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Transient Photo Conductivity Decay Study on Polycrystalline Silicon

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Abstract. — The decay time constants of the transient photo conductivity for six polycrystalline silicon wafers of different grain sizes are analyzed as a function of temperature (90 to 450 K). The photo conductivity decay is split into three components, namely, surface, shallow traps and deep traps in grain boundary, which are analyzed in terms of the effect of surface recombination velocity, changes in carrier mobility and grain boundaries. This is utilized to evaluate the temperature dependence of mobility and grain boundary potential in polysilicon samples.

1. Introduction

In polycrystalline semiconductors, the minority carrier lifetime is greatly affected by the presence of Grain Boundaries (GBs). These GBs give rise to a high density of interface states which trap carriers from the surrounding grains forming a barrier potential, known as grain boundary potential (\( \Phi_B \)) [1]. As polycrystalline material is obtained by fast growth techniques, defects formed due to the grain boundary interfaces and also intra-grain defects are unavoidable. The presence of the grain boundaries affects the mobility of the carriers and hence, the photo conductivity decay of polycrystalline materials takes into account not only the lifetime but also the changes in the effective mobility of the minority carriers. This paper analyses experimentally the effect of the grain boundary on the measured photo conductivity decay time constant.

The Transient Photo Conductivity Decay (TPCD) technique is an usual method to measure the decay time constant in silicon samples. In single crystal silicon material, Haynes and Hornbeck [2] have shown that the TPCD split into three sections viz. (1) rapid decrease due to the recombination of electrons before the occupancy of the traps change (2) decay due to the shallow traps being emptied before the deep traps change appreciably and (3) longest decay due to the emptying of deep traps. In the case of polysilicon, TPCD response is split into three regions viz. (1) the surface recombination denoted in this paper as region-1, (2) recombination in grains due to the recombination centres or shallow traps or permanent traps, denoted as region-2, and (3) interface or grain boundary carrier recombination due to the deep trapping or temporary trapping in the grain boundaries, denoted as region-3. While the

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"surface component" depends on the surface recombination velocity, diffusion coefficient and thickness of the sample [3,4], the other components entirely deals with the traps, their capture cross section and energy levels. Usually, surface carrier lifetime is less than 5 to 10 μs and trapping phenomena occupies in the order of hundreds of microseconds. GBs provide very efficient trap sites whose concentration is decided by the grain size (GS). These trap sites are responsible for the tail of the decay curve with the time constant in the order of milliseconds.

The paper studies the effect of temperature on these three decay components. Though the excitation intensity is very low, it is observed that the carrier mobility also changes in the case of polysilicon. The temperature variation of decay constants are affected by the mixed response due to the variation in the carrier mobility and the grain boundary potential. Using this, the grain boundary potential as well as the temperature dependence of minority carrier mobility are evaluated in these materials.

2. Theory

The application of excitation light on the surface of an n-type semiconductor sample creates excess electron-hole pairs. The excess carriers generated may recombine at the lighted sample surface, diffuse through the bulk of the sample to reach the other surface and recombine there (bulk recombination). Under light excitation, the spatial distribution of the minority carriers can be represented as [5]

\[ D \frac{d^2 \Delta p}{d^2 x} - \frac{\Delta p}{\tau} = G \]  

where \( D \) is the minority carrier diffusion coefficient, \( \Delta p \) is the excess minority carrier concentration, \( G \) is the generation rate, and \( \tau \) is the minority carrier lifetime. Once the excitation source is switched off, then the carriers decay exponentially with time constant, \( \tau \). In the carrier recombination decay (\( 1/\tau = 1/\tau_s + 1/\tau_b \)), two decay channels are distinguished: bulk recombination characterized by bulk carrier lifetime (\( \tau_b \)) and surface recombination (\( \tau_s \)) occurring in a two dimensional region at the large faces of the wafer characterized by the surface recombination velocity (\( S_s \)) defined as [6],

\[ \left| D \left( \frac{dp}{dx} \right)_{x=s} \right| = S(\Delta p)_{x=s} \]  

The minority carrier surface recombination contribution (known as the surface carrier lifetime (\( \tau_s \))) is given by [7] (assuming \( S_s \ll 2D/d \)),

\[ \tau_s = \frac{d}{2S_s} \]  

where \( d \) is the thickness of the material. Equation (3) is for the surface recombination limited case where the minority carrier density gradients induced by surface recombination are compensated by the diffusion instantaneously.

The surface recombination velocity depends on the concentration of trap states (\( N_t \)) and their capture cross section (\( \sigma^{\text{min}} \)) and is given by [8],

\[ S_s = \sigma^{\text{min}} v^{\text{th}}_n N_t \]  

where \( v^{\text{th}}_n \) is the thermal velocity of the carriers.
The grain boundary edges constitute areas of high recombination velocity and it is denoted here as grain boundary recombination velocity \( (S_B) \). The recombination velocity at the grain boundaries is given by [9],

\[
S_B = e^{-1}v_{th}^{\min} \sigma^{\min}(2e\varepsilon_0N_G\Phi_B)^{1/2} \exp \left( \frac{\Phi_B}{kT} \right)
\]

where \( N_G \) is the doping level in the grains and \( \varepsilon, \varepsilon_0 \) are the dielectric permittivity of material and free space respectively.

The resultant decay is the net results of both surface carriers \( (\tau_s) \), shallow traps in grains \( (\tau_g) \) and deep traps in grain boundaries \( (\tau_{gb}) \). It is conventionally followed that the resultant recombination carrier lifetime is given by the inverse addition of all the individual carrier recombination lifetimes.

\[
\frac{1}{\tau} = \frac{1}{\tau_s} + \frac{1}{\tau_g} + \frac{1}{\tau_{gb}}
\]

Though the excess carrier recombination phenomena (Eq. (6)) proposes a single carrier lifetime \( (\tau) \), the trapping-detrapping phenomena is responsible for the actual decay curve to undergo a non-exponential pattern.

In n-type polycrystalline silicon, the transient photo conductivity at temperature, \( T \), and under the excitation intensity, \( I \), is expressed as [10],

\[
\left( \frac{\Delta \sigma(t)}{\sigma_0} \right)_{T,I} = \left[ \frac{1 + \mu_p}{\mu_n} \frac{\Delta p(t)}{n} + \frac{\Delta \mu_n(t)}{\mu_n} \right]_{T,I}
\]

where \( \sigma_0 \) is the dark conductivity, \( \Delta \sigma \) is the increase in conductivity, \( \mu_p \) and \( \mu_n \) are the mobilities of minority and majority carriers respectively, \( \Delta p \) is the excess minority carrier concentration and \( \Delta \mu_n \) is the excess majority carrier mobility (hereafter denoted in this paper as excess mobility, \( \Delta \mu \)).

The \( \Delta \mu \) defined as [11],

\[
\Delta \mu = \mu_g - \mu_{eff}
\]

where \( \mu_g \) is the carrier mobility in single crystal and \( \mu_{eff} \) is the effective carrier mobility measured in polycrystal arising out of the effect of the grain boundaries [12]. The effective mobility \( (\mu_{eff}) \) is a function of the grain boundary potential \( (\Phi_B) \) and decreases exponentially with increase in \( \Phi_B \) [12]. Since \( \Phi_B \) is a function of applied light illumination and temperature, \( \Delta \mu \) is also a function of temperature and applied light illumination. Keeping the applied light illumination constant, using the thermonic emission diffusion model [12], the temperature dependence of \( \Delta \mu \) is written as,

\[
(\Delta \mu)_T = \mu_g(300)T^{-X} \left[ 1 - \frac{qLE_b(T)}{kT} \exp \left( -\frac{\Phi_B(T)}{kT} \right) \right]
\]

where \( q \) is the charge of the carrier, \( L \), diameter of the grain, \( E_b \), the maximum built-in electric field in the space charge layer at the grain boundary and \( \mu_g(300) \) denotes the carrier mobility at grains at 300 K. \( T^{-X} \) represents the reduction in the carrier mobility arising out of carrier-lattice scattering due to increase of temperature. Here, \( \Delta \mu \) is not zero and therefore, the transient nature of the excess conductivity decay does not follow an exponential pattern.

The excess photo voltage \( (\Delta V) \) observed due to the application of excitation light illumination is given by [10],

\[
\Delta V = V_0 \frac{\Delta \sigma}{\sigma_0}
\]
where $V_0$ is the absolute value of the photo voltage. Using equation (8), one can conclude that for an n-type polysilicon, the decay of the excess photo voltage ($\Delta V(t)$) is the function of $\Delta p(t)$ and $\Delta \mu(t)$.

$$\Delta V(t) = f(\Delta p(t), \Delta \mu(t)).$$

Equation (11) points out that the TPCD signal does not follow an exponential due to the involvement of excess majority carrier mobility. Throughout this work, the intensity of the applied light illumination is kept constant while the temperature is varied. It is also assumed that the transient nature of the change in the mobility ($\Delta \mu(t)$) does not affect the decay considerably. But due to the increase in temperature, $\Delta \mu_T$ varies and from this variation, the temperature dependence of minority carrier mobility is calculated.

2.1. Region-1: Surface Carrier Contribution. — In this region, using equations (7), (9) and (10), the temperature dependence of photo voltage decay curve is written as [11],

$$\left( \exp \left( -\frac{t}{\tau^*_s} \right) \right)_T = B_1 \exp \left( -\frac{t}{\tau_s} \right) + A_1 T^{-Y}$$

where

$$T^{-Y} = T^{-X} \left[ 1 - \frac{qL E_b}{kT} \exp \left( -\frac{\Phi_B}{kT} \right) \right].$$

Here it is assumed that the effect of $\Phi_B(T)$ is negligible on $\tau^*_s$. $T^{-Y}$ denotes the temperature dependence of mobility due to the lattice in polycrystal and $Y$ is always greater than $X$. If an intense white background light illumination is applied, the deep traps in the grain boundaries get saturated. In this situation, the value of $\Phi_B$ and $E_b$ approaches zero. Therefore, the value of $Y$ approaches $X$. The value of $X$ for single crystal silicon is 2.5 for electrons and 2.7 for holes [8]. $\tau^*_s$ is the decay constant measured and $\tau_s$ is the actual surface carrier lifetime. $B_1$ and $A_1$ are constants and depend on various parameters at 300 K such as $\mu_p$, $\mu_n$, $n$ (concentration of majority carriers) and $V(0)$. Therefore, from the decay curve obtained at different temperatures, one can get the values of $\tau^*_s(T)$. A power law fitting of $\tau^*_s(T)$ with temperature $T$ gives the value of $Y$.

2.2. Region-2: Shallow Traps in Grains. — This region occupies 20 to 500 $\mu$s in the TPCD response and comprises of recombination centres and shallow trap states in the bulk of the grain. The shallow traps refer to the traps which have lesser holding time when compared to the deep traps.

The form of equation (12) is valid here also but the $\tau_s$ is replaced by $\tau_g$ and the decay constant measured is denoted as $\tau^*_g$. $\tau_g$ depends on the shallow traps in grains and grain boundaries. Since, only the shallow traps are considered, the temperature dependence of $\Phi_B$ is not considered in this region. The temperature dependence of $\tau^*_g$ is proportional to the $(\Phi_B)^{-0.5}(\exp(-\Phi_B/kT))$ since it is inversely proportional to the grain boundary recombination velocity $S_B$. Therefore, the photo voltage decay, at a temperature $T$, is given by,

$$\left( \exp \left( -\frac{t}{\tau^*_g} \right) \right) = B \exp \left[ \frac{-t^* \sqrt{\Phi_B}}{\exp \left( -\frac{\Phi_B}{kT} \right)} \right] + AT^{-Y}$$

where $A$ and $B$ are constants. The values of $\tau^*_g(T)$ are obtained from the decay curves at
2.3. REGION-3: BULK CARRIERS IN GRAIN BOUNDARIES. — The tail region of the TPCD response (> approximately 500 $\mu$s) is dominated by the grain boundary factor and therefore, the temperature dependence of $\Phi_B$ can not be neglected.

Consider that the trap states in the grain boundaries are localized (see Fig. 1a: this figure corresponds the double depletion layer model in an n-type polycrystal presented by Atkinson and Dixon [13]. The plus sign in the figure indicates the distribution of minority carriers around the band bending which are of interest to the lifetime measurements). The charge neutrality
Table I. — Numerical values of various parameters used in the theoretical calculation of temperature variation of grain boundary potential and bulk carrier lifetime in the tail region of TPCD.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T$(eV)</td>
<td>$E_v + 0.63$</td>
</tr>
<tr>
<td>$E_{fb}$(eV)</td>
<td>$E_v + 0.55$</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>12.0</td>
</tr>
<tr>
<td>$\epsilon_0$(f m$^{-1}$)</td>
<td>$8.85 \times 10^{-12}$</td>
</tr>
<tr>
<td>$m_e$</td>
<td>$1.10 m_0$</td>
</tr>
<tr>
<td>$m_h$</td>
<td>$0.59 m_0$</td>
</tr>
<tr>
<td>$N_D$(cm$^{-3}$)</td>
<td>$10^{16}$</td>
</tr>
<tr>
<td>$N_T$(cm$^{-2}$)</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>$Y$</td>
<td>3.4</td>
</tr>
<tr>
<td>$\Phi_B$(meV) (300 K)</td>
<td>25</td>
</tr>
</tbody>
</table>

condition in a grain boundary gives [14],

$$
\sqrt{\left|8\epsilon_0\epsilon N_D \phi_B\right|} = qN_T \left\{ \frac{1}{1 + \exp \left( \frac{E_T - E_{fb} + \phi_B}{kT} \right)} - \frac{1}{1 + \exp \left( \frac{E_T - E_{fb}}{kT} \right)} \right\}
$$

(15)

where $N_D$ is the doping concentration, $N_T$ is the density of interface states localized at a particular energy level $E_T$. $E_{fb}$ is the Fermi level at the grain boundaries. Equation (15) is a transcendental equation and $\phi_B$ can be calculated by using an iterative process. Singh et al. [12] have plotted the theoretical variation of $\phi_B$ with temperature for localized trap state model using the temperature dependence of $E_{fg}$ (the Fermi level at the grains), $E_g$ and $n_i$.

$$
E_{fg}(T) = \frac{E_g(T)}{2} kT \ln \left( \frac{N_D}{n_i(T)} \right)
$$

(16)

where $E_g$ is the forbidden energy gap and $n_i$ is the intrinsic carrier concentration (both are temperature dependant). The theoretical variation of $\phi_B$ calculated assuming the values given in Table I can be utilised to get the temperature variation of grain boundary decay constant.

Similar to equation (14), the photo voltage decay curve at a temperature, $T$, is given by,

$$
\exp \left( \frac{-t}{\tau_{gb}^{*}(T)} \right) = D \exp \left[ \frac{-t \sqrt{\Phi_B(T)}}{kT} \right] + CT^{-X} \left[ 1 - \frac{qLE_b}{kT} \exp \left( \frac{-\Phi_B(T)}{kT} \right) \right]
$$

(17)

where $C$ and $D$ are constants. $\tau_{gb}^{*}(T)$ is obtained from the decay curves at different temperatures. The constants A, B, C, and D are constants of fit. Though these constants can be related to the parameter such as doping concentration, dielectric permittivity, deep trap level, density of interface states at the grain boundary, intrinsic carrier concentration, thermal velocity of carriers, capture cross section of shallow traps, concentration of shallow trap states, mobilities of electrons and holes, it is not much important for the present study which involves the temperature variation of transient photo conductivity decay curve keeping all other parameters as constant throughout the experiment.
Table II. — Polycrystalline silicon samples used in the present study.

<table>
<thead>
<tr>
<th>Code</th>
<th>Grain Size (μm)</th>
<th>Type</th>
<th>ρ (Ω cm)</th>
<th>Thick (μm)</th>
<th>Carrier concentration (×10¹³ cm⁻³)</th>
<th>Mobility (cm² V⁻¹ s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>3000</td>
<td>n</td>
<td>1</td>
<td>300</td>
<td>500</td>
<td>1150</td>
</tr>
<tr>
<td>H</td>
<td>600</td>
<td>p</td>
<td>3.6</td>
<td>380</td>
<td>850</td>
<td>200</td>
</tr>
<tr>
<td>I</td>
<td>350</td>
<td>n</td>
<td>38.9</td>
<td>760</td>
<td>800</td>
<td>370</td>
</tr>
<tr>
<td>J</td>
<td>200</td>
<td>n</td>
<td>23.1</td>
<td>380</td>
<td>75</td>
<td>180</td>
</tr>
<tr>
<td>K</td>
<td>150</td>
<td>p</td>
<td>1.9</td>
<td>320</td>
<td>90</td>
<td>180</td>
</tr>
<tr>
<td>L</td>
<td>50</td>
<td>n</td>
<td>0.93</td>
<td>300</td>
<td>2000</td>
<td>340</td>
</tr>
</tbody>
</table>

3. Experiment

A simple computer controlled experimental arrangement to measure the minority carrier lifetime in silicon for the temperature range 95-450 K is developed in the laboratory and used in the measurements. The schematic drawing of the electrical circuit for measuring the minority carrier lifetime is presented in Figure 1b.

The excess photo conductivity is measured in terms of excess photo voltage generated across the sample by passing a constant current (from a Keithley constant current source (model N°225) in the range of μA). The transient nature of this excess photo conductivity signal is amplified by a wide band (20 MHz) high gain (7500) amplifier. This amplified signal is digitized by a 400 MS/s, 100 MHz L&T - Gould digital storage oscilloscope after averaging the signal for 256 times. The digitized data are transferred to the PC AT/286 computer through RS232 interface.

For measurement below room temperature, a continuous liquid nitrogen flow cryostat is used. For measurement above room temperature, a heater is placed behind the sample. The temperature is controlled by a software routine using the PC AT/286 computer. The temperature is maintained for 15 minutes within ±0.1 K before any measurement is taken.

The observed change in the conductivity due to the application of light is less than 1% of the dark conductivity. As the excitation intensity is very low, the increase in the temperature of the sample due to the excitation intensity is not observed. The ohmic contacts are screened from the excitation pulse. The initial portion of the TPCD affected by the fall region of the excitation pulse is not utilized for the measurement of decay constants. These standard procedures put forward by the IRE standards committee [15] are followed.

The details of the samples are presented in Table II. The samples are prepared by Czochralski method. The respective doping level is achieved while the sample is crystallized. The grain size of the samples are large and are in the range of 50 to 3000 μm. While the average grain size is listed in the Table II, the actual grain size varies by ±50%. In the case of p-type samples, aluminium is used for making ohmic contacts and for n-type samples electroless deposition of nickel is used. The carrier concentration of the samples are around 10¹³ to 10¹⁶ cm⁻³ at 300 K. The surface dimensions of the samples are all in the range of 1.5 x 2.5 cm².

Table III lists the light sources employed in this work. As this study also deals with the deep traps, more emphasis is placed on the tail part of the decay. Therefore, mechanically chopped pulses from the white light (tungsten halogen lamp) and He-Ne laser are used. In order to get the clear picture of the surface effects, LEDs are used and these are biased by short voltage
Table III. — Various sources of light pulses used in the lifetime measurements.

<table>
<thead>
<tr>
<th>Light Source</th>
<th>Intensity (mW cm(^{-2}))</th>
<th>Pulse width ((\mu)s)</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>White light with chopper</td>
<td>4 to 5</td>
<td>40-50</td>
<td>H &amp; K</td>
</tr>
<tr>
<td>He-Ne Laser with chopper (632 nm)</td>
<td>2</td>
<td>25</td>
<td>H &amp; K</td>
</tr>
<tr>
<td>Red LED (620-660 nm)</td>
<td>0.03</td>
<td>0.12</td>
<td>G, I, J &amp; L</td>
</tr>
<tr>
<td>IR LED (900-1000 nm)</td>
<td>0.021</td>
<td>0.8</td>
<td>I, J &amp; L</td>
</tr>
</tbody>
</table>

Fig. 2. — A typical semi-log plot of TPCD response for a polysilicon showing the three regions of interest.

Pulses in the range of microseconds. Wherever necessary, white light (10 mW cm\(^{-2}\)) is used as a background illumination.

Figure 2 gives a typical TPCD response for a polysilicon showing the decay due to surface recombination, shallow traps in grains and deep traps in grain boundaries. Each region is fit with exponentials and the values of \(\tau_s^*, \tau_g^*\) and \(\tau_{gb}^*\) are obtained corresponding to region-1, region-2 and region-3, respectively. Similarly, the decay constants at different temperatures are obtained and using equations (12) and (14), the values of \(\Phi_B\) and \(Y\) are calculated.

3.1. Error Analysis. — The TPCD signal has the distribution of \(\pm 2\) bits in the digital storage oscilloscope (4% error). The amplified TPCD signal normally lies in the range of 20 to 50 mV. The error made in the lifetime values due to the distribution of data for a fixed specific
Table IV. — Surface carrier decay constant measured using IR and Red LEDs with and without background illumination (White: 10 mW cm\(^{-2}\)). Surface recombination velocity is calculated with equation (3) using the surface carrier decay constant obtained from red LED excitation with background illumination.

<table>
<thead>
<tr>
<th>Sample</th>
<th>IR LED Lifetime ((\mu)m)</th>
<th>Red LED Lifetime ((\mu)m)</th>
<th>Surface recombination velocity (cm s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No background</td>
<td>With background</td>
<td>No background</td>
</tr>
<tr>
<td>G</td>
<td>—</td>
<td>—</td>
<td>11.9</td>
</tr>
<tr>
<td>I</td>
<td>9.7</td>
<td>8.1</td>
<td>8.0</td>
</tr>
<tr>
<td>J</td>
<td>12.2</td>
<td>3.6</td>
<td>6.0</td>
</tr>
<tr>
<td>L</td>
<td>—</td>
<td>—</td>
<td>12.4</td>
</tr>
</tbody>
</table>

exponential decay is approximately 2%. Moreover, there is also an error varying from 2 to 4% due to the variation in the selection of exact range of the exponential fit (±5 data). With all these considerations, the error in the measurement of lifetime is within 5% and the accuracy in the measurement of temperature is within ±0.1 K. The fall region of the excitation pulse gives the lower limit in the lifetime measurement. The TPCD curve observed with the mechanical chopper pulses give the lower limit as 25 to 50 \(\mu\)s and LEDs give the lower limit to 1 \(\mu\)s.

4. Results and Discussion

4.1. REGION-1. — The minority carrier lifetime values for single crystal bulk silicon values vary from less than 1 \(\mu\)s to 20 ms [16] depending on various growth parameters like doping density, impurity contents, processing parameters etc. Table IV presents the decay time constants obtained with and without background illumination at 300 K for polysilicon samples along with the calculated values of surface recombination velocity. The application of intense white background light illumination saturates the deep traps in the grain boundary thereby reducing \(\Phi_R\). Therefore, \(\Delta\mu\) decreases and \(\tau_s^*\) decreases and approaches \(\tau_s\). In general, the value of \(\tau_s\) decreases with grain size. But in our work, as the background illumination is not enough to fully saturate the grain boundary traps, this is not observed.

The temperature variation (300 to 450 K) of surface carrier decay time constant (\(\tau_s^*\)) for a polysilicon sample-1 (350 \(\mu\)m:GS) is presented in Figure 3. The power law fit of \(\tau_s^*\) gives the value of \(Y\) as 3.5. By the same procedure, the \(Y\) values obtained for sample-J (200 \(\mu\)m:GS) and another sample having GS around 800 \(\mu\)m using time resolved microwave photo conductivity decay technique [11] are tabled in Table V. Under high background illumination (see Fig. 3), the excess mobility decreases and \(\tau_s^*\) approaches the value of \(\tau_s\).

4.2. REGION-2. — Grovener [9] and Atkinson and Dixon [13] have concluded that if the GBs are increased (\(eg\), in material with reduced GS), the bulk carrier lifetime decreases due to the increase of recombination velocity at the GB edges. The same effect is observed and is shown in Figure 4.

As mentioned earlier, the decay constant reduces due to the increase in excitation light intensity owing to the grain boundary trap states (Tab. VI: for sample-K). Atkinson and Dixon [13] have also reported a decrease in lifetime with increase in intensity and attributed this to the varied capture cross section due to the modulation of grain boundary potential.
Fig. 3. — Variation of decay time constant in region-1 with temperature measured for a polysilicon sample-I using red LED pulses with and without background illumination.

Table V. — The value $Y$ calculated from the temperature dependence of surface carriers and the grain boundary potential obtained from the temperature variation of carrier lifetime in region-3 (above which the minority carrier lifetime increases rapidly) are listed.

<table>
<thead>
<tr>
<th>Gain Size ($\mu$m)</th>
<th>$Y$</th>
<th>$\Phi_B$ (meV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>—</td>
<td>29 (29&lt;sup&gt;a&lt;/sup&gt;)</td>
</tr>
<tr>
<td>150</td>
<td>3.6&lt;sup&gt;a&lt;/sup&gt;</td>
<td>29 (29&lt;sup&gt;d&lt;/sup&gt;)</td>
</tr>
<tr>
<td>200</td>
<td>3.6</td>
<td>28</td>
</tr>
<tr>
<td>350</td>
<td>3.5</td>
<td>27</td>
</tr>
<tr>
<td>600</td>
<td>3.4&lt;sup&gt;a&lt;/sup&gt;</td>
<td>25 (25&lt;sup&gt;e&lt;/sup&gt;)</td>
</tr>
<tr>
<td>800</td>
<td>3.3&lt;sup&gt;b&lt;/sup&gt;</td>
<td>—</td>
</tr>
<tr>
<td>1000</td>
<td>—</td>
<td>23&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup>) Calculated from the fitting parameter of temperature dependence of bulk carrier lifetime in region-2.

<sup>b</sup>) Calculated from the temperature variation of surface carrier lifetime using microwave photoconductivity decay at 9.1 GHz.

<sup>c</sup>) Value obtained using Hall mobility at 300 K based on thermionic emission diffusion model.

<sup>d</sup>) Reported value of $\Phi_B$ using thermionic emission diffusion model for a 1000 $\mu$m GS sample [18].

The temperature variation of $\tau_s^*$ is the net effect due to the temperature dependence of $\Delta\mu$ and $S_B$ due to $\Phi_B$. Both these are not effective at low temperature (< 200 K). The carrier mobility change due to the lattice scattering starts at temperatures higher than 220 K [8] and
Fig. 4. — Temperature variation of decay time constant in region-2 for two polysilicon samples-H and K excited with white light pulses without background illumination. The theoretical fit given to this variation is also shown.

Table VI. — Variation of decay constant with excitation intensity for a polysilicon sample-K (GS: 600 μm).

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Sample K: White light pulses without background illumination:</th>
<th>Decay time in (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>4.3 mW cm⁻²</td>
</tr>
<tr>
<td>302.6</td>
<td></td>
<td>319</td>
</tr>
<tr>
<td>282.2</td>
<td></td>
<td>341</td>
</tr>
<tr>
<td>267.6</td>
<td></td>
<td>377</td>
</tr>
<tr>
<td>232.4</td>
<td></td>
<td>438</td>
</tr>
<tr>
<td>185.3</td>
<td></td>
<td>435</td>
</tr>
<tr>
<td>170.5</td>
<td></td>
<td>431</td>
</tr>
<tr>
<td>141.7</td>
<td></td>
<td>401</td>
</tr>
<tr>
<td>90.9</td>
<td></td>
<td>383</td>
</tr>
</tbody>
</table>
Fig. 5. — Temperature variation of decay time constant in region-3 for four polysilicon samples-H, J, K, and L without background illumination. The theoretical data for grain boundary potential 25 meV and Y as 2.9 is also presented.

Therefore, the temperature variation of the lifetime in this region starts at temperatures more than 250 K (Fig. 4). Fitting the experimentally measured $\tau_g^*$ using equation (14) gives $\Phi_B$. Table V presents the value $Y$ and $\Phi_B$ obtained for samples H and K. Figure 4 gives the measured value of $\tau_g^*$ and fitted curves for these samples.

4.3. Region-3. — For the typical values assumed in Table I, using equations (15), (16) and (17), the variation of decay constant is plotted in Figure 5 along with other experimental curves for comparison. The experimental data available for four polysilicon samples (see Figs. 5 and 6) show that the carrier lifetime remains constant up to a certain temperature ($T_{gb}$) and increases very rapidly at temperatures higher than $T_{gb}$. Though the theoretical and experimental curves look similar, the temperature at which the rapid increase in decay constant observed are far from agreement. This disagreement may be due to the theoretical assumptions made such as (1) regular size and shape of the grains, (2) localised variation at the grain boundaries and (3) the assumed uniformity in the segregation of impurities at the grain boundaries. The experimental measurement takes into all these considerations and hence it is difficult to establish the reason for disagreement. Only by doing more systematic studies with a controlled doping levels and almost uniform grain size materials prepared under the same external conditions, the possible effects can be pointed out. But the theoretical curve confirms that the lifetime increases rapidly as the temperature increases beyond certain value. At this temperature, the $\Phi_B$ reduces to $(1/e)^{th}$ of the value at 300 K. Hence, the temperature at which the decay constant increases can be used to calculate the $\Phi_B$ ($\Phi_B = kT_{gb}$). The TPCD response observed for sample-L at temperature 90, 300 and 364 K shows that the lifetime at tail region is large at 364 K compared with others (see Fig. 7). Using this approach, the $\Phi_B$ measured for four polysilicon samples
Fig. 6. — Temperature variation of decay time constant in region-3 for two polysilicon samples-H and K excited with white light pulses without background illumination.

Fig. 7. — TPCD response for sample-L observed at 90, 300 and 364 K.
are given in Table V. By using the thermoionic emission diffusion model [12], the measured \( \Phi_B \) for sample L is 29 meV and with the present approach the \( \Phi_B \) is measured as 29 meV. The measured \( \Phi_B \) does not include the Fermi level bending near the grain boundary edge. As the excitation level is low, the variation of \( \Phi_B \) with grain size is not much as predicted by Dinesh Prasad Joshi and Devesh Prasad Bhatt [17]. The large value of lifetime hints the possibility of detrapping of deep traps at GBs.

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**References**