Laser induced diffusion of indium in silicon

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In this work, a 300 μs pulsed Nd:YAG laser was employed to induce indium diffusion in silicon wafer. Electrical properties were studied for a range of laser pulse energies (0.225–0.369 J) and substrate temperature (300–398°k). The four point probe measurements showed that a minimum sheet resistance (54 $\Omega/\square$) was resulted at the melting threshold energy and room temperature. The sheet resistance was a decreasing function of the temperature rise of the substrate. The (*I-V*) and (*C-V*) measurements expressed improvement in the characteristics of the fabricated diodes when substrate temperature rises and irradiating pulse energy increases up to melting threshold value after which these characteristics starts to deteriorate.

1. Introduction

Laser beam is widely used nowadays to develop electronic devices. It is employed in etching, drilling and annealing [1]. Laser induced diffusion of impurities in semiconductor has been adopted to manufacture diodes, solar cells [2, 3] and thin film transistor [4]. This technique relies on changing electrical properties of semiconductors was first reported by Narayan *et al.* [5] when large p-n junction of good characteristic where fabricated by boron deposition on silicon, followed by Q. switched ruby laser irradiation. One group irradiated a semiconductor material (immersed in the impurity solvent) with a laser beam [6] while others made use of the gas [7] and solid phase [8] of impurity with a laser beam to obtain diffusion.

In the present work an indium thin film was coated on a silicon wafer then irradiated with a Nd:YAG laser pulses. The characteristics of the manufactured diodes were studied as a function of laser energy and substrate temperature.

2. Experimental work

N-type single-crystal (111) Silicon wafers were doped with indium. The 500 μm thick wafers of (5 $\Omega/\square$) were first washed with warm water and immersed in ethanol container then in an ultrasonic bath for (10) minutes and then dried by hot air. Chemical etching was employed using a mixture comprising CH_3COOH, HNO_3 and HF at ratios (2 : 3 : 2) at concentrations 99%, 70% and 49% respectively for (10) minutes to remove the oxide layer from the silicon surface. This was followed by thorough cleaning by ethanol and finally dried. A thin (300 Å) indium layer was deposited on the surface of the silicon wafer using Balzer (BAE 370) thermal coating unit at vacuum (10^{-7} torr.). Each wafer was cut into (1X1 cm^2) samples that were irradiated by a 300 μs pulsed Nd:YAG laser. The laser pulsed energy (0.225–0.369 J) and substrate temperature (300–398°k) were variable parameters. The small laser spots size (0.028 cm^2) necessitated the use of overlapped laser spots, as shown in Fig. 1, to obtain relevant area required to accomplish electrical measurements. Fig. 2 shows the experimental sketch of induced diffusion. The substrate of the sample was heated using a (650 W)

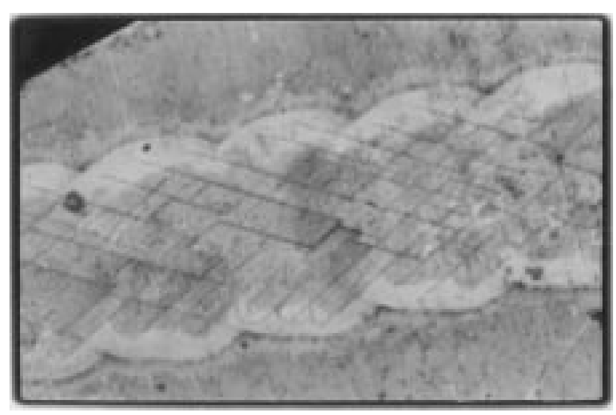

Figure 1 Shows overlapped laser spots.

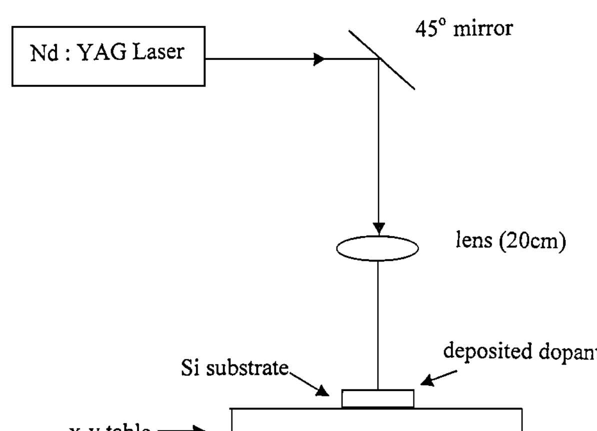

Figure 2 Shows the experimental sketch of induced diffusion.

tungsten lamp in a closed evacuated (10^{-3} torr) quartz envelope and the temperature was calibrated by employing a k-type (NiCr-NiAl) thermocouple. To make the Ohmic contacts, a (100 Å) thick gold layer was deposited on the acceptor side of the sample using a sputtering unit and a (1000 Å) thick Aluminum layer was deposited on the donor side using a thermal coating unit. A four point probe system was used to measure the electrical sheet resistance and a (10 kHz) LRC meter was employed to carry out the (C-V) measurements.

3. Results and discussion

Fig. 3 shows three regions expressing the change in electrical sheet resistance with irradiating energy for indium doped silicon. In region I, a clear decrease in sheet resistance is noticed up to 0.288 J of laser energy. In region II a more or less stable behavior is seen, after which region III an increase in sheet resistance is observed. At the beginning, the laser energy is not enough to diffuse the impurity but when energy increases, melting and diffusion of impurity takes place. At melting threshold, a decrease in sheet resistance comes about indicating the occurrence of subsititional impurity diffusion in the silicon latice [9–12]. Laser energy increased the sheet resistance because of the structural defects that capture the impurity atoms and cancels their role. The 300°A thick indium layer was sufficient to obtain good electrical charateristics, high impurity concentration causes precipitation of impurity on subsequent heating [5]. Fig. 4 shows a degrease in the sheet resistance with the temparature of the substrate. Heating the substrate affects the semiconductor material specifications and influences the crystal growth in the liquid phase. The temparature gradeint lessens with heating leading to a decrease in the re-soldification speed allowing enough time to obtain electrical active doping. In addition to this, heating the substrate helps reducing the structural deffects associating the irradiation process [13] and therefore increasing the subsituting positions for the impurity atoms in the silicon lattice.

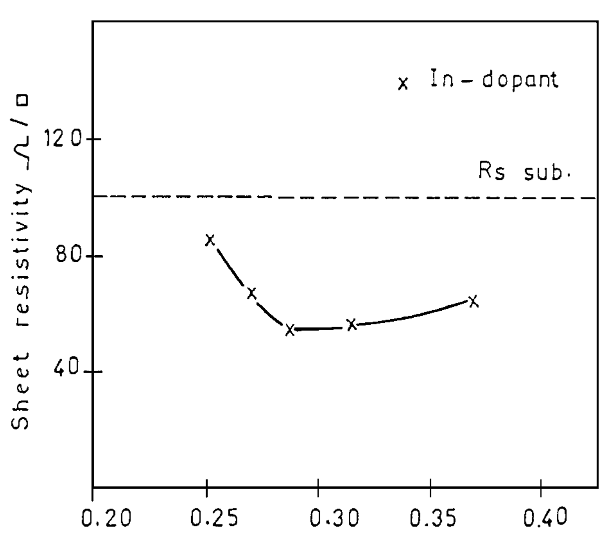

Figure 3 Electrical sheet resistance as a function of laser energy at room temperature.

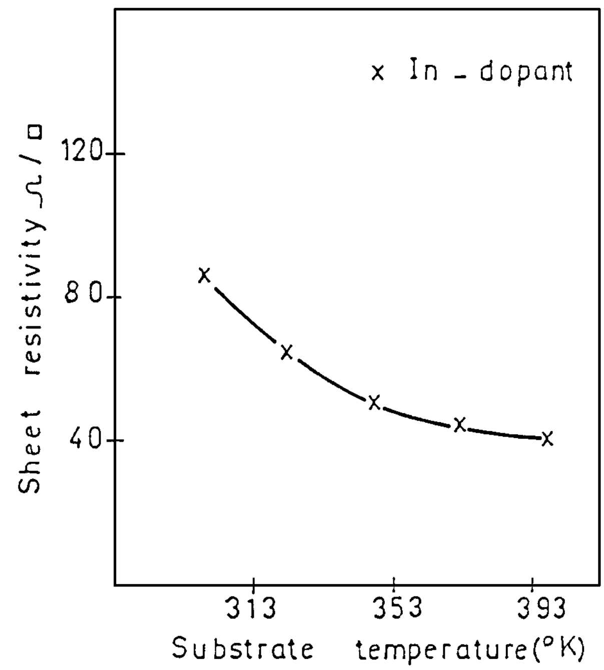

Figure 4 Variation of electrical sheet resistance with substrate temperature.

Fig. 5 shows forward and reverse currents as a function of biasing potential for diodes fabricated with different lasers energies at room temperature. Fig. 5a shows the value of forward current (I) coming near that of the reverse current for diode using (0.252 J) of laser energy. It expresses bad characteristics because of the insufficient laser energy needed for diffusion. Using the formula [14].

$$n = \frac{k_B T}{q} \ln \frac{I}{\mathrm{Is}}$$

Where Is = saturation current, q = electron charge, k_B = Boltezman constant and T = temperature, the ideality factor (n) was (3.4) expressing a clear deviation from good characteristics. An improvement in the diode has resulted when increasing the laser energy to (0.27 J) as shown in Fig. 5b. The rectification became better with linear increase in the forward current till (0.5 V) then started to bend due to the series resistance effect [4]. The ideality factor here was (2.3). Increasing the laser energy to (0.288 J) permitted great improvement in the (I-V) characteristics as shown in Fig. 5c and the ideality factor was (1.95) due to the homogenous melting and diffusion of impurities. At a laser energy of (0.369 J) the diode expressed deterioration in it's rectification, see Fig. 5d, and the ideality factor registered (2.18). The electrical sheet resistance increased at this irradiating laser energy.

The foregoing discussion displays the dependence of (I-V) characteristics on the irradiating energy. The results obtained indicated a dependence of the ideality factor on this energy for diodes at room temperature as

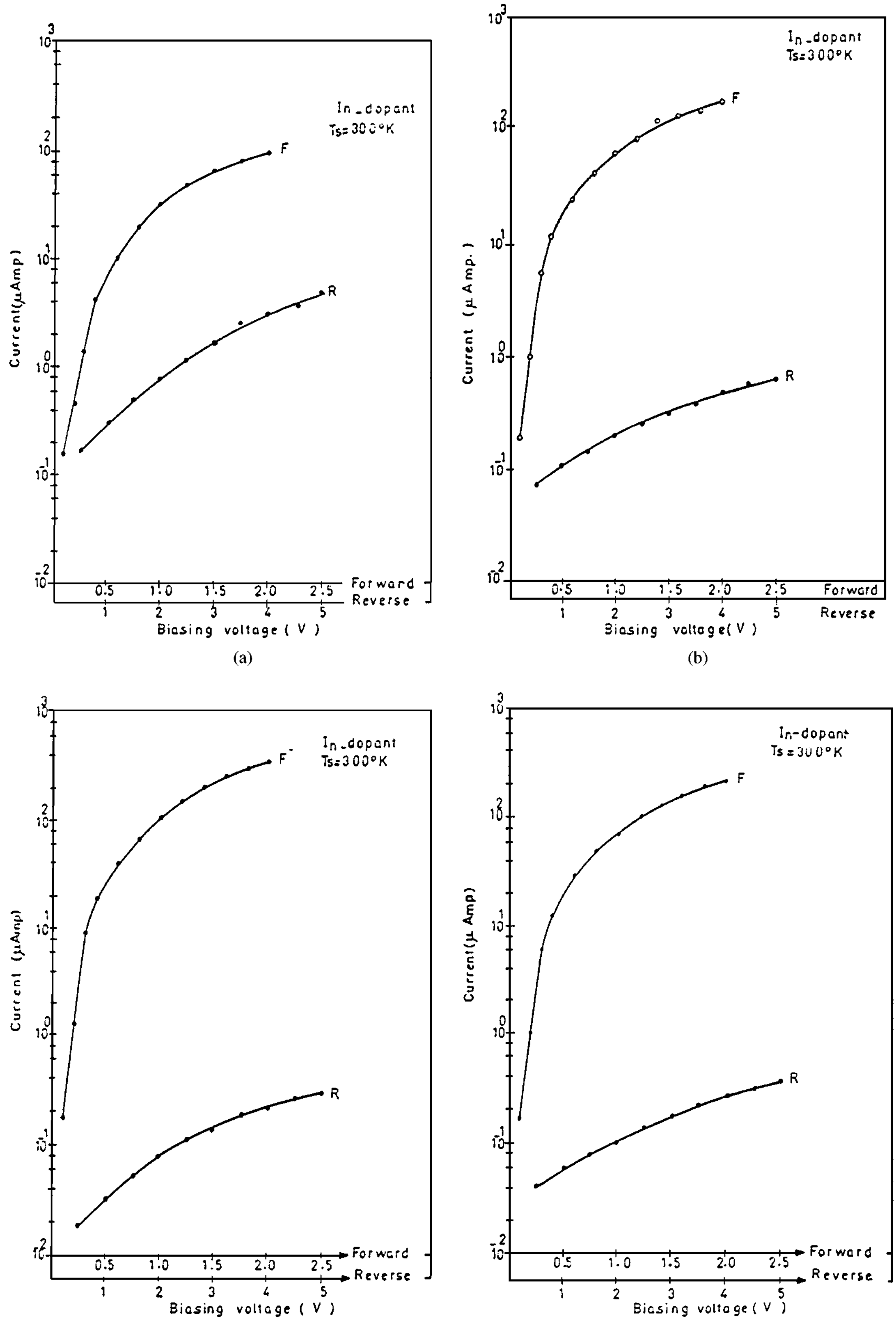

Figure 5 I-V characteristics of p-n Junction diodes fabricated with different laser energies. (a) 0.252 J, (b) 0.27 J, (c) 0.288 J, (d) 0.369 J.

shown in Fig. 6. Fig. 7 explains the (I-V) characteristics for diodes at melting threshold energy and different substrate temperatures. The increase in the forward current and the domination of the diffusion current on the recombination (due to the reduction of defects [13] are clear. The ideality factor was a decreasing function of the substrate temperature because of the improvement in the electrical characteristics of the treated region as shown in Fig. 8. Fig. 9 expresses an exponential decrease of capacitance with the reverse biasing potential due to the increase in the width of depletion layer [15] for diodes fabricated at different energies. At specified value of reverse biasing, a minimum capacitance has resulted at melting threshold energy. This is due to an

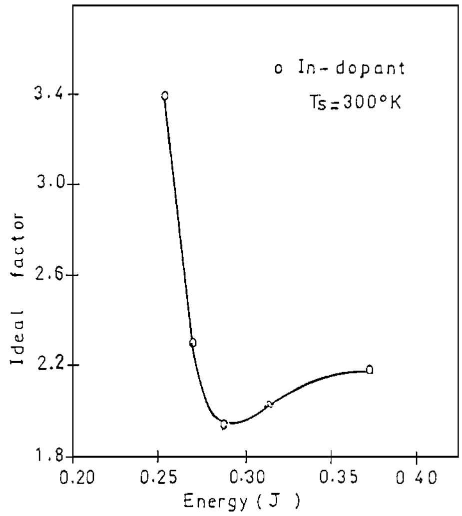

Figure 6 Variation of ideality factor with laser energy.

increase in the doping concentration giving rise to the built-in potential (V_{bi}) as in the following equation [13].

$$V_{bi} = \frac{k_B T}{q} \ln \frac{N_A N_D}{n_i^2}$$

Where N_A: acceptor concentration, N_D: donor concentration, n_i: intrinsic carriers concentration.

This in turn leads to an increase in the depletion layer that is inversely proportional to the capacitance. Fig. 10 is a plot between ($1/C^2$) and the reverse biasing for diodes at room temperature. The built-in potential (V_{bi}) was worked out from the intersect with the reverse biasing axis. The relation is linear and when compared with published literature [16], our diodes are classified under the abrupt type. Fig. 11 explains an increase in (V_{bi}) as a function of the laser energy till melting threshold value due to the increased concentration of impurity.

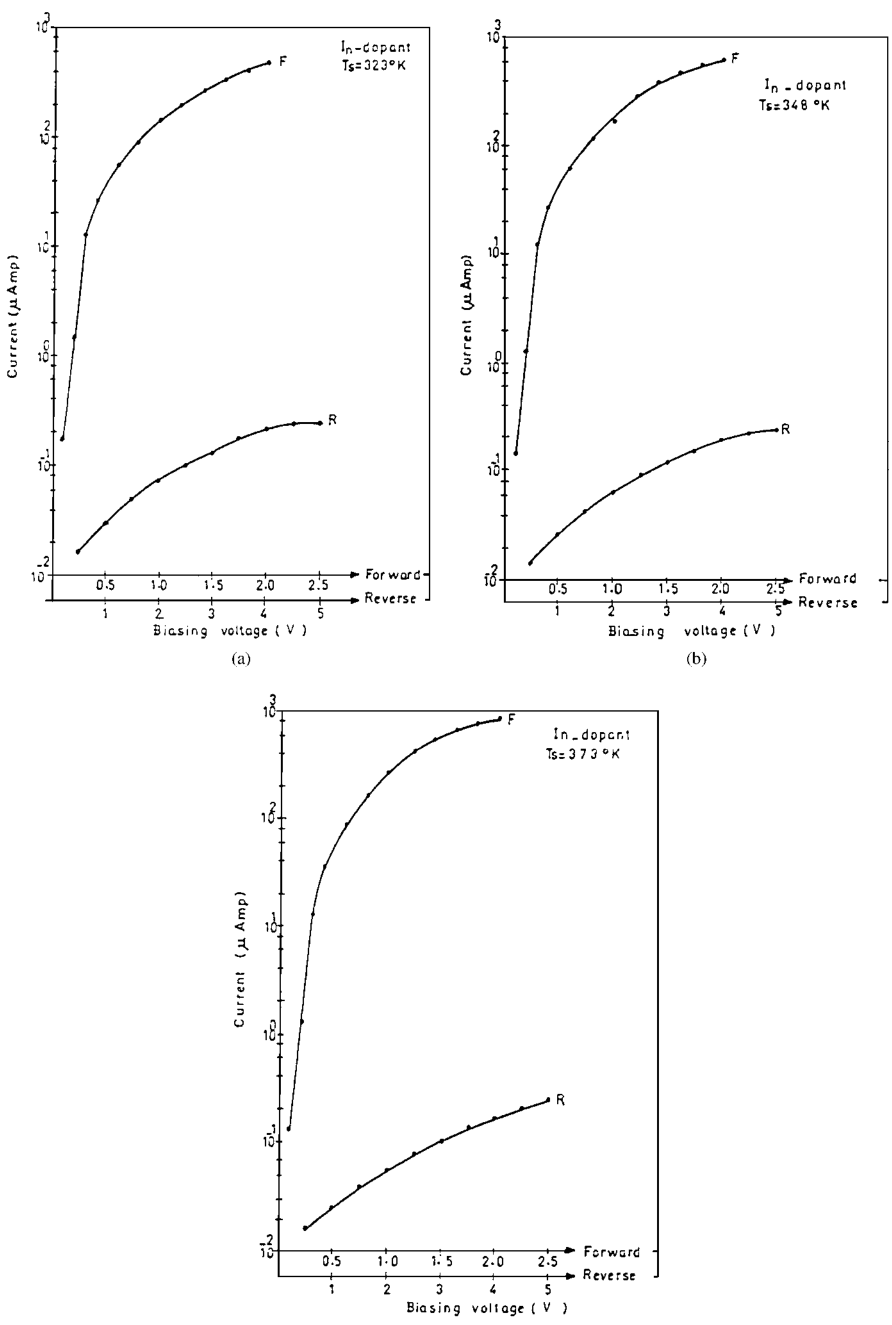

Figure 7 *I-V* characteristics of p-n junction diodes fabricated with different laser energies and substrate temperatures. (a) 0.27 J, 323 °k, (b) 0.252 J, 348 °k, (c) 0.225 J, 373 °k.

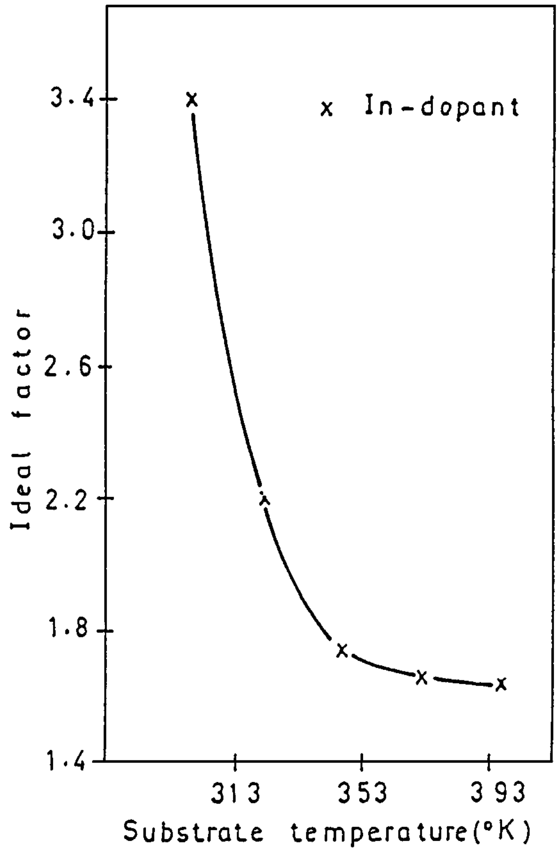

Figure 8 Ideality factor as a function of substrate temperature at laser energy of 0.252 J.

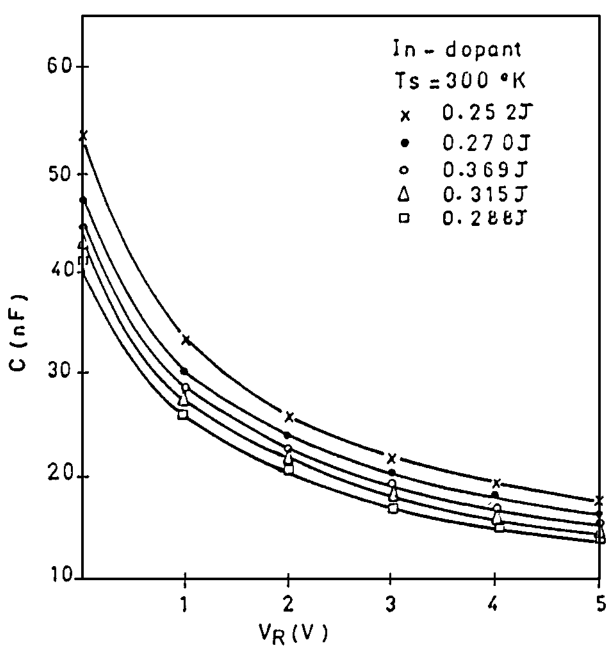

Figure 9 *C-V* characteristics for diodes fabricated with different laser energy.

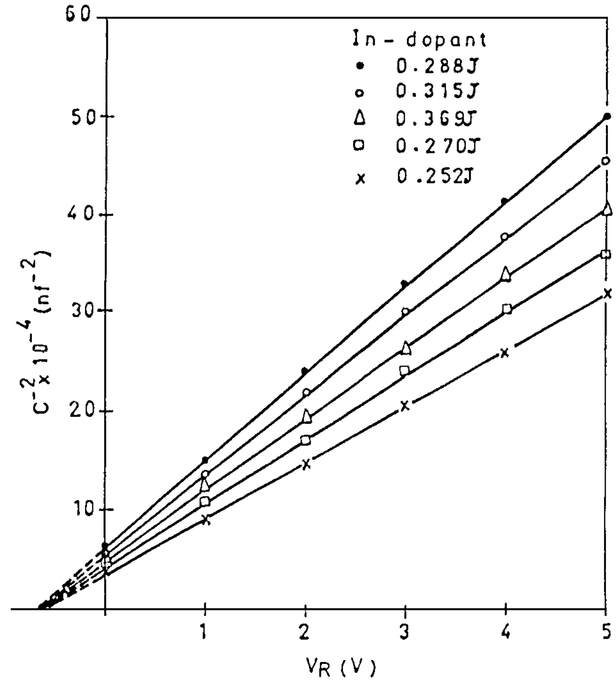

Figure 10 $1/C^2$ versus reveres bias voltage for diodes fabricated with different laser energies.

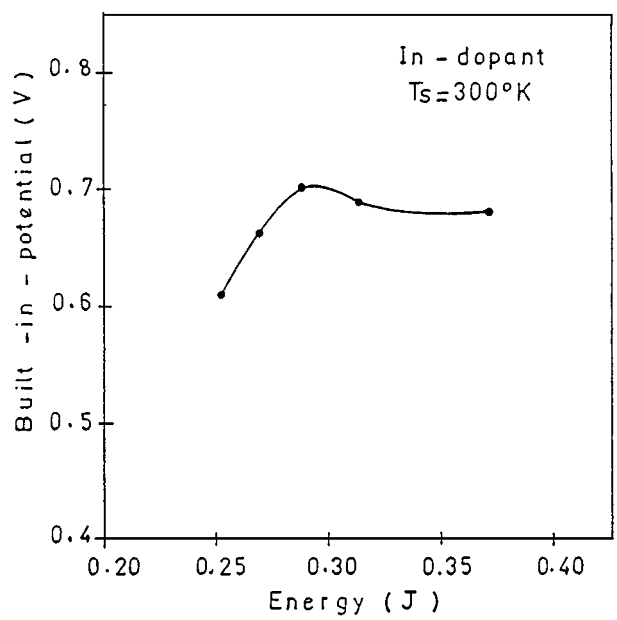

Figure 11 Built-in potential as a function of laser energy for diodes fabricated at room temperature.

After this value (V_{bi}) starts to diminish because of the structural defects induced in the irradiated region that captures the impurity atoms. Fig. 12 shows the effect of heating the substrate on the (C-V) measurements and therefore on (V_{bi}) when using (0.288 J) of laser energy at different substrate temperatures. Fig. 13 reveals an increasing built-in potential with substrate temperature.

At zero potential value, the capacitance decreased with substrate temperature because of the increase in (V_{bi}) leading to an increase in the width of depletion layer as shown in Fig. 14.

4. Conclusion

Abrupt type diodes were fabricated from laser induced diffusion of indium in silicon. The optimum value of electrical sheet resistance, (I-V) and (C-V) characteristics were obtained at melting threshold laser energy

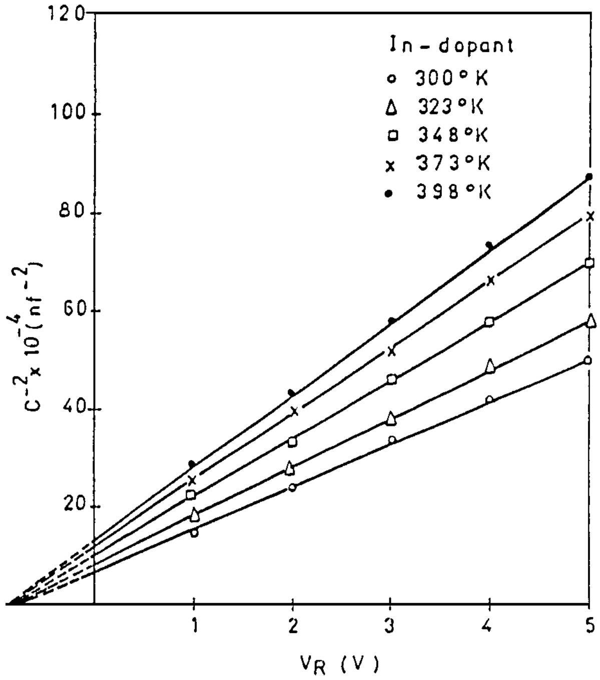

Figure 12 $1/C^2$ versus reveres bias voltage for diodes fabricated with different substrate temperatures.

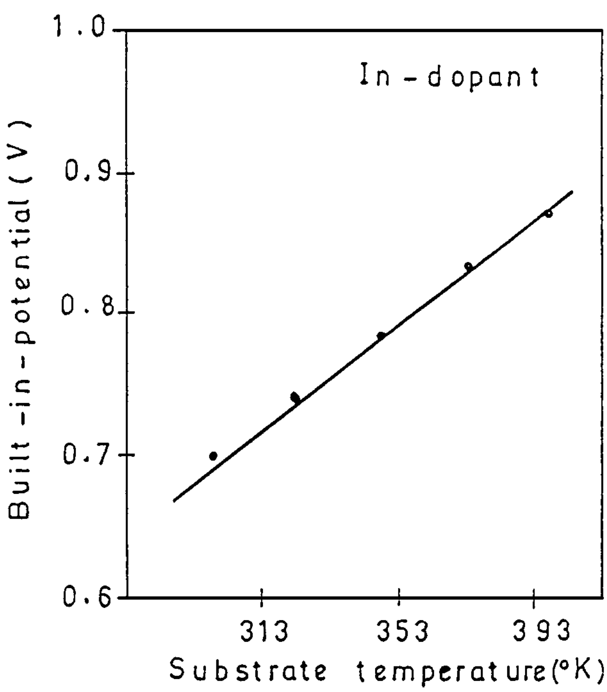

Figure 13 Built-in potential as a function of substrate temperature for fabricated diodes.

due to homogenous melting and diffusion of indium inside the silicon. Higher laser energy than melting threshold has induced defects, which deteriorated the diode. The diodes characteristics became better at increasing substrate temperature where heating process restrained these defects.

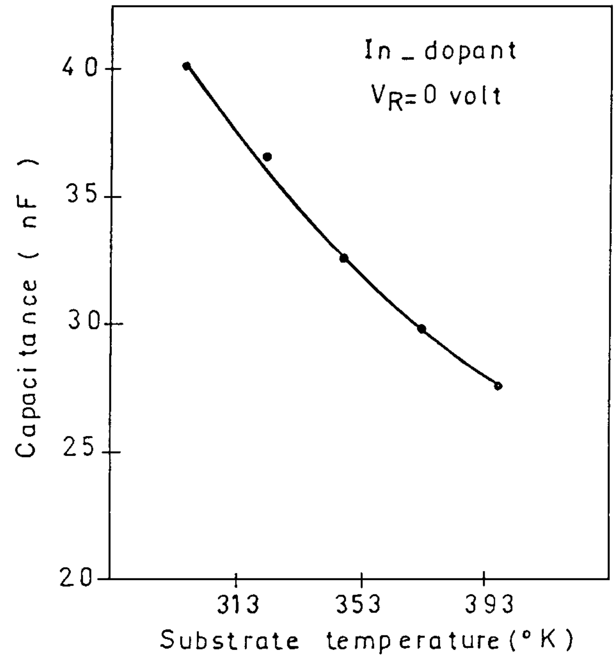

Figure 14 Capacitance as a function of substrate temperature.

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