Materials Science Forum
ISSN: 1662-9752, Vol. 1062, pp 278-282
doi:10.4028/p-85482w

Submitted: 2021-10-14
Revised: 2022-02-08
Accepted: 2022-03-31
Online: 2022-05-31

Optical Characterization of 4H-SiC Thick Epitaxial Layer for Particle Detection

Meli Alessandro[1,2,a*], Muoio Annamaria[2,b], Reitano Riccardo[1,c], Trotta Antonio[3,d], Parisi Miriam[3,e], Meda Laura[4,f] and La Via Francesco[2, g]

[1]Dipartimento di Fisica e Astronomia-Università di Catania, Via Santa Sofia 64, 95123 Catania, italy

[2]CNR-IMM Headquarter, Strada VIII 5,95121 Catania, Italy

[3]ENI-MAFE, Via A. Pacinotti 4, 30175 Venezia, Italy

[4]ENI-Renewable Energy and Environmental TECH R&D Center, Via G. Fauser 4, 28100 Novara, Italy

[a]alessandro.meli@imm.cnr.it, [b]annamaria.muoio@imm.cnr.it, [c]riccardo.reitano@ct.infn.it, [d]Antonio.Trotta@eni.com, [e]miriam.parisi@eni.com, [f]laura.meda@eni.com, [g]francesco.lavia@imm.cnr.it

Keywords: 4H-SiC; neutron detector; epitaxial growth; micro-Raman; i-LOPC, oxidation process, carrier lifetime.

Abstract. In the present work a deep characterization of 4H-SiC epi-layer was done. A thick layer was epitaxially grown through chemical vapor deposition (CVD) process in a horizontal hot-wall reactor to obtain a 250 microns thick epi-layer. This sample will be used as particles detector in hostile environments such as neutron detection in a nuclear fusion reactor. Raman and Photoluminescence (PL) spectroscopy have been used to evaluate the quality of epitaxial layer observing the presence of long-range defects. With the support of the Time Resolved Photoluminescence, also important properties such as carrier lifetime and diffusion length were evaluated. Carrier lifetime evaluation before and after a thermal oxidation process at 1400° C for 48h was estimated, by considering a lifetime increment after oxidation process, due to the decrease of carbon vacancies. Finally, the influence of stacking fault (SF) defects on carrier lifetime was evaluated observing a decrease of the lifetime for the defects at 430 nm (2.88 eV) for both oxidated and non-oxidated samples.

Introduction

Silicon carbide (SiC) is a wide bandgap semiconductor material with a rigid stoichiometry of Si:C=1:1. It has various crystalline structures, among which the most interesting for electronic applications are called 3C, 6H and 4H. These crystalline phases show a band gap with values ranging from 2.9 to 3.2 eV from 3C to 4H polytypes. Furthermore, the thermal conductivity of SiC, much higher than that of Silicon (4.9 versus 1.5 W/cm K), as well as its dielectric strength (4.106 versus 2.105 V/cm) and the electron saturation rate (2.107 against 1.107 cm/s), make this material particularly suitable for high temperature, high voltage or power applications, with non-negligible effects on the efficiency of the electronic systems [1] [2] [3]. A new field of application of 4H-SiC material is as detector in harsh environments, [4] where the temperature and the radiation exposure are critical for other semiconductor devices such as silicon. Therefore, the radiation hardness allows the use of SiC material as neutron detector in thermonuclear fusion reactor. Improvements in SiC wafer growth processes and the good quality of the material, with a low defect density, makes this material competitive with Single-Crystal Diamonds (SCD) detectors, currently used in this field.

In a previous paper [5] a comparison between SCD and SiC detectors was reported, observing an increase in resolution for SCD detectors with increasing thickness. Then to increase the resolution of the SiC detectors is necessary to increase considerably the thickness of the epitaxial layer.

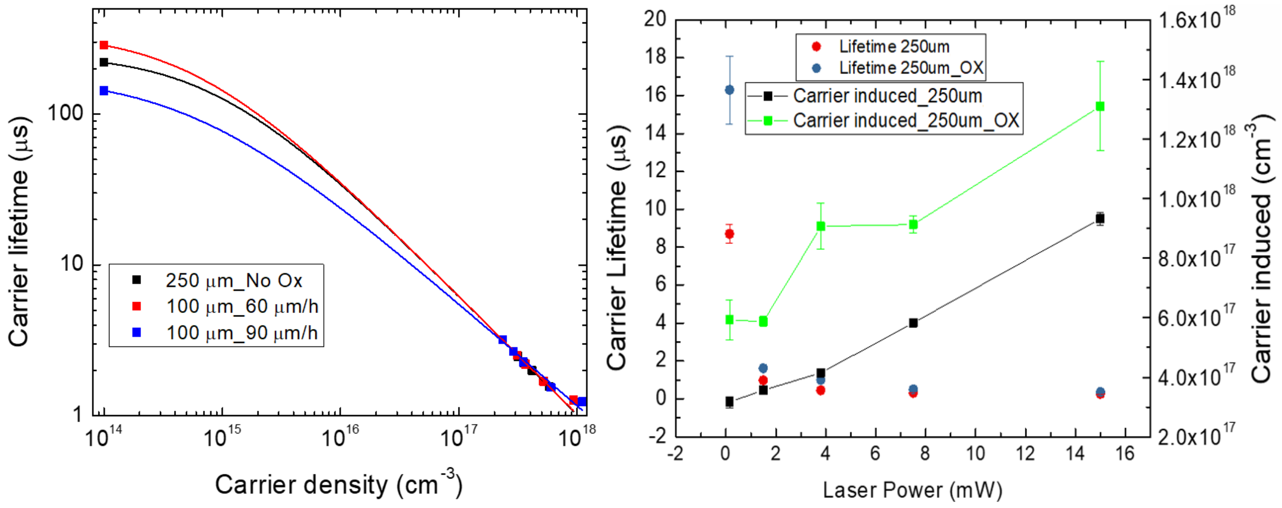
The purpose of this work is to study the 4H-SiC epitaxial layer properties for the fabrication of a device for neutron detection as an alternative material to diamond detectors used in this field. We have studied a high growth rate process to grow a thick epitaxial layer (250 µm) of 4H-SiC [6] and, to estimate the quality of the epitaxial layer, an optical characterization was done through Photoluminescence (PL) spectroscopy for stacking fault defect evaluation. Micro Raman spectroscopy was used for simultaneous determination of both carrier lifetime and induced carriers in equilibrium [7], through the shift of the LO peak. The study of the carrier lifetime and diffusion length is necessary because these parameters are fundamental to collect all charges generated by neutrons, and therefore, to obtain a good signal from these thick detectors. We have compared these results with other two samples with an epitaxial layer of 100 micron (Fig. 1a) obtained with two different growth rates, 60 and 90 µm/h, respectively. From Raman measurements it has been observed that both the growth rate and the grown epitaxial layer thickness influence the measured carrier lifetime [8].

Time resolved photoluminescence (TRPL) characterization was done to estimate the carrier lifetime in a low injection regime and, using different wavelengths of the source, the lifetime trend across the entire thickness was analysed (Fig. 1b). In order to increase the carrier lifetime, a thermal oxidation process was carried out, to reduce the carbon vacancies in the entire epitaxial layer [9]. From these results it has been observed that the oxidation process at high temperature (1400 °C) for long time (48 h) has a large effect both on the maximum carrier lifetime and on the uniformity of this parameter along the entire thickness of the epitaxial layer. Finally, a comparison between different kinds of stacking faults (SF) was done, so evaluating the influence of these defects on the carrier lifetime as a function of the injection level and it was observed that at a low injection level the effect on the carrier lifetime is low.

Results and Discussion

The spectroscopical characterization through Raman and PL maps was done, for carrier lifetime and stacking faults (SFs) defects evaluation respectively. The sample is a 4H-SiC wafer of 4 inches with an epi-layer grown by chemical vapor deposition (CVD) process in a horizontal hot-wall reactor. The volume of the epitaxial layer is fundamental for the neutron detection because the signal analyzed is due to the interaction between neutron with silicon and carbon nuclei generating various reactions, as described in literature [10], and the study of fluence obtained by FLUKA tool [11] highlights the importance of the volume. Therefore, we investigated a 250 µm thick epi-layer which could be used for detection applications.

An important parameter that describes the quality of the epilayer is the carrier lifetime and it was defined through Raman analysis using Longitudinal Optical Phonon-plasmon Coupling (LOPC) mode and Time resolved Photoluminescence (TRPL) to evaluate the lifetime in a high and low injection regime respectively. In Fig. 1 the carrier lifetime as a function of carrier density (Fig. 1a) and laser power (Fig. 1b) are shown. In particular, Fig. 1a shows the comparison between samples with different thickness and growth rates. These 100 µm samples were previously grown epitaxially with the same CVD process in the same horizontal hot-wall reactor with a similar process. The lifetime was evaluated by LOPC mode for high carrier densities induced in the epi-layer and TRPL for lower carrier density. An increase of carrier lifetime when the carrier density decrease is observed. Furthermore, for the 60 µm/h epitaxial growth an epilayer with a lower density of defects with respect to the 90 µm/h is obtained. Then, in the case of the 250 µm thick epi-layer, we have decided to use the same growth rate. This behaviour is connected with the concentration of point defects at higher growth rate as previously defined in literature [12] [13].



a) b)

Figure 1. (a) The figure shows the trends of the carrier lifetimes as a function of carrier density for all analyzed samples; (b) Carrier lifetime(blue and red dots) and carrier induced (green and black lines) as a function of laser power used for 250 um thick sample before and after oxidation process.

A common defect that influences the carrier lifetime is the $Z_{1/2}$ center, defined as a carbon vacancy in the crystalline structure. There are some processes that allows a decrement of these defects such as oxidation and passivation processes. An oxidation process at 1400°C for 48h was done and the carrier lifetime values as a function of laser power used are shown in Fig.1b, compared with values obtained for non-oxidated sample. An increase in lifetime is observed (blue dots) at low power after the oxidation process even if the carrier induced values are higher than the non-oxidated sample. This Raman analysis took place in long-range defect-free areas. However, by photoluminescence maps, some stacking faults (SFs) are found and a study of the influence of these SFs on the carrier lifetime after the oxidation process was evaluated. Fig. 2a shows a PL map of an isolated stacking fault at 430 nm (2.88 eV).

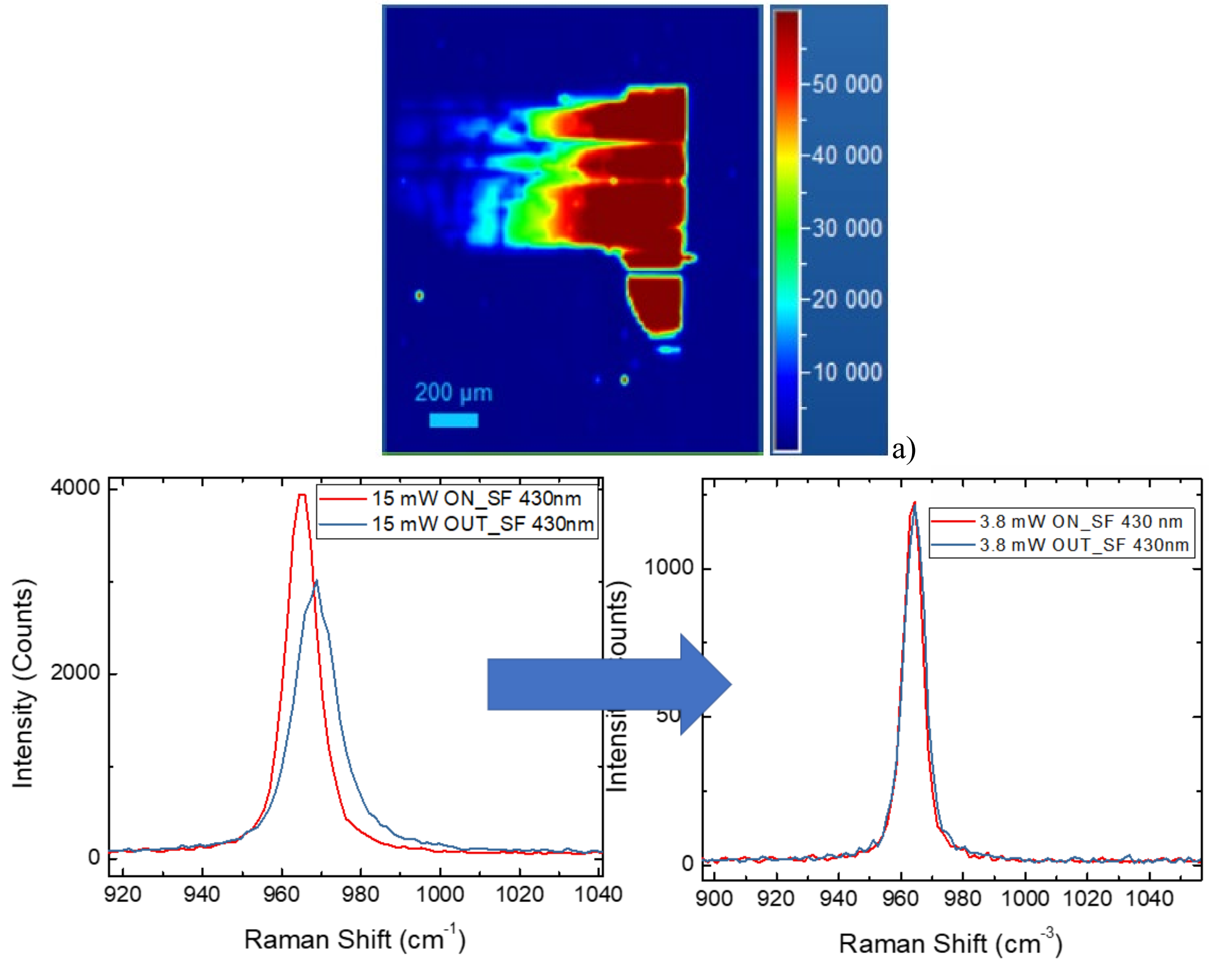


Figure 2. (a) PL map of a stacking fault defect at 430 nm (2.88 eV). (b) LO peak shift at 15 and 3.8 mW, ON and OUT (in proximity) of the defect.

By Raman analysis a comparison between the LO shift ON-SF and in its proximity (OUT-SF) was done, observing a decrease of difference in the peak shape and position when the laser power decreases (Fig. 2b). This effect is probably due to the fact that if the carrier lifetime and the diffusion length increases and then this measure is averaged over a larger region around the SFs, the effect on the carrier lifetime and the induced carrier is lower. Therefore, on a 430 nm defect, which is the most common defect present on the wafer, a lower lifetime than in the SF-free area is observed also after the oxidation process. Furthermore, not all types of stacking faults react in the same way. In facts, the defect at 490 nm, seems to be affected by the oxidation process, leading to a longer lifetime, in any case with a lower value than the value obtained in the defect-free area.

Conclusion

A thorough characterization of 4H-SiC epitaxial layer, previously grown, was done to evaluate, an important parameter for neutron detectors such as carrier lifetime. The thick layer is important for the application of this device, that will be used in a thermonuclear fusion reactor. From this study we have observed that very high carrier lifetime (more than 100 µs) can be obtained using not extremely high growth rate (60 µm/h) and with a high temperature oxidation process. It has been observed also that the different SFs present in the epitaxial layer have a limited effect on the carrier lifetime.

References

[1] P. G. Neudeck, R. S. Okojie and L. Y. Chen, "High-temperature electronics—A role for wide bandgap semiconductors?," *Proc. IEEE,* vol. 90, no. 6, pp. 1065-1076, 2002.

[2] R. Maboudian and e. al., "Advances in silicon carbide science and technology at the micro-and nanoscales," *J. Vac. Sci. Technol. A,* vol. 31, no. 5, p. 050805, 2013.

[3] B. J. Baliga, Fundamentals of Power Semiconductor Devices, New York: Springer, 2008, p. 215.

[4] S. Tudisco, F. La Via and etal, "Silicon Carbide Detectors for Intense Luminosity Investigations and Applications," *Sensors,* vol. 18, no. 2289, 2018.

[5] M. Rebai, D. Rigamonti, S. Cancelli, G. Croci, G. Gorini, E. Cippo, O. Putignano, M. Tardocchi, C. Altana, M. Angelone and e. al., "New thick silicon carbide detectors: Response to 14 MeV neutrons and comparison with single-crystal diamonds," *Nuclear Inst. And Methods in Physics Research,* vol. A 946, p. 162637, 2019.

[6] F. La Via, M. Camarda and A. La Magna, "Mechanisms of growth and defect properties of epitaxial SiC," *Applied physics reviews 1,* no. 031301, 2014.

[7] N. Piluso, M. Camarda and F. La Via, "A novel micro-Raman technique to detect and characterize 4H-SiC stacking faults," *Journal of applied physics,* vol. 116, p. 163506, 2014.

[8] A. Meli, A. Muoio, A. Trotta, L. Meda, M. Parisi and F. La Via, "Epitaxial Growth and Characterization of 4H-SiC for Neutron Detection Applications," *Materials,* vol. 14, no. 976, 2021.

[9] S. Ichikawa, K. Kawahara, J. Suda and T. Kimoto, "Carrier Recombination in n-Type 4H-SiC Epilayers with Long Carrier Lifetimes," *Applied Physics Express 5,* no. 101301, 2012.

[10] F. Ruddy, A. Dulloo, J. Seidel, M. Das, S.-H. Ryu and A. Agarwal, "The fast neutron response of 4H silicon carbide semiconductor radiation detectors," *IEEE Trans. Nucl. Sci.,* vol. 53, p. 1666–1670, 2006.

[11] «http://www.fluka.org/,» [Online].

[12] M. Camarda, A. La Magna, P. Fiorenza, G. Izzo e F. La Via, «Theoretical Monte Carlo study of the formation and evolution of defects in the homoepitaxial growth of SiC,» *Mater. Sci. Forum,* vol. 135, pp. 600-603, 2009.

[13] F. La Via, G. Galvagno, A. Firrincieli, F. Roccaforte, S. Di Franco, A. Ruggiero, M. Barbera, R. Reitano, P. Musumeci, L. Calcagno and e. al, "Epitaxial layer grown with HCl addition: A comparison with the standard process," *Mater. Sci. Forum,* vol. 163, pp. 527-529, 2006.