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Effect of rapid thermal annealing on performance of large area crystalline silicon position sensitive detector

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Abstract

In this paper we report on the effect of rapid thermal annealing (RTA) on the characteristics of diffused crystalline p-n Si one-dimensional (1-D) position sensitive detector (PSD). The Si-PSDs are made with planer technology using thermal diffusion technique for Si doping. The lateral voltage produced by irradiation of He-Ne laser on PSD was parallel to the plane of junction and dependence linearly on laser spot position. The PSD that treated with best RTA condition (850 °C/15s) exhibited higher position sensitivity (104μV/mm) as compared with that for untreated PSD (31μV/mm).Furthermore, the best PSD gave a non-linearity error of 1.46%. The performance improvement factors such as uniformity, linearity, and responsivity of annealed Si-PSDs are presented and analyzed.

Keywords: position sensitive detector, Si, crystalline, rapid thermal annealing
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1. Introduction

Position-sensitive detectors (PSDs) are simple photodiodes capable of detecting the centroid position of a light spot projected on their surface. The position information is evaluated from the relative magnitudes of a few photocurrent signals provided by the PSD. In the lateral effect photodiode (LEP) which is a single photodiode that embedded resistive layers are used to generate the position-sensitive signal currents [1]. PSDs are used in commercial and industrial applications where low-cost or high-speed position sensing is needed. LEPs are probably mostly used in optical distance measurements. Such sensors are used widely to measure height, thickness and vibration needed in industrial fabrication processes, as well as are used in inexpensive cameras to provide the target distance for the autofocus mechanism [2]. In addition to distance measurements, triangulating sensors are used for switching various domestic devices such as electric fans, air conditioners, water taps and sanitary facilities on and off by detecting the presence of a human body. Other applications of PSDs include alignment, leveling and angle measurements and beam tracking applications [3-6].

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There are several types of PSDs based on crystalline and amorphous silicon technology [7-9]. The main targets in the PSD research are increase in linear sensitivity and resolution. Based on this point many structures of PSDs ranging from p-i-n to multilayer systems of a-Si:H/Ti have been proposed [10]. The 1-D position sensing detector (PSD) typically offers less positional sensitivity, but much greater range than multi–element photodiode. On the other hand, PSDs have uniform response performance across the detector aperture with no dead space as in 4-Q PSD and no problem of having the beam in a single detector segment. They are also independent of the light spot profile and intensity distribution that affects the position reading in the segmented diodes. For this reason PSDs are preferred in applications where continuous or fine displacements must be measured in real time.

The aim of this work is to study the possibility of using rapid thermal annealing (RTA) process to improve the performance of inexpensive thermal diffused p-n Si 1-D PSDs.

2. Experiment

The 1-D p-n Si position sensitive detectors with area of 2 cm2 (rectangular shape) were fabricated from silicon n-type Cz wafer with resistivity of 3-5 Ω cm and orientation of (111).An n+ ohmic contact was formed on the back side of Si wafer by phosphorus diffusion at 900 ºC for 1 hour with 1 µm SiO2 covering the front side. The top side p- layer was made by diffusion of boron at 950 ºC for 1 hour using a 1 µm SiO2 mask. The rapid photothermal annealing process was carried out on PSDs using bank of linear tungsten halogen lamps and illuminate p-n Si (one-sided illumination) through evacuated quartz tube as depicted in Fig.1. The annealing was achieved at temperature of 850 °C for different annealing times (5-20 s with 5 s step). The heating rate was calculated from thermal cycle and found to be 15°C/s. After annealing, 1000 Å thick TiO2 film was deposited on the detector window by electron beam evaporator as an antireflective coating (AR) to increase the responsivity for wavelengths of approximately 630 nm. The n- side contacts (common electrode) are formed as a 5000 Å thick layer of aluminum deposit using an electron beam evaporator. On the front side a 5000 Å thick layer of aluminum was evaporated on p-region through special mask. Fig.2 shows the basic design of 1-D Si-PSD.

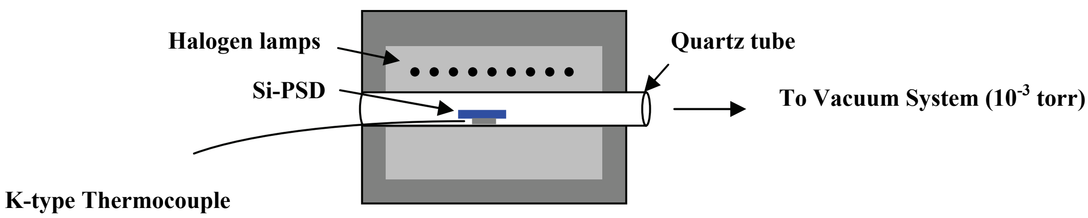

Fig. 1: Schematic diagram of RTA system.

The measurement of linearity and response uniformity of PSDs were accomplished using controlled X-Y table to move the focused laser beam (provided by Spectra physics) with 100 µm step over the whole active length (L) of the detector. For each step, the output data were obtained by digital millimeter (type Hp34401A). The characteristics of laser beam used in this study were presented in table 1.All the measurements on PSDs were carried out in absence of external bias (photovoltaic mode).The spectral responsivity measurements of

PSDs were performed in spectral range between 400 and 1000 nm with aid of monochromator (type SRD 100) and the power calibration was carried out using accurate Si power meter (PM30 Thorlab co.).

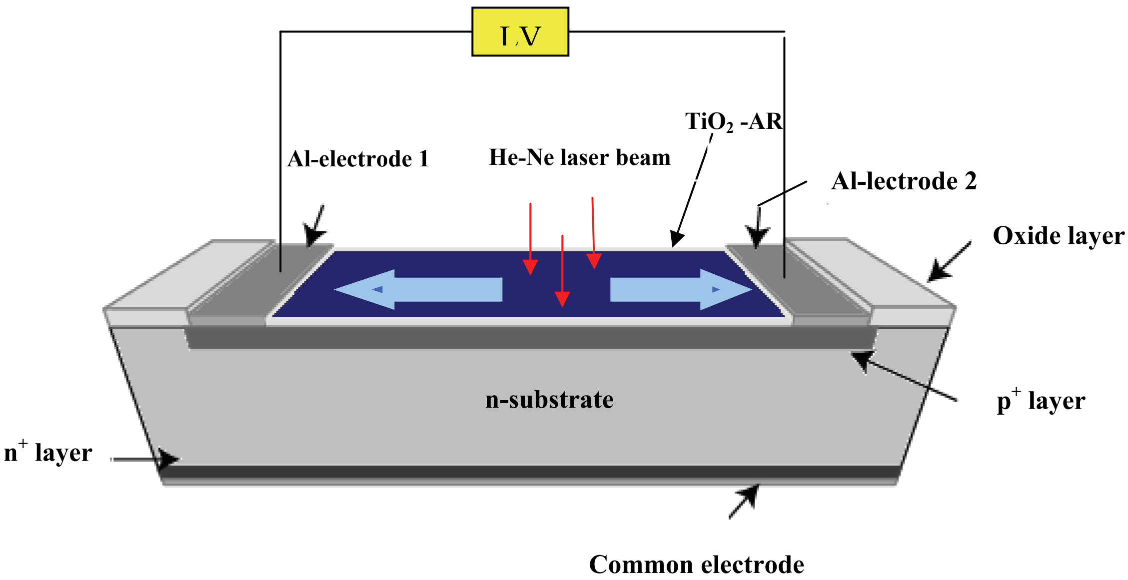

Fig. 2: Schematic diagram of 1-D diffused p-n Si-PSD structure.

Table 1 Specifications of laser beam

Laser type	He-Ne(CW)
Wavelength (nm)	632.8
Beam diameter (mm)	1mm
Beam power (mW)	1

3. Results and Discussion

Fig.3 demonstrates the spatial response uniformity (SRU) maps of the detector before and after RTA (at 850 °C/15 s condition) .It is obvious that SRU of the PSD is enhanced after RTA, and there is no significant deviation in surface response and point responses as compared with untreated PSD. A mean surface response (S_r) and its standard deviation (σ) have been calculated for PSDs before and after annealing at different conditions by averaging their point responses .Table 2 demonstrates the values of SRU ($\frac{\sigma}{S_r}$) and the positive and negative differences between the surface response and point responses (Δ_+, Δ_-). Inhomogeneity of the PSD material itself causes non-formity; Inhomogeneity and by surface recombination centers usually occurred at short wavelength. The improvement of SRU of PSD after RTA can be attributed to the activation of boron dopants and with minimum diffusion and due to minimization of role of recombination and trapping centers. These positive results are supported by sheet resistance Rsh measurements of treated regions as shown in Fig.4. The lowest value of Rsh as shown in Fig.4 was obtained for sample S4. This can be ascribed to the electrical activation of dopants [11,12]. It was seen that the responsivity of all photodiodes increased towards the edges possibly due to the thicker TiO2 layer and therefore higher light absorption in those regions [13].

(a)

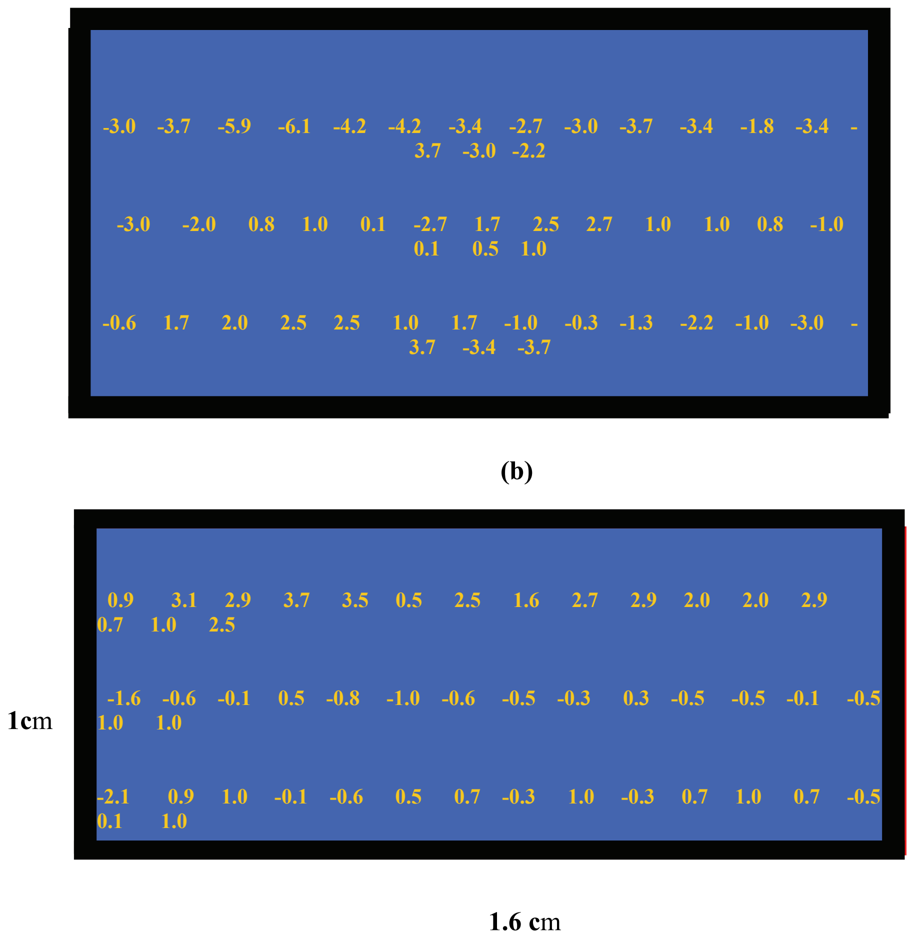

Fig. 3: Spatial responsivity uniformity maps of PSD (a) before RTA (b) after RT.

Table 2 SUR values of PSDs before and after RTA.

PSD	$\frac{\sigma}{S_r}$ %	Δ+ %	Δ- %
S1	2.496	3.71	-6.12
S2	2.29	5.09	-3.96
S3	2.09	4.18	-4.17
S4	1.629	3.67	-3.65
S5	2.3	4	-4.1

S1:untreated sample , S2: annealed with 850°C/5s ,S3 : annealed with 850°C /10s ,S4: annealed with 850°C /15 s , S5 :annealed with 850°C /20s.

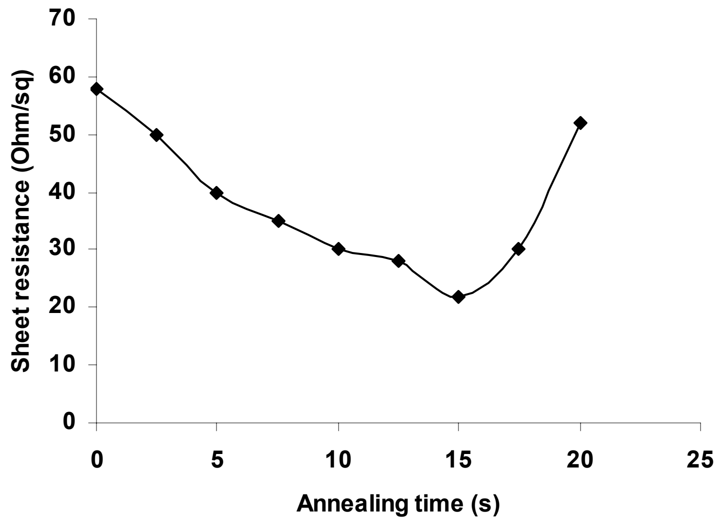

Fig. 4: Sheet resistance of p-Si region as function of annealing time.

To evaluate the dependence of PSDs photocurrents on laser power density, neutral density filters have been used. Fig.5 presents the photocurrent as function of laser power density. It is observed that the photocurrents of all PSDs tend to saturate at power density as high as 0.2 mW/cm2 except S4, which demonstrates good linearity characteristics (power law dependence).

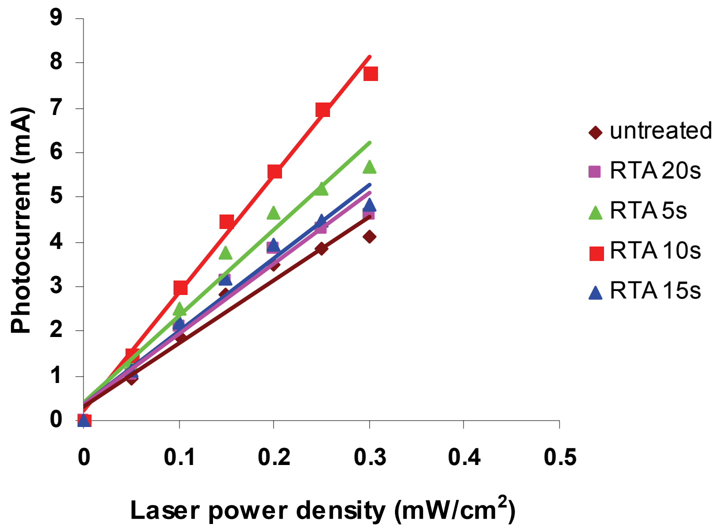

Fig. 5: Photocurrent versus laser power density plot.

Fig. 6 presents the effect of RTA on spectral responsivity plot of PSDs. It is observed from this figure that there is a significant improvement in spectral responsivity after annealing; particularly the PSD annealed with 15s.This is mainly due to the annealing of interface state defects and residual lattice strain relived. The peak response of all PSDs was around 850nm, on the other hand the responsivity of best PSD (at 632 nm) was found to be 0.17A/W. No shift in peak response of PSDs has been observed after RTA.

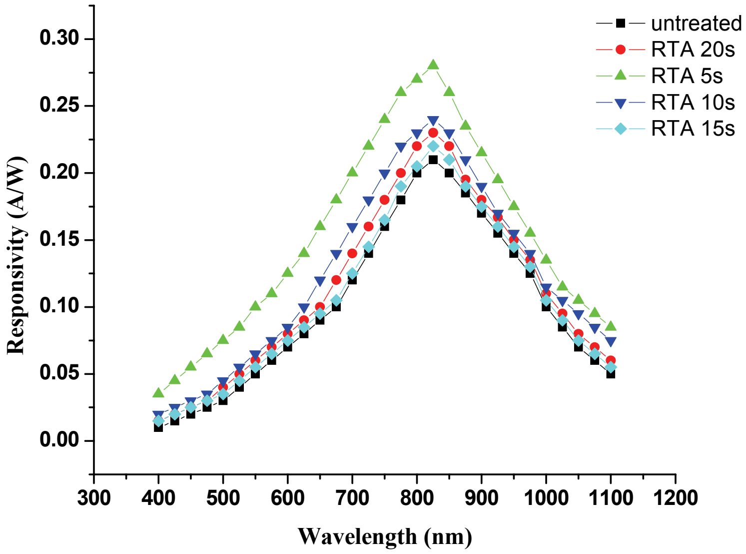

Fig. 6: Effect of RTA time on spectral responsivity characteristics of PSDs.

Fig.7 shows the position sensitivity measurements performed on p-n Si-PSD before and after RTA placed in dark condition, i.e. it is illuminated by laser spot only .When a He-Ne laser spot incident on the active area of PSD creates EHPs, it will be separated by the internal electric field. Electrons will be pulled towards the n+ region, while holes will be pulled towards the p- region. The resistive layer at the top will function as a current divider and hence current received at each electrode. The output signal is inversely proportional to the resistance between the incident light spot and the contact. When the input laser spot is exactly at the device center, equal signals are generated. By moving the light spot over the active length of the detector, the amount of signal generated at the contacts will determine the exact light spot position at each instant of time. These electrical signals proportionately are related to the light spot position from the center. This can be explained as follow : Rs1+Rs2 corresponding to total resistance of PSD ,measured between extremes .When Rs1 decreases by ΔR , Rs2 increases by ΔR, then the lateral voltage (LV) can be given by:

$$LV = I_{RS1}R_{s1} - I_{RS2}R_{S1} \tag{1}$$

It is evident from this Fig.7 that the linearity is maximized over all the active length of detector after RTA (850°C/15s).The values of position sensitivity and position detection error (PDE) or non-linearity are tabulated in table 3. The PDE is the key figure of merit of PSD and can be calculated from the following equation [7] :

$$\delta = \frac{2S}{F} \tag{2}$$

Where S is the root mean square deviation and F is the full scale of the signal .The error is often given as a percentage of the active length, and is calculated within 80 % of the active area. The reason why only 80% is used is that when the light spot reaches the edge of the detector, parts of the spot will strike outside the detector. This moves the calculated position towards the center of the detector and the position becomes unreliable [6].
The PDE of annealed PSDs with 15s is within acceptable range and comparable to that for MIS and p-i-n Si-PSDs [10, 14]. No significant variation in PSDs performance was observed after three months of storing in normal environment.

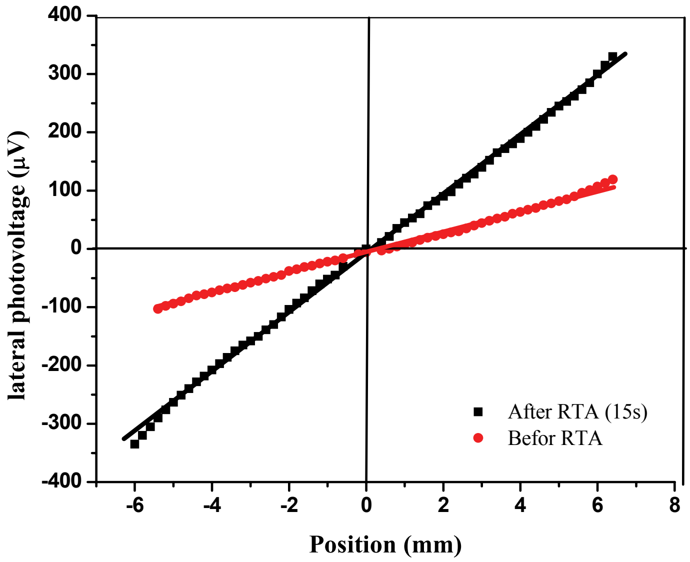

Fig. 7: Lateral photovoltage measured across the PSD as function of laser spot position.

Table 3 Sensitivity and PDE of PSDs

PSD	Position Sensitivity μV/mm	PDE (%)
S1	30.75	2.5
S2	44.35	2.42
S3	63.3	1.94
S4	104.16	1.46
S5	35	2.4

4. Conclusions

The possibility of using classical diffused large area p-n Si as accurate 1-D PSDs after rapid thermal annealing at different annealing times was investigated. The annealed PSDs show encouraged position sensitivity, especially the ones annealed with 15s.The obtained PSDs present good performance concerning position non-linearity 1.46% over 1.6 cm active length. The maximum responsivity of 0.27A/W was obtained for 850 nm and it was 0.17A/W for 632 nm. A significant enhancement was noticed in spatial response uniformity of PSD after RTA. The fabricated PSDs exhibited good stability conditions.

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