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

Tymoteusz Ciuk, PhD

Łukasiewicz Research Network

Institute of Microelectronics and Photonics, Warsaw, Poland

Łukasiewicz
Institute of Microelectronics
and Photonics

Graphene Week 2023 **September 7, 2023**

Presentation outline

Graphene on Silicon Carbide Platform

for **Magnetic Field Detection**

under **Extreme Temperature** Conditions

and **Neutron Radiation**

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

Łukasiewicz
Institute of Microelectronics
and Photonics

Graphene Week 2023 **September 7, 2023**

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

Thermal stability of transport properties

Two-dimensional character **Why graphene on SiC?** Hole mobility up to 5000 cm^2/Vs

Fixed hole concentration

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

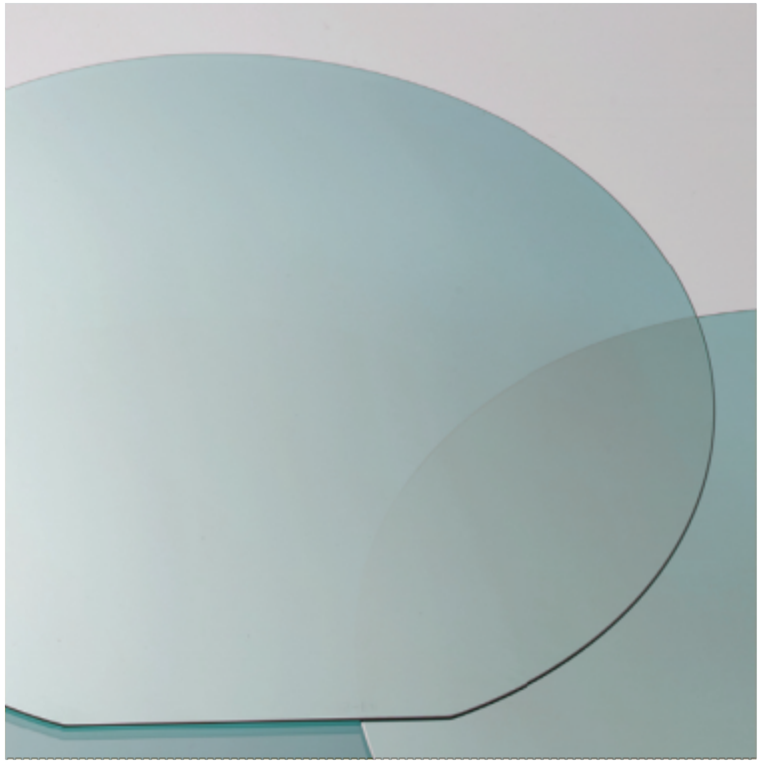
Epitaxy: Chemical Vapor Deposition (CVD)

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

Łukasiewicz
Institute of Microelectronics and Photonics

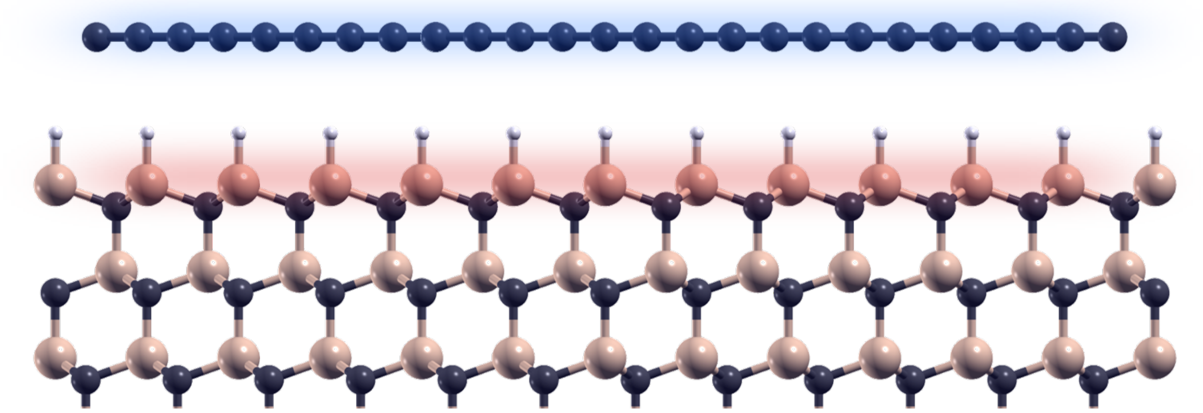
Graphene on Silicon Carbide Platform for Magnetic Field Detection under Extreme Temperature Conditions and Neutron Radiation

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

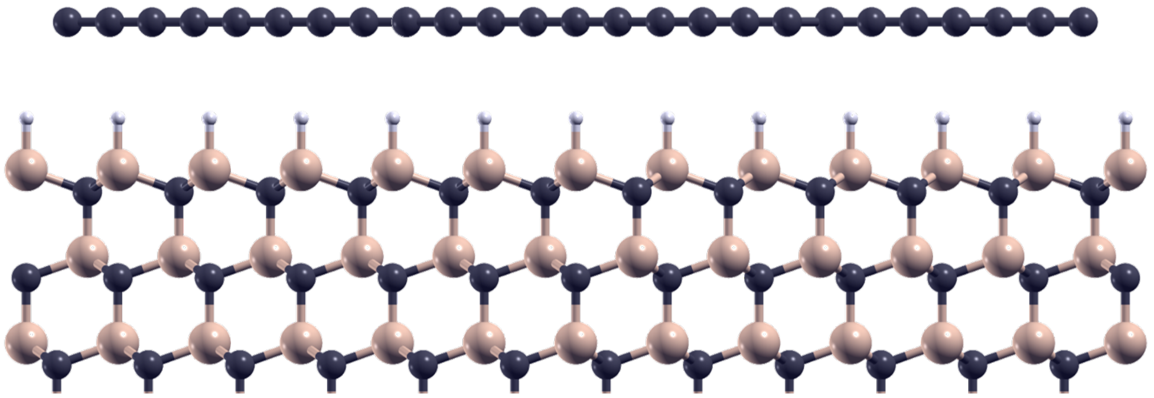
Łukasiewicz
Institute of Microelectronics and Photonics

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

Hydrogen intercalation: quasi-free-standing graphene

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

Łukasiewicz
Institute of Microelectronics and Photonics

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

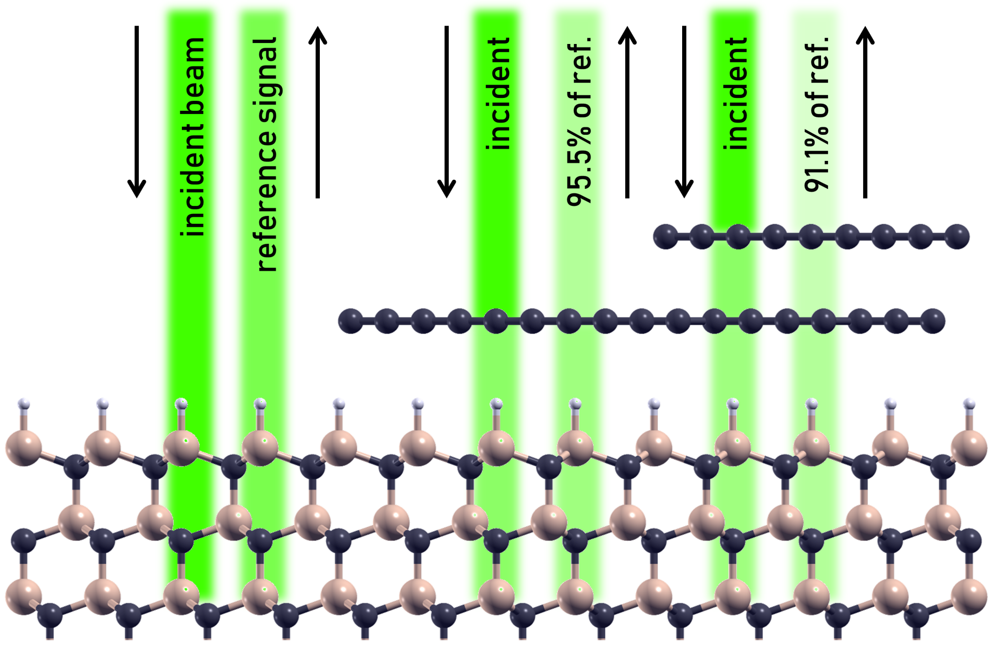
Basis: signal intensity attenuation

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

Number of layers *N*: fractional and statistical

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

Schematic diagram of the measurement principle



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

Łukasiewicz
Institute of Microelectronics and Photonics

Graphene on Silicon Carbide Platform

for **Magnetic Field Detection**

under Extreme Temperature Conditions

and Neutron Radiation

Łukasiewicz
Institute of Microelectronics
and Photonics

Graphene Week 2023 **September 7, 2023**

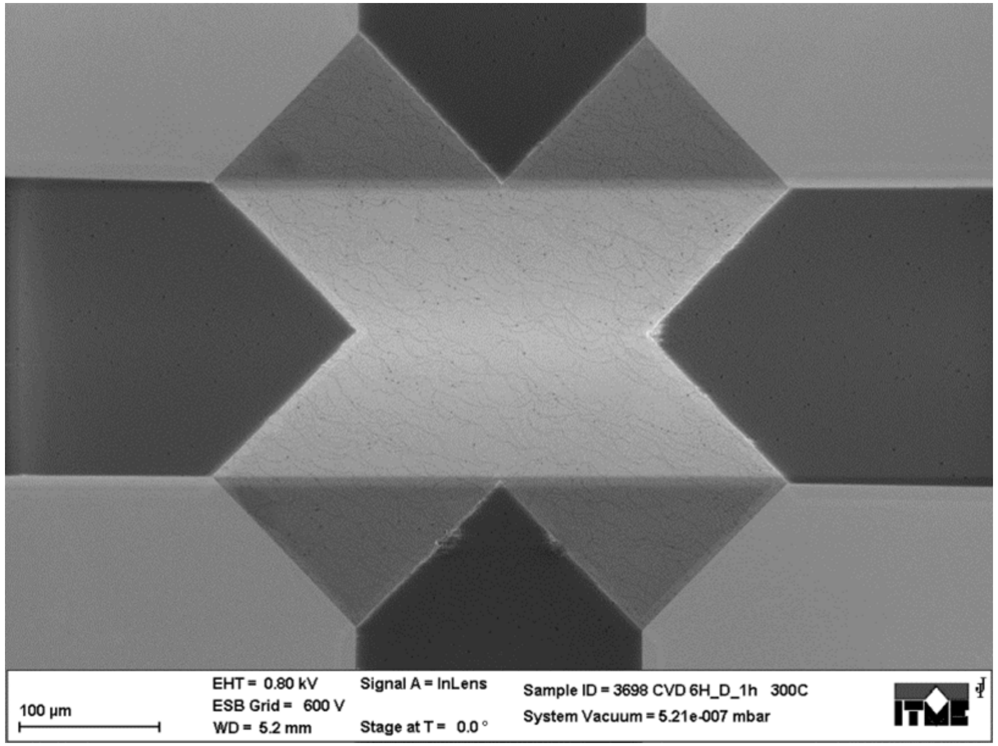
Graphene on Silicon Carbide Platform for Magnetic Field Detection under Extreme Temperature Conditions and Neutron Radiation

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

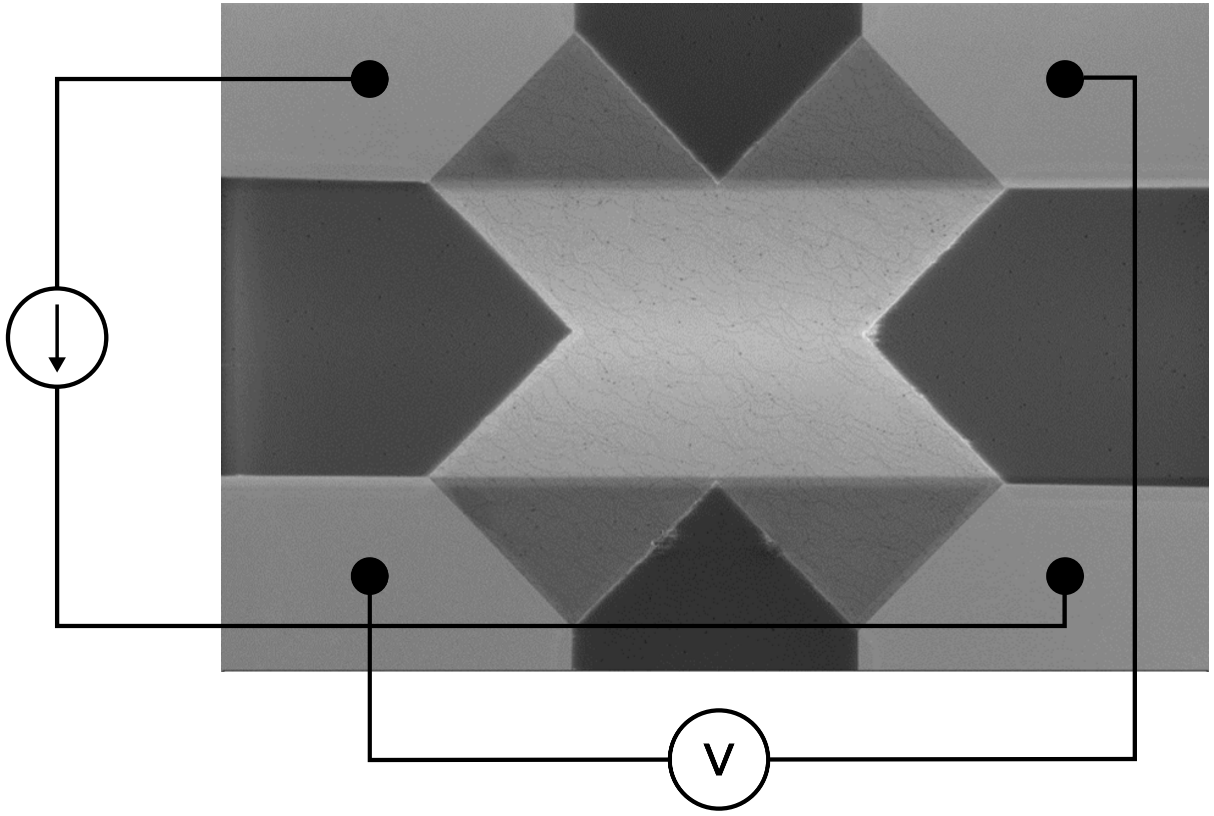


doi.org/10.1016/j.carbon.2018.07.049

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

Input: direct current

Output: offset voltage + Hall voltage



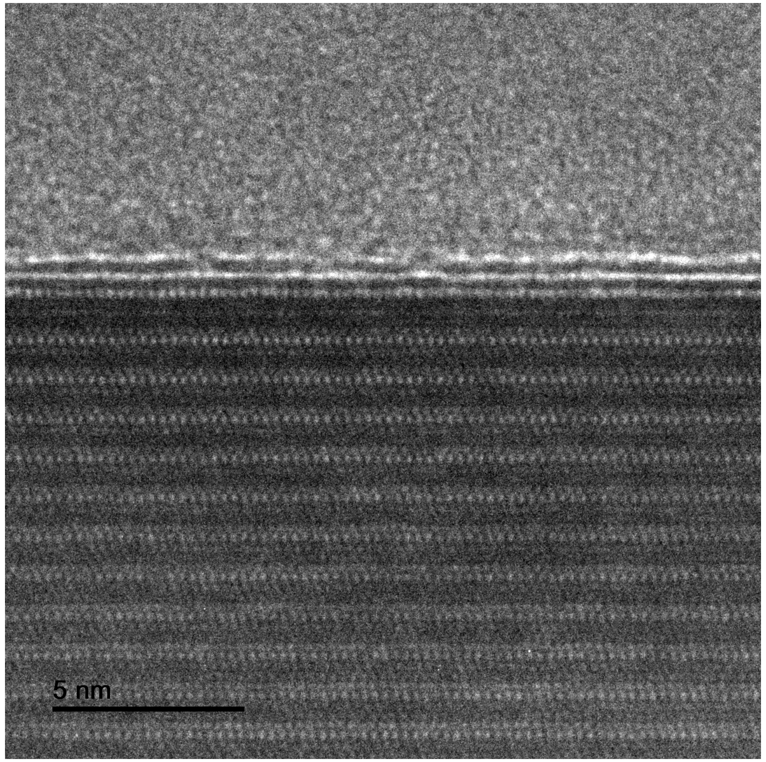
Graphene on Silicon Carbide Platform for Magnetic Field Detection under Extreme Temperature Conditions and Neutron Radiation

Passivation: aluminum oxide

Process: atomic layer deposition

Precursors: TMA and DI

Purpose: environmental protection



doi.org/10.1016/j.physe.2022.115264

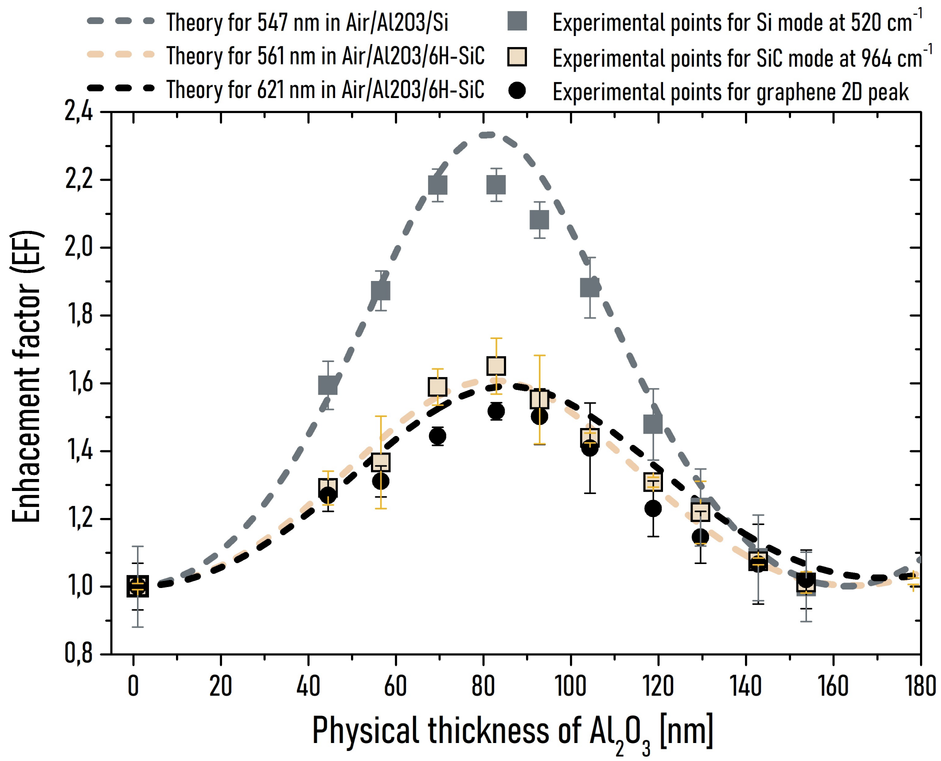
Graphene on Silicon Carbide Platform for Magnetic Field Detection under Extreme Temperature Conditions and Neutron Radiation

Phenomenon: passivation-enhanced Raman spectroscopy

Positive interference: 85 nm

Stoichiometry: oxygen deficiency

Passivation thickness: 100 nm



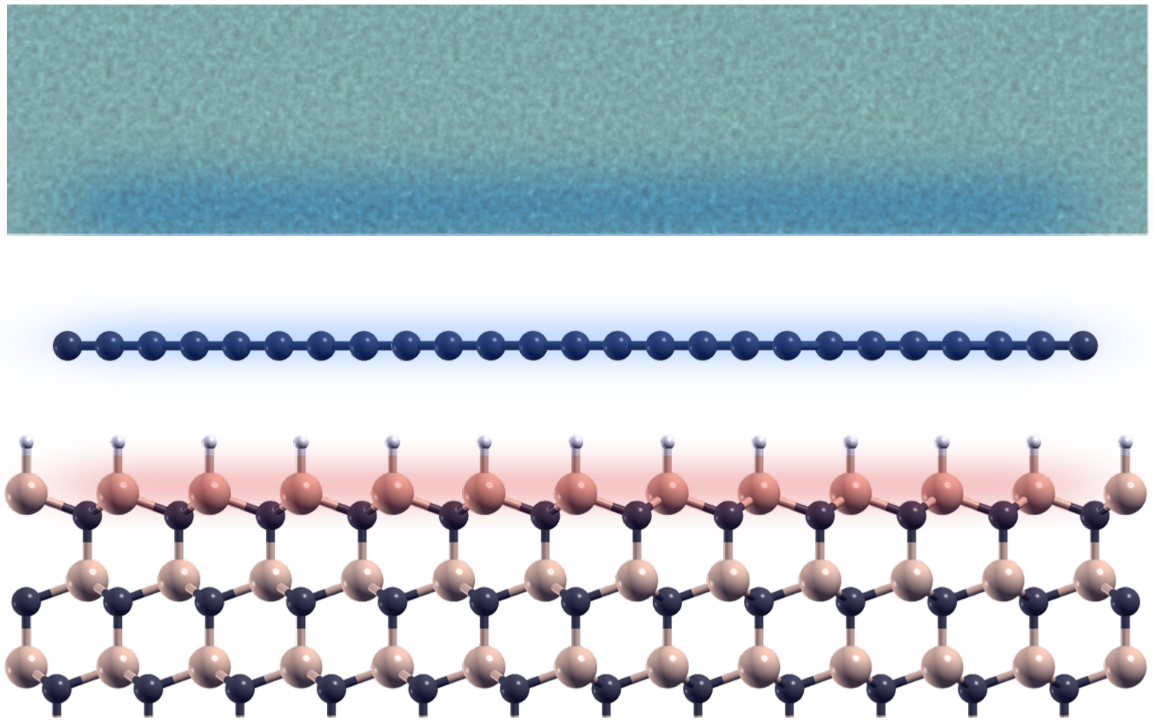
doi.org/10.1063/5.0082694

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

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

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

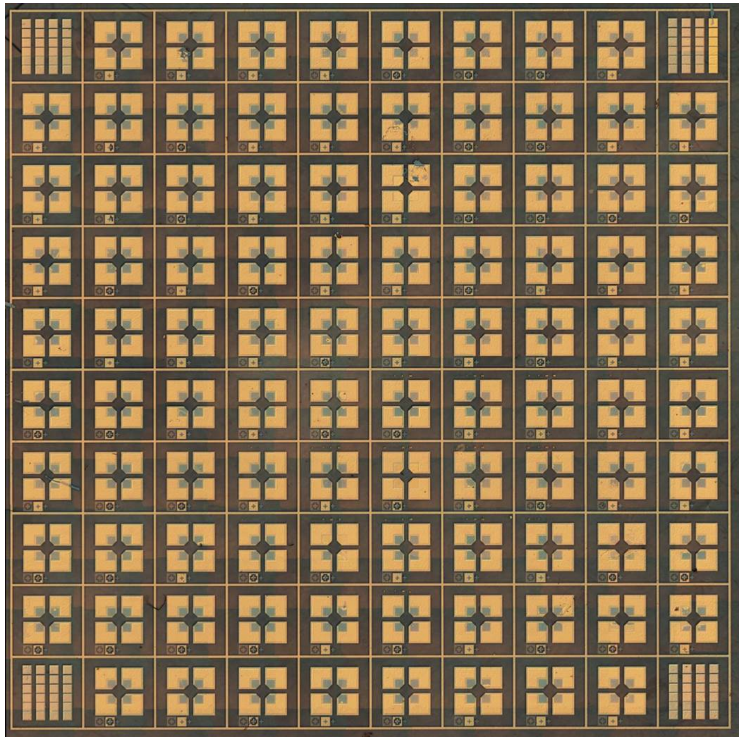
On 6H-SiC(0001): p = +4.6 E12 cm^{-2}

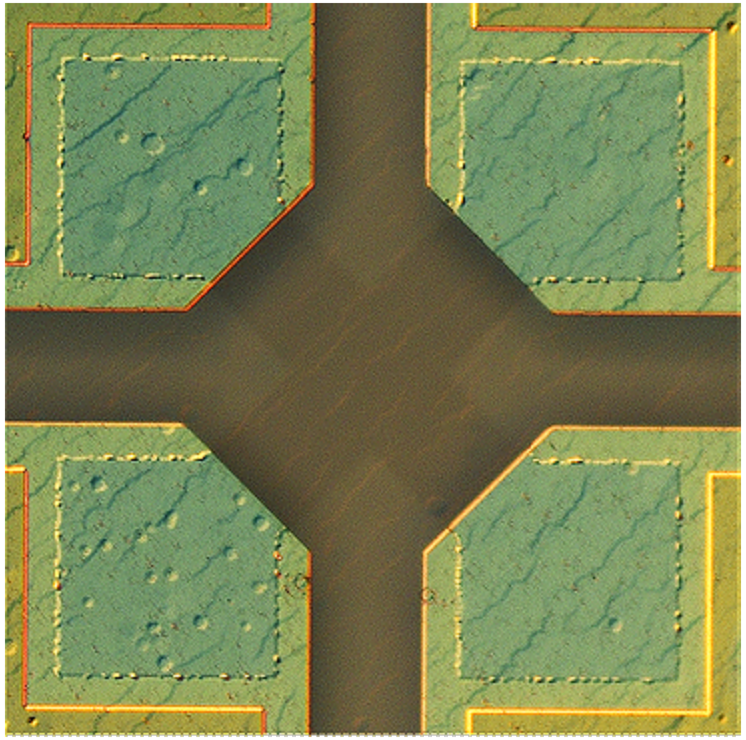


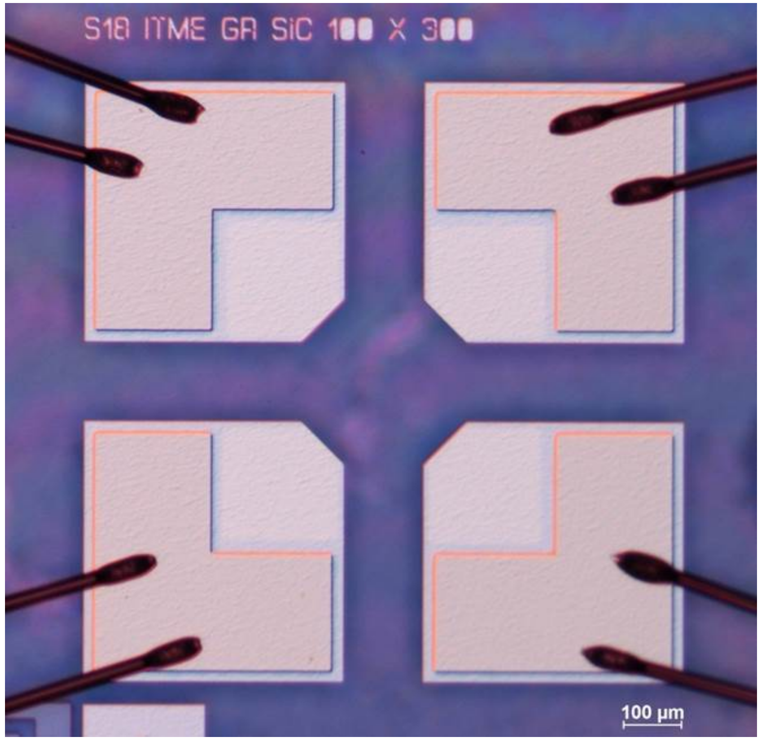
doi.org/10.1016/j.apsusc.2020.148668

Łukasiewicz
Institute of Microelectronics and Photonics

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







doi.org/10.1016/j.physe.2021.114853

Łukasiewicz
Institute of Microelectronics and Photonics

Graphene Week 2023 **September 7, 2023**

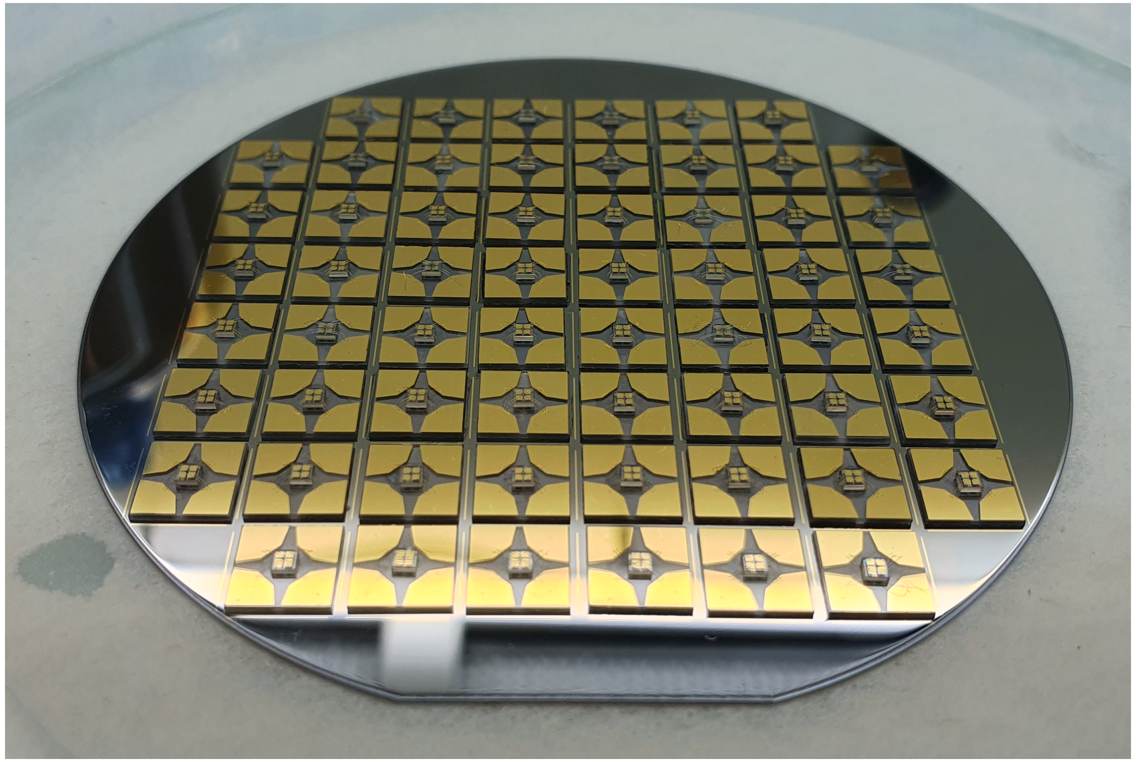
Graphene on Silicon Carbide Platform for Magnetic Field Detection under Extreme Temperature Conditions and Neutron Radiation

Mounting: custom holders

Feed current: < 10 mA

Magnetic induction: 0.55 T

Temperatures: up to 500 °C



10.1109/TED.2019.2915632

Graphene on Silicon Carbide Platform

for Magnetic Field Detection

under **Extreme Temperature Conditions**

and Neutron Radiation

Łukasiewicz
Institute of Microelectronics
and Photonics

Graphene Week 2023 **September 7, 2023**

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

Current-mode sensitivity: $\frac{dU_{Hall}}{dB}/I$

Expressed in: V/AT

Inversely proportional to: hole density

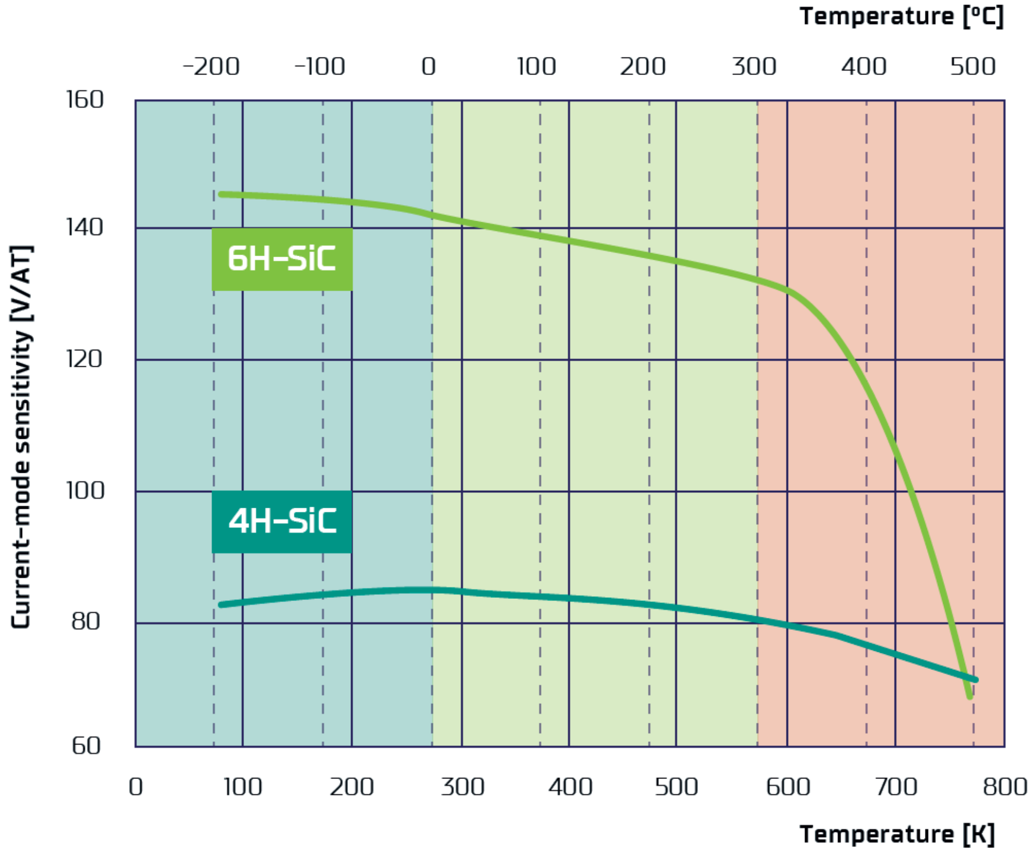
Graphene on Silicon Carbide Platform for Magnetic Field Detection under Extreme Temperature Conditions and Neutron Radiation

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

Two levels of sensitivity: 140 V/AT, 80 V/AT

Start temperature: liquid nitrogen

End temperature: 500 °C



www.researchgate.net/profile/Tymoteusz-Ciuk/publications

Łukasiewicz
Institute of Microelectronics and Photonics

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

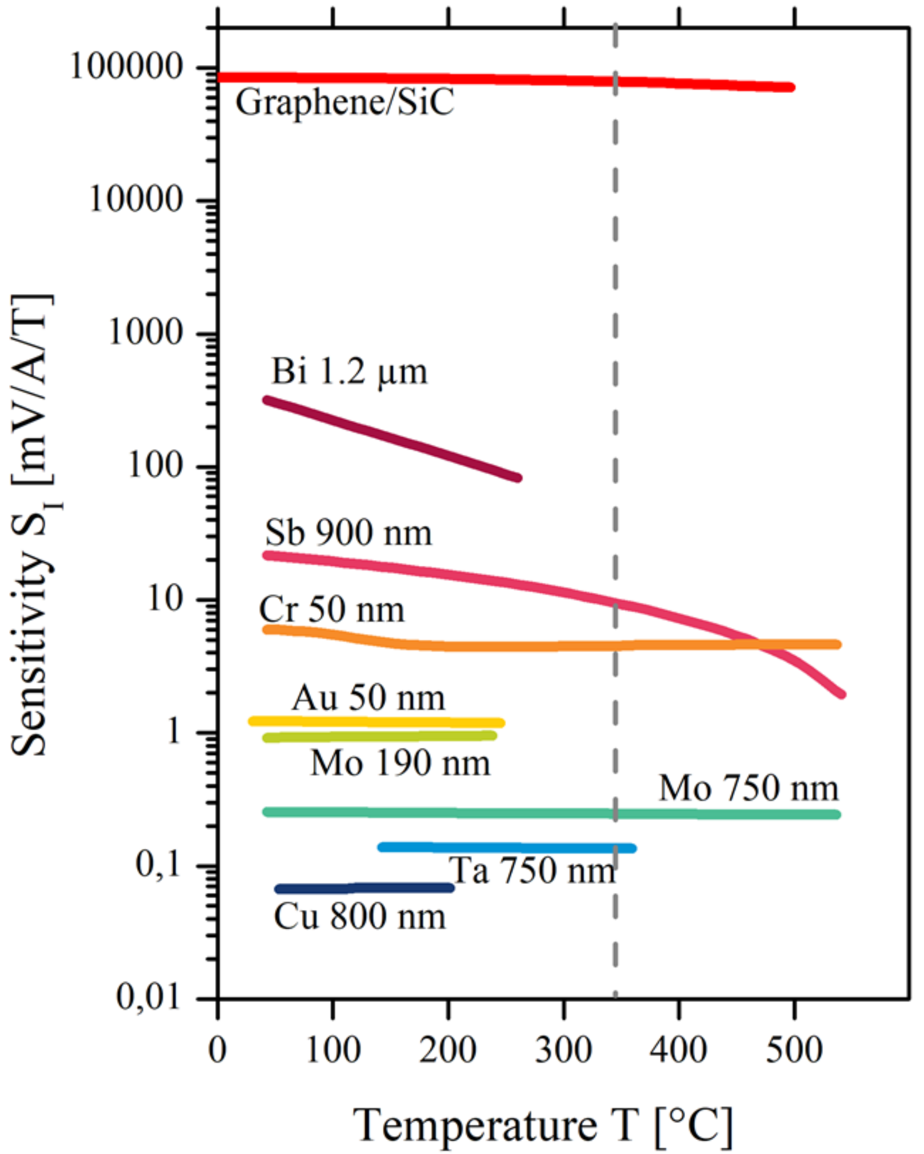
Alternative platforms: Bi, Sb, Cr, Au, Mo, Ta, Cu

Sensitivities: 0.1 mV/AT - 100 mV/AT

Start temperature: 50 °C

End temperature: 500 °C

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



Łukasiewicz
Institute of Microelectronics and Photonics

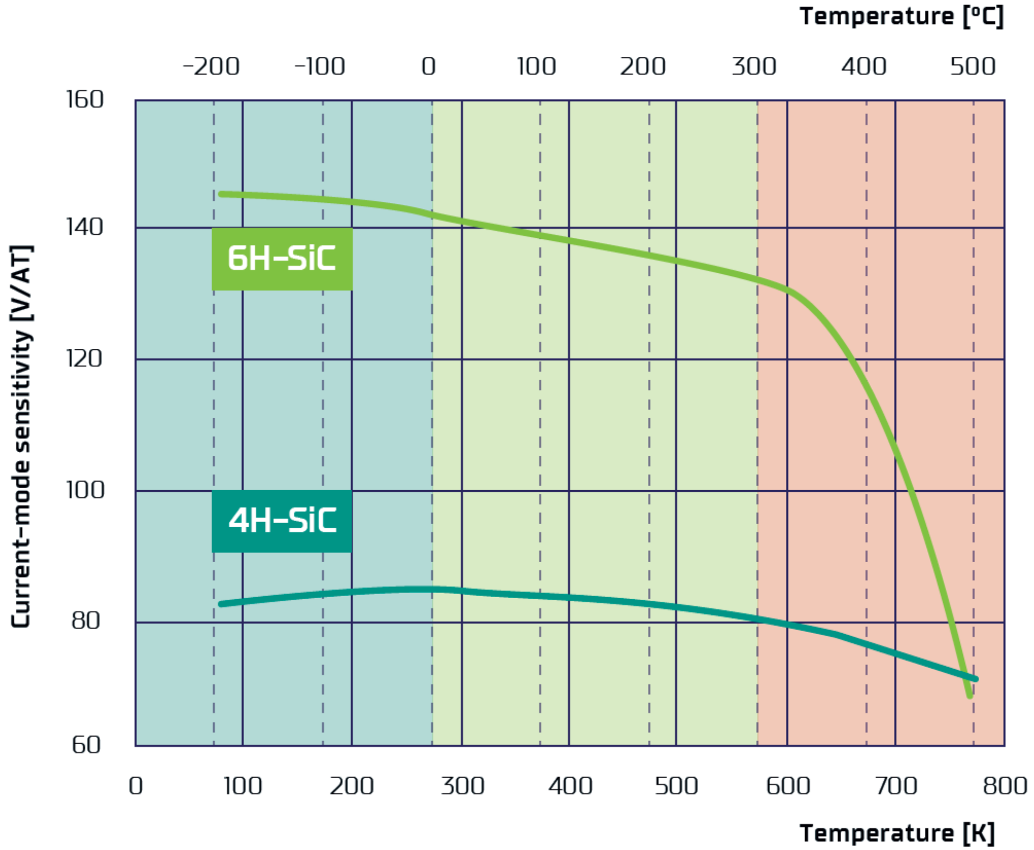
Graphene on Silicon Carbide Platform for Magnetic Field Detection under Extreme Temperature Conditions and Neutron Radiation

Characteristic down-bending: >300 °C

Physical degradation: No

Fully reversible: Yes

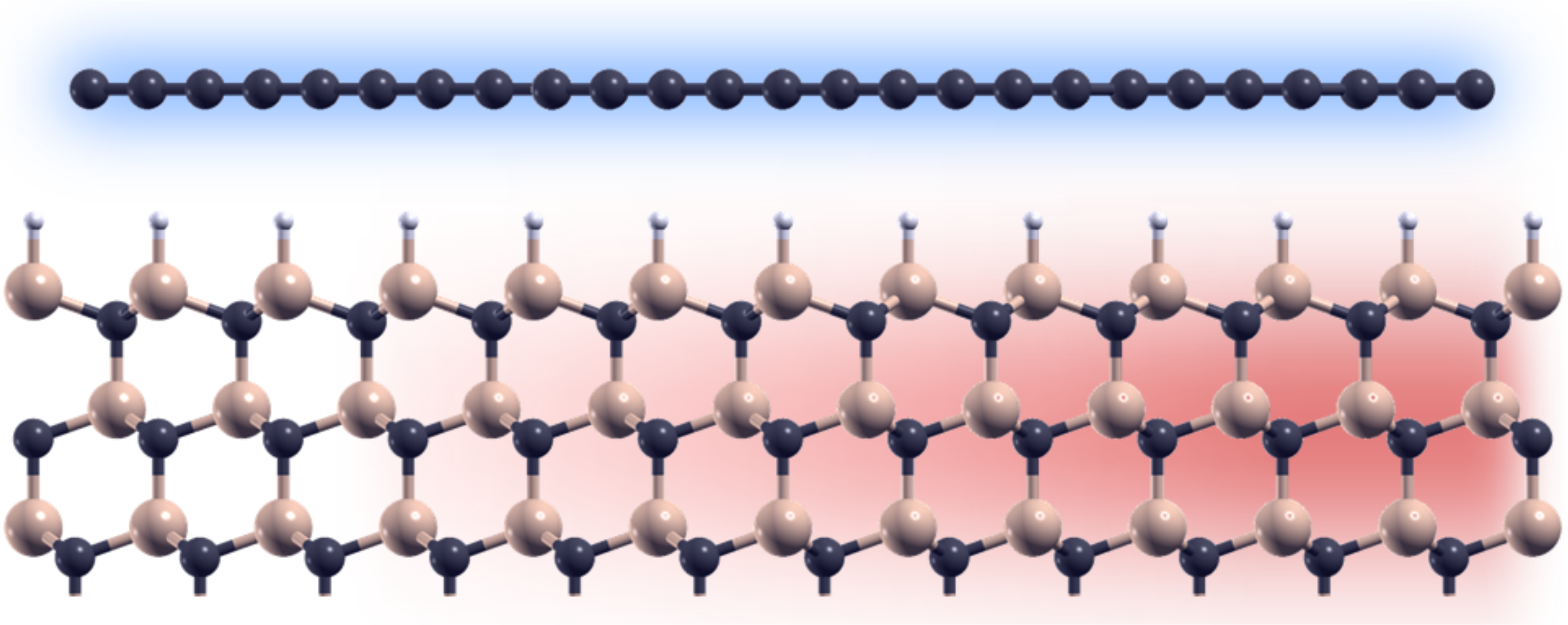
Possible hallmark: Yes



www.researchgate.net/profile/Tymoteusz-Ciuk/publications

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

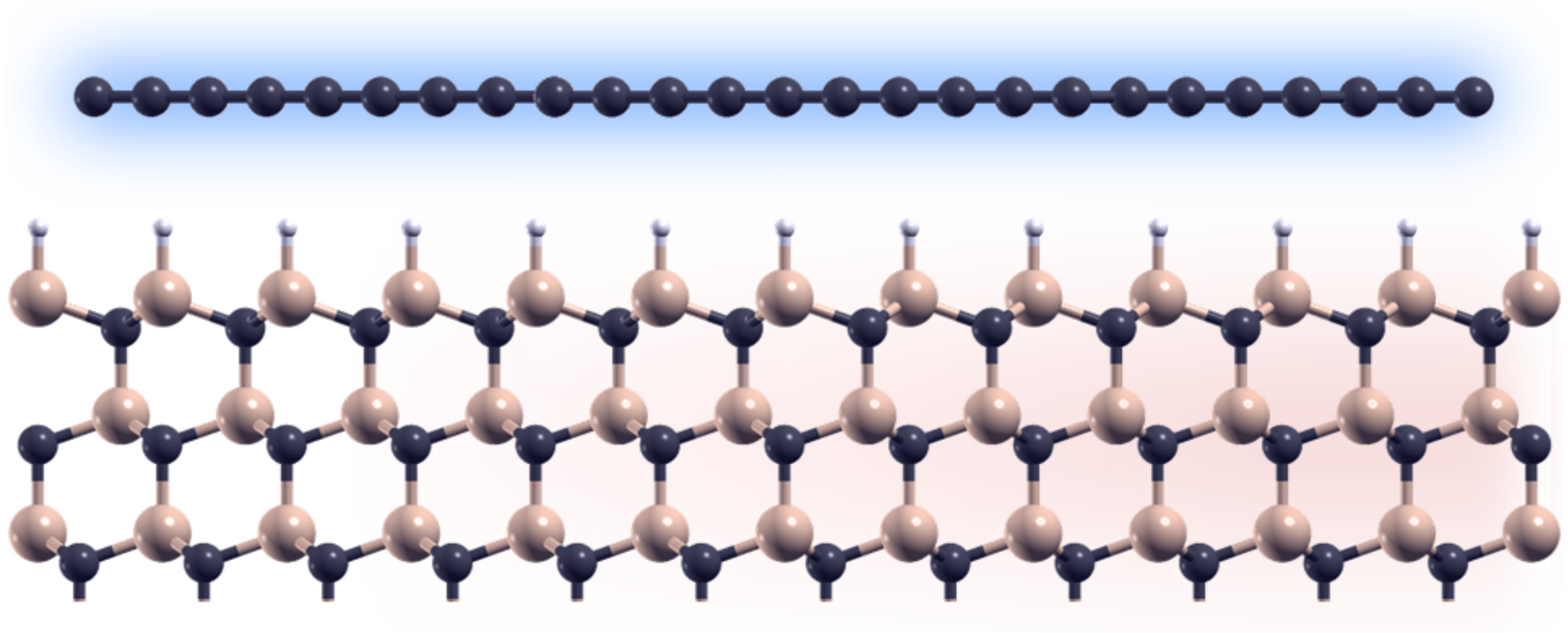
Double-carrier transport: holes in QFS graphene and thermally-activated electrons emitted in the bulk of the semi-insulating 6H-SiC(0001) and 4H-SiC(0001)



Łukasiewicz
Institute of Microelectronics and Photonics

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

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)



Łukasiewicz
Institute of Microelectronics and Photonics

Graphene Week 2023 **September 7, 2023**

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

Łukasiewicz
Institute of Microelectronics and Photonics

Graphene Week 2023 **September 7, 2023**

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

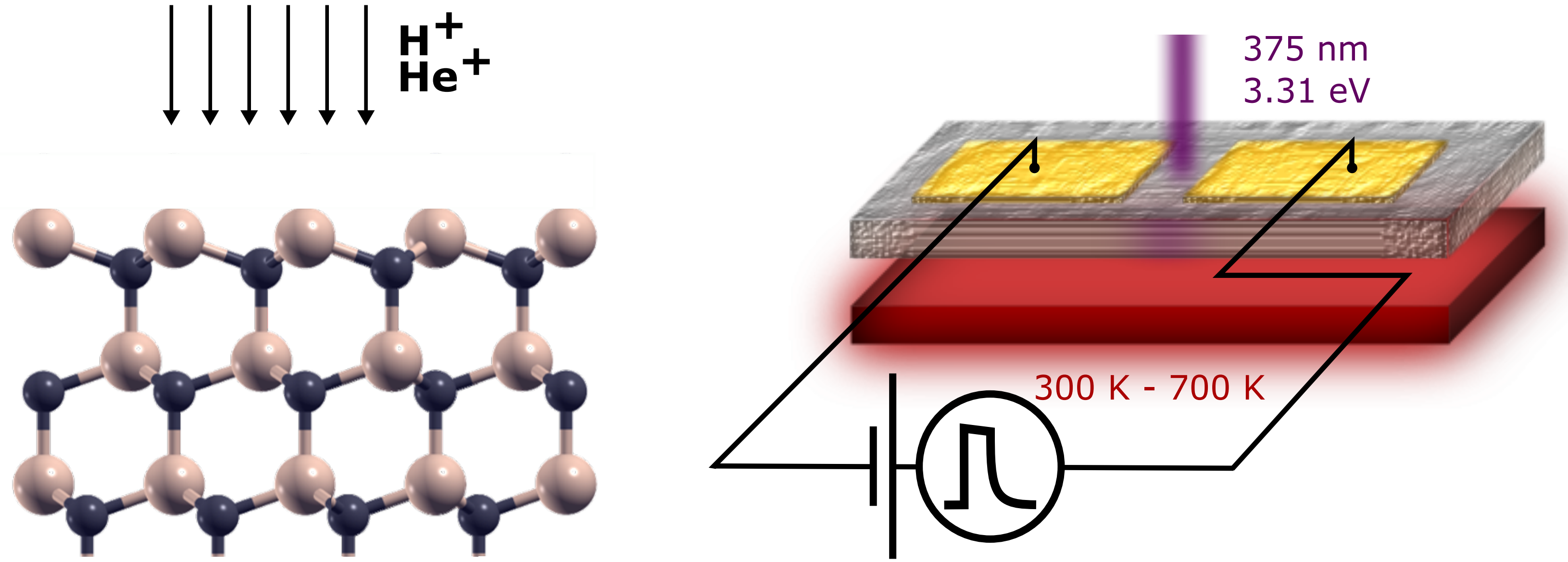
As revealed by High-Resolution Photo-Induced Transient Spectroscopy (**HRPITS**)

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

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

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

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



Łukasiewicz
Institute of Microelectronics and Photonics

Graphene Week 2023 **September 7, 2023**

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

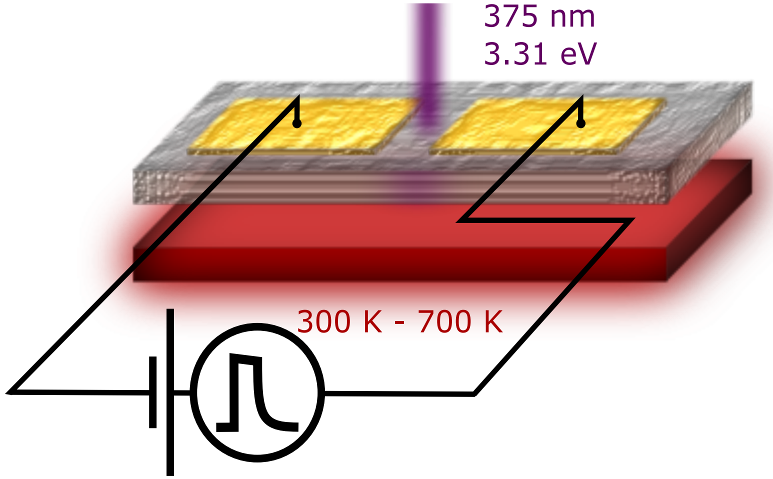
Pre-epitaxial bombardment: H^+ and He^+ ions

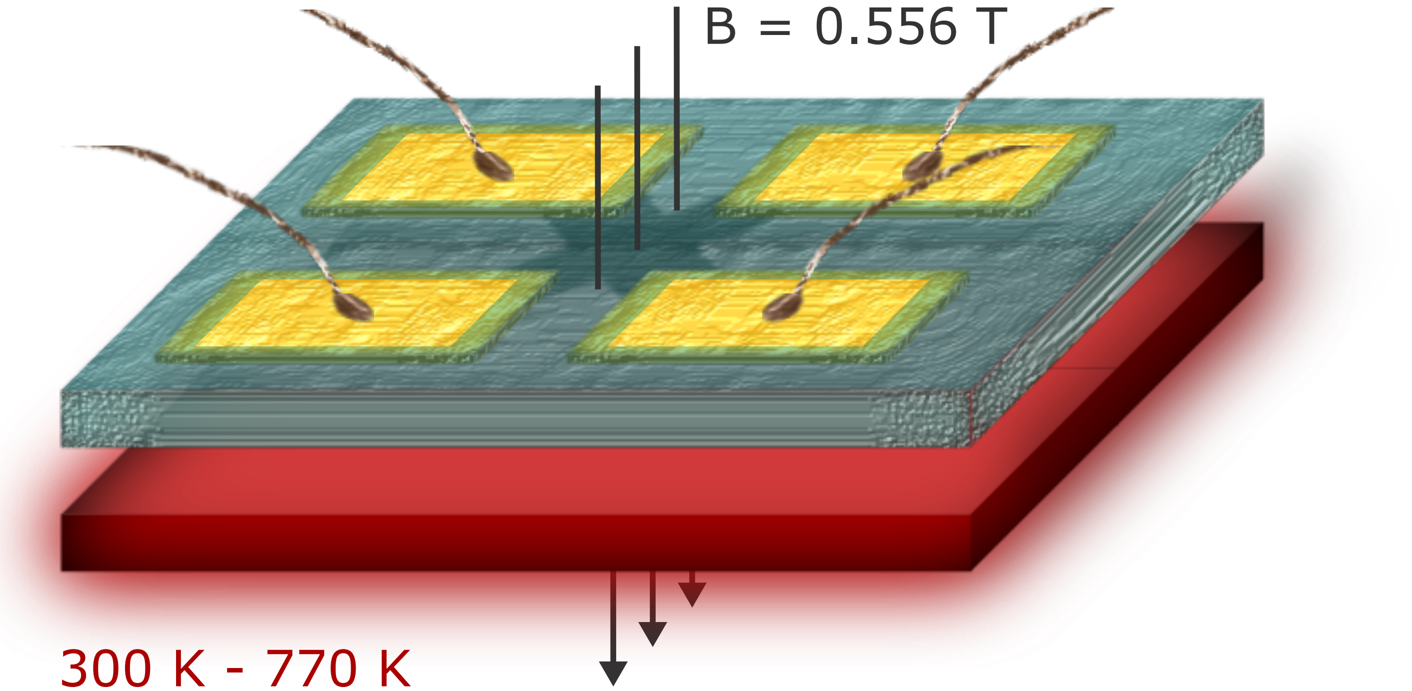
Energies: 20 keV - 50 keV

Effect: 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

$\mathbf{T5_{4H}}$: E_a = 708 meV
$\mathbf{T6_{4H}}$: E_a = 753 meV

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

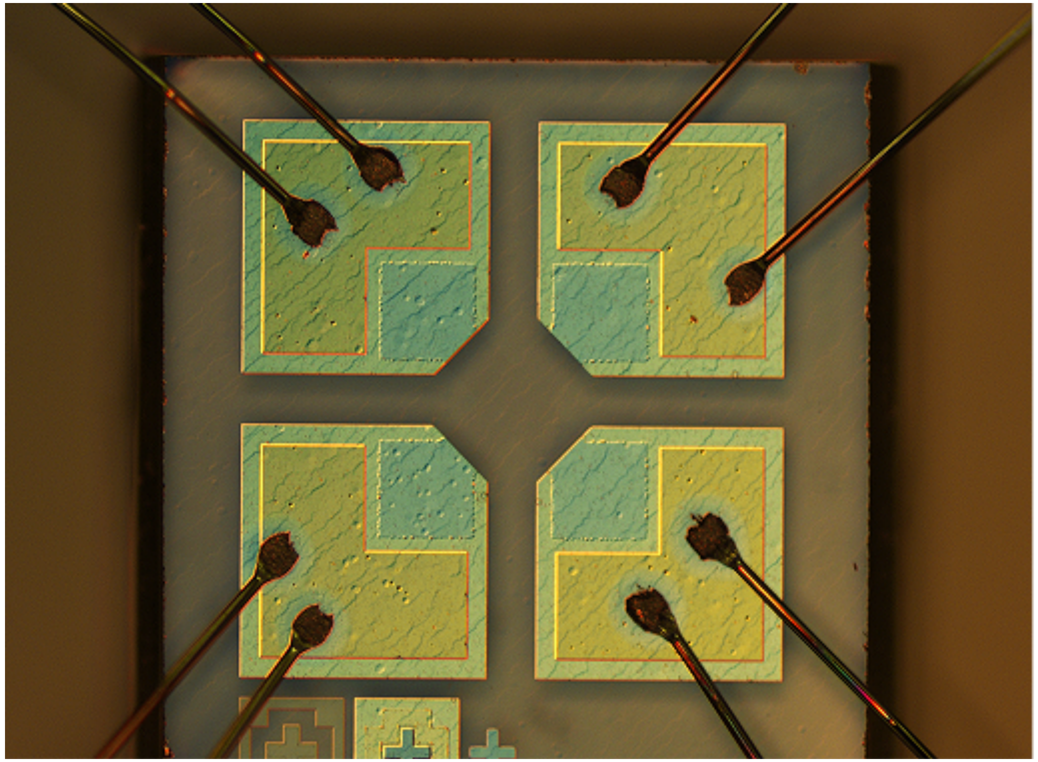


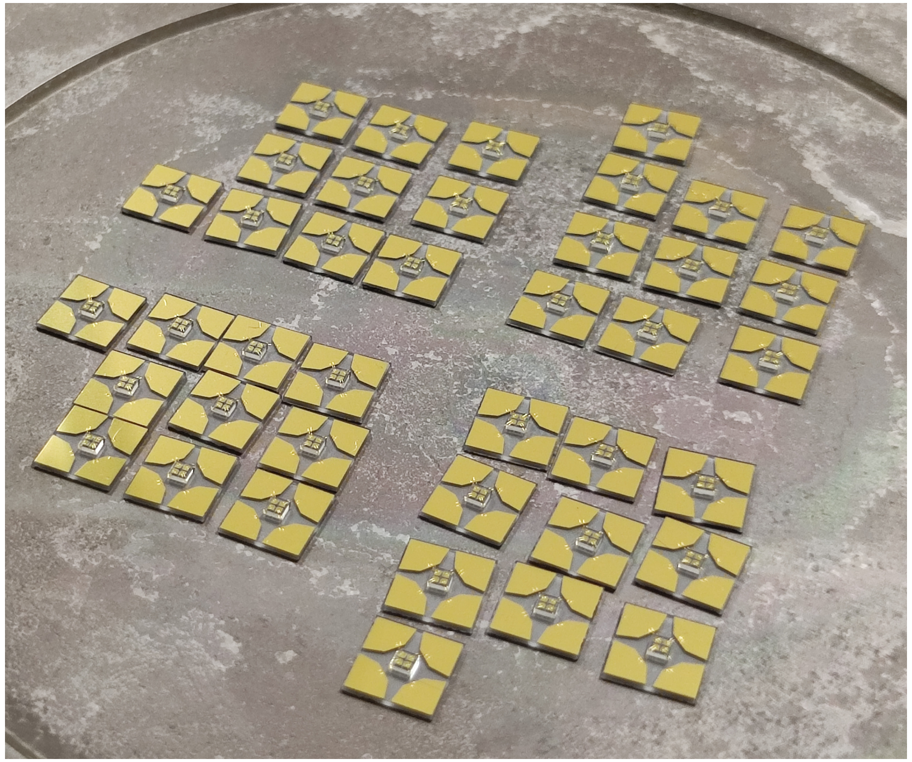


Łukasiewicz
Institute of Microelectronics and Photonics

Graphene Week 2023 **September 7, 2023**

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

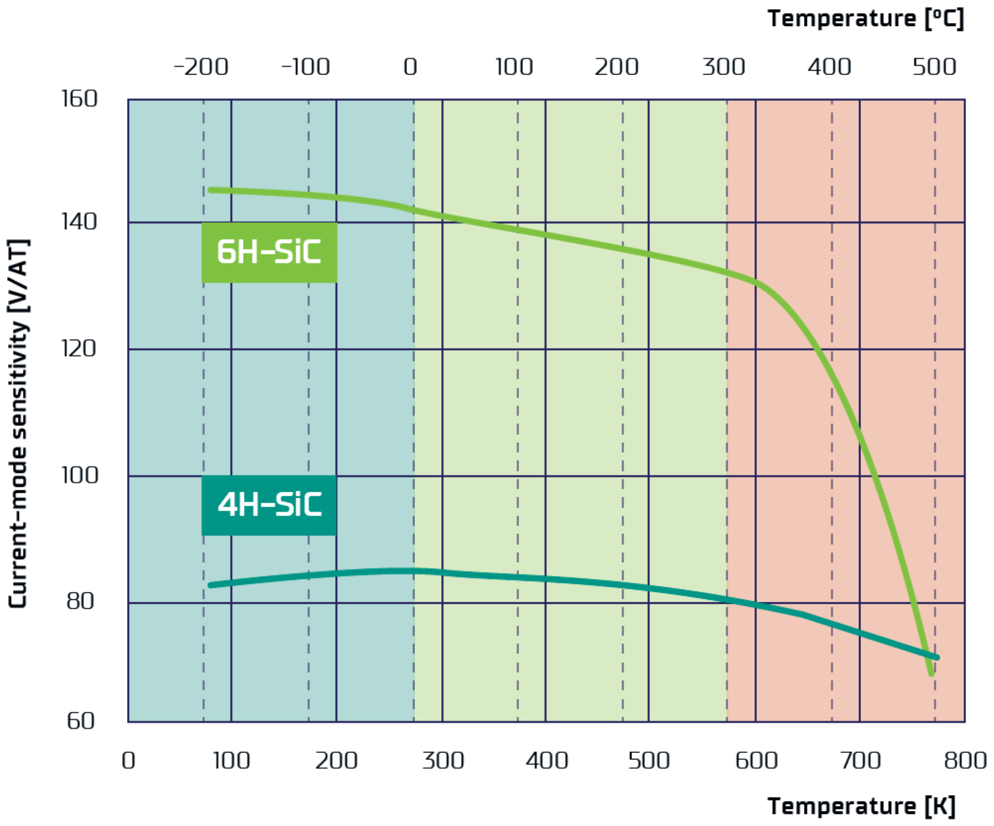


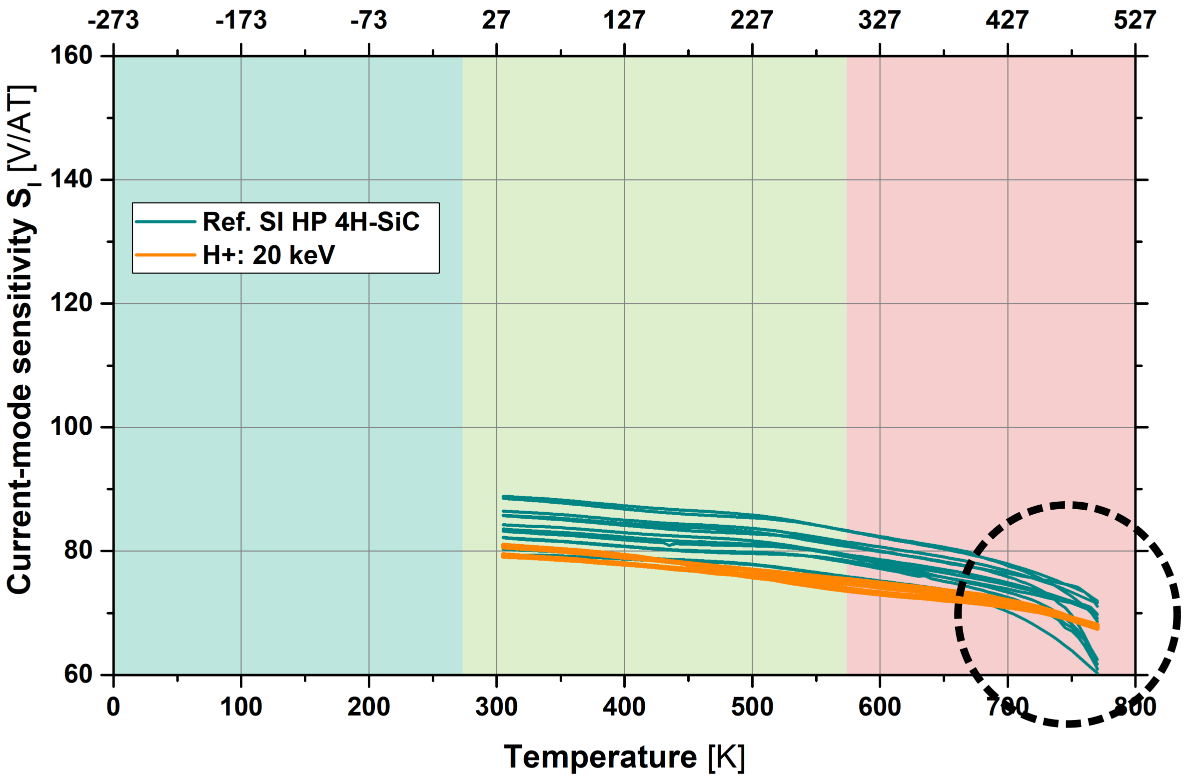


Łukasiewicz
Institute of Microelectronics
and Photonics

Graphene Week 2023 **September 7, 2023**

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





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

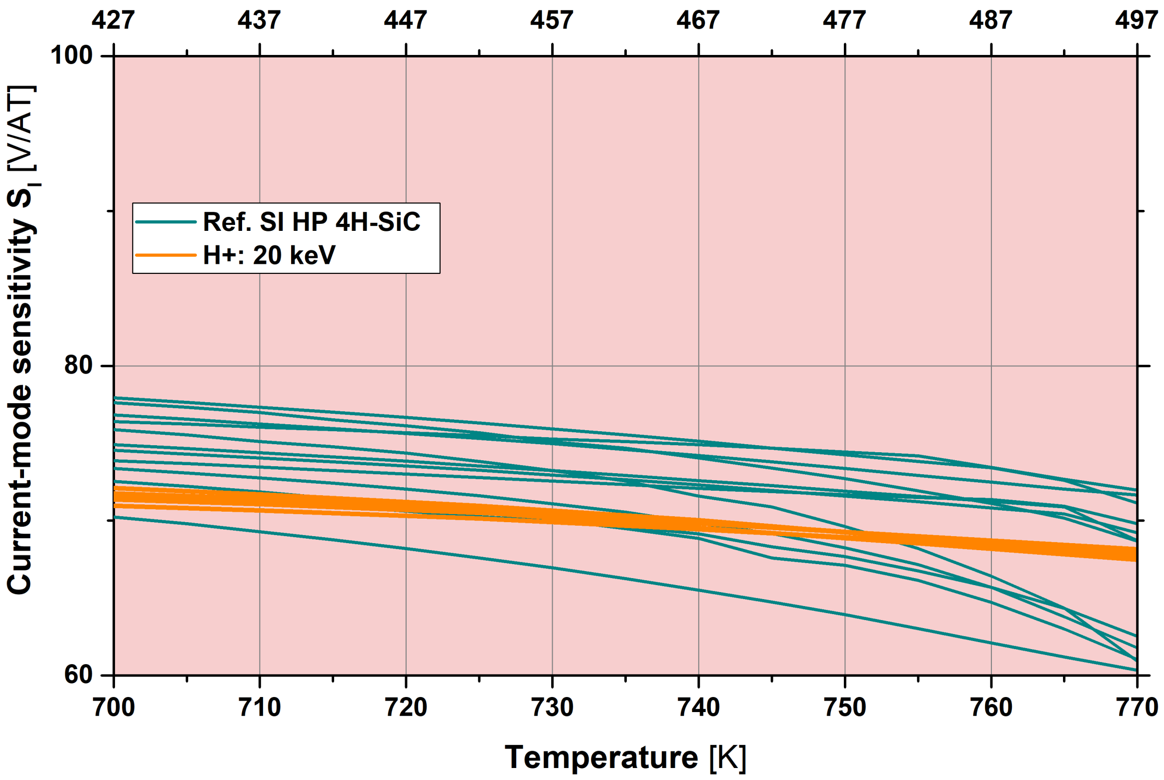
Platform: 4H-SiC

Type: Defect-engineered

Thermal stability: -0.03 %/K

End temperature*: 500 °C

Advantage: linear, without characteristic downward bending



Łukasiewicz
Institute of Microelectronics and Photonics

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

Łukasiewicz
Institute of Microelectronics and Photonics

Graphene Week 2023 **September 7, 2023**

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

Completed and published:

Fast neutron fluence of **6.7 E17** cm^{-2} (peak at 1 MeV)

Completed not yet published:

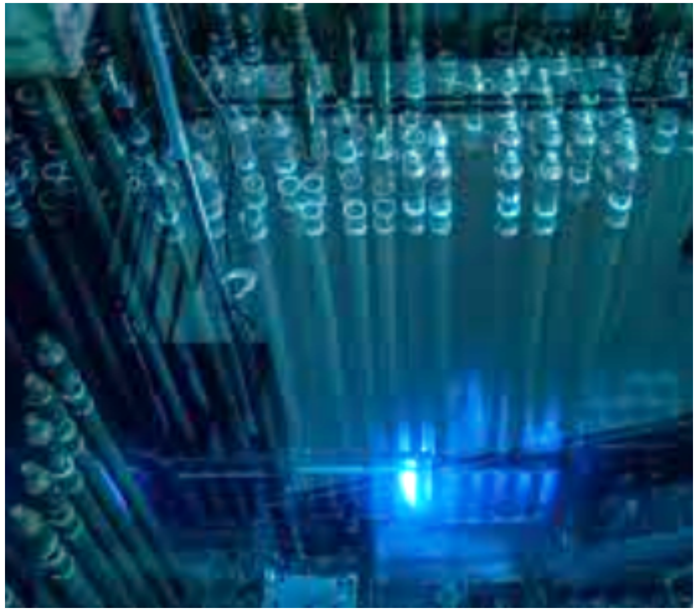
Fast neutron fluence of **2.0 E18** cm^{-2} (peak at 1 MeV)

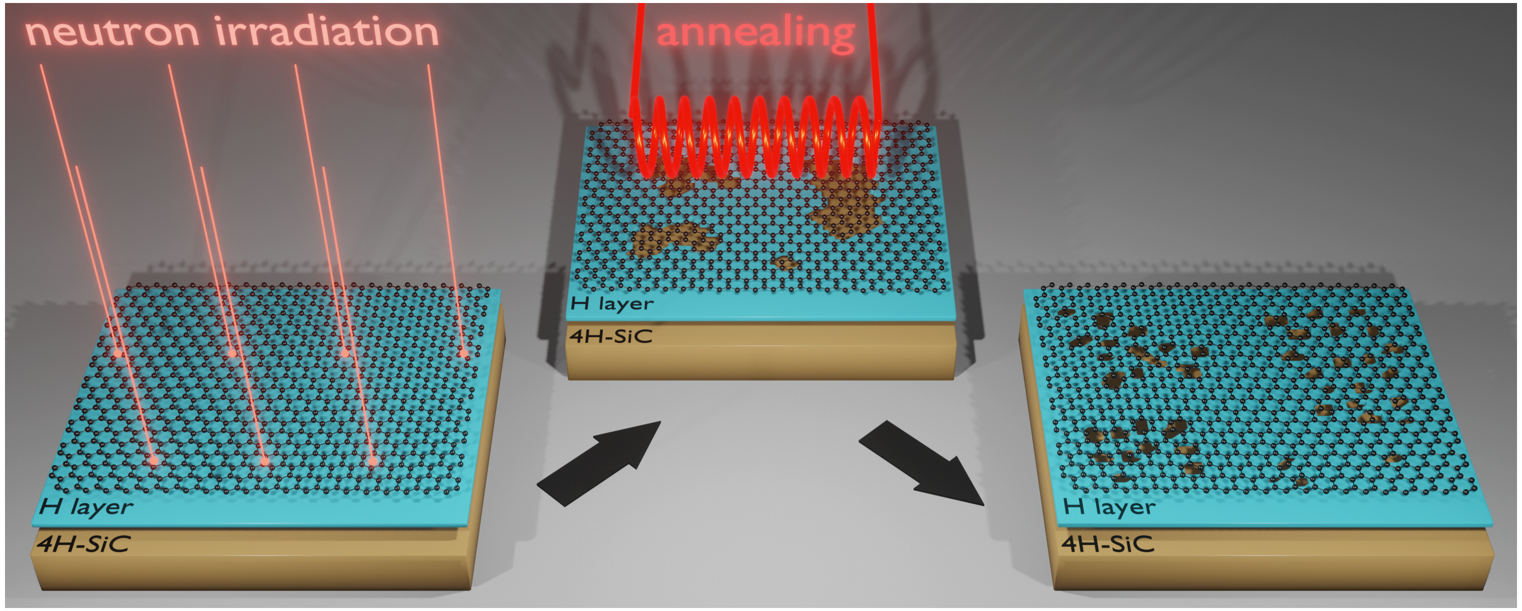
Fast neutron fluence of **4.0 E18** cm^{-2} (peak at 1 MeV)

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

Experiment in MARIA reactor: fast neutron fluence of 6.7 E17 cm^{-2} (peak at 1 MeV)

Estimated defect density: 4 E10 cm^{-2} (low cross-section)





doi.org/10.1016/j.apsusc.2022.152992 doi.org/10.3390/s22145258

Łukasiewicz
Institute of Microelectronics and Photonics

Summary & Conclusions

Material composition: Al_2O_3/QFS-graphene/SiC(0001)

Competitive advantages:

- operates up to 500 °C and possibly beyond
- largely resistant to neutron irradiation

Potential application: magnetic diagnostics in fusion reactors

Do not hesitate to contact us for validation-oriented cooperation!

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

THANK YOU FOR YOUR ATTENTION!

The research leading to these results has received funding from:

- National Science Centre under
Grant Agreement No. OPUS 2019/33/B/ST3/02677

- M-ERA.NET3 under
Grant Agreement MERA.NET3/2021/83/I4BAGS/2022

Tymoteusz Ciuk, PhD

NATIONAL SCIENCE CENTRE POLAND
NCBR Narodowe Centrum Badań i Rozwoju
M-ERA.NET
I4Bags
G-Flake®

Łukasiewicz
Institute of Microelectronics
and Photonics

Graphene Week 2023 **September 7, 2023**

References in order of appearance

10.1016/j.carbon.2015.06.032 Statistics of epitaxial graphene for Hall effect sensors

10.1016/j.carbon.2016.01.093 Charge carrier concentration and offset voltage in quasi-free-standing monolayer chemical vapor deposition graphene on SiC

10.1016/j.apsusc.2020.148668 The impact of partial H intercalation on the quasi-free-standing properties of graphene on SiC(0001)

10.1016/j.physe.2021.114853 Determining the number of graphene layers based on Raman response of the SiC substrate

10.1016/j.apsusc.2022.155054 Layer-resolved Raman imaging and analysis of parasitic ad-layers in transferred graphene

10.1016/j.carbon.2018.07.049 Thermally activated double-carrier transport in epitaxial graphene on vanadium-compensated 6H-SiC as revealed by Hall effect measurements

10.1016/j.physe.2022.115264 Contamination-induced inhomogeneity of noise sources distribution in Al2O3-passivated quasi-free-standing graphene on 4H-SiC(0001)

10.1063/5.0082694 Enhancement of graphene-related and substrate-related Raman modes through dielectric layer deposition

10.1109/TED.2019.2915632 High-Temperature Hall Effect Sensor Based on Epitaxial Graphene on High-Purity Semiinsulating 4H-SiC

10.1016/j.apsusc.2022.152992 Graphene on SiC as a promising platform for magnetic field detection under neutron irradiation

10.3390/s22145258 The Comparison of InSb-Based Thin Films and Graphene on SiC for Magnetic Diagnostics under Extreme Conditions