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Anomalous electrical Characteristics of Ion Implanted $P^+ - N$ Junctions

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Abstract

Electrical characteristics of three $P^+ - N$ diodes fabricated on high resistivity silicon by ion implantation technique are studied by making capacitance-voltage (C-V), reverse current-voltage (I-V) and dielectric spectroscopy of semiconductor (DSS) measurements. The C-V characteristics show abrupt fall in capacitance, while I-V characteristics show abrupt rise in current at the same voltages as in the C-V characteristics. These abrupt discontinuities are ascribed to the formation of defect clusters in the lightly doped base regions where charge transfer might be taking place by thermally assisted tunneling. Low activation energies obtained in the DSS measurements also point toward the same mechanism.

1. Introduction

The ion implantation technique is widely used to form shallow p-n junctions. The main advantage of it is the precise control over doping and lower substrate temperature [1]. However, electrical degradation of material occurs due to high energy of the striking particles on the target area. Annealing of the sample may recover the defects produced by the implanted ions but there is a critical relation between implant energy and annealing temperature.

Electrical properties of semiconductor material profoundly affect the performance of semiconductor devices. Hence, characterization of semiconductor material is an important aspect of device production process. Many techniques have evolved over several years to characterize semiconductor materials and devices [2]. Capacitance measurement is usually made on p-n junctions or Schottky barriers. Impurity density and doping profile in semiconductor material can be determined by making capacitance measurements.

Depletion capacitance per unit aea for a $P^+ - n$ junction is given by [1];

$$C = \sqrt{\frac{q \in_s N_D}{2(V_D - V)}}, \tag{1}$$

where q is electronic charge, $\in_s$ the permittivity of semiconductor material, N_D impurity density in the lightly doped region, V_D diffusion potential and V is the applied bias. Equation (1) can be rearranged as:

$$1/C^2 = \frac{2(V_D - V)}{q \in_s N_D}. \tag{2}$$

If a plot of $1/C^2$ versus bias is a straight line the slope gives impurity density, N_D cm^{-3} and also indicates a uniform doping profile.

Reverse I-V characteristic of a $p - n$ junction ideally is a contant current which is independent of the applied bias. However, reverse characteristics deviates from the ideal behavior in a silicon diode because of generation process in the space charge region. It is expected that the current will increase with the increase in bias. The reverse characteristic may follow the relation given below;

$$I_R = \frac{qn_iW}{t_g}, \tag{3}$$

where n_i is the intrinsic charge carrier density, W is space charge width and τ_g is the generation lifetime.

Junction capacitance can be measured as a function of time/frequency and temperature. There are various experimental techniques available [3,4,5,6] for this purpose. DSS, one of the techniques capable of characterizing semiconductors materials [7,8,9,10], is used to characterize semiconductor materials by measuring complex capacitance over several decades of frequency $(10^{-3}Hz - 10^5Hz)$. The frequency range can be further extended by varying temperature (80 K-300 K). Experimental data is normalized in this technique [11,12] to obtain a master curve and activation energy.

This paper reports C-V, reverse I-V and DSS measurements made on three ion implanted photodiodes fabricated on 1000 Ω-cm silicon wafers. Hexagonal shaped diodes were part of an implant/annealing experiment kindly supplied by the Harwell Laboratories of UKAEA. The diodes designated as H1, H2 and H6 were 5 mm thick with an area of 44 mm^2 and annealed for 30 minutes. Table 1 gives the parameters of these diodes.

Table 1.

Diode	Dopant	Doping density c^{-2}	Energy KeV	Ann. Temp °C
H1	B^+	5×10^{14}	10	500
H2	B^+	5×10^{14}	10	600
H6	BF_2^+	1×10^{15}	40	600

2. Experiment

The C-V and I-V measurements were made at room temperature in an Oxford Instrument's C104 cryostat having a pressure of 10^{-5} torr. The capacitance measurements were made at 100 KHz with a solortron 1250 Frequency-Response-Analyzer (FRA) especially adopted for dielectric Spectroscopy of Semiconductors (DSS) [13] measurements. Reverse I-V measurements were made with a Keithley 617 digital electrometer.

3. Discussion

The C-V characteristics are plotted as $1/C^2$ versus bias at 300 K of all three diodes and are shown in Figure 1. These diodes show unusual characteristics, that is, an abrupt rise in $1/C^2$ values occur at about 3.5, 4.5 and 4.5 volts in diodes H1, H2 and H6 respectively. These changes suggest that the doping densities vary with distance from the junction into the lightly doped base region, since diodes are asymmetric $P^+ - n$ junctions. Asymmetry of the junctions justifies the use of C-V measurements to evaluate doping profile and criteria is that the doping density in the highly doped region should at least be 100 times of the lightly doped region [14]. In our diodes this is the case, for example, peak concentration of B^+ ions in diode H1 is 1.6×10^{17} ions/cm^3 while doping density in the lightly doped region is 7×10^{12} ions/cm^3, much more than 100 times. The magnitude of slopes have higher values before the discontinuity and lower values beyond it. But are comparatively high in the discontinuous region because the change in capacitance is typically two decades or more in this region. This indicates that the doping density varies with the distance. A normal and electrically well behaved diode should have a uniform doping density. The values of doping densities N_D calculated from the all three regions of the curves are given in the Table 2. The order of magnitude is same for all diodes in the three regions. However, the doping density in the low bias region is about a decade higher than the two other regions. This may be due to the impurities gettered in this region because of the proximity to the junction.

Table 2.

Diode	w^* at 0V μm	w^* at -9V μm	$\Delta w^{\pm}$ μm	ΔE meV	$N_D \times 10^{-13}$ cm^{-3} Low bias	$N_D \times 10^{-12}$ cm^{-3} Transition	$N_D \times 10^{-12}$ cm^{-3} High bias
H1	11	35	15	3	3	4	7
H2	12	34	16	-	5	4	6
H6	12	35	19	3	6	4	6

* Space charge width. ± Width of the transition region

The reverse current-voltage characteristics of these diodes also show a similar behavior as in Figure 2. The discontinuities occur more or less at the same values of the bias and values of the slopes are higher in the part of reverse current after the discontinuity as in capacitance data. This similarity is expected since both type of measurements essentially spread the space charge width with the increase in reverse bias. It also clarifies any doubt on part of the measurements by one technique alone. The rise in reverse current in regions before and after the transition region is typical of a silicon diode. However, there is an abrupt rise in the transition region possibly due to unusually large release of charges from that area.

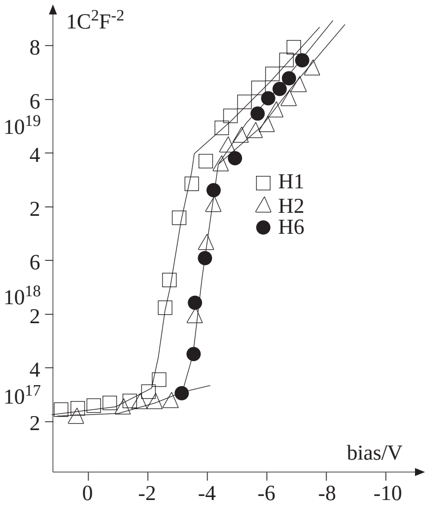

Figure 1. Capacitance-Voltage characteristics of three $P^+ - n$ implanted diodes at 300 K. The abrupt rise in $1/C^2$ value at about 3.5., 4.5 and 4.5 volts are seen in H1, H2 and H6, respectively

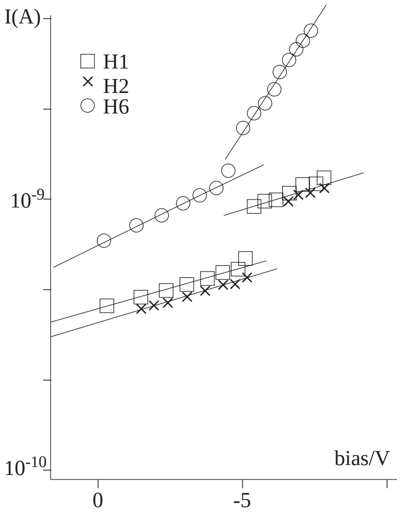

Figure 2. Reverse current-voltage characteristics of the three diodes at 300 K. all three diodes show abrupt rise in current at voltage same as in C-V measurements (see Figure 1)

The C-V and I-V characteristics of the diodes H2 and H6 are quite similar compared to that of diode H1. This may be due to the difference in annealing temperature. Dodes H2 and H6 were annealed at 600° C, while diode H1 was at 500° C. Annealing has improved implant defects more in H2, H6 than in H1 and that is why diodes H2 and H6 show higher capacitance and lower conductivity in C-V and I-V measurements respectively.

Dielectric spectroscopy of the diodes was performed to further investigate the nature of the transitions in these diodes. The DSS measurements were made at a range of temperature (83K-300K). The data were normalized to obtain a master curve and Arrhenius plots to determine activation energies. The normalized dielectric spectra of diodes H1 and H6 are shown in Fiures 3 and 4 along with Arrhenius plots. Both diodes show poor normalization, while it was not possible for diode H2 data. Arrhenius plot of diode H1 shows two distinct regions. One at high temperature giving higher slope corresponding to a deep energy of the impurity level. But the line connects only two points which are not enough to validate determination of activation energy in this part of the curve. At low temperatures, activation energies are quite shallow only 30 meV for diodes H1 and H6 and do not correspond to any known impurities [1] in silicon. This energy could be ascribed to the thermally assisted or phonon assisted tunneling [15,16] of charges in the space charge region. Pons and makram-Ebid [17] have discussed at length phonon assisted tunnelling of electrons in $P^+ - n$ junctions/Schottky barriers. The process is depicted in Figure 5. A trapped charge in the space charge region gains energy ΔE and tunnel through the barrier because of the high junction field.

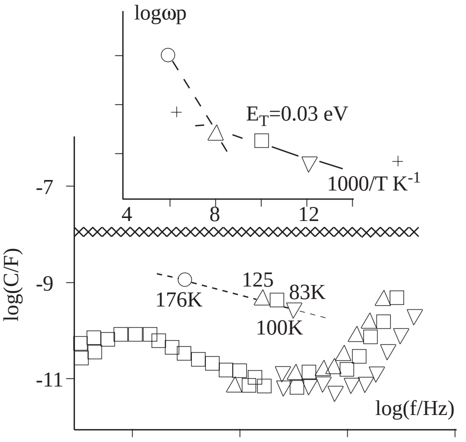

Figure 3. Normalized dielectric data of diode H1. The normalization is poor at the frequencies other than the peak frequency. Locus of the temperature points is also visible showing a downward trend indicating variation of capacitance with temperature as well. The Arrhenius plots showing curvature and gives an activation energy of 300 meV only.

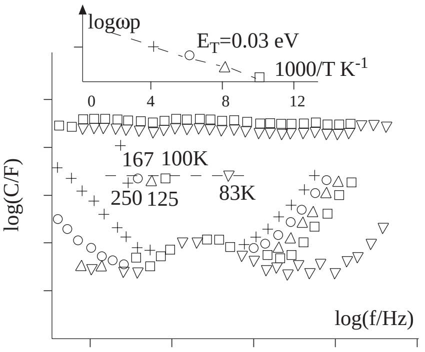

Figure 4. Normalized dielectric data of diode H6. The plot is similar to that of the diode H1. The Arrhenius plot is linear and gives an activation energy of 300 meV

The probable reason for this behavior is the formation of defect clusters in the region specified as transition region. The projected range for 10 keV boron ion in silicon is about 0.02μm and a density of about 2×10^{20} ions/cm^2 of boron ions is required to make amorphous regions in single crystal silicon. Thus, the dose in our case is not enough to make regions amorphus. It appears that the implanted ions have created defect clusters. Though the annealing was carried out at 600° C for all diodes except H1 for 30 minutes, but it seems that either time or temperature was not sufficient to repair the damage in the crystal.

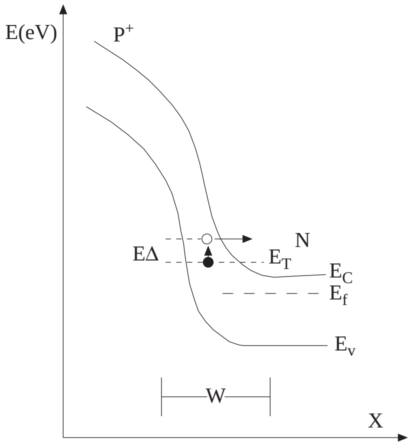

Figure 5. Energy band diagram of a $P^+ - n$ junction showing the thermally assisted tunneling mechanism. A trapped electron gains energy ΔE from the crystal thermal bath and move to a quasi-stable state. It then tunnel through the barrier to the conduction band due to high junction field

An abrupt rise in reverse current occurs due to emission of charges from the defects when the space charge region spreads over the defect cluster region. This loss of charges is also responsible for the fall in capacitance in the C-V measurements.

4. Conclusion

The electrical characteristics of three ion implanted diodes studied show unusual characteristics. All three diodes show abrupt fall in capacitance in C-V measurements and rise in reverse I-V measurements. It appears that this abnormal behavior could be due to the defect clusters in the base material formed during implantation. They perhaps could not be removed owing to insufficient annealing temperature.

The fall in capacitance or rise in reverse current, particularly in the transition region, may have occurred from the emission of charges from these clusters in the high junction field. The low values of activation energies obtained from the DSS measurements substantiate possibility of thermally assisted tunnelling of charges from the clusters to the conduction band.

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