Characterisation of epitaxial SiC charge particle detectors by the Ion Beam Induced Charge Collection (IBICC) technique.

E.Vittone[1], C.Manfredotti[1], A. Lo Giudice[1], C. Paolini[1], P.Olivero[1], F.Nava[2], M.Jaksic[3]

1 Experimental Physics Dept. University of Torino, INFM Unit. Torino, 2 Physics Department. University of Modena, 3 Laboratory for Ion Beam Interactions of the Ruder Boskovic Institute in Zagreb (HR)

I. INTRODUCTION

Silicon carbide has recently emerged as an attractive material for ionization radiation detection [1]. The high band gap and high radiation damage resistance allows the fabrication of detectors capable to operate at high temperature and in high radiation fields. The development of SiC radiation detectors imposes severe constraints in the electronic quality and in homogeneity of the material. A unique method [2] to asses the uniformity of the detector response is IBICC (Ion Beam Induced Charge Collection), which consists in measuring the charge induced at the electrodes by the movement of the charge carriers generated by high energy ions which are suitably focused in the frontal electrode and deflected in order to raster the electrode surface.

This work presents an investigation of the charge-collection properties of a 4H-SiC Schottky diode performed by means of IBICC. Pulse height spectra relevant to different proton energies were obtained using a fixed reverse bias (-40 V) which corresponds to a depletion layer width of about 4.5 ?m. These results were interpreted assuming a complete charge collection generated by ionization in the depletion region (DR) and the injection into DR by diffusion of minority carriers generated in the neutral region. From the analysis of the IBICC spectra obtained at different proton energies from 0.7 to 1.7 MeV, we obtained a value of hole diffusion length Lp = 8.4 ?m.

IBICC maps were obtained by recording the mean pulse height as a function of the ion impact co-ordinates at different ion energies. The uniformity of the charge collection maps decreases as the ion energy increases, i.e. as the ion energy loss occurs deeper in the neutral region. This fact reflects the presence of defects throughout the whole volume studied.

II. EXPERIMENTAL METHOD

The Schottky diode was fabricated on 4H-SiC epitaxial wafers purchased from CREE Research (Fig.1).

The active layer thickness was 30 ?m and the nominal net doping concentration of the active layer was (Nd-Na)=2.2×10^{15} cm^{-3}. The Schottky contact was circular with a diameter of 2 mm and was formed on the silicon surface of the epitaxial layer by deposition of 100 nm of gold. Details on the geometry and on detector fabrication can be found in [1] .

Capacitance-voltage (C-V) measurements provided a doping concentration (Nd-Na=$2.2\cdot10^{15}$ cm^{-3}) which is in perfect agreement with the nominal one and a magnitude of the Schottky barrier height of about 1.6 eV. Reverse bias voltages of up to 40 Volts were used with leakage current less than 10 pA.

The IBICC investigation was performed at the microbeam facility of the Laboratory for Ion Beam Interactions of the Ruder Boskovic Institute in Zagreb (HR) . The microprobe line is attached to a High Voltage 6 MV EN tandem accelerator and is equipped with an OXFORD quadrupole doublet. Scanning coils positioned in front of the focussing lenses are used to scan the ion beam over the sample. A series of IBIC measurements were performed using protons of energy 0.7 – 1.7 in steps of 0.2 MeV and Li^7 ions of 2 MeV energy. The spot size of the microbeam was smaller than 2 ?m. The beam current was kept below 0.1 fA (i.e. below 600 ions/s) in order to reduce the radiation damage.

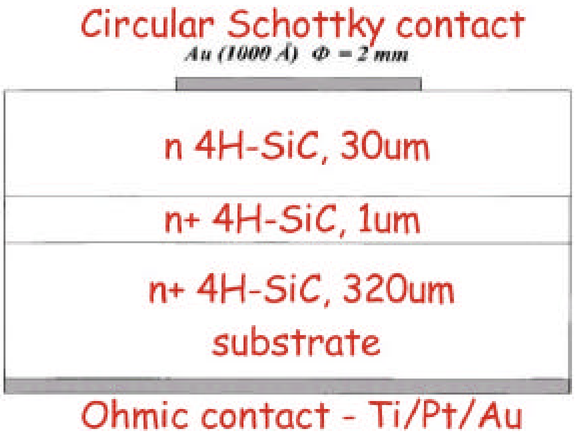

Fig.1 SiC Schottky diode geometry.

The charge induced by a single ion incident on the Schottky diode and collected at the frontal electrode was measured by a standard charge sensitive electronic chain. Finally, a nuclear microprobe data acquisition system records simultaneously the co-ordinates of the incident ion and the pulse height and stores each event in three column files (x,y,pulse height) which are suitable to produce collection efficiency maps [3].

III. RESULTS

Fig.2 shows the stopping power of the ion probes used in this investigation as evaluated by the SRIM2000 code assuming a SiC density of 3.2 g/cm^2. Proton ranges extended from 6 to 24 ?m, whereas for Li ions the range is about 3.1 ?m.

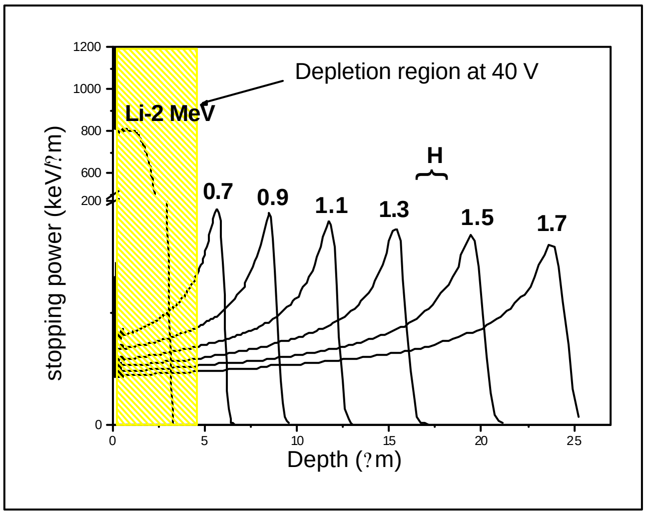

Fig.2 Stopping power in SiC

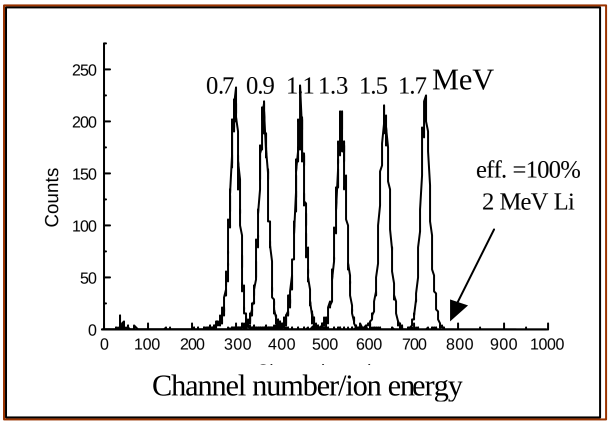

Fig.3 Pulse height spectra for SiC Schottky diode detector with –40 V reverse bias relevant to proton energies ranging from 0.7 to 1.7 MeV.

The Li^7 ion range is smaller than the depletion region generated by the reverse bias voltage at -40 V (4.5 ?m) as evaluated by CV measurements. Therefore, in this case all the carriers are generated within the depletion region where, by virtue of the high electric field, complete charge collection occurs.

Using a fixed reverse bias of –40 V, different spectra were obtained using different proton energies ranging from 0.7 to 1.7 MeV. The relevant pulse height spectra are shown in Fig.3.

Fig.4. shows the behavior of the charge collection efficiency vs. the proton energies, evaluated by assuming a total collection efficiency of charge produced by 2 MeV Li (channel 770 in Fig.3).

It can be observed that efficiency is gradually decreasing with energy. Reduction of energy and therefore ion range, results in more and more energy deposited in depletion layer where fast charge drift occurs. In such circumstances it is obvious that energy resolution (defined as the FWHM of the spectra divided by the relevant peak centroid) is decreasing with ion energy (Fig.5).

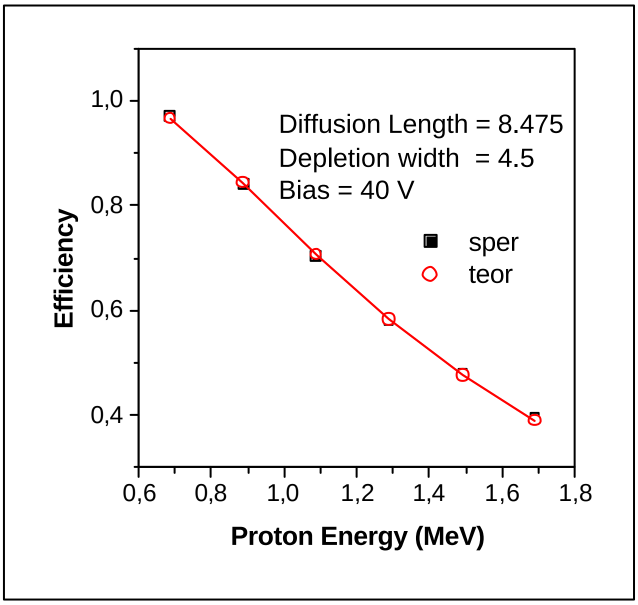

Fig.4 Theoretical and experimental mean charge collection efficiency for different proton energies.

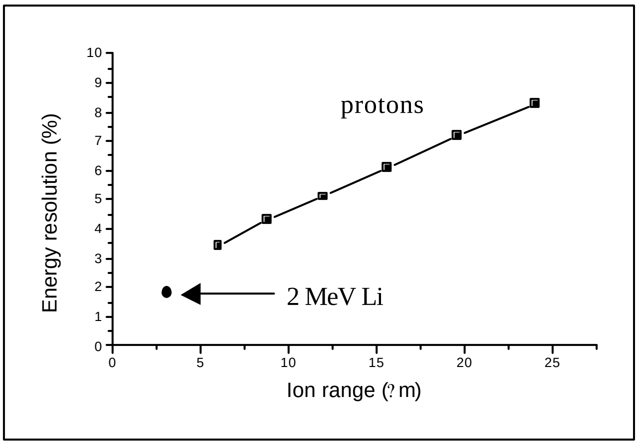

Fig.5 dependence of energy resolution on ion range (b) 0.7–1.7 MeV pulse height spectra for SiC Schottky diode detector with –40 V reverse bias.

From this series of measurements, both depletion layer thickness and diffusion length for holes have been evaluated [4].

The algorithm assumes total charge collection in the depletion layer and an exponential decay in the neutral region. The charge collection efficiency ? ?can be evaluated by means of the following expression:

$$\eta = \int_0^z dx \frac{dE}{dx} + \int_z^d dx \left(\frac{dE}{dx}\right) \exp\left(-\frac{x-z}{L_p}\right)$$

where dE/dx is the ion stopping power, z is the depletion layer width and L_p is the minority carrier diffusion length.

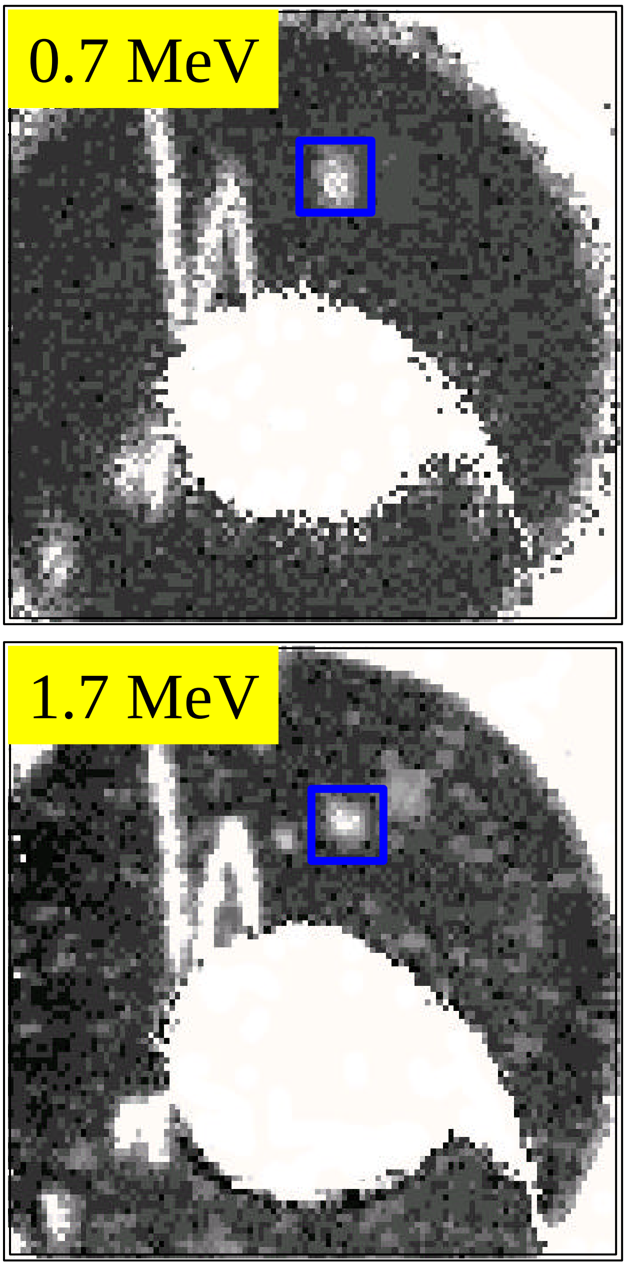

Fig.6 IBIC images of SiC Schottky diode detector, as obtained with three different ion ranges: protons of 0.7 MeV (up) and protons of 1.7 MeV (down).

By fitting the experimental mean collection efficiency measured at different proton energy (Fig.4) considering the stopping powers evaluated by the SRIM2000 program (Fig.2), the two free parameters z and L_p are evaluated. The value of the depletion layer width (z=4.5 ?m) is in good agreement with the measurement carried out by means of the C-V technique [1]. The minority (hole) carrier diffusion length (Lp = (8.4 ± 0.2) ?m) corresponds to a lifetime of about 240 ns, assuming a hole mobility of 120 $cm^2 \cdot V^{-1} \cdot s^{-1}$.

IBIC images obtained at 0.7 and 1.9 MeV proton energies are shown in Fig.6. The big circular white region is due to the silver paint used for bonding. Contact scratches are visible as white segments (low efficiency). The square indicates a region damaged by irradiation of 2 MeV Li ions. The dose was about 500 ions/?m^2. Since the damage mainly occurs at the end of the Li range (3.1 ?m), the damage region is more evident in the map obtained by 0.7 MeV protons (about 5 ?m ion range) than in the map obtained using 1.7 MeV protons (about 24 ?m ion range).

More pronounced inhomogeneities are visible in IBIC images with higher proton energies where most of the ion energy loss occurs deeper in the diffusion region. Brighter spots visible at 1.7 MeV image indicate that the homogeneity of the material decreases as a function of depth from the top (Schottky) surface.

IV. CONCLUSION

In the development of radiation detectors based on silicon carbide, we showed that nuclear microprobe technique IBIC is important tool in quantitative (depletion layer thickness and diffusion length) and qualitative (spatial distribution of defects in material and contact imperfections) characterization of prototype detectors. From these measurements, contributions of various parameters that influence the overall efficiency and energy resolution of final device can be estimated as well as an estimate of the homogeneity of the sample which influences the spectral resolution of the detector.

V. ACKNOWLEDGEMENTS

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