EFFECTS OF TEMPERATURE AND BACKGROUND PHOTON FLUX ON THE
PHOTOCONDUCTIVE RESPONSE TIME IN $\text{Hg}_0.6\text{Cd}_0.4\text{Te}$

by

Jeffrey Don Beck

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Submitted to the Department of Electrical Engineering on May 16, 1972 in partial fulfillment of the requirements for the Degrees of Bachelor Science and Master of Science.

ABSTRACT

An experimental and theoretical study is reported which successfully achieves agreement between the photoconductive properties exhibited in n-type Hg\textsubscript{0.6}Cd\textsubscript{0.4}Te and a model based on the theory of minority carrier trapping. Photoconductive properties are described which were measured over a range of temperature and background conditions. The temperature range was from 80 °K to 300 °K; the background ranged from that due to the 300 °K ambient condition to values up to a factor of 10\textsuperscript{2} higher. At the lower temperature and background conditions long average response times and enhanced photoconductive gains depend inversely on the background photon flux. At temperatures above 200 °K the background dependence ceases and the response times approach 10\textsuperscript{-6} s. At low temperatures asymmetrical rise and decay transient characteristics correspond to neither linear nor quadratic recombination, while at 300 °K the transients are exponential and indicative of linear recombination. Steady state response measurements reveal a nonlinear relationship between \( \Delta n \) and the illumination at low temperatures. The small signal responsivity is characterized under varying conditions of temperature and background.

These results indicate that minority carrier trapping is the dominant low temperature mechanism. Moreover, it is shown that a single level trap model is inadequate to explain the data. It is shown how the assumption of a uniform continuum of trapping levels achieves better agreement with experiment. The continuum approach is then extended to consider an exponential distribution of trapping states which successfully fits the low frequency responsivity data over the range of temperature and background conditions investigated. Finally, a method for deducing the density of states directly from the data is derived. The results of applying this method show agreement with the exponential density of traps model.

THESIS SUPERVISOR: James N. Walpole
TITLE: Associate Professor of Electrical Engineering
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<tr>
<td>(A_S)</td>
<td>Sample area</td>
<td>(\text{cm}^2)</td>
</tr>
<tr>
<td>(c)</td>
<td>Speed of light in a vacuum</td>
<td>(\text{cm/sec})</td>
</tr>
<tr>
<td>(d)</td>
<td>Sample thickness</td>
<td>(\text{cm})</td>
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<tr>
<td>(e)</td>
<td>Electron charge</td>
<td>(\text{coulombs})</td>
</tr>
<tr>
<td>(E)</td>
<td>energy</td>
<td>(\text{eV})</td>
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<tr>
<td>(E)</td>
<td>Electric field</td>
<td>(\text{V/cm})</td>
</tr>
<tr>
<td>(E_g)</td>
<td>Energy of the gap</td>
<td>(\text{eV})</td>
</tr>
<tr>
<td>(E_s)</td>
<td>Trap saturation energy</td>
<td>(\text{eV})</td>
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<tr>
<td>(E_a)</td>
<td>Trap activation energy</td>
<td>(\text{eV})</td>
</tr>
<tr>
<td>(E_x)</td>
<td>Energy at which (N(E) = N(0)/e)</td>
<td>(\text{eV})</td>
</tr>
<tr>
<td>(E_c = E_g)</td>
<td>Conduction band energy</td>
<td>(\text{eV})</td>
</tr>
<tr>
<td>(E_v = o)</td>
<td>Valence band energy</td>
<td>(\text{eV})</td>
</tr>
<tr>
<td>(E_m)</td>
<td>Maximum energy of operant traps (approx)</td>
<td>(\text{eV})</td>
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<tr>
<td>(f_t(E))</td>
<td>Trapped hole occupation probability</td>
<td>---</td>
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<td>(G_t)</td>
<td>Trapping gain</td>
<td>---</td>
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<tr>
<td>(G)</td>
<td>Generation rate of excess carriers</td>
<td>(\text{cm}^{-3}\text{-sec}^{-1})</td>
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<tr>
<td>(h)</td>
<td>Planck's constant</td>
<td>(\text{erg-sec})</td>
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<td>(H)</td>
<td>Spectral irradiance</td>
<td>(\text{watts/cm}^2)</td>
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<tr>
<td>(I)</td>
<td>Current</td>
<td>(\text{Amperes})</td>
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<tr>
<td>(k)</td>
<td>Boltzmann's constant</td>
<td>(\text{eV/°K})</td>
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<tr>
<td>(\lambda)</td>
<td>Sample length</td>
<td>(\text{cm})</td>
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<tr>
<td>(m_{h^*})</td>
<td>Effective hole mass (normalized)</td>
<td>---</td>
</tr>
<tr>
<td>(m_{e})</td>
<td>Effective electron mass (normalized)</td>
<td>---</td>
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<td>(N(E))</td>
<td>Density of trap states at energy (E)</td>
<td>(\text{cm}^{-3}\text{-eV}^{-1})</td>
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<td>(N_t)</td>
<td>Total density of traps</td>
<td>(\text{cm}^{-3})</td>
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<tr>
<td>(N_o,N(0))</td>
<td>Density of traps at (E) = 0</td>
<td>(\text{cm}^{-3}\text{-eV}^{-1})</td>
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<td>(n)</td>
<td>Total concentration of electrons in the conduction band</td>
<td>(\text{cm}^{-3})</td>
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<td>( n_i )</td>
<td>Intrinsic carrier concentration</td>
<td>cm(^{-3})</td>
</tr>
<tr>
<td>( n_0 )</td>
<td>Equilibrium electron concentration</td>
<td>cm(^{-3})</td>
</tr>
<tr>
<td>( \Delta n )</td>
<td>Excess electron concentration</td>
<td>cm(^{-3})</td>
</tr>
<tr>
<td>( n_t )</td>
<td>Total number of trapped electrons</td>
<td>cm(^{-3})</td>
</tr>
<tr>
<td>( n_{to} )</td>
<td>Equilibrium trapped electron concentration</td>
<td>cm(^{-3})</td>
</tr>
<tr>
<td>( \Delta n_t )</td>
<td>Excess trapped electron concentration</td>
<td>cm(^{-3})</td>
</tr>
<tr>
<td>( n_1 )</td>
<td>( N_c \exp \left[ \frac{(E_a - E_c)}{kT} \right] )</td>
<td>cm(^{-3})</td>
</tr>
<tr>
<td>( N_v )</td>
<td>Effective density of states at the valence band edge</td>
<td>cm(^{-3})</td>
</tr>
<tr>
<td>( N_c )</td>
<td>Effective density of states at the conduction band edge</td>
<td>cm(^{-3})</td>
</tr>
<tr>
<td>( N_A )</td>
<td>Acceptor impurity concentration</td>
<td>cm(^{-3})</td>
</tr>
<tr>
<td>( N_D )</td>
<td>Donor impurity concentration</td>
<td>cm(^{-3})</td>
</tr>
<tr>
<td>( p )</td>
<td>Total concentration of holes in the valence band</td>
<td>cm(^{-3})</td>
</tr>
<tr>
<td>( p_0 )</td>
<td>Equilibrium hole concentration</td>
<td>cm(^{-3})</td>
</tr>
<tr>
<td>( \Delta p )</td>
<td>Excess hole concentration</td>
<td>cm(^{-3})</td>
</tr>
<tr>
<td>( p_t )</td>
<td>Total number of trapped holes</td>
<td>cm(^{-3})</td>
</tr>
<tr>
<td>( p_{to} )</td>
<td>Equilibrium trapped hole concentration</td>
<td>cm(^{-3})</td>
</tr>
<tr>
<td>( \Delta p_t )</td>
<td>Excess trapped hole concentration</td>
<td>cm(^{-3})</td>
</tr>
<tr>
<td>( p_1 )</td>
<td>( N_v \exp \left[ \frac{(E_v - E_a)}{kT} \right] )</td>
<td>cm(^{-3})</td>
</tr>
<tr>
<td>( \Delta p_t (E) )</td>
<td>Trapped hole occupation probability</td>
<td>---</td>
</tr>
<tr>
<td>( \phi )</td>
<td>photon</td>
<td>---</td>
</tr>
<tr>
<td>( Q )</td>
<td>Total photon flux</td>
<td>ph/s-cm(^2)</td>
</tr>
<tr>
<td>( Q_B )</td>
<td>Background photon flux</td>
<td>ph/s-cm(^2)</td>
</tr>
<tr>
<td>( Q_s )</td>
<td>Signal photon flux</td>
<td>ph/s-cm(^2)</td>
</tr>
<tr>
<td>( r_s )</td>
<td>Sample resistance</td>
<td>ohms</td>
</tr>
<tr>
<td>( Q_{B_o} )</td>
<td>Room background photon/flux</td>
<td>ph/s-cm(^2)</td>
</tr>
<tr>
<td>SYMBOL</td>
<td>MEANING</td>
<td>UNITS</td>
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</tr>
<tr>
<td>$R_\lambda$</td>
<td>Responsivity at wavelength $\lambda$</td>
<td>V/watt</td>
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<tr>
<td>$R_{vt}$</td>
<td>Excitation rate of electrons from valence band to trap</td>
<td>$\text{cm}^{-3}\text{s}^{-1}$</td>
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<tr>
<td>$R_{ct}$</td>
<td>Excitation rate of electrons from conduction band to trap</td>
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<td>$R_{tc}$</td>
<td>Excitation rate of electrons from trap to conduction band</td>
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<td>$R_{tv}$</td>
<td>Excitation rate of electrons from trap to valence band</td>
<td>$\text{cm}^{-3}\text{s}^{-1}$</td>
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<tr>
<td>$r_v$</td>
<td>Hole capture probability per unit time</td>
<td>$\text{cm}^3\text{s}^{-1}$</td>
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<tr>
<td>$r_c$</td>
<td>Electron capture probability per unit time</td>
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<td>$\eta$</td>
<td>Effective quantum efficiency</td>
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<tr>
<td>$\tau$</td>
<td>Lifetime</td>
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<tr>
<td>$\tau_{\text{SR}}$</td>
<td>Shockley-Read lifetime</td>
<td>s</td>
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<tr>
<td>$\tau_{\text{inst}}$</td>
<td>Instantaneous lifetime</td>
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<tr>
<td>$\mu_h$</td>
<td>Hole mobility</td>
<td>$\text{cm}^2\text{V}^{-1}\text{s}^{-1}$</td>
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CHAPTER 1
INTRODUCTION

The Hg$_{1-x}$Cd$_{x}$Te ternary alloy system has been extensively studied as a variable gap infrared material. In particular, the bandgap of this alloy system depends on the mole fraction x of the CdTe component and can be continuously varied from 1.6 eV in the CdTe rich mixtures through zero to -0.3 eV in HgTe.

Fundamental to the photoconductive process in a semiconductor are the mechanisms by which optically generated hole-electron pairs may recombine. Little work, however, has been published concerning the recombination mechanisms in Hg$_{1-x}$Cd$_{x}$Te (Ref. 1.1).

The opportunity to study what were believed to be trapping effects in Hg$_{0.6}$Cd$_{0.4}$Te provided the motivation for this research.*

*Trapping has been observed in CdTe (Ref. 1.2).
Minority carrier trapping was the mechanism attributed to the low temperature behavior of $\text{Hg}_{0.6}\text{Cd}_{0.4}\text{Te}$. However, verification of this postulated mechanism was impeded by the absence of a substantial foundation of experimental information to which a trapping model could be compared.

Preliminary research, done in part by the author, indicated that at 80 °K the response time and the responsivity were reduced as the applied background illumination was increased. However the detailed nature of this dependence was not known. The importance of understanding this dependence arose from the variety of possible background conditions under which the detector might be called upon to operate. Furthermore, it was known that the responsivity and response time decreased markedly above a certain critical range of temperature. Again the detailed nature of this temperature dependence had not been determined. Both the temperature and the background effects, when characterized, would provide the basis for an understanding of the mechanism responsible for this behavior. The ultimate goal was to model the photoconductor properties of $\text{Hg}_{0.6}\text{Cd}_{0.4}\text{Te}$ under arbitrary conditions of background, temperature, and signal. This research is a step toward the attainment of that goal.
The more immediate objective was to gather enough experimental information so that a comparison with the theoretical trapping behavior would be possible.

Samples fabricated from n-type Hg$_{0.6}$Cd$_{0.4}$Te with a bandgap of about 0.4 eV were the subject of this study*. Although all of the many samples studied exhibited similar behavior, only a few representative samples underwent the extensive characterization to be reported.

The experiments were carried out over temperatures from 80 °K to 300 °K and background conditions from the 300 °K room background $Q_{B_0}$ to backgrounds two orders of magnitude higher. Backgrounds in excess of that quiescently supplied by the room environment (300 °K), were supplied by a GaAs infrared source emitting 0.9 μm radiation. Pulse, frequency response, and signal measurements constituted the major portion of these experiments.

After the experimental phase was completed, the results were compared to the case of minority carrier trapping of holes in n-type material. Fan's analysis of minority carrier trapping (Ref. 1.3) provided the basis for initial comparisons and the later development of the model. Fan considered the case of traps at a single level in the energy gap. Expressions were derived for the dependence of the responsivity on temperature and background illumination by applying his results to the

* In general the bandgap is a function of temperature in Hg$_{1-x}$Cd$_x$Te. However for this composition, the variation from $80K$ to $300 K$ is slight.
specific case of minority carrier trapping in n-type material. Upon comparison with experimental data, it was found that a single trapping level could not account for the observed behavior. However, the general features of minority carrier trapping were nevertheless apparent in Hg$_{0.6}$Cd$_{0.4}$Te.

R. Broudy realized that a continuum of traps in the energy gap would result in better agreement with experiment (Ref. 1.4). Indeed, his initial assumption of a uniform continuum of trapping sites extending from the valence band edge, showed promising correlation with experiment. It was then postulated that even better agreement with experiment would be obtained if the density of trapping states, instead of being uniform were to decrease with energy above the balance band. In particular, a density of trapping states having an exponential dependence of energy was proposed. The background and temperature dependence of the responsivity as predicted by the exponential model was found to provide excellent agreement with experiment.

Up until this point the approach had been mainly empirical. That is, given the experimental results, the density of states was then intuitively assumed. Then the results of this assumption were calculated and compared to experiment. For the case of the exponential model, the parameters were varied until the calculated result gave a close fit to the experimental data.
The desirability of being able to derive the density of trapping states directly from experimental measurements was recognized and a technique for accomplishing this was found. From basic theory an expression was derived which related the density of states directly to the responsivity data. A trial application of this method was carried out using the experimental data to which the empirical model was fit. The resulting density of states obtained by this new method was consistent with that derived empirically.

Because the empirical methods required involved computations and tedious parameter selection, the direct technique for determining the density of states is considered to be a step of considerable importance towards not only the characterization of trapping in \( \text{Hg}_{1-x}\text{Cd}_x\text{Te} \), but in other materials as well.
2.1 THE THEORY OF MINORITY CARRIER TRAPPING

Trapping is believed to occur when either carrier is temporarily imprisoned about an impurity or defect center and is thereby prevented from participating in the normal recombination or conduction processes. Enhanced photoconductivity and extended response times will be observed if the minority carriers are the trapped species. Although the minority carrier does not contribute significantly to the conduction process, its capture by a trap prevents the majority carrier from recombining until the trap releases its prisoner, at which time recombination may occur. However, the lifetime of the excited majority carrier can be considerably enhanced to an extent depending on the amount of time the minority carrier remains trapped.

"Trapping" and "traps" are to be distinguished from "Shockley-Read recombination" and "recombination centers". Both trapping and Shockley-Read recombination occur at localized sites which are capable of capturing and emitting carriers. Some confusion exists because these sites are referred to in general as traps. However, the term "recombination center" will specifically refer to those sites which provide a mechanism for the recombination of electrons and holes. The term "trap" will be reserved for those sites which communicate with only one band.
Minority carrier trapping has been reported in a wide variety of important semiconductors. The earliest accounts of minority carrier trapping dealt with silicon and germanium (Ref.'s 2.1, 2.2). Early indications of the existence of trapping centers resulted from drift velocity experiments (Ref. 2.3) in which a "straggling" of the minority carrier pulse was observed. The phenomenon was seen in silicon at room temperature and germanium at temperatures below 190 °K. Furthermore the straggling effect disappeared when strong illumination was applied to the sample. The straggling of the trailing portion of the pulse indicated that the minority carriers were suffering an additional time delay in their transit down the sample. This simple experiment, known commonly as the Haynes-Shockley Experiment, revealed the basic features of the trapping phenomenon: 1) the temporary removal of the minority carrier from the conduction process; 2) the effects of temperature and background illumination on the presence or absence of this phenomenon.

In 1953, soon after these effects were observed, H. Y. Fan published the now classic paper: "Effects of Traps on Carrier Injection in Semiconductors," (Ref. 2.4). The calculations relevant to his stated topic showed that "trapped minority carriers, by causing an increase in the majority carrier concentration give rise to increased photoconductivity which may be nonlinear with light intensity and have a very long time constant."*

*Quote taken from the abstract of Ref. 2.4.
The essential features of his analysis will be outlined here for the specific case of minority carrier trapping in n-type material. These results, although specific to the case of trapping at a single level, are readily extendable to more complex situations and indeed were basic to the development of the trapping model for Hg$_{1-x}$Cd$_x$Te.

Fan based has analysis on the theory proposed by Shockley and Read (Ref. 2.5) of electron-hole recombination at defect centers in the gap. The well known theory of Shockley and Read showed how recombination might be aided by defect or impurities centers in the crystal. Fan considered the special case whereby the sequential capture of the other carrier (which results in recombination) at such a center is inhibited.*

The basic model, which includes all manifestations of trap behavior in semiconductors, is illustrated in Figure 2.1. Electrons combine with and are excited from trap states with density $N_t$ located at an energy $E_a$ above the valence band. Excitation rates are proportional to the product of carrier density and available sites multiplied by rate constants. $R_{ct}$ and $R_{tv}$ are excitation rates (per unit volume) of electrons from trap to conduction band and from trap to valence band. $R_{ct}$ and $R_{vt}$ represent excitation rates per unit volume of electrons from conduction band and from valence band to the trap level. Excitation constants to conduction and valence

*The following description of Fan's model is taken from Ref. 2.6 with the kind permission of R. Broudy.
Conduction Band

Valence Band

\[ R_{tv} = r_v n_t p \]
\[ R_{vt} = r_v p_1 (N-n_t) \]
\[ p_1 = N_v e^{-E_a/kT} \]

\[ R = \frac{P}{\tau} \]
\[ R_{ct} = r_c n(N-n_t) \]
\[ R_{tc} = r_c n_1 n_t \]
\[ n_1 = N_c e^{-(E_a-E)/kT} \]

Figure 2.1 SEMICONDUCTOR WITH TRAPS AT ENERGY E_a
band are given by \( r_c \) and \( r_v \), respectively. \( G \) is the generation rate (per unit volume) of conduction band electrons and valence band holes, and \( \tau \) is the recombination time constant. The density of occupied (with electrons) traps is given by \( n_t \). The quantities \( p_1 \) and \( n_1 \) are essentially rate probabilities for excitation over energy barriers \( E_a \) and \( E_a - E_c \), where \( N_c \) and \( N_v \) are the densities of states in conduction and valence band, respectively. The net effect of illumination, as illustrated in Figure 2.2 is to generate excess carriers of three types. Since trapping lifetimes can be long, \( \Delta p_t \) can be much larger than \( \Delta p \). Since charge neutrality requires one electron for each trapped hole as well as for each free hole, large photoconductive gain enhancement can be obtained by trapping of holes.

In general, \( \tau \) depends on \( n \) and \( p \) in a rather complex but well known fashion. If recombination proceeds via recombination trap states, Shockley-Read statistics will apply.

For extrinsic semiconductors, such as n-type (Hg,Cd)Te at low temperatures, the electron concentration is changed very little with illumination, and therefore \( \tau \) takes the simple form of a constant which depends only on \( N_D \) and \( N_A \), the donor and acceptor concentrations.

The equations which determine the excitations of carriers referred to in Figure 2.1 are:

\[
\frac{dp}{dt} = G - R = G - \frac{p}{\tau} + \frac{dn_t}{dt} \quad (2-1)
\]

\[
\frac{dn_t}{dt} = R_{vt} - R_{tv} + R_{ct} - R_{tc} \quad (2-2)
\]
Three species develop with illumination

Excess Holes $\Delta p$
Excess Electrons $\Delta n$
Excess Trapped Holes $\Delta p_t$

Charge Conservation

$$\Delta n = \Delta p + \Delta p_t$$

Trap Photoconductive Gain

$$G_t = \frac{\Delta n}{\Delta p} = 1 + \frac{\Delta p_t}{\Delta p}$$

Figure 2.2 Excess Carriers in the Case of Minority Carrier Trapping in an n-type Semiconductor.
Now, let \( n = n + n_o \), and \( p = p + p_o \), where \( n_o \) and \( p_o \) are the electron and hole concentrations with no illumination present. Then for n-type extrinsic material at sufficiently low temperatures,

\[
\Delta n << n_o \text{ and } \Delta p >> p_o \tag{2-3}
\]

The rate equation for trapped holes with \( N_t \) trapping sites becomes:

\[
\frac{dn_t}{dt} = r_v \left\{ \left[ p_1 + \frac{r_c}{r_v} n_o \right] \left[ N_t - n_t \right] - \left[ \Delta p + \frac{r_c}{r_v} n_1 \right] n_t \right\} \tag{2-4}
\]

We now concentrate on hole traps which have transition probabilities to conduction band much smaller than those to valence bands, as postulated by Fan. Thus \( r_c/r_v << 1 \), and equation 2.4 becomes:

\[
- \frac{dp_t}{dt} = \frac{dn_t}{dt} = r_v \ p_1 \ (N-n_t) - r_v \ \Delta p \ n_t \tag{2-5}
\]

where \( p_t = N-n_t \) is the concentration of trapped holes.

The elimination of terms in \( r_c \) states simply that one considers traps which interact only with the valence band. Since there is no excitation to the conduction band, and since \( p_o << \Delta p \), the traps will be filled with electrons (empty of holes) in the absence of illumination. Therefore we can identify \( \Delta p_t \) with \( p_t \).
In the steady state, all time rates can be set to zero, and one obtains from equations 2.1 and 2.5:

$$\Delta p = G\tau = (\eta \tau / d) Q \quad (2-6)$$

$$\Delta p_t = \frac{N_t \Delta p}{p_l + \Delta p} \quad (2-7)$$

Equation 2.7 shows that for small excitation intensities (small Q gives small $\Delta p$ from 2.6) $\Delta p_t$ is proportional to $Q$. As $Q$ (and $\Delta p$) increases beyond $p_l$, the trapped holes saturate to the value $N_t$, and $\Delta p_t$ becomes independent of excitation. Using the expressions for $\Delta n$, $p_l$, and $\Delta p$, from Figure 2.1 and Figure 2.2 and equation 2.6, the excess electrons can be written as follows:

$$\Delta n = \Delta p + \Delta p_t = \frac{n \tau}{d} \left[ 1 + N_t \left( N_v \exp(-E_a / kT) + \eta \tau Q / d \right) \right]^{-1} \quad (2-8)$$

These results will be used in Chapter 5 when the experimental data is compared to this model.

2.2 SHOCKLEY-READ LIFETIME CALCULATIONS FOR Hg$_{0.6}$Cd$_{0.4}$Te

In this section a calculation of the temperature dependence of the Shockley-Read lifetime is described which is based on the approximate carrier concentrations, materials properties and bandgap corresponding to the Hg$_{0.6}$Cd$_{0.4}$Te samples studied during the course of this research. This calculation was done to: (1) confirm the fact that the observed behavior of increased response time at low temperatures could not be justified on the basis of variations in the Shockley-Read lifetime; (2) justify the assertion that the Shockley-Read lifetime for extrinsic Hg$_{0.6}$Cd$_{0.4}$Te is constant.
from 80 °K to 300 °K; (3) provide a background for future more detailed analyses of the Shockley-Read lifetime in Hg$_{0.6}$Cd$_{0.4}$Te.

The expression evaluated was derived by Shockley and Read (Ref. 2.5) for the case of low injection levels. It was also assumed that the concentration of recombination centers $N_t$ is less than any one of the quantities $n_o$, $p_o$, $n_1$, or $p_1$. These represent typical situations in (Hg,Cd)Te. With these assumptions the Shockley-Read lifetime is given by:

$$\tau_{SR} = \tau_{po} \frac{n_o + n_1}{n_o + p_o} + \tau_{no} \frac{p_o + p_1}{n_o + p_o} \quad (2-9)$$

where:

$$n_1 = N_c \exp \left[ \frac{(E_t - E_c)/kT}{} \right]$$

$$p_1 = N_v \exp \left[ \frac{(E_t - E_v)/kT}{} \right]$$

$E_t$ = energy of the recombination center

$p_o$ = equilibrium hole concentration

$n_o$ = equilibrium electron concentration

$N_v$ = effective density of states at the valence band edge

$N_c$ = effective density of states at the conduction band edge

$\tau_{no}$ = lifetime for electrons injected into highly p-type samples
\[ \tau_{po} = \text{lifetime for holes injected into highly n-type samples.} \]

For a compensated n-type material with donar concentration \( N_D \) and acceptor concentration \( N_A \) the following relationships are well known:

\[ p_o = -\frac{N_D - N_A}{2} + \frac{1}{2} \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + 4 n_i^2} \quad (2-10) \]
\[ n_o = \frac{N_D - N_A}{2} + \frac{1}{2} \sqrt{\left(\frac{N_D - N_A}{2}\right)^2 + 4 n_i^2} \quad (2-11) \]

The intrinsic carrier concentration \( n_i \) for Hg\(_{1-x}\)Cd\(_x\)Te is given by (Ref. 2.7):

\[ n_i = (8.445 - 2.2875 x + 0.00342T) \times 10^{14} E_g^{3/4} T^{3/2} \exp\left(-\frac{E_g}{2kT}\right) \quad (2-12) \]

Using these equations and the material parameters given below the temperature dependences of the terms of equation 2-9 were calculated and plotted in Figure 2.3 where the lifetimes \( \tau_{po} \) and \( \tau_{no} \) were set at unity.

**ASSUMED MATERIAL PARAMETERS**

\[ E_g \quad (\text{calculated from } x, \text{Ref. } 2.9) = 0.44 \text{ eV} \]
\[ g_x = 0.4 \]
\[ m_h^* = (\text{Ref. } 2.9) = 0.55 \]
\[ m_e^* = (\text{Ref. } 2.10, 0 \text{ °K}) = 0.03^* \]

* Although \( m_e^* \) exhibits variation with temperature, the exponential dependence of \( N_\text{e} \) will dominate, thus the 0 °K value was used for simplicity.
As can be seen in Figure 2.3, the temperature dependence of $\tau_{SR}$ would not explain the drastic increase in lifetime at temperatures below 300 °K as observed in Hg$_{0.6}$Cd$_{0.4}$Te. The validity of the assumption of a constant $\tau_{SR}$ from 80 °K to 300 °K will depend on the relative value of $\tau_{po}$ to $\tau_{no}$, i.e. the assumption would be valid for $\tau_{po} \gg \tau_{no}$. Since $\tau_{no}$ was not known, the assumption of a constant $\tau_{SR}$ was used however with the knowledge that it could be otherwise. Future research could determine the answers to these details, but for the moment $\tau_{SR}$ is assumed constant.
Figure 2.3  CALCULATED TEMPERATURE DEPENDENCE OF THE TERMS FROM THE SHOCKLEY-READ LIFETIME EXPRESSION (REF. 2.5) FOR Hg-0.55 Cd-0.45 Te. ASSUMES $m^*_{e} = 0.55$ (REF. 2.9) AND $m^*_{h}=0.63$ ($0$ °K VALUE, REF. 2.10). NEGLCTS THE TEMPERATURE DEPENDENCE OF $m^*$. USES SCHMIT'S (REF. 2.7) EXPRESSION FOR $n_1$ FOR Hg$_{1-x}$ Cd$_x$ Te. ASSUMES $N_0-N_A = 2 \times 10^{14}$ cm$^{-3}$. 
3.1 THE Hg$_{0.6}$Cd$_{0.4}$Te SAMPLES

The experiments were performed on Hg$_{0.6}$Te$_{0.4}$Te photocductive samples fabricated from n-type material. Although various measurements were made on many such samples, detailed variable background experiments over the 80 °K to 300 °K temperature range were done on only three samples due to the tedious and lengthy nature of the variable condition measurements.

Indium contacts were used to delineate the active area and provide ohmic contact to the sample.

The concentrations of donor and acceptor impurities were determined by extrapolation between the known values at various positions along the length of the crystal from which the sample was fabricated. This was justified on the basis of the linear gradient in $x$ observed over this region of the crystal. The original determination of the donor and acceptor concentrations were done by W. Scott (Ref. 3.3).
3.2 EXPERIMENTAL APPARATUS

3.2.1 Statement of the Experimental Requirements

In order to carry out the research plan it was necessary to obtain the laboratory hardware to satisfy the requirements of the various experiments planned.

There were four major tasks. The first task was to obtain a photon source which could provide a wide range of background intensities. In addition a photon source was needed which could be modulated in the pulse or sinusoidal mode. The modulation bandwidth requirement was from dc to at least 100 kHz. The second task was to provide a means of accurately measuring the absolute signal and background irradiance levels. The third task entailed the design of a variable temperature dewar to house the detectors and provide a variable and measurable temperature environment ranging from 80°K to 300°K. The fourth task was the design of the electronic measurement support system.

3.2.2 The Photon Source

Solid state gallium arsenide infrared emitters were chosen to provide the required background and signal conditions. These emitters, also called LEDs (for light emitting diode) have the advantage that they can be modulated electronically from dc to frequencies exceeding 1 MHz. The LEDs emit radiation at 0.9 micron and have output ratings in excess of one milliwatt. Two such LEDs were placed in close proximity: one served as the background source; the other
provided the signal. The LEDs were mounted on a copper heat sink inside an aluminum box. The assembly was then mounted on an x-y-z micrometer platform such that the LEDs emitted in the vertical direction in order to interface easily with the downlooking dewar. The LED assembly is shown in Fig. 3.2. (The LEDs were purchased from Monsanto).

3.2.3 Irradiance Level Determination

When a forward bias is applied to the LEDs, they emit 0.9 micron radiation approximately proportional to the forward current. In order to measure and calibrate the output irradiance of the LED, I designed a simple photometer circuit which employed the SGD-100A calibrated silicon photodiode made by EG&G. The circuit shown in Fig. 3.3 is a transimpedance operational amplifier configuration which has an output voltage equal to the product of the gain (the feedback resistance) and the input current from the silicon detector. The bandwidth of the photometer was from dc to 3 dB down at 100 kHz. The absolute sensitivity of the silicon photodiode at 0.9 micron was 0.0226 a-cm²-Watt⁻¹. The relationship between the sensitivity, the irradiance and the photocurrent is given by Eq. 3.1.

$$H = rac{I}{S}$$  \hspace{1cm} (3-1)

Here \(H\) is the irradiance in Watts-cm⁻², \(I\) is the photocurrent in amperes, and \(S\) is the absolute sensitivity in the units given above. It was more convenient to work in the units of photon flux \(Q\) rather than the power irradiance. The simple relationship between these quantities is given by Eq. 3.2.
Figure 3.2 THE LED ASSEMBLY
SGD-100A
Photodiode
GR = Guard Ring
A = Active Area

$V_{in} = -15 \text{ V}$

$V_{out} = \frac{R_f}{R_1} I_{in}$

$C_1 = 1 \text{ pf}$
$C_f = 5 \text{ pf}$
$R_1 = 100 \text{ k}\Omega$
$R_2 = 1 \text{ k}\Omega$
$R_3 = 50 \text{ } \Omega$
$R_f = 100 \text{ k}\Omega$

Figure 3.3 PHOTOMETER CIRCUIT
where: \( \lambda \) is the wavelength  
\( h \) is Planck's constant  
\( c \) is the speed of light

Using these relationships the formula relating the photon flux of the detector to the output voltage \( V \) of the photometer is given by Eq. 3.3a where

\[
Q = \left( \frac{\lambda}{hc} \right) \times \Delta V 
\]

\[
Q = 2.0 \times 10^{15} \times \Delta V \text{ (volts)}
\]

\( R_f \) is the amplifier feedback resistance. For the 0.9 micron radiation of the LEDs and a feedback resistance of 100 k ohms, the calibration factor for the photometer was \( 2.0 \times 10^{15} \) photons-cm\(^{-2}\)-s\(^{-1}\) per volt (Eq. 3.3b). (Note: With the offset control, the offset voltage of the photometer, due to the dark current of the detector, was made negligible).

The calibration of the silicon detector is traceable to the National Bureau of Standards and was done in conformance with mil-C-45662A. Reference to the military specification did not produce an answer as to the accuracy of the calibration. However, a comparison of this photodiode with two others purchased over a year later revealed agreement of close to 5 percent between detectors. The linearity of the response of the silicon photodiode, as quoted by the manufacturer, was to within 5% over seven decades of incident power. This was quite sufficient for the measurements.
The greatest source of light measurement error resulted from measurement errors of the LED to sample distance because of the operating range of only several cm for most experiments. Once standard fixed distances were established, reproducibility of results was generally to within 10%. Thus the light measurements for any given experiment exhibited a good relative accuracy with all absolute errors reduced to a common factor. Because the experiments were concerned with relative changes, errors in the absolute accuracy of the measurements were not critical.

A photograph of the photometer is shown in Fig. 3.4. The photometer was one of the most important instruments composing the experimental setup.

In additional to the measurement of the background radiation from the LED, it was necessary to calculate the radiation due to 300°K background of the laboratory environment to which the sample was always subjected. This is a standard calculation which depends on the cutoff wavelength and the field of view of the sample in addition to the temperature of the surroundings. The background radiation, often referred to as "room background", was calculated for each experiment and added to the background supplied by the LED.

3.2.4 The Variable Temperature Dewar

In order to achieve temperatures ranging from 80°K to 300°K, a variable temperature dewar was designed with the helpful assistance of H. Halpert and B. Musicant. This entailed the design of a cold tip to interface with a dewar purchased
Figure 3.4  THE PHOTOMETER
from Janis Research Company (Model RD). The design goal was to maintain a temperature difference between the cold tip and the reservoir of 125°K with 20 watts of electrical power. Using liquid nitrogen as a coolant, the boiling point of which is 77°K, it would then be possible to get up to 200°K. Above 200°K it was my intention to use a dry ice and methanol mixture to go from 200°K to 300°K.

The cold tip design relied upon providing a thermal path of predetermined thermal conductance from the reservoir to the cold tip platform upon which the samples were to be mounted. The thermal path was provided by three copper legs, the area and length of which were calculated on the basis of the design goal and the thermal conductivity of copper. Two button heaters were mounted underneath the cold tip platform to provide Joule heating. For additional mechanical support, three stainless steel legs were used. Since stainless steel is much less heat conductive than copper, their contribution to the thermal conductance was a negligible 3%. A photograph of the cold tip is shown in Fig. 3.5.

Two thermistors were mounted on the cold tip platform to sense the temperature of the platform. Each thermistor underwent a four-point temperature calibration. This calibration resulted in a table of resistance versus temperature from 77°K to 273°K for each thermistor in increments of 1°K up to 250°K and 5°K up to 273°K. The
Figure 3.5 THE VARIABLE TEMPERATURE DEWAR COLD TIP. THE SAMPLES ARE MOUNTED IN THE CENTER OF THE COPPER PLATFORM (TOP). THE TWO SMALL COPPER CUBES HOUSE THE THERMISTORS.
four-point calibration technique was known to be good to within a few degrees over the temperature range. Indeed, the two thermistors never disagreed by more than 2°K.

The variable temperature met the design goal and the temperature range desired was easily obtained. The temperature curves for the liquid nitrogen and dry ice coolants are shown in Figs. 3.6 and 3.7. The liquid nitrogen boil off time was 45 minutes at a cold tip temperature of 210°K. The temperature stabilization time was about 15 minutes between temperatures with the initial cool down time being almost an hour.

3.2.5 The Electronic Instrumentation

3.2.5a The Preamplifier

A standard low noise preamplifier was used for all sample measurements. Before using this amplifier, the gain versus the source resistance and the frequency response had to be determined. The dependence of the gain on the source resistance $R_s$ is given below.

$$G = 2.6 \times 10^{13} \frac{4300}{R_s + 4300}$$  \hspace{1cm} (3.4)
Figure 3.6 VARIABLE TEMPERATURE DEWAR (VTD-1) TEMPERATURE VS POWER INTO HEATERS (LN₂ COOLANT).
Figure 3.7 VARIABLE TEMPERATURE DEWAR (VTD-1) TEMPERATURE VS POWER INTO HEATER. DRY ICE AND METHANOL USED AS THE COOLANT
3.2.5b LED Modulation and Biasing Control Circuitry

Ideally the output power of an LED is a linear function of the forward bias current. Therefore linear modulation is best achieved by current source driving of the LED. Since the "on" resistance of the LED is a fraction of an ohm, the current source requirement is easily met by a function generator, a 50 ohm series resistor and a dc bias. As long as modulation about the bias point is small, the harmonic distortion was negligible. For larger signals, the heating of the junction results in a nonlinear output. For my purposes, a small signal modulation was desirable so this never presented a problem. Of course pulse modulation was also no problem due to the fast response of the LEDs and the on-off nature of the modulation.

Light emitting diode biasing currents of up to one ampere were required to provide the desired background range at a workable distance. In order to conveniently provide a calibratable and accurate current supply, I designed the transistor circuit shown in Fig. 3.8. The switch selected one of two current ranges: 1) 10 mA to 100 mA 2) 100 mA to 1 A. The ten-turn pot provided continuous current control over these two ranges. Calibration was achieved by measuring the voltage drop across the 2.5 ohm resistor in series with the LED. If desired, a modulation signal could be applied to the input of the first stage transistor because the current source requirement for linearity was met by the high impedance drive network of the second stage. The response of this circuit was flat from less than 1 Hz,
Figure 3.8 LED BIAS AND MODULATION CIRCUIT. $R_1$ IS THE FINE CURRENT CONTROL. SW-1 IS THE HIGH AND LOW CURRENT SELECTOR.
however, above 100 kHz the performance was hampered by the stray inductances in the circuit.

As a dc bias supply the circuit had the following advantages: 1) Fine current control was possible because the low current first stage permitted the use of a precision 10-turn pot; 2) The large currents were limited to the second stage; and 3) As opposed to a divider design, this current used only as much as necessary.

3.2.5c The Experimental Test Station

A complete experimental test station was designed to provide a housing for the LED - detector assembly and the supporting electronic equipment. The design was approved by HRC and the equipment was purchased with capital funding. I would like to acknowledge F. McCanless and N. Aldrich for their helpful suggestions during the design and construction phases of this effort. The completed test station is shown in Figure 3.9.

3.3 EXPERIMENTAL SETUP AND PROCEDURES

3.3.1 Pulse Response Measurements

The experimental configuration used for pulse response measurements is depicted in Figure 3.10. The procedure entailed the application of an electrical pulse train to the LED from the function generator as shown. The rise
Figure 3.9  THE EXPERIMENTAL TEST STATION. LEFT (FROM TOP TO BOTTOM): PULSE GENERATOR, FUNCTION GENERATOR, OSCILLOSCOPE AND CAMERA, AND X-Y PLOTTER. RIGHT (FROM TOP TO BOTTOM): VARIABLE TEMPERATURE DEWAR; PHOTOMETER, LED ASSEMBLY, CONTROL PANEL, AND WAVE ANALYZER.
Figure 3.10 (Hg,Cd)Te PULSE RESPONSE MEASUREMENT
and fall times of the resulting optical pulse were less than 1 \( \mu \text{s} \) and much less than the response times of the samples studied. The rise and fall times of the optical pulse were measured with a very high speed silicon detector.

The pulse photon flux level was measured with the photometer at a known distance from the LED. The output voltage pulse height of the photometer, measured by the oscilloscope, was then used, via Eq. 3.3b, to determine the optical signal flux.

After calibration of the pulse, the Hg\(1-x\)Cd\(x\)Te sample was placed at the same distance (to within \( \pm 0.05 \) inch) from the LED and adjusted laterally for peak response. The output of the detector preamp was applied to the oscilloscope. The pulse duration was then adjusted to allow the sample to reach its steady state response amplitude. The excitation and relaxation characteristics of the rise and decay of the sample were displayed on the scope and photographed. The delayed sweep feature and the 150 MHz bandwidth of the oscilloscope were adequate for detailed time domain measurements. For pulse waveforms obscured by random noise, the PAR Boxcar Integrator was found to be quite useful. (See Ref. 3.2 for a description of boxcar integrator technique of extracting repetitive pulse signals from noise.)
3.3.2 Responsivity Measurements

The experimental configuration used for is shown in Figure 3.11. Signal and background levels were set using the photometer as described in the previous section. The figure illustrates that the wave analyzer served both as the modulator and the signal receiver. The modulating signal from the BFO was applied to the LED driver which in turn modulated the output of the LED. The sample sensed the signal which was then amplified and sent to the wave analyzer which measured the signal output. The signal was either measured on the rms voltmeter in the wave analyzer or was plotted as function of frequency on an x-y plotter.

3.3.3 The Measurement of \( \Delta n \)

When illuminated, the resistance of the sample changes due to an increase in the excess carrier concentration. For theoretical purposes it is necessary to know how \( \Delta n \), the excess majority carrier concentration, varies as a function of some experiment condition. It will be shown that the signal voltage is directly proportional to \( \Delta n \) provided \( \Delta n \) is small compared to the equilibrium concentration \( n_0 \).

Consider the photoconductor to be in series with a current source supplying a constant current \( I \). Assume an amplifier monitors the voltage that appears across the sample and, of course, amplifies the signal by some known gain factor. (For the rest of the discussion we will forget the amplifier because it was introduced only for the purpose of illustrating how the signal voltage is obtained experimentally).
Figure 3.11  RESPONSIVITY MEASUREMENT
The quantity of interest is the signal voltage that develops across the sample due to some change $\Delta n$ that occurs in the carrier concentration. The material is assumed n-type with $\Delta n \ll n_0$. The conductivity of the sample is given by:

$$\sigma = e ((n_0 + \Delta n) \mu_e + (p_0 + \Delta p) \mu_h)$$  \hspace{1cm} (3-5)

where $\mu_e$ and $\mu_h$ are the electron and hole mobilities. In the case of (Hg,Cd)Te, $\mu_e \gg \mu_h$. Thus $\sigma$ becomes:

$$\sigma = e \mu_e (n_0 + \Delta n)$$  \hspace{1cm} (3-6)

the equilibrium conductivity $\sigma_o$ is:

$$\sigma_o = e \mu_e n_0$$  \hspace{1cm} (3-7)

If the sample is of length $l$, width $w$, and thickness $d$, then the resistance $r_S$ is given by:

$$r_S = \frac{l}{w d \sigma_o}$$  \hspace{1cm} (3-8)

the voltage across the detector with illumination is therefore:

$$V = \frac{I l}{e \mu_e (n_0 + \Delta n)}$$  \hspace{1cm} (3-9)

Since $\Delta n \ll n_0$, we obtain the approximation:

$$V \approx \frac{I l}{e \mu_e n_0} \left[1 - \frac{\Delta n}{n_0}\right]$$  \hspace{1cm} (3-10)
Thus:

\[
V_{\text{sig}} = \frac{I \ell \Delta n}{e \mu_e n_0^2}
\]  \hspace{1cm} (3-11)

This proves the linear relationship between \( V_{\text{sig}} \) and \( \Delta n \). For the experimental situations with which this research deals, the condition of low level injection will always be satisfied.

Quite often Equation 3-11 is expressed in a more useful form. If \( E \) is the applied electric field given by:

\[
E = \frac{I r_s}{\ell}
\]  \hspace{1cm} (3-12)

Then expressing Equation 3-11 in terms of \( E \):

\[
V_{\text{sig}} = E \ell \frac{\Delta n}{n_0}
\]  \hspace{1cm} (3-13)
CHAPTER 4
EXPERIMENTAL RESULTS

4.1 PULSE RESPONSE EXPERIMENTS

4.1.1 Large Signal Pulse Decay Measurement at 80 °K

At low temperatures asymmetrical rise and decay pulse response characteristics were observed in Hg$_{0.6}$Cd$_{0.4}$Te photoconductive. The decay was marked by an initially rapid fall which then gradually became relatively extended, requiring a substantial period of time before achieving the steady state condition. These features can be observed in Figure 4.1 which exhibits the pulse response of sample 3-2* at 80 °K for an input illumination (1.9 x $10^{15}$ ph/s-cm$^2$) much greater than the background.

On the other hand, at 300 °K the pulse response was symmetrical and much more rapid. In the low temperature case it was impossible to define a single response time which is the general case for a nonlinear recombination process. However, it is possible to define an instantaneous lifetime $\tau_{\text{inst}}$ (Ref. 4.1):

$$\tau_{\text{inst}} = -\frac{\Delta n}{d\Delta n/dt}$$

(4.1)

Since $V_{\text{sig}}$ is directly proportional to $\Delta n$, experimentally $\tau_{\text{inst}}$ is determined by Equation 4-2.

$$\tau_{\text{inst}} = -\frac{\Delta V_{\text{sig}}}{d\Delta V_{\text{sig}}/dt}$$

(4.2)

*Abbreviation for K13-18B-3-2
Figure 4.1  THE LARGE SIGNAL PULSE RESPONSE OF SAMPLE 3-2 AT 80 °K. THE ASYMMETRICAL NATURE OF THE RISE AND DECAY PORTIONS IS APPARENT
By following the procedure outlined in Section 3.3.1, an experiment was carried out which looked at the detailed features of the decay shown in Figure 4.1. In Figure 4.2 the normalized decay curves are plotted on a linear scale. In Figure 4.3 the decay during the first 28 μs is plotted on a semilog scale. The slope of the curve, when plotted in this way, reflects the value of the instantaneous lifetime at a particular time \( t \) via Equation 4.3 (derived from Equation 4.2).

\[
\frac{1}{\tau_{\text{inst}}} = -\frac{d}{dt} \ln \Delta V_{\text{sig}} \quad (4.3)
\]

The continuous variation of the slope as a function of time is indicative of a nonlinear recombination process. (For linear recombination \( \tau_{\text{inst}} \) is a constant independent of time.) In Figure 4.4 the decay during the first 300 μs is plotted on a semilog scale. In the range of time from 200 μs to 300 μs, the slope seems to be approaching a constant value giving a time constant of 350 μs. However, even at 300 μs the decay is still over 10% of its final steady state value. Accurate determination of the behavior of the decay after 300 μs became prohibitively difficult. Reference again to Figure 4.1 indicates that it took about 2 ms to reach to 0% value!

The instantaneous lifetime as a function of time was calculated from 0.4 μs to 300 μs and plotted in Figure 4.5. At 0.4 μs, \( \tau_{\text{inst}} \) is approximately 12 μs, then gradually enters a region of more rapid variation, ultimately reaching a value of 350 μs at \( t = 300 \mu s \). The dependence strongly suggests asymptotic limits of approximately 10 μs and 500 μs for \( \tau_{\text{inst}} \).
Figure 4.2 THE DECAY RELAXATION CURVES FOR SAMPLE K13-18B-3-2 AT 83 °K. SINCE $V_{\text{sig}}$ IS PROPORTIONAL TO $\Delta n$, THESE CURVES REPRESENT THE RELAXATION OF THE NON EQUILIBRIUM DENSITY OF CARRIERS UPON REMOVAL OF THE ILLUMINATION.
Figure 4.3 FIRST 28 μsec OF THE PULSE DECAY OF SAMPLE K13-18B-3-2. THE CONTINUOUS VARIATION OF THE SLOPE IS INDICATIVE OF A NON-LINEAR RECOMBINATION PROCESS (J. Beck, Jan. 22, 1972).

\( Q_s = 1.9 \times 10^{15} \text{ photons-sec}^{-1}\text{-cm}^2 \)

\( Q_B (300 \, ^\circ\text{K}, 120 \, ^\circ\text{FOV} \)

\( V_{bias} = 0.2 \text{ volts} \)

\( T = 83 \, ^\circ\text{K} \)
Sample: K13-18B-3-2

Pulse Decay Behavior Experiment

Conditions:

\[ T = 83 \, ^\circ\text{K} = (300 \, ^\circ\text{K}, 180 \, ^\circ\text{FOV}) \]
\[ Q_B = \text{Room temperature background} \]
\[ \Delta Q_s = 1.9 \times 10^{15} \, \text{ph-s}^{-1}\text{-cm}^{-2} \]
\[ E = 20 \, \text{V/cm} \]

\[ \tau = 350 \, \mu\text{s} \]

J. Beck (Jan. 1972)

Figure 4.4 THE DECAY RELAXATION CURVE FOR SAMPLE K13-18B-3-2. THE INSTANTANEOUS TIME CONSTANT IS SHOWN TO BE APPROACHING A LIMIT OF APPROXIMATELY 350 \( \mu\text{s} \). (see Figures 4.2 and 4.3 for further characterization of this decay behavior).
Sample: K13-18B-3-2

$\Delta Q_s = 1.9 \times 10^{15} \text{ ph-sec}^{-1} \text{ cm}^{-2}$

$Q_B =$ Room temperature background

$E = 20 \text{ V/cm}$

Temperature = $83 \degree \text{K}$

Figure 4.5 THE TIME VARIATION OF THE INSTANTANEOUS LIFETIME CALCULATED FROM THE PULSE DECAY OF SAMPLE K13-18B-3-2 (J. Beck, Jan. 1972)
The decay was next plotted on log-log paper to determine if the recombination process was quadratic in which case the plot would appear linear with a slope of -1. This was not the case. Indeed, for quadratic recombination Ryvkin (Ref. 4.2) shows that $\tau_{\text{inst}}$ would exhibit a linear dependence on time which also was not observed.

In conclusion, this experiment characterized the low temperature relaxation of excess carriers in a particular, yet typical, Hg$_{0.6}$Cd$_{0.4}$Te sample at low temperatures. It proved that the recombination mechanism was nonlinear and that it was not quadratic. The decay characteristics revealed an initially rapid fall followed by an increasingly slow decay which extended over a relatively long period of time before reaching equilibrium.

4.1.2 Pulse Response Measurement at 300 °K

Sample 3-2 was brought up to room temperature and the pulse response was again measured. This time noise obscured the pulse waveform necessitating the use of the boxcar integrator. At room temperature the rise and fall times were equal indicating linear recombination. By measuring the 90% to 10% fall time, the time constant was found to be about 2.7 μs.

The pulse waveform as obtained by the boxcar integrator is shown in Figure 4.6.

4.1.3 An Experiment to Determine The Relationship Between the Steady State Value of $\Delta n$ Versus the Input Illumination Intensity at 80 °K

It was desirable to investigate the relationship between the steady state change in the excess carrier concentration $\Delta n$ and
Figure 4.6 PULSE RESPONSE OF SAMPLE 3-2 AT 300 °K
the illumination $Q$. This was done indirectly by applying optical pulses over a range of values and measuring the steady state value of $\Delta V_{\text{sig}}$, the zero to peak change in the signal voltage. Again the linear relationship between $\Delta n$ and $\Delta V_{\text{sig}}$ (justified in Section 3.3.3) was assumed.

The experiment was performed on sample 3-2 at a temperature of 80 °K. The range of signal flux $\Delta Q_s$ was from $5 \times 10^{12}$ to $1.9 \times 10^{15}$ ph/s-cm$^2$. The results were graphically displayed (Figure 4.7) by plotting $\Delta V_{\text{sig}}$ versus $\Delta Q_s$, where $\Delta Q_s$ is the photon flux applied in addition to the background $Q_B$ of $2 \times 10^{13}$ ph/s-cm$^2$. The graph indicates increasingly nonlinear behavior with increasing $\Delta Q_s$. In Figure 4.8 $\Delta V_{\text{sig}}$ is plotted versus $\log (1 + \Delta Q_s/Q_B)$. This resulted in a nearly straight line dependence which has the theoretical implications discussed in Section 5.2.3.

4.2 The Dependence of the Frequency Response on the Background Photon Flux at 80 °K

The purpose of this experiment was to determine the effects (at 80 °K) of background photon flux on the frequency response for small signal sinusoidal modulation. From this information the functional dependence of the low frequency responsivity on background was found. In addition the response time was found which corresponded to the frequency at which the signal was 3 dB down from its low frequency plateau. The procedure entailed the application of a small sinusoidal signal from an LED. (By small, it is meant that the signal was a factor of

*An independent measurement of the change in resistance of sample 3-2 over this range of $Q$ showed a change in resistance of less than 2%. Thus validating the linear relationship between $\Delta n$ and $V_{\text{sig}}$. 61
Figure 4.7 THE STEADY-STATE PULSE RESPONSE VOLTAGE AMPLITUDE VERSUS THE
MAGNITUDE OF THE INPUT LIGHT PULSE FLUX.

Data of J. Beck (Jan. 1972)

K13-18B-3-2

T = 83°K

E = 20 V/cm

Q_B(300°K, 180° FOV)
Figure 4.8 EXPERIMENTAL PLOT OF $\Delta V_{\text{sig}}$ (STEADY-STATE) VERSUS LOG $\left(1 + \frac{Q_{s}}{Q_{B}}\right)$

THE UNIFORM CONTINUUM MODEL PREDICTS A STRAIGHT LINE DEPENDENCE WHICH IS BORN OUT BY THIS EXPERIMENT.
ten less than the lowest background value. Another LED was accurately calibrated to provide a range of background levels. (see Section 3.3.2 for details as to the procedure.) By varying the signal frequency but maintaining a fixed amplitude, the frequency response was obtained for a fixed background condition. The background was then changed and the experiment was repeated.

The "room background" was added to the background supplied by the LED to give the total background illumination. The experiment generated the set of frequency response curves shown in Figure 4.9 for sample 3-7.* Several features of frequency response were revealed. At room background the frequency rolloff was more gradual and distinctly different from the single time constant behavior. In particular, the frequency response rolled off very slowly, taking two decades of frequency before entering the 6 dB per octave region. At higher backgrounds the frequency response approached a single pole behavior. At the highest background the frequency response was single pole to within experimental accuracy. Attempts to justify the lower background behavior by the claim that the small signal really wasn't so small proved invalid because the observed behavior was duplicated for signals a factor of 100 less than room background.

*Abbreviation for K13-20B-3-7
Figure 4.9 EFFECT OF BACKGROUND ON THE FREQUENCY RESPONSE
As in the pulse response experiments at 80 °K, a unique time constant was impossible to define from the frequency response data (except at high backgrounds). However, a general extension of the frequency rolloff into higher frequencies with increased background was quite apparent. To obtain a more quantitative idea of this behavior, a response time was calculated which corresponded to the frequency at which the response was 3 dB down from the plateau value. It was found that this time constant exhibited a nearly $1/Q_B$ dependence (Figure 4.10). The functional dependence of the low frequency responsivity on background was also determined from this data at 50 Hz (the upper plot in Figure 4.11). In another experiment this dependence was measured at 1000 Hz (the lower plot in Figure 4.11). Since both frequencies were on or near the low frequency plateau, the similar inverse background dependence shown in Figure 4.11 is not surprising. The departure of the lowest background point from the straight lines is thought to be due to an error in the determination of the room background photon flux. At higher backgrounds the contribution of the room background becomes insignificant.

In conclusion this experiment proved that the "response time" and the low frequency responsivity depend inversely on the background photon flux at 80 °K. This dependence is close to, but not quite $Q_B^{-1}$.*

*A more accurate measurement of the dependence of the responsivity on the background will be presented in Section 4.3.
Figure 4.10 RESPONSE TIME VERSUS BACKGROUND PHOTON FLUX

K13-20B-3 #7
I_{Bias} = .1 mA
T = 77 °K
K13-20B-3 #7

$I_{Bias} = 0.1 \text{ mA}$

$T = 77^\circ \text{K}$

Total Background Photon Flux (Relative Units)

$V_{Sig}$ (Volts, Relative Units)

Figure 4.11  SIGNAL VOLTAGE VERSUS $Q_B$ FOR A SMALL SIGNAL
At high frequencies the background dependence becomes less strong. The merging of the rolloff portions at high frequencies indicates the preservation of an effective gain-bandwidth product and a definite relationship between an average photoconductive lifetime and the photoconductive gain.

4.3 THE DEPENDENCE OF THE SMALL SIGNAL, LOW FREQUENCY RESPONSIVITY ON TEMPERATURE AND BACKGROUND AT CONSTANT ELECTRIC FIELD

The purpose of this experiment was to measure the small signal, low frequency responsivity as a function of background and temperature. This experiment was the most important of all the experiments performed because it characterized an important parameter in great detail over the entire range of temperature and background conditions investigated. The small signal responsivity in the low frequency limit turned out to be readily calculable from the theoretical models which were later developed. Therefore this experiment provided the basic criterion against which all theoretical models were compared.

The responsivity is defined as the ratio of the rms signal voltage vs the rms incident signal power on the sample $HA_S$ where $H$ is the rms signal irradiance (Watts/cm$^2$) and $A_S$ is the area of the sample (cm$^2$). Thus the responsivity $R$ is defined in units of volts/watt.

$$R = \frac{V_S}{HA_S}$$ (4.4)
The well known expression for the photoconductive responsivity in the small signal limit is given by Equation 4.5.*

\[ R_\lambda = \frac{\lambda}{hc} \eta e r_s G \]  

(4.5)

where

- \( r_s \) = sample resistance
- \( \eta \) = the quantum efficiency
- \( G \) = the photoconductive gain

Before proceeding, it was necessary to determine carefully the controls needed to insure a valid experimental approach. In particular it was desirable from a theoretical standpoint to determine only the temperature dependence of the photoconductive gain. However the responsivity \( R_\lambda \) as shown in equation 4.5 depends on the gain \( G \), the resistance of the sample \( r_s \), the wavelength \( \lambda \) and the quantum efficiency \( \eta \).

Experimentally \( \lambda \) was fixed and \( \eta \) was assumed to be a constant. As \( r_s \) in n-type Hg_{0.6}Cd_{0.4}Te was known to increase with temperature due to a reduction in the electron mobility (Ref. 4.3), it was desirable to eliminate the effects of \( r_s \) on the responsivity. A simple analysis revealed that the maintenance of a constant electric field across this device at all temperatures would alleviate this factor. Thus conclusion was contingent on

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*The derivation of this expression relies upon the calculation of \( V_{sig} \) carried out in Section 3.3.3.
the condition that the photoconductive material remained extrinsic over the temperature range. It was found that the mobility, which effects $G$ and $r_S$, cancels out. At the same time the extrinsic condition fixes the equilibrium carrier concentration $n_o$ which also determines $r_S$. Since the samples remained extrinsic over the temperature range, the experiments were carried out under a constant field and therefore reflected only the temperature dependence of $G$. *

The analysis is summarized in the equations below. The assumption that $n_o >> p_o$ is used. It can be seen that $\mu_e$ cancels out.

$$r_S = \frac{\ell}{\text{ewd} \ n_o \mu_e}$$  \hspace{1cm} (4-6)

$$G = \frac{E \mu_e \tau}{\ell}$$  \hspace{1cm} (4-7)

where:

$\ell$ = sample length

$w$ = sample width

$d$ = sample thickness

$E$ = electric field

$\tau$ = response time

$n_o = N_D - N_A$ (extrinsic case)

thus:

$$R_\lambda = \frac{\lambda \eta}{hc} \frac{E \tau}{\text{wd} (N_D - N_A)}$$  \hspace{1cm} (4-8)

*Under the assumption of a constant $\eta$. 

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The temperature range investigated was from 83 °K to 295 °K, while the background was varied. The background radiation was supplied by an LED emitting at 0.9 micron. In addition, a constant background \(Q_{\text{Bo}}\) resulted from a 120 degree FOV and a 300 °K background. This "room background" value was computed on the basis of the energy gap of the samples. A small sinusoidal signal modulated at 1000 Hz was provided by the same LED. The rms signal flux was measured at each calibrated background level. The signal was always a factor of more than 10 below the background. The modulation frequency of 1000 Hz was on or very near the frequency response plateau and thus the results reflect the low frequency case.

The resistance of the detectors was measured at each temperature in order that the gain of the preamp \(G(r_s)\) could be calculated. The rms signal voltage was measured at each data point and the responsivity was calculated by Equation 4-9.

\[
R_\lambda = \frac{V_{\text{sig (rms)}}}{G(r_s)} \frac{\lambda}{Q_s (\text{rms}) A_s \text{hc}}
\]

(4-9)

where Equation 4-9 is obtained from Equation 4-4 by the substitution of \(V_{\text{sig}}/G(r_s)\) for \(V_s\) and \(Q_s \text{hc}/\lambda\) for the irradiance \(H\).

In Figure 4.12 the resistance of the detectors is plotted vs 1000/T. The general increase in resistance is indicative of the reduction of the electron mobility due to ionized impurity scattering at low temperatures and lattice scattering at higher temperatures. (ref 4.2). When the intrinsic temperature is reached the
resistance is known to decrease rapidly with increasing temperature. The fact that the resistance is still increasing at 300 °K indicated that the detectors were still in the extrinsic region. (ref 4.3).

Figures 4.13 and 4.14 depict the behavior of the constant field responsivity. The responsivity is plotted versus reciprocal temperature at each background level. The enhancement of the photoconductive gain (equation 4.5) at lower temperatures is apparent. The responsivity behavior can be divided into the three temperature regions illustrated in Figure 4.15.

REGION 1: LOW TEMPERATURES

In the low temperature region $R_\lambda$ is characterized by a strong background dependence and a gradual temperature dependence. In this region we find that $R_\lambda$ varies as $1/Q_\gamma^{\gamma}$ where $\gamma$ is almost unity at 83 °K. The responsivity is seen to gradually increase with decreasing temperature. The high background level nearly negates the gain enhancement observed at lower backgrounds.

REGION 2: INTERMEDIATE TEMPERATURE

In Region 2 $R_\lambda$ rapidly decreases with increasing temperature approaching a nearly exponential dependence. At the same time the background dependence is less strong. At higher backgrounds the point at which $R_\lambda$ begins to rapidly fall occurs at higher temperatures. Furthermore the transition is sharper at higher backgrounds.
Figure 4.12 DETECTOR RESISTANCE VS 1000/T

Sample K13-18B-3-1

Sample K13-18B-3-2
Figure 4.13 Small signal voltage versus 1000/T at different background levels $Q_{BT}$. Test Frequency: 1000 Hz.
Figure 4.14 Small signal voltage versus $1000/T$ at different background levels $Q_{BT}$. Test Frequency: 1000 Hz.
Figure 4.15 REGIONS OF OPERATION FOR A NEAR IR (Hg,Cd)Te SAMPLE EXHIBITING MINORITY CARRIER TRAPPING. 1) STRONG BACKGROUND DEPENDENCE; 2) STRONG TEMPERATURE DEPENDENCE; 3) BACKGROUND INDEPENDENT DISAPPEARANCE OF MINORITY CARRIER TRAPPING. $T_{c1}$ AND $T_{c2}$ ARE TEMPERATURES WHICH DEFINE THESE REGIONS.
REGION 3: HIGH TEMPERATURE

Here the background dependence was unobservable to within experimental error. Furthermore $R_\lambda$ seems to be approaching a constant value or at least a minimum. In this region it is believed that the effects of trapping have given way to Shockley-Read recombination (see Section 2.1 and 2.2).

The results are plotted in a different perspective in Figure 4.16. Here $R_\lambda$ versus $Q_B$ is plotted at several different temperatures for sample 3-1. At $83^\circ K$ the responsivity goes as approximately $1/Q_B^{0.9}$. At higher temperatures the strength of this dependence diminishes until at $252^\circ K$ it is unnoticeable.

In conclusion this experiment provided a detailed picture of the functional dependence of $R_\lambda (Q_B, T)$ that would be compared to theoretical models. Later theoretical analysis would eventually allow the calculation of the density of trapping states $N(E)$ directly from this data. Therefore, although this represented the most time consuming and tedious of all the experiments performed, the information obtained proved to be quite worth the time and effort.
Figure 4.16  Dependence of the Signal Voltage on the Background Photon Flux at Several Temperatures.  1KHz Test Frequency.  Small Signal Case.
5.1 THE SINGLE TRAP MODEL

The first model used to account for minority carrier trapping in Hg$_{1-x}$Cd$_x$Te assumed the trapping states to be localized at a single energy $E_a$ above the valence band (Figure 5.1 and Figure 2.1). A discussion of this case was carried out in detail by H. Y. Fan (Ref 5.1) with the essential features reported in Section 2.1. In order that a comparison with experiment might be made, the small signal responsivity in the low frequency limit, as predicted by the single trap model, required derivation. The fundamentals of the following derivation will be applied to the other models analyzed later.

5.1.1 Derivation of the Small Signal, Low Frequency Responsivity from the Single Trap Model

From Section 2.1 the fundamental results of applicability to the derivation to follow are summarized below. We found the following relationships to hold for minority carrier trapping at a single level in an n-type semiconductor. Under steady state conditions, Shockley-Read recombination is the assumed mechanism by which holes and electrons eventually recombine (Section 2.2).

\[ \Delta n = \Delta p + \Delta p_t \]  
\[ \Delta p_t = \frac{N_t \Delta p}{\Delta p + p_1 (E_a)} \]
\[ N_t = \text{total number of traps/cm}^3 \]
\[ \Delta n = \Delta d \left[ 1 + \frac{N}{\Delta d + p_1 \Omega_a} \right] \quad (5-3) \]
\[ \Delta d = \frac{\eta \tau_{SR} Q}{d} \quad (5-4) \]
\[ p_1 \left( \frac{E_a}{\alpha} \right) = N_v \exp \left( -\frac{E_a}{kT} \right) \quad (5-5) \]

In order to derive the responsivity we start with the general definition which does not assume anything about the magnitude of the signal voltage \( V_{\text{sig}} \) that results from an optical signal power \( H \) \( A_S \) incident on the sample.

\[ R = \frac{V_{\text{sig}}}{A_S H} \quad (5-6) \]

For the small signal responsivity, we recognize that it is the limit of the above expression as \( V_{\text{sig}} \) and \( H \) go to zero. This is just the derivative. Hence for the small signal responsivity:

\[ R = \frac{1}{A_S} \left( \frac{\partial V_{\text{sig}}}{\partial Q} \right) \frac{\lambda}{\partial H} \quad (5-7) \]

In Section 3.3.3 the following formula for the signal voltage was derived

\[ V_{\text{sig}} = E \xi \frac{\Delta n}{N_o} \quad (5-8) \]

Substituting Equation 5-8 into Equation 5-7 and carrying out the differentiation of \( Q \) with respect to \( H \) from the well known relationship we obtain:

\[ R_\lambda = \frac{\lambda E \xi}{\hbar c A_S} \frac{\partial \Delta n}{\partial Q} \quad (5-9) \]
Differentiation of $\Delta n$ with respect to $Q$ gives Equation 5-10 which when substituted into Equation 5.9 gives the desired expression for the responsivity.

$$\frac{\Delta \Delta n}{\Delta Q} = \frac{\eta \tau_{SR}}{d} \left[ 1 + \frac{N_t p_1 (E_a)}{p_1 (E_a) + \Delta \rho} \right]$$ (5-10)

$$R_\lambda (Q_B, T) = \frac{e^\lambda \eta r_S}{hc} \left( \frac{E_{\mu} e \tau_{SR}}{E} \right) \left[ 1 + \frac{N_t p_1 (E_a)}{(p_1 (E_a) + \Delta \rho)^2} \right]$$ (5-11)

where:

$$r_S = \frac{\ell}{e n_o w d \mu}$$ (5-12)

The factor in parentheses is the photoconductive gain in the absence of trapping. The factor in brackets embodies the effects of trapping and contains the temperature and background dependence of interest. This factor is referred to as the trapping gain enhancement factor $G_t(Q_B, T)$ because it results in an effective gain enhancement when trapping is operative.

$$G_t(Q_B, T) = \left[ 1 + \frac{N_t p_1 (E_a)}{[p_1 (E_a) + \Delta \rho]^2} \right]$$ (5-13)

Hereafter, the "trapping gain enhancement factor" will be referred to as the "trapping gain." Also when trapping is operative, the responsivity will often be expressed by $R_\lambda(Q_B, T)$ to emphasize the dependence on $Q_B$ and $T$ and denote trapping responsivity. When trapping is not operative, the symbol $R_\lambda$ will be used.
With these notational conventions $G_t(Q_B, T)$ is related to experimental data via Equation 5-14:

$$G_t(Q_B, T) = \frac{R_\lambda(Q_B, T)}{R_\lambda}$$  (5-14)

Therefore, if the responsivity can be measured under a set of conditions such that trapping is inoperative, then the trapping gain can be determined by taking the ratio $R_\lambda(Q_B, T)/R_\lambda$. This will be valid if the responsivity is measured under constant $E$ field conditions as described in Section 4.3. Also $\tau_{SR}$, $\eta$, and $n_0$ must not vary with temperature. The extrinsic condition insures us that $n_0$ and $\tau_{SR}$ do not vary appreciably with temperature. (See Section 2.2 for a discussion of the temperature dependence of $\tau_{SR}$.) The assumption of a constant quantum efficiency $\eta$ is less substantiated. However, it is believed that $\eta$ does not strongly depend on temperature for lack of evidence that it does. Furthermore, surface recombination effects have not been considered. Indeed, the excellent agreement between the model eventually formulated in Section 5.3 and the experimental results added credibility to the validity of these initial assumptions.

Under these assumptions the responsivity will have the same relative functional dependence on temperature and background as the trapping gain $G_t(Q_B, T)$. Therefore theoretical and experimental comparisons of the functional dependence are possible even if the experimental determination of the absolute value of $G_t(Q_B, T)$ is impossible.
It must be emphasized that this derivation is valid in the limit of zero modulation frequency. Practically speaking, this requires that the modulation be sufficiently slow in time such that equilibrium conditions are reached at a rate much faster than the rate of signal fluctuation. This occurs in the plateau portion of the frequency response (Section 4.2).

5.1.2 Comparison Between the Single Trap Model and the Experimental Responsivity

Given the results of this preceding section, a comparison with experiment is now possible.

The trapping gain versus $1000/T$ at different background levels is plotted in Figure 5.2.

The parameters $E_a$, $d$, and $\tau$ were chosen to best represent the detectors experimentally studied. In particular, $E_a$ is derived from the slope of the straight line asymptote of the responsivity versus $1/T$ data in the high temperature region (Region 2, Figure 4.15). The time constant $\tau$ is typically $10^{-6}$ s from room temperature measurements (Section 4.1.2) where it is believed that trapping is inoperative and thus the lifetime measured is $\tau_{SR}$. In this case $\tau$ corresponded to the lifetime measured at room temperature for sample K13-18B-3-2. (This sample was one of the samples on which extensive variable temperature data was taken and with which many of the theoretical calculations were compared.)
Figure 5.2 TRAPPING GAIN VS $1000/T$ FOR THE SINGLE LEVEL TRAP AT ENERGY $E_a = 0.2$ eV AND TOTAL TRAP CONCENTRATION $N_t = 5 \times 10^{13}/\text{cm}^3$. THE EFFECT OF BACKGROUND IS SHOWN TO DECREASE THE GAIN.
A comparison of Figure 5.2 with Figures 4.13 and 4.14 reveals that the temperature and background dependence (going from left to right) is approximately correct until the maximum is reached. After the maximum there ceases to be any similarity except that increased background does reduce the responsivity in both cases. However, the single level model predicts a dependence approaching $Q_B^{-2}$ as the temperature is decreased while a dependence faster than $Q_B^{-1}$ has never been observed experimentally. Obviously the temperature dependence beyond the maximum is in disagreement with experimental findings.

In conclusion, the assumption of traps at a single energy failed to agree with experimental results. Experimental results seemed to indicate that trapping effects were extended over a greater range of temperatures than predicted by traps at a single energy level in the gap.

5.2 THE UNIFORM CONTINUUM OF TRAPS MODEL

5.2.1 The Development of the Model

As pointed out in Section 5.1.2, the single level model does show qualitative agreement with experiment up to the maxima in the trapping gain functions. Indeed the qualitative features of enhanced photoconductive gain and strong temperature and background dependence is present in both the simple theory and experiment. For this reason trapping was still felt to be the mechanism responsible, however, a different model was needed.
Realizing that the addition of different trapping levels in closer proximity to the valence band could extend the trapping plateau region to lower temperatures, R. Broudy postulated the following model (Ref. 5.1). A multiplicity of trapping levels was assumed to extend throughout the energy gap. All traps were considered to behave independently, i.e., they interact only with the valence band and the trap-to-trap transition probability is assumed to be negligible.

The initial model assumed a continuum of trapping states extending from the valence band to an energy $E_m$ where

$$E_m \approx \frac{E_g}{2} + 4kT \quad (5-15)$$

and $E_g$ is the bandgap. (The approximate determination of $E_m$ (Ref. 5.3) was accomplished by an estimation of the interaction rates between the traps and the conduction band which result in a loss of electrons to the upper band. This fills the traps with holes, thus making them no longer available for occupation due to optical excitation. The estimation of the energy above which this interaction with the conduction band becomes appreciable determined $E_m$. From Equation 5-15 it is obvious that the dependence of $E_m$ on temperature is of secondary importance when $E_g >> 8 kT$.) Furthermore, Broudy assumed that the density of such trapping states from $E_v$ to $E_m$ was constant in order to quickly evaluate the validity of the continuum approach. The distribution of traps in the bandgap is illustrated in Figures 5.3 and 5.4.
Figure 5.3 UNIFORM CONTINUUM OF TRAPS

\[ N_t = \int_0^{E_m} N_0 \, dE = N_0 \, E_m \, (\text{cm}^{-3}) \]
Figure 5.4  PHOTOCIONDUCTIVITY WITH TRAP CONTINUUM. (FROM REF. 5.3) $E_s$ IS THE HALF OCCUPANCY ENERGY (SEE SECTION 6.1.1).
If \( N(E) \) is the density of states and \( \Delta \rho_t (E) \) is the occupation probability of a trap of energy \( E \), we obtain Equation 5-16 for the number of traps occupied by holes.

\[
\Delta \rho_t = \int_0^{E_m} N(E) \Delta \rho_t (E) \, dE \tag{5-16}
\]

The occupation probability for trapped holes at energy \( E \) \( \Delta \rho_t (E) \) (Ref 5.3) is given by:

\[
\Delta \rho_t (E) = \frac{\Delta \rho}{\rho_1 (E) + \Delta \rho} \tag{5-17}
\]

Substitution of Equation 5-17 into Equation 5-16 and assuming the constant density of states obtain:

\[
\Delta \rho_t = N \int_0^E \frac{\Delta \rho \, dE}{N_v \exp (-E/kT) + \Delta \rho} \tag{5-18}
\]

where the explicit formula for \( \rho_1 (E) \) has been used. \( N \) is the density of trap levels between \( E \) and \( E + dE \) and \( \Delta \rho_t \) is the density of trapped holes due to traps at all energies. \( N_v \) is the density of states at the valence band edge.

Integration of Equation 5-18 gives:

\[
\Delta \rho_t = N E_m + N k T \log \frac{N_v \exp (-E_m/kT) + \Delta \rho}{N_v + \Delta \rho} \tag{5-19}
\]

Using the fact that \( N_v >> \Delta \rho \) this becomes:

\[
\Delta \rho_t + N k T \log \left[ 1 + \frac{\Delta \rho}{N_v e^{-E_m/kT}} \right] \tag{5-20}
\]
where from Equation 2-6:

$$\Delta p = G \tau = \frac{\eta Q \tau}{d} \quad (5-21)$$

Q is the radiation flux, $\eta$ the quantum efficiency, d the detector thickness and $\tau$ the recombination lifetime.

Finally, from Equation 5-1, 5-20, and 5-21 the total conductivity due to recombination and trapping effects becomes:

$$\Delta n = \frac{\eta Q}{d} + NkT \log \left[ 1 + \frac{\eta Q/d}{N_{v} \exp \left( \frac{-E_{m}}{kT} \right)} \right] \quad (5-21)$$

Note that the total number of traps per cm$^2$ $N_t$ is given by:

$$N_t = \int_{0}^{E_m} N(E) \, dE \quad (5-22)$$

Thus for the uniform continuum case $N_t$ is:

$$N_t = N \cdot E_m \quad (5-23)$$

5.2.2 Comparison Between the Uniform Continuum Model and the Experimental Responsivity

Following the procedure outlined in Section 5.1.1 the expression for the small signal solution is obtained. Differentiation of Equation 5-21 with respect to $Q$ gives:

$$\frac{d \Delta n}{dQ} = \frac{\eta \tau}{d} \left[ 1 + NkT \frac{1}{N_{v} \exp \left( \frac{-E_{m}}{kT} \right)} \right]$$

$$\left( \frac{\eta Q}{d} + \frac{1}{N_{v} \exp \left( \frac{-E_{m}}{kT} \right)} + \frac{\eta Q/d}{N_{v} \exp \left( \frac{-E_{m}}{kT} \right)} \right)$$

(5-22)
where $Q_B \gg Q_s$. Thus $G_t(Q_B, T)$ for the uniform continuum model is:

$$G_t(Q_B, T) = 1 + \frac{NkT}{N_v} \exp \left(-\frac{E_m}{kT}\right) + \left(\eta Q/d\right) \quad (5-23)$$

Figure 5.5 shows the functional behavior of $G_t(Q_B, T)$ vs $1000/T$. As before, the parameters we selected to reflect the approximate values determined experimentally for a typical $\text{Hg}_0.4\text{Cd}_0.6\text{Te}$ detector.

In comparison with the variable temperature responsivity data (plotted in Figures 4.13 and 4.14), it is obvious that the continuum model shows much better agreement with experiment. The constant density continuum model has indeed resulted in an extension of the plateau region to lower temperatures. It also predicts that trapping should become nearly inoperative ($G_t \approx 1$) at room temperature ($1000/T = 3.3$) in accordance with the experimental findings.

In the low temperature region a $Q_B^{-1}$ dependence is predicted which nearly agrees with the experimental dependence of approximately $Q_B^{-0.9}$ (Figure 4.16). The only blatant discrepancy arises from the effect of the linear temperature factor in the second term of Equation 5-23 which results in a gradual decline of $G_t(Q_B, T)$ with lower temperature. Over the 80 °K to 300 °K temperature range, such a decline had never been observed experimentally in $\text{Hg}_0.6\text{Cd}_0.4\text{Te}$.

5.2.3 Comparison Between the Uniform Continuum Model and the Experimental Measurement of $\Delta n$ vs $\Delta Q$
Figure 5.5 TRAPPING GAIN VS 1000/T FOR THE UNIFORM CONTINUUM OF TRAPS AT DIFFERENT BACKGROUND LEVELS.
In Section 4.1.3 an experiment was described which determined the steady state change of $A_n$ versus the input illumination intensity at 80 °K. The total illumination is given by

$$Q = Q_B + \Delta Q_s$$  \hspace{1cm} (5-24)

The experiment is summarized as follows. The background $Q_B$ was fixed while pulses of known magnitude $\Delta Q_s$ were applied to the detector. The pulses were of sufficient duration to allow $A_n$ to reach a steady state value proportional to the steady state value of the zero-to-peak signal voltage measured on an oscilloscope. This signal voltage was plotted versus $\Delta Q_s$ indicating a nonlinear relationship between $A_n$ and $\Delta Q_s$ (see Figure 4.7).

From the uniform continuum model an approximate relationship between $A_n$, $Q_B$, and $\Delta Q_s$ was derived and compared to the experimental findings reported above.

The relationship between $A_n$ and $Q$, given by Equation 5-21, is:

$$A_n = \frac{n \tau Q}{d} + NkT \log \left[ 1 + \frac{n \tau Q}{p_1(E_m)} \right]$$  \hspace{1cm} (5-25)

At 80 °K we are in the plateau region (Figure 5.4, $1000/T = 12.5$). In this region trapping effects are strong and:

$$\frac{n \tau Q}{d} / p_1(E_m) \gg 1$$  \hspace{1cm} (5-26)

also:

$$\Delta p_t \gg \Delta p$$  \hspace{1cm} (5-27)

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Thus:
\[ \eta \tau Q/d \ll NkT \log \left[ 1 + \frac{n \tau Q/d}{p_1(E_m)} \right] \]

We can therefore approximate Equation 5-25 by the following:
\[ \Delta n \approx NkT \log \left[ \frac{\eta \tau Q/d}{N_v e^{-E_m/kT}} \right] \]  \hspace{1cm} (5-28)

\[ \Delta n \approx NE_m + NkT \log \frac{\eta \tau Q}{dN_v} \]  \hspace{1cm} (5-29)

Substituting \( Q_B + \Delta Q_s \) for \( Q \), and after some manipulation we obtain the desired expression for \( \Delta n \):
\[ \Delta n \approx NE + NkT \log \frac{\eta \tau Q_B}{dN_v} + NkT \log \left( 1 + \frac{\Delta Q_s}{Q_B} \right) \]  \hspace{1cm} (5-30)

Since the first two terms were constants during the experiment, it was realized that by plotting \( \Delta N_{o-p} \) vs \( \log (1 + \Delta Q_s/Q_B) \), a simple comparison between the predicted straight line dependence and experiment would be possible. This was done in Figure 4.8.

As can be seen, the experimental points fall very close to the straight line drawn. At the lower signal levels there is a small departure from the line.

In spite of the possibility that the small departures observed could be due to inaccuracies in the model itself, the excellent agreement over two orders of magnitude in \( \Delta Q_s \) led us to the conclusion that the uniform continuum quite accurately predicts the steady state behavior of the photoconductivity at 80 °K.
5.2.4 Transient Behavior

The validity of the continuum approach is further justified by the experiment which measured the instantaneous lifetime at a function of time during the decay of excess carriers after the removal of strong illumination on the detector (Section 4.11). It was noted that the instantaneous lifetime exhibited a continuous increase with time (Figure 4.5). It has been well established that the presence of one or more discrete trapping levels, well separated in the bandgap, would result in one or more observed trapping time constants. In this case the instantaneous lifetime would be constant over certain intervals of time representing the successive emptying of the traps beginning with those closest to the band with which they interact. Fan shows this for the single level trap (Ref. 5.1) while Hornbeck and Haynes (Ref. 5.4) discuss experimental lifetime measurements in terms of deep and shallow traps in Si. Therefore it seems reasonable to me that by an extension of these ideas, a continuum of traps would account for the continuous change in the instantaneous lifetime observed experimentally.

Furthermore it has been well established that the initial value of the instantaneous lifetime reflects recombination via the faster Shockley-Read centers before the traps have time to start emptying. Thus the asymptotic limit of approximately 10 $\mu$s (Figure 4.5) should reflect the Shockley-Read lifetime of detector 3-7. Indeed the initial variation of $\tau_{\text{inst}}$ is comparatively slow. In the other extreme the relatively large value of $\tau_{\text{inst}}$ should reflect the emptying of the deeper traps near the final equilibrium point.
I did not go into the details of the transient response as predicted by the continuum model. However, R. Broudy and M. Reine have carried through an analysis of the predicted transient behavior which has yet to be compared in detail with experimental data (Ref. 5.3).

5.2.5 Concluding Remarks

The uniform continuum model could be considered a complete success in that it did what it was intended to do, i.e., to validate the continuum approach. The jump in our thinking from single level trapping to continuum trapping, and the success of the latter, constituted the most significant advance in our efforts to model the trapping behavior in Hg$_{1-x}$Cd$_x$Te. R. Broudy (Ref. 5.2) can take full credit for this unique approach.

The assumption of a continuum of traps could be interpreted physically as saying that the various discrete trapping states in the bandgap are in close proximity compared to the thermal energy $kT$, and therefore appear to be continuously distributed when their effects are measured experimentally.

In any event the uniform continuum has met with some success in predicting experimental behavior. This was especially true for the experiment described in Section 5.2.3. Although the background and temperature dependence of the predicted responsivity was a vast improvement over the single level assumption, the detailed qualitative agreement desired was not realized by this model. However, the partial success of the uniform continuum motivated the consideration of other possible trap distributions. This will be the subject of the next section.
5.3 EXPONENTIAL DENSITY OF TRAPPING STATES MODEL

Previously two models for the distribution of trapping states in the energy gap were discussed: (1) the single level trap (Figure 5.1); (2) the uniform continuum of traps (Figure 5.3). The temperature and background dependence of the small signal responsivity was derived for each model and compared to experimental measurements performed on 0.4 eV samples over temperatures ranging from 77 °K to 300 °K. From this information it was concluded that a distribution of traps more highly concentrated near the valence band would bring experiment and theory into closer agreement. When it was realized that an exponential distribution would satisfy this intuitive requirement, the density of states \( N(E) \) given by Equation 5.31 and illustrated in Figure 5.6 was assumed.

\[
N(E) = \begin{cases} 
N_0 e^{-E/F_x} & \text{for } 0 \leq E \leq E_m \\
0 & \text{for } E > E_m 
\end{cases} \tag{5-31}
\]

where:

\( N(E) \) = density of trapping states in the gap
\( N_0 \) = density of trapping states at valence band edge where \( E = E_c \equiv 0 \)
\( E_x \) = the energy at which \( N(E) \) has fallen to \( N_0/\epsilon \)
\( E_m \) = \( E_g/2 + 4kT \)

The trapping gain enhancement factor was derived for the exponential distribution and the result is given by Equation 5-32.
Figure 5.6  EXPONENTIAL DISTRIBUTION OF TRAPS
\[ G_t(Q_B, T) = 1 + \frac{1}{N_v} \int_0^E \frac{N_v e^{-E/kT}}{\left[ e^{-E/kT} + \frac{\eta Q}{N_v} \right]^2} dE \quad (5-32) \]

where:

\( \eta \) = effective quantum efficiency

\( \tau \) = minority carrier lifetime (\( \mu \)s)

\( Q \) = background photon flux (photons-sec\(^{-1}\)-cm\(^{-2}\))

\( d \) = sample thickness (cm)

\( N_v \) = density of states in the valence band

\( T \) = temperature (\( ^\circ \)K)

\( k \) = Boltmann's constant

The next step entailed fitting the calculated function to experimental data. This required the selection of the two unknown parameters \( E_x \) and \( N_0 \). The parameter \( E_x \) reflects the rate at which the density of trapping states falls off with increasing energy. Consequently \( E_x \) primarily affects the nature of the high temperature roll-off of \( G_t(T, Q_B) \). In the limit as \( E_x \to \infty \), \( G_t(T, Q_B) \) approaches that of the uniform continuum. The parameter \( N_0 \) is the density of trapping states at the valence band edge. The total number of traps \( N_t \) is dependent upon \( N_0 \) and \( E_x \) via Equation 5-33

\[ N_t = \int_0^{E/2 + 4T} N_0 \exp(-E/E_x)dE \quad (5-33) \]

Thus, \( N_t \) is an effective number of traps which has a negligible temperature dependence if \( \sim 4kT \) as is true for most practical situations. As expected, \( N_0 \) determines the magnitude of the trapping gain as it is related to the total number of traps.
The trapping gain calculation necessitated the use of standard computerized numerical techniques. Initial calculations revealed promising qualitative agreement with experiment. The next step was to obtain a quantitative fit to experimental data. All parameters except $E_x$ and $N_0$ were approximately known. The minority carrier lifetime $\tau$ was measured at room temperature where trapping is mostly inoperative in 2.9 micron detectors. The temperature dependence of $\tau$ was assumed to be constant for lower temperatures since $\tau$, which is a Shockley-Read recombination time, depends on carrier concentrations which are fixed by $N_D - N_A$ for temperatures below the intrinsic temperature. (The intrinsic temperature is somewhat above 300 °K for Hg$_{0.6}$Cd$_{0.4}$Te.

The unknown parameters $E_x$ and $N_0$ were found by comparison with experiment. First $E_x$ was varied until the temperature dependence of the trapping gain was in rough qualitative agreement with experiment. Then the parameter $N_0$ was chosen such that the calculated and experimental value of the trapping gain coincided at a particular temperature and background. Having done this, the other background values corresponding to actual experiment were inserted into the calculations and the resulting functions were plotted against experimental data (Figure 5.7). In Figure 5.8 the results of the same procedure are shown for another sample.
Figure 5.7: Calculated and Experimental Dependence of the Trapping Gain on Temperature and Background. 102
Figure 5.8 Calculated and Experimental Dependence of the Trapping Gain on Temperature
As predicted by theory and observed experimentally, the strength of the background dependence of the responsivity decreases with increasing temperature. The measured and calculated background dependence of sample KL3-18B-3-1 is plotted in Figure 5.8. A comparison reveals good general agreement. Most significant is that the exponential model predicts a low temperature background dependence slightly less than $Q_B^{-1}$ ($Q_B^{-0.9}$ in this case) in accordance with experimental findings.

5.3.1 Conclusion

The assumption of a decreasing density of trapping states above $E_V$ in the energy gap has resulted in excellent agreement with experiment when an exponential distribution was introduced. Although the actual physical distribution may be other than an exponential, it has been shown that the density of states is a decreasing function of energy in the gap. It has also been established that the exponential model does provide good agreement with experiment over the temperature and background ranges that have been investigated for Hg$_{0.6}$Cd$_{0.4}$Te.
Figure 5.9  CALCULATED AND EXPERIMENTAL DEPENDENCE OF THE TRAPPING GAIN ON THE TOTAL BACKGROUND AT SEVERAL TEMPERATURES. SAMPLE 3-1.
CHAPTER 6
THE DETERMINATION OF THE DENSITY OF TRAPPING STATES
DIRECTLY FROM EXPERIMENTAL DATA

6.1 INTRODUCTION

In this chapter an approximate method for determining the density of trapping states directly from the temperature dependence of the responsivity will be presented. The method will then be applied to a particular case from which a density of states will be determined. This density of states will then be compared to the exponential density of states obtained in chapter 5 for the same sample. Finally the implications of this approach as to the interpretation of the experimental data will be discussed.

The case considered is that of minority carrier trapping in n-type material. It was assumed that the lifetime of the minority carrier for normal recombination is invariant with temperature. Furthermore extrinsic temperatures are assumed. The responsivity is assumed to be measured under small signal, low frequency, constant electric field, and fixed background conditions. No initial assumptions, however, are made concerning the density of trapping states.

6.2 THE DERIVATION OF THE METHOD

Fan has shown (Ref. 6.1) that the occupation probability \( \Delta p_t(E) \) for trapped holes at energy \( E \) is given by Equation 6-1,

\[
\Delta p_t(E) = \frac{\Delta p}{\Delta p + p_1(E)} \quad (6-1)
\]
where
\[
\Delta p = \text{is the steady state density of holes in the valence band under constant illumination } Q
\]

\[
\Delta p = \eta \tau Q/d \quad \text{(6-2)}
\]

\[
p_\perp = N_v e^{-E/kT} \quad \text{(6-3)}
\]

\[
N_v = \text{density of states in the valence band}
\]

\[
N_v = 2 (2\pi m_h kT/h^2)^{3/2} \quad \text{(6-4)}
\]

We can define the energy \( E_s \) at which \( \Delta p_t(E) \) is equal to \( 1/2 \) by setting \( \Delta p \) equal to \( p_\perp(E) \) and solving for \( E \). Thus \( E_s \) is given by:

\[
E_s = kT \ln \frac{d N_v}{\eta \tau Q} \quad \text{(6-5)}
\]

The occupation probability \( \Delta p_t(E) \) can now be expressed entirely in terms of \( E_s, E, \) and \( kT \).

\[
\Delta p_t(E) = \frac{1}{1 + \exp \left[ (E_s - E)/kT \right]} = f_t(E_s - E) \quad \text{(6-6)}
\]

Henceforth \( \Delta p_t(E) \) will be denoted by \( f_t(E_s - E) \) to prevent confusion with \( \Delta p_t \) and to emphasize the form of Equation 6-6.

The form of \( f_t(E_s - E) \) is very similar to the Fermi function. (see Figure 6.4) Upon obtaining this expression, it became apparent that the often used approximation techniques employed in Fermi statistics might also be applicable here.
The total number of traps (per cm$^3$) occupied by holes is given by:

$$\Delta \varphi_t = \int_0^{E_g} f_t(E_s - E) N(E) \, dE$$

(6-7)

where $N(E)$ is the density of trapping states in the energy gap.

The next step entailed taking the partial derivative of $\Delta \varphi_t$ with respect to $E_s$.

$$\frac{\partial \Delta \varphi_t}{\partial E_s} = \int_0^{E_g} N(E) \frac{\partial}{\partial E_s} \frac{f_t(E_s - E)}{E_s} \, dE$$

(6-8)

It was recognized that \(\frac{\partial f_t}{\partial E_s}\) is a sharply peaked function having a symmetrical minimum about $E_s$ and a width of a few $kT$. (see Figure 6.4) Explicitly the derivative is given by:

$$f'_t(E_s - E) = \frac{\partial}{\partial E_s} \left( \frac{f_t(E_s - E)}{E_s} \right)$$

(6-9)

$$f'_t(E_s - E) = - \frac{1}{kT} \frac{\exp \left[ \frac{(E_s - E)}{kT} \right]}{[1 + \exp \left[ \frac{(E_s - E)}{kT} \right]]^2}$$

(6-10)

By a consideration of the relative values of $E_s$ and $kT$ via Equation 6-5 it can be shown that, except for extremely large values of $Q$, $E_s >> kT$. This implies that no matter how close $E_s$ comes to the conduction band energy $E_c = 0$, the width of $f'_t(E_s - E)$ is of negligible value at $E = 0$. Therefore the limits of integration can be extended to $\pm \infty$ where it is assumed, of course, that $N(E)$ terminates in the gap and that
E_s is more than a few kT away from E_g. In this case f'_t(E_s - E)
is also negligible at E = E_g. This will be the case except at high temperatures where the approximation is inapplicable.

Thus with the new limits of integration Equation 6-8 becomes:

\[ \frac{\partial \Delta \rho}{\partial E_s} = \int_{-\infty}^{\infty} N(E) f'_t(E_s - E) \, dE \]  \hspace{1cm} (6-11)

In this form Equation 6-11 is immediate recognizable as a convolution integral, a very useful and descriptive integral of wide applicability in the fields of physics and systems theory.

If N(E) does not vary appreciably over a few kT then N(E) will take on the approximately constant value of N(E_s) over the range of f'_t(E_s - E). Thus we can bring N(E_s) out of the integral. (see Figure 6.4)

\[ \frac{\partial \Delta \rho}{\partial E_s} \cong N(E_s) \int_{-\infty}^{\infty} f'_t(E_s - E) \, dE \]  \hspace{1cm} (6-12)

This is the approximation essential to this derivation. It relies on the sharply peaked nature of f'_t(E_s - E) which, in the limit as kT \to 0, approaches an impulse function of unity value.

The integral of f'_t(E_s - E) given in 6-12 can be evaluated as follows. We have:

\[ - \frac{1}{kT} \int_{-\infty}^{\infty} \exp \left[ \frac{(E_s - E)/kT}{1 + \exp \left[ (E_s - E)/kT \right]} \right] \, dE \]  \hspace{1cm} (6-13)
If we let \( x = \exp \left( \frac{(E_s - E)}{kT} \right) \) and substitute this into 6-13 we have the easily evaluated integral:

\[
\int_{0}^{\infty} \frac{1}{[1 + x]^2} \, dx
\]

and finally:

\[
\int_{-\infty}^{\infty} f'(E_s - E) \, dE = -1
\]

thus:

\[
\frac{\partial \Delta P_t}{\partial E_s} \approx -N(E_s)
\]

There it was apparent that if an experiment could be conceived which would give the dependence of \( \Delta P_t \) on \( E_s \), then at least the functional dependence of \( N(E) \) on energy could be found.

The next step was to search for such an experiment.

It was found that the variable temperature responsivity experiment more than satisfied the requirement just stated as to the type of experiment from which \( N(E) \) could be calculated. By "more", it is meant that the small signal responsivity automatically takes the derivative \( \frac{\partial \Delta P_t}{\partial E_s} \), evaluating it at \( E_s \), and thus gives \( N(E_s) \) by a simple formula.
The derivation proceeds as follows:

1. With trapping: \( \Delta n = \Delta p + \Delta n_t \) \hspace{1cm} (6-17)

2. Without trapping: \( \Delta n = \Delta p \) \hspace{1cm} (6-18)

3. The trapping gain is therefore:
   \[
   G_t = 1 + \frac{\Delta n_t}{\Delta p} \hspace{1cm} (6-19)
   \]

4. In the small signal case, the trapping gain is:
   \[
   G_t = 1 + \frac{\partial \Delta n_t}{\partial \Delta p} \hspace{1cm} (6-20)
   \]

5. \( E_s = kT \ln \frac{d N}{\eta \tau Q} = kT \ln \frac{N}{\Delta p} \) \hspace{1cm} (6-22)

6. Substitution of 6-16, and 6-23 into 6-21 gives
the desired expression for the trapping gain in the
small signal, low frequency limit:

   \[
   G_t (Q, T) = 1 + \frac{kT}{\Delta p} N(E_s) \equiv G_t (E_s) \hspace{1cm} (6-24)
   \]

   \[
   G_t (E_s) = 1 + \frac{kT d}{\eta \tau Q} N(E_s) \hspace{1cm} (6-25)
   \]
7. Solving for $N(E_s)$ we obtain the equation which can be used to find $N(E)$ from the responsivity data.

$$N(E_s) = \frac{n \tau Q}{d k T} [G_t(E_s) - 1]$$  \hspace{1cm} (6-26)

The procedure is simple. Each data point is obtained at a certain background and temperature. From Equation 6-5 the value of $E_s$ is then determined which corresponds to this data point. If the data point is the trapping gain $G_t(Q_B, T)$, it is therefore transformed to $G_t(E_s)$ and used to compute $N(E_s)$, which is just the density of states at an energy corresponding to $E_s$. Another data point at another temperature or background will determine $N(E)$ at another energy. In this manner $N(E)$ is determined over the range of $E_s$ that the experiment conditions of temperature and background covered.

The method of extracting $G_t(Q_B, T)$ from the responsivity data is given in Section 5.1.1, Equation 5-14. It relied on the determination of $R_\lambda$, the responsivity when trapping effects are negligible. This occurs near room temperature for samples 3-1 and 3-2 on which the detailed variable temperature measurements were performed. Therefore determination of $N(E)$ from Equation 6-26 was possible for these samples. This was indeed tried, and the results are described in the next section.

If $G_t(Q_B, T)$ cannot be determined in the event that $R_\lambda$ occurs at temperatures experimentally unaccessible, then the relative functional dependence of $N(E)$ can still be found.
The inability to measure $R_\lambda$ might be due to the fact that trapping is still operative at room temperature as is the case for 1.8 $\mu$m Hg$_{1-x}$Cd$_x$Te (Ref. 6.2). However, it this is the case, then the trapping gain is much greater than unity because, if it were not, $R_\lambda$ could at least be approximately determined. Therefore Equation 6-26 becomes

$$N(E_s) = \frac{\eta \tau Q}{d k T} \frac{R_\lambda (Q_B, T)}{R_\lambda}$$

(6-27)

where $R_\lambda$ is unknown but assumed constant.

Therefore Equation 6-27 represents a method for determining the relative dependence of $N(E)$ on $E$ from responsivity data taken when the effects of trapping are strong over the range of experimental conditions.

There is one more case to consider, that is, the case where $N(E)$ varies rapidly compared to $f'(E_s - E)$. The case of a single trap level at energy $E_a$ is considered in which $N(E)$ is modeled as a delta function (like that shown in Figure 5.1).

$$N(E) = N_o \delta (E - E_a)$$

(6-28)

Substitution of Equation 6-28 into Equation 6-11 gives:

$$\frac{\Delta P}{\Delta E_s} = \int_{-\infty}^{\infty} N \delta (E - E_a) f'(E_s - E) dE$$

(6-29)

$$\frac{\Delta P}{\Delta E_s} = N_o f'(E_s - E_a)$$

(6-30)
Substitution of Equation 6-30 into 6-21 gives:

$$G_t(E_s) = 1 - \frac{kT}{\eta \tau Q} N_o f'_t(E_s - E_a)$$  \hspace{1cm} (6-31)

Inserting the explicit form of $f'_t(E_s - E_a)$ as given by Equation 6-10 into 6-31:

$$G_t(E_s) = 1 + \frac{d N_o}{\eta \tau Q} \frac{\exp [(E_s - E_a)/kT]}{[1 + \exp [(E_s - E_a)/kT]^2}$$  \hspace{1cm} (6-32)

Consideration of Equation 6-32 reveals that maximum occurs at $E_s = E_a$ and has a value:

$$G_t(E_s = E_a) = 1 + \frac{d N_o}{4 \eta \tau Q}$$  \hspace{1cm} (6-33)

From this it is concluded that if $G_t(Q_B, T)$ is determined experimentally and $Q_B$ and $T$ are related to $E_s$, then the maximum value of $G_t(E_s)$ will occur at $E_s = E_a$. Furthermore the total number of traps can be determined by Equation 6-33. Therefore this technique is applicable for the limiting case of $N(E)$ localized at a single energy since $E_a$ and $N_o$ can be found.

The test as to whether or not the actual distribution is exactly localized at $E_a$, or instead exhibits a distribution of energies about $E_a$, could be made by comparing the width of the experimental function $G_t(E_s)$ with that calculated from Equation 6-32 for the delta function case. Indeed, an approximation for the width of such a distribution could be deduced from such a comparison.
In summary, it has been shown that this technique of determining \( N(E) \) directly from experimental responsivity data is of general applicability. If the width of the "sampling function" \( f'_t(E_s - E) \) is small compared to variations in \( N(E) \), then \( N(E) \) may be determined directly from the responsivity data.

On the other hand, if \( N(E) \) varies more rapidly than \( f'_t(E_s - E) \) important information as to the nature of \( N(E) \) may still be inferred by the use of arguments similar to those proposed above for the localized distribution of traps. Knowledge of the width of \( f'_t(E_s - E) \) and hence the resolution of the measurement permits such inferences to be made.

There are surely other experiments which measure \( \Delta p(E_s) \) from which \( N(E_s) \) could also be determined. Variable temperature experiments seem to be the most promising means of varying \( E_s \) as compared to varying the background, since orders of magnitude change in background are necessary to appreciably effect \( E_s \) due to the logarithmic dependence of \( E_s \) on \( Q \). (See Figure 6.5). The power of the "responsivity versus temperature" approach lies in the fact that it takes the derivative \( \partial \Delta p_t / \partial E_s \). Analogous differential methods are used in wide variety of experimental situations.

6.3 APPLICATION OF THE METHOD

The method for determining \( N(E) \) from \( G_t(Q_B, T) \) was applied to the variable temperature data taken on sample K13-18B-3-1 measured at a fixed background of \( 6 \times Q_{B_0} \).
The trapping gain $G_t(Q_b,T)$ was calculated by taking the ratio of $R_\Lambda(Q_b,T)$ to $R_\Lambda$ at 300 °K. The value of $E_s$ at each temperature was then computed by Equation 6-5. The constants $\eta$, $\tau$, $d$, $m_h^*$, and $Q_B$ used to compute $E_s$ and $N(E_s)$ are given in Table 6.1. These are the same constants as those used to obtain the fit of the data to the exponential model (Section 5.3, Figure 5.6).

Table 6.1

ASSUMED CONSTANTS

\[
\begin{align*}
\eta &= 0.5 \\
\tau &= 3 \times 10^{-6} \text{ s} \\
m_h^* &= 0.55 \\
Q_B &= 6 \times Q_{B0}
\end{align*}
\]

Equation 6.8 was then used to determine $N(E)$. The results are summarized in Table 6.2.

Table 6.2

$N(E_s)$ VERSUS $E_s$, SAMPLE K13-18B-3-1, $T = 80$ °K TO $300$ °K, $Q_B = 6 \times Q_{B0}$

<table>
<thead>
<tr>
<th>$T$ °K</th>
<th>$kT$ eV</th>
<th>$E_s$ eV</th>
<th>$G_t$</th>
<th>$N(E_s)$ eV$^{-1}$ cm$^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>83</td>
<td>.00714</td>
<td>.115</td>
<td>34.0</td>
<td>$8.32 \times 10^{14}$</td>
</tr>
<tr>
<td>99</td>
<td>.00852</td>
<td>.138</td>
<td>30.0</td>
<td>$6.16 \times 10^{14}$</td>
</tr>
<tr>
<td>125</td>
<td>.01087</td>
<td>.179</td>
<td>23.5</td>
<td>$3.76 \times 10^{14}$</td>
</tr>
<tr>
<td>150</td>
<td>.0129</td>
<td>.219</td>
<td>19.0</td>
<td>$2.50 \times 10^{14}$</td>
</tr>
<tr>
<td>175</td>
<td>.0151</td>
<td>.260</td>
<td>14.7</td>
<td>$1.63 \times 10^{14}$</td>
</tr>
</tbody>
</table>
The density of trapping states $N(E)$ is plotted versus the energy $E$ in Figure 6.1. In Figure 6.2 the same data is plotted in the format of log $N(E)$ versus $E$. The straight line dependence of the points from 0.115 eV to 0.26 eV indicates an exponential dependence: $\exp \left(-E/E_x\right)$ with $E_x$ approximately 0.09 eV. For energies beyond 0.26 eV the density of states decreases rapidly as exhibited by the second straight line region with a slope corresponding to another $E_x$ of about 0.0017 eV.

The next logical step was to compare this experimentally determined $N(E)$ to that determined by the methods described in Section 5.3. But first the distinction between these two methods should be emphasized. The First method entailed guessing an $N(E)$, calculating $G_{t} (Q_{B}, T)$ from this guess, comparing the calculations to the data, and then adjusting the model until the calculations fit the data. For model distributions more complicated than a uniform continuum, numerical integration was required for each calculated point. This was time consuming and expensive. On the other hand,
Figure 6.1 DENSITY OF TRAPPING STATES $N(E)$ CALCULATED FROM THE RESPONSIVITY DATA ON SAMPLE 3-1.
Figure 6.2  DENSITY OF TRAPPING STATES $N(E)$ CALCULATED FROM THE RESPONSIVITY DATA ON SAMPLE 3-1. THE STRAIGHT LINE DEPENDENCE INDICATES AN EXPONENTIAL DISTRIBUTION.
the method derived in this chapter makes no a priori assumptions about \( N(E) \), but instead permits the direct determination of \( N(E) \) from the data. However, this method is an approximation, while the indirect method, in principle could be arbitrarily exact if it were not limited by experimental errors and validity of the fundamental assumptions upon which the calculations are based. Because the agreement of the exponential model with experiment was quite good (as shown in Figure 5.7 and 5.8), it was assumed that the exponential model was a valid approximation to \( N(E) \). Therefore a comparison between the exponential model and the density of states just derived would permit and evaluation of the approximate technique for obtaining \( N(E) \) directly from experiment. The parameters given in Table 6.1 were the same as those used in the previous calculations so that both a qualitative and quantitative comparison could be made.

In Figure 6.3 the exponential density of states model is plotted in conjunction with the density of states calculated from Equation 6-26 and given in Table 6.2. The quantitative agreement at low energies correspond to low temperatures as can be verified by looking at Table 6.2. (Consequently the width of \( f'(E_s - E) \) is narrow and thus accurately samples \( N(E) \) as evident from the excellent correlation.)

At higher energies disagreement is exhibited although both show a rapid decrease in \( N(E) \) beyond 0.3 eV. The abrupt cutoff of \( N(E) \) at \( E_m \) for the exponential model is, of course, an approximation and would account for the difficulty in obtaining an accurate experimental fit in the temperature
Figure 6.3  ILLUSTRATION OF THE CORRELATION BETWEEN THE TWO INDEPENDENT TECHNIQUES FOR DETERMINING N(E) FOR SAMPLE K13-18B-3-1: 1) THE SOLID LINE REPRESENTS THE EMPIRICALLY DERIVED EXponential MODEL; 2) THE CIRCLES REPRESENT N(E) AS CALCULATED DIRECTLY FROM THE R vs T DATA.
rolloff region (see Figures 5.7 and 5.8). The cutoff at $E_m$ was an approximation to the rapid exponential decrease in the density of operant traps due to thermal interaction with the conduction band at energies above $E_g/2$ (Section 5.2.1). The second exponential region of the calculated $N(E)$ looks suspiciously like what could be this effect. However, it must be remembered that the resolution of the technique degrades as $kT$ increases; thus the determination of a rapid decrease in $N(E)$ at these energies is limited. In conclusion the actual density of states is probably somewhere in between the two representations in Figure 6.3.

6.4 THE IMPLICATIONS OF THIS METHOD AS TO THE INTERPRETATION OF EXPERIMENTAL DATA

The development of this technique for the direct determination of $N(E)$ from experimental data brought to light some important aspects of this research. Although these aspects were always present, this approach permitted the visualization of the processes involved. The result was a much better intuitive feel for the experiments and the theoretical models used to justify the experimental results.

The important underlying concepts are placed in visual form in Figure 6.4 which depicts the experimental condition at $80 \, ^\circ K$ and $Q_B = 1.0 \times 10^{14} \, \text{ph/s-cm}^2$, where the parameters as given by Table 6.1 have been used in the calculations of the position of $E_g$. The normalized exponential density of states used to fit the data is also shown. The energy gap $E_g$ defines the range of pertinent energies and corresponds to the bandgap
Figure 6.4 "THE DENSITY OF STATES SAMPLING FUNCTION" $\frac{\partial f_T}{\partial E}$ ILLUSTRATED FOR THE TWO TEMPERATURES 20 °K AND 80 °K. FOR PURPOSES OF ILLUSTRATION THE EXPONENTIAL DISTRIBUTION OF TRAPS IS SHOWN. THE OCCUPANCY OF THE TRAPS BY HOLES IS DENOTED BY THE SMALL CIRCLES AND IS DONE FOR THE 80 °K CASE.
of the samples studied. The occupation probability \( f(E_s - E) \) corresponding to 80 °K is included to illustrate the transition between empty traps below \( E_s \) and full traps above \( E_s \).

From Figure 6.4 it can be seen how \( f'_t(E_s - E) \) acts to sample \( N(E) \) as \( E_s \) is changed. In Figure 6.5 the dependence of \( E_s \) on temperature and background is shown along with the energies corresponding to \( kT \). Thus with the aid of Figures 6.5 and 6.4 the position and width of \( f'_t(E_s - E) \) can be found in relation to the energies in the bandgap. At 20 °K \( E_s \) is much closer to the valence band and the half width resolution of \( f'_t(E_s - E) \) is less than 0.01 eV. As the temperature is increased to 80 °K, \( E_s \) increases and the half-width of \( f(E_s - E) \) increases to 0.025 eV.

The most significant fact that came from this analysis, was the realization that our experiments essentially left the first 0.1 eV of the energy gap unexplored. The 80 °K condition shown in Figure 6.4 nearly corresponds to the lowest value of \( E_s \) obtained. The 100 x \( Q_{BO} \) background at 80 °K corresponded to the minimum value of \( E_s \) reached experimentally: 0.95 eV. Therefore, although the various models assumed an \( N(E) \) from zero eV to \( E_m \), the density of trapping states below 0.95 eV is unknown as it had no effect on the experimental measurements. The obvious way to determine the distribution and density of whatever traps exist below 0.95 eV is to take responsivity data at low temperatures.

Indeed plans are being made to carry out such experiments down to 4.3 °K. Not only will \( N(E) \) be determined at these lower energies, but also the fine structure of the distribution could possibly be found due to the higher resolution of the sampling function \( f'_t(E_s - E) \) at lower temperatures.
Figure 6.5  $E_s$ VERSUS TEMPERATURE AT SEVERAL BACKGROUND ILLUMINATION INTENSITIES. THIS ILLUSTRATES THAT THE DEPENDENCE OF $E_s$ ON TEMPERATURE IS MUCH STRONGER THAN ITS DEPENDENCE ON BACKGROUND. $E_s$ WAS CALCULATED FROM $E_s = kT \ln \left( \frac{d N_v}{\eta \tau Q} \right)$ (REF. 5.3).
CHAPTER 7
CONCLUSIONS

Initially this research had the goal of characterizing the photoconductive behavior of Hg$_{0.6}$Cd$_{0.4}$Te in terms of its response time as a function of temperature and background. Further, the hypothesis of minority carrier trapping was to be tested on the basis of these results.

Experimental techniques were devised to carry out this research. The most significant aspect of the experimental approach was the use of solid state GaAs emitters as background and signal sources. These sources emit in the infrared at 0.9 \( \mu \text{m} \) and can be easily biased and modulated to provide a range of measurable background and signal conditions. Measurement of these illumination levels was accomplished by a photometer employing a calibrated silicon photodiode.

The photoconductive process is characterized by a time dependence reflecting the mechanisms of excess carrier capture and recombination in the energy gap. Preliminary experimental results proved this process to be nonlinear and proved a single response time to be undefinable at low temperatures. Thus another experimental approach was pursued which indirectly reflected the recombination process in Hg$_{0.6}$Cd$_{0.4}$Te. The small signal responsivity in the low frequency limit became the principle factor which enabled the study of the recombination process.

The temperature and background dependence of the responsivity has shown the single level trap hypothesis to be unable to account for the data. The introduction of a continuum of traps...
ultimately resulted in a model consistent with the data. In particular, this model assumed a continuous distribution of noninteracting traps whose density of states exhibited a decreasing exponential dependence on energy which terminates at a maximum energy near one half the bandgap.

Finally a method was found for calculating the density of states directly from the responsivity data. Application of this method confirmed the exponential dependence. It further pointed out that the exponential model, based on the experimental results, was validated only for energies above .095 eV. Trapping states of lower energy were found to have negligible effect on the experimental measurements performed.

It is, therefore, concluded that the theory of minority carrier trapping has adequately explained the behavior of Hg$_{0.6}$Cd$_{0.4}$Te within the confines of the experimental measurements. More specifically, the assumption of an exponential distribution of traps has resulted in agreement with the essential features of the experimental results obtained at temperatures from 80 °K to 300 °K in n-type Hg$_{0.6}$Cd$_{0.4}$Te.
There are many areas open to further research. Investigation of the defects or impurities responsible for trapping in Hg$_{0.6}$Cd$_{0.4}$Te immediately comes to mind. Furthermore, the cause of the distribution of traps in the gap warrants further study. One explanation for a distribution has been that the activation energy of a particular acceptor-like impurity or defect center could be modulated by the many short range environments possible in a mixed compound semiconductor. Experiments are being planned which would determine the density of trapping states at lower energies by measuring the responsivity down to temperature as low as 4.3 °K. This experiment is expected to add considerable insight as to the nature and the range of the trap energies thereby aiding the determination of the cause of the distribution in energy. Finally a study of the effects of material parameters on trapping is being undertaken. This includes not only the material parameters specific to Hg$_{0.6}$Cd$_{0.4}$Te, but also the composition parameter x in order that general trapping phenomena in (Hg,Cd)Te can be understood.
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CHAPTER 4


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