Nuclear Instruments and Methods in Physics Research A 652 (2011) 193–196

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

# Advances in silicon carbide X-ray detectors

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ARTICLE INFO

Available online 31 August 2010

*Keywords:*
Silicon Carbide
Semiconductor radiation detectors
X-ray detectors
X-ray spectroscopy
Low noise electronics

ABSTRACT

The latest advances in SiC X-ray detectors are presented: a pixel detector coupled to a custom ultra low noise CMOS preamplifier has been characterized at room and high temperature. An equivalent noise energy (ENE) of 113 eV FWHM, corresponding to 6.1 electrons r.m.s., has been achieved with the detector/front-end system operating at +30 °C. A Fano factor of $F=0.10$ has been estimated from the $^{55}$Fe spectrum. When the system is heated up to +100 °C, the measured ENE is 163 eV FWHM (8.9 electrons r.m.s.). It is determined that both at room and at high temperature the performance are fully limited by the noise of the front-end electronics. It is also presented the capability of SiC detectors to operate in environments under unstable temperature conditions without any apparatus for temperature stabilization; it has been proved that a SiC detector can acquire high resolution X-ray spectra without spectral line degradation while the system temperature changes between +30 and +75 °C.



## 1. Introduction

Silicon Carbide is a semiconductor having attractive properties for radiation detection and spectroscopy: its wide bandgap (from 2.2 to 3.2 eV for different polytypes [1]) implies low leakage currents of junctions at room and high temperature; the high critical breakdown field (2 MV/cm vs. 0.3 MV/cm for Si) allows operation at high internal electric fields, minimizing the carrier transit time and the trapping probability; the high carrier saturation velocity (200 μm/ns vs. 100 μm/ns for Si) implies fast signals [2], the high displacement energy of atoms is beneficial to the radiation hardness, as experimentally demonstrated [3,4].

SiC devices can be realized using the standard microelectronics planar technology applied to bulk or epitaxial SiC wafers, which are commercially available up to 100 mm diameter [5,6]. Detector-grade high purity SiC epitaxial layers with thickness up to 150 μm have been recently obtained [7]. Both semi-insulating bulk SiC and epitaxial layers have been used to manufacture radiation detectors but currently only the latter have that high purity and low defectivity necessary for high performance detectors [8,9].

In the last ten years, a significant progress has been made in manufacturing SiC detectors for alpha [10], beta [11], ions [2], neutrons [12], gamma [13] and X-rays [14,15]. In particular, X-ray detectors are the most challenging devices because of low charge signal amplitudes involved. Specifically, SiC has a linear absorption coefficient very similar to that of silicon [1]; in case adequate detection efficiency is required, SiC detectors can be used in the energy range of soft X-ray ( $<20$ keV), which implies charge signals of less than 2600 electron–hole pairs.

In this paper the latest advances in SiC detectors for high resolution X-ray spectroscopy are presented and analyzed. In Section 2 the ultra low noise characteristics of SiC detectors are discussed on the basis of experimental data. Results of soft X-ray spectroscopy are shown in Section 3 and critically analyzed in section 4, in which an updated estimation of the Fano factor is given. In Section 5 the result obtained with the detector/front-end working under unstable temperature condition is presented and analyzed.

## 2. SiC detector characteristics and intrinsic noise

### 2.1. Leakage current noise densities

Semiconductor detectors for soft X-rays, other than SiC, are generally cooled at temperatures between −196 and -30 °C in order to reduce the leakage current and so its noise contribution, that is significant at room temperature. On the contrary, SiC detectors do not require any cooling because of their extremely low currents even at high temperatures. Fig. 1 shows the current density of a SiC pixel detector (size: 200 μm × 200 μm) measured as function of the temperature from +27 up to +107 °C. The measurements have been done at two bias voltages, corresponding to mean internal electric fields of 53 and 103 kV/cm, which are extremely high for a semiconductor detector. It can be observed that at room

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doi:10.1016/j.nima.2010.08.046

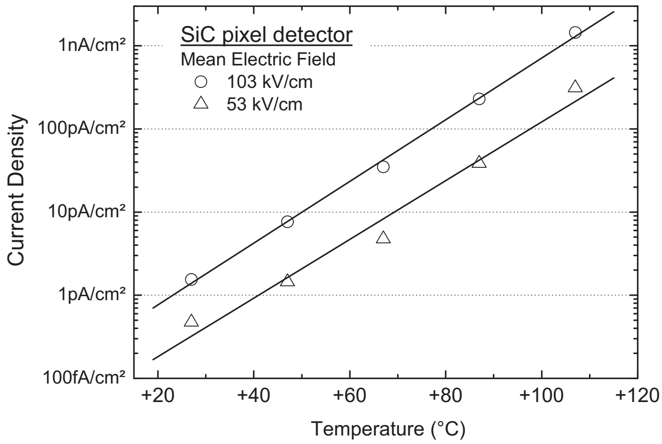


**Fig. 1.** Measured current density of a SiC pixel detector (200 μm × 200 μm) as a function of temperature. The measurement was done at two bias voltages, corresponding to mean electric fields of 53 and 103 kV/cm. At room temperature the typical current density is of the order of 1 pA/cm$^2$.

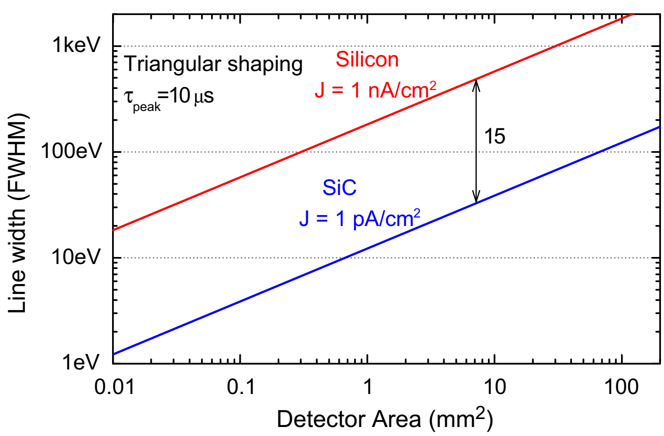


**Fig. 2.** Contribution of the leakage current noise to the pulser line width as function of the area of Silicon and SiC detectors. Typical current densities measured at room temperature have been assumed: 1 nA/cm$^2$ for Silicon and 1 pA/cm$^2$ for SiC. The calculation is made using a triangular pulse shaping with 10 μs peaking time.

temperature the current density is of the order of 1 pA/cm$^2$ while at +100 °C it is around 1 nA/cm$^2$, even at very high internal electric fields. These current densities are typical since we have measured these values on several SiC detectors employing Au or Ni Schottky barriers with junction areas up to 5 mm$^2$.

### 2.2. Electronic noise of SiC detectors

The calculated contributions of the detector noise to the spectral line widths as a function of the areas of Silicon and SiC detectors are shown in Fig. 2. Typical current densities at room temperature have been assumed: 1 nA/cm$^2$ for Silicon and 1 pA/cm$^2$ for SiC. Calculations are made supposing pure shot noise and a triangular pulse shaping with 10 μs peaking time. It can be observed that SiC detectors give line widths smaller by a factor of 15 with respect to silicon detectors, as can be easily calculated

$$\frac{ENE_{SiC}}{ENE_{Si}} = \frac{\varepsilon_{SiC}}{\varepsilon_{Si}}\sqrt{\frac{J_{SiC}}{J_{Si}}} \cong \frac{1}{15}$$

in which $\varepsilon$ indicates the electron–hole pair generation energy ($\varepsilon_{SiC}=7.8$ eV and $\varepsilon_{Si}=3.67$ eV), ENE$=\varepsilon\times$ENC is the equivalent noise energy (ENC the equivalent noise charge) and $J$ indicates the leakage current density. It can be observed that the ENE ratio is independent of type of the pulse shaping and shaping time and indicates that SiC detectors have signal to noise ratio higher than Silicon, despite $\varepsilon_{SiC}$ is almost twice $\varepsilon_{Si}$. For example, it can be derived (Fig. 2) that in order to have ENE < 100 eV, the area of a Si detector must be smaller than 0.3 mm$^2$, while the SiC area can be up to 70 mm$^2$. It can be also observed that SiC detectors with areas smaller than 2 mm$^2$ add a noise contribution lower than 18 eV FWHM, that is less than 1 electrons r.m.s..

The upper limit to the SiC detector area and the lower limit to the system noise are actually imposed by the noise contribution of the front-end electronics (FEE), which increases with the detector capacitance. So, low capacitance detectors, such as pixel or drift type, must be used to minimize the FEE noise.

In any case, nowadays there is no front-end transistor that can allow SiC detectors to reach their energy resolution limit. In particular, small area (< 2 mm$^2$) SiC detectors are almost electronic noiseless and can potentially give energy resolution limited only by the fluctuations of the generated electron–hole pairs (Fano limited detectors) even at room temperature and at very low photon energies.

## 3. Experimental apparatus and results

### 3.1. Detector and front-end electronics

In order to experimentally demonstrate the great potential of SiC detectors, a pixel was selected for its low capacitance in order to minimize the noise of the front-end electronics as much as possible. The detector is consisted of a circular Au-4H SiC Schottky junction of 200 μm diameter. The 4H-SiC is a 70 μm thick epitaxial layer with n-type doping of $5\times10^{14}$ cm$^{-3}$. The epitaxial layer has been grown by CREE Inc. on a 2 in. highly conductive n-type 4H-SiC wafer [6]. The ohmic contact has been realized on the back surface of the wafer. The detector has been manufactured at Selex Sistemi Integrati [16]. The pixel was connected to a custom CMOS integrated preamplifier by wire bonding [17]. When no detector was connected, the intrinsic equivalent noise charge of the preamplifier operating at room temperature and coupled to a triangular shaper [18] is 3 electrons r.m.s. at peaking time longer than 32 μs. The detector was biased at 300 V, which implies a depletion depth of about 25 μm in the epitaxial layer and a capacitance of the order of 0.1 pF.

### 3.2. X-ray spectroscopy

Fig. 3 shows a $^{55}$Fe spectrum acquired at $T=+30$ °C and 12.8 μs of peaking time. The 5.9 keV line has a width of 196 eV FWHM and the pulser line width is 113 eV FWHM corresponding to 6.1 electrons r.m.s. of electronic noise.

The detector/preamplifier system has also been characterized at high temperatures by placing it inside a thermostatic chamber, constantly monitoring the temperature with a thermocouple positioned close to the detector. Fig. 4 shows the spectrum acquired at $T=+100$ °C and 8 μs peaking time: the pulser line width is 163 eV FWHM (8.9 electrons r.m.s.) and the 5.9 keV line has a width of 233 eV FWHM.

Finally, Fig. 5 shows two $^{241}$Am X-ray spectra acquired at +30 and +100 °C and superposed for comparison. The pulser widths are 120 eV FWHM (6.5 electron r.m.s.) at +30 °C and 177 eV FWHM (9.6 electron r.m.s.) at +100 °C.

## 4. Analysis of the experimental results

### 4.1. Fano factor estimation

The X-ray spectra here presented have the highest energy resolution ever achieved with SiC detectors and allow a new