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Electrical Optical and Structural Properties of p-type Silicon

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Abstract

Electrical, optical and structural properties of p-type single crystal silicon were investigated in this work. Electrical conductivity of p-type silicon was measured in the temperature ranges 190 - 300 K. The acceptor ionization energy (□E_A) was between 0.047 - 0.051 eV. Photoconductivity of the material was investigated by varying sample current, light intensity and temperature at a constant chopping frequency of 45.60 Hz. Absorption co-efficient (□) of the material was calculated from optical transmittance and reflectance measurements at room temperature (300 K) in the wavelength range of 300 -2500 nm. The direct optical band gap energy was found between 2.10 - 2.20 eV and the indirect optical band gap energy was found between 0.95 – 1.0 eV. The lattice parameter (a) was found to be 5.419Å from X-ray diffraction method (XRD).

Keywords: Electrical conductivity, Photoconductivity, Absorption co-efficient, Optical band gap.

I. Introduction

Silicon (Si) is a well known intrinsic semiconductor which shows various interesting electrical and optical properties when doped with impurity (such as B, Al, P, As etc.). p-type Si has wide applications in the field of solar cells, light emitting diodes, photo detectors, lasers, transistors, specialized IC's etc. Electrical properties of single crystal silicon containing arsenic (As) and boron (B) were studied[1] and the boron acceptor level was found to be 0.045 eV for low impurity concentration. Infrared absorption measure-ments have shown the existence of shallower acceptor levels associated with both boron and gallium in silicon and the optical ionization energies of boron and silicon were obtained[2] as 37.1±0.3 and 57.0±0.3 meV respectively. Deep Level Transient Spectroscopy (DLTS) and Energy Resolved Tunneling Photoconductivity (ERTP) spectroscopy measurements were studied[3] at cryogenic temperatures on silicon, where electrically active defects were induced by ion implantation of boron and phosphorus into silicon. Intrinsic optical absorption in single crystal germanium (Ge) and Si was studied[4] at the temperatures 77 and 300K, the threshold for direct transition was found to be at 2.5 eV and that for indirect transitions were at 1.06 eV and 1.16 eV at 300 and 77K, respectively. Microwave Photoconductive decay (μ-PCD) was used[5] to find out the copper (Cu) contamination in p-type Si and it was found that the method was capable of measuring Cu concentrations down to 10^{10} /cm^3. The optical parameters and the thickness of Si: H thin films were determined[6] from transmission spectrum in the range of 400–2500 nm using the envelope method and detailed analysis was carried out to obtain the optical band gap (E_g) using Tauc's method and the estimated values were 1.99 eV, 2.01eV and 1.75 eV. Optical properties such as dark conductivity and photoconductivity were investigated[7] on nano crystalline silicon dark conductivity activation energy was found as 0.43 eV and optical band gap was in the range 2.3–2.5 eV. The photovoltaic effect in silicon solar cells were investigated[8] by using a near-field scanning microwave microscope (NSMM) technique and it was found that photoconductivity in the solar cells varied due to the incident light intensities and the wavelength. Optical properties such as absorption co-efficient, reflectivity, band gap of intrinsic silicon was studied[9] at 300 K between the wavelength range 400-1100nm. XRD, Raman Spectroscopy, TEM and SEM of the silicon films were carried out[10] and the optical band gap was found to be varying from 2.19 to 2.63 eV.

In this work, electrical conductivity (□) of p-type single crystal Si was studied by the variation of temperature between 190 to 300 K to determine the acceptor ionization energy. The effects of variation of sample current, light intensity and temperature on photoconductivity of the p-type Si were studied at constant chopping frequency of 45.60 Hz. Absorption co-efficient (□) and optical band gap of p-type Si was obtained from the measurements of optical transmittance and reflectance with a UV-vis-NIR spectrometer of photon wavelength range 300 - 2500 nm. Similar works have been reported[11, 12] on gallium arsenide (GaAs). The aim of present work was to observe the nature of electrical conductivity of p-type Si below room temperature, photoconductive response, the nature of optical absorption, inter-band transition and estimating optical band gap energy.

II. Methods

Rectangular shaped pieces of different dimensions were cut by a diamond cutter (Buehler®, ISOMET™, Low Speed Saw, USA) from a round shaped p-type single crystal Si wafer (purchased from wafer technology, UK) of 3.5cm in diameter. The mechanically damaged surfaces of the samples were polished with 100 grit SiC powder and 1.0 micron alpha alumina powder respectively in polisher (Buehler Ecomet III Grinder, U.S.A). The samples were then cleaned with acetone and de-ionized water in an ultrasonic bath (Kerry, USA)[13]. Electrical leads were soldered to the end faces of the samples by Indium. The electrical resistivity of the p-type Si wafers was measured by both four point probe at room temperature and that of the rectangular shaped samples was measured by two point probe method by varying the temperature from 190 K- 300 K. To decrease the temperature of the samples a liquid

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Nitrogen cryostat was used. A Copper-Constantan thermocouple was attached to the sample holder and the temperature was measured by a digital temperature controller (cyber). The cooling rate was maintained at 0.00533K/sec[14].

Modulated illumination[15] method was used for measuring photoconductivity. 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 the sample above room temperature a nicrome heater (35W) and power supply (Philips) were used. The temperature was measured using Copper-Constantan thermocouple and digital temperature controller. Heating rate was maintained at 0.00533 K/sec. Light source used was 100 W quartz halogen lamp. Intensity of light was measured by a lux meter (LX 101). Optical transmittance (T %) and reflectance (R %) of p-type Si samples were investigated using a UV-3100 (dual beam) recording spectrophotometer in the wavelengths (λ) range 300-2500nm and absorption co-efficient (α) was calculated from those data.

Lattice parameter of the p-type Si was determined by X-ray diffraction (XRD) method using a Philips PW 3040 X' Pert PRO XRD system with Cu-Kα radiation, operated at 40 kV and 30 mA, with angular range $20° \leq 2\theta \leq 80°$.

III. Results and Discussion

Resistivity of the p-type Si wafers were measured at 300 K temperature by four point probe method, the values obtained were 2.26 and 1.18 Ω-cm, respectively. The resistivity of p-type Si was also measured at 300 K temperature by two point probe method and the values were 2.38, 3.94 and 2.91 Ω-cm, respectively. The current-voltage (I-V) characteristics curves of the samples are shown in Fig. 1. Since the I-V plots are linear, it can be concluded that the contacts were ohmic.

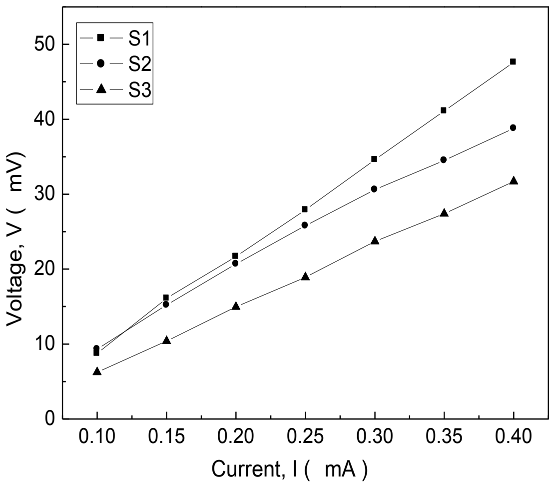

Fig. 1. Voltage (V) versus Current (I) graphs of p-type silicon.

Temperature dependence of electrical conductivity of an intrinsic semiconductor can be written as an exponential function of T as follows [16],

$$\sigma_i(T) = Ae^{-\frac{E_g}{2kT}} \quad (1)$$

Equation (1) may be converted into equation (2).

$$\ln\sigma_i(T) = \ln A - \frac{E_g}{2kT} \quad (2)$$

A plot of $\ln\sigma_i$ versus 1/T appears almost linear with a negative slope. The fobbiden energy gap (E_g) and acceptor ionization energy (ΔE_A) of a semiconductor impurity level can be determined from the slope of the straight line at higher and lower temperature regions, respectively[16].

The temperature dependence of electrical conductivity (Fig.2) indicates exponential increase with temperature[16]. This may be because of the generation of free charge carrier due to thermal excitation.

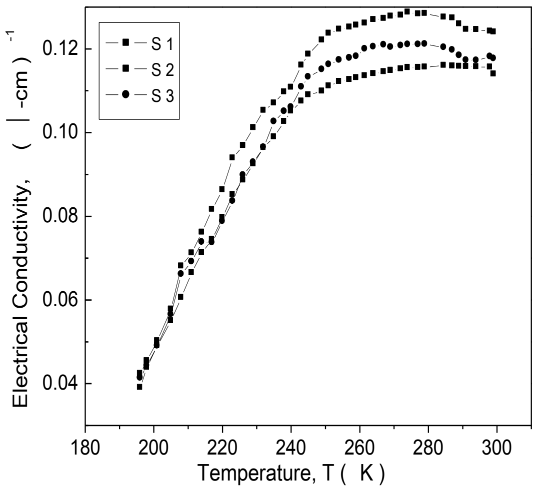

Fig. 2. Electrical conductivity (σ) versus temperature (T) of p-type silicon.

The curve in Fig.3 shows linearity in the temperature range (200 - 300 K). From the slope of straight portion of the curve ionization energy of B acceptor in p-type Si samples were calculated as 0.047, 0.049 and 0.051 eV [1, 2], respectively.

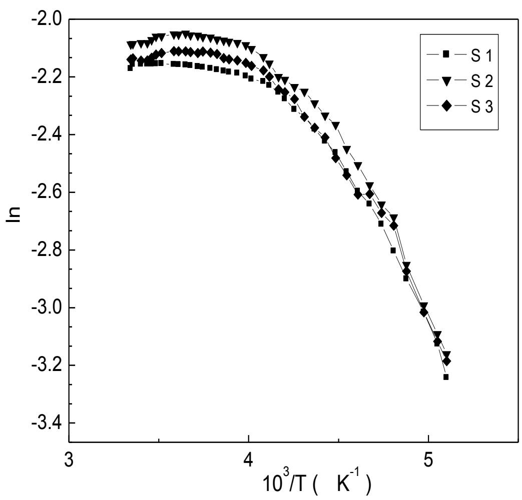

Fig. 3. $\ln\sigma$ versus 1/T temperature curve of p-type silicon.

Photoconductivity of a semiconducting crystal means the increase of electrical conductivity caused by the incident radiation on the crystal. The direct effect of illumination is to increase the density of charge carriers (electron-hole pairs) [17].The change in conductance when sample being illuminated is given by the relation[15].

$$□□ = \frac{□V(R+r^0)}{r^{0^2}VR - □Vr^0R(R+r^0)} \quad (3)$$

where □V is the change in voltage when the sample is illuminated, R is the load resistance, r^0 is the dark resistance of the sample and V is the supply voltage. When R= r^0 (Maximum sensitive regime), □V attains the maximum value □V_m and photoconductivity □□$^*_{pc}$, can be expressed in terms of dark conductivity □^{0} of the sample as[15].

$$□□^*_{pc} = 4\frac{\Delta V_m}{V}\sigma^0 \quad (4)$$

Photoconductivity of the p-type Si samples was measured by varying the sample voltage, hence the sample current at a constant light intensity 2020 Lux at room temperature (300K). It was found in Fig.4 that photoconductivity remains almost constant with the increase of sample current (0.1 – 0.8 mA) and hence with the sample voltage (4 -14 V).

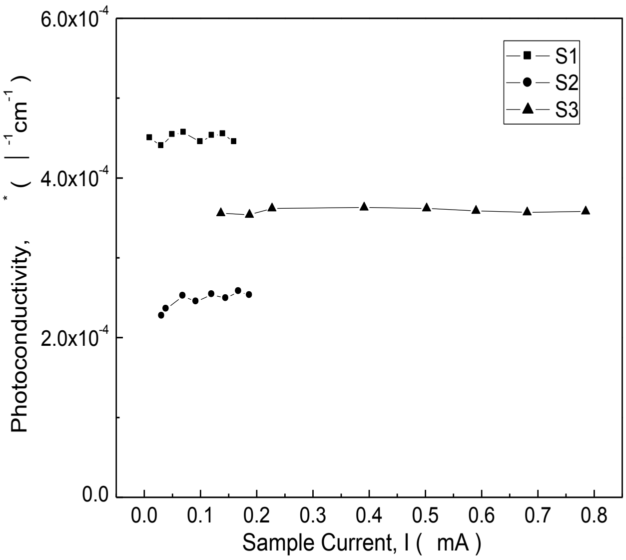

Fig. 4. Photoconductivity (□□*) versus sample current (I) graph of p-type silicon at 300K.

Photoconductivity of the p-type Si was measured by varying light intensity in the range 37 -2780 Lux) at a constant sample voltage (7 V) and chopping frequency 45.60 Hz at room temperature (300K). Non-linear increase of photoconductivity of p-type Si is found in Fig.5 with the increase of light intensity. This may be due to increase of the minority carriers due to the increase of light intensity [17, 18].

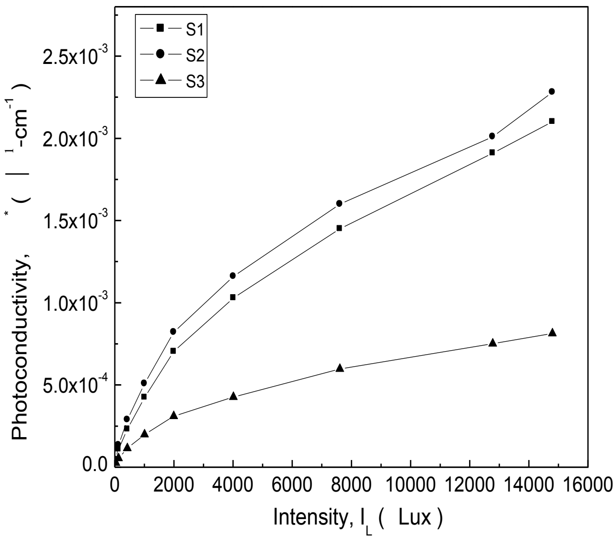

Fig. 5. Photoconductivity (□□*) versus light intensity (I_L) graph of p-type silicon at 300K.

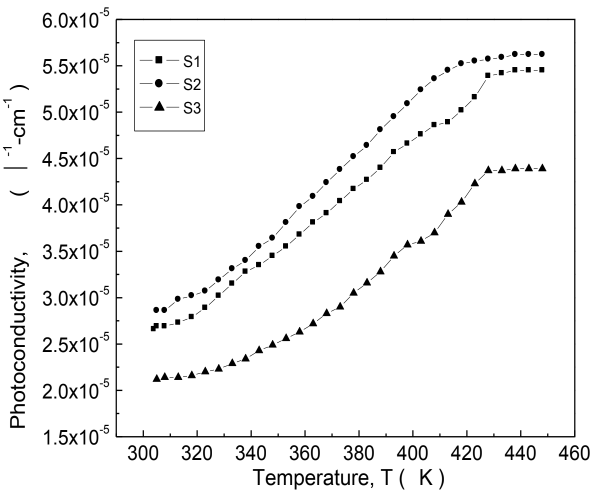

Fig. 6. Photoconductivity versus temperature graph of p-type silicon.

Temperature variation of photoconductivity of the p-type Si was also measured at constant sample voltage (7 V) and chopping frequency 45.60 Hz in the temperature range 308 - 423 K. It is observed from Fig.6 that photoconductivity increase was almost linear with temperature in the range 308 - 423 K which may be due to the generation of free carriers as a result of thermal excitation and it becomes constant after 423 K [17-19].

Optical transmittance and reflectance of p-type Si was measured in the wavelength range 300 - 2500 nm at room temperature (300K). Absorption co-efficient (□) was calculated from the transmittance (T) and reflectance (R) data with the help of the following equation [18],

$$□ = \frac{1}{d}\left[1 - \frac{T(R^2+1)}{(R-1)^2 + 2TR^2}\right] \quad (5)$$

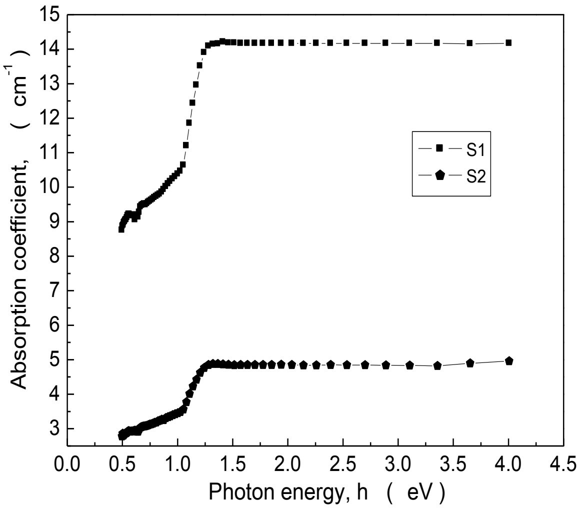

Fig. 7. Absorption co-efficients versus photon energy graph of p-type silicon.

Calculated values of absorption co-efficient (α) of p-type Si were plotted against the photon wavelength as shown in Fig.7, there is no point at which the clear cut division can be seen between absorption due to direct and indirect processes.

Optical Energy gap (Eg) of materials is related to absorption co-efficient (α),

$$\alpha h\nu = A\left(h\nu - E_g\right)^n \quad (6)$$

This is known as Tauc's relation [20]. Where A is Tauc's parameter, $h\nu$ the photon energy, E_g is the band gap and n is an index which is taken n =1/2 for an allowed direct transition and n=2 for indirect transition.

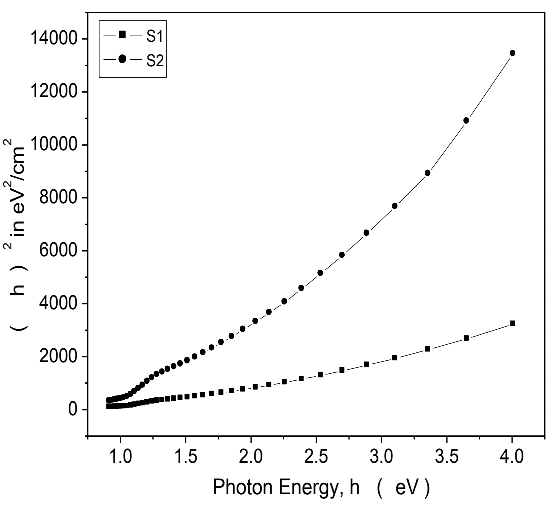

Fig. 8. $(\alpha h\nu)^2$ vs. photon energy ($h\nu$) graph of p-type silicon

Fig.8 shows the plot of $(\alpha h\nu)^2$ with photon energy ($h\nu$) in the wavelength range 300-2500 nm at room temperature 300 K. The extrapolation of the straight line in the higher energy region gives the value of direct band gap of the p-type Si, which was found to be 2.2 and 2.1eV [4, 7, 10], respectively. There is another transition region found in the lower energy region which appears due to indirect transition.

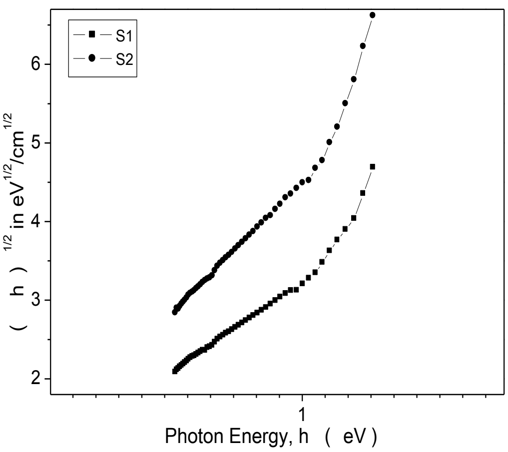

Fig. 9. $(\alpha h\nu)^{1/2}$ vs. photon energy ($h\nu$) of p-type silicon.

The indirect band gap of p-type Si was found from the extrapolation of the straight line part of the graph (Fig.9) in the lower energy region. The values were between 0.95 and 1.0 eV[4, 10], respectively.

The X-ray diffraction (XRD) pattern of p-type Si is shown in Fig.10, where the peaks due to (1 1 1), (2 2 0), (3 1 1), (4 0 0) and (3 3 1) planes were found, which is consistent with the XRD pattern of diamond cubic lattice structure [20, 21]. Lattice parameter is calculated to be 5.419Å from the XRD data which was near the standard value [22]. Some impurity peaks were found in the diffraction pattern, which may be due to p-type doping.

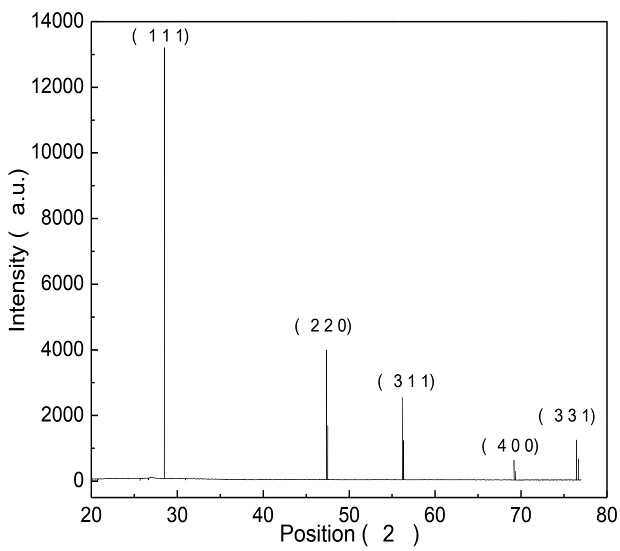

Fig. 10. The X-ray diffraction pattern of p-type silicon.

IV. Conclusions

Electrical conductivity of p-type Si shows an increase with temperature in the range 190 - 300K and the acceptor ionization energy (ΔE_A) obtained was between 0.047 - 0.051 eV. Photoconductivity measurement shows that sample current has almost no effect on photoconductivity in the range (0.1 - 0.8 mA). Photoconductivity is found to be increasing nonlinearly with the increase of light intensity and linearly with the increase of temperature. It can be said that p-type Si shows nice photoconductive response to both light intensity and temperature. Direct band gap of p-type Si is found to be 2.2 and 2.1 eV and indirect band gap is found to be 0.95 and 1.0 eV. The X-ray diffraction (XRD) pattern of p-type Si was consistent with the XRD pattern of diamond cubic type of crystal structure and Lattice parameter is calculated to be 5.419 Å. It may be concluded that the material shows good electrical and optical properties and it may be quite suitable in fabrication of electronic and photoconductive devices.

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