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Q- Switched Nd:YAG Laser Annealing of Phosphorus Diffused Silicon Photodiodes

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Abstract: Improvement of optoelectrical characteristics of phosphorus diffused silicon photodiodes by Q-switched Nd:YAG laser pulses was investigated. Laser pulses have dissolved the precipitation of phosphorus resulted during thermal diffusion process. The experimental data show that responsivity higher than (0.32 A/W) at 850 nm can be achieved after laser annealing with (1.5 MW/cm^2) for 6 shots.

Introduction

The most widely used technology for the production of terrestrial solar cells is the diffusion the phosphorus in p-type silicon substrate. To obtain low series resistance long minority carrier lifetime, high open– circuit voltage, and high spectral response, the diffusion process should result in a highly doped layer with shallow junction [1].

Unfortunately, the concentration of active phosphorus, which can be introduced by thermal diffusion, is not exceeding (2 to 4 x 10^{20} cm^{-3}). Since phosphorus in access of this concentration is lead to formation of precipitates when the solid solubility limit is attend [2] and pairing with vacancies. As consequently it is difficult to obtain sheet resistance less than 35 Ω/☐.

Several authors have used many types of laser beams to decrease the sheet resistance of thermal diffused layer to enhance the performance of silicon solar cells [3 - 6].

In this work, we applied Nd:YAG laser illumination to phosphorus diffused p-type silicon photodetectors, and we determine the number of successive laser pulses that gave the best results.

Experiment

CZ-single crystal (SX) silicon substrate with specification presented in Table (1) have been used in present work. The diffusion of phosphorus in Si have accomplished using $POCl_3$ source at 850 ºC for1 hr. The sheet resistance of diffused layer measured by four – point probe was 54 Ω/ ☐ and the junction depth was around 0.3 μm. The samples placed in an evacuated (10^{-3} Torr) stainless steel cell were irradiated with Q-switched Nd:YAG laser pulses of 35 ns FWHM with multiple shots to generate annealing spots with 1.5 MW.

Table 1 Specification of silicon substrate.

Conductivity type	P
Dopant	Boron
Electrical resistivity	3-5 Ω-cm
Orientation	(111)
Dimensions	5 x 4 x 0.5 mm^3

The laser was operated in TEMoo mode with diameter of 2 mm on the substrate, overlapping of laser spots with 50% ratio had been used to cover the sensitive area of photodiodes .The schematic diagram of laser annealing set-up revealed in Fig.(1). After laser annealing ohmic contacts have been made on both n- and p-type side by depositing of Al and Ni-Cr layers respectively . TiO_2 antirefiecting coating was deposited on Si using electron gun technique .To investigate the photoresponse of annealed and unannealed photodiodes , monochromator in the range of (500-1100) nm had been employed. GaAlAs pulse laser (τ= 200 ns, λ= 905 nm) was used to monitor the rise time of photodiodes.

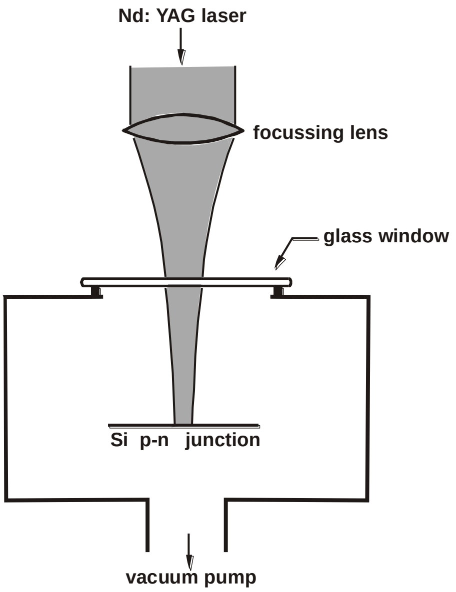


Fig. 1
Experimental set-up of laser annealing system.

Results and Discussion

Fig. (2) reveals the dependence of electrical sheet resistance of annealed layer on number of laser shots (N). The sheet resistance is decreased up to 5 shots; this decrease may arise as a result of fully activation of phosphorus after laser annealing [1]. Sheet resistance for annealed samples was less than non-annealed by factor of 0.96. On the other hand, it is well established that for laser energy and number of shots used here the surface is locally melted. In the liquid phase the diffusion coefficient of phosphorus dopant is very high, so that they are redistributed in the melt and hence no precipitation occurs at all. Since phosphorus is more soluble than during diffusion because of the strong thermodynamic non-equilibrium character of the process. Less sheet resistance (20 Ω / cm^2) has been obtained using ruby laser to anneal silicon [7] because the absorption depth α^{-1} is very close to the diffusion depth. Annealing with N>5 leads to increase the sheet resistance. This can be attributed to the structural defects, recombination and trapping centers, and ripples created in treated region [8].

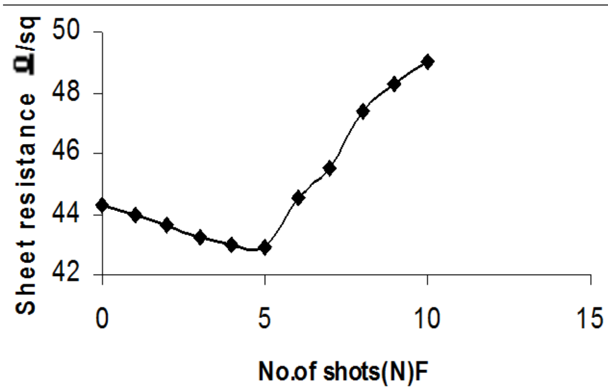


Fig. 2
Dependence of sheet resistance on the number of laser shots.

The spectral responsivity curve of annealed photodiodes is presented in Fig. (3) . It is clear that responsivity improvement has been accomplished after laser pulse annealing. The enhancement can easily be explained by the increase in the concentration of active phosphorus dopants and the n+ layer and may be related to the decrease in the sheet resistance which leads to better collection efficiency. The optimum spectral responsivity obtained was for samples annealed with N=5.

Increasing of laser shots result in increase the junction depth which in turns degrade responsivity in the near infrared region.

No remarkable shifting in peak response was observed after annealing as shown in Fig. (3). Another opto-electrical property that is superior in photodiode made from laser annealed p-n silicon is the quantum efficiency. Comparison of quantum efficiency of laser annealed and unannealed photodiode is given in Fig. (4)

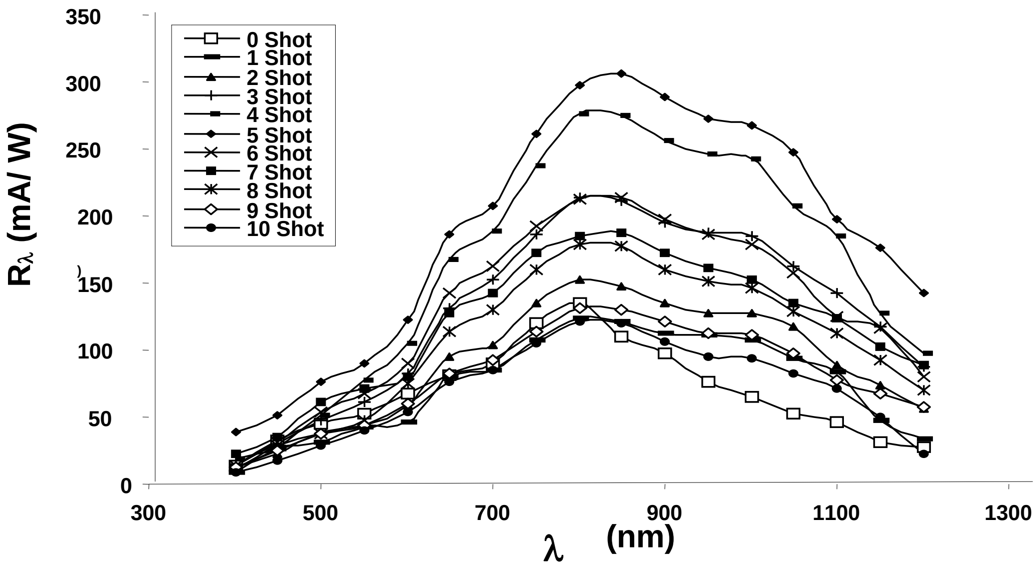


Fig. 3 Spectral responsivity of photodiodes annealed with different laser shots.

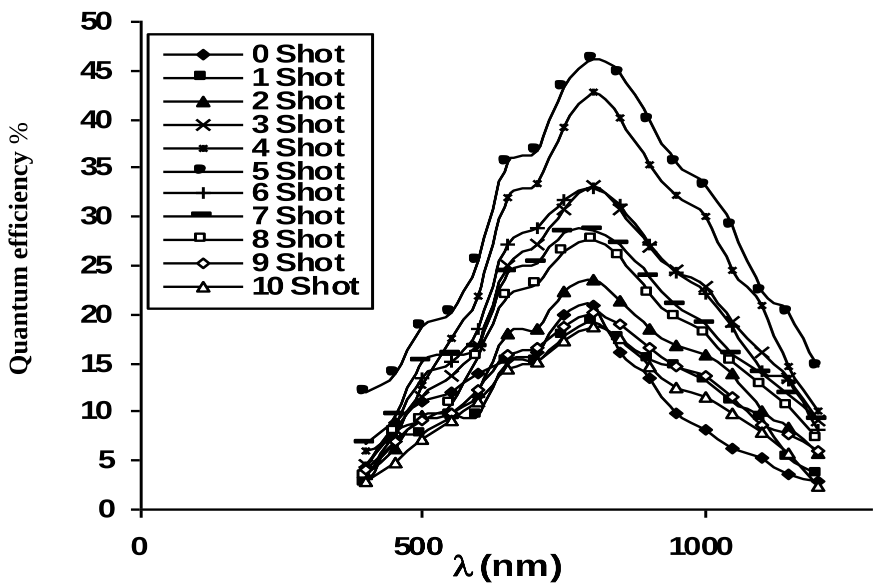


Fig. 4 Quantum efficiency of photodiodes as function of laser shot number.

which reveals that the response of the laser treated junction detector is superior throughout the visible and near–IR spectrum. This improvement can be ascribed to retention of long minority carrier lifetime of substrate and complete absence of extended defects which might give rise to trapping and excessive e-h recombination [9-10].

The number of laser shot is taken as the parameter and marked on the curve. The samples annealed with N>6 exhibits drop in quantum efficiency; this is at least in part due to defects and junction degradation. This hypothesis was supported by photo response at near–IR region, which was highly degraded for N > 6.

The curve shown in Fig. (5) is the dependence of rise time of photodetectors on number of laser shots.

Improvement in response speed of photodiode was observed after annealing with N < 6. The waveforms of laser pulses for both annealed and unannealed photodiodes taken at zero bias were recorded as shown in Fig. (6).

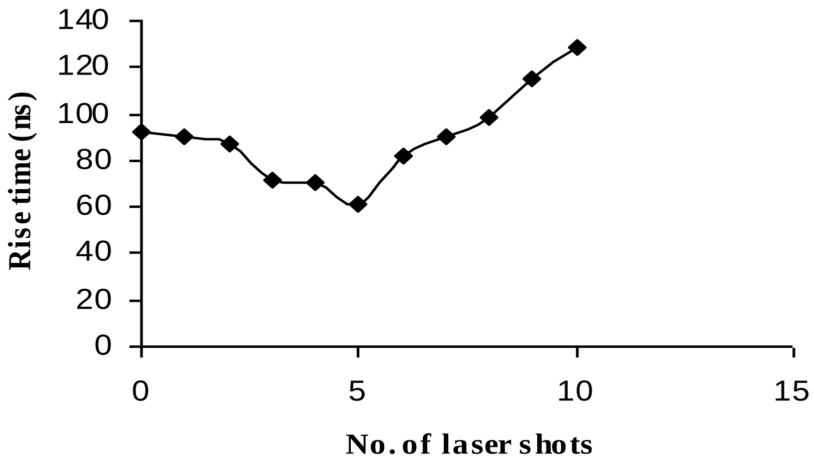
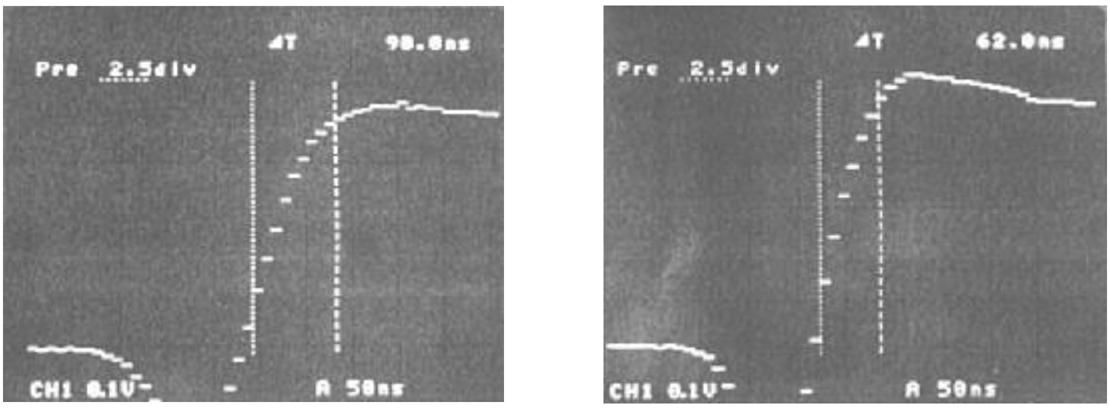


Fig. 5 Variation of rise time with annealing laser shots



(a) (b)

Fig. 6 Rise time of the photodetector (a) before and (b) after laser annealing.

Conclusions

The present investigation shows that phosphorus diffused silicon junction photodetectors annealed by means of short laser pulses have superior opto-electrical characteristics. It was found that annealing with 6 laser shots were sufficient for annealing out the defect in thermally diffused layers. The maximum value recorded for responsivity at 850 nm is 0.32 A/W of phosphorus diffused silicon which in among the highest value reported so far.

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التلدين بواسطة النبضة العملاقة لليزر النيوديميوم – ياك لثنائي ضوئي سليكوني مشاب بالفسفور

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الخلاصة

جرى فحص التحسن للخصائص الكهروبصرية لثنائي وصلة ضوئي نوع سليكوني مشاب بالفسفور بعد التلدين بالنبضة العملاقة لليزر النديميوم – ياك . أن التلدين بنبضات الليزر أدت إلى إذابة الفسفور المترسب نتيجة عملية الانتشار الحراري . لقد أوضحت النتائج العملية أن الاستجابية التي تم الحصول عليها عند الطول الموجي 850 nm كانت أعلى من 0.32 A/W عند التلدين بكثافة قدرة ليزر $1.5\ MW/cm^2$ وبستة نبضات .