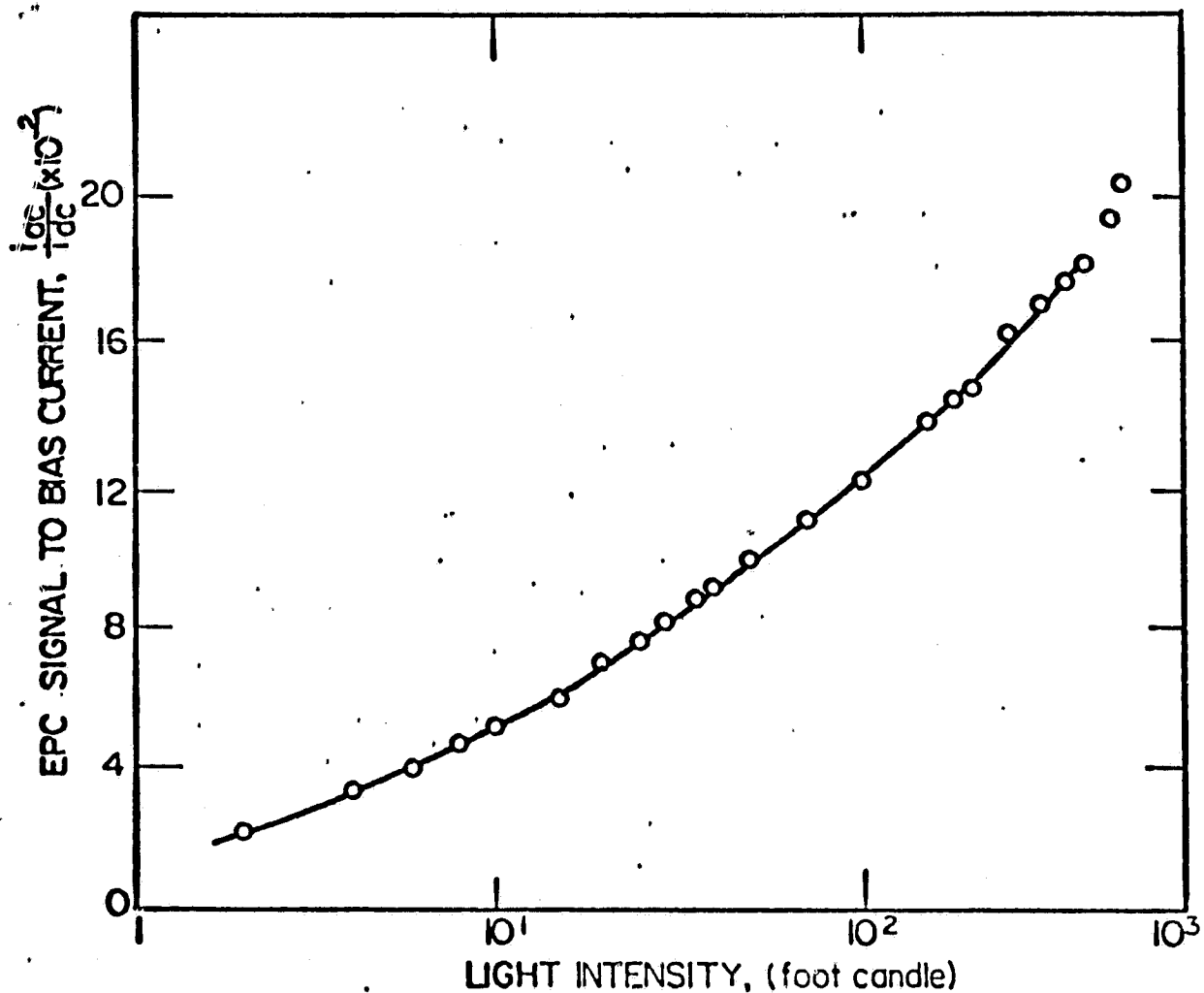
Figure 17 Normalized signal current as a function of light intensity for a film which was heat treated in the absence of all the dopants that we use in our conventional heat treating method.

If we call them $(n_o)_{max}$ and L_{max}, then the maximum in i_{ac}/i_{dc} is

expected to be attained whenever $(n_o)_{max}$ and L_{max} are achieved. More-

over, a set of n_o and L, corresponding to some light intensity on

the film at room temperature, can be obtained at much lower light

levels if the film is cooled down to lower temperature. This means

that for a film at a temperature below room temperature, η_{max} will

occur at a light intensity lower than the one for which η becomes

maximum at room temperature. According to this argument the position

of the maximum in i_{ac}/i_{dc} should shift toward lower excitation inten-

sities by lowering the film temperature. It was indeed experimentally

observed that the maximum in i_{ac}/i_{dc} moves toward lower light intensi-

ties as the film temperature decreases. For example, in Fig. 18 curve

I is a plot of measured normalized signal current, i_{ac}/i_{dc}, as a function

of light intensity when the film was kept at room temperature while

curve II is the result of similar measurements made when the film was

at -160^oC. It is clear that the excitation level corresponding to the

maximum has moved from about 100 foot-candles at room temperature to

about 5 foot candles at -160^oC, as we expected. The flatness of the

curve II around its maximum can partly be due to the change in light

dependency of the photoconductivity of the CdS films from superlinear

at room temperature to sublinearity at lower temperatures.

We have also studied the effect of the change in film temperature

on the normalized EPC signal current, i_{ac}/i_{dc} at constant excitation

intensity. This was done by measuring the normalized EPC signal at various

temperatures (usually below room temperature) while the intensity of the

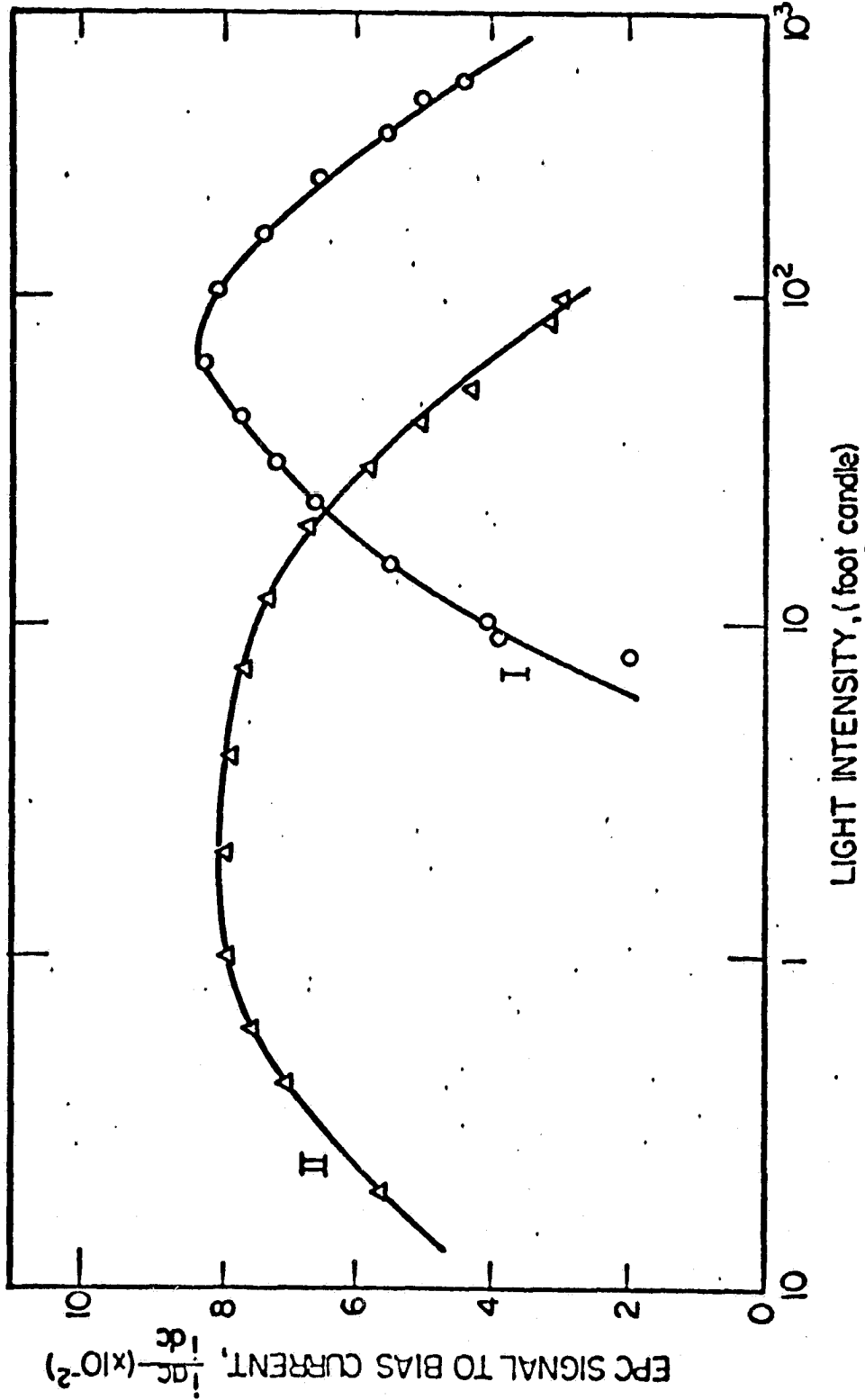light pattern projected on the film was kept constant. A typical result

Figure 18 Normalized signal current, i_{ac}/i_{dc}, as a function of light intensity. Both curves correspond to the same CdS film, film was at room temperature for Curve I and at $-160°C$, for Curve II.

is given in Fig. 19. It demonstrates the fact that starting at room
temperature, the fractional change in photoconductivity of the film in-
creases to an almost steady-state regime (the flat portion of the curve).
The maximum in i_{ac}/i_{dc} shifts to higher temperatures as the intensity of
light on the film increases. Interestingly enough, this is also consis-
tent with, and indeed justifies, our foregoing discussions, and should
have been expected. For instance, consider the point corresponding to
room temperature on curve I in Fig. 19. This point is actually the
same as the point corresponding to 10 foot-candles on curve I in Fig. 18.
Consequently, starting from this point the decrease in temperature
(curve I in Fig. 18) ought to have the same effect on n_o and L as does
the increase in light intensity (curve I in Fig. 18). This is due to
the fact that the increase in light intensity and decrease in temperature
have similar effects in displacing the quasi-Fermi levels in the band
gap. Increasing the light intensity or decreasing the temperature have
the same effect on i_{ac}/i_{dc}.

Though the steady-state concentration, n_o, of the photogenerated
electrons is always proportional to some power of the illuminating light
intensity, the value of L is almost entirely decided by the density of
imperfection states at the electron Fermi level. Let us assume that the
impurity state distribution, $g_i(E)$, is such that the change in L, as the
electron Fermi level moves toward or away from the conduction band, is
slower than the change in n_o. This means that L will not be as sensitive
to light intensity changes as is n_o. In a situation like this, any change
in the position of the electron Fermi-level will alter L more through the
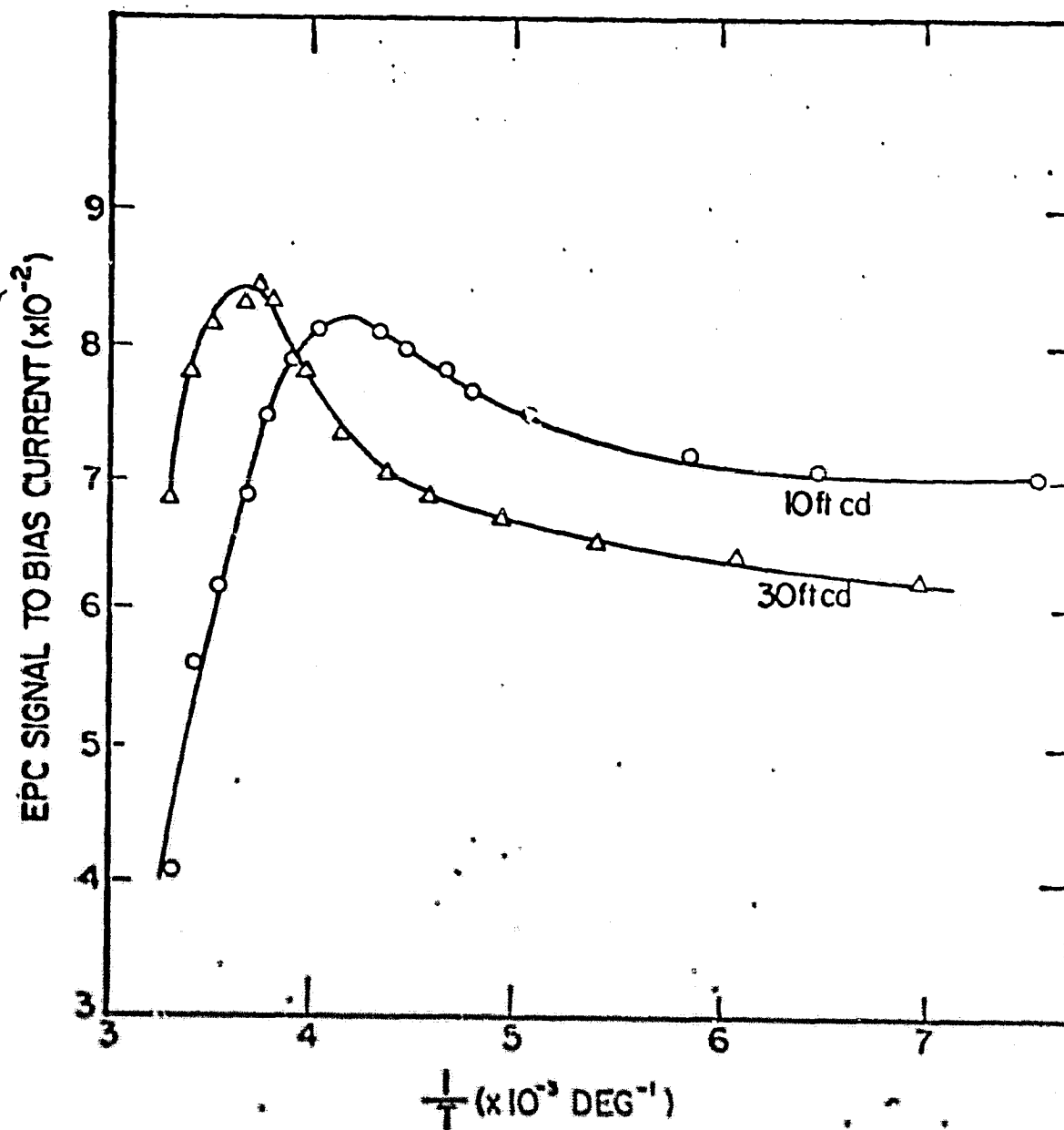changes in n_o rather than L. In this case the effects of the excitation

Figure 1° Normalized signal current, I_{ac}/I_{dc}, versus reciprocal temperature when the light intensity was kept unchanged at 10 and 30 foot candles.

intensity and temperature on i_{ac}/i_{dc} are mostly influenced by their effect

on n_o rather than on L or the location of the electron Fermi-level. This

means that the normalized EPC signal, i_{ac}/i_{dc}, becomes maximum whenever

n_o reaches a particular value, regardless of the level of excitation and

temperature. In other words the fractional change in conductivity remains

unchanged as long as there is no change in the density of free electrons

in the conduction band. This can clearly be seen from the flat portion

of the curves in Fig. 18. In this regard we would like to emphasize

the fact that our model for electric field modulation of the photocon-

ductivity is based only on the existence of the fast communicating

electron traps in the band gap. It is only the interaction of these

fast trapping states with conduction electrons which brings about the

kind of modulation that we have studied here. According to this model

the electric field induced change in photoconductivity does not depend

on the detail of the steady-state photoconductivity characteristics like

its superlinear or sublinear light dependency. The modulation is governed

only be the density of free electrons in the conducttion band and the

parameters corresponding to the fast electron traps.

For instance the free electron concentration n_o at which the maximum

in curve I (Fig. 18) has occured is almost equal to the electron concen-

tration corresponding to the maximum in curve II in the same figure. This

can easily be seen from Fig.10 and Fig. 12 by realizing the fact that the

maximum in curve I corresponds to 100 ft. cds. at room temperature while

the light intensity and temperature for the maximum point on curve II are

respectively about few foot-candles and -160°C. Moreover, the steadiness of i_{ac}/i_{dc} on the flat portions of the curves in Fig. 17 is due to the fact that the density of the photogenerated electrons is almost constant, and does not change due to a further drop in film temperature. This is evident from the temperature dependence of the photoconductance of the CdS films shown in Fig. 11. Thus, we may conclude that L is indeed a slowly varying function of the excitation intensity in our photoconductive CdS films.

Further justification for this may come from the fact that for the theoretically calculated curve I in Fig. 3, when the electron concentration changes from $10^{15}/cm^3$ to $10^{19}/cm^3$, the value of KTL changes only from about $5 \times 10^{18}/cm^3$ to $10^{20}/cm^3$. This means that over a light intensity range for which the density of photogenerated electrons, n_o, changes by a factor of 10^4, the value of L changes only by a factor of 20. One should recognize that the theoretical curve I in Fig. 3 resembles the experimental curve I in Fig. 18.

We explained in Section 1 how the penetration of the acoustically induced electric fields into a photoconductive CdS film produces a space charge in the film due to the redistribution of the free charge carriers. The change in local density of free electrons is proportional to the intensity of the inducing acoustic-electric field E_a, and the steady state density of free electrons n_o, i.e. $n_o E_a$. This, requires the existance of a signal current flowing through the film and oscillating with the different frequency of the two acoustic waves, even in the absence of an applied drift voltage. These signals which we have called "unbiased signals" should obviously be proportional to the steady-state density of photo-

electrons n_o. This demands an identical light intensity dependency for both the ordinary photoconductance and the unbiased signals in a CdS film. Since these quantities both are proportional to n_o which is a function of excitation intensity. We were able to detect and measure some unbiased signals in some of our films at relatively high excitation intensities (usually above 60 foot-candles). These signals were usually large enough to be detected when both surface acoustic waves were traveling in the direction perpendicular to the contact electrode lines. In Fig. 20 and Fig. 21 we have plotted the ordinary photoconductance and an unbiased signal as a function of light intensity for two different CdS films. It is clear from these plots that the photoconductance and the unbiased signals in a CdS film both have exactly the same light intensity dependecies.
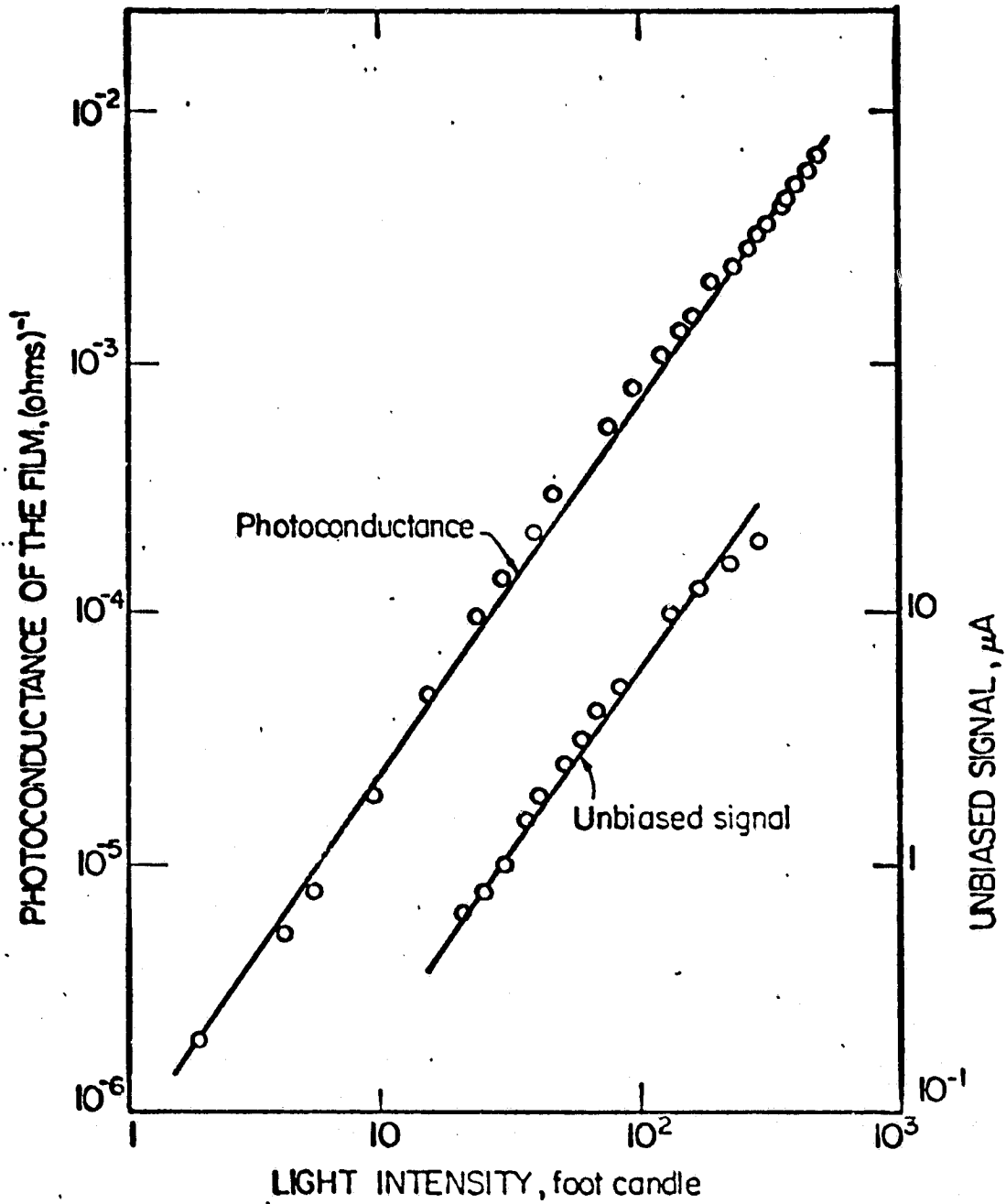
Figure 20   The photoconductance and unbiased signal as a function
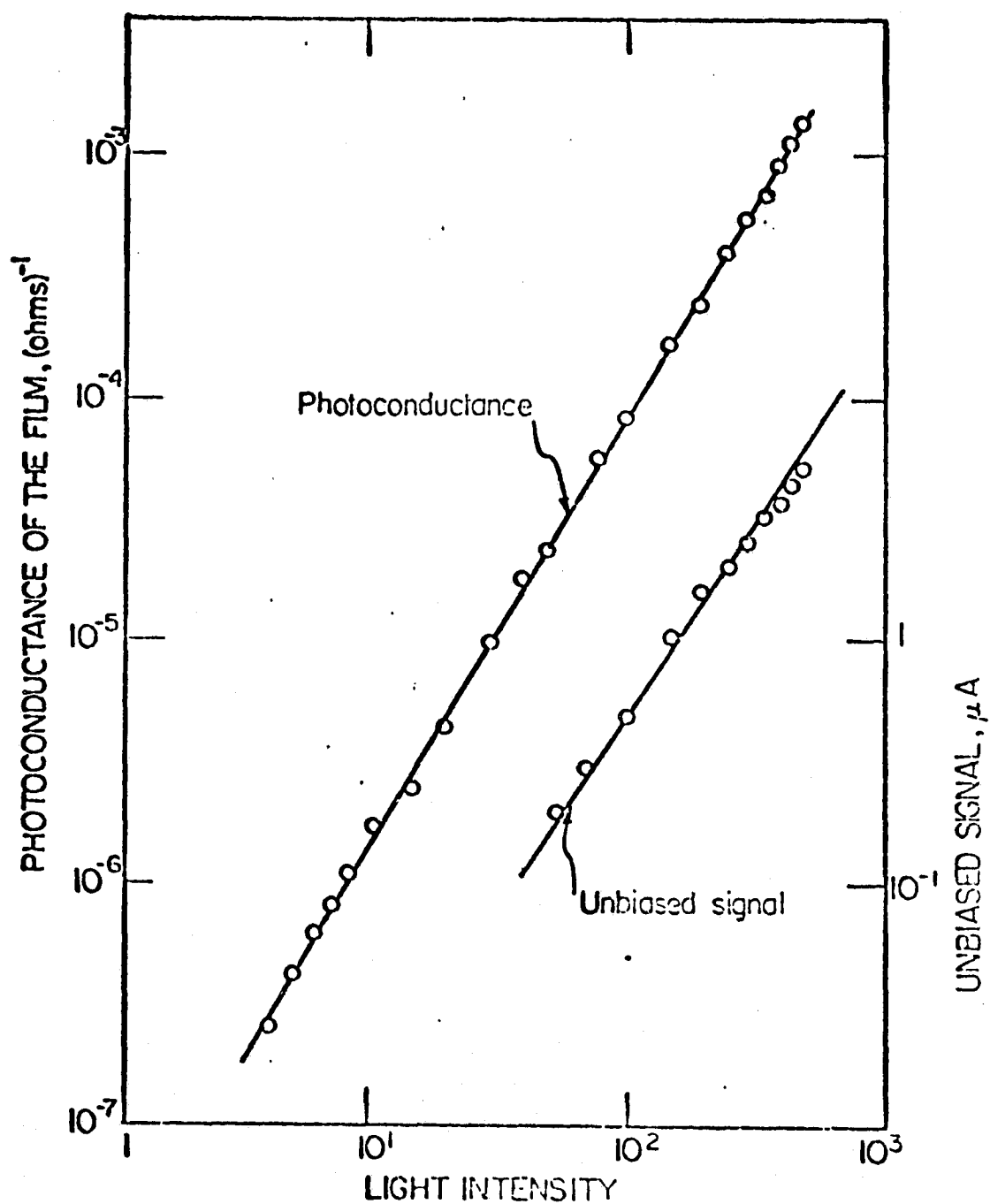of light intensity in a CdS film.

Figure 21. The photoconductance and the unbiased signal as a function of light intensity in a CdS film.

5. CONCLUSIONS

Our studies demonstratéd that the photoconductivity of polycrystal-
line CdS films deposited on a $LiNbO_3$ substrate is modulated by electric
fields associated with surface acoustic waves (SAW) traveling on the
piezoelectric substrate of the film. This change is conductivity of
the film in the presence of light proved to be a large effect and a non-
linear function of the acoustically induced electric field. For instance,
conductivity changes up to 25% and proportional to the square of the
acoustic-electric field were detected. It is also evident that the
fractional change in conductivity of the CdS films is strongly dependent
on the excitation intensity and the film temperature.

Our conclusions tend to reject the possibility that the existing models,
concerning the electric field induced changes in the phtoconductivity of
materials, can explain our experimental observations. On the other hand,
the theoretical model that we have developed which was presented in Section
3 seems to be successful in explaining and predicting the electrophotocon-
ductance in our CdS films. This model is based on the presents of shallow
trapping states in the photoconductor and redistribution of photocarriers
by electric fields accompanying the SAW waves propagating on the film's
piezoelectric substrate. According to this model the important parameters
affecting the size of the change in photoconductivity of the films are the
intensity of the acoustic electric field, the mobility of free carriers in
the film, and the density and energy distribution of electron traps in
the band gap. For instance, at fixed values of the acoustic-electric
fields, the fractional change in photoconductivity approaches its maximum
value whenever the density of free photogenerated electrons becomes com-
parable to the density of electron trapping states at the position of the