Silicon Carbide devices for radiation detection and measurements

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Abstract. In the last decades Silicon Carbide (SiC) received special attentions, in particular as semiconductor material, because is considered as alternative to Silicon for the future high-power, low consumption, radiation-hard microelectronics devices. This ambitious goal is particularly interesting also for the physics of the detectors. In this work are discussed some of the recent results obtained by SiCILIA collaboration, a joint research activity between INFN and IMM institutions to increase the level of technological development in the field of SiC detectors.

1. Introduction

Compared with the most commonly used Silicon, wide-bandgap semiconductors such as Silicon Carbide allow the operation of radiation detectors at room temperature, with high performance. In the last decades, SiC has received increasing interest in the field of radiation detectors due to the achievement of a high purity level in the crystal structure and considerable thickness (up to 150 μm) in the epitaxial layer. There are certain properties that make SiC suitable for the manufacture of ionizing radiation detectors; thanks to the wide energy bandgap (for the polytype 4H-SiC is 3.26 eV), which is three times higher than that of Si, electronic devices fabricated in such material can operate at extremely high temperatures. The wide bandgap allows the achievement of very low leakage currents and then a very low noise levels, even at the high electric fields applied during their operation mode. The high thermal conductivity of 4H-SiC enables SiC devices to dissipate large amounts of excess generated heat, which would cause a temperature increase, responsible for degradation of the device's performance. High thermal conductivity is useful for increasing the radiation hardness of the detector. Furthermore, SiC can withstand an internal electric field over eight to ten times greater than the common used wide-bandgap semiconductors without undergoing avalanche breakdown. This property enables the fabrication of very high-voltage devices.

2. Recent developments on SiC detectors technologies

In view of the potential application of SiC as a radiation hard material for detector implementation, and thanks to the request for several new and ambitious projects by the Italian National Institute of Nuclear Physics (INFN) in fundamental [1-3] and applied physics [4-10] (NUMEN [11-12], NuReLP [13], ELIMED [14], FAZIA [15], etc.), in 2016 a joint agreement started between INFN and IMM-CNR for a common R&D activity regarding silicon carbide technology (SiCILIA) [16].

All the cited projects require radiation hard detectors with excellent performance in terms of stability, energy resolution, timing, and insensitivity to the visible light. Some of them require also a relatively large detection area (greater than 1 cm^2) and thicknesses in the range 50 - 500 μm, without dead layers in order to guarantee the implementation of more complex detection systems, such as (ΔE-E) telescope detectors. Apart from the specific research activities on the material development, one of the goals of the activity was also the possibility to push the technology beyond state of art going from making Schottky devices to p-n junctions.

The main strategy of the R&D was to use the epitaxially grown material as the active layer for prototype construction. Today the quality of 4H/6H SiC epitaxy is very high, considering the achievements of the last decades in the growth layer. Normally the epitaxial growth was performed in a horizontal hot-wall reactor; Trichlorosilane, ethylene and Hydrogen were often used as Silicon and Carbon precursors and gas carrier, respectively. Nitrogen was used for n-type doping and Trimethylaluminum for p-type doping.

The materials were characterized with different techniques and instrumentation: the inspection with Candela CS920 by KLA-Tencor [17] scan was used to evaluate the presence of the surface defects (droplet, carrots, triangles, micropit, etc.) characterizing the epitaxial layers. Micro-photoluminescence and time-resolved photoluminescence at room temperature were performed to analyze the crystal quality. Candela analysis was performed for the 10 μm thick epitaxy, in order to have a reference point for the next thicker epitaxies. The defect density was obtained and the main defects was triangles, followed by bar stacking faults. The total density of defects is around 3/cm^2, and these defects have been observed essentially on the edge of the wafers. With such values, a maximum yield of 65–70% can be achieved for the manufacture of 1x1 cm^2 devices. Simultaneously 4H–SiC epitaxial films, 100 μm thick was grown at two different growth rate, 90 μm/h and 60 μm/h. The obtained defects density is lower in the sample grown at 60 μm/h, indicating that a fast deposition induces a formation of triangles, bumps, and epi-defects.

After these initial steps, thanks to the collaboration with the ST-Microelectronics (STM) prototype manufacture was started in STM clean rooms in order to investigate the processes production of detection devices with 10/100 μm epi-layers. For devices manufacture the first step is the grow of an epitaxy double layer necessary for the p^+/n junction implementation. A p^+ layer 0.3–0.5 μm thick with a doping concentration of the order of 10^{18}–10^{19}/cm^3 was grown over the n^- epi-layer with a doping concentration in the range of 5–8 × 10^{13}/cm^3 (10/100 μm epi-layer). After this step, a photolithography

(PL) was performed for the definition of the detector surface by a plasma etching and a second PL was implemented for the edge structures. The edge structures are fundamental for the reduction of the electric field at the device borders; several solutions were investigated, from a simple large floating ring (obtained by ion implantation) to the metal field plate or floating rings manufactured with the p^+ epitaxial layer. At the end the flow is closed with a deposition of an isolation oxide and the opening of the contacts with a further photolithographic process. Then, the front metallization (Ni) was deposited, defined with a further photolithographic process and subsequently annealed to form a good ohmic contact on the p^+ region. Only on the periphery of the detector, a thicker layer of Ti and Al was deposited for the bonding.

3. Overview on the main experimental test performed on SiC prototypes

Several tests were conducted in order to study the devices performance, by using both standard radioactive sources and ions and electrons beams, but also for neutrons detection.

Prototypes were tested by using a radioactive alpha (^{239}Pu, ^{241}Am, ^{244}Cm) source and a standard spectroscopic electronic chain consisting of: *i)* charge preamplifier from the ASCOM company [18]; *ii)* spectroscopy amplifier by ORTEC corporation (mod. 572, settled with 2 µs of shaping time). Signals was collected by an ORTEC multi-channel analyzer to perform the particles energy spectra. SiC are very stable and linear devices, they exhibit an energy resolution, for alphas coming from ^{241}Am, of the order of 42.8 ± 1.1 keV FWHM [16].

Some tests were conducted, at the Laboratori Nazionali del Sud (LNS) of Catania, with heavy ion beams ^{40}Ca and ^{48}Ca at 40 A·MeV, used to produce nuclear collisions on a thin ^{12}C target. A telescope configuration was arranged by using a 100 μm thick ΔE SiC detector and a 500 μm thick standard silicon detector [19]. Good element identification, at least up to Z =20 and isotopic identification up to Z =14 was obtained.

Moreover, our prototypes were tested also as neutrons detector. The neutrons detection is based on the collection of the e–h pairs produced by neutron interaction with ^{12}C and ^{28}Si. The response function of SiC detector, together with their neutron resistance and stability, has been investigated [20] at the ENEA-Frascati Neutron Generator facility by irradiating the detectors with 14.1 MeV neutrons. The absence of instabilities during neutron irradiation up to a 14 MeV neutron fluence of $4.45*10^{11}$ n/cm^2 suggests a straightforward use of this detector as a fast neutron diagnostic. The Pulse Height spectrum obtained from the SiC detector revealed a very complex response function due to the presence of both ^{12}C and ^{28}Si. This complexity limits the sensitivity of the SiC when used as a neutron spectrometer for Deuterium–Tritium plasma diagnostics, though it could be well suited to measure the temperature in thermal plasmas. Furthermore, it could be successfully used as a neutron diagnostic tool in those environments in which small size is a requirement, such as in a neutron camera. In addition, the possibility of growing Silicon Carbide layers with different thicknesses allows for tuning the neutron detection efficiency, and, therefore, using SiC crystals as charged particle detectors in those environments where high neutron fluxes are an issue.

Prototypes were also irradiated by a protons and electrons beam in order to test their resistance to the radiation damage. Irradiation with protons was performed at the CATANA (Center for Hadrontherapy and Advanced Nuclear Applications) proton therapy facility by using a 60 MeV H+ beam delivered by the superconducting cyclotron of LNS. The devices were placed in front of the beam in order to deliver a total dose of about 10^{13} H$^+$/cm^2 [21]. From the main electrical characteristics (current-voltage, capacitance-voltage) measured before and after irradiation, no appreciable changes were observed. Also, the energy resolution measured before and after the irradiation by using a radioactive alpha source don't reveal any significative change. In figure 1a is plotted the measurement of the charge collection efficiency as a function of the bias voltage for alpha particles exposure obtained before and after the proton beam irradiation; also in this context no significative changes were observed.

The devices were also irradiated by 5 MeV electrons beam delivered by the LINAC accelerator of Messina University, a research facility devoted to radiation processing studies [22]. Devices was exposed directly to the beam, after the spot adjustments in order to guaranties a uniform distribution of incident electrons. Figure 1b shows the evolution of charge collection efficiency (obtained by alpha source exposure) as a function of the beam fluence. A slight decrease in efficiency (of about 10%) was observed starting from 10^{14} e/cm^2.

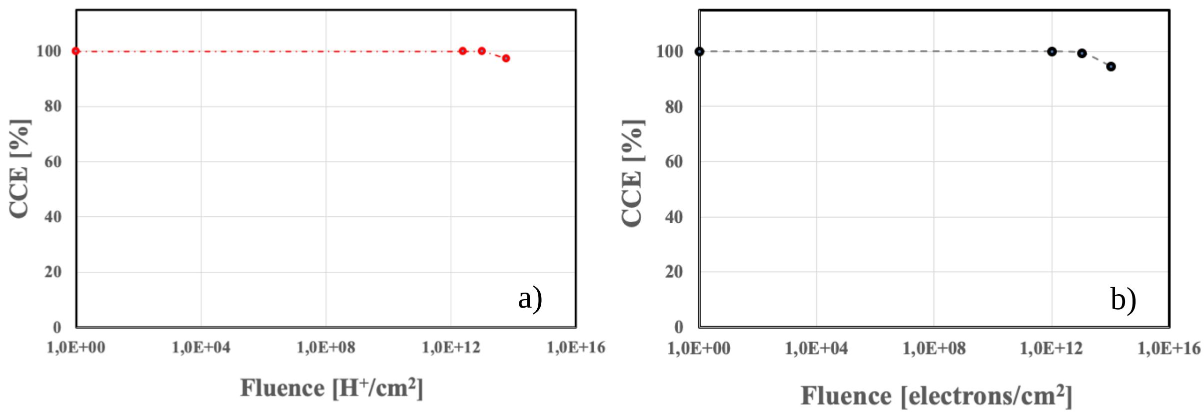

Figure 1. Evolution of charge collection efficiency as a function of beam fluence for p-n junctions devices, 10 μm thick, irradiated by protons (a) and electrons (b).

4. Conclusion

In this work Silicon carbide appears to be a very promising material for the construction of radiation detectors. New devices, with large detection area, thickness up to 150 μm, developed in a new p-n junction technology by a SiCILIA collaboration, were described.

The carried-out measurements on SiC prototypes, by using different particles, have allowed to demonstrate that such detectors are suitable as semiconductor ionizing radiation detectors. It exhibits excellent performance in terms stability, linearity and energy resolution and also when mounted in a telescope configuration they show an optimal elemental identification. Moreover, the prototypes were used as neutrons detectors, obtaining encouraging results for fast neutron diagnostics and in environments with high neutrons fluxes. An excellent resistance to the radiation damages have been also observed by testing our prototypes with ions, electrons and neutrons beams.

References

[1] Mascali D et al 2010 *Radiation Effects and Defects in Solids* **165** (6-10) 730-6
[2] La Cognata M, Del Zoppo A, Figuera P et al 2008 *Physics Letters* B **664** (3) 157-161
[3] Tudisco S et al 2020 *EPJ Web Conf.*. **227** 01017
[4] Cristoforetti G, Anzalone A, Baffigi F et al 2014 *Plasma Physics and Controlled Fusion* **56** (9) 095001
[5] Lanzanò L et al 2007 *European Biophysics Journal with Biophysics Letters* **36** (7) 823-9
[6] Costanzo E et al 2008 *European Biophysics Journal with Biophysics Letters* **37** (2) 235-8
[7] Gambino N et al 2013 *Applied Surface Science* **272** 69-75
[8] Finocchiaro P et al 2007 *Journal of Modern Optics* **54** (2-3) 199-212
[9] Mazzillo M et al 2007 *Sensors and Actuators* A - Physical **138** (2) 306-12
[10] Mascali D et al 2012 *Europhysics Letters EPL* **100** (4) 45003
[11] Cappuzzello F et al 2018 *European Physical Journal* A **54** (5) 72
[12] Cappuzzello F et al 2015 *J.Phys.: Conf. Ser.* **630** 012018
[13] Negoita F et al 2016 *Roman. Rep. Phys.* **68** S37–S144
[14] Schillaci F et al 2014 *J. Phys.:Conf. Ser.* **508** 012010

[15] Bougault R et al 2014 *Eur. Phys. J.* A **50** 47
[16] Tudisco S et al 2018 *Sensors* **18** (7) 2289
[17] Available online: http://www.lpe-epi.com/pe106.aspx?sm=sm21 (accessed on 12 July 2018)
[18] Bojano C et al 2004 *IEEE Trans. Nucl. Sci.* **51** 1931–5
[19] Ciampi C et al 2019 *NIM* A **925** 60-9
[20] Rebai M et al 2019 *NIM* A **946** 162637
[21] Tudisco S et al 2019 *Nuovo Cimento* C - Colloquia and Communications in Physics **42 (**2-3) 74
[22] Visco A et al 2009 *Journal of Biomedical Materials Research* - Part B Applied Biomaterials **89**(1) 55-64 doi:10.1002/jbm.b.31187 (2009)