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How can we use SiC

Piergiulio Lenzi[*]
INFN Firenze
E-mail: `lenzip@fi.infn.it`

Salvo Tudisco[†]
INFN-LNS Catania
E-mail: `tudisco@lns.infn.it`

We discuss the possible use of silicon carbide (SiC) based devices for applications in nuclear and particle physics, involving the detection of photons, charged particles and neutrons. The growing maturity of this semiconductor material and its properties in terms of ultraviolet (UV) light detection capability, visible blindness, and radiation hardness make it a very promising material for future detectors.

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[*] On behalf of the CLASSiC collaboration

[†] On behalf of the SiCILIA collaboration

1. Introduction

Silicon carbide (SiC) is a semiconductor with a wide, indirect band gap. Among all the wide band gap semiconductors, SiC is presently the most intensively studied and the one with the highest potential to reach market maturity in a wide field of device applications. Silicon carbide was discovered in 1824 by the Swedish scientist Jons Jakob Berzelius [1], in the same year when he also discovered elemental silicon [2]. Its importance was quickly recognized due to its extreme hardness of about 9.5 on the ten point Mohs scale. In spite of the comparatively high turn-on voltage, silicon carbide crystal detectors were used in the early days of radio telecommunication under the brand name Carborundum. The advances in technology and the need for high-power electronic devices resulted in the on-going research activity, which led to the availability of high quality silicon carbide material and to the commercialization of silicon carbide devices in the beginning of the 21^{st} century. Silicon carbide crystallizes in the form of silicon-carbon bilayers with a bond length d = 1.9 Å, which also is the arithmetic average between the C-C bond in diamond and the Si-Si bond in crystalline silicon. In the silicon carbide crystal lattice these bilayers are closely packed. Silicon carbide has the quite unique property of showing a large variation in crystal lattices, which are all built up by these stacked bilayers. This property is known as polytypism and is to a certain degree also observed for some III-nitride and II-VI compounds. The stacking sequence causes the presence of inequivalent hexagonal and cubic lattice sites. The different crystal structures can be identified by their characteristic stacking sequence. One of the most studied polytypes, 4H-SiC, is actually used for micro and opto-elevctronic application.

2. SiC properties

The main characteristics of SiC are:

- large band-gap (3.27 eV), which makes it insensitive to visible light;
- low intrinsic carrier concentration, which, together with the large band-gap allows the device to be operated with very low reverse bias, even after irradiation;
- high atomic displacement threshold (> 20 eV), which makes the material very radiation resistant;
- fast saturated electron velocity ($\sim 2 \times 10^7$ cm/s at room temperature), twice faster than silicon.

The large band-gap makes SiC devices insensitive to visible radiation above 400 nm, making it an ideal choice for UV light detectors, especially in conditions in which contamination from visible light is present. These properties have been successfully implemented for the realization of visible blind Shottky photodiodes, as reported in [3]. The R&D on SiC based Shottky photodiodes has also led to the realization of commercial products by ST microelectronics [4].

The high radiation resistance properties [5] make SiC very attractive for applications in which extreme radiation resistance is needed. Radiation damage can affect various properties of a detector. Common effects include leakage current increase, charge collection efficiency (CCE) reduction and the removal of free carriers from the conductive regions of the device. SiC, due to its wide gap and the strength of its chemical bonds, has been seriously considered as a valid alternative to silicon for the production of radiation hard ionizing particle detectors. The wide band-gap is useful, as it reduces significantly the rate of thermally generated charge carriers raising the noise level, especially under irradiation. On the other hand, it also represents a disadvantage: a particle with a certain energy, ideally transforming all its energy for the generation of electron-hole pairs, generates 3 times more charge carriers in Si than in SiC. Detectors based on SiC, therefore, have lower pulse amplitudes. However, for low signals, the reduction of the noise level is more important than the reduction of the signal level, so that the overall signal-to-noise ratio (SNR) is improved for SiC-based detectors. Furthermore, SiC-based detectors still have a high SNR at temperatures which are unattainable for Si-based devices, needing external cooling to keep the intrinsic carrier level sufficiently low [6]. Defect analysis and even defect engineering was widely investigated in the R&D collaborations Rose, RD48, RD50 at CERN [5, 7].

3. Material growth

Unlike most other semiconductor materials of technological interest, silicon carbide does not show a liquid phase. The only way to synthesize, purify and grow silicon carbide raw material for device processing is by means of gaseous phases. While research is carried out on the field of liquid phase epitaxy (LPE), where silicon carbide layers are deposited from a supersaturated solution of carbon in silicon (or silicon and carbon in a different solvent at high temperatures), these techniques are merely used in experimental work.

Silicon carbide can be synthesized by reducing sand (SiO_2) in the presence of excess carbon in electrical arc furnaces. In this process, developed by Acheson in 1891, silicon carbide is formed as a sintered mass of small crystallites. Under certain growth conditions, larger single crystalline platelets of silicon carbide can be found in cavities and at the outer surface of the synthesized material. Bulk material is obtained with these techniques. However SiC wafers grown in this way still cannot be used as device active region, because of the presence of defects directly impacting the charge collection efficiency. Instead, these bulk wafers are used as substrate for epitaxial growth.

Epitaxy allows for a much more precise control of layer thickness, doping and homogeneity than achievable in bulk material growth. The gaseous source materials are available with a higher purity than solid silicon carbide source materials. The dopants are also provided by means of gaseous precursors, and a free control over the ratio between those different source gases determines the amount of incorporated doping impurities [8]. In particular, for the epitaxial layer, it is necessary to realize a process that introduces a low density of stacking faults and point defects. Furthermore, a small portion of basal plane dislocations (BPDs) propagates into the epilayers from the substrate, and acts as a primary source of stacking faults, which are carrier lifetime killers. Regarding deep traps in SiC, correlation with carrier lifetime has been suggested. Therefore, the reduction of deep traps is also required [9, 10].

Ion implantation techniques in SiC are possible, as reported in [11] and [12]. High temperature post implantation baking at 1700°C is needed for both defect annealing and dopant activation.

4. SiC devices applications

4.1 UV light detection

The problem of UV light detection appears in several applications. Traditional phototubes, and silicon based photodiodes usually have relatively low quantum efficiency for deep UV radiation. Moreover, they do not usually show sensitivity exclusively to UV radiation, rather they have very broad response spectra, which makes them sensitive also to higher wavelengths. This is problem especially when a UV component needs to be disentangled from a longer wavelength one. One such use case is, for example, the detection of Cherenkov light in scintillating crystals. The detection of both Cherenov and scintillation light separately is used in dual readout hadronic calorimetry as a means of achieving electron/hadron compensation [13].

SiC based photodiodes are particularly interesting in this respect. The spectral sensitivity for a 4H-SiC Shottky device with inter-digit Shottky contacts is discussed for example in [3]. The SiC device used consisted of a 4 μm thick n-type layer with a semi-transparent Shottky contact (called "interdigit" contact) made of 2 μm wide metalized strips with an inter-strip distance of 10 μm, which allows transparency to the incident UV radiation. The peak sensitivity is around 280 nm and the response drops to 0 at 380 nm, proving excellent visible blindness. It is also interesting to notice that already with 0 V reverse bias the device is capable of functioning. This is possible thanks to the low doping concentration of the epitaxial layer, which is already depleted at 0V. Similar SiC devices studied in [14] showed an internal quantum efficiency (QE, defined as the number of photoelectrons produced per incident photon) of 78% at 254 nm.

One of the limitation of the Shottky approach is the absence of an internal multiplication mechanism, which makes the device unable to detect a small amount of light. Similarly to what has been done in silicon, attempts have been pursued also in SiC to build avalanche photodiodes based. SiC based APD are reported for example in [15]. Those devices are based on epitaxial p-i-n junction. Etching and passivation processes (MESA structures) are necessary around the detector's active area for lateral device field confinement and edge leakage suppression implying a large dead space between contiguous devices and complex fabrication processing.

4.1.1 CLASSiC

A collaboration between INFN and CNR-IMM has been put in place in 2015 joining the INFN interest in the Cherenkov light detection and the CNR-IMM competence in SiC device fabrication. The collaboration is named CLASSiC, Cherenkov Light detection with Silicon Carbide.

The aim of the CLASSiC project is the realization of a SiC based APD with single photon detection capabilities. In order to achieve this goal, without the limitations mentioned above concerning the devices reported in [15], we have studied p-i-n diodes obtained via ion implantation. The device produced, documented in [12], consists of a 4 μm thick n-type epitaxial layer with a very thin p implant on top. The device is 1mm^2, exhibits leakage current lower than 1nA/cm^2 and has a peak quantum efficiency of 50% at 280 nm. The visible light rejection above 400nm exceeds a factor thousand. The device is completely planar, so it has very small dead space around the edges.

Following the studies documented in [12] the CLASSiC collaboration is working on the development of a Separate Absorption and Multiplication APD.

4.2 X-ray spectroscopy

Photon detection, spectroscopy and imaging in the X-ray energy range constitutes the most challenging field for semiconductor detectors for ionizing radiation because X photons have energies (typically from few hundreds eV to few tens keV) lower than other radiations (alpha, beta, gamma, protons) so they generate a small electric charge signal in the semiconductor. A high quality device is therefore necessary to achieve an adequate signal to noise ratio. Specifically, the detector must have the lowest dark current, which determines the device noise, and it must have an efficient transport of the electric charges toward the electrodes in order not to degrade the signal. Both the charge trapping and the detector speed are common problems affecting all detectors made by compound semiconductor such as GaAs, CdTe, CdZnTe, HgI2. On the other hand, it has been experimentally demonstrated that detectors made with epitaxial Silicon Carbide are not affected by charge trapping and give extremely fast response [16, 17]. These features are essential for realizing a high quality X-ray detector [18]. X photons interact with SiC lattice mainly by photoelectric effect up to 50 keV of photon energy. The linear attenuation coefficient μ of SiC is almost identical to that of Silicon for photon energies E_{ph} >1.7 keV, while for E_{ph} <1.7 keV μ_{SiC} is slightly higher than μ_{Si} because of the presence of Carbon atoms. In those cases where the efficiency is an important constraint, SiC detectors are adequate for low energy X-rays (<20 keV) due to the relatively low thickness (<150μm) of the presently available epitaxial layer. The capability of SiC detectors for X-ray detection and spectroscopy at high resolution even at temperatures forbidden to any other semiconductor has been experimentally demonstrated [19]. In terms of response speed, SiC detectors can profit from the high saturation velocities of the charge carriers (2×10^7 cm/s) in the semiconductor - two times higher with respect to Silicon - and to the possibility to effectively operate the devices at or close to the carrier velocity saturation condition. This because the breakdown field in SiC is 2MV/cm - seven times higher than in Si or GaAs - so that junctions on SiC can be reverse biased realizing extremely high internal electric field in the depleted region. A timing resolution of the order of one hundred ps has been measured [16].

4.3 Neutron detection

The need for advancements in neutron detection methods emerges in a variety of fields in applied physics, e.g. for dosimetry and monitoring of beam losses at accelerators (including those used for hadrotherapy), fusion neutron measurements at reactors and characterization of fast neutron irradiation experiments, just to name a few. The state of the art in these measurements is represented by diamond detectors. An issue with the use of diamonds is the long term stability of the detector response. It is well known that diamond detectors suffer from polarization effects during calibration with charged particles. As a result the detector gain changes and detection pulses are distorted in shape. This is interpreted as due to charge trapping in the crystal. The effect is also observed - with differences - under irradiation by fast neutrons. It can be mitigated by applying periodically a reverse bias to the detector but it does not seem possible at present to remove long term drifts in detector performance.

There have been several exploratory tests of SiC detectors for fast neutron measurements, mainly limited by the lack of SiC crystals of suitable quality. Here we only mention an application to the monitoring of spent nuclear fuel. Spent-fuel environments are characterized by very high gamma-ray intensities of the order of 1,000 Gy/hr and very low neutron fluence rates of the order of hundreds per cm^2 per second. Long-term monitoring carried out over a 2050 hour period and a total gamma-ray dose to the detector of over 6000 Gy did not induce gain drifts in the detector [20]. This is still a limited test in terms of total neutron fluence but is nevertheless encouraging for performing more extensive tests of SiC detectors in a high neutron flux environment.

The use of SiC as an alternative to diamond at neutron energies in the MeV range is particularly attractive. Several neutron-induced threshold reactions with the Si and C nuclei of the detector become viable. These reactions lead to the creation of ionizing particles which enable neutron detection and, to some extent, neutron spectroscopy.

4.4 Charged particles Detection

Nonionizing energy loss (NIEL) is a useful tool for characterizing the energy dependence of displacement damage effects in semiconductor devices. Since the nuclear stopping power, by definition, does not involve electronic excitations, NIEL can be regarded as a proxy for nuclear stopping in the absence of nuclear reactions. NIEL calculations are reported in several works in the literature. SiC is for example discussed in [21], especially for what concerns NIEL of different ion species at different energy. From such comparisons, a picture emerges that nuclear physics experimental (NPE) conditions are very far from LHC or TEVATRON physics, where detection is restricted to minimum ionizing particles (MIP) and where the main radiation damage effects are connected to charge collection efficiency and to the increase of leakage currents. NIEL effects in case of a MIP are small and the cooling of silicon detector at about -20°C is still one of the best solutions to cope with radiation damage. For NPE the situation is completely different because they work with light and heavy ions at energies from zero to tens MeV/A where the NIEL function for each ion have its maximum values. In these conditions, mid-gap defects are constantly produced during experiments. They degrade mainly the lifetime of charge carriers (being efficient electron-hole pair generators) and also the leakage current, which drastically increases with the fluency.

Several works concerning radiation hardness of SiC material are available in literature, but most of them address the problem of MIP detection, which is quite different with respect to that of intermediate energies heavy ions. Some experimental results concerning a SiC devices realized at IMM-CNR Catania are reported in [22]. Such work shows results of irradiations studies performed with ^{16}O ions beam at some tens of MeV and it proves clearly that SiC detectors are able to work up to 10^{14} heavy ions/cm^2 of fluence, which is a big improvement in respect to the typical values of few 10^9 heavy ions/cm^2 of a commercial Silicon detector.

4.4.1 SiCILIA

The construction of innovative detection systems for next generation nuclear physics experiments at high beam luminosity (NUMEN [23]) or in a plasma environment (NRLP-Nuclear Reaction in Laser-Plasmas [24]) has triggered a collaboration between INFN and CNR-IMM. The collaboration named SiCILIA aims to develop innovative processes, which allows a massive production of thick (>100μm) and large area (about 1 cm^2) SiC detectors with unprecedented level of defects. In particular two solutions will be investigated: the Shottky and the p/n junctions. The Shottky represents today the state of art for SiC detectors. The project aims to push forward the limits for this technology in relation to the thickness and the active area. The p/n represents a novel solution for SiC, that is particularly promising in analogy to similar junctions based on Silicon devices. Included in the project, after a first production of detector prototypes, there is also a complete characterization by different kind of radiation (heavy-ions, electrons, neutrons and photons) and in conjunction with standard and customized low-noise electronics will be performed. The resolution, charge collection efficiency, timing, linearity and pulse-shape capability will be determined. The fallout of SiCILIA will be useful also for other fields of fundamental and applied research. Some of these aspects are included in the project.

5. Conclusion

Silicon carbide is a very interesting semiconductor material for applications in particle and nuclear physics. The maturity of the production processes and the active research in the field put SiC in a distinctive positions with respect to other semiconductors alternative to silicon for what concerns the possibilities for future large scale productions.

SiC properties in terms of large bandgap, radiation resistance, capability of operating at room temperature even after irradiation, make it particularly attractive for a wide ranger of applications, from UV light detection, to X-ray spectroscopy, neutron and charged particle detectors. Interest in SiC development clustered in INFN into two detector R&D initiatives, CLASSiC focusing on the development of SiC based APDs for UV light detection, and SiCILIA, for the development of particle detections applications in nuclear physics experiments. Both initiatives, although they started recently, are in good shape and producing interesting preliminary results.

References

[1] J. J. Berzelius, *Annalen der Physik 1*. 1824.

[2] S. Engels and A. Nowak, *Auf der Spur der Elemente*.

[3] A. Sciuto, M. Mazzillo, P. Badala, M. Scuderi, B. Carbone, and S. Coffa, "Thin Metal Film Ni2Si/4H-SiC Vertical Schottky Photodiodes,"*Photonics Technology Letters, IEEE* **26** (Sept, 2014) 1782–1785.

[4] http://www.st.com/web/catalog/sense_power/FM89/SC2014/PF261045.

[5] F. Moscatelli, A. Scorzoni, A. Poggi, M. Bruzzi, S. Lagomarsino, S. Mersi, S. Sciortino, and R. Nipoti, "Measurements and simulations of charge collection efficiency of p+/n junction SiC detectors," *Nucl. Instrum. Meth.* **A546** (2005) 218–221.

[6] A. Lebedev, A. Ivanov, and N. Strokan, "Radiation Resistance of SiC and Nuclear-Radiation Detectors Based on SiC Films," *Semiconductors* **38** (2004) 125.

[7] M. Moll *et al.*, "Development of radiation tolerant semiconductor detectors for the Super-LHC," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **546** (2005) no.~1âĂ§2, 99 – 107. Proceedings of the 6th International Workshop on Radiation Imaging DetectorsRadiation Imaging Detectors 20046th International Workshop on Radiation Imaging Detectors.

[8] F. La Via, M. Camarda, and A. La Magna, "Mechanisms of growth and defect properties of epitaxial SiC," *Appl. Phys. Rev.* **1** (2014) 031301.

[9] F. La Via, G. Galvagno, G. Foti, M. Mauceri, S. Leone, G. Pistone, G. Abbondanza, A. Veneroni, M. Masi, G. L. Valente, *et al.*, “4H SiC epitaxial growth with chlorine addition,” *Chemical vapor deposition* **12** (2006) no. 8-9, 509–515.

[10] F. La Via, G. Izzo, M. Mauceri, G. Pistone, G. Condorelli, L. Perdicaro, G. Abbondanza, L. Calcagno, G. Foti, and D. Crippa, “4H-SiC epitaxial layer growth by trichlorosilane (TCS),” *Journal of Crystal Growth* **311** (2008) no. 1, 107–113.

[11] S. Biondo, L. Ottaviani, M. Lazar, D. Planson, J. Duchaine, V. Le Borgne, M. El Khakani, F. Milesi, W. Vervisch, O. Palais, and F. Torregrosa, “4H-SiC P^+N UV Photodiodes : A Comparison between Beam and Plasma Doping Processes,”*Materials Science Forum* **717-720** (May, 2012) 1203–1206.

[12] A. Sciuto, M. Mazzillo, S. Di Franco, F. Roccaforte, and G. D’Arrigo, “Visible Blind 4H-SiC P^+-N UV Photodiode Obtained by Al Implantation,”*Photonics Journal, IEEE* **7** (June, 2015) 1–6.

[13] N. Akchurin, M. Alwarawrah, A. Cardini, G. Ciapetti, R. Ferrari, *et al.*, “Dual-Readout calorimetry with crystal calorimeters,” *Nucl.Instrum.Meth.* **A598** (2009) 710–721.

[14] A. Sciuto, F. Roccaforte, S. Di Franco, V. Raineri, and G. Bonanno, “High responsivity 4H-SiC Schottky UV photodiodes based on the pinch-off surface effect,” *Applied physics letters* **89** (2006) no. 8, 1111.

[15] X. Bai, X. Guo, D. McIntosh, H.-D. Liu, and J. C. Campbell, “High Detection Sensitivity of Ultraviolet 4H-SiC Avalanche Photodiodes,” *Quantum Electronics, IEEE Journal of* **43** (2007) no.~12, 11591162.

[16] G. Bertuccio, S. Caccia, D. Puglisi, and D. Macera, “Advances in silicon carbide X-ray detectors,”*Nuclear Instruments and Methods in Physics Research A* **652** (Oct., 2011) 193–196.

[17] X. Zhang, J. Cates, J. Hayward, G. Bertuccio, D. Puglisi, and P. Hausladen, “Characterizing the Timing Performance of a Fast 4H-SiC Detector With an ^{241}Am Source,”*Nuclear Science, IEEE Transactions on* **60** (June, 2013) 2352–2356.

[18] G. Bertuccio, D. Puglisi, A. Pullia, and C. Lanzieri, “X-γ Ray Spectroscopy With Semi-Insulating 4H-Silicon Carbide,”*Nuclear Science, IEEE Transactions on* **60** (April, 2013) 1436–1441.

[19] G. Bertuccio, S. Caccia, D. Puglisi, and D. Macera, “Advances in silicon carbide x-ray detectors,” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **652** (2011) no.~1, 193 – 196. Symposium on Radiation Measurements and Applications (SORMA) {XII} 2010.

[20] T. Natsume, H. Doi, F. Ruddy, J. Seidel, and A. Dulloo, “Spent Fuel Monitoring with Silicon Carbide Semiconductor Neutron/Gamma Detectors,” *Journal of ASTM International* **Online Issue 3** (2006) .

[21] S. Messenger, E. Burke, M. Xapsos, G. Summers, R. Walters, I. Jun, and T. Jordan, “Niel for heavy ions: an analytical approach,”*Nuclear Science, IEEE Transactions on* **50** (Dec, 2003) 1919–1923.

[22] G. Raciti, M. de Napoli, F. Giacoppo, E. Rapisarda, and C. Sfienti, “Detection Properties and Radiation Damage Effects in SiC Diodes Irradiated with Light Ions,”*Nuclear Physics A* **834** (Mar., 2010) 784–787c.

[23] F. Cappuzzello, C. Agodi, M. Bondì, D. Carbone, M. Cavallaro, and A. Foti, “The role of nuclear reactions in the problem of $0\nu\beta\beta$ decay and the NUMEN project at INFN-LNS,” *J. Phys. Conf. Ser.* **630** (2015) no.~1, 012018.

[24] F. Negoita *et al.*, “Laser Driven Nuclear Physics @ ELI-NP,” *in press, Romanian Report in Physics* .