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CHARACTERISTICS OF PULSED LASER DEPOSITED N-CARBON /P-SILICON HETEROJUNCTION

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ABSTRACT

Heterojunction diodes, fabricated by depositing phosphorus (P) doped carbon thin film on p-type crystalline silicon substrate by pulsed laser deposition technique, are analyzed and device parameters are determined using experimental data. Camphor ($C_{10}H_{16}O$), a natural source, was used as a starting precursor for the carbon layer of the heterojunction. Carbon layers of the heterojunction were obtained using target containing different amounts of phosphorus. Optical absorption, temperature dependent conductivity data of carbon thin films and current density-voltage (J-V) characteristics of the heterojunction are analysed and device parameters such as intrinsic carrier concentration, donor concentration, conduction band effective density of states, electron effective mass, hole mobility, hole diffusion constant, hole diffusion length and minority carrier lifetime in the n-type carbon side of the heterojunction are determined. All the device parameters except donor concentration show increasing tendency with increased P content in the target. Donor concentration increases up to 5% P content in the target but then decreases for 7% P.

1. INTRODUCTION

Silicon has been dominating the field of semiconductor industry for many years. Researchers are looking for alternative materials for semiconductor devices since long. Carbon has by this time shown very interesting electrical, physical and optical properties. All these properties can be varied in a wide range by changing the optical gap (band gap, E_g) of the material. Interestingly, the optical gap of carbon can be tailored over an unusual wide range from that of semi-metallic graphite (~0.0 eV) to that of insulating diamond (~5.5 eV) simply by changing the precursor material and growth procedure and condition. This extraordinary property has increased interest in amorphous diamond like carbon (DLC) thin films for device fabrication purpose and carbon has been emerging as an important material for the application in the field of electronic and optical devices. Appreciable work has already been done on amorphous thin film carbon grown on silicon substrate [1,2]. Carbon-based heterostructures such as, metal insulator semiconductor (MIS) diodes, Schottky diodes, heterojunction diodes [2,3] on silicon have already been reported and thereby demonstrate the potentiality of carbon materials in electronic devices.

But carbon has some limitations due to its complex structure and presence of high density of defects at its present state. Graphite is the most common solid target used in physical vapour deposition methods for carbon films. We have been working on semiconducting carbon, obtained from camphor ($C_{10}H_{16}O$), a natural source [1,4-5]. The starting precursor, camphor, has both sp^2 and sp^3 hybridized bonds while graphite has 100% sp^2 bonded structure. The properties of carbon thin film can be changed by controlling the relative amount of sp^2 and sp^3 hybridized bonds in the film. We have used pulsed laser deposition (PLD) method to deposit phosphorus doped carbon on p-type silicon. PLD system is a very efficient method to deposit high quality diamond like carbon thin film. Successful doping of phosphorus in carbon thin film using PLD has already been reported [4].

In this work, we investigate the experimentally obtained data to find the properties of phosphorus doped carbonaceous thin films (n-type), deposited on p-type Si (n-C/p-Si). Properties like conduction band effective density of states, electron effective mass, hole diffusion length, minority carrier (hole) lifetime in the carbon side of the heterojunction are reported in the paper for the first time.

2. EXPERIMENTAL

Carbonaceous thin films were deposited on silicon and quartz substrates by excimer laser (NISSIN 10X, XeCl, λ = 308 nm, τ = 20 nsec, repetition rate = 2 Hz, spot size = 5.5 mm^2), which is focused on the target at an incident angle of 45^0 to the target normal. The substrate was mounted parallel to the target at a distance of 45 mm. The films were deposited at room temperature at a base pressure of 10^{-6} Torr. The laser pulse energy was 150mJ on the window. Details of the chemical structure of the starting precursor (camphor), the camphor burning system and the target preparation method have been described elsewhere [4]. In brief, camphor was burnt in a quartz tube and the soot deposited along the walls of the tube was collected, dried in the oven for an hour and pressed into pellets in order to use them as targets in PLD. In order to dope, the camphoric carbon soot was mixed with varying amount of red phosphorus powder (1, 3, 5 and 7% by mass) and compressed into pellets. The undoped carbon film is reported to show p-type characteristics [6]. Therefore, we have deposited P incorporated carbon films on p-type Si substrates. Gold electrode of about 15 nm is deposited on carbon film and gold electrode of about 100 nm is deposited on p-Si by conventional electron beam evaporation method. The contacts are found to be ohmic.

3. RESULTS AND DISCUSSION

The current density-voltage (J-V) characteristics of n-C/p-Si heterojunction, where carbon layer was deposited from the target containing varying amounts of phosphorus (1%, 3%, 5% and 7% by mass) are similar to the typical diode J-V characteristics [5]. The forward current in a junction can be expressed by equation (1)[7]

$$J = J_0 (e^{qV/\eta kT}) \qquad (1)$$

Where J_o is the reverse saturation current density and η is the diode quality factor. The forward J-V characteristic curves show two distinct regions. The η of the n-C/p-Si heterojunctions for lower voltage region is close to unity, therefore, current conduction is diffusion limited. However, the quality factor in the higher voltage region is high (about 17). This reveals that, current conduction is dominated by resistive effect [6]. The Y-axis intercept of the extrapolation of the linear part of the ln(J) vs. V characteristics at low voltage region gives the value of $\ln(J_0)$. Optical gap of the phosphorus incorporated films are obtained form the Tauc plot using the Transmittance/Reflectance measurement in the UV-VIS-IR range (300-2500 nm). Activation energy was calculated from temperature dependent conductivity data [4]. The variations of optical gap (Eg) [1] and activation energy as a function of % P content in the target are shown in Fig. 1.

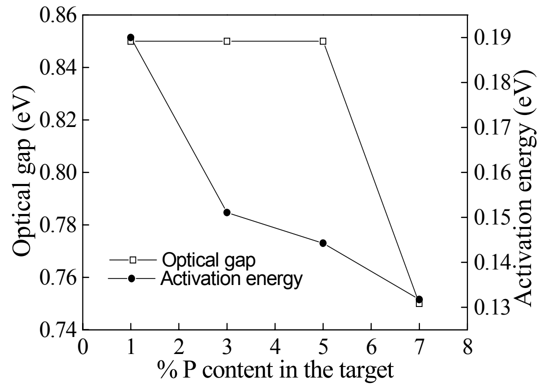

Fig. 1 Plot of optical gap (left axis) and activation energy (right axis) as a function of % P content in the target.

Our challenge was to find out intrinsic carrier concentration (n_{iN}), donor concentration (N_D) and ratio of minority carrier diffusion constant to diffusion length (D_p/L_p) from obtained values of reverse saturation current (J_o), activation energy and optical gap.

$$J_o = q(\frac{D_p}{L_p} n_{iN}{}^2 / N_D + \frac{D_n}{L_n} n_{iP}{}^2 / N_A) \qquad (2)$$

$$E_F - E_i = \frac{kT}{q} \ln \frac{N_D}{n_{iN}} \qquad (3)$$

Equations (2) and (3) [7] are fitted with the values of n_{iN}, N_D and D_p/L_p that give the least error in J_o and E_F-E_i. Here we use one constraint: intrinsic carrier concentration must remain constant for first three dopant contents (1%, 3%, and 5% of P), since optical gap (0.85 eV) is constant for them.

The intrinsic carrier concentration (n_{iN}) in P incorporated carbon films remains constant ($3.1\times10^{11} cm^{-3}$) for first three samples, but increases for 7% P ($10.9\times10^{11} cm^{-3}$). This happens, as the optical gap of the carbon film deposited from target containing 7% P decreases compared to that of other doping concentrations. The donor carrier concentrations in the thin film increases with the increase in dopant content for the first three samples as expected. But interestingly, it is seen to decrease for the sample grown from target containing 7% P. This is due to the fact that, though activation energy decreases for the sample grown from 7% P, (E_F -E_i) does not increase, because the band gap decreases for

7% P due to graphitisation of the film. The variations of n_{iN} and N_D for different P content in the target are shown in Fig. 2.

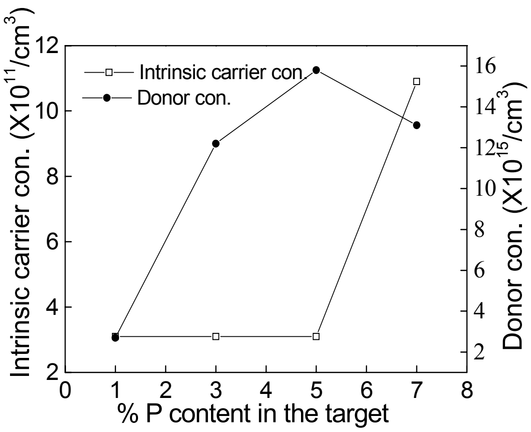

Fig. 2 Plot of intrinsic carrier concentration (left axis) and donor concentration (right axis) as a function of % P content in the target.

The variations of conduction band effective density of states and electron effective mass with the %P content are shown in Fig. 3.

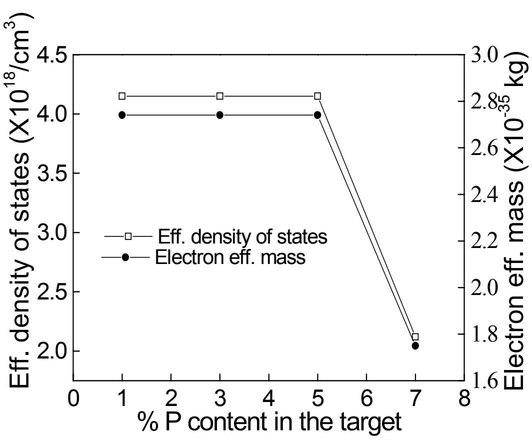

Fig. 3 Plot of effective density of states (left axis) and electron effective mass (right axis) as a function of % P content in the target

Conduction band effective density of states (N_C) is constant for the first three samples (4.82×10^{18} cm^{-3}) as expected since optical gap is constant for the first three cases but it decreases for 7% P (2.12×10^{18}cm^{-3}). Electron effective mass in the carbon thin film shows the same trend. Since the film becomes more graphitic for 7% P due to decrease in optical gap (0.75 ev), that is, the density of the film decreases, the decrease in effective density of states and hence the decrease in effective mass is justified. Equation (4) [7] gives the relationship of N_C with N_i and E_g.

$$N_C = n_{iN} \exp(\frac{E_g}{2kT}) \qquad (4)$$

Here for 7% P n_{iN} increases but E_g decreases. The decrease in E_g predominates and as a result N_C decreases.

The hole (minority carrier) mobility (μ_p) is calculated from room temperature conductivity data and calculated donor concentration, with the assumption that, hole mobility in carbon is one tenth of the electron mobility in carbon using equation (5)

$$\sigma = q(N_D \mu_n + \frac{N_i^{\ 2}}{N_D} \mu_p) \qquad (5)$$

Then diffusion constant (D_p) is calculated using equation (6) [7]

$$\frac{D_P}{\mu_P} = \frac{kT}{q} \qquad (6)$$

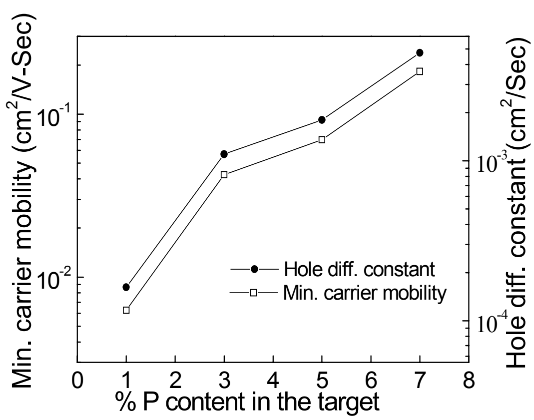

Fig. 4 Plot of minority carrier mobility (left axis) and hole diffusion constant (right axis) as a function of % P content in the target.

The variations of D_p and μ_p with the % P content are shown in Fig. 4. The obtained value of minority carrier mobility is very small (less than 1). This is because of amorphous nature and high defect density of carbon thin film. Both D_p and μ_p increase with the increase in % P content in the target. The increase of hole mobility with dopant content contradicts the usual trend of decrease in carrier mobility with carrier concentration. This increase of hole mobility is because of the fact that defect states decrease with the increase in the dopant content as seen from the electron spin resonance (ESR) spectroscopy analysis [4].

As seen from the Fig. 5, the values of both minority carrier lifetime and hole diffusion length are very small. This is because of high defect density of the amorphous carbon thin film. However, with the increase of dopant content in the target material, defect states in the thin film decrease [4]. So both L_p and τ_p should increase with the increased dopant content in the target as is also vindicated in our experimental result.

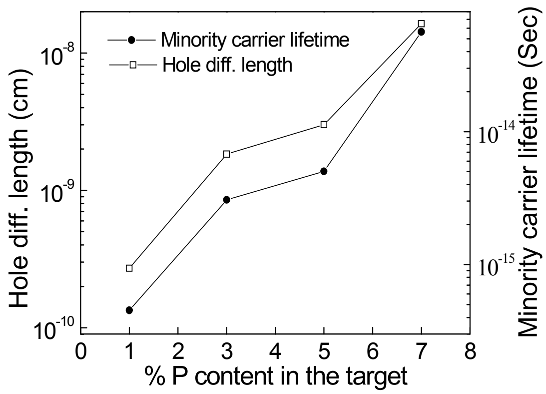

Fig. 5 Plot of hole diffusion length (left axis) and minority carrier lifetime (right axis) as a function of % P content in the target.

4. CONCLUSIONS

Phosphorus doped carbon (n-C) films are deposited on p-type Si substrate by pulsed laser deposition technique using a camphoric carbon soot target. The structural and optoelectronic studies reveal successful doping of P in the films deposited from target containing up to 5% P. But for 7% P, effective doping is seen to be reduced. Some important device parameters such as, intrinsic carrier concentrations, donor concentrations, conduction band effective density of states, effective mass of electrons for the carbon thin films are obtained by J-V characteristics, optical absorption and temperature dependent conductivity data analysis. The characteristics of P doped carbon films in n-C/p-Si heterojunction are observed to vary with phosphorus content and are in good agreement with the experimental observations. Device characteristics as well as device parameters are observed to improve significantly with P content. The device parameters obtained in the analyses will help to understand the behaviour of doped carbon thin film and n-C/p-Si heterostructure and are expected to be useful for their practical implementation in electronic device application.

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