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Post-acceleration of ions from the laser-generated plasma

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Abstract. An application of the laser-generated plasma for multi-energetic ion implantation is reported. In an experiment performed at Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud (INFN-LNS) of Catania, Italy the Nd:YAG laser was used, operating at the 1064 nm wavelength with the intensity of 10^{10} W/cm^2. A laser pulse of 9 ns duration and 300 mJ energy was employed to ablate a solid target placed in a high vacuum. The free ion expansion occurred in a constant potential chamber placed at 30 kV positive voltage with respect to the ground, which allowed to extract ions with energy proportional to the charge state. In an another experiment, performed at the PALS Prague laser facility (1315 nm, 400 ps pulse width and the laser pulse energy delivered on target equal to about 35 J) Ti ions were obtained through the ablation of solid targets in vacuum by means of 10^{15} W/cm^2 laser pulses. In both cases ion energy analyzers were used to measure the energy-to-charge ratio of the ions. The ion energy distribution was determined from the time-of-flight measurements. The depth profiles measured through Rutherford backscattering spectrometry (RBS) analysis are in good agreement with the ion energy analyzer spectroscopy measurements.

Key words: laser ablation • laser-plasma • post-acceleration • ion implantation • Rutherford backscattering spectrometry (RBS) analysis

Introduction

The ion implantation process introduces a controllable amount of energetic ions into a thin layer at the surface of different materials. A sufficiently high ion dose may modify the chemical and physical superficial properties of the implanted sample (hardness, wear, wetting ability and so on).

Laser ion sources (LIS) of a new generation are able to deliver high currents of energetic ions with a high directivity. Ions produced in such sources have energies that follow a Boltzmann distribution, which results in the implantation at different depths inside the sample placed in front to the plasma plume. Laser beams of low intensity, of the order of 10^{10} W/cm^2, can produce ions with energy of about few keV, which need to be post-accelerated up to energies of the order of 100 keV in order to be implanted at reasonable depths [2]. Laser beams of high intensity, of the order of 10^{15} W/cm^2, produce ions with energies of the order of 1 MeV, which is sufficient for the implantation [4]. In this paper we describe the laser-driven ion implantation processes that were performed using the Nd:YAG operated at INFN-LNS of Catania and the iodine laser at Prague PALS laser facility.

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Experimental setup

The Nd:YAG laser, was operated at the 1064 nm fundamental wavelength, delivering a pulse of 9 ns duration, 0.9 J maximum pulse energy, at the 1–30 Hz repetition rate. The laser beam was focused through the glass window on a Ti target placed inside the vacuum chamber. The incidence angle of the laser beam was 43°, while the ion diagnostic apparatus and the samples to be implanted were placed along the normal to the target surface. The accelerating setup consisted of a cuboid expansion chamber, 26 cm long and 11 cm side square cross section. The target was placed at the centre of the cuboid. The target and the expansion chamber were $\partial^2/\partial z^2$ kept at the same electrical potential – set between 0 and +30 kV – using a high voltage power supply (Heinzinger, 30 kV/200 mA). The front part of the extraction chamber was completely open in order to permit the plasma to exit along the normal to the target surface. Above this box aperture a system of 12 parallel metallic discs – each with a central aperture of 8 mm diameter – was placed along the chamber longitudinal axis. The discs were separated from each other by a distance of 5 mm and were connected serially together through the 1 MΩ resistance. The first disc was connected to the 30 kV positive voltage, while the last disc was grounded. In this way the system generated a uniform accelerating voltage across a distance of 60 mm. The corresponding accelerating electric field was 5 kV/cm. A schematical drawing of this experimental setup is shown in Fig. 1a. The Opera-3d simulation package [5] was employed to study the pattern of electric field lines and equipotential surfaces in the extraction zone, as well as trajectories of particles ejected from the target and arriving in the extraction-acceleration zone, as is shown in Fig. 1b.

An ion collector (IC) was used to detect the laser generated ions emitted from the plasma along the normal to the target surface.

In order to estimate the total ion dose emitted from the plasma, the RBS analysis was performed, using 2.25 MeV α particles at a detection angle of 170°.

Results and conclusions

The IC detector was placed at the distance of 0.56 m along the normal to the target surface in order to detect the ion component of the plasma. The time-of-flight technique (TOF) was used by connecting the detector with a fast storage oscilloscope. The measurements on ablating Ti target were performed in two arrangements: without the post-acceleration (Fig. 2a) and with the post-acceleration via +30 kV potential difference (Fig. 2b). In the first case the peak of the TOF signal occured at 30 μs; this corresponds to the Ti energy of 675 eV. Knowing the input resistance of 1 MΩ of the fast storage oscilloscope, it is possible to estimate the implanted ion dose by considering the total current of the IC signal. The measured value is 10^9 Ti particles/pulse. For comparison, in the second case the TOF peak is located at 1.1 μs, corresponding to the mean energy of 62 keV.

A different test about the ion implantation was performed both at the INFN-LNS of Catania and PALS laboratory in Prague. Figure 3a shows a typical RBS spectrum obtained by implanting Ti in C substrates using the Nd:YAG laser in Catania with an intensity of about 10^{10} W/cm^2, while applying +30 kV potential in the post-acceleration system. Energetic ions (~ 0.1–1 MeV) were implanted on a silicon substrate surfaces placed at different distances from the target and different angles from the normal to the target surface. In order to increase the ion dose, implantation was performed by using more laser shots in the same experimental conditions. Using standard formulae of the RBS theory [1] we find that the total Ti ion dose was around 8.9×10^9 atoms/pulse/cm^2 and the thickness of the implant is

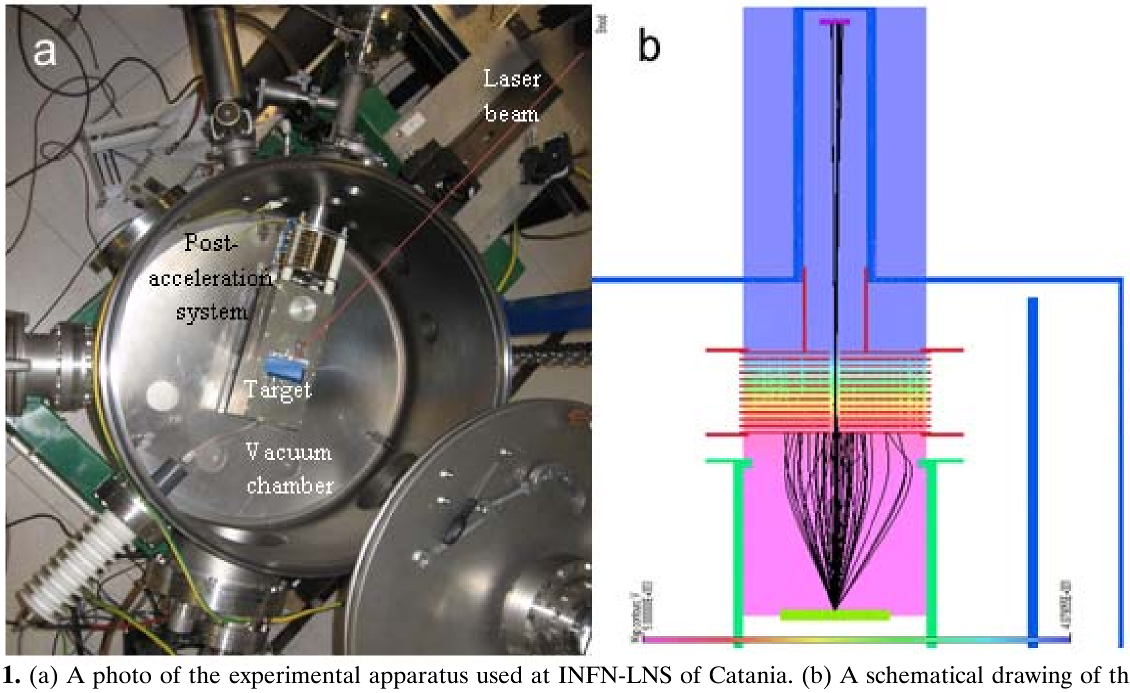

Fig. 1. (a) A photo of the experimental apparatus used at INFN-LNS of Catania. (b) A schematical drawing of the post-acceleration system, created using the Opera-3d code.

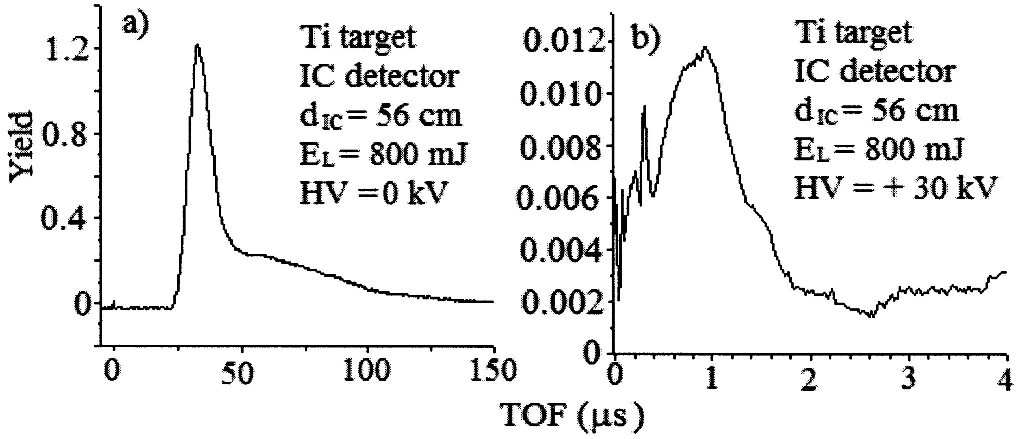

Fig. 2. IC spectra obtained with the TOF technique using Ti ions: (a) without the post-acceleration, and (b) with +30 kV applied in the post-acceleration system.

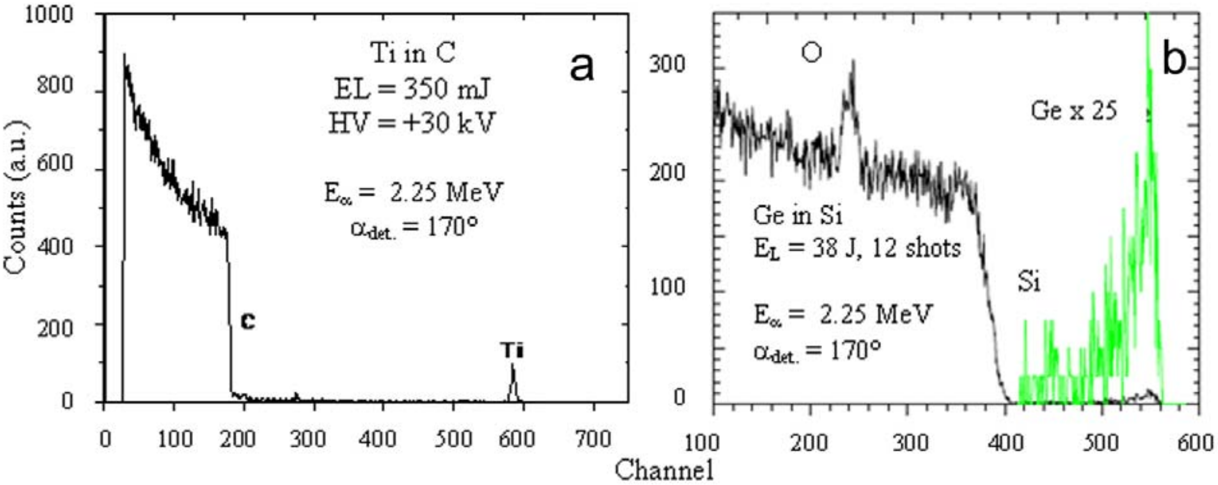

Fig. 3. Typical RBS spectra of Ti ions in the C sample, obtained at INFN-LNS of Catania with 30 kV post-acceleration (a), and the spectra of Ge ions implanted in Si, obtained at PALS laboratory (b).

around 40 nm. Using the TRIM code [3], we find this corresponds to the energy of 50 keV.

Figure 3b shows a typical spectrum obtained with the iodine laser at PALS laboratory, with the intensity approximately equal to 10^{15} W/cm^2, which allows for sample implantation without the post-acceleration system. In this case, using the formulae of the RBS theory, it is possible to estimate that the Ge ion dose was approximately 2.67×10^{14} atoms/pulse/cm^2, and the thickness of the implanted layer was 530 nm, which corresponds to the Ge ion energy of 750 keV.

In both cases the results are in good agreement with the value obtained from the ion collector data.

These results demonstrate that the laser-generated, non-monoenergetic ion beams can be employed with success in the field of ion implantation, both with post-acceleration, if we use both laser intensity of the order of 10^{10} W/cm^2, and without the post-acceleration, for laser intensity higher than 10^{15} W/cm^2.

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