SiC detectors for fast diagnostic of high intensity laser-generated plasmas

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Abstract

SiC detectors, with 80 micron depletion layer, can be used with success in order to detect the radiations emitted from hot plasmas generated by fast and intense laser pulses. Due to the high energy gap with respect to the Si detectors, SiC doesn't detect the high visible intensity radiation emitted from plasmas but it detects very well UV, X-rays, electrons and ions with high signal-to-noise ratio also at room temperature. It can be employed in two regimes: that of proportionality with the energy deposited in the sensitive volume and that of time-of-flight triggered by the laser shot. In both cases it permits to monitor photons, electrons and ions plasma emitted, giving information on their energy distribution. In particular the electron and ion spectra can be elaborated to permit the measurement of particle energy and of the equivalent plasma temperature. Some investigations performed at Physics Department of Messina University will be presented and discussed.

Introduction

Nowadays there is considerable evidence of the importance of semiconductors technology that find important applications in a wide range of fields. The limit imposed by silicon in applications which include high temperatures and high doses encourage the development of devices with wide band gap such as silicon carbide or diamond.

In addition to the wide band gap (3.26 eV), SiC operates at high temperatures (20-200 C°), has high response velocity, high thermal conductivity and high critical field (see Tab. 1). For these reasons SiC detectors, compared with conventional devices, have many advantages: fast collection time, room temperature operation and low dark current. Moreover SiC detectors could sustain high current and voltage up to 1 A and 1 kV, respectively. As evidenced by literature, 4H-SiC is the most favourite polytype of SiC. Table 1 reports the main properties of SiC, at room temperature, compared to other semiconductor detectors. The current response of SiC devices (see Fig. 1a) is proportional to the incident radiation energy released into the detector active region, whose depth depends on the doping concentration and reverse applied voltage. Generally it is used a voltage ranged between 600 V and 800 V which corresponds to a depth of 60 μm - 70 μm. SiC detectors are based on a semiconductor junction inversely polarized (see Fig. 1b) and have already been used successfully for alpha [1], ions [2], electrons, neutrons and X-rays [3] detection, but certainly the most interesting application refers to the monitoring of the radiation emitted by a non-equilibrium plasma generated by laser [4].

Property	4H-SiC	Si	Diamond
Crystal structure	Hexagonal	Diamond	Diamond
Energy gap (eV)	3.26	1.12	5.45
h mobility (cm^2/Vs)	100-115	450-600	1200-1600
e mobility (cm^2/Vs)	800-1000	1400-1500	1800-2200
Breakdown electric field (MV/cm)	2.2-4.0	0.2-0.3	10
Thermal conduct. (W/cm °C)	3.0-5.0	1.5	20
Saturation velocity (cm/s)x10^7	0.8-2.2	0.8-1.0	2.2-2.7
Max working temperature (°C)	1240	300	1100
e-h pair energy (eV)	7.78	3.62	13
Density (g/cm^3)	3.21	2.33	3.52

Tab. I Principal properties at room temperature of SiC compared to other materials interesting for radiation detection.

In this kind of measurements it isn't possible to employ a standard chain of detection because of the very short duration of the plasma (few microseconds). So it is necessary to adopt a Time-Of-Flight configuration (TOF).

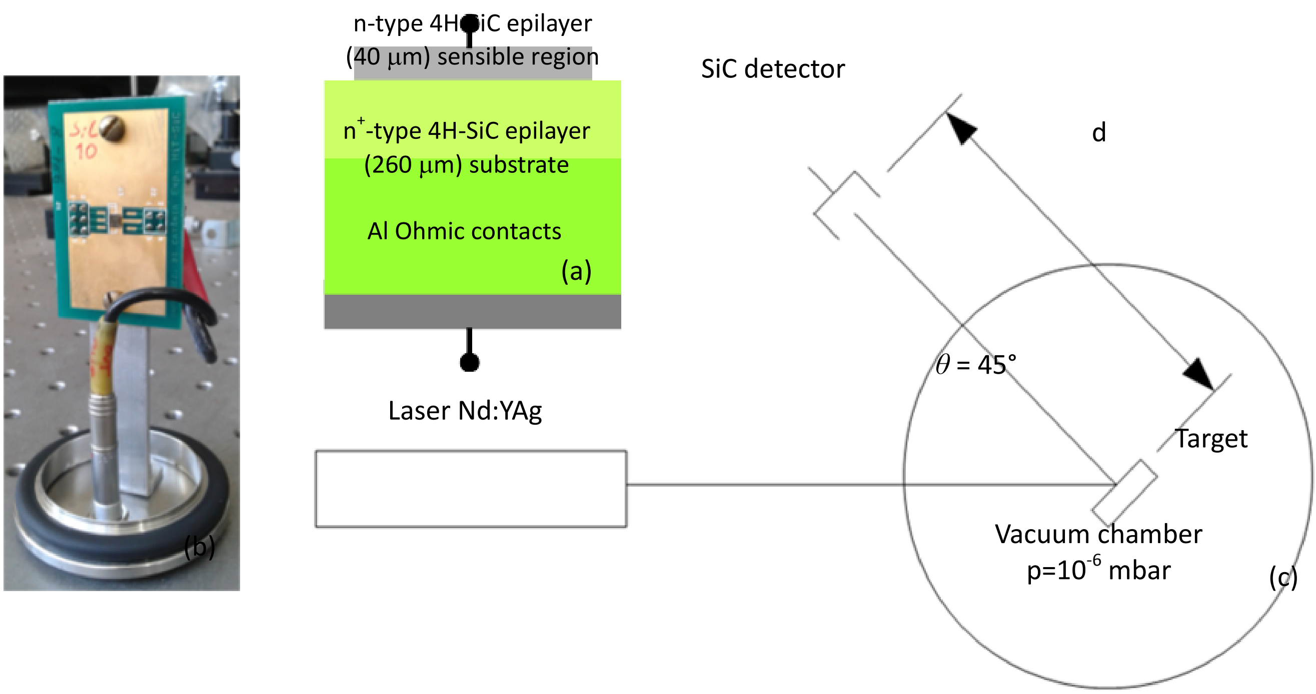
The TOF spectra, acquired with SiC detectors, are usually composed by a fast photopeak and one or more structures due to the charge particles collection.

Materials and methods

In this investigation SiC was employed as single-crystal 4H-SiC Schottky diode detector to monitor the energy of radiations ejected from low temperature plasma.

The detector was built at CNR-IMM of Catania through the collaboration with ST-Microelectronics.

The experiments were performed in the Laboratory of Plasma Physics of Messina University. A Nd:Yag laser operating in single pulse at 1064 nm wavelength, 3 ns pulse duration, 10^9 W cm^{-2} pulse intensity and 1 mm^2 spot size was employed. The targets used for laser irradiations were thick Al and Ta sheets. The incidence angle was 45°. A scheme of the experimental set-up is reported in Fig. 1c.



setup (c).

We applied a reverse voltage bias of 300 V which produces an active region of about 40 μm depth. Although the detector has a surface with Ni_2Si metallization 200 nm thick, which stops low energy radiations, it has the possibility to detect UV, electrons, protons and heavier ions of low energy due to a little amount (~ 10%) of the total sensible area (4 mm^2) uncovered by metal and directly exposed to vacuum.

Time-Of-Flight configuration was employed in these measurements and the spectra were recorded with a fast oscilloscope (20 GS/s) using the laser shot as a start signal and the impulse generated by the particles as stop signal. The detector was placed along the normal to the target surface (0°). The flight distance *d* between the target and the SiC was 110 cm.

Results

The photopeak is generated by photons coming from the plasma that could produce photoelectrons on the metallic surface of the detector and by photons generating e-h couples in the depletion layer. In time scale this peak is followed by signals due to fast electrons and successively due to protons and heavier ions detection.

In Fig. 2a are compared the two TOF spectra obtained irradiating the Al and Ta targets.

The photopeak indicates the start signal and it is set approximately in the 0-20 ns region (see Fig. 2b).

On the tails of the two photopeaks there is an overlap of a structure between about 20-50 ns due to hot electrons emitted form the plasma.

An electron peak is detected for both spectra at 24 ns, corresponding to a kinetic energy of 5.7 keV, indicating the presence of fast electrons accelerated by the electromagnetic wave. The tail of this peak is extended up to about 50 ns corresponding to electrons at energy of about 1.4 keV. The electron yield in tantalum is a factor 4 times higher than aluminium, as expected due to the higher atomic number. The cold electron component is so low that was not detected in our system, thus it was not usable to measure the plasma temperature.

SiC spectra show a broad structure between 10-20 μs that can be identified as detection of protons. Their yield for Al is about a factor 4.5 higher than for Ta target, as expected due to the higher absorption of hydrogen. By knowing the Time-Of-Flight it is possible to determine the proton velocity and the kinetic energy.

In aluminum, considering a TOF = 12.1 μs for proton we obtained a mean energy of 43 eV.

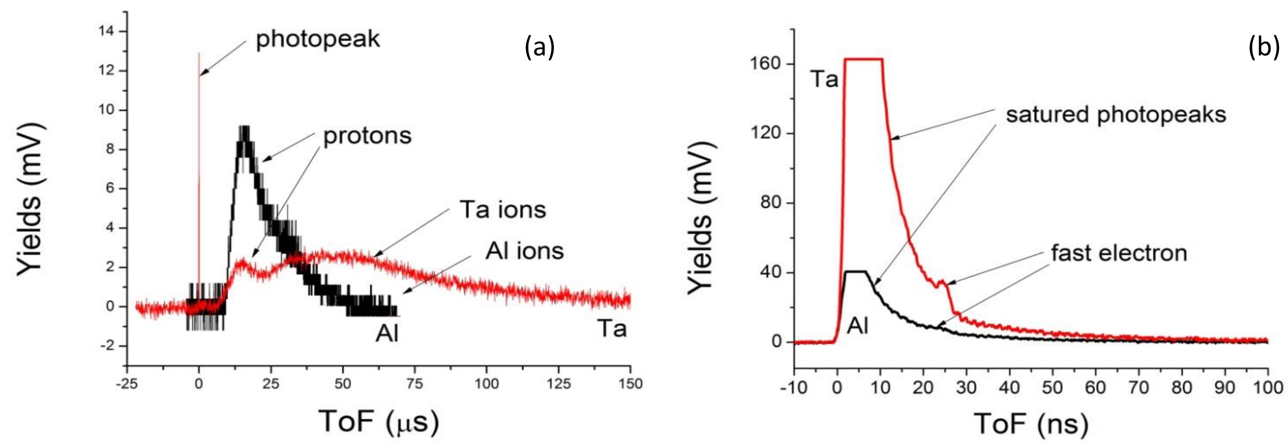


Fig. 2 Comparison between the spectra obtained irradiating Al and Ta targets (a). Detailed analysis of the two photopeaks which show and overlapping structure due to the presence of fast electrons (b).

In tantalum we measured a TOF = 9.8 eV

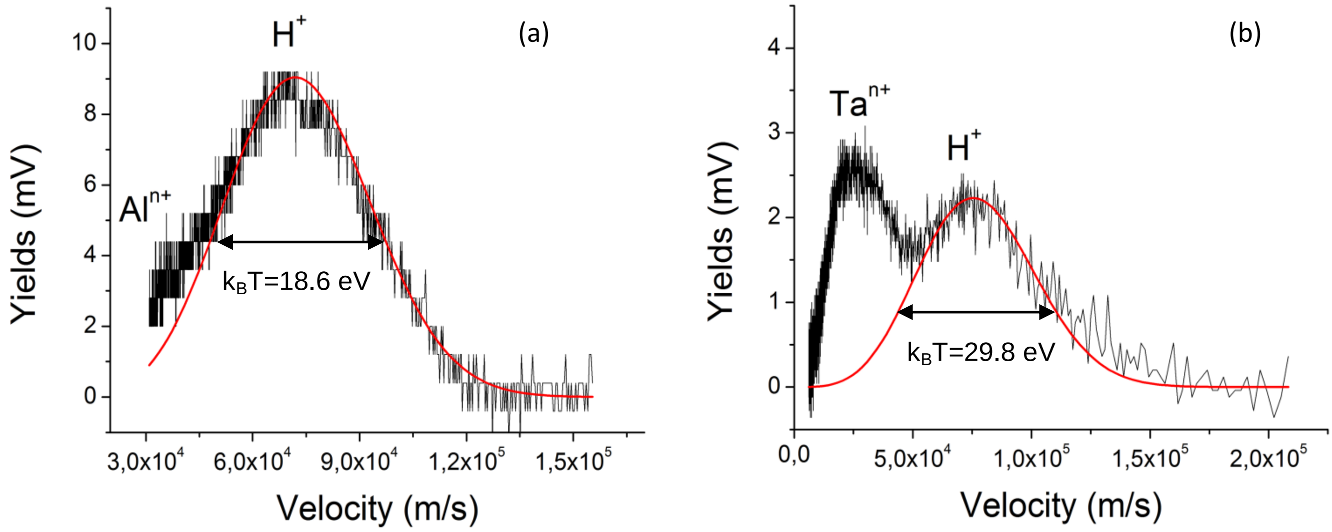


Fig. 3 Fit deconvolution of the peaks of protons in aluminum (a) and tantalum (b).

corresponding to an energy of 66 eV.
Moreover, in the spectra, there are other broad structures that start at about 25 μs. They are related to the Al and Ta ions detection.
This information permits to calculate the maximum ion energy of 272 eV and 1.82 keV, for Al and Ta ions, respectively. An interesting information that can be obtained is the measurement of the most probable equivalent temperature of the plasma. Assuming the particles to have a Maxwellian velocity distribution, the spectra were deconvolved in order to separate the contribution of different kind of particles.
In particular for electrons we used a simply Maxwell function. Instead in the case of proton it is necessary to use a more complex function i.e. a Coulomb-Boltzmann-shifted function (CBS) [5]:

$$F(v) = \left(\frac{m}{2\pi\, k_B T}\right)^{\frac{3}{2}} v^3 exp\left[-\frac{m}{2k_B T}(v - v_k - v_c)^2\right]$$

By using this function and taking in account the thermal and Coulombian interactions, the deconvolution of the different ion species and charge state contributions has been performed.
Through the fit deconvolution of our spectra (see Fig. 3 a and b) we extracted a temperature value of about 18.6 eV for Al and 29.8 eV for Ta plasmas.

Discussion and Conclusions

In this work it is shown how to get information about laser-generated plasma analyzing TOF spectra obtained by SiC detectors.
According to the literature [6] we expected a greater acceleration energy for particles emitted from the interaction between laser and Ta target compared to those emitted from Al target.
The results obtained for the protons seem to confirm these predictions. In fact under the same experimental conditions we measured a mean energy of 43 eV for protons emitted from Al target, which increases up to 66 eV for those emitted from Ta target.
These results are in agreement with literature reporting a high temperature for high electron density plasmas, here obtainable using Ta target instead that Al.
Nowdays the research in this field is very important because SiC devices could radically change the fields of research, industrial and medical imaging in the near future. For example at the Institute of Optoelectronics-MIT of Warsaw such devices can improve the control the soft X-ray microscope system [7].

In this regard is ongoing testing of new devices with new geometries obtained by means of nickel silicide interdigit contacts. This geometry has the advantage to leave the SiC active region directly exposed to radiation without any absorber with good results for soft UV detection and low energy particles [8]. On this subject measurements are still in progress.

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