Epitaxial graphene technology for the future nuclear industry

Semir El-Ahmar,[1] Maciej J. Szary,[1] Wiktoria Reddig[1], Jakub Jagiełło[2], Rafał Prokopowicz[3], Maciej Ziemba[3], Artur Dobrowolski[2] and Tymoteusz Ciuk[2]

[1]Institute of Physics, Poznan University of Technology, Piotrowo 3, 61-138 Poznan, Poland, [2]Łukasiewicz Research Network - Institute of Microelectronics and Photonics, Aleja Lotników 32/46, 02-668 Warsaw, Poland, [3]National Centre for Nuclear Research, 05-400 Otwock, Poland

e-mail: semir.el-ahmar@put.poznan.pl

In the development of magnetically confined fusion reactor technologies, our understanding of high-energy particle radiation environments is continually advancing. This creates an urgent need for diagnostic technologies that can endure extreme radiation exposure. As these technological boundaries expand, materials face radiation intensities that far exceed those encountered in previous decades, pushing conventional systems to their operational limits. This challenge is especially critical in the pursuit of practical fusion energy, where the creation of robust magnetic sensor technologies capable of continuous and reliable operation under intense neutron flux is essential.

Our research explores the potential of using two-dimensional (2D) carbon structures as magnetic field detectors capable of operating in the extreme conditions of future thermonuclear power plants. In such reactors, electronics will be exposed to high temperatures and radiation damage. We demonstrate the experimental study on the impact of neutron radiation and determine its influence on the electrical parameters of epitaxial graphene-based systems. We have conducted preliminary research to investigate the impact of high temperature[1] and neutron radiation[2,3]. For this purpose, we fabricated a hydrogen-intercalated quasi-free-standing graphene on semi-insulating 4H-SiC(0001) and 6H-SiC(0001), passivated with an Al_2O_3 layer[4]. The systems were exposed to neutron fluxes using the MARIA research nuclear reactor.

Key open questions include the ultimate neutron fluence tolerance of graphene-based systems and whether the reduced dimensionality offers a significant advantage over traditional 3D materials. Additionally, it's crucial to consider the impact of substrate interactions in 2D/3D heterostructures, as these can undermine or complicate the benefits of 2D architectures. By addressing these challenges and identifying future directions, we can develop a roadmap for epitaxial graphene-based electronics that can withstand and operate reliably in extreme radiation environments, where conventional materials are likely to fail.

[1] W. Reddig et al., *IEEE Sensors Lett.*, **2023**, 7, 2502204.
[2] S. El-Ahmar et al., *Appl. Surf. Sci.*, **2025**, 685, 161953.
[3] S. El-Ahmar et al., *Appl. Surf. Sci.*, **2022**, 590, 152992.
[4] T. Ciuk et al., *Carbon Trends*, **2023**, 13, 100303.

Acknowledgments: The authors would like to thank the Ministry of Education and Science (Poland) for support under the project no. 0512/SBAD/2520.