Structure of semiconductor detectors for characterization of ionizing radiation sources

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Abstract

Detectors based on Silicon and Silicon Carbide are employed to monitor and characterize different sources of ionizing radiations, such as laser-generated plasmas, UV and radioactive sources. Surface and depth active depletion zones are employed to detect low and high energetic particles and soft and hard X-ray emission, depending on the detection efficiency of each device. The different gap, geometry and leakage currents characterize the response of the detectors. SiC detectors with metalized and interdigited contacts, traditional silicon surface barrier detectors and diamond detectors can be employed in time-of-flight configuration and in spectroscopic mode depending on the fluence value of the ionizing radiation. Particle and photon energy distribution, plasma temperature, radioactive source activities, ion fluxes, dose-rates and other parameters can be monitored on-line, as 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, high visible background and high doses encourage the study and development of devices with wide band gap.

Between these, the most promising is 4H-SiC that has been long identified as a radiation hard and physically rugged material with superior electronic properties which are appropriate for nuclear radiation detection purpose and plasma monitoring [1-4].

Due to the high energy gap (3.26 eV) with respect to Silicon (1.12 eV), 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 thanks to its very low leakage current in the order of pA. Moreover 4H-SiC has a higher value of breakdown electric field (3 MV/cm) and thermal conductivity (4 W/cm°C) with respect to Silicon (0.25 MV/cm and 1.5 W/cm°C, respectively), giving the possibility to employ SiC as high power and high voltage devices. Another important aspect is the Silicon-Carbon energy bonding, which is stronger than Silicon-Silicon ones, consequently the displacement energy in SiC (25 eV) is higher respect to silicon

(16.5 eV). For this reason SiC devices have a greater resistance to damage during the radiation detection. In addition SiC operates at high temperatures (up to 1240 C°) and it has a high response velocity and a fast collection time thanks to high electrons (900 cm^2/V s) and holes (107 cm^2/V s) mobility.

However the mean energy necessary to produce an electron-holes pair is lower in Silicon (3.63 eV) with respect to 4H-SiC (7.78 eV) so by sending the same radiation to the two devices, in the silicon detector a greater number of electron-holes pairs will be produced with respect to SiC ones.

As it will be discussed Silicon Carbide detectors can be employed in many applications only by changing the readout electronics.

Materials and methods

In this investigation it was employed a single-crystal 4H-SiC Schottky diode detector. The detector was built at CNR-IMM of Catania through the collaboration with ST-Microelectronics [5].

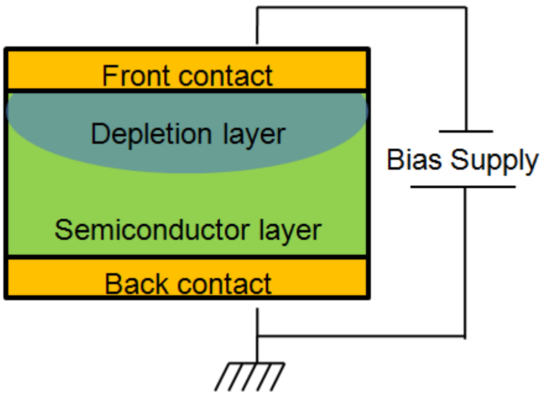

Figure.1 General representation of a SiC detector.

In Fig.1 there is a schematic representation of a typical SiC detector. It consists in a semiconductor layer interposed between two electrodes: a first metallization layer (front contact) of 200 nm of Nickel Silicide (ρ=7.21 g/cm^3), which produces a Schottky barrier and a back Ohmic contact. The active region (depletion layer) in this diode grows approximately with 10 μm/100 V and it was controlled up to 80 μm depth.

The readout electronic was changed according to the characteristics of the radiations that have to be analyzed.

At low fluence condition it is possible to use a typical electronic chain for alpha particles spectroscopy, as reported in Fig. 2a. In this scheme we have proportionality between the output signal from the detector and energy released by radiation in the active layer. The electronic chain consists in an ORTEC Preamplifier (142 A Model), an ORTEC Amplifier (672 Model) and a compact digital Multi Channel Analyzer (Amptek MCA-8000D) interfaced with a laptop PC through DppMCA Digital Acquisition Software. No pileup effects were observed for ion fluxes of the order of 10 pA current.

In high fluence regime, such as during the detection of plasmas emitting radiations, when produced by sub-nanosecond laser pulses, or detecting ion current above 100 nA, produced by accelerators, a different technique must be employed. Generally, when a start signal is available, a time of flight technique (TOF) can be employed. In this configuration the start signal is sent as trigger by the laser together with the pulse that generates plasma. The stop signal identifies the time of arrival of a particle in the detector and it is recorded by a fast storage oscilloscope as reported in the scheme of Fig. 2b. The detector–oscilloscope coupling is performed with a suitable capacitance and the oscilloscope has large bandwidth and high GS/s sampling in order to have very fast response, under 1 ns (Tektronik TDS5104B, with 5 Gs/s and 1 GHz). Thanks to this configuration it is possible to process until 10^{15} particles/cm^2 for each laser pulse, and more.

Finally SiC device can be also employed as dosimeter, reading the reverse current that flow in the device while it is exposed to radiation, through a Keythley pico-amperometer (mod. 6485) inserted in the bias electrical circuit, as reported in the scheme of Fig. 2c.

c)

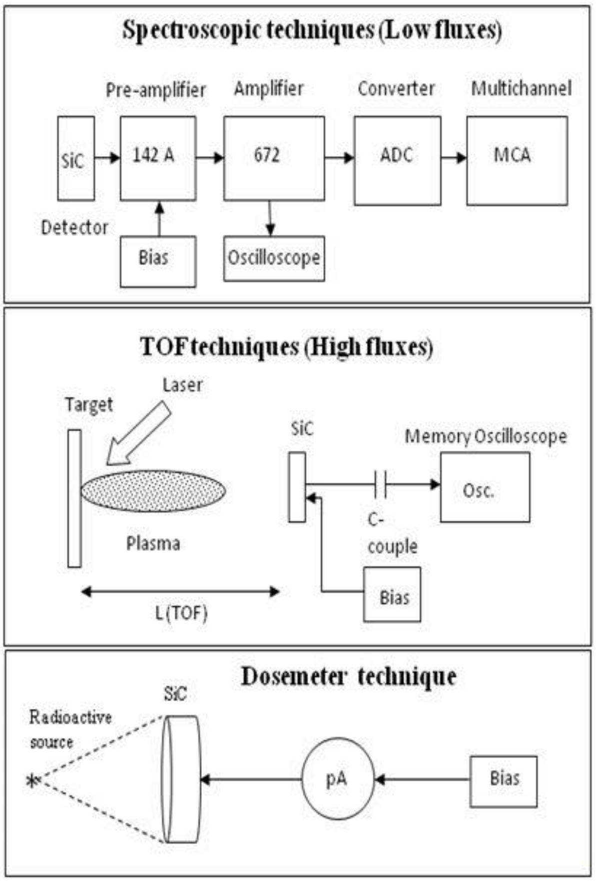

Figure.2 Scheme of the different experimental setup.

The experiments on plasma diagnostic were performed in the PALS Facility in Prague. An Iodine laser operating in single pulse at 1315 nm wavelength, 300 ps pulse duration, 600 J laser energy and $2{\cdot}10^{16}$ W cm^{-2} pulse intensity was employed [6]. The target used for laser irradiations was a thin layer of Polyethylene (10 µm in thickness). The incidence angle was 0° and the SiC detector was placed at 0° in the forward direction at a flight distance from the target of 72cm.

Results

1) Radioactive source monitoring

Using the electronic chain reported in Fig. 2a was obtained the alpha source spectrum shown in Fig. 3, with 8000 sec of time acquisition. The alpha source used in this case is a radioactive compound of 239-Pu emitting mainly at 5.1 MeV, 241-Am emitting at 5.4 MeV and 244-Cm emitting at 5.8 MeV. According to the activities of the three elements it was obtained a relative ratio of 1/0.75/0.25 from the alpha yields with respect to the Pu peak, as expected.

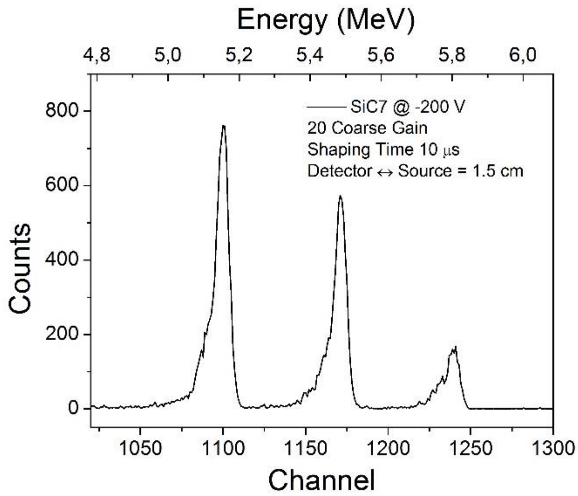

Figure.3 Typical alpha spectrum.

Thanks to the pulser generator connected to the preamplifier it was possible to calibrate in energy the energy-channel scales through the following equation:

$$E[keV] = 39.51 + 4.65\ \frac{keV}{channel} \cdot channel \qquad (1)$$

From the spectrum reported in Fig. 3 it is possible to define a resolution of 0.8% for the Pu peak, 0.74% for the Am peak and 0.71% for the Cm peak.

These results demonstrate that with SiC detectors it is possible to obtain energy resolution values very near to Silicon devices. In fact, as reported in literature [7], at the same alpha energies Silicon detectors have a resolution of about 0.2%.

The regime of proportionality used is valid up to a flux of about $2\text{x}10^6$ particles/s. For higher values a pile-up effect is produced.

2) Plasma monitoring

In Fig. 4 there is a typical TOF spectrum acquired at PALS facility. This spectrum, was obtained irradiating with the laser a thin foil of

PE. It presents an intense peak, called photopeaks, due to X–rays and relativistic electrons detection, followed by a little tail due to cold electrons and a wide complex structure due to ions detections from the faster protons to the massive and slower CxHy groups detected at time of flight higher than 150 ns.
More information can be extracted from this spectrum by taking into account $F(v)$ the Coulomb-Boltzmann shifted distribution [8]:

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

where A is a normalization constant, m is the mass of the considered particles, $k_B T$ corresponds to the equivalent temperature in eV and v represents the total ion velocity along the normal to the target surface. This model allows to take into account thermal, adiabatic and Columbian effects during ions flight because v is given by the sum of the following contributions:

- the thermal velocity

$$v_{th} = \sqrt{\frac{3\, k_B T}{m}} \quad (3)$$

- the adiabatic expansion velocity

$$v_k = \sqrt{\gamma \frac{k_B T}{m}} \quad (4)$$

- the Coulomb velocity

$$v_C = \sqrt{\frac{2ZeV_0}{m}} \quad (5)$$

where γ is the adiabatic coefficient (1.67 for monoatomic species), Ze is the ion charge and V_0 is the equivalent voltage.
Eq. (2) is valid from low intensities, of about 10^9 W/cm^2 up to high intensity of the order of 10^{16} W cm^{-2}. It permits to separate protons from Carbon ions, to distinguish the six different charge state of Carbon and to evaluate the ion acceleration produced by the plasma. The graph reported in Fig. 4 is one of the possible solutions of the fitting procedure on the experimental data. From this fitting process can be evaluated some important values of plasma such as the equivalent ion temperature that in this case is about 150 keV and the acceleration energy of 4.2 MeV for charge state. These results are in good agreement with data reported in literature [9].

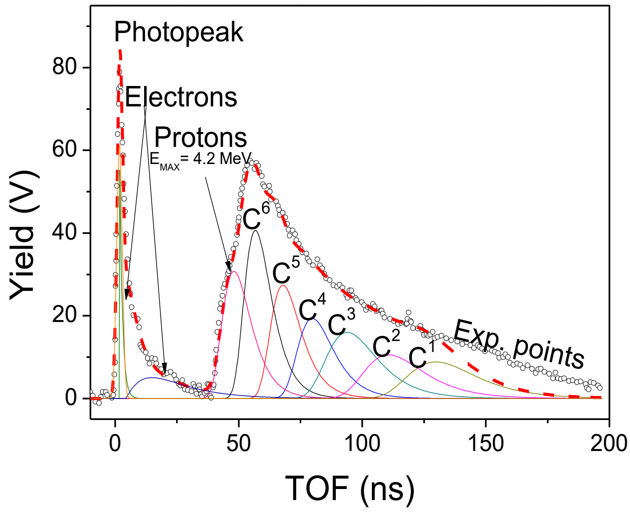

Figure.4 Typical TOF spectrum.

3) *Dosemeter applications*

The use of SiC detector has been tested also for dosimeter applications by measuring the reverse current of the diode as a function of the absorbed energetic photons dose rate for soft X-rays.

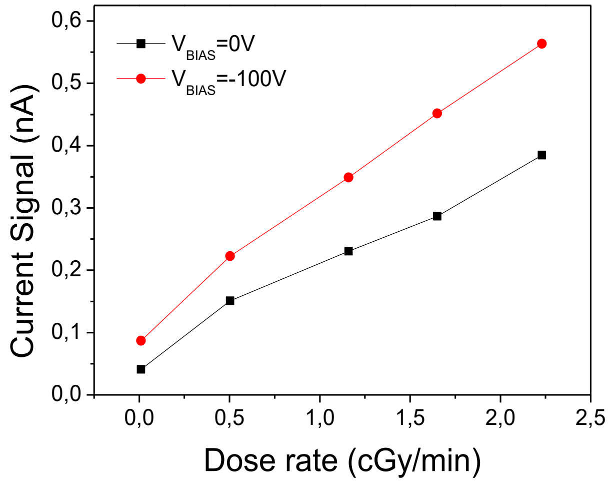

Figure.5 Reverse current of the diode as a function of dose rate for soft X-rays.

Fig. 5 shows two sets of preliminary measurements obtained using a SiC detector placed near to a calibrated FAG dosimeter in air. The SiC was covered with 10 µm polyethylene to be in the electronic equilibrium during the detection. Both detectors were irradiated, separately, with a 20 kV X-ray tube. The SiC was monitored through the reverse current with the Keythley picoamperometer, which was correlated to the dose rates measured with the FAG dosimeter. The two set of measurements show that the reverse current ranges from the leakage value of about 10 pA, maintained at low dose rates, to a maximum value of about 0.5 nA obtained at high dose rates. The increment is linear with the dose rate using both 0 V and -100 V as detector bias voltage, in agreement with literature [9].

Discussion and Conclusions

In this work it is reported the usage of SiC detectors in different applications concerning detection of radiations at low and at high fluence, such as the radiations emitted from low activities radioactive sources and the monitoring of radiations emitted by laser-generated plasma, respectively.

Two different methods of measurements are used in the two cases, one of proportionality of the detector signal with the energy deposited in the active region from the radiation and the other based on TOF approach. Moreover the possibility to use SiC as dosimeter in regime of proportionality was also presented with preliminary results.

The research on SiC is very important, as testified by the wide literature about this material. SiC devices could radically change the fields of research, industrial and medical imaging in the near future. Recently very interesting results have been carried out with different diodes having new geometries of top contacts and thickness of active region [10]. For example new diodes with interdigit contact [11], with a direct active area exposed to radiation, are now under investigation to realize, together with a thick detector, a "telescope" detector [12] for charged particle identification.

References

[1] L. Torrisi *et al.*, Single crystal silicon carbide detector of emitted ions and soft X-rays from power laser-generated plasmas, journal of applied physics **105**, 123305 (2009)

[2] D. Puglisi, SiC Nuclear Detector, Ph.D. thesis, University of Catania, 2009

[3] M. De Napoli, G. Raciti, E. Rapisarda, C. Sfienti, Light ions responsse of silicon carbide detectors, Nucl. Instrum. Meth. A **572** (2007) 831-838

[4] F. Nava *et* al., Investigation of Ni/4H-SiC diodes as radiation detectors with low doped n-type 4H-SiC epilayers, Nuclear Instruments and Methods in Physics Research A **510** (2003) 273–280

[5] M. Cutroneo, L. Torrisi, F. La Via, *et al.*, High performance SiC detectors for MeV ion beams generated by intense pulsed laser plasmas, J. Mater. Res., Vol. **28**, No. 1, 2013

[6] Actual PALS web sites: http://www.pals.cas.cz

[7] A. Cannavò, L. Torrisi and L. Calcagno, SiC detector characterization for radiation emitted by laser-generated plasmas, JINST (2016) **11** C05008

[8] L. Torrisi, Coulomb Boltzmann Shifted function (CBS) in laser generated plasmas from 10^{10} up to 10^{19} W cm^{-2} intensities, REDS, **171**; 1-2, 34-44

[9] L. Torrisi and A. Cannavò, SiC detectors to monitor ionizing radiations emitted from nuclear events and plasmas, REDS, in press

[10] A. Cannavò, L. Torrisi, A. Sciuto, Characterization of new gneration of SiC detectors, PhD Activity Reports 2016 University of Messina, ISSN 2038-5889

[11] A. Sciuto *et al.*, Highly Efficient Low Reverse Biased 4H-SiC Schottky Photodiodes for UV-Light Detection, IEEE Photon. Technol. Lett., vol. **21**, no. 23, (2009)

[12] L. Torrisi and A. Cannavò, Silicon Carbide for realization of "Telescope" Ion Detectors, IEEE Transation on Electron Device, vol. **63,** no. 11, 2016.