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CHARACTERISTICS OF NOVEL SILICON PIN PHOTODIODE MADE BY RAPID THERMAL DIFFUSION TECHNIQUE

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ABSTRACT
In this paper, a silicon p-i-n photodiode was fabricated by rapid thermal diffusion (RTD) of Sb and Al dopants in a highly resistive silicon wafer to create n-type and p-type regions, respectively. The diffusion of Al and Sb dopants were carried out with the aid of incoherent high power halogen lamp at a temperature of 650˚C for 3 minutes. The electrical properties and figures of merit of photodiode such as I-V, C-V, rise time, spectral responsivity, and detectivity were investigated and analyzed.
Keywords: rapid thermal diffusion, PIN, silicon, figures of merit

I. INTRODUCTION
Silicon wafers have the lowest cost per unit area with the highest crystal quality of any semiconductor materials. The industry is able to manufacture microprocessors with hundreds of millions of components—all integrated onto thumb-sized chips and offers them at such low prices that they are increasingly used in consumer electronics. Silicon manufacturing represents the most spectacular convergence of technological sophistication and economics of scale [1-3]. The silicon p-i-n photodiode is compact, cheap, and demanding low power to operate. High energy physics have employed p-i-n widely in the last 2 decades [4,5].The operation of a silicon p-i-n photodiode is simple and reliable. It has a high responsivity and low dark current when compared to pn photodiode. Conventional methods used to fabricate PIN silicon photodiode include ion implantation and furnace thermal diffusion of boron (P-type dopant), and phosphorus (n- type dopant dopants at high temperature cycle for long time. Rapid thermal diffusion (RTD) is a promising technique used efficiently in semiconductors processing [6,7]. Thermal diffusion for short time is not easily achievable in traditional furnace at low temperature since the desired dopants activation cannot be always ensured [8]. Extensive work has been reported on using rapid thermal annealing technique for the improvement of Si p-i-n junction [9, 10]. Up to best of our knowledge, no data have been published on fabricating Si p-i-n photodetector using RTD technique. Herein, a rapid thermal diffusion technique is used to synthesize silicon p-i-n photodiodes and to study their figures of merit.

II. EXPERIMENTAL
The Si p-i-n photodiode was fabricated on a 1cm^2, 150μm thick, (111)-oriented mirror-like intrinsic silicon wafer of 47Ω.cm resistivity. The Si wafer, considered here as the intrinsic region, was first cleaned using standard RCA methods. Thin layer of SiO_2 was then formed on the front layer of the Si wafer by thermal oxidation. Hydrofluoric acid is used to remove certain area of SiO_2 and open window of Si. High purity Al and Sb films were deposited on the front and back sides of Si respectively using thermal resistive technique under a vacuum of 10^{-7} torr.

Following the deposition process, the samples were transferred to the rapid thermal diffusion system (see Figure1). The system consists of evacuated quartz ampoule, high power tungsten halogen lamp, a parabolic reflector and a K-type thermocouple. The PIN photodiode fabrication necessitated the diffusion of Al on the front surface and Sb on back surface of the silicon wafer at 650°C for 3min. The non-diffused layers are removed by NaOH .The sheet resistance and conductivity type of the diffused silicon were measured using the four point probe. Ohmic contacts were made on both diffused regions by depositing In-Sn thick films using thermal evaporation through a specific mask and annealed for 10 minutes at 300˚C under nitrogen gas. Figure 2 shows the cross sectional view of silicon PIN photodetector. The spectral responsivity of PIN photodetector was investigated by using a monochromator after making power calibration with standard silicon power meter. Rise time measurement was accomplished by using 200MHz oscilloscope and a pulsed laser diode of a pulse duration of 100ns and a wavelength of 904nm

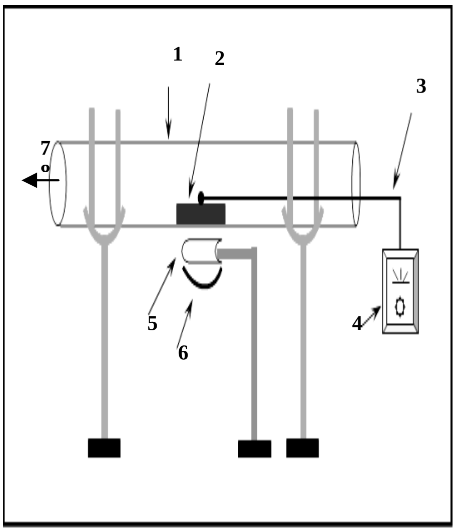

Figure 1: Rapid thermal diffusion system

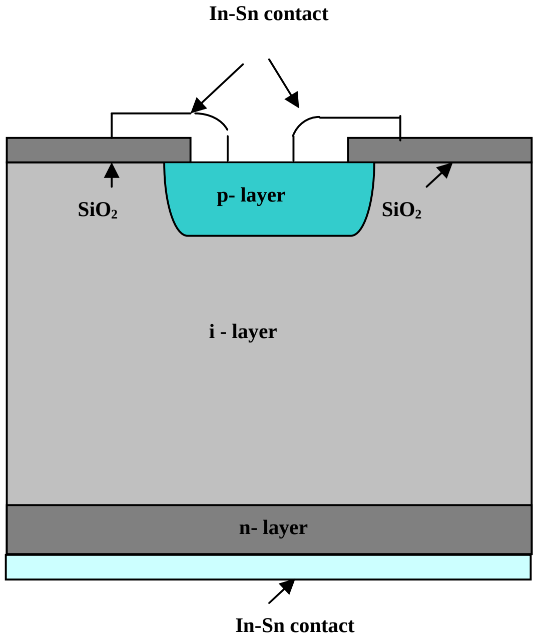

Figure 2: Cross sectional view of PIN silicon photodetector

III. RESULTS AND DISCUSSION

Four point probe measurements revealed that the Al-diffused silicon layer was p-type and the sheet resistance was 80Ω, whereas the antimony–diffused silicon layer gave an n-type region with a sheet resistance of 30 Ω. Figure 3 shows current–voltage characteristics of PIN photodiode. The forward current at low bias voltage (<0.4V) is the recombination current, while the diffusion current dominates at voltage > 0.4V. The current–voltage characteristics of Si PIN photodiode is given by diode equation

$$I = I_o (e^{qV/nkT} - 1) \ldots\ldots\ldots\ldots \qquad (1)$$

Where I_0 is the saturation current, q is the electron charge, V is the bias voltage, k is Boltzmann constant and n is the ideality factor. The rectification factor at 0.7V was found to be $5x10^3$. It is clear from Figure 1 the forward voltage drop is observed at 0.7V.

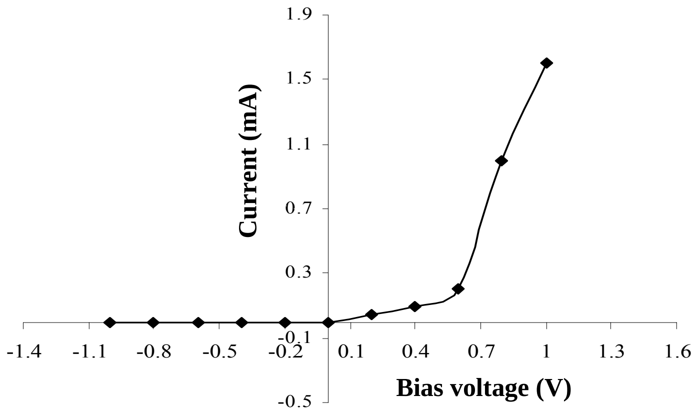

Figure 3: I-V characteristics of silicon p-i-n photodetector

The maximum forward current density was 7mA/cm^2 and the saturation current density, measured from Log I-V plot, was 0.04mA/cm^2. The ideality factor was calculated from equation 1 and found to be 2.1; a higher than for an ideal diode. This can be ascribed to the surface states and trapping centers that were induced during the diffusion process. The variation of junction capacitance with reverse bias is demonstrated in Figure 4. It is clear from this figure that the capacitance of the photodiode decreases when increasing bias voltage, and reaches a saturation value at higher value.

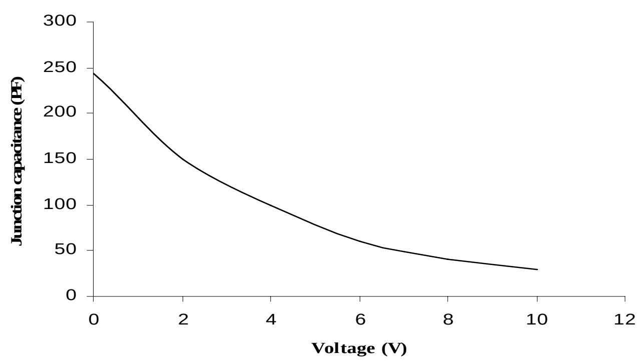

Figure 4: C-V characteristics of the photodiode

Figure 5 presents typical responsivity plot of photodiode at -5 V bias voltage. A maximum value of responsivity was found to be 0.5A/W at 850nm corresponds to a quantum efficiency of 74%. This value is very close to that for silicon PIN photodiode prepared by conventional diffusion method [1] .The spectral range of the fabricated photodiode ranged from 500nm to 1000nm with a detectivity, D*, calculated from the following equation:

$$D^* = \frac{(A\Delta f)R_\lambda}{I_n} \quad \ldots\ldots\ldots \qquad (2)$$

where A is the area of the detector, Δf is the bandwidth of photodiode, and In is noise current. A detectivity of 6x10^{11} cm Hz$^{1/2}$ W^{-1} at 850nm was obtained when the detector was biased to – 5V.

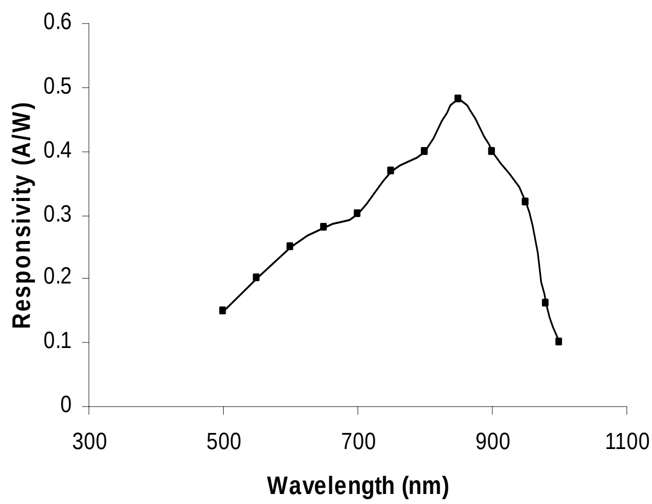

Figure 5: Responsivity versus wavelength plot at -5V bias

A rise time (t_r) of 40 ns was measured using a 100 ns laser diode operated at 904nm. This rise time is longer than that for PIN photodiode prepared by conventional method; this result can be ascribed to trapping centers produced via rapid cooling. Figure 6 shows the fall time t_f of the detector that is longer than the rise time, meaning that the rise time is not dominated by RC due to the large series resistance and structural defects. The response time is determined by three factors, first factor is the charge collection time in depletion region, the second factor is the time of charge collection in diffusion region and third factor is RC time.

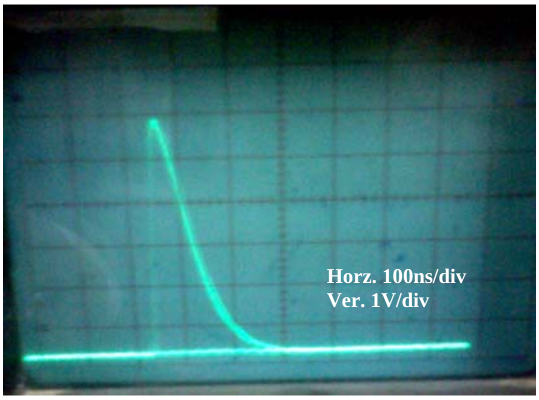

Figure 6: Laser pulse recorded by p-i-n photodetector

IV. CONCLUSION

In this paper we demonstrate a silicon p-i-n photodetector fabricated by novel rapid thermal diffusion technique. We have characterized the photodetector by I-V, C-V, responsivity and rise time. A peak responsivity of 0.5A/W at 850nm was obtained. The rise time of the photodiode was found to be 40ns. Based on obtained results, the rapid thermal diffusion technique is promising, encouraging, competitive, and reliable for fabrication of high performance silicon p-i-n photodiode.

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