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The laser-produced plasma as a modern repetitive ion source for technological applications

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1. Introduction

The study described in this paper is focused on ion emission from plasma produced by low energy repetitive laser as well as on preparation, tests and application of tabletop laser ion source. The plasmas generated with laser beams of low and medium intensity has many important applications such as use of laser ion sources for technological processes, surface modification by laser ablation and laser-induced material deposition [1-4]. The laser-produced ions are useful for a direct ion implantation or with additional electrostatic acceleration. Among other ion implantation techniques, the application of laser-induced ion implantation is a novel and competitive method for production of semiconductor nanocrystals [5-7]. In the method, control of the beam parameters in broad energy and ion current density ranges is possible due to application of electrostatic fields for acceleration and formation of laser-generated ion beams. The flexibility and accuracy of the method is possible due to opportunity of electrostatic selection of ion groups with user-defined parameters. The investigation and applications described in this paper concern implantation of laser-produced Ge ions directly or after acceleration into SiO_2 substrates for production of Ge nanocrystals.

2. Experimental arrangement

The experimental arrangement at IPPLM consists of an interaction vacuum chamber, cylindrical accelerating/deflecting electrodes, a high voltage supply system and a device for fast pulsation of the electric field. As the ion source the repetitive Nd:glass laser system (1.06 μm, 3.5 ns, <0.8 J, <10 Hz) has been used which allowed material ablation and production of ions suitable for modification of semiconductor materials. The laser beam was focused onto a pure germanium target surface for the production of Ge ions. The laser spot had diameter D_f = 3 mm. To prevent neutral particles sputtered at the target from reaching the implanted sample the focus spot was shifted in respect to the normal of the implanted sample. The experiments were performed using a laser pulse energy, $E_L = \sim 0.5$ J, laser pulse duration, t_L = 3.5 ns, pulse repetition rate of up to 10 Hz and intensity on the target of up to 10^{11} W cm^{-2}.

The experimental arrangement used for ion acceleration which shows the ion diagnostic is presented in Fig. 1. To measure the characteristics of the laser-generated ions the ion collector (IC) and a cylindrical electrostatic ion energy analyzer (IEA) have been used. Both of these diagnostics are based the time-of-flight method [8,9]. The IEA enables to collect spectra of different ion species by changing the deflecting voltage of cylindrical electrodes inside the analyser. An example of IEA spectrum of Ge ions recorded at distance of 177 cm from the target and at laser intensity $I_L = 2.5 \times 10^9$ W cm^{-2} (E_L= 0.5 J, D_f = 3 mm) is shown in fig. 2.

Due to the potential difference formed between the box and the grounded cylindrical electrode the ions passing through the diaphragm were accelerated. The characteristics of the accelerated ions were measured with the use of an ion collector located on the axis of the grounded electrode at the distance of ~ 30 cm from the target (15 cm from the grid).

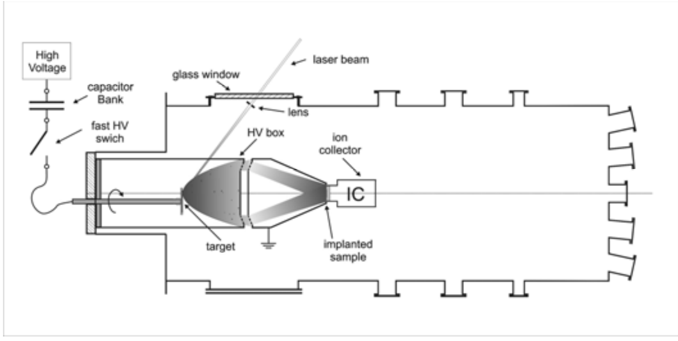

Fig. 1. The scheme of experimental arrangement for acceleration and separation of specific group of laser-produced ions.

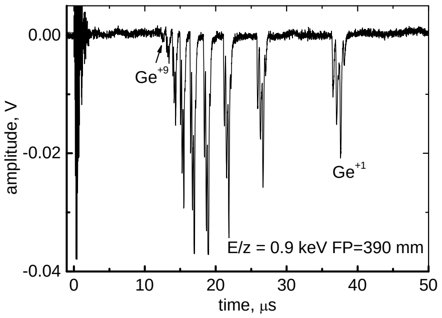

Fig. 2. An ion charge state spectrum measured by the IEA.

The voltage of power supply ranges from 0 to +45 kV. The accelerating potential can be applied to electrodes with the use of fast switch at different time delays regarding the laser pulse. This switch enables also to obtain the accelerating voltage for selecting a specific group of ions and removal of contaminant ions from the ion stream directed on sample. The accelerating voltage, the shape of the accelerating electrodes, the distance of the diaphragm from the target, the diaphragm diameter and the gap width were adjusted to for optimise the system. The distance between the diaphragm and the grid was about 1 cm.

3. Results of measurements

The experiments on implantation of Ge ions into SiO_2 substrate with the use laser ion source tested the usability of the method. The measurements of laser-produced Ge ions have shown that at laser intensities $5x10^9 \div 10^{11}$ W/cm^2 the maximum measured energy of freely expanding ions was ~3 keV.

At the distance of 30 cm the beam of Ge ions emitted from the target was $>10^{12}$ ions/cm^2 for single laser shots. The accelerating system enabled to increase the energy of slow Ge ions more than ten times. The Ge ions produced at different laser shots were directly, or after acceleration, implanted in SiO_2 substrate of thickness of 20 ÷ 40 nm which was prepared on the Si single crystal. An ion collector located on the target normal recorded the characteristics of accelerated ions. An example of gated IC signal of accelerate ions is shown in Fig. 3.

The time of flight of ions from target to IC decreases with the increase of accelerating potential as shows in Fig. 4. It means that the accelerating potential increase the energy of ions passing through the electric field. The increase of electric potential allows to significantly increase the current of accelerated ions.

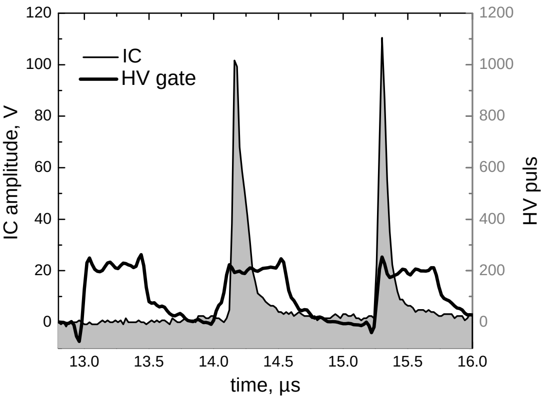

Fig. 3. The gated ion collector signal with the shape of the accelerating high voltage impulse in background.

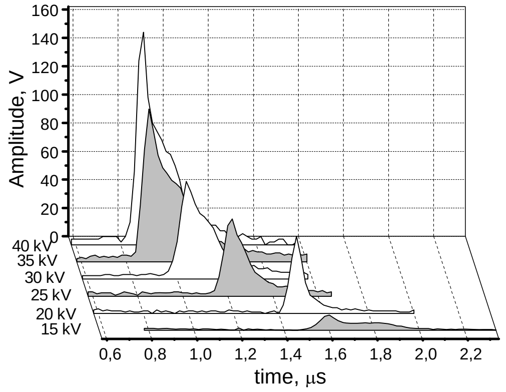

Fig. 4. The IC signals of Ge ions recorded for different accelerating voltages.

The depth profiles of Ge laser-produced ions implanted into SiO_2 were measured in Warsaw University of Technology with the use of AES – Auger Electron Spectroscopy. These experiments were performed for samples implanted without ion acceleration and for samples implanted with ions additionally accelerated in pulsed (gated) electric field. An example of AES depth profiles which is shown in Fig. 5 indicates that most of carbon contamination is accumulated at surface (at depth below 7 nm). In this case the Ge ions implanted into SiO_2 layer of thickness of 40 nm prepared on Si crystal (“n”) were accelerated to energy of 7 keV. The AES depth profile of Ge in the SiO_2 layer presented in Fig. 6 shows that most of Ge ions are implanted at depth of about 10 nm but also significant amounts (>1%) are implanted at depths up to 20 nm. The concentration at 7 nm reaches about 5%.

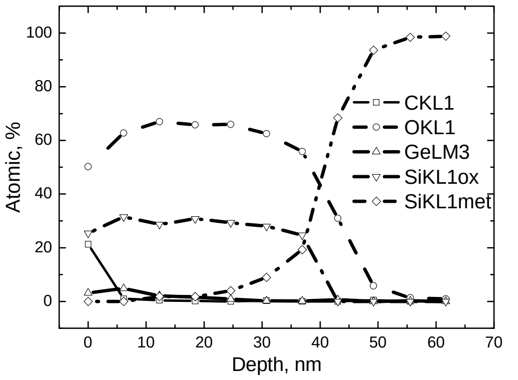

Fig. 5. AES depth profiles of sample implanted with accelerated Ge ions.

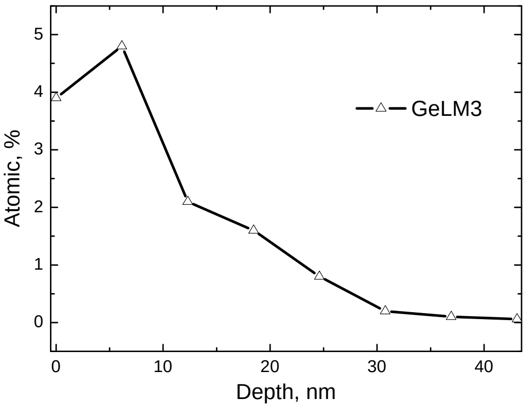

Fig.6. AES depth profile of implanted Ge ions.

4. Summary

The experiments performed at IPPLM led to development of the system consisting of a vacuum chamber, optimised accelerating/deflecting electrodes, a high voltage supply system and a device for fast pulsation of the electric field which allowed for the effective acceleration of laser-produced ions and selection of a specific group. The depth profiles of SiO_2 / Si samples implanted with accelerated laser-produced Ge ions were obtained in WUT with the use of AES method. The investigation has confirmed that the ion implantation of accelerated laser-produced ions can be considered as a new technique for modification of semiconductor materials.

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