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Measurement of minority carrier lifetimes in semiconductors

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MEASUREMENT OF MINORITY CARRIER LIFETIMES IN SEMICONDUCTORS

By
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G. C. Danielson

March 1957

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F. H. Spedding, Director, Ames Laboratory.

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ABSTRACT

The bulk lifetimes of minority carriers in n-type germanium, in both n and p-type silicon and in n-type magnesium germanide have been investigated at room temperature. The sample was illuminated with periodic light flashes produced by a spark gap. The transient change in conductance of the sample after illumination gave the lifetime. In germanium and silicon the measured bulk lifetimes had values from 15 to 140 microseconds with estimated errors of 4 to 15 per cent, respectively. It was not possible to measure the lifetime in magnesium germanide because the particular sample used in this experiment was not sufficiently pure. The general solution of the equation of continuity for the minority carriers in a rectangular sample has been obtained. The particular solution for the boundary and initial conditions of this experiment is discussed.

*This report is based on an M. S. thesis by Yuichiro Nishina submitted March, 1957, to Iowa State College, Ames, Iowa. This work was done, in part, in the Ames Laboratory of the Atomic Energy Commission.
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I. INTRODUCTION

One of the most important physical constants which characterize the behavior of minority carriers in semiconductors is the lifetime of the carriers. This quantity is concerned with the average time for an excited minority carrier to recombine with a majority carrier and thus return to its equilibrium state. It is known that recombination of holes and electrons occurs both on the surface and in the volume of a semiconductor crystal. The lifetime due to volume recombination is the quantity of principal interest in this investigation. Although the mechanism of recombination is not yet completely understood, it is believed that, in substances such as germanium for example, recombination takes place through recombination centers in the crystal. These centers may be considered as trapping levels in the forbidden energy gap (1). Since the recombination centers are formed by imperfections in the crystal, lifetime is also sensitive to crystal perfection.

Lifetime is one of the most important parameters which must be considered in the design of electronic devices which make use of semiconductors.

Since 1949 various methods have been used to measure the lifetime of minority carriers. Shockley and Haynes (2), in the course of their experiment on the measurement of drift mobility, measured the lifetime of minority carriers in ger-
manium and silicon for the first time. This method, which depends upon the broadening of an injected pulse of minority carriers due to diffusion, sometimes encounters difficulty in providing enough carrier injection and in assuring adequate collector linearity (3). With this method it is difficult to measure a lifetime which is less than a few microseconds. In 1952, Valdes (4) reported an equally simple method which depends upon the measurement of photoconductivity with chopped light falling on the sample. This method also determines the lifetime by determining the carrier diffusion length. Serious errors may occur owing to temporary trapping of minority carriers and to collector-nonlinearity (5). The photoelectromagnetic effect is also useful in lifetime measurements and the theoretical analysis and experimental results given by Moss (6) show the possibility of measuring lifetimes smaller than one microsecond. The approximations, however, may not be sufficiently good for Ge or Si, the lifetimes of which are usually 10 to $10^3$ microseconds.

In this investigation, we have attempted to measure carrier lifetimes in germanium, silicon and Mg$_2$Ge single crystals by illuminating the samples with pulsed light from a high voltage spark gap and measuring the transient change in conductance due to the excess minority carriers. The original work using this method was reported by Stevenson and Keyes in 1955 (7). The principal advantage of this method lies in the
technical simplicity of the experiment. In connection with this measurement, the exact solution for the excess minority carrier density was calculated for the case of a rectangular sample and the solution is discussed for the particular conditions encountered in this experiment.
II. THEORY

A. Experimental Principle

The schematic diagram is shown in Fig. 1. When the semiconductor sample is illuminated with pulsed light from the high voltage spark gap, hole-electron pairs are created in the sample and, in this way, a density of minority carriers in excess of the normal equilibrium density is produced. Since charge neutrality has to be conserved even in the unequilibrium state (8), the excess majority carriers have a distribution which is identical to that of the minority carriers. Hence, the relative change in conductivity is,

\[
\frac{\Delta \sigma}{\sigma} = (1 + b) \frac{n}{N},
\]

where

- \( n \) = density of minority carriers in excess of the number in the equilibrium state,
- \( N \) = density of majority carriers at equilibrium,
- \( b \) = mobility of the minority carriers * mobility of the majority carrier.

*This is not necessarily the mobility ratio, electron mobility divided by hole mobility, which is also frequently represented in the literature by the letter b.
Fig. 1. Schematic Diagram of Experiment
The density of minority carriers at equilibrium is assumed to be negligible compared to the density of majority carriers at equilibrium.

Now consider a sample cut in a rectangular shape with dimensions 2A by 2B by 2C in the x, y, and z-directions, respectively. Then, the conductance of the sample between the x-planes, before illumination, is

\[ G = \int_{A}^{A} \frac{dS}{dx} \], \hspace{1cm} (2)

where \( dS = dydz \). The conductance, after illumination, is

\[ G + \Delta G = \int_{\sigma + \Delta \sigma}^{\sigma} \frac{dS}{dx} \]. \hspace{1cm} (3)

For a first-order approximation,

\[ \Delta G = \int_{A}^{A} \left[ \frac{\Delta \sigma}{\sigma^2} \right]^2 \frac{dx}{\sigma} \cdot \int_{A}^{A} \sigma dx dy dz \]. \hspace{1cm} (4)

From (1) and (4), the relative conductance change due to n is

\[ \frac{\Delta G}{G} = \frac{1 + b}{vN} \int n dv \], \hspace{1cm} (5)

where

\[ dv = dx dy dz, \text{ and} \]

\[ v = 8ABC. \]

The relative conductance change, therefore, is proportional to the total number of minority carriers in the sample.
If a constant direct current is flowing along the x-direction, the relative change in the voltage across the sample is \(- \frac{\Delta G}{G}\). The time dependence of this voltage can be observed on the oscilloscope if an adequate amount of voltage amplification is used.

The question thus reduces to obtaining the solution for \(n\), which is subject to the equation of continuity under given boundary and initial conditions. The time dependence of \(n\) is related to the bulk lifetime which is to be measured in this experiment.

B. Solution of the Equation of Continuity

The density of excess minority carriers, \(n(x, y, z, t)\), satisfies the equation of continuity,

\[
\frac{\partial n}{\partial t} = - \frac{n}{\tau} - \mu \vec{E} \cdot \nabla n + D \nabla^2 n, \tag{6}
\]

where

\(\tau\) = the bulk lifetime,
\(D\) = the diffusion constant,
\(\mu\) = the drift mobility, and
\(\vec{E}\) = the electric field applied to the sample.

The coordinate axes are shown in Fig. 2 with the origin at the center of the rectangular sample. The sample plane \(z = C\) is illuminated with visible light of uniform intensity
Fig. 2. Coordinate Axes for the Sample

Shaded planes, \( x = -A \), were lapped. The rest of the surfaces, \( y = -B \) and \( z = -C \), were etched.
for a period small compared to the lifetime. The constant
direct current along the x direction is produced by the applied
electric field $E_x = E$.

Using the method of separation of variables, we let
\[ n(x,y,z,t) = X(x) Y(y) Z(z) T(t). \]  
(7)
The solution to equation (6) is determined by the following
boundary conditions;

\[
\begin{align*}
\mu E n - D \frac{\partial n}{\partial x} &= \pm S_x n \quad \text{at } x = \pm A, \\
- D \frac{\partial n}{\partial y} &= \pm S_y n \quad \text{at } y = \pm B, \\
- D \frac{\partial n}{\partial z} &= \pm S_z n \quad \text{at } z = \pm C;
\end{align*}
\]
(8)
and by the following initial conditions at $t = 0$, when the
pulsed illumination stops;
\[ X(x) = H_x, \text{ which is constant for } -A < x < A, \]
\[ Y(y) = H_y, \text{ which is constant for } -B < y < B, \]
\[ Z(z) = H_z e^{\lambda z} \text{ for } -C < z < C. \]
(9)
The constants $S_x$, $S_y$ and $S_z$ are surface recombination veloc-
ities of the $x$, $y$, and $z$ surfaces of the sample respectively,
and $\lambda$ is the absorption constant for the light.

It can be shown (9) that the general solution consists
of the infinite series,
\[
n(x,y,z,t) = \sum_{ijk} n_{ijk} + \sum_{ik\ell} n_{ik\ell} = \sum X_i(x) Y_j(y) Z_k(z) T_{ijk}(t) \\
+ \sum X_i(x) Y_j(y) Z_\ell'(z) T_{ij\ell'}(t),
\]
(10)
where \( i, j, k, \) and \( \ell = 1, 2, 3, \ldots \).

In this expression,

\[
X_i = e^{\frac{\mu E x}{2D}} (C_{1i} \cos a_{xix} + C_{2i} \sin a_{xix}),
\]

\[
Y_j = C_{3j} \cos a_{yjy},
\]

\[
Z_k = C_{5k} \cos a_{zkz},
\]

\[
Z_\ell = C_{6\ell} \sin a_{z\ell z}, \text{ and}
\]

\[
T_{ijk} = H_t \exp \left\{ -\frac{1}{\ell} + D \left( a_{xix}^2 + a_{yjy}^2 + a_{zkz}^2 \right) + \frac{\mu E^2}{4D} \right\} t,
\]

where \( H_t \) is a constant.

The quantity \( T_{ij\ell} \) is similar to \( T_{ijk} \) except that \( k \) and \( H_t \) are replaced by \( \ell \) and \( H_t' \), respectively.

In equations (11), the \( a \)'s are eigenvalues which satisfy the following equations:

\[
\tan 2a_{xix} = \frac{2 S_x D a_{xix} \left( \frac{\mu E}{2} \right)}{\left( \frac{\mu E}{2} \right)^2 + \left( D a_{xix} \right)^2 - S_x^2},
\]

\[
a_{yjy} \tan a_{yjy} = \frac{S_y B}{D},
\]

\[
a_{zkz} \tan a_{zkz} = \frac{S_z C}{D},
\]

\[
a_{z\ell} \cot a_{z\ell} = \frac{-S_z C}{D},
\]

\[
(12)
\]
The boundary conditions (8) give (12) and the following relation:

\[
\frac{C_{2i}}{C_{1i}} = \frac{a_{x1} D \tan a_{x1} A + \frac{\mu E}{2} - S_x}{a_{x1} D - \left(\frac{\mu E}{2} - S_x\right) \tan a_{x1} A} = -\frac{a_{x1} D \tan a_{x1} A + \frac{\mu E}{2} + S_x}{a_{x1} D + \left(\frac{\mu E}{2} + S_x\right) \tan a_{x1} A}.
\]

The multiplicity of \(a_{x1}, a_{y1}, a_{z1}\) and \(a_{z1}\) indicates that the carrier density distribution, in general, consists of various modes of density change in the \(x, y\)- and \(z\)-directions. Each combination of \(a\)'s, which are the solutions of equation (12), has its own characteristic decay time constant which can be obtained by substituting these \(a\)'s in \(T_{ijk}\) of (11).

As in the cases of Fourier series expansion, the ortho-normality of each term of the series in (11) and the initial conditions (9) determine the \(C_{1i}, C_{2i} ---- C_{6i}\) as follows:

\[
C_{1i} = \frac{\int_{-A}^{A} H_x e^{-\frac{\mu E x}{2D}} \cos a_{x1} x \, dx}{\int_{-A}^{A} \cos^2 a_{x1} x \, dx} = \frac{2H_x a_{x1} \left[ \cosh \frac{\mu E}{2D} A \sin a_{x1} A + \frac{\mu E}{2D} \sinh \frac{\mu E}{2D} A \cos a_{x1} A \right]}{\left( \frac{\mu E}{2D} \right)^2 + a_{x1}^2 \left[ A + \frac{1}{2a_{x1}} \sin 2a_{x1} A \right]};
\]

(14)
\[ C_{3j} = \frac{H_y \int_B^0 \cos a_{yj}y \, dy}{\int_B^0 \cos^2 a_{yj}y \, dy} \]

\[ = \frac{4H_y \sin a_{yj}B}{B + \frac{1}{2a_{yj}} \sin 2a_{yj}B} ; \quad (15) \]

\[ C_{4j}, \text{ corresponding to } \sin a_{yj}y, \text{ is zero because of the symmetry in the } y \text{ distribution;} \]

\[ C_{5k} = \frac{H_z \int_{-c}^{c} e^{\lambda z} \cos a_{zk}z \, dz}{\int_{-c}^{c} \cos^2 a_{zk}z \, dz} \]

\[ = \frac{(2a_{zk})^2 H_z \left[ \cosh \lambda C \sin a_{zk}C + \frac{\lambda}{a_{zk}} \sinh \lambda C \cos a_{zk}C \right]}{\left( \lambda^2 + a_{zk}^2 \right) (2a_{zk}C + \sin 2a_{zk}C)} ; \quad (16) \]

\[ C_{6\ell} = \frac{H_z \int_{-c}^{c} e^{\lambda z} \sin a_{z\ell}z \, dz}{\int_{-c}^{c} \sin^2 a_{z\ell}z \, dz} \]

\[ = \frac{(2a_{z\ell})^2 H_z \left[ \frac{\lambda}{a_{z\ell}} \cosh \lambda C \sin a_{z\ell}C - \sinh \lambda C \cos a_{z\ell}C \right]}{\left( \lambda^2 + a_{z\ell}^2 \right) (2a_{z\ell}C - \sin 2a_{z\ell}C)} . \quad (17) \]
The total number of minority carriers in the sample volume is,

\[ \int n \, dv = \sum_{ijk} Q_{ijk} + \sum_{ij \ell} Q'_{ij \ell} = \sum_{ijk} Q_{ijk}, \]

over \( v \)

where

\[ Q_{ijk} = \int n_{ijk} \, dv = T_{ijk} \int \limits_{-A}^{A} X_{i} \, dx \int \limits_{-B}^{B} Y_{j} \, dy \int \limits_{-C}^{C} Z_{k} \, dz, \]

(18)

and \( Q'_{ij \ell} = 0 \) since \( \int \limits_{-C}^{C} Z_{\ell} \, dz = 0. \)

From (11),

\[ \int \limits_{-A}^{A} X_{i} \, dx = \frac{4DC_{11}}{\mu E} \left[ \frac{2D}{E} a_{x1} C_{21} \right] \cos a_{x1} A \sinh \frac{\mu EA}{2D} \]

\[ + \left( \frac{2D}{E} \frac{a_{x1}}{C_{11}} + \frac{C_{21}}{C_{11}} \right) \sin a_{x1} A \cosh \frac{\mu EA}{2D} \],

(19)

\[ \int \limits_{-B}^{B} Y_{j} \, dy = \frac{2C_{31}}{a_{yj}} \sin a_{yj} B, \]

(20)

\[ \int \limits_{-C}^{C} Z_{k} \, dz = \frac{2C_{5k}}{a_{zk}} \sin a_{zk} C. \]

(21)

Equations (14) to (21) show how the higher modes of carrier distribution are superposed upon the fundamental
The time constant of the fundamental mode is important for bulk lifetime measurement. Thus the measurement of the time constant of $T_{111}(t)$ gives the bulk lifetime, $\tau$, if the diffusion constant, $D$, the surface recombination velocities, $S$'s, the drift mobility, $\mu$, and the applied electric field, $E$, are known.

For the special case of this experiment the surface treatment was made on the sample such that $S_x$ was very large and both $S_y$ and $S_z$ were small. Then, from (13),

$$1 - \frac{2Da_1C_{11}}{\mu E C_{11}} = \frac{2S_x^2}{(Da_1)^2 + 2S_x^2},$$  \hspace{1cm} (22)

or

$$\frac{2Da_1}{\mu E} + \frac{C_{21}}{C_{11}} = \frac{2Da_1}{\mu E} + \frac{\mu EDa_1}{2[(Da_1)^2 + 2S_x^2]}.$$

These two expressions are to be substituted in (19). If $S_x = \infty$, the first equation of (22) gives

$$1 - \frac{2Da_1}{\mu E} \frac{C_{21}}{C_{11}} = 1$$  \hspace{1cm} (23)

which is equivalent to $\frac{C_{21}}{C_{11}} = 0$ in the second equation.

If $S_x$ is sufficiently large so that $\frac{S_x}{Da_1} \gg 1$, the first equation in (12) gives the following two solutions:
\( a_{x1} \tan a_{x1}A = \frac{S_x A}{D} \) for \( i = 1, 3, 5 \ldots \) (24)

\( a_{x1} \cot a_{x1}A = \frac{-S_x A}{D} \) for \( i = 2, 4, 6 \ldots \)

Using (24) and (13), if \( S_x = \infty \),

\[
C_{2i} = 0 \quad \text{for} \quad i = 1, 3, 5 \ldots \quad (25)
\]

\[
C_{1i} = 0 \quad \text{for} \quad i = 2, 4, 6 \ldots
\]

Also, if \( S_y = 0 \), the second equation in (12) gives

\[
a_{yj} = \frac{(j-1) \pi}{B}
\]

\[
\int_{-B}^{B} Y_1 \, dy = 2 \, C_{31} B = \int_{-B}^{B} Y \, dy \quad \text{for} \quad j = 1
\]

\[
\int_{-B}^{B} Y_j \, dy = 0 \quad \text{for} \quad j = 2, 3 \ldots
\]

Similarly, if \( S_z = 0 \), the third equation in (12) gives

\[
a_{zk} = \frac{(k-1) \pi}{C}
\]

\[
\int_{-C}^{C} Z_1 \, dz = 2 \, C_{51} C = \int_{-C}^{C} Z \, dz \quad \text{for} \quad k = 1
\]

\[
\int_{-C}^{C} Z_k \, dz = 0 \quad \text{for} \quad k = 2, 3 \ldots
\]
For determining the bulk lifetime, it is necessary to measure the time constant of the fundamental mode of the density distribution, namely the exponential factor of $T_{ijk}$ in (11) for $i = j = k = 1$. As shown in (26) and (27), there are no contributions from the higher modes in the $y$ and the $z$ directions for the particular case of the present experiment. Only the higher modes in the $x$-direction can contribute to the change in conductance of the sample.
III. EXPERIMENTAL ARRANGEMENT

A. Sample Illumination

In order to present on the scope the transient voltage proportional to $\int n \, dv$ in (18), the sample must be illuminated with pulsed light of fixed repetition frequency. The triggering circuit for producing a spark between the needle gap in Fig. 1 consists of a high voltage thyratron 5C22 and a pulse generator which is connected to the thyratron grid. This arrangement provides the light pulse of about 0.1 to 0.5 microsecond with a repetition frequency of 3.3 kc/sec.

A tungsten wire of diameter 1.0 mm was used for the needle gap. The gap distance was made adjustable by the screw supporting rod.

The focusing arrangement shown in Fig. 3 throws the beam of light on the whole z-plane of the crystal surface with uniform intensity. Such illumination corresponds to the initial conditions expressed in (9).

For future work further improvements on stabilization of the light pulse would be desirable, since fluctuations give rise to a 10 to 20 per cent change in signal height. In the present experiment, this difficulty was alleviated by an adjustment of the triggering level of the scope to the highest signal output, although this adjustment involved considerable sacrifice of signal intensity.
Fig. 3. Optical System
B. Constant Current Source

As in Fig. 4, the insertion of a high resistance in series with the sample and voltage source provides a constant direct current which is stable enough for this measurement. The choice of series resistance was made so that the sample resistance would be less than 2 per cent of this series resistance. The entire current supply was shielded in order to minimize electrical noise from the spark gap.

The decay time constant of this circuit without sample connection was over two milliseconds. This time was much longer than the 10 to 50 microseconds time constant for the voltage change across the sample. So the effect of the decay time constant of the circuit on the transient voltage across the sample was considered negligible.

C. Presentation System

The transient signal produced across the sample was amplified by the preamplifier of the Los Alamos Model 500 pulse amplifier* which was connected to a Tektronix 511 AD scope. The gain of the preamplifier was 29.4 db at 5 kc/sec.

Fig. 4. Constant Current Circuit
The amplifier in the scope was used at maximum amplification throughout all the measurements. At 5 kc/sec the sinusoidal input signal of 0.375 rms volts to the scope gave 3 units of peak-to-peak deflection on the scale of the scope. The highest voltage change observed across the sample was 90 ± 5 millivolts which corresponds to 4.5 ± 0.1 units of positive deflection on the scope scale.

Amplitude and sweep linearity of the over-all amplifying system was calibrated with a Hewlett-Packard 650 A test oscillator. The relative accuracies of amplitude and sweep correction were 2 per cent and 1 per cent, respectively.

The frequency characteristic of the over-all amplifying system showed the cut-off frequency to be 2.4 Mc/sec at 2 db down with respect to the mid-band gain. An analysis was made on the relationship between the cut-off frequency and the relative error of the measured time constant, $\tau_m$. For the voltage signal, we have

$$V = \text{Const.} \ e^{-t/\tau_m}, \quad (28)$$

where $0 < t < T$, $T$ is the repetition period, and $\tau_m$ corresponds to the time constant of $T_{111}(t)$ in (11). Under the assumption that the frequency characteristic of the amplifier is uniform up to the cut-off frequency, $\omega_c$, the maximum relative error in $\tau_m$ is,
Max. \left[ \frac{\Delta \tau_m}{\tau_m} \right] = \text{Max.} \left[ \frac{e^{t/\tau_m}}{t} \right] \frac{1}{2 \pi \omega_c}, \quad (29)

where \text{Max.} \left[ \frac{e^{t/\tau_m}}{t} \right] \text{ is dependent on the time range of measurement. According to (29) the maximum of } \frac{\Delta \tau_m}{\tau_m} \text{ is not more than 0.4 per cent for the samples used in this experiment. This amount of uncertainty is not serious compared to the other sources of errors.}

D. Sample

The lifetime measurement was made on several samples described in Table 1. In germanium and silicon, x-planes of

<table>
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<tr>
<th>Sample No.</th>
<th>Substance</th>
<th>Sample Size A</th>
<th>Sample Size B</th>
<th>Sample Size C</th>
<th>Resistance* at 25°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Ge n-type</td>
<td>7.25 m.m.</td>
<td>4.50 m.m.</td>
<td>1.00 m.m.</td>
<td>0.120 k.ohm</td>
</tr>
<tr>
<td>2.</td>
<td>Si p-type</td>
<td>6.65 m.m.</td>
<td>4.20 m.m.</td>
<td>0.70 m.m.</td>
<td>10.0</td>
</tr>
<tr>
<td>3.</td>
<td>Si n-type</td>
<td>12.10 m.m.</td>
<td>3.75 m.m.</td>
<td>0.45 m.m.</td>
<td>1.25</td>
</tr>
<tr>
<td>4.</td>
<td>Mg₂Ge n-type</td>
<td>5.75 m.m.</td>
<td>0.65 m.m.</td>
<td>0.60 m.m.</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

*Measured at the lead ends soldered to the sample.
the samples were lapped with chrome rouge*. The ultrasonic soldering gun** was used to solder the copper lead wires to the x-planes since ordinary soldering methods were not effective for these substances. The y- and z-planes were etched with C-P 4 etching solution***.

In calculating the bulk lifetime from the measured time constant, \( \tau_m \), of the transient voltage change across the sample, it was assumed that the recombination velocities for the x planes were infinite and those for the y- and z-planes were zero. These assumptions correspond to the case where the density of carriers at the \( x = \pm A \) is zero and there are no higher modes of density distribution in the y- and z-directions.

Actually, the effect of surface recombination on the measured time constant, \( \tau_m \), is not significant unless the sample dimension is of the order of 1 mm or smaller****.

---


**Mfd. by Mullard Co. London, England. Solder consists of 90 per cent Sn and 10 per cent Zn.

***15 per cent acetic acid, 25 per cent conc. HNO₃, 15 per cent HF and 0.3 per cent Br.

****This means that, \( \frac{1}{\tau} \Rightarrow D(a_{x_i}^2 + a_{y_j}^2 + a_{z_k}^2) \) in (11).
For this reason it may be considered that the higher modes in the x distribution do not affect $\tau_m$ by any measurable amount.

Both ends of the sample were covered with black tape so that the photo-voltaic effect at the lead junction would not disturb the measurement. This effect was observed in Si samples and it gave an exponential signal on the scope similar to that produced by the photoconductive decay. The former could be identified, however, by the fact that this signal remained present even in the absence of current through the sample, whereas the latter was dependent on the magnitude and polarity of the current.
IV. RESULTS AND DISCUSSION

A. Germanium and Silicon

For Ge and Si samples, the transient signal on the scope was copied on tracing paper and the voltage change was plotted on semilog graph paper by use of a calibration process.

For example, the case of n-type Ge (No. 1) is shown in Fig. 5 and in Fig. 6. The calibration of the signal pattern along the horizontal and vertical axes of Fig. 5 gave the curve in Fig. 6. The curve indicates that the contribution from the fundamental mode of density distribution is predominant over the most range of the voltage change. Thus, from Fig. 6,

\[ T_m = 46.8 \pm 0.5 \text{ microseconds} \quad \text{and} \]

\[ \frac{1}{T_m} = \frac{1}{\tau} + D (a_{xl}^2 + a_{yl}^2 + a_{zl}^2) + \left( \frac{\mu E}{4D} \right)^2. \]

The measured value of the electric field was

\[ E = 0.93 \pm 0.05 \text{ volt/cm}. \]

Assuming \( S_x = \infty \), \( S_y = S_z = 0 \)

\[ a_{xl} = \frac{\pi}{2A} = \frac{\sqrt{3} \cdot 1.14}{2 \times 0.725} = 2.16 \text{ (1/cm)} \quad \text{from (24)} \]

\[ a_{yl} = a_{zl} = 0 \quad \text{from (26) and (27)}. \]

For the given values of the hole mobility, \( \mu = 1700 \text{ cm}^2/\text{V sec} \), and the hole diffusion constant \( D = 44 \text{ cm}^2/\text{sec} \),
Fig. 5. C.R.O. Trace of Photoconductive Voltage
Fig. 6. Photoconductive Voltage vs. Time
Hence, the bulk lifetime is given by

\[
\frac{1}{\tau} = (2.14 - 1.42 - 0.02) \times 10^4 \pm 0.12 \times 10^4 \text{ (second)}^{-1}
\]

or \( \tau = 140 \pm 20 \) microseconds.

The results of calculated bulk lifetimes for the three samples are shown in Table 2. Due to the limitation on available gain of the amplifying system the dc field was certain to be large so that the electric field term could not be ignored.

Table 2. Measured Results of Lifetimes in Ge and Si*

<table>
<thead>
<tr>
<th>No.</th>
<th>Sample</th>
<th>Diff. Const.</th>
<th>Elec. Field</th>
<th>Mobility</th>
<th>Measured Time Const.</th>
<th>Bulk Lifetime ( \tau )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Ge n-type</td>
<td>44.0</td>
<td>0.93±0.05</td>
<td>1700</td>
<td>46.8±0.5</td>
<td>140±20</td>
</tr>
<tr>
<td>2.</td>
<td>Si p-type</td>
<td>31.0</td>
<td>0.52±0.05</td>
<td>1200</td>
<td>13.9±0.2</td>
<td>14.7±0.5</td>
</tr>
<tr>
<td>3.</td>
<td>Si n-type</td>
<td>6.47</td>
<td>0.20±0.02</td>
<td>250</td>
<td>29.5±1.3</td>
<td>30±2</td>
</tr>
</tbody>
</table>

*Measured at 25°C
neglected in the calculation of \( \tau \) from \( \tau_m^* \). The electric field in the sample was measured with a dc potentiometer and a drift mobility probe set. As shown in Table 2, the accuracy of the calculated \( \tau \) was determined principally by the accuracies of \( \tau_m \) and \( E \).

The intensity of the pulsed light was adjusted to the appropriate level by changing either the spark gap separation or the dc high voltage so that over-injection of minority carriers would not take place in the neighborhood of the illuminated surface. When over-injection was present, the initial decay rate of the photoconductance was smaller than for the case of small injection, as shown in Fig. 7. In the region where over-injection exists, bulk lifetime is no longer independent of the carrier density and this fact can cause a deviation from exponential decay (10). Such deviations were observed oftener in the case of Si samples than in the case of Ge samples. According to Walters and Ludwig (11), Si has more tendency to cause over-injection than Ge because the absorption coefficient of Si is higher than that of Ge. Also, the difference in the over-injection might have been caused by

\[ \frac{1}{\tau} \approx \left( \frac{\mu_E}{\mu_D} \right)^2 \text{ in (11)}. \]
Fig. 7. Example of C.R.O. Pattern for Over-Injection
the difference in quantum efficiency over the wavelength of the spark light or by the difference in mobility and diffusion constant.

In n-type Ge sample (No. 1) \( \tau_m \) decreased about 17 per cent as the temperature was changed from 312 to 358°K. Additional measurements would be necessary over a wider temperature range in order to determine the temperature dependence of the bulk lifetime.

B. Magnesium Germanide

It was not possible to observe photoconductive decay in the available Mg\(_2\)Ge single crystal at room temperature for sample currents from 0 to 10 milliamperes\(^*\).

The dc conductivity was also measured with a potentiometer when the sample, supplied with constant current, was illuminated with a 75-watt tungsten lamp. Without illumination the voltage across the sample was 50.60 ± 0.01 millivolts. The voltage change due to the illumination, however, was less than 0.005 millivolts or essentially zero.

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\(^*\)This sample was in the saturation range from 77 to 435°K. The resistance of the sample was 2.5 at 298°K, which corresponds to the resistivity of about 0.04 ohm cm.
The principal reason for this difficulty is probably that the particular sample used in this measurement was not sufficiently pure. The resistivity of the Mg$_2$Ge at room temperature was smaller than the resistivities of Ge and Si by at least a factor of 10. Since the voltage change due to the photoconductivity is inversely proportional to the square of sample conductance for constant direct current, the photoconductive voltage was not large enough to be observed on the scope. Also, it is possible that if the density of impure atoms were high, the density of imperfections in crystal structure would also be high. The lifetime might then be smaller than 0.1 microsecond and such short lifetimes could not have been measured with the pulsed light described in this experiment.

Recently samples of higher purity have been developed in the solid state physics group at the Ames Laboratory and the dc photoconductivity of these crystals is large enough to be measured with the technique described above.*

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*Private communication from R. D. Redin.
V. CONCLUSION

Among the various ways of measuring minority carrier lifetime, the pulsed illumination method was chosen because of its technical simplicity and its freedom from some serious errors which may exist in other methods.

The exact solution of the equation of continuity has been obtained for the case of a rectangular sample. The general solution indicates that the carrier density distribution consists of a linear superposition of various modes in sample space, each mode having its own characteristic decay time constant. Only the fundamental mode is important for bulk lifetime measurements and the presence of higher modes is not desirable. Equations have been obtained for the relative amplitude and time constant of each mode.

The measurements were made for n-type germanium, for both n- and p-type silicon, and for n-type magnesium germanide (Mg₂Ge). In Ge and Si the bulk lifetimes were found to be in the range from 15 to 140 microseconds. It was impossible to observe photoconductivity in the only Mg₂Ge sample which was available.

If some trapping level exists, it has been suggested (12) that the ordinary photoconductive decay may be followed by a long tail which can be eliminated by steady back-ground light. None of the samples used in our experiment showed this effect.
The lower limit for the measurable lifetime is determined by the pulse-width of the illumination and by the gain bandwidth of the amplifying system. With the present experimental arrangement it was not possible to measure lifetimes less than 0.1 microsecond.
VI. LITERATURE CITED