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New particle identification system for MAGNEX: The ΔE SiC stage

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Summary. — In the view of the NUMEN experiments with high beam intensity, the MAGNEX magnetic spectrometer focal plane detector will be equipped with a new particle identification system based on telescopes. The new energy-loss stage of it consists on large area silicon carbide detectors. The devices and first characterisation tests are presented.

1. – Introduction

The MAGNEX large acceptance magnetic spectrometer [1] and the superconducting cyclotron installed at INFN-Laboratori Nazionali del Sud (INFN-LNS) are the fundamental instruments to perform the experimental activity of the NUMEN (NUclear Matrix Elements for Neutrinoless double beta decay) project [2-4], aiming at the measurement of absolute cross sections of heavy ion induced double charge exchange (DCE) reactions as a tool to access quantitative information relevant for $0\nu\beta\beta$ decay nuclear matrix elements (NMEs) [5-7]. These processes are characterized by very low cross sections (few nb) and high resolution measurement are required to isolate the transitions of interest. Thus, an upgrade of the LNS cyclotron is under way to deliver beam intensities from two to three orders of magnitude higher than the present ones. Consequently, an upgraded MAGNEX set-up is also necessary and under development [8].

In particular, new detectors based on state-of-the-art technologies are under construction: i) a gamma array detector, denominated G-NUMEN [9,10], consisting in more than 100 $LaBr_3$(Ce) crystal scintillator detectors; a new 3D gas tracker for the MAGNEX focal plane detector (FPD) that will provide a high resolution measurement of the phase space parameters at the focal plane ($X_{foc}, Y_{foc}, \theta_{foc}, \phi_{foc}$) being also very fast since it should be able to bear a rate of the order of 40 kHz/cm [11], iii) a new particle identification (PID) system based on Silicon Carbide (SiC) - Cesium Iodide(Tallium doped) CsI(Tl) telescopes as the stop detector of the FPD. Also radiation tolerant targets with a dedicated cooling system will be used [12].

2. – Silicon Carbide detectors

Large area SiC detectors will be used in the NUMEN project as the ΔE stage of the new PID system of MAGNEX. The most stringent requirement for the devices that will compose the new MAGNEX PID wall is the radiation hardness. SiC, due to its wide gap (3.23 eV) and strength of its chemical bonds, is nowadays a valid candidate to produce radiation hard detectors [13]. The SiC detectors have recently received special attentions also thanks to technological improvements within the SiCILIA project [14]. In the case of small SiC detectors (2×2 mm^2, 30 μm thick) irradiated with heavy ions stopping in, it was proved that the detectors could accept fluencies as large as 10^{14} heavy ions/cm^2, thus matching with main requirements of NUMEN in terms of radiation hardness.

Timing resolution of hundreds of ps has been measured for SiC pixel detector [14]. Indeed, SiC detectors can profit from the high saturation velocities of the charge carriers (2×10^7 cm/s) in the semiconductor —two times higher than in silicon— and to the possibility to effectively operate the devices at or close to the carrier velocity saturation condition. This is because the breakdown field in SiC is 3 MV/cm, ten times higher than in Si or GaAs. Electric field as high as 10^5 V/cm has been reached without suffering junction breakdown or significantly increasing the reverse current.

The detector is based on deposition of epitaxial layers. In the past few years, steep improvements in the density of defects of the substrates and of the epitaxial layers have been achieved, with a consequent large reduction of micropipes and stacking faults. It is now possible to build detectors characterized by lower leakage current and a better signal-to-noise ratio. Nowadays, an advanced task consists in decreasing the doping concentration to values smaller than 8x10^{13} atm/cm^3 to reduce the full depletion voltage to few hundreds of volts. This is a crucial requirement for the MAGNEX PID system since it will work in low pressure gas environment. This condition inevitably reduces the maximum tolerable bias voltage to few hundreds of volts. The thickness of SiC must be chosen to allow the detection of the ejectiles in the wide dynamical range of incident energies foreseen in the NUMEN experiments, *i.e.*, 10 to 35 AMeV for the (^{20}Ne,^{20}O) DCE reactions and 10 to 60 AMeV for the (^{18}O,^{18}Ne) DCE reactions. An appropriate thickness for the ΔE stage is about 100 μm, which correspond to an energy loss ΔE about 25 MeV for ^{20}O at 40 AMeV and ΔE about 180 MeV for ^{18}Ne at 10 AMeV. In this framework, thickness and charge collection uniformity within each detector is necessary to guarantee high energy and time resolution performances of the PID. Moreover, homogeneity among different detectors in terms of depletion voltage, thickness, resolution, etc. is needed since 720 SiC will be used to cover the large MAGNEX detection area (154×1260 mm^2).

State-of-the-art SiC detectors 100 μm thick, 10 μm dead layer on the back side, 15.4 $\times$ 15.4 mm^2 area including 200 μm edge structure have been already produced.Accurate characterizations of these new devices must be performed to establish to what extent the mentioned requirements are fulfilled and then guide further R&D activities.

3. – SiC characterizations

The first prototypal devices were delivered to INFN-LNS in the last few months. Preliminary characterizations were performed in terms of inverse current, barrier capacitance, and energy resolution. Irradiation tests were also done with α-sources. Some results are discussed in the following sections.

3˙1. *C-V measurements.* – Measurement of the barrier capacitance is an important step in the characterization of p-n junction semiconductor devices. The C-V correlation between the measured capacitance (C) and the reverse bias (V) applied to the device gives the possibility to extract (in a non-destructive way) the concentration of dopant impurities in the p-n junction. This information is of paramount importance for both the characterization of the device and for the optimization of manufacturing processes. The C-V measurement provides information on the SiC full depletion voltage (FDV). The capacitance of the device is expected to be smaller and smaller increasing the applied reverse bias up to the FDV, where a constant value is expected to be joined. For a full depleted SiC detector with thickness d = 100 μm and the area A = 15.4 × 15.4 mm^2:

$$C = \epsilon_0 \epsilon_r A/d \approx 200pF \tag{1}$$

being $\epsilon_r = 9.7$ (ref. [3]) and $\epsilon_0 = 8.854\times10^{(-12)}$ F/m the vacuum permittivity.

Preliminary C-V measurements were done on SiC detectors coming from two different wafers. The resulting FDV values is about ≈ 350 V for the SiC detectors from one wafer and ≈ 850 V for the others. These corresponds to a different doping concentration of ≈ 5x10^{13} atm/cm^3 and ≈ 8x10^{13} atm/cm^3, respectively.

3˙2. *Energy resolution and charge collection efficiency.* – Energy resolution measurements was performed using a ^{228}Th α-decay source, characterized by a wide energy spectrum of the emitted alphas (E_α = 4 to 9 MeV) penetrating and probing the SiC device at different depths. Furthermore, the ^{228}Th source can be used to irradiate the device from the back side being the most energetic emitted alphas able to cross the ≈ 10 μm dead layer and release a measurable residual energy in the SiC active region. This approach can be used to perform an energy-loss based measurement of the real thickness of the dead layer.

An uncollimated 80 Bq ^{228}Th source was placed 2-3 cm above the front side of the SiC detector, inside a vacuum chamber (≈ 10^{-6} mbar). The SiC device was placed in a drilled PCB (see inset in fig. 1) through a conductive tape providing the electronic ground to the back side. The signal was collected from the front side that is wire bonded and placed at negative potential (-100 to -1000 V). A 40 mV/MeV charge sensitive preamplifier [15], placed inside the vacuum chamber, was used to read-out the signal and to apply the bias. The signal was shaped and amplified by the ORTEC 572 Amplifier and acquired by the ORTEC EASY-MCA ADC. An example of ^{228}Th α-decay spectrum is shown in fig. 1. The energy resolution is of ≈ 0.8%. More accurate measurements, in which both the source and the SiC device are collimated, will be performed using a more intense ^{228}Th source that will be soon available at INFN-LNS.

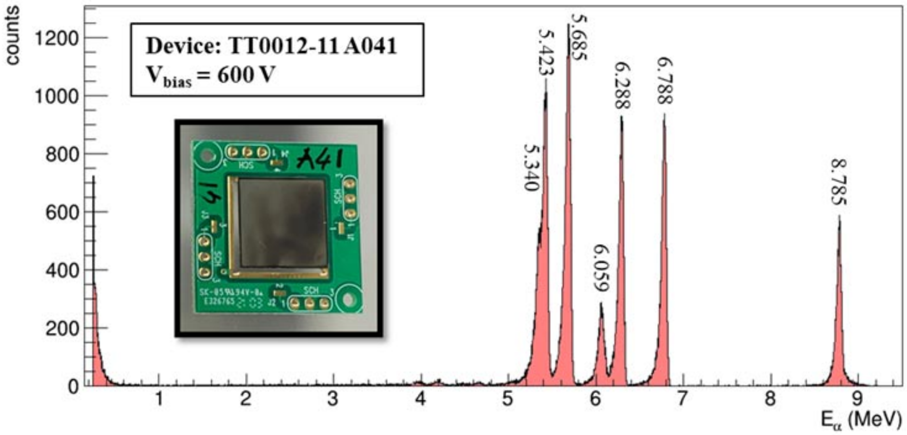

Fig. 1. – Calibrated α-decay spectrum for the ^{228}Th source. Peak labels indicate the energy in MeV. Inset: picture of a SiC detector mounted on a drilled PCB (see text).

4. – Conclusions

First characterizations of state-of-the-art SiC detectors were performed in order to verify their performances in terms of the NUMEN project requirements. Further investigations regard how the charge collection efficiency behaves in the full active volume and near the edges of the detectors. This can be studied using 3D microscopic characterization techniques as the Ion beam-induced charge (IBIC) that utilizes focused MeV range accelerated ions to probe charge transport [16]. Using the same IBIC beams or the above mentioned collimated alpha sources at different incident angles, it will be possible to measure the dead layer thickness on the back of the epitaxial layer or study possible channeling effects.

REFERENCES

[1] Cappuzzello F. *et al.*, *Eur. Phys. J. A*, **52** (2016) 167.
[2] Cappuzzello F. *et al.*, *Int. J. Mod. Phys. A*, **36** (2021) 2130018.
[3] Cappuzzello F. *et al.*, *Eur. Phys. J. A*, **54** (2018) 72.
[4] Agodi C. *et al.*, *Universe*, **7** (2021) 72.
[5] Cappuzzello F. *et al.*, *Prog. Part. Nucl. Phys.*, **128** (2023) 103999.
[6] Calabrese S. *et al.*, *Acta Phys. Pol.*, **49** (2018) 275.
[7] Soukeras V. *et al.*, *Res. Phys.*, **28** (2021) 104691.
[8] Cappuzzello F. *et al.*, *Front. Astron. Space Sci.*, **8** (2021) 668587.
[9] Finocchiaro P. *et al.*, *Universe*, **6** (2020) 129.
[10] Oliveira J. R. B. *et al.*, *Eur. Phys. J. A*, **56** (2020) 153.
[11] Ciraldo I. *et al.*, *Nucl. Instrum. Methods A*, **1048** (2023) 167893.
[12] Iazzi F. *et al.*, *WIT Trans. Eng. Sci.*, **116** (2017) 61.
[13] Muoio A. *et al.*, *EPJ Web of Conferences*, **117** (2016) 10006.
[14] Tudisco S. *et al.*, *Sensors*, **18** (2018) 2289.
[15] Boiano C. *et al.*, *IEEE Trans. Nucl. Sci.*, **51** (2004) 1931.
[16] Jakšić M. *et al.*, *Front. Phys.*, **10** (2022) 877577.