4H-SiC RADIATION HARD PHOTODETECTOR FOR UV PHOTONS AND SOFT X-RAYS

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1. Introduction

SiC is a wide bandgap (up to 3.26 eV) semiconductor, which became object of an intensive study during last decade, thanks to its unique physical properties including high saturation velocities of the charge carriers, high breakdown field, high thermal conductivity and device stability to operate at elevated temperature [1]. Its absorption length is almost identical to Si [2]. The main photonic applications of mostly used 4H-SiC polytype with the highest bandgap energy (3.26 eV) present the detection of UltraViolet (UV: 100-400 nm and Extreme UV: 10-121 nm [3]) parts of the spectrum. Such detectors are attractive for applications in astronomy, military, photolithography and biomedicine. Their high radiation resistance to damage by neutrons and gamma rays was also recently demonstrated [4]. Important attractive feature of the detectors presents, beside high quantum efficiency, their blindness in the visible (vis) and near infrared (nir) spectral ranges. Hence no usage of a special expensive filter, required by e.g. Si detectors, or bulky, short lifetime photomultipliers, is necessary. More recently, 4H-SiC has been considered also for applications in the field of radiation detection in harsh environments particularly in hot plasmas in nuclear fusion reactors. Such detectors could operate at room (RT) or elevated temperatures with superior spectrometric characteristics in low energy X-ray detection, particularly in the region of 1-10 keV [5]. There, the required energy resolution of the spectrometric channel should be better than 500 eV in FWHM (full width at half maximum) and the noise threshold should be below 1 keV. In spite of the drawback related to the high energy for electron-hole pair production (~7.8 eV) the 4H-SiC is presently widely investigated for its potentially high operation stability in harsh environments. Moreover it must be pointed out that the Schottky diodes on 4H-SiC have RT reverse currents 2–4 orders of magnitude lower than those of junctions on Si, GaAs and CdTe, implying that they are detectors with the lowest noise even at RT [6]. This characteristic compensates for lower signal related to higher electron-hole pair generation energy. Recently, the excellent spectrometric performances of epitaxial 4H-SiC radiation detectors were demonstrated [7-9] showing energy resolution under 350 eV FWHM at elevated temperature (100 $^{\circ}$C) with small pixel or microstrip coupled to an ultra low noise preamplifier. One of the best value at RT, 195 eV FWHM, was achieved by Bertuccio et al. [8] using epitaxial 4H-SiC with free electron concentration of ~3.7×10^{13} cm^{-3} and pixel dimensions 0.16 mm^2 (at bias of 200 V).

The present work is devoted to: (i) X-ray characterization of high purity n-type 4H-SiC layers grown by liquid phase epitaxy (LPE) by the L.P.E. spa, Catania, (ii) preparation technology of the Schottky barrier Ni/4H-SiC, and (iii) characterization of fabricated detectors by current-voltage (*I-V*), and demonstration of photoresponse in UV region together with the ^{241}Am pulse height spectra measurements. Preliminary test of the 4H-SiC detector resistance to a mixed neutron and gamma ray flux is also reported.

2. 4H-SiC material and detector fabrication

4H-SiC detector structures were prepared from a 100 μm thick nitrogen-doped layer grown by LPE on a 3” 4H-SiC highly doped n^{++} substrate (350 μm thick), by the insertion of a 0.5 μm thick n^{+} buffer layer with concentration of 1×10^{18} cm^{-3}. The epitaxial 4H-SiC polytype with hexagonal layer structure was analysed by high resolution X-ray diffraction. The lattice parameters for this structure are c = 10 Å and a = 3.0730 Å. The sample surface was 8° off the 0001 basal plane. The 0004 diffraction from the basal plane corresponding to a Bragg angle of 17.83° was obtained by a high resolution X-ray diffractometer using a Bartel Ge220 monochromator, with an instrumental resolution of approximately 12 arcseconds. The 0004 rocking curve of the measurement is shown in Fig. 1a. The peak has an FWHM of 18 arcseconds, just slightly more than the 12 arcseconds instrumental resolution, corresponding to a very good crystal quality. The very narrow and sharp 0004 peak, with no broadening or diffuse scattering indicates that the crystal quality of epilayer and SiC substrate are equivalent. These results are confirmed by X-ray double crystal topography in reflection mode using a laboratory Cu anode X-ray generator, a Ge 620 as a monochromator with the 11-28 reflection for the SiC substrate. The reflection planes were chosen in order to have a Bragg angle of the 11-28 plane close to the Ge620 Bragg angle (θ_B = 59.44) and to achieve a high sensitivity to local strain and lattice inclination. In the topograph of Fig. 1b the dislocation outcrops are seen as dark spots in the image. We evaluate the dislocation density of the order of 2×10^{3} cm^{-2} as one of the best reported in literature for bulk 4H-SiC [10-12]. Dislocation lines inclined with respect to the surface are also visible as segments due to the large penetration CuKα X-rays in SiC.

The detectors were obtained by evaporation of a double layer of Au-Ni on 4H-SiC with thicknesses of 5-10 nm on the top and 40-60 nm on the bottom sides of the wafer fragment, respectively, with a high vacuum electron gun apparatus. The Schottky barrier contacts, circular 0.64 mm^2 (100 nm) and square 2×2 mm^2 (15 nm) were formed on the epitaxial layer through a contact metal mask while a full area contact was evaporated on the substrate backside. The simplest topology with no guard ring was used. Just before the evaporation the sample was cleaned in boiled acetone and isopropyl alcohol, washed in deionized water and dried by nitrogen flow.

3. Current-voltage characteristics

I-V characteristics of the prepared structures were measured using Keithley 237 source controlled by personal computer. Measurements were performed at RT in the dark using

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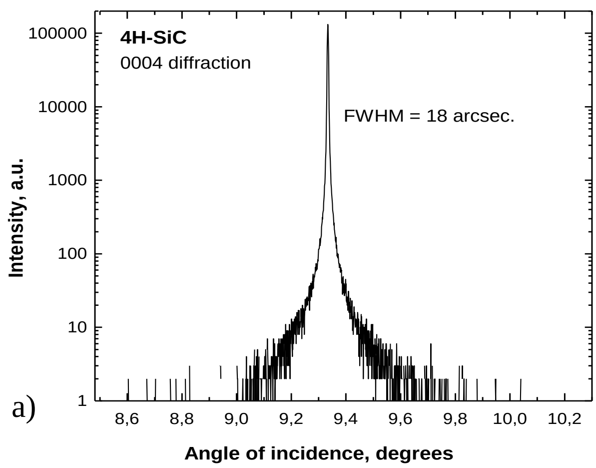


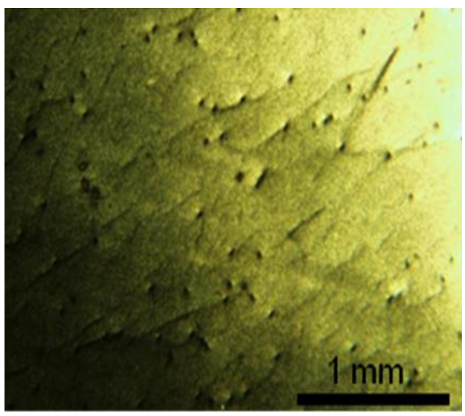
b)


Fig. 1: *High resolution X-ray characterization of the 4H-SiC epitaxial layer: diffraction (a) and topography (b). The optimum crystal order is confirmed by the FWHM of the diffraction peak. Dislocation density is under 2x10^3 cm^{-2}.*

an electrically shielded probe station with temperature stabilisation and tip contact on the topside. The „reverse“ (negative bias voltage) branches correspond to the negative bias polarity applied to the blocking Schottky barriers on the top (small defined circular, square or thin, full area semitransparent contact). *I-V* characteristics of the fabricated a large area 4H-SiC detector (2×2 mm^2) measured in the dark and under illumination using deuterium lamp (power density ~3 μW/cm^2 at 250 nm) in both bias polarities are shown in Fig. 2a. As can be seen, the reverse current under illumination increases by about three orders of magnitude, while sensitivity in the forward direction is very low. The reverse dark current density exceeds by about one order of magnitude the lowest reported values probably because of avoiding surface passivation and annealing of the blocking contact after evaporation.

4. Photocurrent spectra

Photocurrent spectra measurements were performed in dc regime at RT in the dark using an electrically and optically shielded probe station using tip contact on the topside (defined circular or full area semitransparent contact). Spectra in the 200-400 nm UV and vis-nir (600-1000 nm) ranges were taken using a deuterium and halogen lamps, respectively, an SPM1 monochromator with radiation focused on the sample and a calibrated detector.

The UV spectra taken by the fabricated 4H-SiC detector at different reverse bias voltages are depicted in Fig. 2b. The obtained spectra indicates a high sensitivity in the photon energy region between 3.7 and 6.0 eV with a sharp decrease of the sensitivity under about 3.5 eV due to the absorption edge of SiC. From the linear part of the absorption edge the optical bandgap energy was estimated to be ~3.3 eV. As it can be seen the detector is almost “blind” in the visible region under 3 eV. The spectral response reaches a value of ~0.08 A/W at 4.5 eV. The value increases under reverse bias by about 50 % while the responsivity peak shifts toward lower energies, at about 4.2 eV (295 nm) at -5 V. Such a spectral response reaching about 0.12 A/W exceeds the best reported values [13].

5. ^{241}Am pulse-height spectra and radiation hardness

The spectrometric performances of 4H-SiC radiation detector with the contact diameter 0.8 mm was investigated by pulse-height spectra measurements of the ^{241}Am radionuclide. A preamplifier, based on CREMAT CR 102B with the *RC* feedback (*R* = 1 GΩ, *C* = 0.5 pF) across the input JFET 2SK152 giving a noise of 120 e^- rms corresponding to 2.2 keV in FWHM (4H-SiC, zero capacitance) was used in the measurements with the detector dc-coupled to the preamplifier input. The observed spectra measured at reverse bias

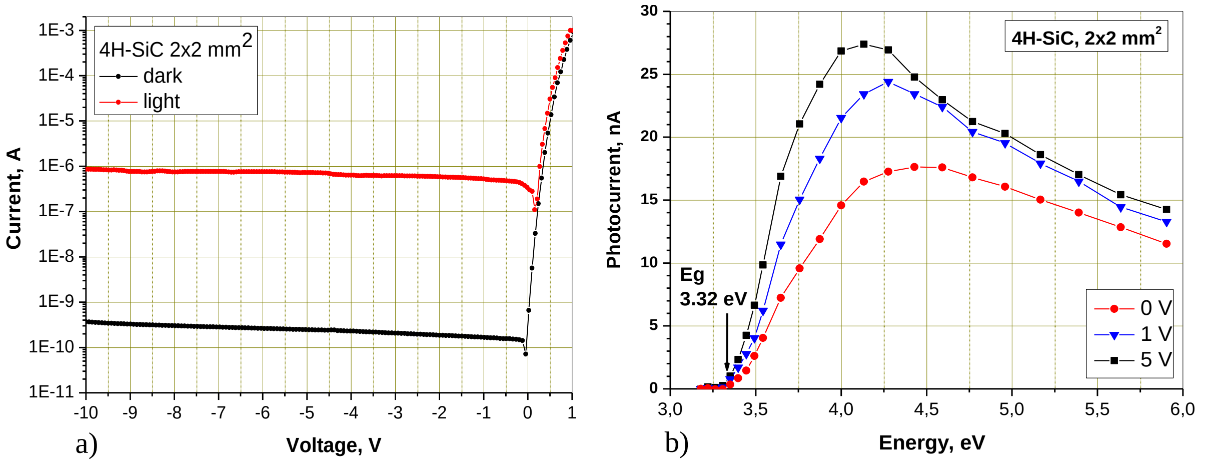


Fig. 2: *Dark and light I-V characteristics (a) and photocurrent spectra (b) in UV region (3-6 eV) measured by the fabricated 4H-SiC detector.*

of 100 V and shaping time of 1 μs, before and after irradiation with neutrons and gamma rays are shown in Fig. 3. With reference to the not-irradiated sample (full symbols in Fig. 3), the FWHM of the 59.5 keV photopeak has been estimated to be about 3.2 keV. The Np X-ray lines at 13.9, 17.8 and 20.8 keV are also detected, while the noise threshold, determined by the used preamplifier, is about 6.0 keV. However a particular attention must be devoted to the application of the 4H-SiC detectors in low noise spectrometry; indeed, due to the wide band gap of SiC, the energy for the production of electron-hole pair is 7.8 eV, more than twice than that of Si. Nevertheless, SiC detectors exhibit an extremely low noise, much lower than Si or GaAs-based detectors at room and higher temperatures, so that the full exploitation of their capabilities requires ultra low noise preamplifiers. For example Bertuccio et al. [14], using a preamplifier with a very low noise, measured an energy resolution of a 4H-SiC detector of the order of 100 eV, still limited by the electronics and not by the detector.

For a preliminary evaluation of the detector hardness to fast neutrons a set of detectors was exposed to combined neutron and gamma radiation induced by $^{18}O(p, n)^{18}F$ nuclear reaction. The integral number of neutrons impacting on the area unit was estimated to be ~$(3\pm1)\times10^{12}$ cm^{-2}. The gamma radiation component consists mostly of prompt gammas and bremsstrahlung with a spectrum intensity continuously decreasing towards energy up to approximately 10 MeV [15]. The absorbed dose was measured by the combination of alanine and thermoluminescent dosimeters (TLD700), showing that gamma contribution is only one seventh of the total absorbed dose. In Fig. 3 the spectroscopic performances of the irradiated detector (crosses) are compared to the non-irradiated one. As it can be seen the influence of the induced damage in the energy region below 30 keV is almost negligible; on the contrary it is well visible for the 59.5 keV photopeak which shows i) a broadening toward the low energy side coupled with a decreasing of peak-to-valley ratio and ii) a FWHM increase from 3.2 to 4.5 keV, evaluated after the subtraction of the background present on the left side of the photopeak. Further studies on the resistance of 4H-SiC detectors to the damage induced by neutrons and gamma rays are in progress. However, from a preliminary comparison of the characteristics of simultaneously neutron irradiated 4H-SiC and Si pin detectors, at doses for which the pin diodes completely lost their spectrometric ability [16], a substantially higher neutron radiation hardness of SiC detectors has been observed. It must be pointed out that in order to reach the available spectrometry of the 4H-SiC detector (<0.5 keV FWHM) the noise and the detectable energy threshold of the used preamplifier should be considerably reduced.

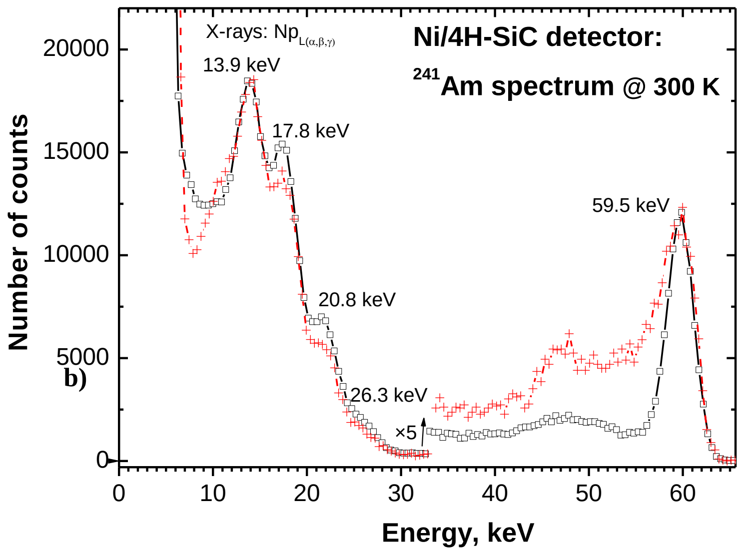


Fig. 3: ^{241}Am pulse height spectra before (empty squares) and after (crosses) neutron bombardment and gamma ray irradiation revealed by the fabricated Ni/4H-SiC detector (contact diameter 0.8 mm) at RT.

6. Conclusions

Schottky barrier large area (up to 4 mm^2) photon detectors were fabricated on high purity epitaxial layers of n-type (nitrogen doped) 4H-SiC grown by LPE on SiC substrates using Au-Ni metallization and characterized by using X-ray diffraction, *I-V*, photoresponse and ^{241}Am pulse height spectra measurements. The obtained results indicate a high purity and an excellent crystallographic quality of the grown epitaxial layer. Low free carrier concentration ~1×10^{14} cm^{-3} and dislocation density lower than 2×10^{3} cm^{-2} were observed in the epilayer. The fabricated 4H-SiC detectors exhibited at RT a current density one order of magnitude lower than Si detectors, excellent rectifier characteristics, high sensitivity in UV region with a maximum at 4.3 eV with blindness in vis-nir region and a promising X-ray spectrometry limited by the noise of the employed spectrometric preamplifier. A preliminary test indicated a much higher resistance of 4H-SiC detector to the damage induced by high energy neutrons and gamma rays in comparison with Si pin diodes.

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