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Photoconductivity Studies of Crystalline Si:H p-i-n

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Abstract

Optically modulated photoconductivity (PC) properties of hydrogenated crystalline silicon (c-Si:H) with p-i-n junctions were investigated by frequency-resolved spectroscopy in the temperature range 20-290 K. The PC lifetime measurements of c-Si:H p-i-n show a second lifetime distribution which only dominates at low temperature under low illumination levels of excitation. Unlike the room temperature single lifetime distribution seen in c-Si:H p-i-n, the maximum of this second lifetime distribution shifts to longer times when the excitation intensity decreases, which reconciles with non-geminate pair recombination and thus the distant-pair model. In addition to lifetime measurements, the direct current-voltage (I-V) characteristics, the excitation light intensity- and electric field-dependence of the PC were also measured under various conditions. The results are discussed in terms of PC models proposed.

1. Introduction

Solar power has attracted attention of late as the most advanced of the alternative energy resources [1, 2]. Solar power generation exploits the properties of solar cells or photodiodes, which generate d.c. electricity when light falls on a cell made from the p-i-n junction Si (silicon) material.

Simply, light impinging on a material system can be absorbed and some absorption processes result in mobile particles (electrons, holes, excitons, and polarons) which can move about the solid by transport in bands or by hopping. If mobile photogenerated charge carriers are created in or diffuse to a built-in electrostatic field region in a solid, this built-in electric field can separate these carriers according to charge and sweep them out, setting up a current density. The internal field is provided by p-n junctions, p-i-n junctions, heterojunctions, Schottky barriers, etc.

Recently the p-i-n junction has been regarded as a more promising candidate for solar cells because of its high stability against light soaking and the high absorbance for near-infrared light [3, 4, 5]. The relationship between the electrical conductivity of p-i-n junction and its device performance, however, is not clearly understood. PC is a powerful tool for determining the properties of solar cells (photodiodes), as well as optical sensors and other optical devices. In this work, we used frequency-resolved spectroscopy on a c-Si:H p-i-n photodiode, at different excitation light intensities and over the temperature range of 20-290 K. The exponent ν in the power law relationship $I_{ph} \propto G^{\nu}$ between the photocurrent and the generation rate was also determined over the same temperature range. The results are discussed in the light of proposed PC models.

2. Experimental

The sample used here is a BPX65 series c-Si:H p-i-n photodetector diode from Centronic, and has a wide variety of applications. In structure, the BPX65 is a planar silicon p-i-n photodiode housed in a modified TO-18 case incorporating a plain glass flat window which has no influence on the beam path of optical lens systems. The cathode is electrically connected to the case. Because the BPX65 is capable of detecting wide bandwidth signals due to its excellent high frequency response, this coupled with its high sensitivity makes the device ideal for signal detection applications.

For I-V characteristics (d.c), an HeNe laser (633 nm) was used as excitation, with the light intensity being controlled through the use of calibrated neutral density filters. A Keithley 616 digital electrometer was used for measuring currents.

The quadrature frequency-resolved photocurrent (FRPC) measurements were made with a lock-in amplifier (SR 530, Stanford Research Systems). These measurements yield lifetime distributions directly. The details of FRPC measurements are described elsewhere [6]. The advantage of this frequency-locked a.c. measurement is that it rejects any stray light, dark current and any other unmodulated signals. For FRPC measurements, the HeNe laser beam (1.96 eV) was modulated by an acousto-optic modulator (IntraAction Corp., Model AOM-125). The modulation amplitude amounted to 46 % of the bias light intensity. The HeNe laser was replaced by an Ar^{+} dye laser for high excitation intensities. All FRPC measurements were performed under reverse bias (d.c.) conditions. During the measurements, the p-i-n photodiode sample under investigation was held in a helium exchange-gas cryostat in which the sample temperature could be varied between room temperature (RT) and 20 K. The vacuum pressure of the cryostat was kept less than about 10^{-6} Torr. The heating effect due to the high excitation intensity (up to 11 mW at 488.0 nm) of the powerfil Ar^{+} dye laser was minimized by using heat absorbing filters (KG3).

3. Results

Basically, a photodiode can be visualized as an equivalent electrical circuit [1, 2, 7] in which it may be represented by a photogenerated current source feeding into an ideal p-i-n diode. Its internal characteristics may be better modelled by the introduction of a shunt resistor, a shunt capacitor and a series resistor. In operation, two different modes are possible. In the photovoltaic mode an external high value resistor (load resistor) is connected across the output and the voltage across this measured. In the photoconductive mode an external bias is applied in conjunction with a series load resistor. The current flowing through this load resistor is monitored by measuring the voltage across it.

Figure 1, which corresponds to the photoconductive mode mentioned above, shows the current/voltage (I-V) characteristic of c-Si:H p-i-n photodiode under dark and various illumination levels of the HeNe laser beam (633 nm). Here, 1 mW corresponds to an intensity of about 10^{19} photons $\times$ s^{-1} cm^{-2}. Obviously, under increasing levels of illumination, the curve is progressively shifted downwards. We can explain this result in the light of a simple physical model of transport for p-i-n solar cells proposed by Crandal [8, 9]. According to this model, for weakly absorbed light, the shape of photocurrent-voltage curve is completely specified by the electron and hole drift lengths. Furthermore, it is the carrier with the longer drift length that determines the current-voltage curve and hence the photodiode fill factor.

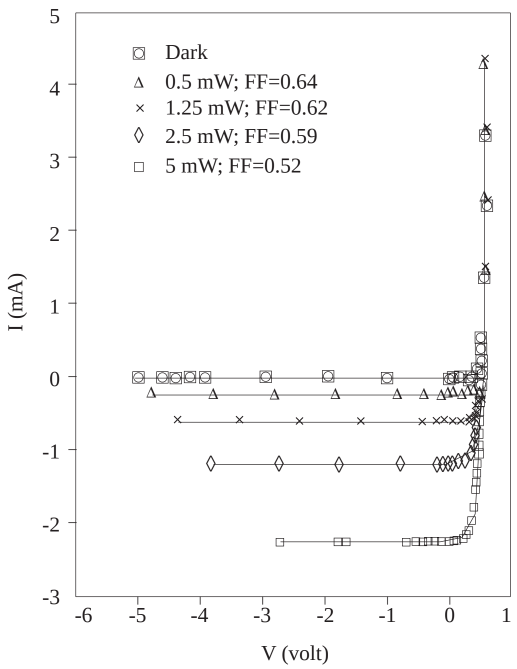

Figure 1. Current-voltage (I-V) curves of c-Si:H p-i-n photodiode at 290 K, under dark and different illumination (633 nm) levels. Lines are drawn as guides for the eye. The fill factor FF is indicated in each case.

Photodiodes operate without an externally applied voltage and the collection of carriers results from the internal field at the junction. This is refereed as the fourth quadrant in Figure 1. Of all the parameters used to characterize photodiodes, the conversion efficiency η is the most important and defined as the percentage of the total power in light that is converted into electrical power. It may be expressed as [10]

$$\eta = \frac{I_m V_m}{P_i} = (FF)\frac{I_{sc} V_{oc}}{P_i}, \tag{1}$$

where I_m and V_m are the output current and voltage of a photodiode operating under maximum power conditions, respectively, and P_i is the incident power density of the illumination. I_{sc} is the short-circuit current and V_{oc} is the open circuit voltage. A "fill factor" FF, which shows how closely $V_m I_m$ approaches $V_{oc} I_{sc}$ and acts as a useful figure of merit for solar-cell or photodetector diode design, is often defined by

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}}. \tag{2}$$

From the fourth quadrant of Figure 1, the determined values of FF of c-Si:H p-i-n photodetector diode were presented on Figure 1 for the indicated excitation intensities. As can be seen, the FF decreases with increasing excitation intensities. The FF is thus dependent on incident light intensity because of changes in series and parallel resistance of photodiode by light illumination.

The current of an ideal p-i-n photodetector diode or solar cell in dark obeys the diode relation

$$I_i = I_0\{\exp(qV/\xi kT) - 1\}, \tag{3}$$

where I_0 is the reverse saturation current, q is the electron charge, V is the applied voltage, k is Boltzmann's constant, T is the absolute temperature and ξ is the diode quality factor: $\xi = 1.0$ for an ideal diode while $\xi = 2.0$, if recombination and generation effects dominate [10]. The saturation current I_0 (sometimes called the dark current) is obtained when a large negative voltage is applied across the diode. It is a measure of the built-in potential or barrier height of a semiconductor junction. When light impinges on the junction, the electron-hole pairs are created at a constant rate providing electrical current flow across the junction. The net electrical current is thus the difference between the normal diode current and the light generated current I_L,

$$I = I_L - I_i = I_L - I_0\{\exp(qV/\xi kT) - 1\}. \tag{4}$$

A plot of this equation follows Figure 1.

The quality factor as well as the series and shunt resistances of a photodiode affect its fill factor FF and thus efficiency η [1, 2, 7]. But this being not the main goal and scope of the present investigation, we instead concentrate on FRPC measurements in this paper.

Figure 2 shows the frequency-resolved photocurrent (FRPC) response of c-Si:H p-i-n photodiode at low temperature (20 K) for different illumination (488.0 nm) levels of the Ar^+ laser. The applied voltage was -1 volt. In the frequency-resolved spectroscopy (FRS) method [11, 12, 13, 14, 15] the photocarrier lifetime τ can be obtained from the peak frequency f_{peak} as

$$\tau = \omega^{-1} = \frac{1}{2\pi f_{peak}}. \tag{5}$$

The lifetime τ is also related to the generation rate G, which is proportional to excitation intensity F, as $\tau = n/G$ [16], where n is the density of charge (electron) carrier. Obviously, as can be observed in Figure 2, the spectra are dominated at low temperature (20 K) by the combination of two peaks, one which we shall call the main peak, at $\sim$ 40 kHz (4 μs) and the other, called the second peak here, at $\sim$ 70 Hz (2.3 ms) for the lowest excitation intensity (1 μW) used.

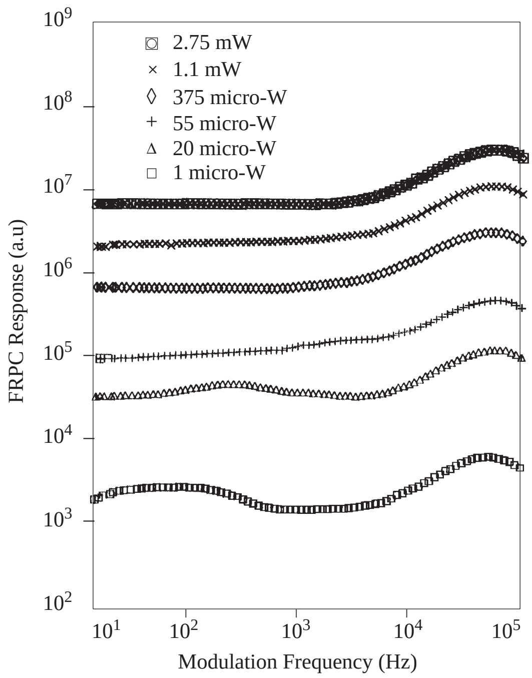

Figure 2. Frequency-resolved photocurrent (FRPC) response of c-Si:H p-i-n photodiode at 20 K, for the indicated excitation (488.0 nm) intensities.

The main peak is independent of excitation intensity and temperature. However, the second peak, observed by us for the first time, is intensity and temperature dependent. It shifts and narrows to higher frequencies with increasing excitation. We should note that this finding (the second peak) only appears at temperatures below about 60 K and low excitation intensities below about 55 μW. Further, it markedly dominates and broadens when the temperature and excitation intensity are reduced. Similar results were also observed in amorphous Si:H p-i-n solar cells (photodiodes) which do not have crystal-like periodicity or symmetry. In a Sanyo-type p-i-n cell [13] the second peak almost appears at the same low frequency range, while it is presumably centered at a frequency below 10 Hz for a Casio-type p-i-n cell [17] at low temperatures ($<$ 60K), depending upon the excitation intensity used. It has been suggested that these results can provide a way of distinguishing between capture and recombination rates; if the carriers move in extended states, and detrapping is not important, then only one peak is expected in the FRPC, corresponding to the total capture rate into localized levels. At higher temperatures carriers may be thermally ionised from recombination or trapping states. Simple models indicate that a second lifetime proportional to the detrapping rate will be even if only one recombination path is present. However, because the release rate is thermally activated both the second lifetime and the strength of its contribution will be strongly temperature dependent [13].

The distribution of lifetimes ($\tau \propto f_{peak}^{-1}$) with respect to generation rate have been used to determine what kind of recombination occurs between the photoexcited carriers [18, 16]. It has been suggested that in the geminate type of recombination the distribution of lifetimes will be insensitive to generation rates, whereas in distant pairs model DP where it is assumed that recombination takes place between nearest available neighbours non geminately, the lifetimes should decrease with increasing generation rate. The result shown in Figure 2 shows that the peak frequencies (the second peak), and consequently the lifetimes, are dependent on the generation rate and therefore can be interpreted as supporting the DP model.

Both spectra peak position maximums shown in Figure 2 are independent of the applied electric field.

Figure 3 shows the variation in the photocurrent I_{ph} with illumination level F for different wavelengths at room temperature (290 K) and low temperature (20 K). The data were taken with a reverse bias of -1 volt. The modulation frequency of excitation light was held at 10 Hz. The linear behaviour of $\ln I_{ph}$ against $\ln F$ plots indicates that the photodiode follows a power-law dependence, that is

$$I_{ph} \propto F^{\nu}. \tag{6}$$

The exponent ν in this equation determines whether the recombination process is monomolecular or bimolecular. This distinction is often made in the case of semiconductors with the help of the simple relation [19]

$$G = C_n(\Delta n^2 + 2n_0\Delta n), \tag{7}$$

where G is the generation rate, C_n is the capture coefficient, n_0 is the density of thermally generated carriers and Δn is the excess carrier density. This relation gives direct insight into the dependence of Δn on the generation rate G, and consequently on the excitation light intensity F, which is proportional to G. For a monomolecular recombination process, where $\Delta n << n_0$, Equation 7 reduces to

$$\Delta n \approx \left(\frac{G}{2n_0C_n}\right) \approx F \tag{8}$$

which indicates that the photocurrent varies linearly with the illumination level. For a bimolecular recombination process, where $\Delta n >> n_0$, Equation 7 reduces to

$$\Delta n \approx \left(\frac{G}{C_n}\right)^{1/2} \propto F^{1/2}, \tag{9}$$

and the photocurrent should be proportional to the square root of the illumination level. Furthermore, a continuous distribution of localized states is expected to occur if the exponent ν lies between 0.5 and 1.0 depending upon the intensity and temperature range [20]. As can be seen from Figure 3, the value of ν is close to unity for both temperatures (290 K and 20 K) and wavelengths (488.0 nm and 633 nm), and suggests monomolecular recombination. If it is thought that in c-Si:H p-i-n photodiode the photocurrent is carried by electrons, the governing processes in the recombination is the capture of electrons at deep traps unaffected by the light intensity. In other words, the constant value of $\nu \sim 1$ indicates a region of virtually uniformly distributed recombination centers through which the electron quasi Fermi level is swept as the intensity of illumination is increased. This results in monomolecular recombination and an electron lifetime which varies only slightly with illumination [21]. A very little wavelength dependence of ν seen in Figure 3 comes through the intensity dependence. This is because the incident power is absorbed within a depth $1/\alpha$ (α: absorption coefficient), and the power density increases with decreasing wavelength.

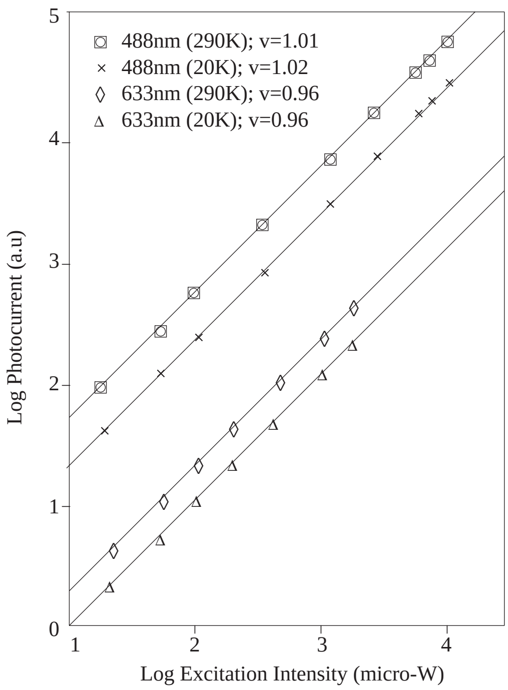

Figure 3. Variation in photocurrent of c-Si:H p-i-n photodiode with illumination level at 20 K and 290 K, for the indicated wavelengths. The modulation frequency of excitation light was kept constant at 10 Hz. The exponent ν in the relationship $I_{ph} \propto F^{\nu}$, is indicated in each case.

Although values of ν are not shown in Figure 3 at other temperatures between room temperature and 20 K for clarity, should they be shown they would all lie between 0.96 and 1.02 for both wavelengths (488.0 nm and 633 nm) used. The ν values were also found to be independent of the applied electric field and frequencies up to 10 kHz.

Figures 4 and 5 show the reverse applied electric field dependence of FRPC for different excitation intensities (488.0 nm) and temperatures, respectively. In both results, the thickness of the intrinsic (i)- layer was supposed to be about 1 μm. The modulation frequency of excitation light was kept constant at 10 Hz. In Figure 4 the measured temperature was held at 20 K, while an excitation intensity value of 11 mW (488.0 nm) was used in Figure 5. The frequency-resolved photocurrent is seen to increase linearly with increasing electric field at higher temperatures and then saturate at a sufficiently large reverse bias. A reasonable mechanism [8, 9] to explain this result is that electron-hole recombination in the undoped i-layer reduces the photocurrent at low field. In this regime, the photocurrent will vary linearly with the electric field (Ohms law behaviour). At high fields, recombination is unimportant compared with transport during which all the excited electron-hole pairs are collected.

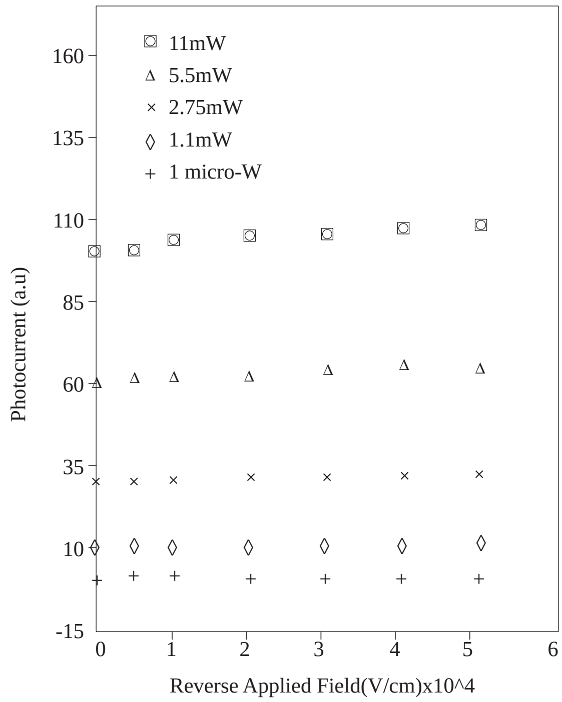

Figure 4. Reverse applied electric field dependence of photocurrent in c-Si:H p-i-n photodiode at 20 K, for the indicated excitation (488.0 nm) intensities. The modulation frequency of excitation light was kept constant at 10 Hz.

The photocurrent saturates at large reverse bias because the photogenerated carriers are not replenished at the contacts. The n-i and p-i interfaces act like blocking contacts for the photogenerated carriers. Nevertheless, these interfaces can be injecting contacts for the thermally generated carriers.

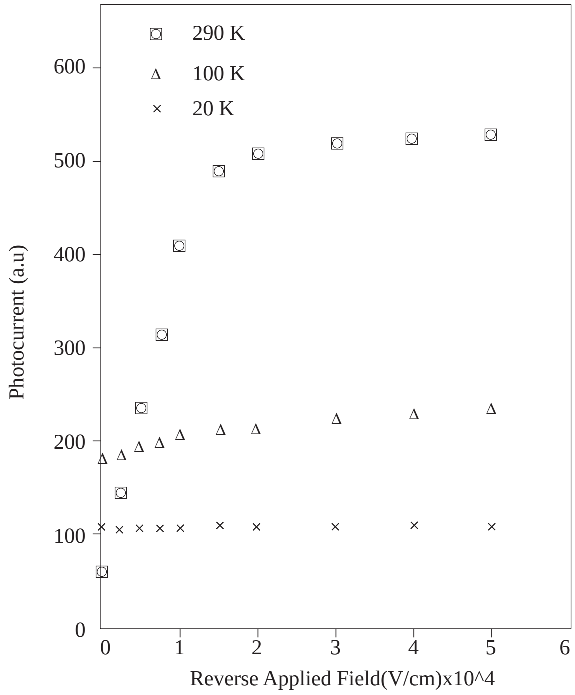

Figure 5. Reverse applied electric field dependence of photocurrent in c-Si:H p-i-n photodiode at the indicated temperatures for an excitation (488.0 nm) intensity of 11 mW. The modulation frequency of excitation light was kept constant at 10 Hz.

4. Conclusion

The I-V characteristics of c-Si:H p-i-n photodiode were preliminarily measured in dark and under different illumination levels, and thereby the values of fill factor were obtained. It was reported that the fill factor is dependent on excitation intensity.

The FRPC response of c-Si:H p-i-n photodiode was measured. The FRPC spectra was found to be dependent on excitation conditions such as temperature and intensity. At lower temperatures and excitation intensities, the spectra were dominated by the combination of two peaks: one (the main peak) at $\sim$ 40 kHz (4 μs) and the other (the second peak) at $\sim$ 70 Hz (2.3 ms) (for 1 μW). However, the lifetime of the second peak depends on excitation intensity and quenches above about 55 μW. Further, above about 60 K this second peak is not seen in the spectra, and only the main peak, which is intensity and temperature independent, dominates. We suggest that the second peak can be related to the detrapping rate and can be interpreted as supporting the DP model in which the lifetimes should decrease with increasing intensities.

From the light intensity-dependent photocurrent measurements, the value of exponent ν in the relation $I_{ph} \propto F^{\nu}$ was determined. The ν values lie between 0.96 and 1.02 depending upon excitation wavelength and temperature used. The constant value of $\nu \sim 1$, indicates a region of virtually uniformly distributed recombination centers through which the electron quasi-Fermi level is swept as the intensity of illumination is increased. This results in monomolecular recombination.

The electric field dependence of FRPC was also measured under different intensities and temperatures. The results show that the photocurrent increases linearly with increasing electric field and then saturates at a sufficiently large reverse bias. At low fields where the sum of the drift lengths for electrons and holes is less than i-layer thickness, recombination of electron-hole pairs dominates the transport, while at higher fields the recombination is unimportant and all the excited electron-hole pairs are collected (saturation) in the external circuit.

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