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Analysis of laser-generated plasma ionizing radiation by synthetic single crystal diamond detectors

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ABSTRACT

Diamond based detectors have been used in order to analyze the ionizing radiation emitted from the laser-generated plasma. High energy proton/ion beams were generated at Prague Asterix Laser System (PALS) Centre by the sub-nanosecond kJ-class laser at intensities above 10^{16} W/cm^2.

The tested detectors consisted of a photoconductive device based on high quality chemical vapor deposition (CVD) single crystal diamond, produced at Rome "Tor Vergata" University. They have been operated in planar configuration, having inter-digitized electrodes.

The proposed diamond detectors were able to measure UV, X-rays, electrons and ions. They have been employed in time-of-flight (TOF) configuration and their reliability was checked by comparison with standard ion collectors (mostly used at PALS). Both the forward and backward expanding plasma was characterized in the experiment. The results indicate that diamond detectors are very promising for the characterization of fast proton and ion beams produced by high power laser systems.

1. Introduction

The investigation of fast ion emission from laser plasmas is crucial for future applications of laser-accelerated ion beams in different areas, such as warm dense matter generation, probing of high electric and magnetic fields, nuclear applications (compact neutron sources, isotope production, fission reactions), medicine, astrophysics, etc. Recently, the generation of ions with energy of few MeV/u and current densities of few A/cm^2 by the use of the sub-nanosecond, kJ-class laser at Prague Asterix Laser System (PALS) laboratory has been reported [1–3]. The beam parameters are estimated with application of various devices and techniques usually operated in "single shot" mode. In particular, time-of-flight (TOF) spectrometry is an effective diagnostic tool [4] since it provides time-resolved measurements which are fundamental for a detailed study of ion beam parameters, such as species and charge-states, their kinetic energy, and total charge. However, there exist various difficulties in such diagnostic techniques when high-energy laser pulses are used, e.g. high electromagnetic noise, overlapping of the signal due to photopeak, difficulties in separation of the ion signals from it, breakdowns at very high ion currents, low sensitivity to fast electrons and protons or to low charge state ions. To overcome the above measurement difficulties, the development of new detectors is in continuous growing. In particular, semiconductor detectors seem to be very promising for detection of fast protons and ion beams produced by high power laser systems [5–7]. Among them, the use of diamond detectors, producing signals proportional to the energy deposited by the incident radiation, is very attractive because these detectors are not sensitive to the visible light (band gap 5.48 eV). Moreover, high thermal conductivity, high resistivity, low dielectric constant, high carrier mobility and radiation hardness [8,9] suggest that diamond is an ideal material for monitoring the radiation emission from laser-generated plasmas. Thanks to the fast response time, detectors based on natural and synthetic diamond have been employed in TOF techniques in several experiments reported in literature, in particular for the detection of electrons [10] and heavy ions [11]. Detectors based on high quality chemical vapor deposition (CVD) single crystal diamond have been developed at the Department of Mechanical Engineering of University of Rome "Tor Vergata" for both nuclear particles (thermal and fast neutrons, high energy ions, charged particles) [12] and photon radiations (X-rays, UV, etc.) [13]. Such diamond detectors have been permanently installed at Joint European Torus (JET) to measure UV/X-ray radiation and neutrons produced by JET plasma demonstrating a fast time response, good sensitivity, high signal-to-noise ratio and a good stability and reliability of the response [14].

In this work, single-crystal CVD diamond detectors are employed in TOF technique to monitor the different plasma

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products (i.e. photons, electron and ions) generated by high power pulses focalized on different targets at PALS laboratory in Prague. Both forward and backward emission of the plasma was characterized. In particular, different thin hydrogenated targets were used in the experiment in order to generate forward protons, i.e., proton emission from the rear target sides. A different electrode configuration was adopted for the single crystal diamond detectors with respect to Refs. [12–14] in order to improve the time resolution and better separate the different reaction products.

In this work, single-crystal CVD diamond detectors operating in planar configuration are employed in TOF technique to monitor the emission of photons, electron and ions ejected from both forward and backward emission of the plasma produced at PALS laboratory in Prague.

2. Material and methods

The diamond detectors were fabricated in a planar interdigitized electrode configuration. A nominally intrinsic diamond layer, which operates as the detecting region, was homoepitaxially grown by Microwave Plasma Enhanced Chemical Vapor Deposition (MWPECVD) on a 4 mm × 4 mm × 0.5 mm commercial low-cost synthetic High Pressure High Temperature (HPHT) diamond substrate. The thickness of the intrinsic layer was chosen to be approximately 50 μm. The hydrogen termination of the as grown diamond surface was removed by isothermal annealing at 500 °C for 1 h in air. Finally, 50 nm thick aluminum fingers were patterned by a standard lift-off photo-lithographic technique and by thermal evaporation. The metal fingers were processed to 5 μm in width with spacing between the electrodes of 20 μm. The detector active area was approximately 8 mm^2. Such a structure, operating in planar configuration, acts as a two terminal metal-diamond-metal (MDM) device. An external voltage of 50 V was applied between the metal contacts generating an electric field perpendicular to the incoming light across the device. Mobile charges produced by the absorbed radiation drift in this electric field and generate a current in the external circuit. From simulations based on the Shockley–Ramo–Gunn theory with the help of Comsol Multiphysics finite element software [15], the charge collection efficiency of the MDM detector is such to allow collecting electron–hole pairs generated up to about 25 μm below the superficial metallic electrodes. So that the diamond substrate, which is poor in electrical quality, does not contribute to the detection process. The sensitive layer is thick enough to collect most of the energy of the emitted ions and, in particular, protons of energy up to 2 MeV are fully captured in this layer (SRIM Monte Carlo code [16]).

In order to reduce electromagnetic noise, the diamond detectors were placed in a shielded holder having a pin-hole to collimate the radiation only on the detector sensitive area. The output signal was recorded with a 1 GHz, 5 GS/s fast oscilloscope through a bias-T. All inputs to scope were terminated in 50 Ω. Fig. 1 shows the schematic structure of the MDM device with the scheme of the used electronic circuit (a), a photo of Al inter-digitized electrodes (b) and its assembly in the experiment (c). The diamond detectors were employed in TOF measurements to detect all the components of the radiation emitted from the laser-generated plasma.

The experiment has been performed at the PALS facility by focusing the first harmonics (λ_0 = 1315 nm) of the 300 ps pulsed laser at a maximum laser energy of 600 J and laser intensity above 10^{16} W/cm^2. Thick and thin metal layers or polymers were employed as targets. Moreover, multilayered films, most of them constituted by hydrogenated polymers coupled to thin metallic films (Mylar/Al, Al/Mylar/Al, Au/polyethylene, polymers containing nanoparticles and/or nanostructures, etc.), were used in order to increase the energy of ejected ions. Investigation of proton and ion emissions in backward and forward directions (thick and thinner targets, respectively) of the plasmas was analyzed. Forward emission of ions (mainly protons) was measured from the rear-side (target back side) of thin targets along the normal to the target surface, besides backward emission of the plasma is from the front side of the target.

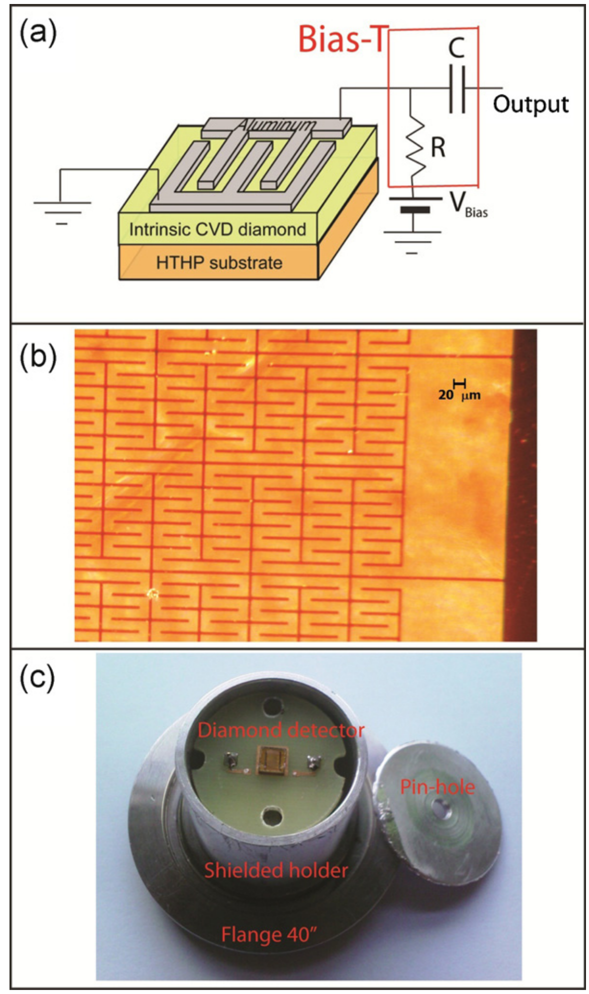

Fig. 1. Schematic structure of the MDM device with the scheme of the used electronic circuit (R = 3.3 MΩ and C = 0.68 μF) (a), a photo of Al inter-digitized electrodes (b) and its assembly in the experiment (c).

The MDM detectors were placed at a distance of 101 cm and 123 cm from the target surface in forward and backward directions, respectively, and at 30° angle with respect to the target normal direction in both cases. A simple sketch of the experimental setup is shown in Fig. 2.

Finally, a Faraday Cup was employed as an ion collector (IC) at a distance of 100 cm from the target in forward direction and at 30° angle in order to compare the experimental data obtained from Diamond with that from IC.

3. Results and discussion

First, the time resolution analysis of the MDM detectors has been performed in our laboratories. Then, the results obtained by two photodetectors, one placed in forward and another one in backward direction of the plasma at PALS laboratory, are reported in the following.