Ion Implantation for Innovative Interface modifications in BAttery and Graphene-enabled Systems

Programme: M-ERA.NET Call 2021

Call topic: Innovative surfaces, coatings and interfaces

Full title: **I**on **I**mplantation for **I**nnovative **I**nterface modifications in **BA**ttery and **G**raphene-enabled **S**ystems

Acronym: **I4BAGS**

I4Bags

Ion Implantation for Innovative Interface modifications in BAttery and Graphene-enabled Systems

Belgian participants: Materia Nova R&D Center and IONICS S.A.

Polish participants: QWED SP. Z O. O. and Institute of Microelectronics and Photonics

Funding organisations: Service Public de Wallonie (Belgium)
and National Centre for Research and Development (Poland)

Duration: 01.09.2022 - 31.08.2025

NCBR
Narodowe Centrum Badań i Rozwoju

Wallonie

SPW
Service public
de **Wallonie**

Ion Implantation for Innovative Interface modifications in BAttery and Graphene-enabled Systems

MATERIA
NOVA Materials R&D Center

ionics
surface technologies

QWED

Łukasiewicz
Institute of Microelectronics
and Photonics

Ion Implantation for Innovative Interface modifications in BAttery and Graphene-enabled Systems

General objectives:

- Incorporate **ion implantation** to boost the performance of **solid-state batteries**
- Incorporate **ion implantation** to boost the performance of **graphene-on-SiC devices**
- Develop advanced **microwave** and **mm-Wave characterisation** methodologies
- Develop **demonstrators** and high-score **publications**

I4Bags

Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

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www.graphene2get.com **I4BAGS Public Workshop** **May 16, 2024**

Graphene on Silicon Carbide Platform

for **Magnetic Field Detection**

under **Extreme Temperature** Conditions

and **Neutron Radiation**

Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

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Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

Thermal stability of transport properties

Two-dimensional character

Why graphene on SiC?

Hole mobility up to 5000 cm^2/Vs

Fixed hole concentration

Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

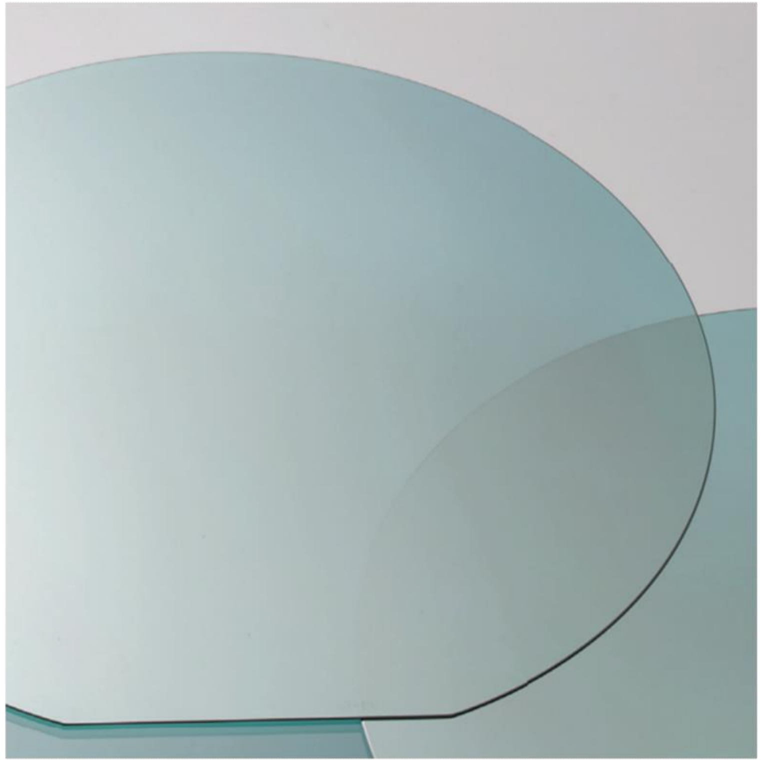
Epitaxy: Chemical Vapor Deposition (CVD)

Carbon source: methane or propane

Substrate: 4H-SiC(0001) or 6H-SiC(0001)

Type: semi-insulating on-axis

Dimensions: 20 mm x 20 mm



dx.doi.org/10.1016/j.carbon.2015.06.032 dx.doi.org/10.1016/j.carbon.2016.01.093

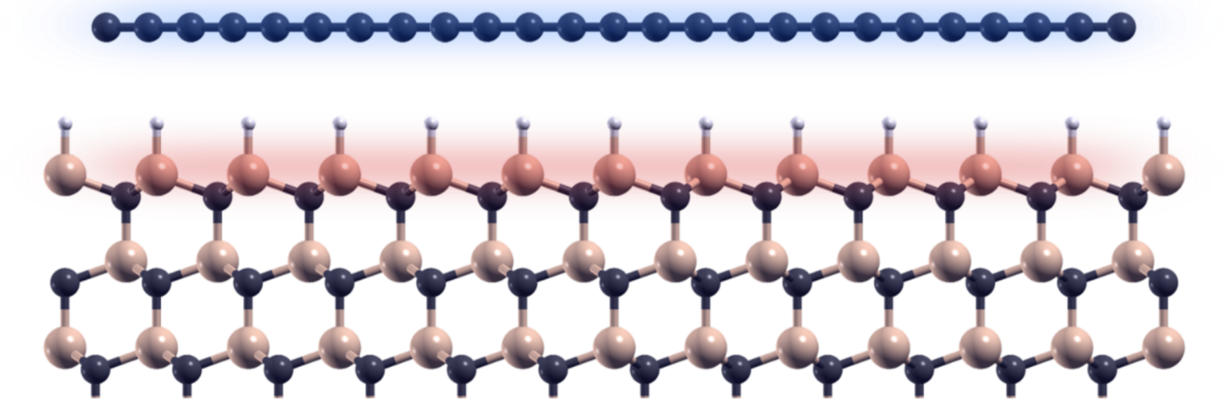
Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

Hydrogen intercalation: quasi-free-standing graphene

Spontaneous polarization vector: P_0

Surface-bound pseudo charge: P_0/e

Reflected in QFS graphene as: $-P_0/e$



doi.org/10.1016/j.apsusc.2020.148668 doi.org/10.1016/j.apsusc.2023.158617

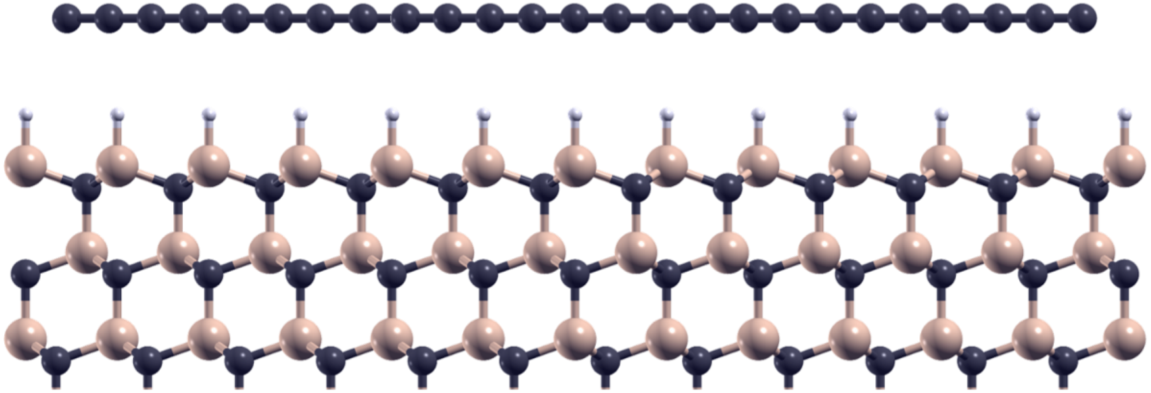
Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

Hydrogen intercalation: quasi-free-standing graphene

Polarization effect: positive

On 4H-SiC(0001): $p = +1.2\ E13\ cm^{-2}$

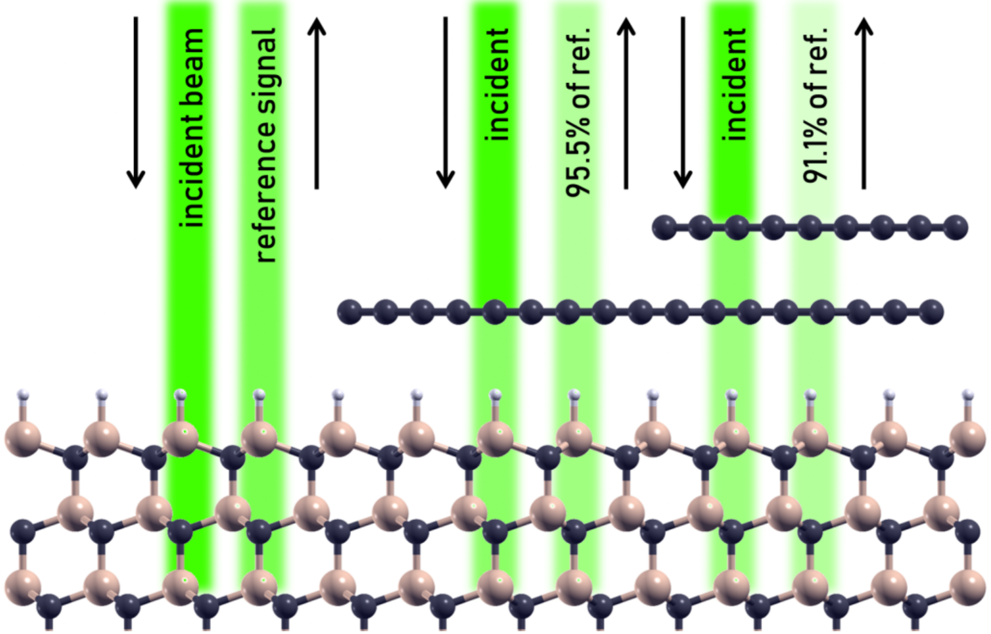
On 6H-SiC(0001): $p = +7.5\ E12\ cm^{-2}$



doi.org/10.1016/j.apsusc.2020.148668 doi.org/10.1016/j.apsusc.2023.158617

Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

Schematic diagram of the measurement principle



Basis: signal intensity attenuation

Implementation: shadow cast on LO 964 cm^{-1}

Number of layers *N*: fractional and statistical

Alternative to: 2D width, 2D-to-G ratio

doi.org/10.1016/j.physe.2021.114853 doi.org/10.1016/j.apsusc.2022.155054

Graphene on Silicon Carbide Platform

for **Magnetic Field Detection**

under Extreme Temperature Conditions

and Neutron Radiation

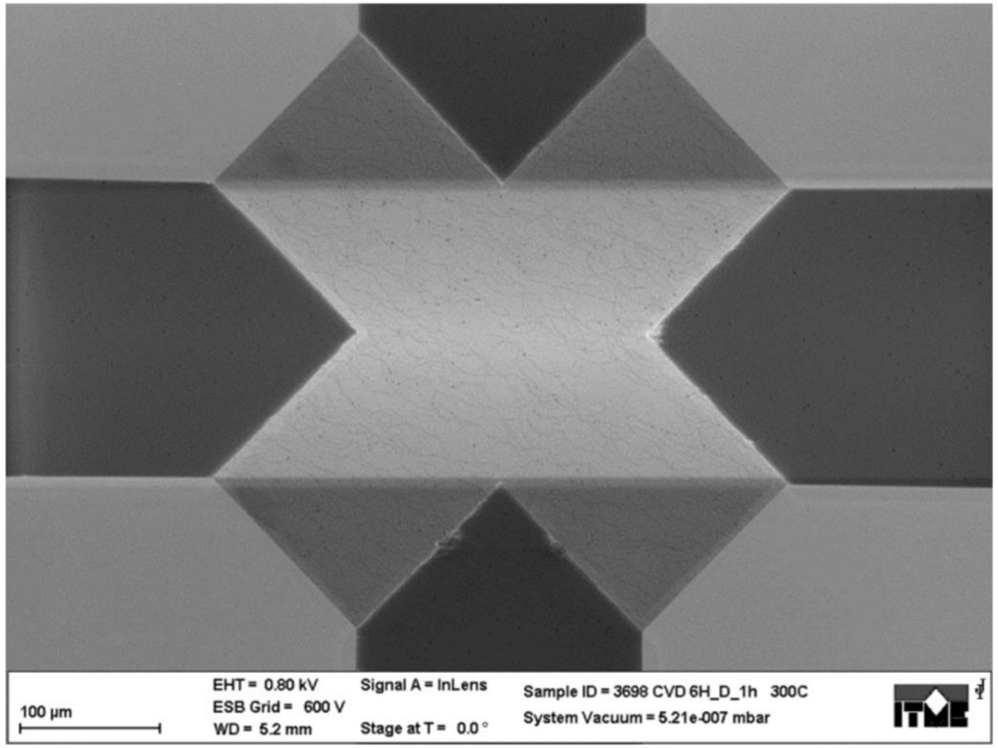
Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

Principle of operation: classical Hall effect

Configuration: van der Pauw

Active area: equal-arm cross 100 µm x 300 µm

Total dimensions: 1.4 mm x 1.4 mm

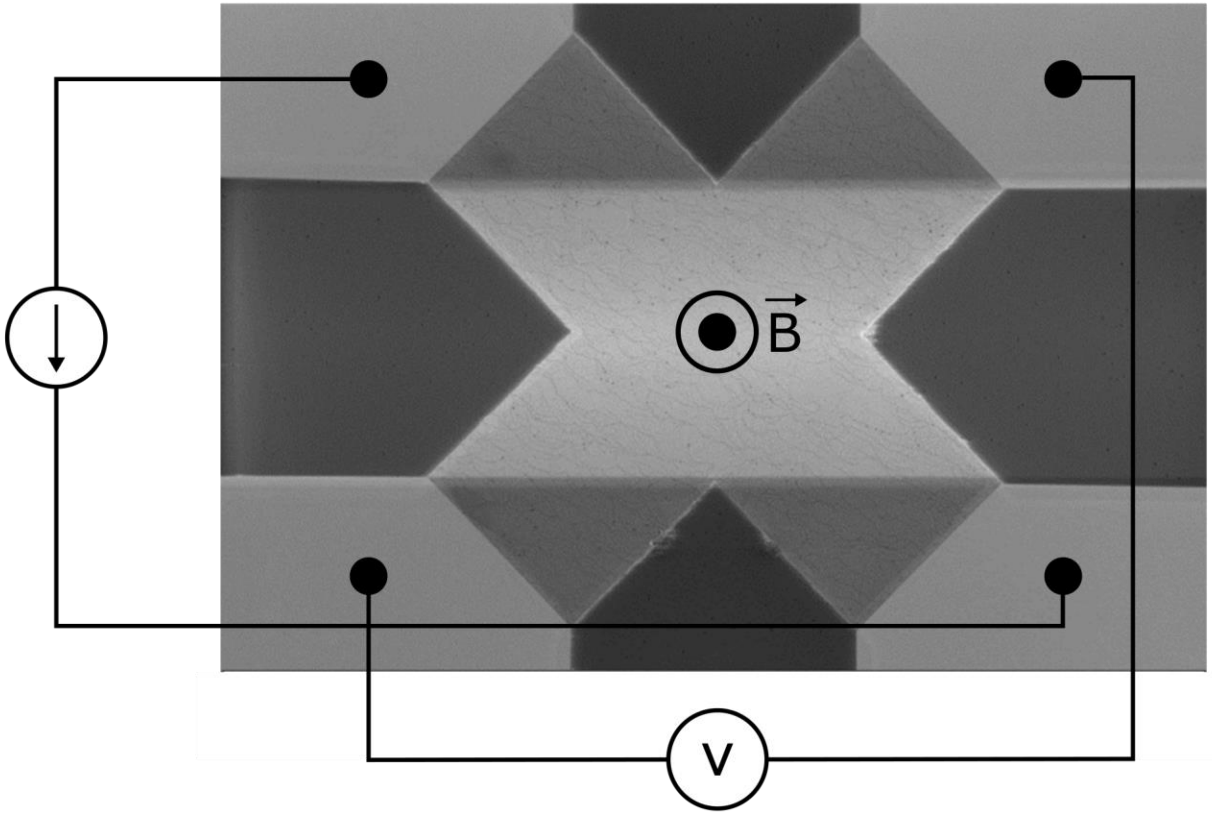


doi.org/10.1016/j.carbon.2018.07.049

Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

Input: direct current

Output: offset voltage + Hall voltage($\vec{B}$)



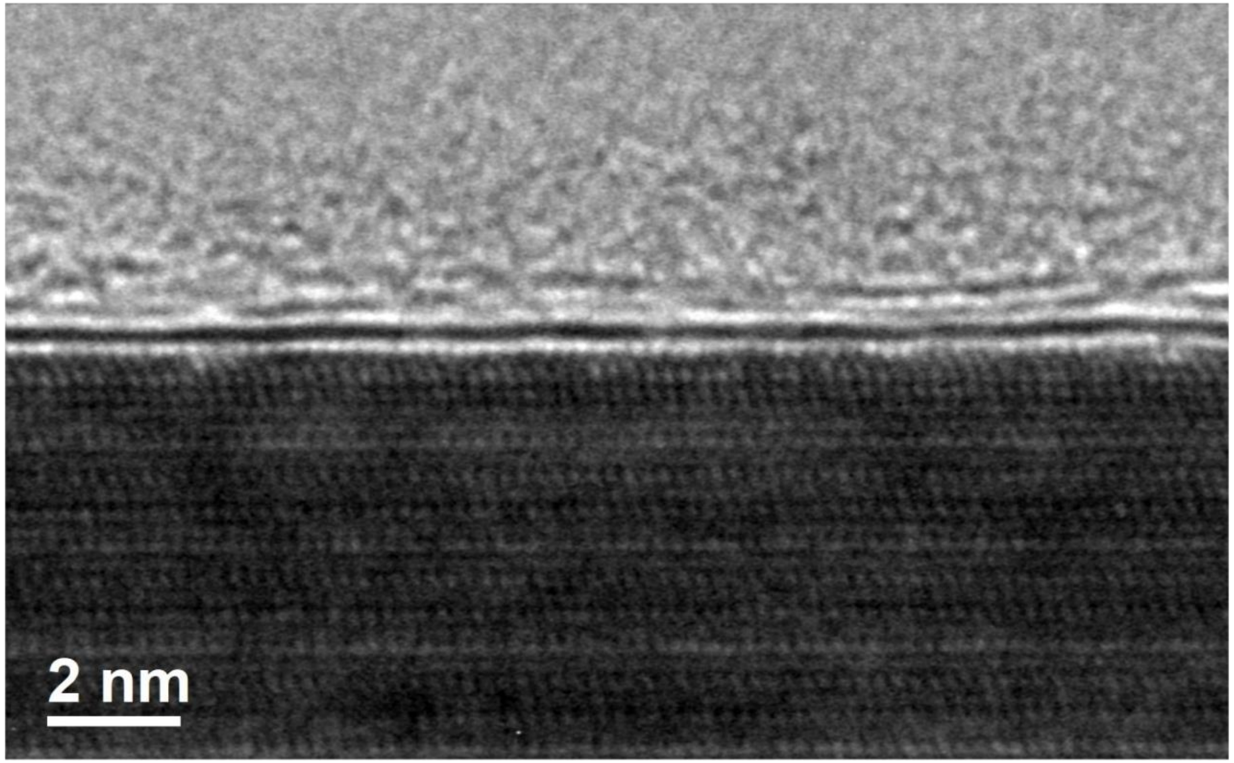
Graphene on Silicon Carbide Platform for Magnetic Field Detection under Extreme Temperature Conditions and Neutron Radiation

Passivation: aluminum oxide

Process: atomic layer deposition

Precursors: TMA and DI

Purpose: environmental protection



doi.org/10.1016/j.physe.2022.115264

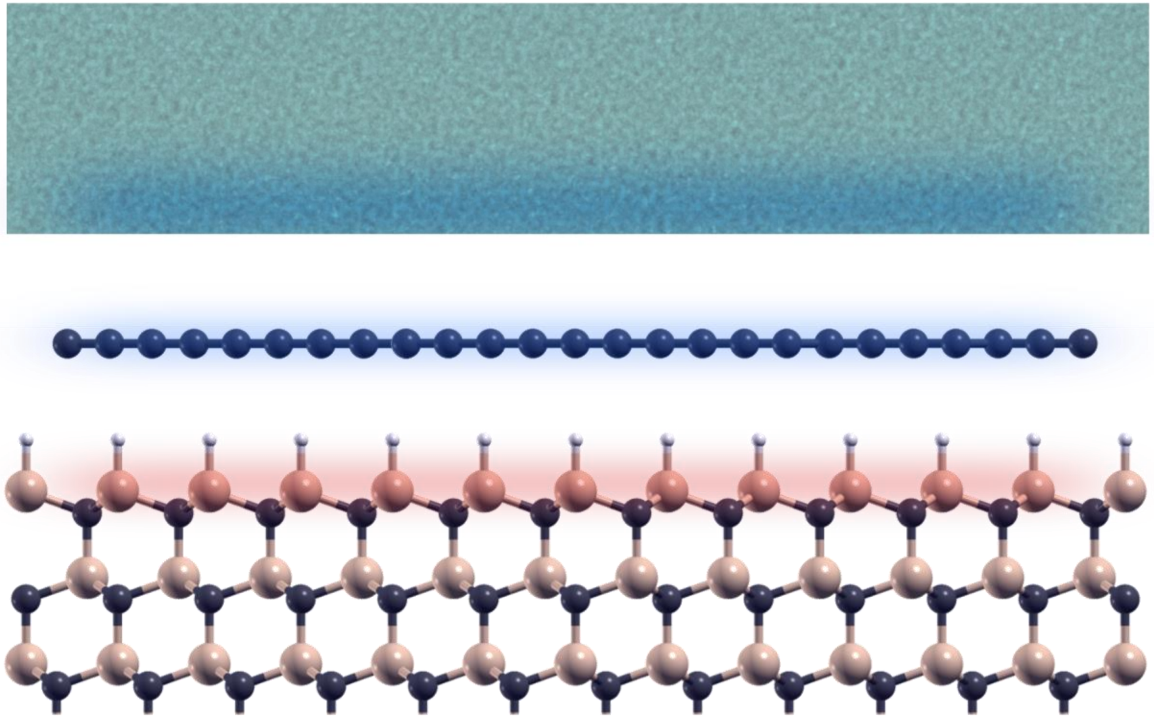
Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

100-nm *a*-Al2O3: excess positive charge

Polarization effect: negative

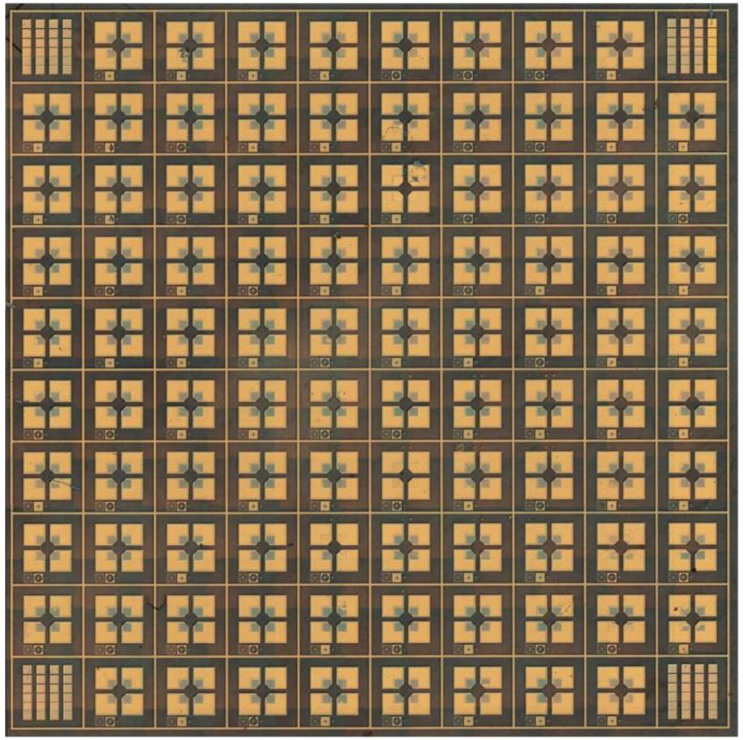
On 4H-SiC(0001): p = +7.5 E12 cm^{-2}

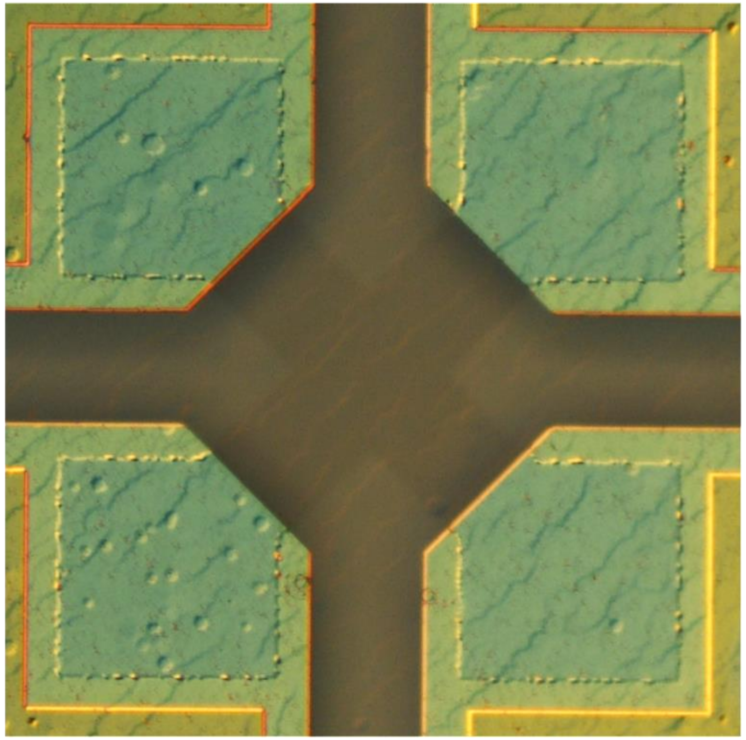
On 6H-SiC(0001): p = +4.6 E12 cm^{-2}

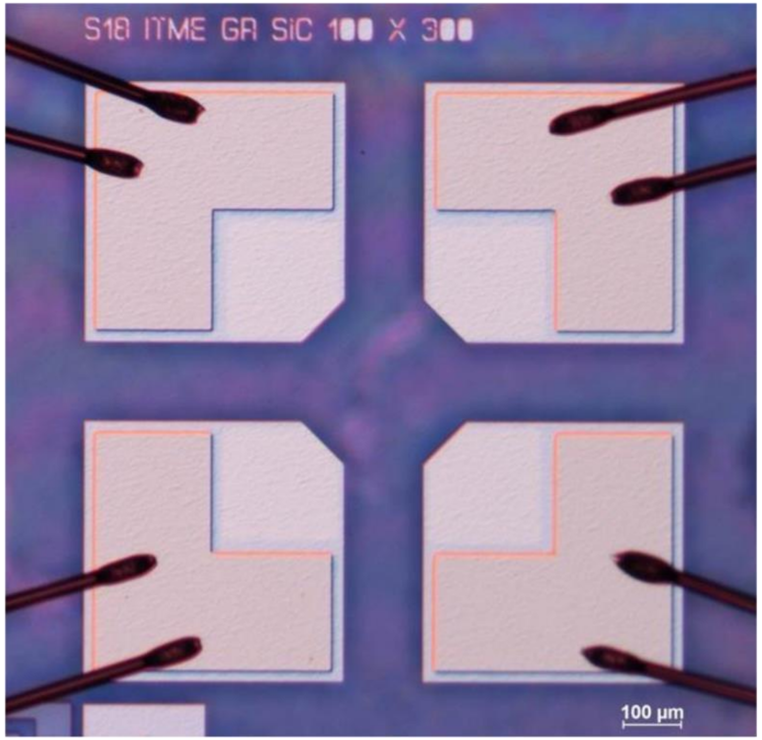


doi.org/10.1016/j.apsusc.2020.148668

Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors







doi.org/10.1016/j.physe.2021.114853 doi.org/10.1016/j.physe.2022.115264

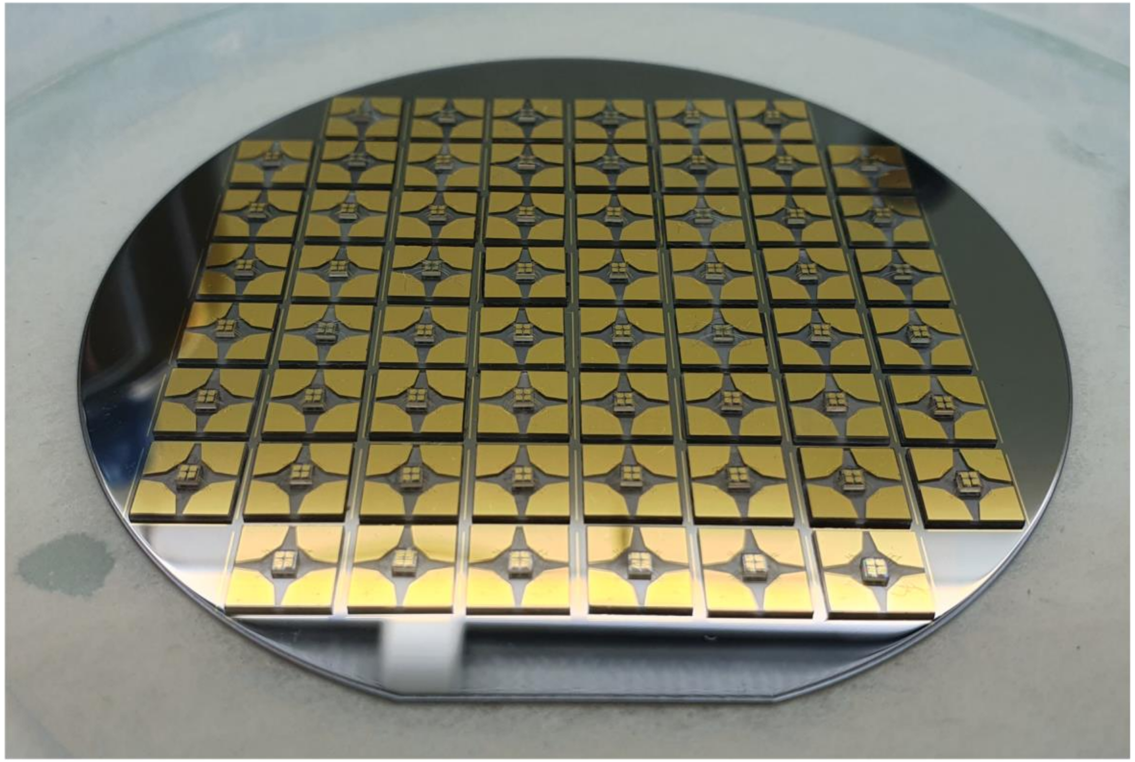
Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

Mounting: custom holders

Feed current: < 10 mA

Magnetic induction: 0.55 T

Temperatures: up to 500 °C



10.1109/TED.2019.2915632

Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

Graphene on Silicon Carbide Platform

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Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

Current-mode sensitivity: $\frac{d\mathrm{U}_{\mathrm{Hall}}}{d\mathrm{B}}/\mathrm{I}$

Expressed in: V/AT

Inversely proportional to: hole density

Polytype dependent: Yes

Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

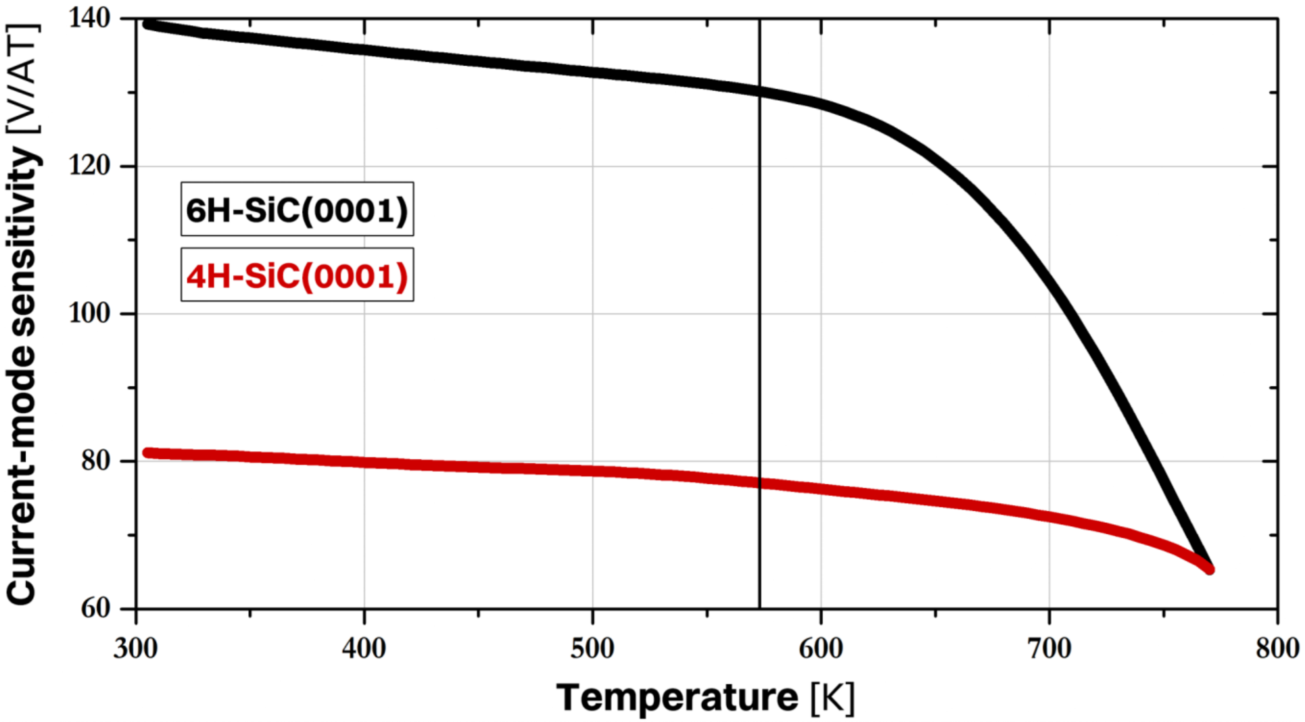
Two platforms: 6H-SiC and 4H-SiC

Two levels of sensitivity:

6H-SiC: 140 V/AT
4H-SiC: 80 V/AT

Start temperature: RT

End temperature: 770 K (497 °C)



Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

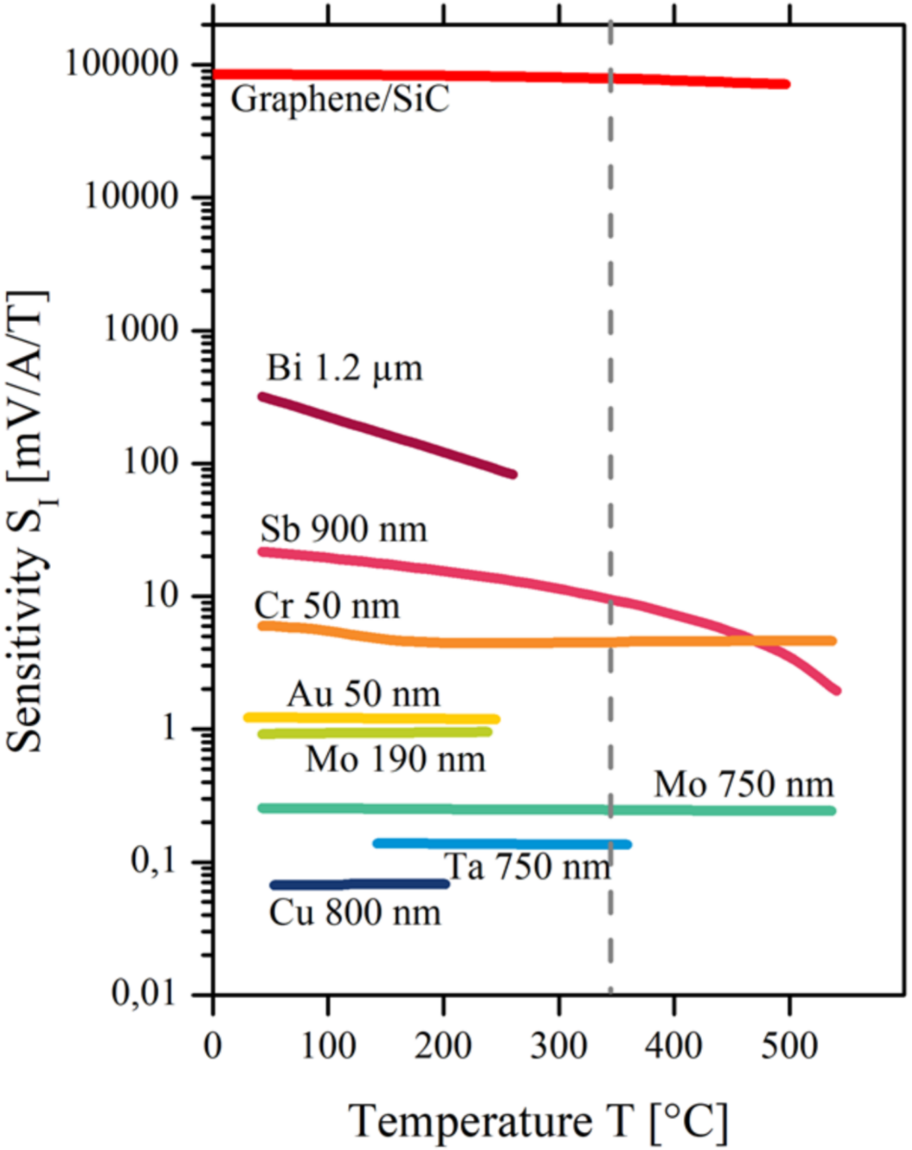
Alternative platforms: Bi, Sb, Cr, Au, Mo, Ta, Cu

Sensitivities: 0.1 mV/AT - 100 mV/AT

Start temperature: 50 °C

End temperature: 770 K (500 °C)

Source: Entler S., et al., Sensors 2021, 21, 721.



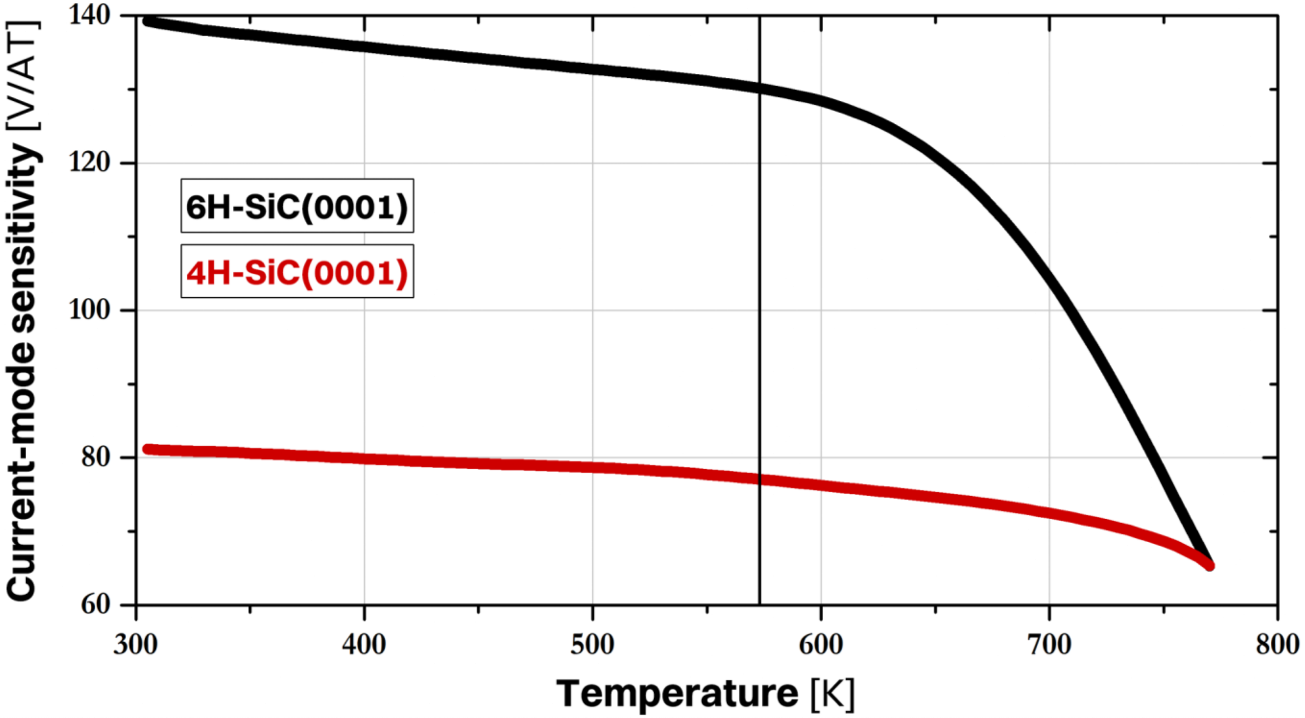
Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

Down-bending: >300 °C

Physical degradation: No

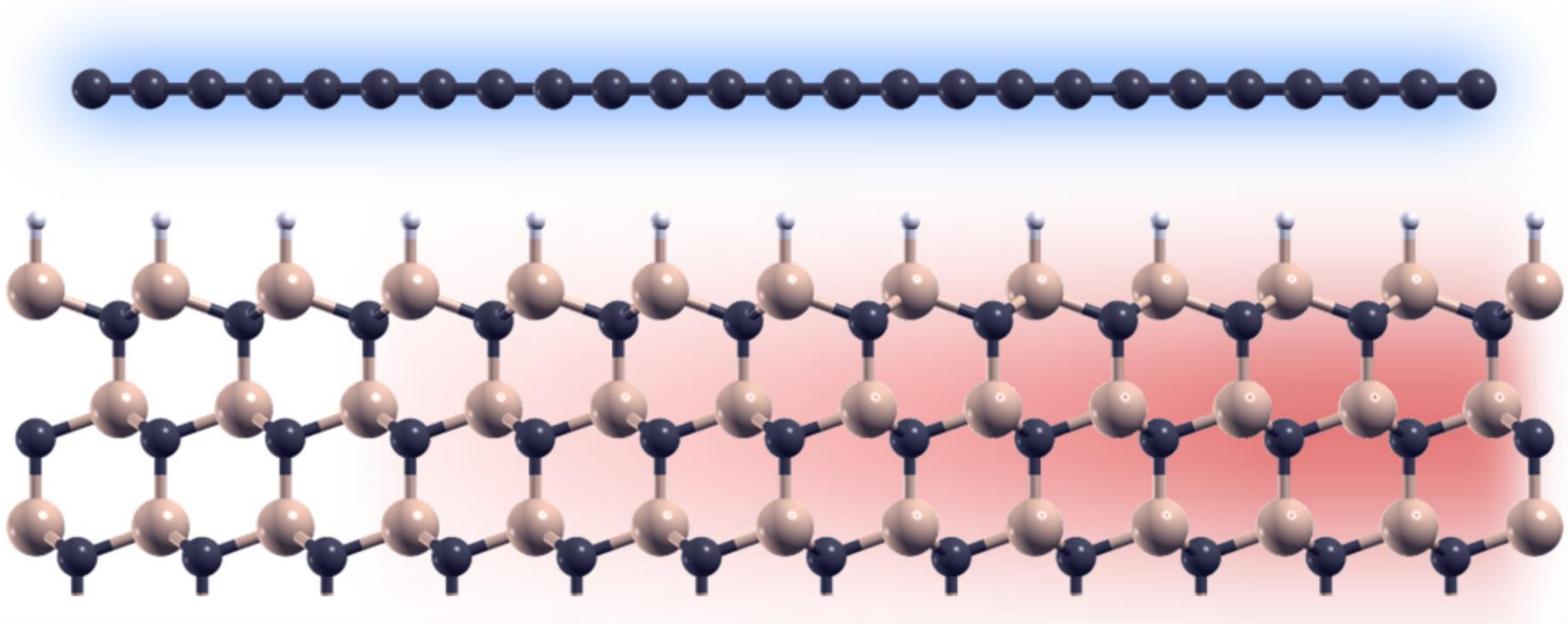
Fully reversible: Yes

Possible hallmark: Yes



Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

Double-carrier transport: holes in QFS graphene and thermally-activated electrons emitted in the bulk of the semi-insulating 6H-SiC(0001) and 4H-SiC(0001)



Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

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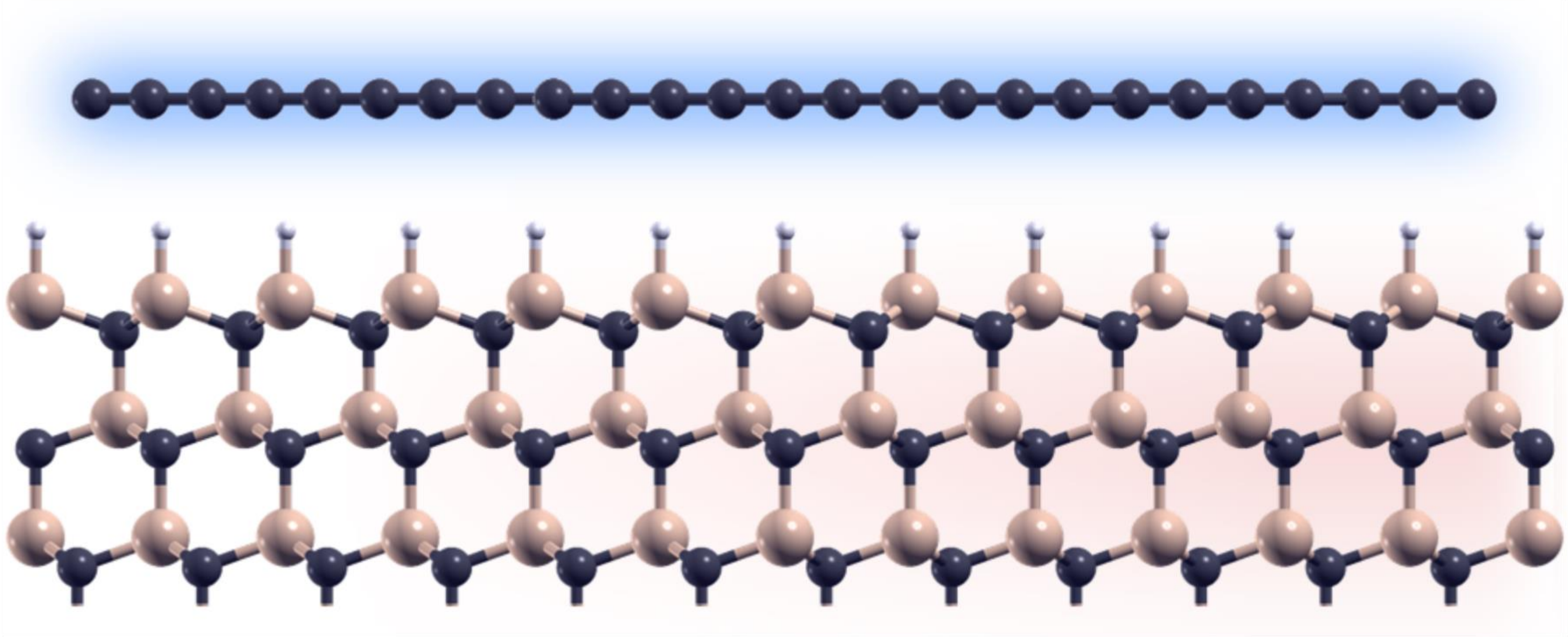

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Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

Graphene on **Ion-implanted** Silicon Carbide Platform

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Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

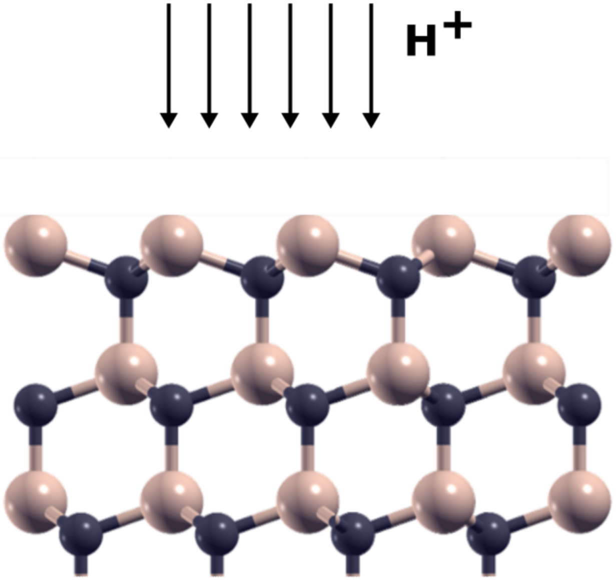
As revealed by High-Resolution Photo-Induced Transient Spectroscopy (**HRPITS**)

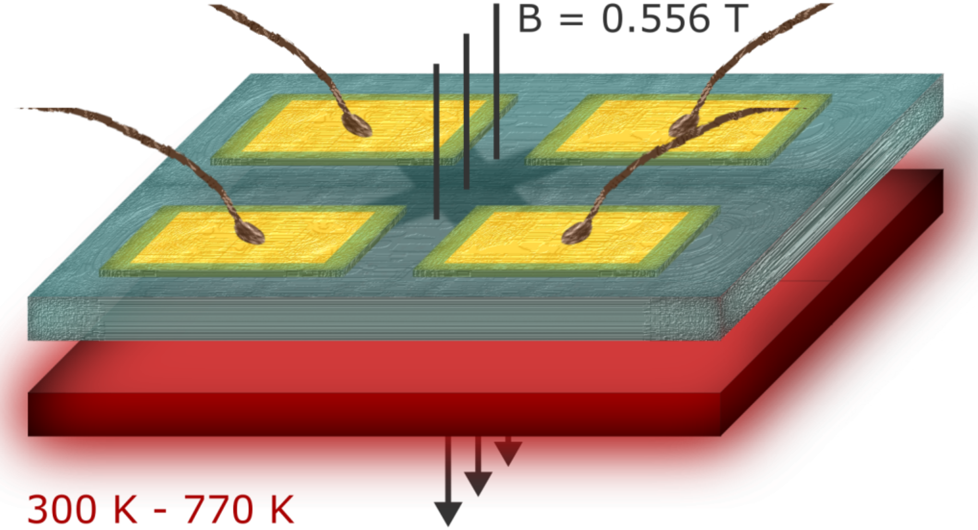
SI vanadium-compensated 6H-SiC has 9 trap levels

SI HP intrinsically-compensated 4H-SiC has 17 trap levels

Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

Pre-epitaxially modify the semi-insulating high-purity 4H-SiC by **implanting hydrogen (H^+) ions**





doi.org/10.1016/j.cartre.2023.100303

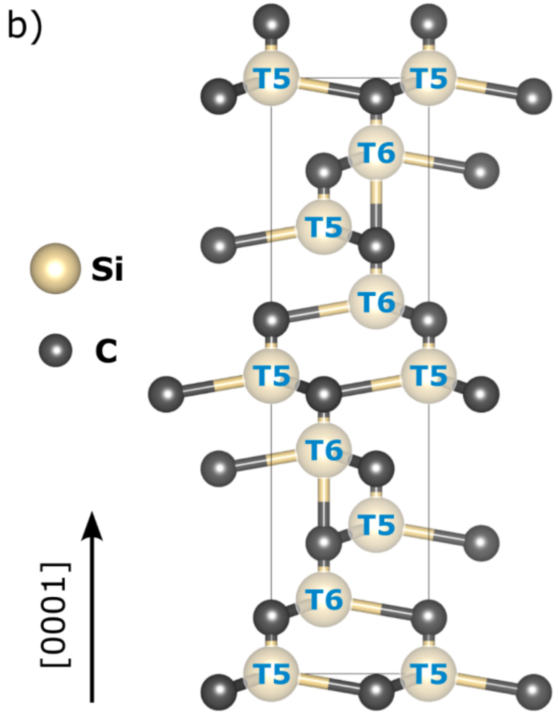
Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

Pre-epitaxial bombardment: H^+ ions

Energy: 20 keV

Objective: elimination of deep electron traps related to silicon vacancies in the charge state (2-/-) occupying the *h* and *k* sites of the 4H-SiC lattice

T5$_{\mathbf{4H}}$: E_a = 708 meV
T6$_{\mathbf{4H}}$: E_a = 753 meV



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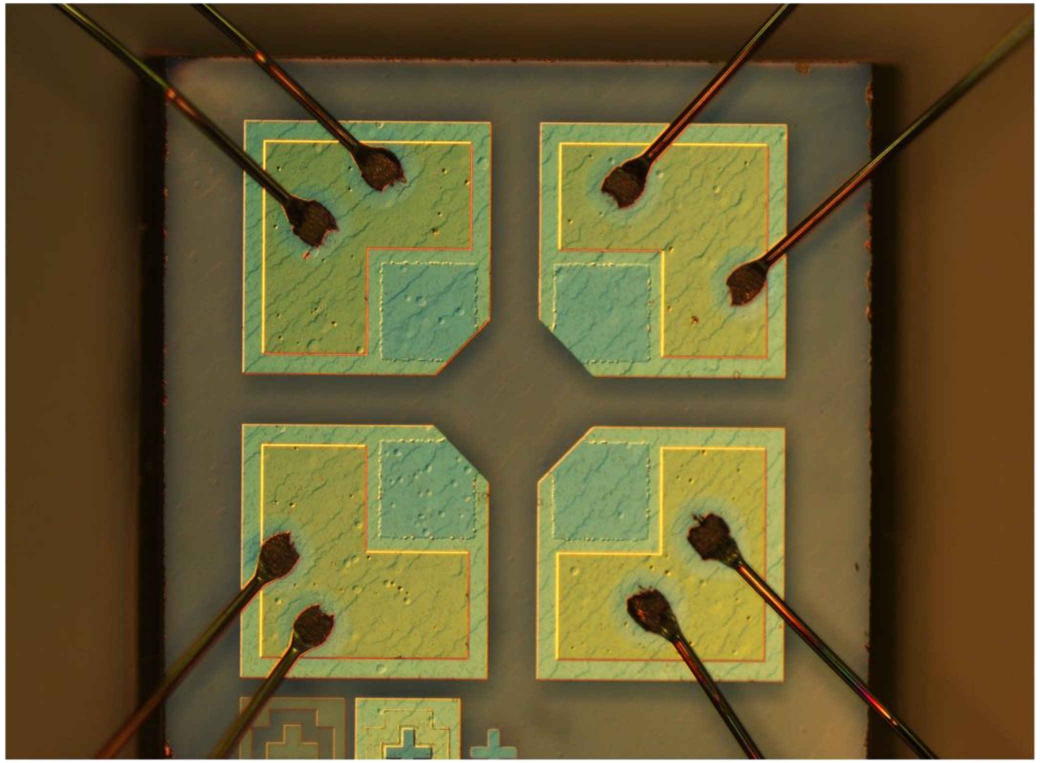
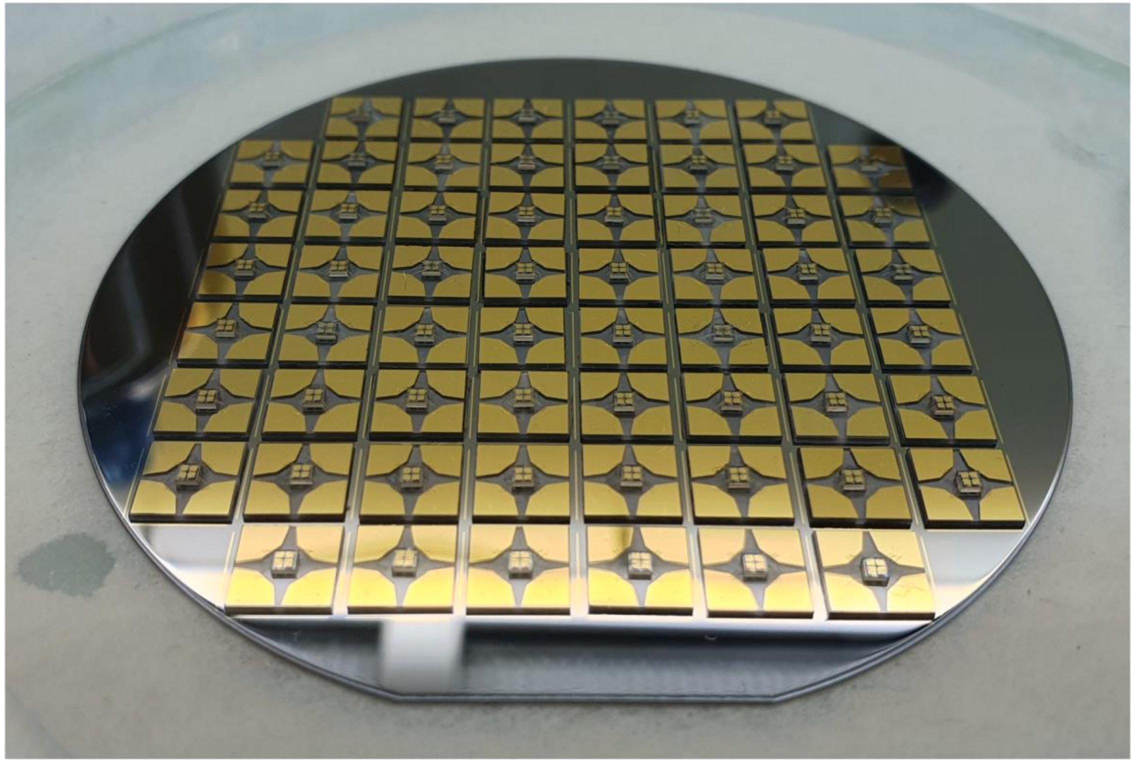
Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors





Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

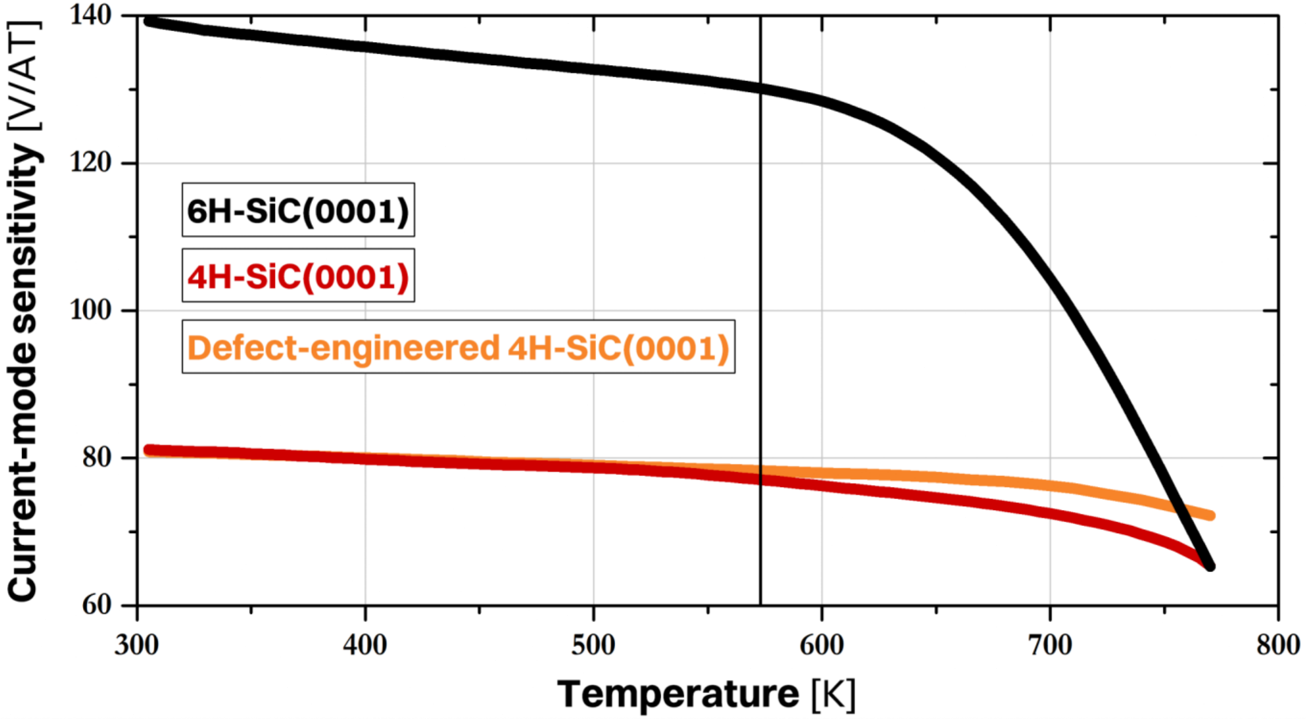
Platform: 4H-SiC

Type: Ion-implanted

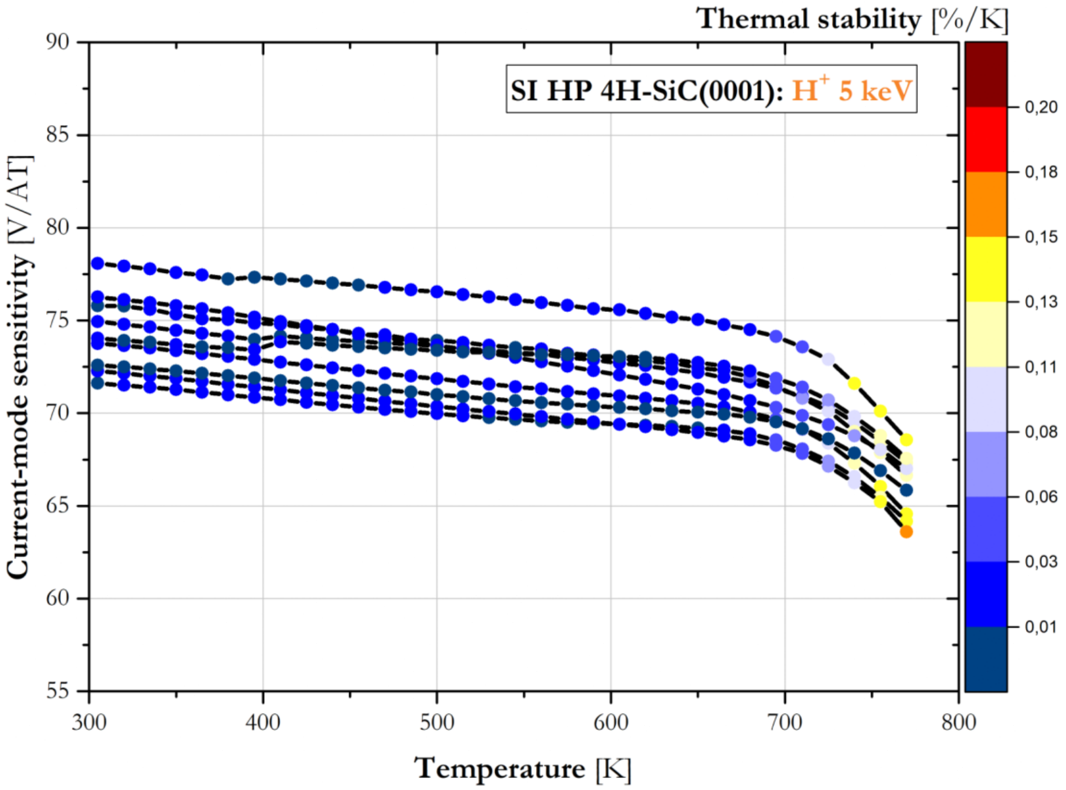
Current-mode sensitivity: **80 V/AT**

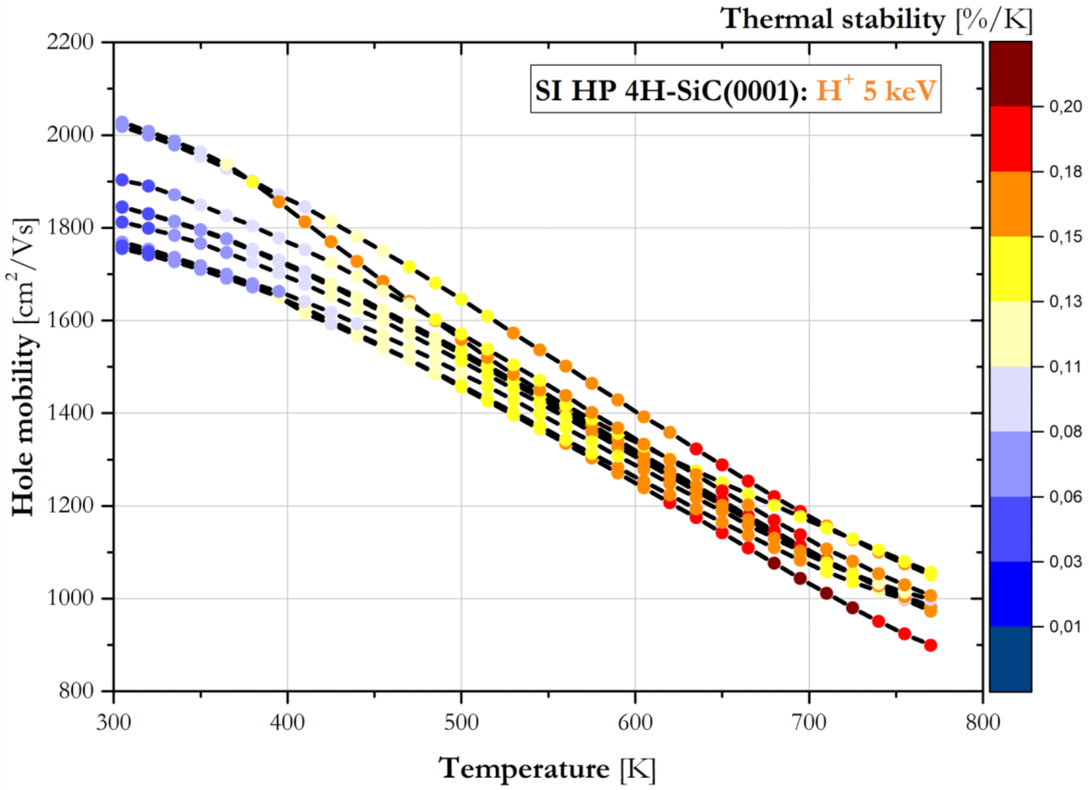
End temperature: **770 K (497 °C)**

Advantages: more linear, less dispersed



Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors





Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

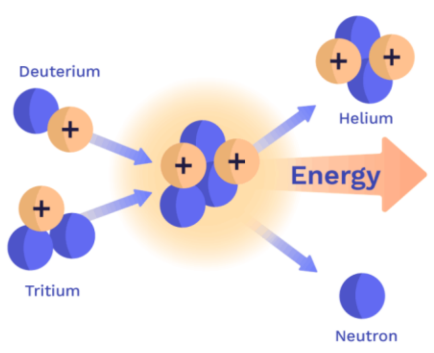
EUROfusion: transition from science-driven International Thermonuclear Experimental Reactor (**ITER**) to the industry-driven **DEMO**-class reactor

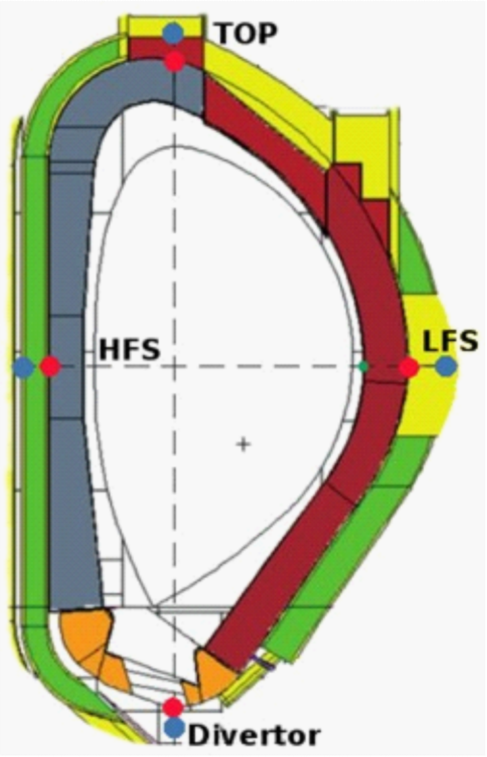
Magnetic diagnostics: 5.8 T with 2.5-mT accuracy

Ex-vessel: 473 K

In-vessel: 773 K (500 °C)

Hazard: neutron radiation up to **2E18** cm^{-2}





Graphene on Silicon Carbide Platform

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Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

Completed and published:

Fast neutron fluence of **6.7 E17** cm^{-2} (peak at 1 MeV) Exposure time: **5 days**

Completed but not yet published:

Fast neutron fluence of **2.0 E18** cm^{-2} (peak at 1 MeV) Exposure time: **10 days**

Fast neutron fluence of **4.0 E18** cm^{-2} (peak at 1 MeV) Exposure time: **23 days**

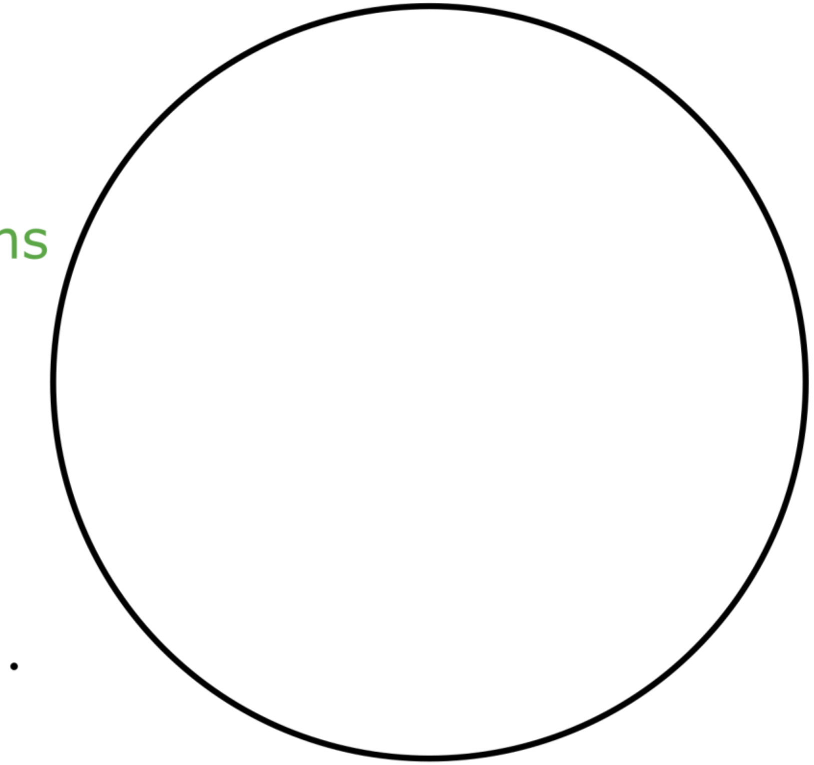
Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

Number of carbon atoms in graphene: 3.8 E15 cm^{-2}

Neutron fluence (dose): E17 - E18 cm^{-2}

There are 100 to 1000 more neutrons than carbon atoms

Neutrons are 100000 times smaller than carbon atoms



doi.org/10.1016/j.apsusc.2022.152992 doi.org/10.3390/s22145258 doi.org/10.1109/LSENS.2023.3297795

Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

MARIA reactor: fast neutron fluence of 6.7 E17 cm^{-2}

Estimated defect density: 4.0 E10 cm^{-2}

MARIA reactor: fast neutron fluence of 2.0 E18 cm^{-2}

Estimated defect density: 1.4 E11 cm^{-2}

It takes **over a dozen mln neutrons** to introduce **1 defect in graphene**

Summary & Conclusions

Material composition: *a*-Al2O3/QFS-graphene/SiC(0001)

Additional modification: low-energy ion implantation

Competitive advantages:

- operates up to 770 K (497 °C), and likely beyond
- largely resistant to neutron irradiation

Potential application: magnetic diagnostics and plasma control in fusion reactors

Ion implantation for graphene-enabled magnetic diagnostics: application perspectives in modern fusion reactors

THANK YOU FOR YOUR ATTENTION!

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NCBR Narodowe Centrum Badań i Rozwoju M-ERA.NET I4Bags

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For details, please visit: **www.graphene2get.com**

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