

# N<sup>+</sup>P photodetector characterization using the quasi-steady state photoconductance decay method

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**Abstract:** When a material is irradiated, it becomes more electrically conductive due to the absorption of the electromagnetic radiation. As a result, the number of free electrons and holes changes and raises its electrical conductivity. A simple but interesting phenomenon to characterise a fabricated n<sup>+</sup>p photodetector in order to determine its linearity (photoresponse) and photoconductance was employed. Using the transient decay when the irradiation source is switched off, the minority carrier concentration, effective lifetime and surface recombination velocity present at the surface of the detector were measured.

**Key words:** photoconductance decay; photodetector characterization; minority carrier lifetime; surface recombination velocity

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## 1. Introduction

One of the basic principles of the solid-state physics of semiconductors is that when a semiconductor device is excited, mobile charge carriers (electrons and electron holes) are created and eliminated. These creation and elimination processes are respectively known as carrier generation and recombination. Carriers have a lifespan and the time it takes before they recombine is known as the carrier lifetime,  $\tau$ . In the charge conservation equation, it is used as the time constant of the exponential decay of carriers and is dependent on the carrier density by

$$\frac{1}{\tau_p(N)} = r_{\text{non}} + Nr_{\text{rad}} + N^2r_{\text{aug}}, \quad (1)$$

where  $r_{\text{non}}$ ,  $r_{\text{rad}}$  and  $r_{\text{aug}}$  are the non-radiative, radiative and auger recombination coefficients respectively and  $\tau_p(N)$  is the carrier lifetime.

The resultant mobile charge carriers created during excitation often recombine at the surface of a semiconductor and the measure of the rate of recombination between electrons and holes at these centres is referred to as surface recombination velocity,  $v_s$ . Several methods have been proposed for determining  $v_s$  present on the surface of semiconductor devices. They include: the use of low-voltage cross-sectional electron beam-induced current (EBIC)<sup>[2]</sup>; the use of electrical techniques for the measurement of the interface recombination velocity based on a multiple test structure;<sup>[3]</sup> and by diffraction from picosecond transient free-carrier gratings<sup>[4]</sup>. This paper explores the use of the minority carrier lifetime  $\tau_{n,p}$  from the analysis of the photoconductance decay transients by using a light pulse to estimate the surface recombination velocity  $v_s$ .

## 2. Theories

In the basic analysis of photoconductance, equilibrium exists between the rate of generation and recombination of elec-

tron-hole pairs in a semiconductor under steady-state irradiation. With the assumption that there is an absence of space-charge dependence and a device has a thickness much smaller than the inverse of the optical absorption coefficient, using the classical experimental procedure as developed by Stevenson and Keyes<sup>[5]</sup> (shown in Fig. 1), a continuity equation in a simplified form can be described as

$$\frac{dp_n}{dt} = G_p - \frac{p_n - p_{n0}}{\tau_p}, \quad (2)$$

where  $p_n$  is the hole concentration in an n-type semiconductor (minority carriers);  $p_{n0}$  is the  $p_n$  in thermal equilibrium;  $G_p$  is the hole generation rate and  $\tau_p$  is the effective carrier lifetime for holes.

At a non-equilibrium condition in which the constant optical generation of electron-hole pairs is just balanced by recombination, the change in the hole concentration in the semiconductor over time becomes zero and the ratio of  $p_n - p_{n0}$  to  $\tau_p G_p$  becomes constant. If the irradiation source is switched off at a time assumed to be zero, the differential equation can then be described as

$$\frac{dp_n}{dt} = -\frac{p_n - p_{n0}}{\tau_p}, \quad (3)$$

which has the solution with the boundary conditions  $p_n(t=0) = p_{n0} + \tau_p G_p$  and  $p_n(\infty) = p_{n0}$ :

$$p_n(t) = p_{n0} + \tau_p G_p e^{-t/\tau}. \quad (4)$$

The above equation signifies that under irradiation, the conductivity of a semiconductor increases over its equilibrium value and as such a measurement of the change in conductivity will yield information relating to the concentration of excess carriers generated by the irradiation. With the well known fact that under excitation electrons and holes are generated in pairs, the change in conductivity is proportional to the number of excess carriers  $\delta p$  generated:

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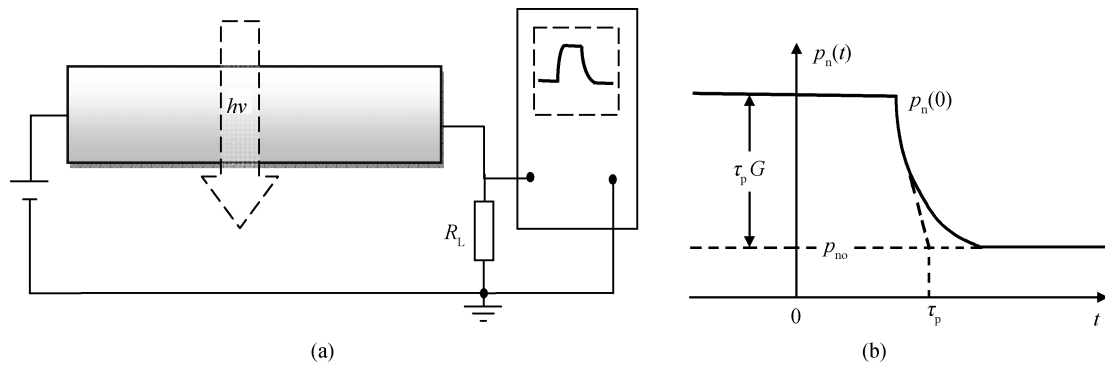


Fig. 1. Decay of photo-excited carriers based on the method developed by Stevenson and Keyes[5]. (a) Basic schematic arrangement for a photoconductivity decay and minority carrier lifetime measurement. (b) Decay of minority carriers (holes) from a steady state to equilibrium state.

$$\Delta\sigma = q(\mu_n + \mu_p)\delta p, \tag{5}$$

where  $q$  is the electron charge,  $\mu_n$  and  $\mu_p$  are the electron and hole mobilities, respectively.

If a constant voltage  $V_R$  is assumed to be maintained across the semiconductor with a cross-sectional area  $A$  and length  $l$ , the current change due to illumination passing through (from the derivation of Ohm’s law) is inversely proportional to its conductivity

$$\Delta I = \frac{V_R A}{l} \Delta\sigma. \tag{6}$$

Therefore if the change in current as a function of time for an illuminated semiconductor can be measured, the change in conductivity over time can be derived. The excess carrier concentration as a function of time can also then be derived from Eq. (5). If  $\delta p(0)$  is the steady-state excess carrier concentration when the irradiation source is on, the excess carrier concentration decaying to equilibrium can be defined as:

$$\delta p(t) = \delta p e^{-t/\tau}. \tag{7}$$

By substituting into Eqs. (5) and (6), the exponential current decay after the irradiation source is switched off can be described as

$$\Delta I(t) = \frac{V_R A}{l} q (\mu_n + \mu_p) \delta p e^{-t/\tau}. \tag{8}$$

Thus an observation of the rate of exponential decay of the measurable current yields a measurement of the effective minority carrier lifetime  $\tau_{n,p}$  and one can therefore see the similarity between Eqs. (4) and (8).

It is important to state that the current  $I_d$  through the detector which is primarily generated as result of the irradiation is depicted by  $\Delta\sigma AF$  where  $F = V_o/l$  represents the electric field applied. Also important is that a small portion of the excess minority carriers is weakened by getting entangled at various defects such that not every element of the minority carriers  $\delta p$  contributes equally to the photoconductivity. The resultant effect of such trapping on the photoconductivity becomes obvious in the use of values assigned to  $\mu_n$  and  $\mu_p$  that are lower — and not necessarily symmetrically lower — than the theoretical free mobility  $\mu_o$ [7].

With the effective minority carrier lifetime known, a measure of the rate of recombination between the electrons and holes at the surface of the device can be characterized using the equation below when the bulk lifetime  $\tau_{bulk}$  is also known as[8]

$$v_s = \frac{\tau_{bulk} - \tau_p}{\tau_p \tau_{bulk}} \frac{W}{2}, \tag{9}$$

where  $W$  is the wafer thickness.

### 3. Experimental procedures

#### 3.1. Sample fabrication

To carry out the experiment, a photodetector (see Fig. 2) was fabricated at the Mid Sweden University clean room. The detector was made on a p-doped high-purity, high-resistivity substrate with 1-1-1 orientation and an average axial resistivity of 0.0045 MΩ·cm as measured by the 4-point method as defined by SEMI MF43. The datasheet of the starting wafer specifies its bulk lifetime  $\tau_{bulk}$  as 1.2 ms. A thin layer of 57 nm thick SiO<sub>2</sub> was grown through dry oxidation on the top layer of the wafer. This was to act as a “thin mask” during the process of implantation. We then introduced donor impurities doping by implanting a  $0.4 \times 10^{15}$  ions/cm<sup>2</sup> dose of arsenic at an accelerating voltage of 56 keV through the thin SiO<sub>2</sub> with the ion beam incident on the wafer at an angle of 7°. Thereafter, the wafer was annealed at 900 °C in nitrogen ambient for a period of 30 min to take care of the lattice damage which may have resulted from collision between ions and the lattice atoms during the implantation process. At every step of the photolithographic process, a positive photoresist was used and thereafter soft baked at 115 °C for 60 s while wet etching was employed during the etching processes.

The contacts were made using the vapor deposition technique of evaporation. The front and back contacts were made orthogonal to each other and were 0.3 μm thick. Thin copper wires of about 0.08 μm thick were then bonded to the contacts to a copper-clad FR4 PCB and the whole top of the device was shielded with thin fiberglass to protect it, as shown in Fig. 2(b).

#### 3.2. Experimental setup and measurement

The photoconductance and minority carrier lifetime were measured using the experimental setup as shown in Fig. 3. The

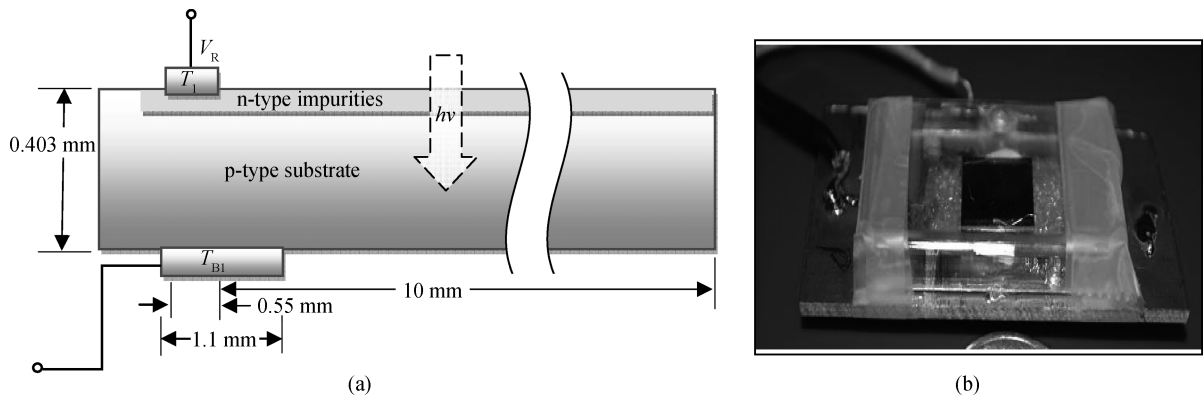


Fig. 2. (a) Schematic of the fabricated photo-detector made on a wafer thickness,  $W$  of 0.403 mm. (b) Image of the device. The contacts were bonded to a copper-clad FR4 PCB and shielded with thin fibreglass.

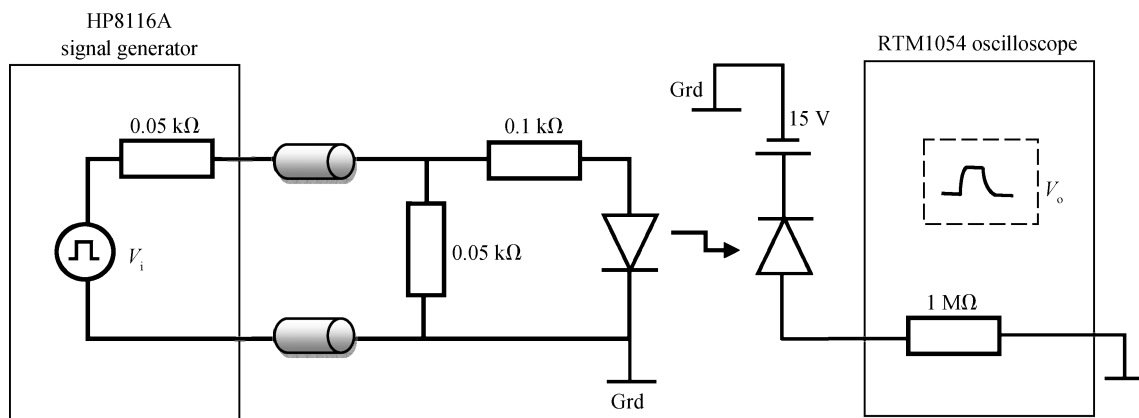


Fig. 3. Schematic of the photoconductance measurement set-up. The distance between the fibre cable and the detector was about 5 cm and the beam was perpendicularly focused on the detector. The oscilloscope was set to display the output in current (ampere) mode.

Table 1. Optical power of the different focus beams used in the experiment.

Parameter	$\rho_1$	$\rho_2$	$\rho_3$	$\rho_4$	$\rho_5$
Optical power	2.15 mW	5.92 mW	6.97 mW	8.27 mW	8.6 mW

experiment was performed by connecting the bottom contact of the detector directly to a RTM1054 oscilloscope featuring a plug-in with 1 MΩ input resistance to prevent any parasitic capacitances while a reversed bias voltage  $V_R$  of 15 V was applied to the top contact. The light source used was an 850 nm multi-mode oxide isolated vertical-cavity surface-emitting laser diode (HFE4192-581) with a negligible rise/fall time and a relative intensity noise of 130 dB/Hz at 1 GHz bandwidth and forward current of 7 mA. A model of the normalized photoconductance of the silicon detector to a square pulse of light from a signal generator through an HFE4192-581 VCSEL laser diode is shown in Fig. 4. The measured results from varied optical power from the light source (see Table 1) are shown in Fig. 5 to Fig. 9.

### 4. Results

Using the theories mentioned in the previous section, the minority carrier concentration  $p_n$ , the effective lifetime  $\tau$  and the surface recombination velocity  $v_s$  present in the device were determined. The average photogeneration rate  $G_p$  of the

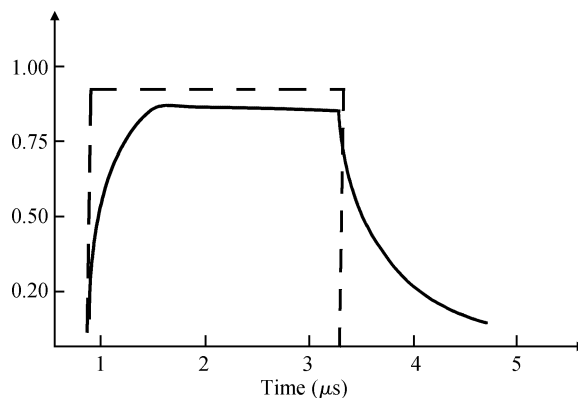


Fig. 4. Model of the normalized photoconductance (solid line) of a p+n-doped high purity, high resistivity substrate silicon detector to a square pulse of light (dash line) from a signal generator to a HFE4192-581 VCSEL laser diode.

device was determined to be  $3.78 \times 10^{17} \text{ cm}^{-2}\cdot\text{s}^{-1}$ . The measured minority carrier concentrations for the different measure-

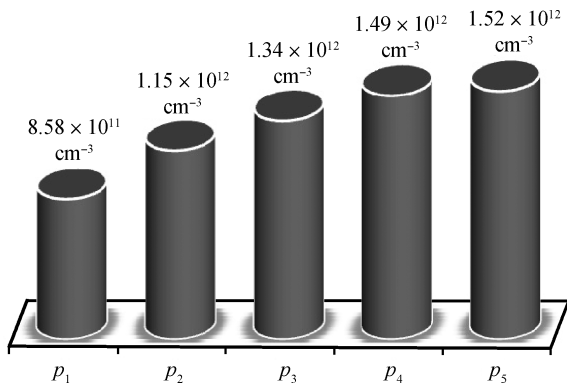


Fig. 5. Measured excess minority carrier concentrations for the different optical powers.

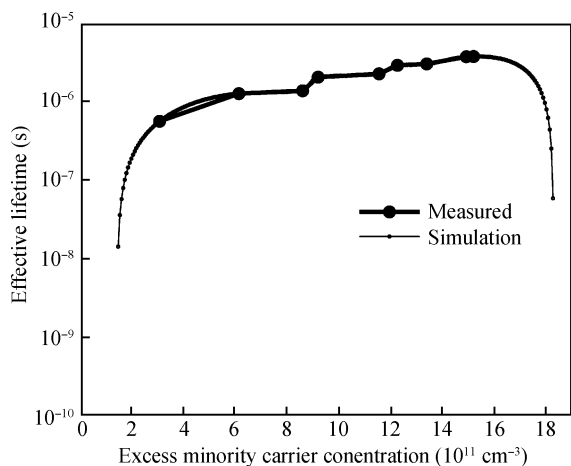


Fig. 6. The result of a Matlab simulation and the measured effective lifetime of a 403- $\mu\text{m}$  thick  $n^+p$  detector with 1.18 ms bulk lifetime as a function of excess minority carrier concentrations at  $\lambda = 850$  nm.

ments are shown in Fig. 5 and their relationship with the effective minority carrier lifetime is shown in Fig. 6. To determine the average excess carrier concentration  $p_{nAV}$ , it is necessary to divide  $p_n$  by the thickness of the device.

Figure 6 confirms the fact that the effective minority carrier lifetime can vary as the injection level changes. As the injection level increases, the effective lifetime also increases and it gets to a level where it becomes constant.

A saturation point is reached where an additional increase in the level of injection no longer has any increasing effect on the lifetime. But instead any increase in the excess minority carrier concentration causes a decrease in the minority carrier lifetime. This phenomenon is in agreement with results obtained by previous studies<sup>[9, 10]</sup>.

Using the measured values of minority carrier lifetime as shown in Fig. 7, the average time  $\tau$  needed for a decrease of  $1/e$  to its thermal equilibrium value were derived. It was determined that the mean value of the average time  $\tau$  it takes for the minority carrier in the device to recombine was 2.83  $\mu\text{s}$ . This value holds as long as their concentration is not too far off the equilibrium value. As a result of the fact that the minority carrier lifetime of indirect semiconductors is dominated by defects and/or by impurities, the measured value can give a good perspective of the level of defects present in the device.

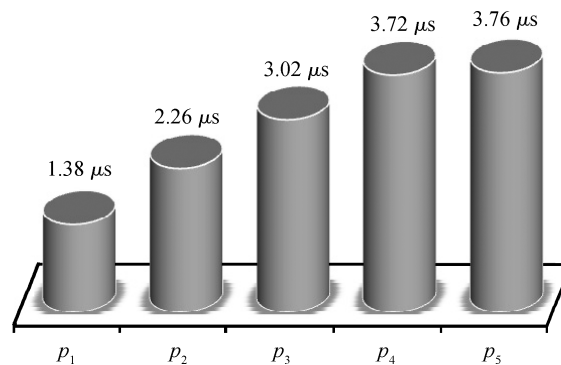


Fig. 7. Measured minority carrier lifetime for the different optical powers.

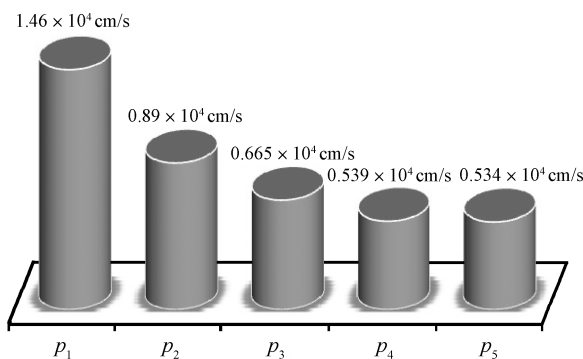


Fig. 8. Measured surface recombination velocity in cm/s for the different optical powers.  $v_s$  can also be expressed as a ratio of the surface recombination rate per unit area and photogenerated excess carrier density.

The surface recombination velocity can generally be expressed as a ratio of the component of the electron or hole current density normal to the surface of the excess electron or hole volume charge density close to the surface.

The measured surface recombination velocity  $v_s$  for the different optical powers is shown in Fig. 8. Taking the mean of the results,  $v_s$  was determined to be  $0.82 \times 10^4$  cm/s. This value is thus a measure of the rate at which the minority carriers migrate towards the surface of the device. Analogous to the minority carrier lifetime of indirect semiconductors like silicon,  $v_s$  is a determinant of the defects present at the silicon surface caused by the interruption to the periodicity of the crystal lattice, which generates dangling bonds at the silicon surface.

It was also of interest to measure the behavior of the device under a different irradiation condition. Using a Stereoscan 360 scanning electron microscope (SEM), one was able to characterize the linearity and photoresponse of the detector of electron energy ranging from 1 keV to 20 keV

The appropriate beam current  $I_0$  determined by the quantity and velocity of electrons in the electron beam through a Faraday cup was chosen for each electron energy measured. The photoresponse was calculated as

$$R_m = \frac{(I_p - I_d) \mu\text{A}}{I_0 V_0}, \tag{10}$$

where  $I_p$  = measured detector current;  $I_d$  = measured detector leakage current;  $I_0$  = incident beam current;  $V_0$  = electron

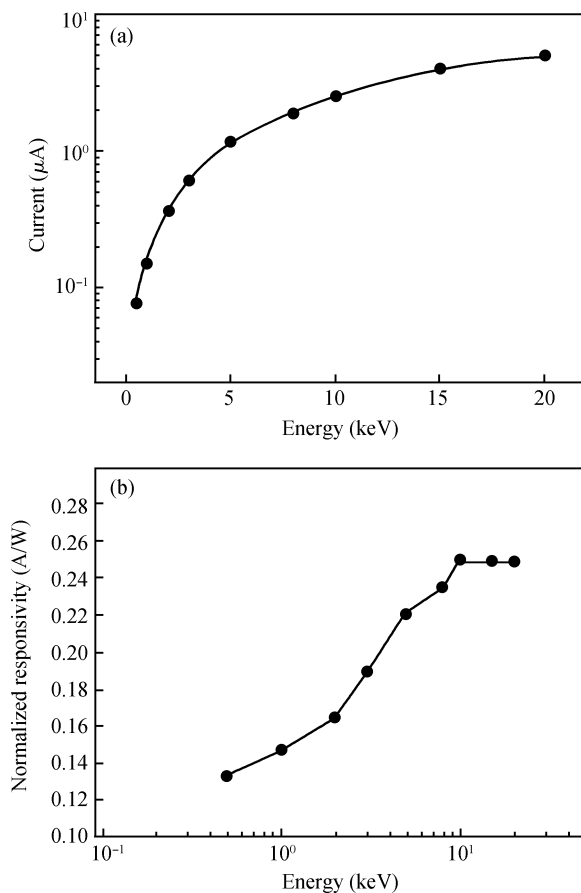


Fig. 9. (a) Current versus energy response curve of the detector when irradiated with electrons. (b) The photoresponse of the detector irradiated with electrons ranging from 1 to 20 keV. To reduce the effect of voltage bias noise, the measurement was done with the detector unbiased.

acceleration voltage.

It is seen from Fig. 9(b) that the detector response is somewhat linear between 1 and 10 keV, where it then becomes saturated. The maximum responsivity is also shown to be about 0.25 A/W, which is quite close to theoretical value of 0.27 A/W. One can use this experimental procedure to infer the minority carrier lifetime and then the surface recombination present by calculating the exponential decay of the response when the electron irradiation is abruptly switched off.

## 5. Conclusion

A simple technique to determine the surface recombina-

tion velocity of silicon and other semiconductor surfaces has been investigated and reported in this paper. It involves a simple method for implementing the steady-state photoconductance technique for also determining the minority-carrier lifetime of semiconductor materials and the material photoconductance which is measured by using a slow varying light pulse and the use of simple electronics.

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