Dual-beam Irradiation Stability of Amorphous Silicon Oxycarbide at 300 and 500 °C

Qing Su¹, Graeme Greaves², Stephen E. Donnelly², Shinsuke Inoue³, Manabu Ishimaru³, and Michael Nastasi^{1,4,5,6*}

¹Department of Mechanical and Materials Engineering, University of Nebraska-Lincoln, Lincoln, NE 68583-0857, USA

²School of Computing and Engineering, University of Huddersfield, Huddersfield HD1 3DH, UK

³Department of Materials Science and Engineering, Kyushu Institute of Technology, Tobata, Kitakyushu, Fukuoka 804-8550, Japan

⁴Nebraska Center for Energy Sciences Research, University of Nebraska-Lincoln, Lincoln, NE 68583-0857, USA

⁵Nebraska Center for Materials and Nanoscience, University of Nebraska-Lincoln, Lincoln, NE 68588-0298, USA

⁶Department of Nuclear Engineering, Texas A&M University, College Station, TX 77843-3128, USA

*Email address: mikenastasi@tamu.edu

ABSTRACT

The irradiation stability of a material in the temperature range from 300C to 500C represents an important step for a variety of nuclear applications. Here we used dual-beam irradiation to investigate the response of an amorphous silicon oxycarbide (SiOC) to extreme environments (temperature and irradiation). The amorphous SiOC was prepared in thin film form by sputtering and then fabricated into cross-sectional transmission electron microscopy (TEM) specimens, and finally irradiated with helium (He) and krypton (Kr) ions inside a TEM. In-situ TEM observations revealed that He bubble and void formation are highly suppressed after irradiation up to 95 dpa with simultaneous He implantation up to 231 at.%. Atomic pair-distribution functions suggested that the amorphous structures are almost the same before and after irradiation, and no crystallization, nor phase separation was detected. This study demonstrates the stability of amorphous SiOC under dual-beam irradiation at nuclear reactor operation temperatures, suggesting that this material is applicable as a structural material for advanced nuclear reactors.

Introduction

For the successful operation of next generation nuclear reactors, it is of technological importance to develop new radiation-tolerant materials that can withstand extreme environments of irradiation, including helium (He) incorporation and elevated temperature.^{1,2,3,4,5} Over recent decades, extensive research has been undertaken to improve the radiation tolerance of structural materials and to suppress radiation-induced dimensional and property changes. The introduction of interfaces into crystalline materials is one of the possible ways of enhancing radiation resistance, because grain boundaries and surfaces act as effective defect sinks. For example, oxide-dispersion-strengthened steels with metal/oxide nanoscale interfaces have improved radiation damage and He swelling resistance.^{6,7} Several other incoherent interfaces in binary metallic systems (Cu/V,⁸ Cu/Nb,^{9,10} and Fe/W¹¹) have also demonstrated the ability to suppress radiation damage and He bubble formation. Although grain stability under thermal aging and irradiation remains a challenge, the grain boundaries in nanocrystalline metals have been shown to promote defect annihilation under certain conditions.^{12,13}

In addition to traditional approaches which strive to delay the deleterious effects of combined radiation damage, He incorporation, and temperature aging in crystalline metallic systems, amorphous ceramics could be another strong option because of their demonstrated high temperature stability and high radiation tolerance. Amorphous materials inherently contain the structural flexibility associated with free volume and local bonding topology, which helps the elimination of radiation-induced point defects.¹⁴ Because of this, amorphous materials are anticipated as a new class of radiation-tolerant structural materials. We have recently studied the radiation behavior of amorphous silicon oxycarbide (SiOC) which consists of tetrahedral units of

SiO_xC_{4-x} with x = 0, 1, 2, 3, or 4. Although previous work has shown that SiOC possesses high temperature stability, irradiation stability, and He outgassing capability through pre-defined separate irradiation experiments,^{15,16,17,18,19,20,21} the response of the structure of amorphous SiOC to extreme environments with combined thermal, irradiation, and He implantation is still largely unknown.

In the present study, dual-beam irradiations [krypton (Kr) irradiations and He implantation] were conducted inside a TEM at temperatures of 300°C and 500°C, to better mimic nuclear reactor environments and examine the radiation response of amorphous SiOC. The simultaneous dual-beam irradiation creates a combination of large damage cascade zones (primarily by Kr-induced collisions), scattered point defects (primarily by He-induced collisions) and He incorporation, and thus simulates both the displacement damage and the incorporation of transmutation gases (H and/or He) that occur simultaneously under neutron irradiation in a reactor. By carrying out the experiments inside a TEM, it is possible to observe variations in the microstructure in real time.

Experiment

Specimen preparation.

Amorphous SiOC thin films with a thickness of 300 nm were deposited on surface oxidized Si substrates with a 300-nm top SiO₂ layer using radio frequency co-sputtering from SiC (purity 99.5%) and SiO₂ (purity 99.995%) targets at room temperature. The composition of the SiOC was 30 at.% Si, 40 at.% O, and 30 at.% C, as suggested by Rutherford backscattering. The argon (Ar) partial pressure was 0.65 Pa for the sputter deposition, while the base pressure was 9.8×10^{-6} Pa or lower prior to the deposition. The cross-sectional TEM samples for in situ irradiation experiments were prepared by mechanical polishing followed by ion milling with a low glancing

angle (5°). To minimize ion milling damage, the acceleration voltage for the Ar ion milling was initially 4 keV and 3 keV was adopted for the final stage (GATAN, PIPSII).

In situ Kr irradiation and He implantation:

The dual-beam irradiations and in-situ TEM observations were performed using the Microscopes and Ion Accelerators for Materials Investigations (MIAMI-2 system)²² at the University of Huddersfield. The MIAMI-2 system consists of a 350 kV NEC ion accelerator and a 20kV Colutron ion accelerator both coupled with a 300 kV Hitachi H-9500 TEM in which both ion beams follow the same final trajectory and are incident at 18.7° to the electron beam at the sample position. To minimize electron-induced effects the electron beam was only incident on the sample during imaging. Dual beam irradiation/implantation was conducted using 500 keV Kr²⁺ ions (displacement damage) at a flux of 7.0×10^{16} ions/m²/s to a fluence of 5.0×10^{20} ions/m² and 3 keV He⁺ ions (implantation of transmutation gas) with a flux of 1.0×10^{17} ions/m²/s to a fluence of 7.1×10^{21} ions/m². The electron beam was normal to the cross-sectional surface of the TEM specimen so that the Si, SiO₂ and SiOC layers were subjected to dual-beam irradiation at the same time. Experiments were conducted at 300°C and 500°C.

The depth-dependent damage and He concentration profiles were simulated using the Stopping and Range of Ions in Matter (SRIM)-2008 software with the ion distribution and quick calculation of damage option.²³ The displacement energies of Si, O, and C elements were assumed to be 15 eV, 28 eV, and 28 eV, respectively.

PDF characterization:

In addition to the direct observations of structural evolution using in situ TEM, the atomistic structure variation before and after dual-beam irradiation was examined by atomic pair-distribution functions (PDF) in which amorphous networks are characterized by the probability of finding

atoms as a function of radial distance, r , from a specific atom. The PDF can be extracted by a quantitative analysis of electron diffraction intensities.^{24,25,26} The electron diffraction patterns for PDF analyses were recorded on imaging plates using a JEOL JEM-3000F TEM operated at an acceleration voltage of 300 kV. To avoid contamination during the observations, the specimens were cooled by a liquid nitrogen holder. The detailed procedures of electron diffraction radial distribution analysis have been described elsewhere.^{24,27,28}

Results

The structural stability of amorphous SiOC was examined following simultaneous 500-keV Kr irradiation and 3-keV He ion implantation at 300 and 500°C. Figure 1 shows (a) the depth profiles of the implanted He ions and (b) the Kr-induced irradiation damage, calculated by SRIM-2008. SRIM does not consider the substrate temperature in its calculations. As shown in Fig. 1a, the implantation depth of 3-keV He is 20 nm and the He implantation produced approximately 25 displacements per atom (dpa) peak damage for the film at maximum dose. Compared with the He implantation, during Kr irradiation there is a negligible amount of Kr implanted and the Kr irradiation produces a flat damage profile with maximum damage of approximately 70 dpa. The peak in the implanted He concentration reaches an effective value of approximately 231 at.% (note that the presence of He in the implanted layer is not taken into account in calculating this profile). The same irradiation parameters were used in both the 300 and 500°C irradiation experiments. The cross-sectional bright-field TEM image of the as-deposited “tri-layer” specimen is shown in Fig. 2a. From diffraction contrast, a ~300-nm-thick SiOC surface layer, a ~300-nm-thick amorphous SiO₂ layer, and a thick Si substrate can be clearly observed. Both the SiOC and SiO₂ layers show uniform contrast, suggesting that these layers are an amorphous phase. A series of the

microstructural changes in specimens irradiated with different doses at 300°C are shown in Fig. 2b, c, d, and e. These pictures were taken from the identical region of the TEM specimen. The diffraction contrast due to damage clusters is observable in the Si substrate, indicating that the area was irradiated by ions. The SiOC layer exhibits fairly uniform contrast in all pictures, and no void formation is present throughout the amorphous SiOC layer. It should be noted that the formation of He bubbles is highly suppressed even at the highest fluence (corresponding to a effective implant concentration of 231 at.%). The absence of He bubbles is attributed to rapid He diffusion in amorphous SiOC, as observed in our previous study.²⁹ Figure 2f shows a high-resolution TEM image of the SiOC layer after exposure to 95 dpa as well as 231 at.% He implantation. The SiOC layer exhibits a typical maze-like pattern due to its amorphous structures, and no remarkable phase separation nor crystallization was detected. Indeed, weak halo rings are observed in the corresponding electron diffraction pattern shown in the inset of Fig. 2f. These data clearly demonstrate the high degree of tolerance of the SiOC to dual-beam irradiation at 300°C.

Figure 3 shows cross-sectional TEM micrographs of the tri-layer (a) before and (b–e) after He- and Kr-ion irradiation at 500°C. The interface between amorphous SiOC and SiO₂ is clearly visible in the irradiated specimens, suggesting that no remarkable mixing of elements occurs between these layers. A high-resolution TEM image and corresponding selected-area diffraction pattern of the SiOC after irradiation at 500°C are shown in Fig. 3f. As with irradiation at 300°C it can be seen that the SiOC maintains its amorphous state with no He bubble or void formation observed after 95-dpa irradiation and corresponding 231 at.% He implantation at 500°C. In contrast to the SiOC layers, the Si substrate contains numerous nanoscale He bubbles and defect clusters after both 300°C and 500°C dual-beam irradiation. There appears to be little densification (< 10%) following the dual-beam irradiation, but the specimen did exhibit some curvature at the

end of the experiments. It is interesting to note the contrast difference at the SiO₂/SiOC interface as well as at the SiO₂/Si interface after irradiation. These contrast-different regions expand as the irradiation dose increases and they are probably due to ion beam mixing. In addition, the ion irradiation leads to some sample bending, as evidenced by the curved SiO₂/SiOC interface after 20-dpa Kr irradiation damage.

To examine the structural variation of amorphous SiOC after dual-beam irradiation, a radial distribution function analysis was performed. Figure 4 shows the PDF, $g(r)$, of the SiOC irradiated at 300°C (green) and 500°C (red), obtained by a quantitative analysis of halo intensities. For comparison, the $g(r)$ of the as-deposited amorphous SiOC is also indicated as open squares. A prominent peak corresponding to the first nearest neighbor of Si-O atomic pairs appears at 1.60 Å, whereas the second nearest neighboring peaks due to O-O and Si-Si are located at 2.60 Å and 2.99 Å, respectively. In addition to these peaks, small peaks related to C atoms exist in the range of 1.34–1.37 Å (C-O) and 1.88–1.89 Å (Si-C).^{20,21,30,31} The profiles gradually converge to unity at radial distances larger than 5 Å, suggesting dual-beam irradiation at 300°C and 500°C did not lead to long-range order/correlation. The average interatomic distances and bond angles extracted from $g(r)$ of SiOC are summarized in Table 1. Minor changes of bond lengths and bond intensity after irradiation are observed for Si-O, C-O, Si-Si, and Si-C bonds, indicating changes in the number of these bonds and bonding angles. The PDF profile of SiOC film after 500°C almost matches with that of as-deposited SiOC. The PDF after irradiation at 300°C shows significant peak intensity variation which is most probably due to irradiation-induced sample bending. That is, the thickness of the sample changes along the electron beam incident direction; and as a consequence, the electron diffraction intensity used for PDF analysis is affected. However, regular topological short-range order consisting of the SiO_xC_{4-x} tetrahedral units is still evident in the SiOC films after

irradiation. As shown in Fig. 4 and Table 1, the peak locations hardly change, suggesting very few structural variations or changes in atomic density before and after dual-beam irradiation at 300°C and 500°C. It is worthwhile emphasizing that the dual-beam irradiation at 300°C and 500°C represents a complex damage process. First of all, scattered point defects and large damage cascade zones coexist during the irradiation. Secondly, both atomic displacements and He incorporation may affect the amorphous structure of SiOC. Finally, the dual-beam irradiation performed at two different temperatures, defect creation, diffusion, interaction, and consequences could yield quite different results. The effects of separate displacement damage and He incorporation on the amorphous SiOC have been reported in a previous study.²⁸ The He implantation has a negligible effect on the SiOC structure;²⁹ it is argued that the implanted He atoms rapidly diffuse in the SiOC even at liquid N₂ temperature and are released from the material without producing any resolvable damage. From the TEM data it is apparent that He release also occurs in the present dual-beam irradiation at 300°C and 500°C. Compared with the PDF result of the SiOC film which experienced just the He implantation,²⁹ the PDF in the current study exhibits no further changes to the SiOC amorphous structure. These findings indicate that the amorphous SiOC structure reaches an energetically local minimum state, which appears to persist under continued steady-state dual-beam irradiation.

Conclusion

The structural stability of amorphous SiOC during dual-beam Kr irradiation/He implantation at 300°C and 500°C was examined using in situ TEM. It was found that no remarkable He bubbles nor volume swelling were observed even after an effective 231 at.% He implantation plus 95 dpa. High-resolution TEM observations and PDF analysis revealed that the material retains its glassy

properties and no crystallization was detected under the present dual-beam irradiation conditions. The observations suggest that the amorphous SiOC structure can tolerate high levels of atomic displacements together with high levels of He implantation at elevated temperatures. Our present study shows the structural stability of amorphous SiOC under displacement irradiation coupled with He implantation. Understanding the effects of irradiation/implantation on amorphous materials is of technological importance for the design of radiation-tolerant and He-swelling resistant materials for potential nuclear energy applications.

References

- 1 Odette, G. R., Alinger, M. J. & Wirth, B. D. Recent developments in irradiation-resistant steels. *Annual Review of Materials Research* **38**, 471-503, doi: 10.1146/annurev.matsci.38.060407.130315 (2008).
- 2 Bloom, E. E. *et al.* Critical questions in materials science and engineering for successful development of fusion power. *J. Nucl. Mater.* **367**, 1-10, doi: 10.1016/j.jnucmat.2007.02.007 (2007).
- 3 Bloom, E. E. The challenge of developing structural materials for fusion power systems. *J. Nucl. Mater.* **258–263, Part 1**, 7-17, doi: 10.1016/S0022-3115(98)00352-3 (1998).
- 4 Muroga, T., Gasparotto, M. & Zinkle, S. J. Overview of materials research for fusion reactors. *Fusion Engineering and Design* **61–62**, 13-25, doi:10.1016/S0920-3796(02)00219-3 (2002).
- 5 Was, G. S. Materials degradation in fission reactors: Lessons learned of relevance to fusion reactor systems. *J. Nucl. Mater.* **367–370, Part A**, 11-20, doi:10.1016/j.jnucmat.2007.03.008 (2007).
- 6 Odette, G. R. & Hoelzer, D. T. Irradiation-tolerant Nanostructured Ferritic Alloys: Transforming Helium from a Liability to an Asset. *Jom-Us* **62**, 84-92, doi: 10.1007/s11837-010-0144-1 (2010).
- 7 Wong, C. P. C. *et al.* Helium-cooled refractory alloys first wall and blanket evaluation. *Fusion Engineering and Design* **49-50**, 709-717, doi: 10.1016/S0920-3796(00)00176-9 (2000).

- 8 Fu, E. G., Misra, A., Wang, H., Shao, L. & Zhang, X. Interface enabled defects reduction in helium ion irradiated Cu/V nanolayers. *J. Nucl. Mater.* **407**, 178-188, doi: 10.1016/j.jnucmat.2010.10.011 (2010).
- 9 Misra, A., Demkowicz, M. J., Zhang, X. & Hoagland, R. G. The radiation damage tolerance of ultra-high strength nanolayered composites. *Jom-Us* **59**, 62-65, doi: 10.1007/s11837-007-0120-6 (2007).
- 10 Zhernenkov, M. *et al.* Design of radiation resistant metallic multilayers for advanced nuclear systems. *Appl. Phys. Lett.* **104**, doi: 10.1063/1.4883481 (2014).
- 11 Li, N. *et al.* He ion irradiation damage in Fe/W nanolayer films. *J. Nucl. Mater.* **389**, 233-238, doi: 10.1016/j.jnucmat.2009.02.007 (2009).
- 12 Bai, X. M., Voter, A. F., Hoagland, R. G., Nastasi, M. & Uberuaga, B. P. Efficient Annealing of Radiation Damage Near Grain Boundaries via Interstitial Emission. *Science* **327**, 1631-1634, doi: 10.1126/science.1183723 (2010).
- 13 Samaras, M., Derlet, P. M., Van Swygenhoven, H. & Victoria, M. Computer simulation of displacement cascades in nanocrystalline Ni. *Phys. Rev. Lett.* **88**, doi: 10.1103/Physrevlett.88.125505 (2002).
- 14 Baumer, R. E. & Demkowicz, M. J. Radiation response of amorphous metal alloys: Subcascades, thermal spikes and super-quenched zones. *Acta Mater.* **83**, 419-430. doi: 10.1016/j.actamat.2014.10.020 (2015).
- 15 Nastasi, M. *et al.* Superior radiation tolerant materials: Amorphous silicon oxycarbide. *J Nucl Mater* **461**, 200-205, doi:10.1016/j.jnucmat.2015.02.039 (2015).
- 16 Su, Q., Cui, B., Kirk, M. A. & Nastasi, M. Cascade effects on the irradiation stability of amorphous SiOC. *Philosophical Magazine Letters* **96**, 60-66, doi:10.1080/09500839.2016.1147655 (2016).
- 17 Su, Q., Cui, B., Kirk, M. A. & Nastasi, M. In-situ observation of radiation damage in nano-structured amorphous SiOC/crystalline Fe composite. *Scripta Materialia* **113**, 79-83, doi: 10.1016/j.scriptamat.2015.10.009 (2016).
- 18 Su, Q., Price, L., Shao, L. & Nastasi, M. High temperature radiation responses of amorphous SiOC/crystalline Fe nanocomposite. *J. Nucl. Mater.* **479**, 411-417, doi: 10.1016/j.jnucmat.2016.07.037 (2016).

- 19 Su, Q., Price, L., Colon Santana, J. A., Shao, L. & Nastasi, M. Irradiation tolerance of amorphous SiOC/crystalline Fe composite. *Materials Letters* **155**, 138-141, doi:10.1016/j.matlet.2015.04.085 (2015).
- 20 Su, Q., Inoue, S., Ishimaru, M., Gigax, J., Wang, T., Ding, H., Demkowicz, M., Shao, L., & Nastasi, M. *Sci Rep-Uk*, 7,8 (2017)
- 21 Mizuguchi, S., Inoue, S., Ishimaru, M., Su, Q., & Nastasi, M. *J. Nucl. Mater.* 518, 241–246 (2019).
- 22 Greaves, G., Mir, A., Harrison, R.W., Tunes, M.A., Donnelly, S.E., & Hinks, J.A. *Nucl. Instrum. Meth. A* 931, 37–43 (2019).
- 23 J.F. Ziegler, J. B. B., U. Littmark. *The Stopping and Range of Ions in Solids*, Pergamon Press, New York (1985).
- 24 Ishimaru, M., Bae, I.T., Hirata, A., Hirotsu, Y., Valdez, J.A., & Sickafus, K.E. *Phys. Rev. B*, 72, 024116, 8 (2005).
- 25 Sheng, H. W., Luo, W. K., Alamgir, F. M., Bai, J. M. & Ma, E. Atomic packing and short-to-medium-range order in metallic glasses. *Nature* **439**, 419-425, doi: 10.1038/nature04421 (2006).
- 26 Naito, M., Ishimaru, M., Hirotsu, Y., & Takashima, M. *Jpn. J. Appl. Phys.* 42, L1158–L1160 (2003).
- 27 Ishimaru, M. Electron-beam radial distribution analysis of irradiation-induced amorphous SiC. *Nucl. Instrum. Meth. B* **250**, 309-314, doi: 10.1016/j.nimb.2006.04.129 (2006).
- 28 Hirotsu, y., Ishimaru, m., Ohkubo, T., Hanada, T., & Sugiyama, M. *J. Electron Microsc.* 50, 435–442 (2001).
- 29 Su, Q., Ding, H., Price, L., Shao, L., Hinks, J. A., Greaves, G., Donnelly, S. E., Demkowicz, M. J., & Nastasi, M. Rapid and damage-free outgassing of implanted helium from amorphous silicon oxycarbide. *Sci Rep-Uk*, 8, (2018).
- 30 Brequel, H., Soraru, G. D., Schiffini, L. & Enzo, S. Radial Distribution Function of amorphous silicon oxycarbide compounds. *Mater. Sci. Forum* **343-3**, 677-682, doi:10.4028/www.scientific.net/MSF.343-346.677 (2000).
- 31 Brequel, H. *et al.* Systematic structural characterization of the high-temperature behavior of nearly stoichiometric silicon oxycarbide glasses. *Chem. Mater.* **16**, 2585-2598, doi: 10.1021/cm049847a (2004).

Acknowledgements

This research was funded by DoE Office of Nuclear Energy, Nuclear Energy Enabling Technologies, award DE-NE0008415. This work was supported by the U.S. Department of Energy, Office of Nuclear Energy under DOE Idaho Operations Office Contract DE-AC07-051D14517 as part of a Nuclear Science User Facilities experiment. The research was performed in part in the Nebraska Nanoscale Facility: National Nanotechnology Coordinated Infrastructure and the Nebraska Center for Materials and Nanoscience, which are supported by the National Science Foundation under Award ECCS: 1542182, and the Nebraska Research Initiative. MI was supported by the Kazuchika Okura Memorial Foundation and Grant-in-Aid for Scientific Research (B) (Grant No. 16H04518) from the Ministry of Education, Sports, Science, and Technology, Japan (MI). The MIAMI facility is part of the EPSRC UK National Ion Beam Centre a(UKNIBC) and has been support by grants EP/E017266/1 and EP/M028283/1.

Author contributions Statement

Q. S. prepared SiOC specimens and designed the experiment with M. N.; G. G., performed the dual-beam ion irradiation experiments with supervision of S. D. at University of Huddersfield. M. I. performed RDF experiments. Q. S. wrote the original draft of the paper and all authors discussed the results and commented on the manuscript.

Competing financial interests statement

The authors declare no competing financial interests.

Figures

Figure 1. The simulated depth profile of implanted concentration and radiation damage from (a) 3 keV He and (b) 500 keV Kr. Values calculated using a fluence of 7.1×10^{21} ions/m² for He implantation and 5.0×10^{20} ions/cm² for the Kr irradiation. Both 300 and 500 °C dual-beam irradiation used the same flux and fluence.

Figure 2. The cross-sectional TEM micrographs of (a) as-deposited amorphous SiOC specimen and (b-e) during in-situ dual-beam irradiation at 300 °C. (f) High resolution TEM image of amorphous SiOC film and corresponding SAD pattern after dual-beam irradiation at 300 °C. No crystallization, He bubble or void formation, or segregation are observed suggesting dual-beam irradiation stability at 300 °C.

Figure 3. The cross-sectional TEM micrographs of (a) as-deposited amorphous SiOC specimen and (b-e) during in-situ dual-beam irradiation at 500 °C. (f) High resolution TEM image of amorphous SiOC film and corresponding SAD pattern after dual-beam irradiation at 500 °C. No crystallization, He bubble or void formation, or segregation are observed suggesting dual-beam irradiation stability at 500 °C.

Figure 4. The PDF of SiOC film before and after dual-beam irradiation at 300 and 500 °C. The change of peak location is very small suggesting very few structural variations or changes in atomic density before and after dual-beam irradiation at 300 and 500 °C.

Table 1. Average peak position of neighbor shells and bond angles in SiOC before and after He irradiation/implantation.

	Peak position (Å), and its representation		
	First shell	Second shell	

SiOC samples	C-O	Si-O	Si-C	Si-Si	1 st NN O-O	1 st NN Si-Si	Si-O-Si Bond angle (°)
As-deposited	1.34	1.60	1.86	2.32	2.62	3.00	139.3
After 300 °C dual-beam irradiation	1.34	1.60	1.87	2.32	2.62	2.99	138.3
After 500 °C dual-beam irradiation	1.35	1.61	1.89	2.32	2.64	2.99	135.5
After He implantation at RT	1.37	1.61	1.87	2.28	2.63	2.99	135.5