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Ge/Si heterojunction photodetector for 1.064 µm laser pulses

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Abstract. Iso- and anisotype heterojunction Ge/Si photodetectors were made by depositing Ge layer onto monocrystalline Si using a vacuum evaporation technique. These detectors before and after annealing were utilized to detect 1.064 µm Nd:YAG laser pulses. The study also included determination of the optimal Ge thickness and annealing conditions. The experimental results show that the photoresponse was highly improved after classical thermal annealing and rapid thermal annealing (RTA). The voltage responsivity and signal rise time results strongly depended on the annealing type and conditions. It was found that the optimal conditions can be obtained for *n*-Ge/*p*-Si photodetector prepared with Ge 200 nm thick and treated with RTA at 500 ºC for 25 s.

Keywords: Ge/Si photodetector, thermal annealing, Nd:YAG laser pulse.

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1. Introduction

The wide use of Nd:YAG laser in industrial, medical, and military applications has initiated extensive researches on photon detectors for the wavelength 1.064 µm [1-4]. Nowadays, fabrication of IR-detectors is directed principally towards heterojunction photodetectors. The fabrication simplicity and absence of high-temperature diffusion processes were an incentive to use a heterojunction as IR-detector. Ge/Si heterojunction is an appropriate junction for detectors in the visible and IR ranges 500 to 1800 nm [2, 5-6]. The high mismatch (about 4.2 %) takes place between Ge and Si would degrade the detector properties. Many studies were devoted to reduce the mismatch effect by varying the Ge layer thickness when using Ge_xSi_{1-x} [6] and $Ge_{1-x}C_x$ layers [7] as well as by post-deposition thermal annealing [8]. Previous study on the Ge/Si heterojunction was centered on its optoelectronics properties after and before annealing [9]. In this study, the effect of the Ge-layer thickness and annealing conditions (involving classical thermal annealing (CTA) and rapid thermal annealing (RTA) techniques) on Ge/Si photodetector main parameters for 1.064 µm laser pulses were described.

2. Experimental procedure

High purity germanium (99.99 %) was deposited on (111)-oriented monocrystalline silicon wafers of *n*- and *p*-type conductivity and 3…5 Ohm·cm resistivity using the thermal resistive technique (pressure in vacuum chamber was less than 10^{-6} Torr). The thickness of the Ge layer varied from 50 to 250 nm at 50-nm intervals. As ohmic contacts, Al and Sn were deposited onto Si and Ge, respectively. Photoresponse of the detectors (Ge-side) was measured by exposure to the 400 µs single pulse of Nd:YAG laser, and the output voltage signal was recorded across a load resistance of 5 kOhm connected in series with the reverse biased detector and monitored by storage oscilloscope (100 MHz). In a tube furnace, CTA was performed at various temperatures 200 to 600 °C for 30 min, while RTA was made by utilizing incoherent light from a halogen lamp (one sided illumination mode) at temperatures 200 to 600 °C for 25 s. The set-up of RTA system is schematically shown in Fig. 1. Four-point probe measurement was used to investigate the conductivity type of the Ge deposited layer. The signal rise time of photodetectors was measured using 2 ns (FWHM) diode pumped Nd:YAG laser pulses formed with the aid of 300 MHz CRO.

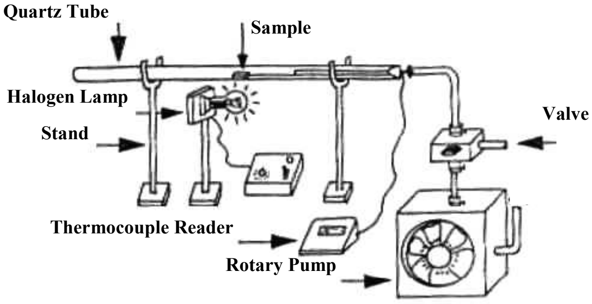

Fig. 1. Scheme of RTA system.

3. Results and discussion

Using the four-probe technique, it was revealed that the type of conductivity of Ge layers is *n*-one, thereby, it is anticipated that the anisotype heterojunction can be formed by depositing the Ge-layer onto *p*-Si substrate, while the deposition of Ge-layer onto *n*-Si substrate will form an anisotype heterojunction. The voltage responsivity of photodetectors to Nd:YAG laser pulses versus the reverse bias voltage for variuos thicknesses is given in Fig. 2. It is obvious that the responsivity to the wavelength 1.064 μm increases with reverse bias voltage. This can be accounted for definetely by the increase in the depletion region width with the reverse bias, and hence most of generated carriers will be accumulated near the junction. The observed saturation refers to full accumulation in the space charge region and may take place due to increasing the noise voltage of detector at high-voltage biases. Moreover, it can be seen that the photoresponse increases with increase of the thickness up to 200 nm and then decreased clearly. This observation may be interpreted by the reduction of the resistance in series with increasing the thickness in addition to the location of the depletion region far from the surface, which in turns reduces the surface recombination. While in the case of the large thickness (more than 200 nm) the role of dislocations will be significant due to lattice mismatch and will negatively affects the device operation. Furthermore, the anisotype *n*-Ge/*p*-Si heterojunction detector exhibits better results than the isotype *n*-Ge/*n*-Si one, which is in a full agreement with published results.

Results of treating the photodetector by CTA for the anisotype Ge/Si detector with the Ge-layer thickness of 200 nm and the annealing time 20 min are shown in Fig. 3. It is obvious that the detector properties are enhanced with increase of the annealing temperature (up to 500 °C). This enhancement is probably ascribed to the reduction in structural defect density of the Ge-layer [10]. An annealing cycle with the high temperature $T_a > 500$ °C degrades the detector characteristics because of the effects occuring at the interface and bulk properties as well as those caused by nondesirable diffusion of Si into Ge at the interface [11].

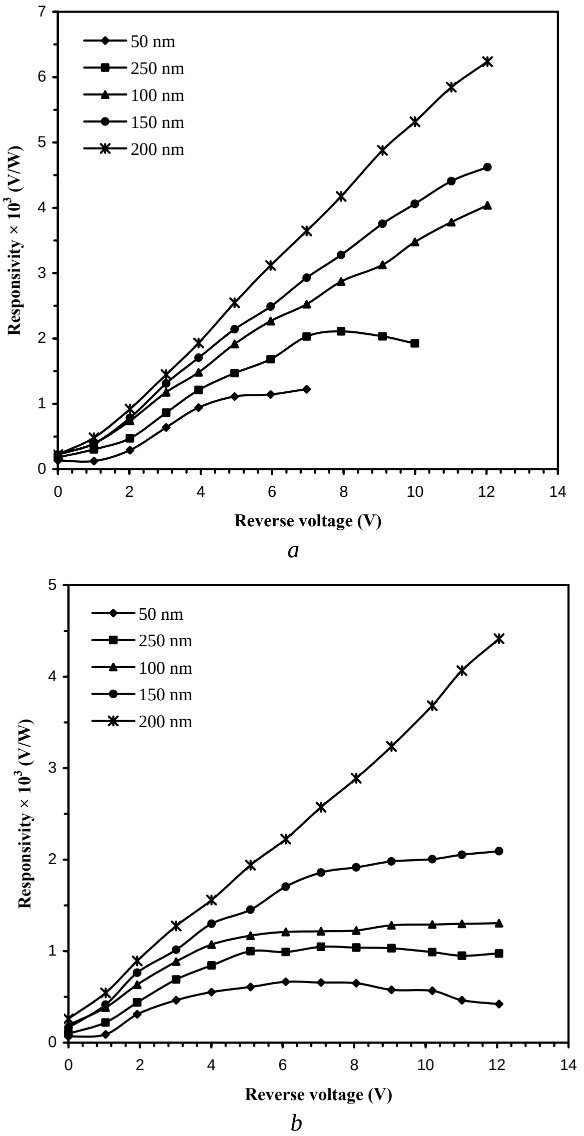

Fig. 2. The variation of voltage responsivity with the reverse bias voltage for various Ge-layer thicknesses: anisotype (a) and isotype (b) *n*-Ge/*n*-Si heterojunction detectors.

Fig. 4 depicts the influence of RTA on *n*-Ge/*p*-Si responsivity with Ge-layer thickness of 200 nm and annealing time of 25 s. The figure shows that this responsivity increases remarkedly after RTA compared with that for unannealed detectors. The photodetector annealed at 500 °C/25 s gave best results, and further increase in the temperature annealing results in decreasing the voltage responsivity. This can be ascribed to excess of Si diffusion into Ge since the activation energy of Ge is higher than that of Si [8]. On the other hand, the beneficial effect of post-annealing on the electrical and structrural properties of Ge epilayers on the detector operation has resulted from the decrease of threading the dislocation densities [11].

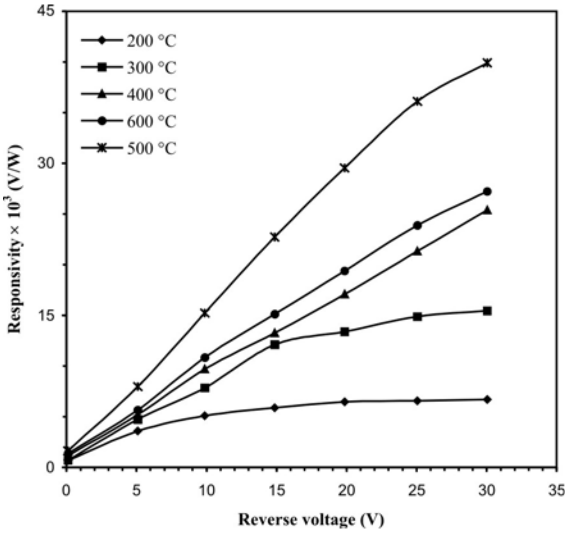

Fig. 3. *n*-Ge/*p*-Si photodetector (200 nm thick Ge) voltage response for Nd:YAG laser at the various CTA temperatures.

Fig. 5 shows a laser pulse recorded by unannealed and annealed photodetectors. It is obvious that the annealed samples show higher response than the unannealed ones. When the incident laser pulse power increases, the detector output voltage will be increased as shown in Fig. 6. The figure illustrates that at a high power a saturation region did not appear. From this curve, linearity deviation *K* was calculated and approximately equals to 10 % for unannealed samples and 6 % for the annealed ones.The time analysis shows that the optimal annealed photodetector gave the rise time close to 18 ns and the other photodetectors exhibited the rise time ranging between 75 and 90 ns depending on preparation conditions. The previous measurements were repeated after six months and no remarkable degredation was observed.

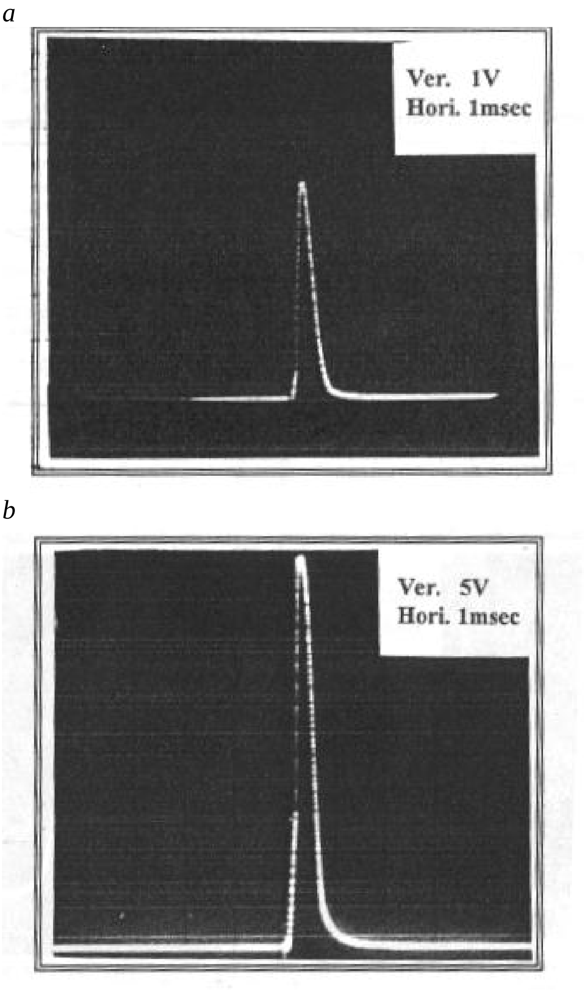

Fig. 5. Photographs of laser waveform recorded by detectors with the Ge-layer thickness of 200 nm and at 20 V reverse bias before annealing (a) and after RTA (b) at 500 ºC and 25 s. (Hor. ms/div), (Ver. V/div).

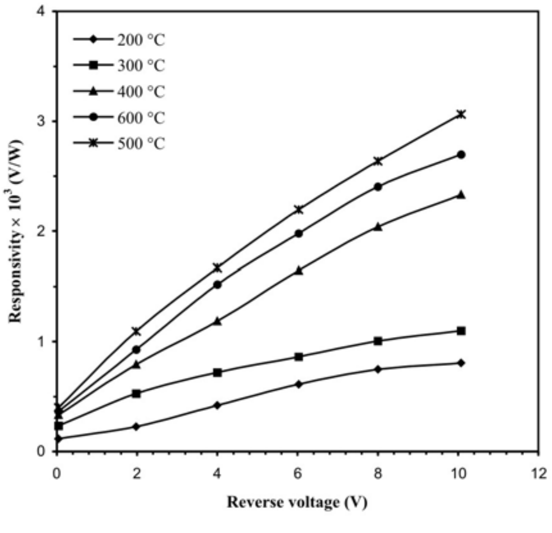

Fig. 4. Anisotype photodetector response for Nd:YAG laser at the various RTA temperatures.

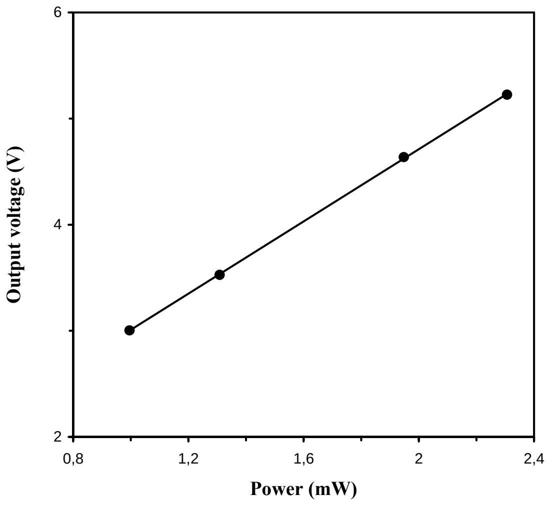

Fig. 6. Linearity characteristics of the best photodetector for Nd:YAG laser.

4. Conclusions

Demonstrated were *p*-*n*- and *p*-*p*-photodetectors capable to register Nd:YAG laser pulses and made from heterojunctions of *p*-type Ge epilayers on *n*- and *p*-type Si substrates without using a buffer interface layer and without anti-reflection coating. The detecton ability for Nd:YAG laser pulses were investigated as a function of Ge thickness and annealing conditions. Post-annealing of these photodetectors leads to a significant improvement in their important characteristics, namely, voltage responsivity, linear characteristics, and rise time. The photodetector treated by RTA (500 °C/25 s) demonstrates superiour detection properties comparing to conventional *p*-*n* and *p*-*i*-*n* silicon homojunction photodetectors. These photodetectors exhibits a good stability of their characteristics.

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