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Optical Properties of n – type Silicon

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Abstract

Photoconductivity ($\Delta\sigma^*_{pc}$) and minority carrier lifetime(τ_p) of n - type single crystal silicon were measured in the temperature range 300 - 418 K. The effect of varying sample current and light intensity (I_L) on photoconductivity and carrier lifetime at room temperature (300 K) were also investigated. Photoconductivity increases with the increase of light intensity and also with temperature. Variation of photoconduction with light intensity is nonlinear and with temperature is linear. The value of lifetime of holes was found to be 1.29 ms. Nearly constant value of carrier lifetime was observed with the variation of light intensity and temperature. .The diffusion length for holes (L_p) was estimated to be 0.13 cm. The carrier concentration (n) and Hall mobility (μ_H) at room temperature were determined from the Hall Effect measurement. The values of n and μ_H at room temperature were 7.85 x10^{14} cm $^{-3}$ and 1344 cm^2 / V.s respectively. The value of lattice parameter a (Å) of Si was found to be 5.428 Å.

I. Introduction

Photoconductivity, minority carrier lifetime, diffusion length, diffusion constant, surface recombination velocity and absorption coefficient are important optical parameters which characterize a semiconductor material used for the fabrication of photosensitive devices including solar cell. Photoconductivity measurement can be used to determine minority carrier lifetime, carrier mobility, trapping phenomena, imperfection or impurity - level location and capture cross section of defect centres for free carriers. Considerations in choosing a photoconductor for a given application include the sensitive wavelength range, time response and optical sensitivity of the semiconductor.

Extensive studies of photoconductivity and carrier lifetime were made on Si. Apart from dependence of photoconductivity on wavelength and intensity of light, the presence of impurities or defects in the sample, however, influences the process of photoconductivity in variety of ways – depending on whether they act as traps or recombination centres [1]. If the impurity centres act as traps then a major effect of trapping is to make the observed decay time longer than the carrier lifetime. If no trapping centres are present, then the observed photocurrent will decay in the same way as the density of free carriers, and the observed decay time will be equal to the carrier lifetime. If trapped carrier density is small compared to free carrier density the decay curve remains unaffected. On the other hand, if it is comparable or greater than that of free carriers ,the thermal freeing of trapped carriers during the course of the decay can prolong the decay so that the observed decay time is longer than the actual recombination – determined lifetime of a free carrier. If density of trapped carriers is much greater than the density of free carriers, the rate of trap emptying rather than rate of recombination dominates the decay of photocurrent. This results in a non –exponential decay curve and prolongs the decay of photocurrent. In addition, presence of traps may decrease the sensitivity of the photoconduction process. On the other hand presence of impurities acting as pure recombination centres will not affect the nature of the decay curve although it may reduce the carrier lifetime.

The effects of trapping centres in n-type Si was found by Haynes and Hornbeck [2]. The effect was due to the presence of two hole traps at 0.47 and 0.72 eV above the top of the valence band. Minority carrier lifetime in both n-type and p-type silicon single crystal in the range 75 - 20,000 μsec were obtained by T.L. Chu and E.D. Stokes [3] . J.Schmidt and A.G.Aberle [4] used Microwave- detected photoconductance technique for the determination of bulk minority carrier lifetimes of p- and n-type silicon wafers of thickness (< 0.5 mm) with doping concentrations in the 10^{14}–10^{17}cm^{-3} range .Effective Value of carrier lifetime obtained by them was 1224 μs for n-Si .Diffusion lengths of minority carriers in the range 1- 1200 μm were measured in n- and p-type silicon single crystals with a wide range of resistivities by the surface photovoltage method [5]. Single bulk Crystalline silicon solar cells [6] were fabricated on a variety of silicon substrates materials having effective carrier lifetimes in 1 – 2 ms range. The observed effective carrier lifetimes were higher for n-type than p- type substrates.

Some devices [7] are usually operated near and somewhat above room temperature. Previously,[8] electrical and optical properties of p-type silicon in the temperature range 300 – 415 K were investigated . The purpose of this work was to determine the optical parameters of the n-Si sample in the temperature range 300 - 418 K. The results of the effects of variation of sample current and light intensity on photoconductivity and carrier lifetime of the samples at room temperature were also reported. Lattice parameter of the sample was determined by X- ray diffraction (XRD) method.

II. Theoretical Formulation

Photoconductivity is the increase of electrical conductivity of a semiconducting crystal caused by radiation incident on the crystal. The direct effect of illumination is to increase the density of charge carriers (electron - hole pairs). The theory for photoconductivity measurement with lock - in amplifier has been described in Ref.[9]. The change in conductance ,$\Delta\sigma$, of the sample being illuminated is given by the following relation

$$\Delta\sigma = \frac{\Delta v(R + r_0)^2}{r_0^2 VR - \Delta v r_0 R(R + r_0)} \quad (1)$$

where $\Delta\nu$ is the change in voltage when the sample is illuminated. R, V and r_0 are load resistance, supply voltage and dark resistance of the sample. When $R = r_0$ (Maximum sensitivity regime), $\Delta\nu$ attaints the maximum value $\Delta\nu_m$ and photoconductivity, $\Delta\sigma^*_{pc}$,can be expressed in terms of dark conductivity σ_0^* of the sample as

$$\Delta\sigma_{pc}^* = 4.\frac{\Delta\nu_m}{V}.\sigma_0^* \quad (2)$$

The excess conductance of the sample is directly proportional to the total number of excess charge carriers produced. For a small conductance change the voltage at the terminals of the constant current source is proportional to the conductance change. The voltage, therefore, decays back to its original value with the same time dependence as the number of excess carriers in the silicon samples. The time dependence of the excess charge carriers density is obtained from the display of the voltage change on the oscilloscope. From this curve the mean lifetime of the carrier is determined. It is observed that the decay of photoconductivity is exponential. The excess carriers $\Delta p(0)$ decay with time t approximately as

$$\Delta p(t) = \Delta p(0)\, e^{-t/\tau} \quad (3)$$

where τ is the lifetime of excess carriers.

The lifetime of holes is determined by noting the time required for the amplitude of the decaying signal to drop ½ its original value, at $t = t_{1/2}$

$$\tau_p = \frac{t_{1/2}}{\ln 2} \quad (4)$$

The carrier concentration and Hall mobility at room temperature were determined from Hall effect measurement. The experimental arrangement was described earlier[8] .

Hall coefficient, R_H in cm^3/C was determined as

$$R_H = \frac{tV_H}{HI} \times 10^8 \quad (5)$$

where t is the sample thickness in cm ,V_H the Hall voltage in V, H the magnetic field in G and I is the current in A. Carrier concentration was computed from Hall data using the relation $n = 1 / e R_H$, where e is the charge of electron . Conductivity (σ) and R_H data were combined to give Hall mobility of electrons μ_n defined as $\mu_n = \sigma R_H$.

The lattice parameter a(Å) of the n-type silicon sample was determined by X-ray diffraction (XRD) method. The interplanar spacing d was calculated using the formula :

$$2d \sin\theta = \lambda \quad (6)$$

where λ is the wavelength of the incident radiation and for Cu-Kα, λ = 1.54178 Å was used.

III. Experimental

Sample preparation

Rectangular shaped pieces having different dimensions were cut by a diamond cutter from a n-type single crystal silicon wafer of diameter 5 cm and of thickness 2 mm. The mechanically damaged surfaces of the samples were polished with 1000 grit SiC powder and 1.0 micron alpha alumina powder respectively in a polisher (Buehler Ecomet III Grinder U.S.A). The samples were then cleaned with acetone and de-ionized water in an ultrasonic bath and finally etched in Beize solution(2HNO_3 (86%) :1 HF(48%) :1 CH_3COOH(98%). The samples were etched inside a fume chamber. Electrical leads were soldered to the end faces of the samples by indium.

Measurements

The experimental arrangement for measuring photo-conductivity with lock-in amplifier was described elsewhere[9]. Chopping frequency was measured by a light chopper (125/99,EG&G, PARC). The DSP Lock-in amplifier (7225, Signal Recovery) was used for photoconductivity measurements. To increase the temperature of sample above room temperature a heating coil (35 W) and power supply (Philips) were used. The temperature was measured by using copper - constantan thermocouple and digital temperature controller. Heating rate was maintained to be 0.40 K /min. Light source used was 100 W quartz halogen lamp. Intensity of light was measured by a lux meter (LX 101). Lifetime of the charge carriers is determined from the decay of photoconductance trace displayed on an oscilloscope. The carrier concentration and Hall mobility at room temperature were determined from Hall effect measurement. The experimental arrangement was described earlier[8] .The X- ray diffraction (XRD) was used to determined lattice parameter of silicon sample. The XRD pattern was recorded using a Philips PW 3040 X' Pert PRO XRD system with Cu-Kα radiation, operated at 40 kV and 30 mA , with angular range $20° \leq 2\theta \leq 80°$.

IV. Results and Discussion

Resistivity of the silicon samples was measured by four-point probe method. The voltage current (V-I) characteristics of the samples is shown in Fig.1.The resistivity of the samples was in range 5.35 – 6.95 Ω.cm at room temperature.

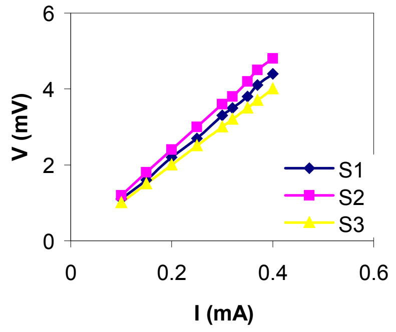

Fig.1. Voltage (V) vs Current (I) curve for n-Si

Photoconductivity and carrier lifetime of the samples were measured for sample current varied from 2.0 to 8.5 mA at fixed light intensity of 2360 Lux and chopping frequency of 45 Hz. Photoconductivity obtained was $4.23\text{–}4.97\times10^{-4}\Omega^{-1}cm^{-1}$. The value of hole lifetime τ_p was of the order of 1.29 ms.

Fig.2. shows the variation of photoconductivity with temperature in the range 300–418 K. It has been found that photoconductivity increases with the increase of temperature. This is due to the increase of minority carrier concentration with temperature. A linear dependence of photoconductivity on temperature has been observed in this investigated temperature region.

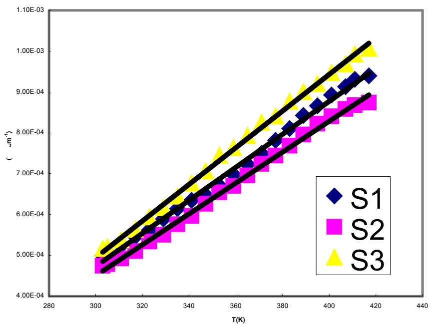

Fig.2. Variation of photoconductivity ($\Delta\sigma$*) with temperature T

The variation of lifetime with temperature is shown in Fig.3. The variation of τ_p with temperature has been found to be negligible for all samples. From the variation of lifetime with temperature the location of trapping levels, if present, can be determined. The value of lifetime of holes remained constant in this investigated temperature range, which indicates that there is no significant trapping level present in the samples.

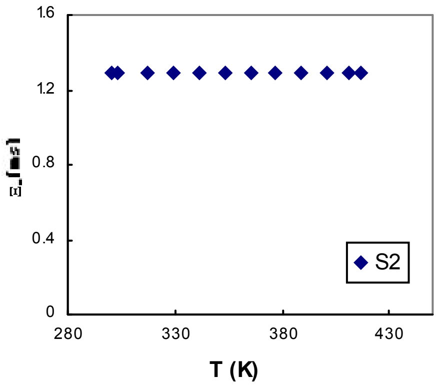

Fig.3. Variation of carrier lifetime (τ_p) with temperature T

The variation of photoconductivity $\Delta\sigma^*_{pc}$ with light intensity I_L (138 – 17500 lux) is shown in Fig.4 for certain samples. The intensity of incident light was controlled by varying the voltage of the light source. The sample was illuminated over its entire front surface. It has been observed that photoconductivity increases with the increase of light intensity. This is because increase of light intensity increases excess minority carriers. It is further noted that photoconductivity $\Delta\sigma^*_{pc}$ varies with light intensity $I_L$as $\Delta\sigma^*_{pc} \propto I_L^x$, where x is found to lie between 0.55 and 0.61 and hence variation of photoconduction with intensity of light is nonlinear.

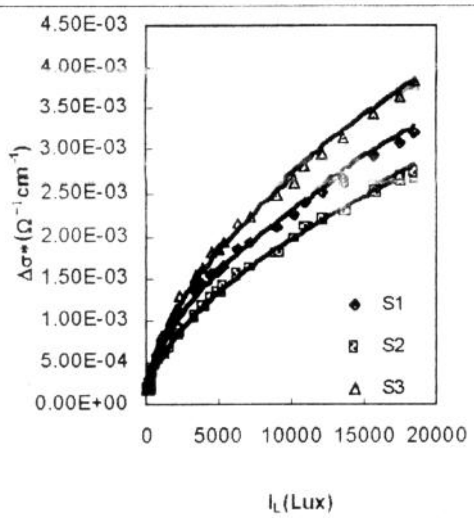

Fig.4. Variation of photoconductivity ($\Delta\sigma$*) with light intensity (I_L)

Fig.5 shows τ_p as a function of light intensity. No significant variation in τ_p with light intensity has been observed. Nearly constant value of τ_p of 1.29 ms has been estimated for all samples with increasing light intensity. The diffusion length for holes (L_p) obtained using the relationship $L_p=\sqrt{D_p\tau_p}$ has been calculated to be 0.13 cm.

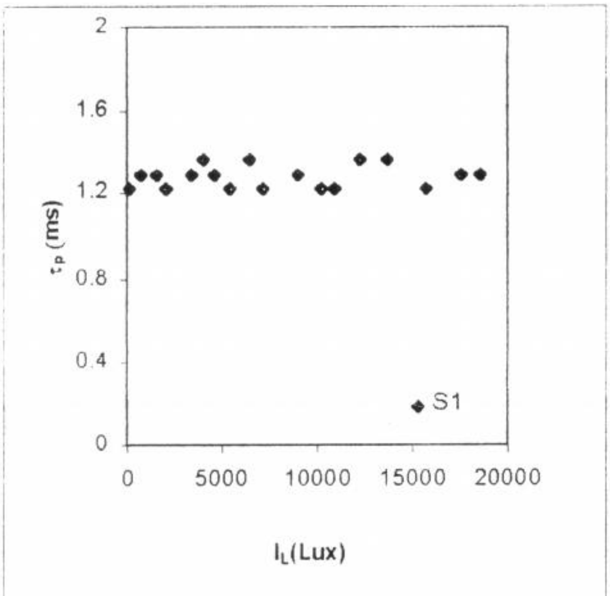

Fig.5. Variation of carrier lifetime (τ_p) with light intensity (I_L)

A magnetic field of 2.72 Kilogauss was used for Hall coefficient measurement. The values of R_H of -7.95×10^3 cm^3/C and n of $7.85 \times 10^{14} cm^{-3}$ were obtained at room temperature. Hall mobility μ_n was found to be 1344 cm^2/V.s. This value of mobility is consistent with that obtained by Putley et al[10-11].

Fig.6. shows the X – ray diffraction pattern of the sample. The calculated value of the lattice parameter has been found to be 5.428Å. This value is well comparable with the published data [11] .

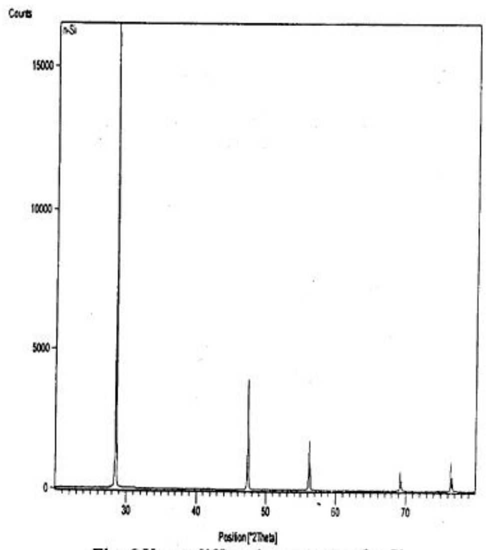

Fig. 6 X-ray diffraction pattern of n-Si

Conclusions

From the above investigations, it may be concluded that the material has immense importance for use in the fabrication of photoconductive devices. Results showed that photoconductivity increased linearly with temperature and nonlinearly with light intensity. Variation of carrier lifetime with temperature and light intensity was insignificant.

Acknowledgement

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