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SUB-MICRON ULTRA THIN SiC FREE STANDING MEMBRANES FOR SOFT X-RAYS BEAM MONITORING

G. Trovato[1,2,3,4], M. Camarda[2,3,5], N. La Rosa[2,6], M. Andrä[7], K. Desjardins[7], S. Finizio[8]
[1]Dipartimento di Fisica e Astronomia "E. Majorana", Università degli studi di Catania, Catania, Italy
[2]STLab s.r.l., Catania, Italy
[3]CNR-IMM, Catania, Italy
[4]Istituto Nazionale di Fisica Nucleare, Sezione di Catania, Catania, Italy
[5]SenSiC GmbH, Villigen, Switzerland
[6]DIEEI, Via Santa Sofia, Catania, Italy
[7]Synchrotron SOLEIL, L'Orme des Merisiers, Saint-Aubin, Gif-sur-Yvette, France
[8]Swiss Light Source, Paul Scherrer Institute, Villigen, Switzerland

ABSTRACT

X-ray beam position monitors (XBPMs) are essential diagnostics in modern synchrotron light sources, where they must operate with minimal beam disturbance, excellent linearity and stability under intense photon fluxes. For soft X-ray beamlines, the limited photon penetration depth demands highly transparent detectors. Single-crystal CVD diamond devices, the current standard for many XBPM applications, have been thinned down to a few micrometres to improve transmission, but fabrication challenges and residual absorption below 2 keV remain.

In this work, we characterize a submicrometric free-standing 4H-SiC membrane for the first time using a soft X-ray source, proving such a device to be effective as a beam monitoring element. The membrane, fabricated using a doping-selective electrochemical etching process, has a nominal thickness of 220 nm and a 2 mm × 2 mm active area, with Al electrodes deposited on both sides. Measurements were carried out at the Pollux beamline (SLS) and the Metrologie beamline (SOLEIL) using photon energies of 900 eV and 1000 eV, respectively. Raster-scan transmission mapping demonstrated good and uniform transparency, while current–voltage and beam-induced current measurements yielded the charge collection efficiency across the device.

These results demonstrate that ultra-thin 4H-SiC membranes combine exceptional transparency, mechanical integrity, and electrical performance, making them a promising alternative to diamond for non-invasive beam diagnostics in soft X-ray synchrotron beamlines.

INTRODUCTION

X-ray beam intensity monitors (XBIMs) and X-ray beam position monitors (XBPMs) are essential diagnostics in synchrotron light sources, where they provide continuous, high-precision measurements of beam position and number of photons. XBIMs and XBPMs must operate with minimal disturbance to the beam, maintain excellent linearity, and remain stable under intense photon fluxes. Solid-state detectors are now a consolidated reality as in-line elements for beam diagnostic, and it is especially true for hard and tender X-rays. For soft X-ray applications, an additional challenge arises from the limited photon penetration depth, making high transmission through the detector a key requirement. This capability is particularly critical for soft X-ray beamlines, where advanced spectroscopic and microscopic techniques require beam stability over extended time scales.

Over the past years, single-crystal chemical vapour deposition (scCVD) diamond has become the material of choice for XBPMs in many synchrotron facilities. Diamond offers a unique combination of low atomic number (Z), excellent thermal conductivity, high carrier mobility, and exceptional radiation hardness. These properties enable reliable operation under high heat loads and intense radiation while maintaining a linear response over a wide dynamic range. Diamond detectors with thickness of 20 µm and 50 µm are now standardized products [1, 2]. Although offering good performance, such devices are still too thick to be used below 2 keV in energies. An attempt to obtain even thinner beam monitors was made by Desjardins et al. [3]. Starting from a 60 µm thick scCVD chip, a 3.3 µm thick membrane was realised using an argon-oxygen plasma etching. This device operates in the low keV range, having high transparency, but showing a 50 % intensity variation in the beam-induced current.

In recent years, 4H-SiC has emerged as a promising alternative material for radiation detectors, including XBIMs and XBPMs [4–6]. 4H-SiC is a wide-bandgap semiconductor with high radiation resistance, good carrier transport properties, and the ability to operate at elevated temperatures. Furthermore, it benefits from mature wafer-scale growth and Silicon-like manufacturing techniques. SiC free standing membranes are produced by SenSiC GmbH with an innovative doping selective electrochemical etching technique. This wet-etching process is favorable to produce membranes given the improved membrane uniformity compared to dry etching techniques. SenSiC's membranes are already a standard in beamline instrumentation technology, offering commercially available devices with thickness >2 µm for tender and hard X-rays applications.

To the same extent of the works on scCVD diamond, submicrometric SiC free-standing membranes would drastically

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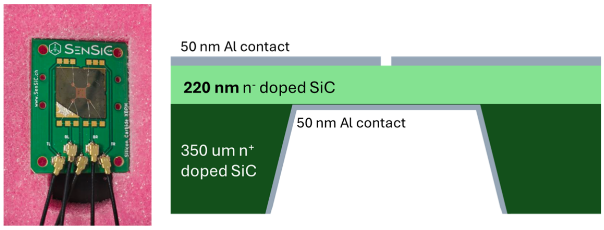

Figure 1: Picture and schematic of the ultra thin SiC membrane.

improve transmission in the 0.5–2 keV photon energy range, enabling efficient beam monitoring in soft X-ray beamlines without degrading beam quality.

In this work, we present the first characterization of Ultrathin 4H-SiC membrane XBPM (UT-SiC) using soft X-rays of 900 eV and 1000 eV.

MATERIALS AND METHODS

A SiC chip, extracted from the border of a 6 inch. Epiworld International Co., Ltd wafer, was cut selecting a 15 mm × 15 mm area. The devices consist of a nominal 220 ± 56 nm n^- doped ($<1 \times 10^{14}$ cm^{-3}) epitaxial layer and a 370 µm n^+ (1×10^{18} cm^{-3}) SiC substrate. The 'free standing membrane' is obtained in the center of the chip using a doping-selective electrochemical etching process (Nida et al., 2019), which erodes the thick n^+ layer, leaving a nominal 220 nm thick window, 2 mm × 2 mm large in area.

After the electrochemical etching process, two 50 nm thin Al layers are deposited on both top and bottom sides of the device to form the electrodes. On the front side of the device, the metalization is splitted in four quadrants with a 10 µm gap. The SiC chips are then glued onto a vacuum compatible PCB using a conductive epoxy paste. The electrical connections are ensured using 25 µm diameter *Al* wire bonds. The PCB features 5 UMC connectors carefully soldered onto the front side. The final device manufactured by SenSiC GmbH is shown in Fig. 1.

The signal is collected using a PCR4 picoammeter, produced by SenSiC, which is specifically realised for XBPM applications, reading 4 channels simultaneously with a 3 fA nominal resolution in the lowest current reading channel.

The measurements were conducted at the Pollux beamline in Swiss Light Source (SLS), Paul Scherrer Institute (PSI), using 50 µm spot size beam of 900 eV photons. Downstream to the SiC membrane, a Hamamatsu R647/P photomultiplier and a UKL59CF/UF-R1 phosphor powder screen are present to register the number of photons emitted by the beamline.

Additional measurements were performed at the Metrologie beamline of the Soleil Synchrotron, France, using 1000 eV photons and a Si diode to check the response linearity, as shown in Fig. 2 [7]. The produced signal has been acquired using a 4 channel low current monitor LoCuM-4.

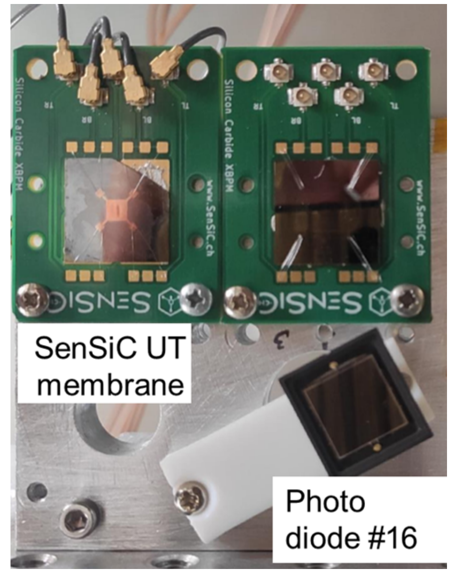

Figure 2: Picture of the setup used in the metrologie beamline of the Soleil synchrotron, featuring the SenSiC UT membrane and the reference Si photodiode.

RESULTS

From a current - voltage (I-V) characteristic of the freestanding membrane diode, once mounted onto the PCB support and connected with UMC cable connections, it has been possible to observe the low leakage (<80 pA) for every channel of the XBPM.

The transmission of the entire membrane area is obtained by performing a raster scan measurement of the SiC device with the photomultiplier downstream. This measurement was performed at Pollux beamline in SLS, PSI, using 900 eV photons. Knowing the flux emitted by the beamline under the same conditions without the SiC membrane inline, it is possible to determine the transmission coefficient as the ratio of the photons collected by the photomultiplier:

$$T(E) = \frac{\Phi_{\mathrm{SiC}}}{\Phi_{\mathrm{noSiC}}}. \quad (1)$$

Figure 3 shows a complete transmission map of the diode, obtained using an average flux of 1.18×10^7 s^{-1} 900 eV photons, with a spot size of 50 µm × 50 µm and a step size of 20 µm. The theoretical transmission of a 220 nm SiC membrane with two 50 nm Al contracts is estimated to be 80.7 %. The discrepancy of the experimental data with this number is likely due to an incomplete etching of the n^+-doped substrate, which lies underneath the membrane.

Figure 4 reports a map of the current produced by the beam in the same raster scan. The current produced by each quadrant of the device has been collected using the four channels of the PCR4 picoammeter, produced by SenSiC, using the last range of measurements, which allows reading of currents below 200 nA, with a nominal resolution of 3 fA.

The CCE of the membrane under 900 eV photons and with 0 V applied is shown in Fig. 5. The CCE is estimated

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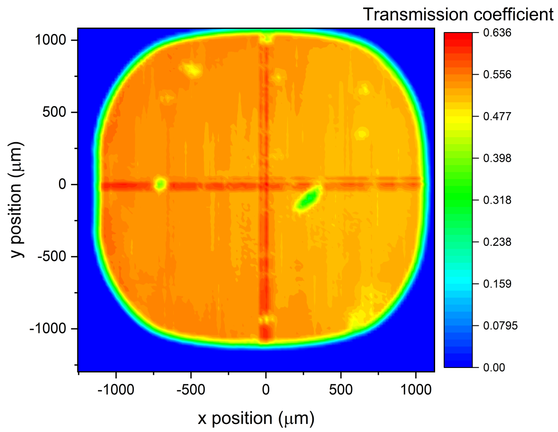

Figure 3: 2D map of the transmission coefficient of the membrane.

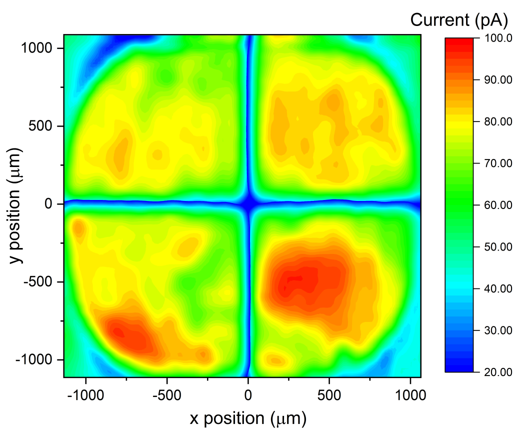

Figure 4: 2D map of the beam induced current produced by the UT SiC free standing membrane irradiated by 900 eV photons at the Pollux beamline.

as

$$CCE = \frac{I_{exp}}{I_{th}}, \tag{2}$$

where I_{exp} is the current measured during the raster scan, while I_{th} is the expected beam-induced current, estimated as $I_{th} = en_{e-h}$, with e the electron charge and n_{e-h} the number of electron-hole couples produced by the beam on the SiC.

$$n_{e-h} = n_{abs}\frac{E_{photon}}{E_{e-h}} = n_{abs}k, \tag{3}$$

with $k = 7.8$ eV, energy to produce a electron - hole pair in 4H-SiC and n_{abs} the number of absorbed photons.

The linearity of the diode has been tested in the Metrologie beamline of the Soleil Synchrotron, using a $0.3 \times 0.3\,\mathrm{mm}^2$ 1000 eV X-ray beam, varying the intensity of the beam spanning the aperture of the entrance slit up to 1000 µm. The diode has been polarized in reverse mode at 1.4 V. The linearity curve of the TL, TR and BR channels of the free

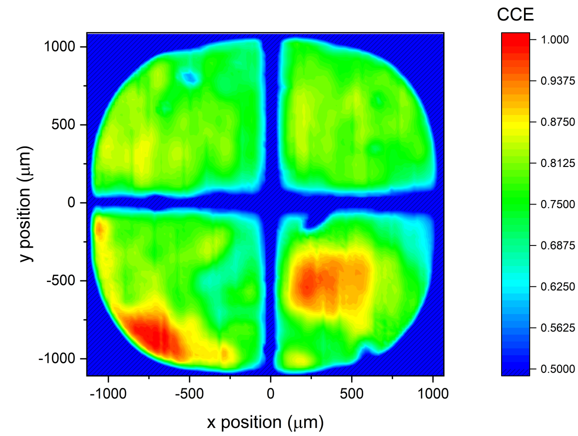

Figure 5: 2D map of the CCE of the SenSiC Ultra-thin membrane obtained with a raster scan using 900 eV X-rays.

standing membrane versus a reference Silicon diode is shown in Fig.6. The BL is not reported due to an electrical connection issue during the measurement. The curves related to the SiC membrane show an exponential decay of the signal when the aperture slits open. Such behaviour is supposedly given by the high capacitance of the thin membrane, which is easily estimated using the relation for a plane capacitor:

$$C = \frac{\varepsilon A}{d}, \tag{4}$$

where ε is given by the product ε_0, the vacuum permittivity, and ε_{SiC}, equal to 9.7. Considering the thickness of the membrane of 220 nm and the area of the Al metallization approximately $2 \times 2\,\mathrm{mm}^2$, it is possible to determine a capacity of 1.6 nF. Such capacitance, combined with the low frequency bandwidth of the instrument used, the measuring procedure, from close to open gaps, and the little 0.1 s delay time, gives a non-negligible exponential decay effect on the measurements, which affected the 0–100 µm region of the plot.

Cutting out the first 100 µm on the x-axis of the linearity plot, it is possible to estimate the correlation between the behaviour of the SiC membrane channels and the reference Si diode. The comparison with the Si diode of the TL, TR and BR channels gives Pearson's coefficients of 0.989, 0.995, and 0.995, respectively, highlighting the linearity of the SiC diode.

CONCLUSION

We have demonstrated the fabrication of a sub-micrometric 4H-SiC free-standing membrane and its first characterization as diagnostic element for soft X-ray beams. Using a doping-selective electrochemical etching process, we realized membranes with a nominal thickness of 220 nm and a $2 \times 2\,\mathrm{mm}^2$ active area, equipped with Al electrodes for current readout.

Measurements performed at the Pollux (SLS) and Metrologie (SOLEIL) beamlines confirmed the high trans-

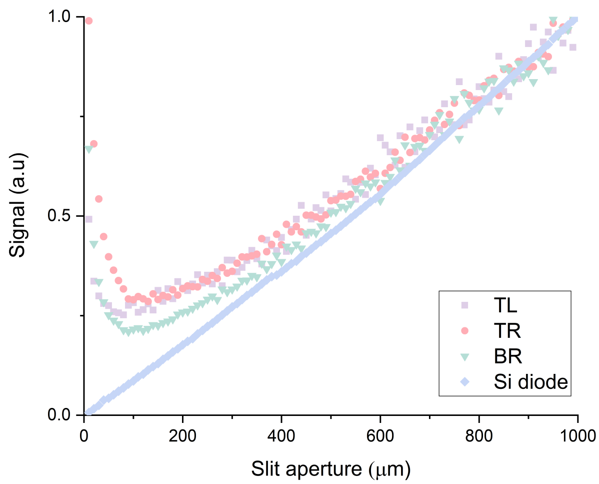

Figure 6: Linearity of the TL, TR and BR channels of the UT-SiC membrane compared with the signal produced by a silicon photodiode.

parency of the membrane using soft X-rays. Raster-scan mapping further showed the uniformity of the transmission across the device area. Current–voltage characterization and beam-induced current measurements demonstrated stable electrical behavior and measurable charge collection efficiency even at zero bias, highlighting the suitability of the membrane for operation as XBIM and XBPM.

The effect given by the high capacitance of the diode leads to an unfavorable slower dynamic, which is not comfortable in the case of synchrotron experiments. This issue is possible to resolve in newer devices reducing the active area. E.g. moving from a 2 mm^2 × 2 mm^2 to a 0.5 mm^2 × 0.5 mm^2 metallization would be already enough to lower the diode capacitance from 1.6 nF to 98 pF. Furthermore, to achieve a faster transitory of the signal, a readout system with higher bandwidths would be beneficial.

These results establish sub-micrometric SiC membranes as a promising new platform for non-invasive soft X-ray beam monitoring, combining mechanical robustness, radiation hardness, and manufacturability with exceptional transparency in the soft X-ray regime. Future work will address optimization of the thinning process for improved uniformity and of the metallization area for improved electrical performance, plus comparisons with gold meshes currently in use in soft X-rays beamlines.

ACKNOWLEDGEMENTS

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