MEASUREMENT OF MINORITY CARRIER LIFETIME IN SILICON SOLAR CELLS USING AN A.C. LIGHT SOURCE

ALKA NAGPAL, R. S. GUPTA and G. P. SRIVASTAVA

Department of Electronic Sciences, University of Delhi, South Campus, New Delhi 110021 (India)

V. K. JAIN

Solid State Physics Laboratory, Delhi 110007 (India)

G. S. CHILANA

Department of Physics and Astrophysics, University of Delhi, Delhi 110007 (India)

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Summary

A simple technique for the measurement of minority carriers lifetimes is proposed. It is based on the modification of the junction structure by the addition of a d.c. bias to the a.c. source. This always keeps the solar cell in the forward biased condition and also keeps it in the operating range. This method provides a direct measurement of minority carriers lifetimes. The lifetime is found to increase from 2.89 μs at 30 °C to 4.55 μs at 120 °C. The lifetime reduces to 1.45 μs at liquid air temperature. Based on these lifetime measurements, the diffusion length of the carriers has also been calculated.

1. Introduction

The minority carrier lifetime is one of the most important parameters affecting the performance of a solar cell. Therefore, it becomes important to know its value and also its variation with temperature. The lifetime in the top heavily doped layer, is not considered in this article.

A number of methods [1 - 8] exist for measuring minority carriers lifetimes, the most popular being the open-circuit decay technique. These methods can be classified into two groups (1) those requiring electrical contacts and (2) those which are non-destructive and require no conductive electrodes on the sample.

The present paper proposes a simple technique for the measurement of minority carriers lifetimes, based on junction structure modification by the addition of a d.c. bias proposed by Moore [5], and the non-destructive technique given by Munakata and coworkers [6, 7]. The modified technique has been used to measure the minority carrier lifetime in the base of highly

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doped p–n junction solar cells at liquid air temperature and also in the temperature range 30 - 120 °C. Calculated values of the diffusion length based on minority carrier lifetime measurements are also given.

2. Theoretical considerations

In the open-circuit voltage decay measurement technique, during pulse injection the system reaches a steady state, when the injection pulse is cut off the diode is open-circuited. The pair concentration in the base decays almost entirely by recombination and not by diffusive flow. The short-circuit current I_{sc} *vs.* open-circuit voltage V_{oc} curve of the solar cell shows a static situation; however, in the dynamic situation (during decay) the junction capacitance that shunts the voltage source discharges through the dynamic junction resistance. At low junction voltages, this effect can dominate the decay. According to Moore, dynamic I_{sc}–V_{oc} includes the capacitance term

$$I_0\left\{\exp\left(\frac{qV_{oc}}{nkT}\right)-1\right\}+C_0\,\frac{\mathrm{d}V_{oc}}{\mathrm{d}t}=I_{sc} \tag{1}$$

Although, the junction capacitance C_0 is voltage dependent, it may be taken as a constant for small voltages. In the same voltage range, after expansion of the exponential, to linearize the differential equation and assuming $nkT/qI_0 = R_0$ and $R_0C_0 = \tau_j$ we derive

$$\tau_j\,\frac{\mathrm{d}V_{oc}}{\mathrm{d}t}+V_{oc}=R_0I_{sc} \tag{2}$$

R_0 is the dynamic resistance of the junction near $V = 0$ and τ_j is the junction time constant.

The decay of V_{oc} is dominated by τ_n (minority carrier lifetime) or τ_j (junction time constant), whichever is larger. Generally τ_j is quite high in comparison to τ_n. Thus a non-linear region is normally observed in the tail of the open-circuit decay. This does not give the correct value of the lifetime at low levels where decay is approximately exponential.

Moore [5] suggested a small signal V_{oc} decay, by illuminating the cell with a d.c. light in addition to the injection pulse. The time dependence of the pair concentration after termination of the pulse is

$$\Delta p(t) = P + \Delta p\,\exp(-t/\tau) \tag{3}$$

where P is the steady state or pair concentration due to d.c. light while the second term describes decaying. This relieves the interference effect of τ_j which prevents the simple application of exponential decay at low level. It requires only a small amount of d.c. light to bias the junction sufficiently in the forward direction to reduce R_0.

A new method has been proposed in this paper based on the theory given by Munakata *et al.* [6] in which the solar cell is kept in the forward biased condition as suggested by Moore [5]. They have used a chopped photon beam as the light source for the measurement of minority carriers lifetime. Under the a.c. mode of chopped photon beam excitation the photocurrent I_{ph} is effectively determined by the excess minority carriers generated and $L_n(w)$ a kind of diffusion length of excess minority carriers has been given as

$$L_n(w) = \frac{L_n}{(1 + jw\tau_n)} \tag{4}$$

where j denotes the imaginary part, τ_n is the lifetime to be measured and w is the angular frequency of the chopped light.

At very low frequencies, when $w\tau_n$ is much smaller than unity, $L_n(w)$ becomes L_n. The photovoltage V_{oc} in this low frequency region is given by

$$V_{oc} = I_{ph}R_0 \tag{5}$$

where I_{ph} is the photocurrent and R_0 is the junction dynamic resistance. R_0 should be frequency dependent, but its dependence is negligible in the frequency range lower than first bending point f_c. Due to the effect of the junction capacitance C_0, V_{oc} decreases with increasing frequency and is given by

$$V_{oc} = I_{ph}(1/jwC_0) \alpha 1/f \tag{6}$$

In the higher frequency region when $w\tau_n \gg 1$, $L_n(w)$ becomes shorter than L_n depending on f and V_{oc} decreases, being proportional to $f^{-3/2}$, because of its dependence on the diffusion length [7].

Hence two bending points appear on the curve between V_{oc} and frequency on a logarithmic scale. The first bending point is related to the junction parameters and the second bending point occurs at the frequency f_b given by

$$f_b = 1/2\pi\tau_n$$

Thus τ_n can be calculated by the knowledge of f_b.

The assumption that R_0 and C_0 are independent of frequency is true only when V_{oc} does not exceed the equivalent thermal voltage of about 25 mV at room temperature. This fact puts a severe limitation on the existing method. Also, when the light pulse is off, the junction dynamic resistance plays an important role (as suggested by Moore [5]).

The present method is a modification of Munakata's method [6, 7] based on the suggestion given by Moore [5]. The method has been modified by always keeping the solar cell in the forward biased condition and using a d.c. light source in addition to the pulsed light. By this arrangement the interference effect of the junction time constant is removed. Experimental details for these measurements with the modifications suggested is discussed in Section 3.

3. Experimental details

3.1. Solar cell used

Space quality solar cells were taken for the measurements. The n^+pp^+ structure was formed by diffusion of phosphorous at the front and aluminium at the back of the solar cell wafers. These cells were fabricated in ideally controlled conditions. The top contact structure was made by deposition of a three layer structure of Ti/Pd/Ag using a Varian coating unit. The top contact fingers were made using photolithography and the covered area was controlled between 7% and 8%. The back contact was made of Al/Ti/Pd/Ag for the BSFR structure. An antireflection coating of titanium oxide was deposited on to the front surface of the cells.

About 80 cells were made in each batch; the average efficiency of these cells was 12% - 13% (AM 0). The measurement system was calibrated each time by a standard solar cell supplied by Spectro Lab., U.S.A.

3.2. a.c. light source

A source of fast light flashes was made using a bunch of red light emitting diodes (LEDs) ($\lambda \approx 0.69$ μm). It was found to be difficult to get sufficient light intensity for operating the solar cells with LEDs of other colours.

A bunch of 10 LEDs was given a constant d.c. bias and an a.c. signal was modulated on it to yield sufficient output from the solar cells (Fig. 1). In this case the light chopper used by other workers has been replaced by LED source, which can give an a.c. output up to very high frequencies in comparison to the mechanical chopper. Their frequency modulation responds to a very high frequency signal because their own (LED source) minority carriers lifetime is in the nanoseconds range. The solar cell was kept in front of the LED source and the a.c. output of the cell was fed to an oscilloscope.

The frequency of the flashing source was varied from 100 Hz to 250 kHz or more and the permanent d.c. bias given to the source was sufficient to keep the solar cell always in the forward biased condition. The magnitude of the generated a.c. photovoltage was measured on an oscilloscope by varying the frequency.

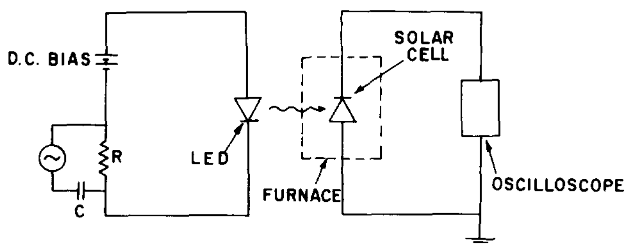

Fig. 1. Experimental set-up.

3.3. *Temperature variation*

For temperature variation of the solar cell, a small furnace was designed in which the cell was fixed on a copper sample holder. The pulsed light source was kept outside at room temperature. The temperature was controlled by varying the current through the coil of the furnace. A hand probe digital thermometer was used for accurate temperature measurements.

For measurements at liquid nitrogen temperature, the cell was fixed on a metallic finger of a cryostat with a quartz window in front of the sample. The cell was kept in vacuum to avoid any deposition of moisture and was illuminated through the quartz window. A constant flow of liquid nitrogen was ensured through the cryostat to keep the temperature constant.

4. Results and discussion

The experimental arrangement for the measurement of the output a.c. voltage with frequency variation is shown in Fig. 1. The amplitude of the a.c. photovoltage remains constant up to a certain value of frequency but then starts decreasing and finally gives two bending points as shown in Fig. 2. The light source flickers from 100 Hz to 250 kHz. On a logarithmic scale, the two bending points are distinctly marked as predicted. Figure 2 gives the results in the temperature range 30 - 120 °C and at liquid air (77 K) temperature. It was established before taking the measurements that input light amplitude does not change with frequency. From the second bending point the minority carriers lifetime has been calculated with the help of the relation given in the theoretical section. The lifetime is found to increase from 2.89 μs at 30 °C to 4.55 μs at 120 °C. At liquid nitrogen temperature the lifetime is 1.45 μs. The variation of lifetime with temperature is shown in Fig. 3. The increase of minority carrier lifetime with temperature may be attributed to the reduced availability of recombination centres at higher temperatures. Following Shockley Read [9] one may assume an inverse proportionality between lifetime and recombination centre concentration

$$N_r = N_0 \exp(-E/kT)$$

or

$$N_0 = N_r \exp(E/kT)$$

where N_r is the recombination centre density and N_0 is the potential availability of centres. Therefore, N_0 decreases with increasing temperature and leads to higher lifetimes.

The diffusion length of minority carriers, *i.e.* of electrons, at different temperatures has been calculated using the well known relation between L_n and τ_n

$$L_n = (D_n \tau_n)^{1/2}$$

D_n, the diffusion coefficient of minority carriers is given by

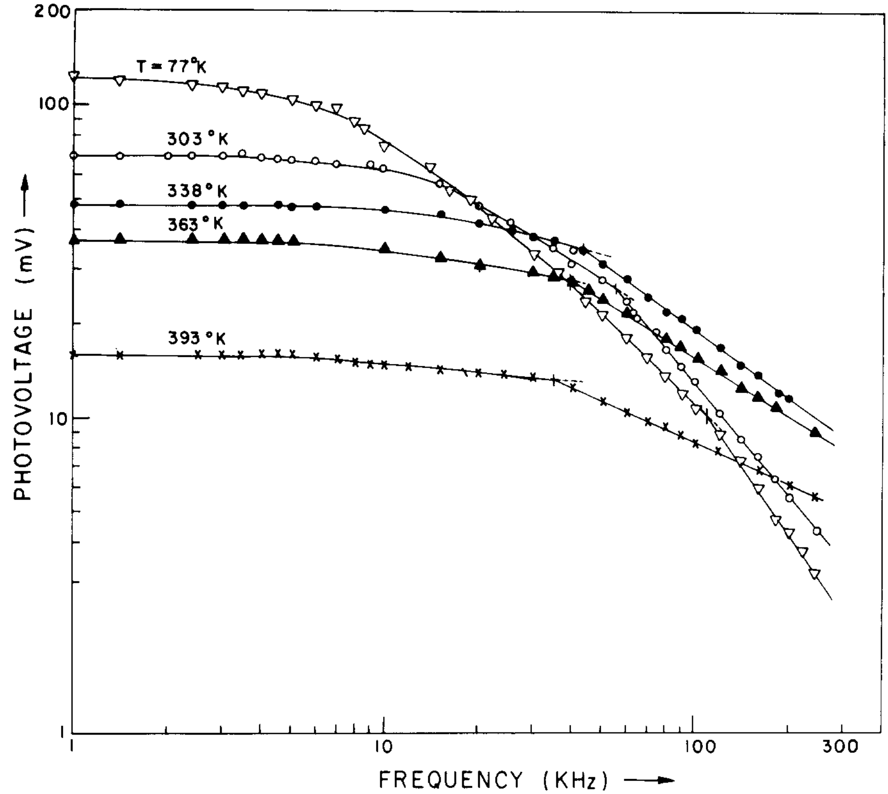

Fig. 2. Variation of a.c. photovoltage with frequency at different temperatures.

$$D_n = (kT/q)\mu_n$$

where k is the Boltzmann's constant, T is the temperature, q the electronic charge and μ_n is the mobility of the electrons.

The values of the minority carrier mobility at different temperatures in 2 Ω cm resistivity material are taken from Gartner's work [10]. Figure 3 shows that the rate of increase of diffusion length with temperature is not very high as compared with that of lifetime. At liquid air temperature, the carriers diffuse a very short distance of about 38 μm.

In this technique, a d.c. bias to the LED source always keeps the solar cell in the forward biased condition. To study the dynamic properties of the junction, measurements of junction resistance and capacitance were taken at different self-biased voltages. The self-biased voltages in the solar cell were produced by changing the intensity of the LED source or the distance between the source and the solar cell. The variation of RC, the time constant of the junction, with open-circuit d.c. voltage developed can be seen in Fig. 4. The short-circuit current obtained at these open-circuit voltages is measured and plotted in Fig. 5. It gives the operating point of the solar cell

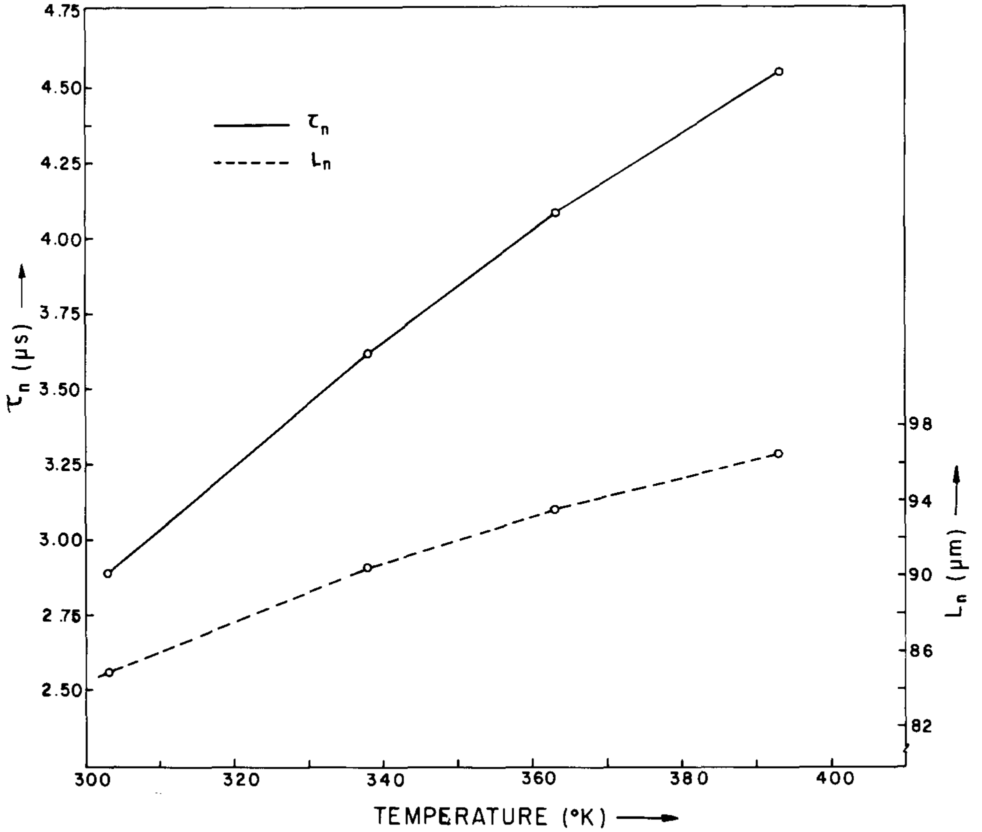

Fig. 3. Lifetime and diffusion length as a function of temperature.

between 0.1 and 0.112 V. During the measurement of a.c. photovoltages with frequency variation at the source, the cell was always kept within this operating range. One can see from Fig. 4 that in this range the RC time constant does not change much. Even at high frequencies, where the second bending point occurs, the d.c. light always keeps the cell in the operating range. Therefore it also avoids the anomaly of giving the wrong values of the lifetime calculated from the tail of the V_{oc} decay curve suggested by Moore [5]. The d.c. bias does not allow decay in the lower range of V_{oc}.

5. Conclusions

Fast light flashes have been used to measure minority carrier lifetime. In addition, a d.c. bias to the source always keeps the solar cell in the forward biased condition. This eliminates the limitation on the open-circuit voltage of the solar cell, which can now go beyond the equivalent thermal voltage. The lifetime is found to increase with temperature but the diffusion

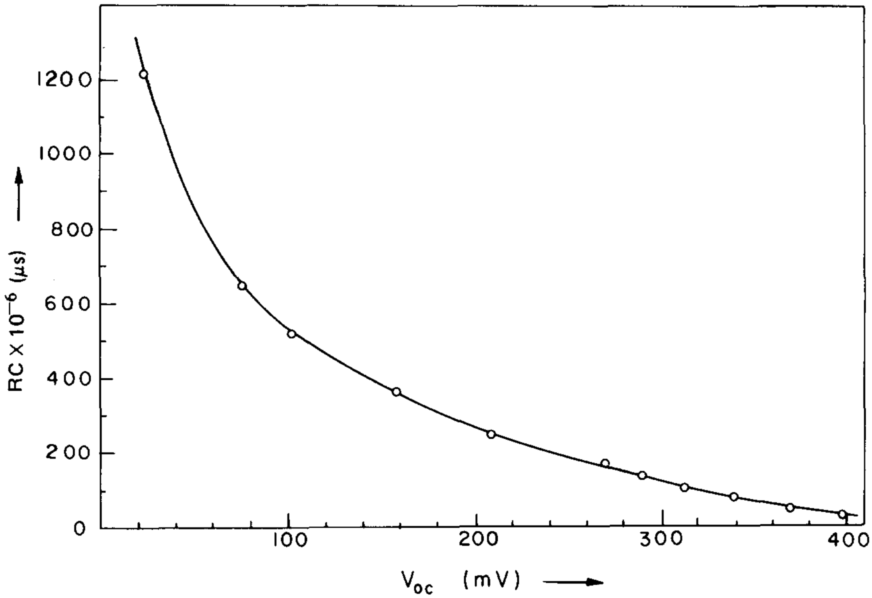

Fig. 4. Variation of RC, the junction time constant, with V_{oc}.

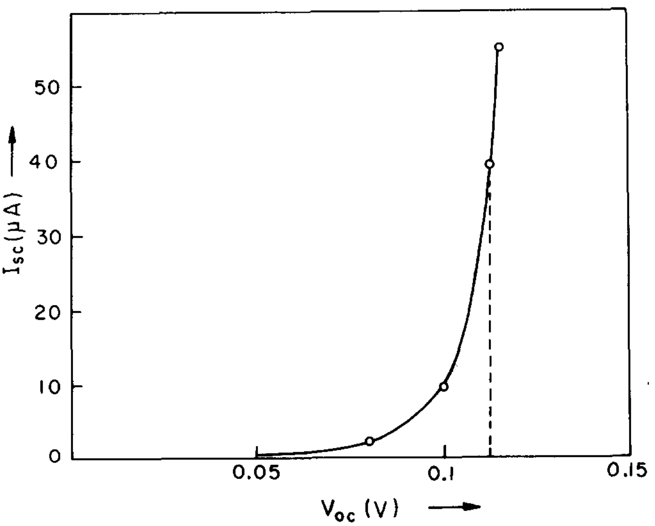

Fig. 5. I_{sc}–V_{oc} characteristics of the solar cell.

length does not increase much in the range 30 - 120 °C. The increase in lifetime is compensated for to some extent by a decrease in mobility.

At liquid air temperature, the lifetime of the minority carriers decreases to 1.45 μs and the carrier diffusion length is reduced considerably. One reason for it may be that most of the carriers are in a frozen state at such low temperatures.

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