Defect-engineered two-dimensional graphene-on-silicon-carbide platform for high-temperature magnetic diagnostics in modern fusion reactors

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Defect-engineered two-dimensional graphene-on-silicon-carbide platform for high-temperature magnetic diagnostics in modern fusion reactors

Motivation

Graphene on Silicon Carbide

Magnetic Field Detection

Extreme Temperatures (Defect engineering)

Neutron Radiation

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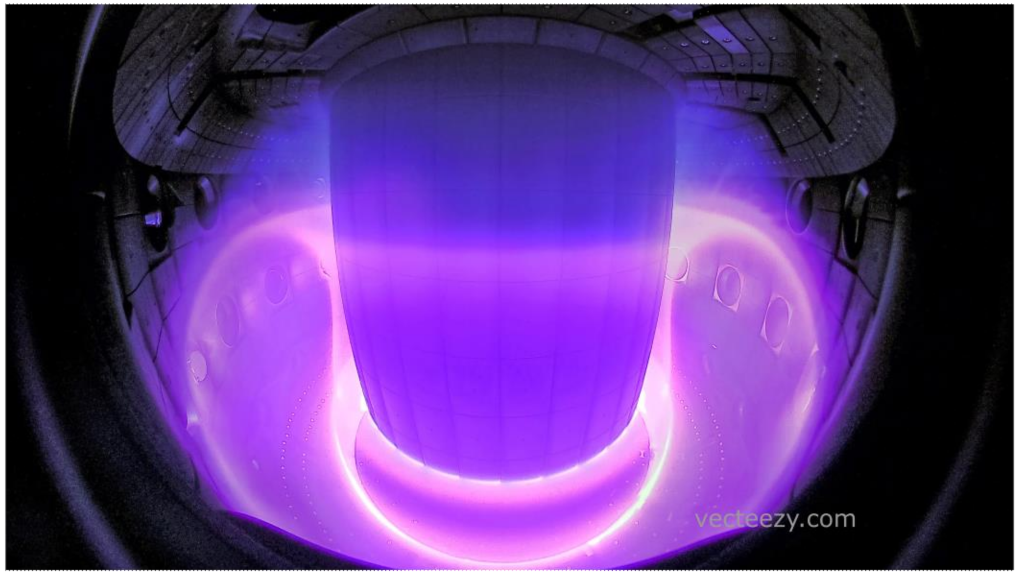
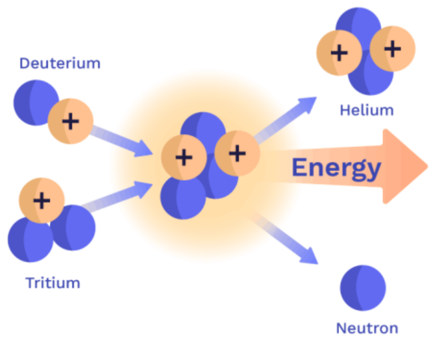


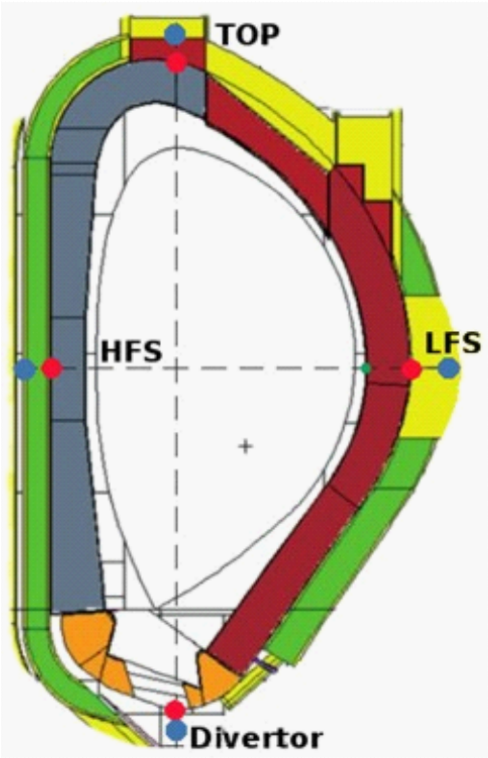
EUROfusion: transition from science-driven International Thermonuclear Experimental Reactor (**ITER**) to the industry-driven **DEMO**-class reactor

Defect-engineered two-dimensional graphene-on-silicon-carbide platform for high-temperature magnetic diagnostics in modern fusion reactors

Ex-vessel: 473 K (200 °C)

In-vessel: 773 K (500 °C)





Energy source: 80% radiates as neutrons

Hazard: neutron fluence of **E16 - E22** cm^{-2}

Magnetic diagnostics: **5.8 T** with 2.5-mT accuracy

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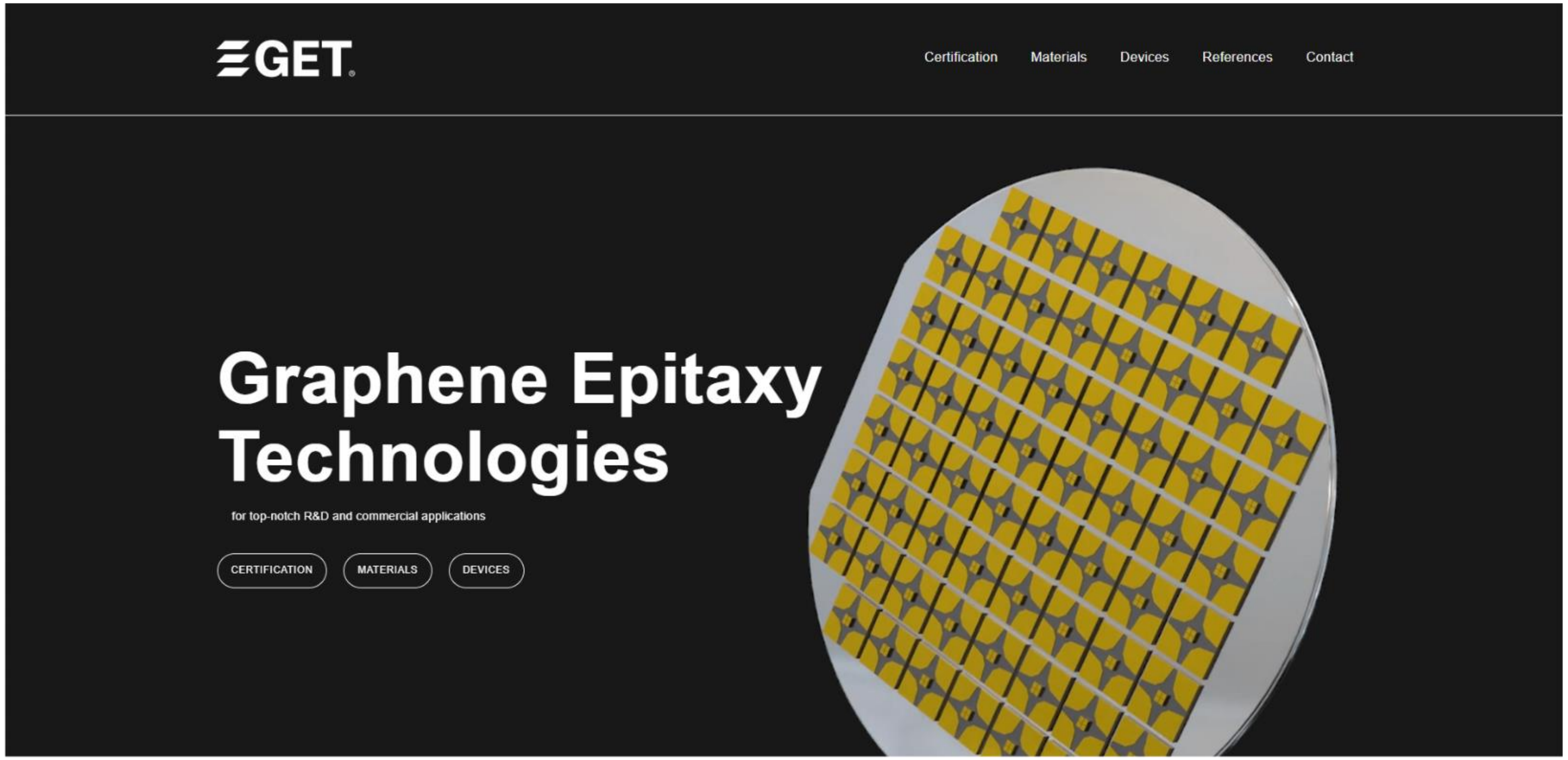

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Defect-engineered two-dimensional graphene-on-silicon-carbide platform for high-temperature magnetic diagnostics in modern fusion reactors

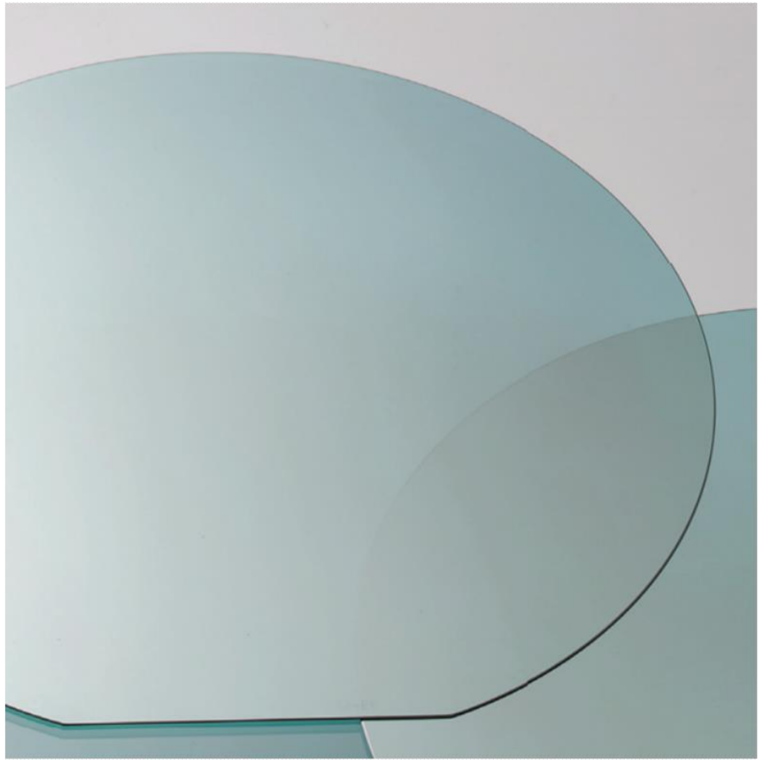
Epitaxy: Chemical Vapor Deposition (CVD)

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

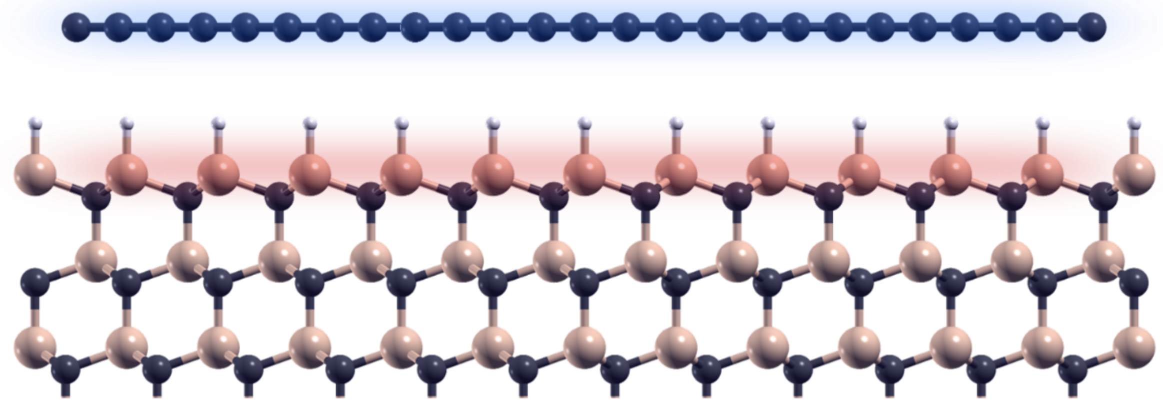
Defect-engineered two-dimensional graphene-on-silicon-carbide platform for high-temperature magnetic diagnostics in modern fusion reactors

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

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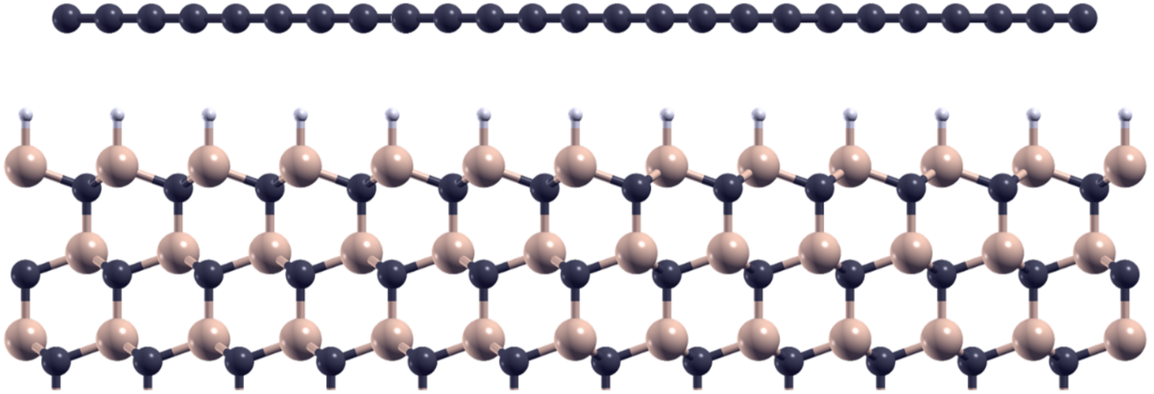
Defect-engineered two-dimensional graphene-on-silicon-carbide platform for high-temperature magnetic diagnostics in modern fusion reactors

Hydrogen intercalation: quasi-free-standing graphene

Polarization effect: positive

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

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



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Defect-engineered two-dimensional graphene-on-silicon-carbide platform for high-temperature magnetic diagnostics in modern fusion reactors

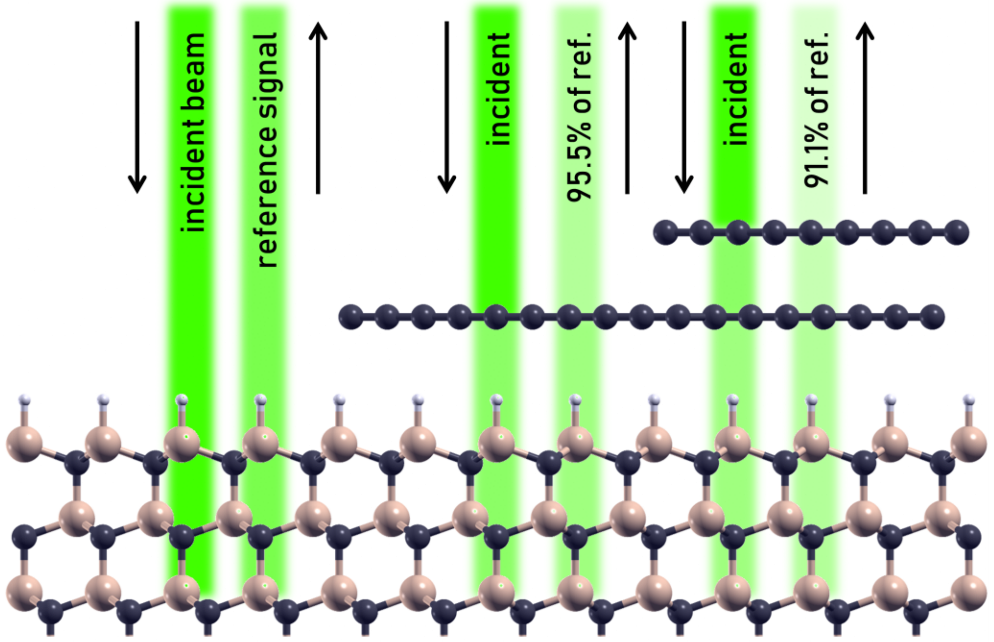
Basis: signal intensity attenuation

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



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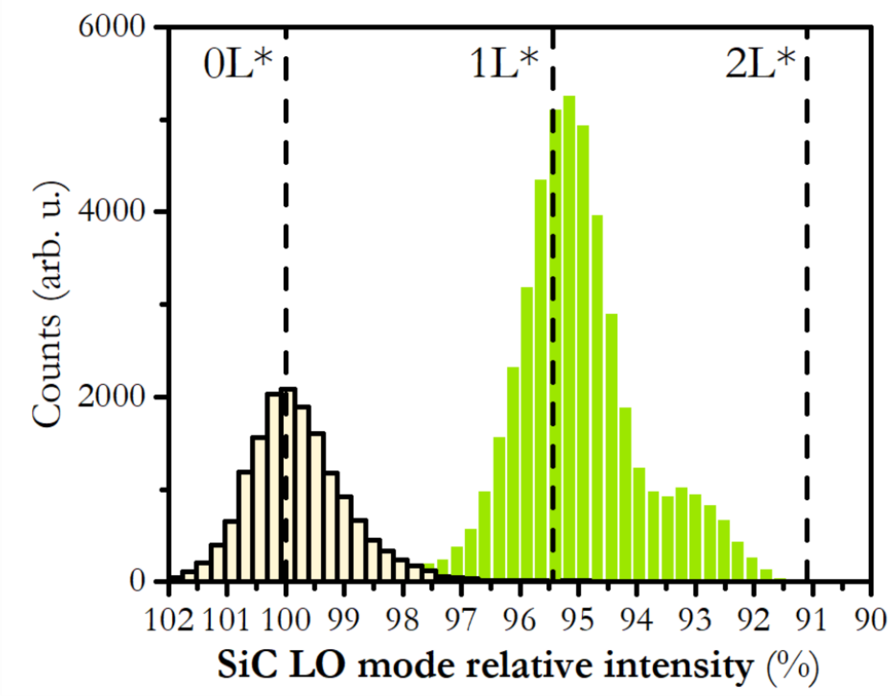

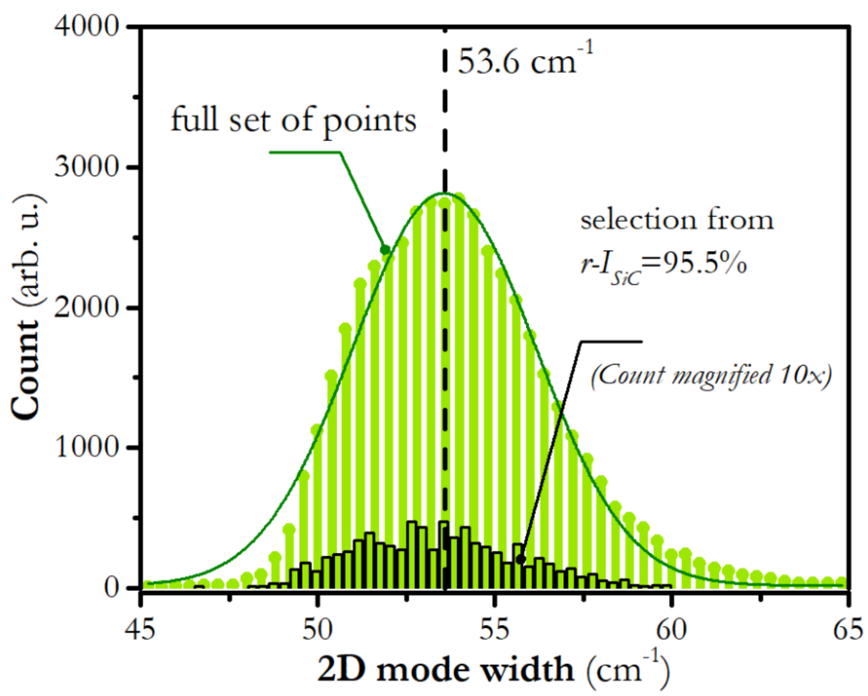

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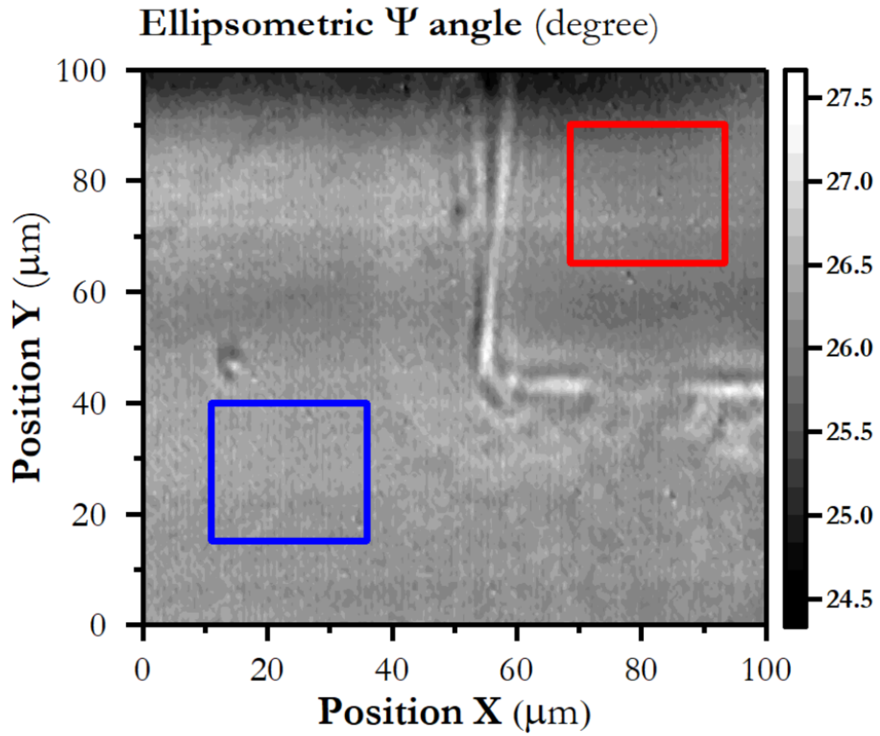

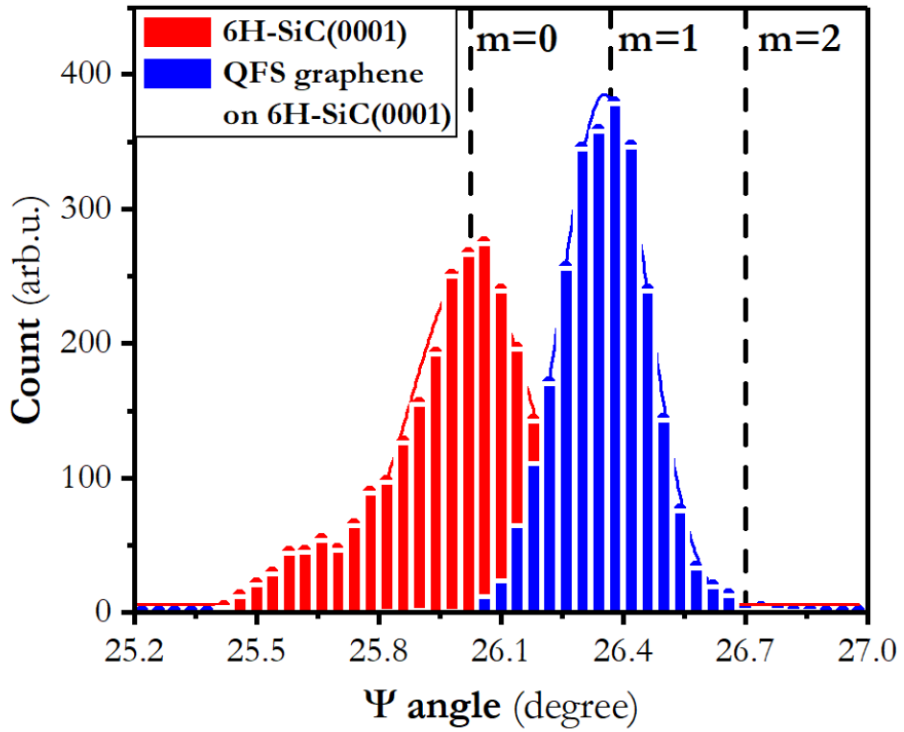

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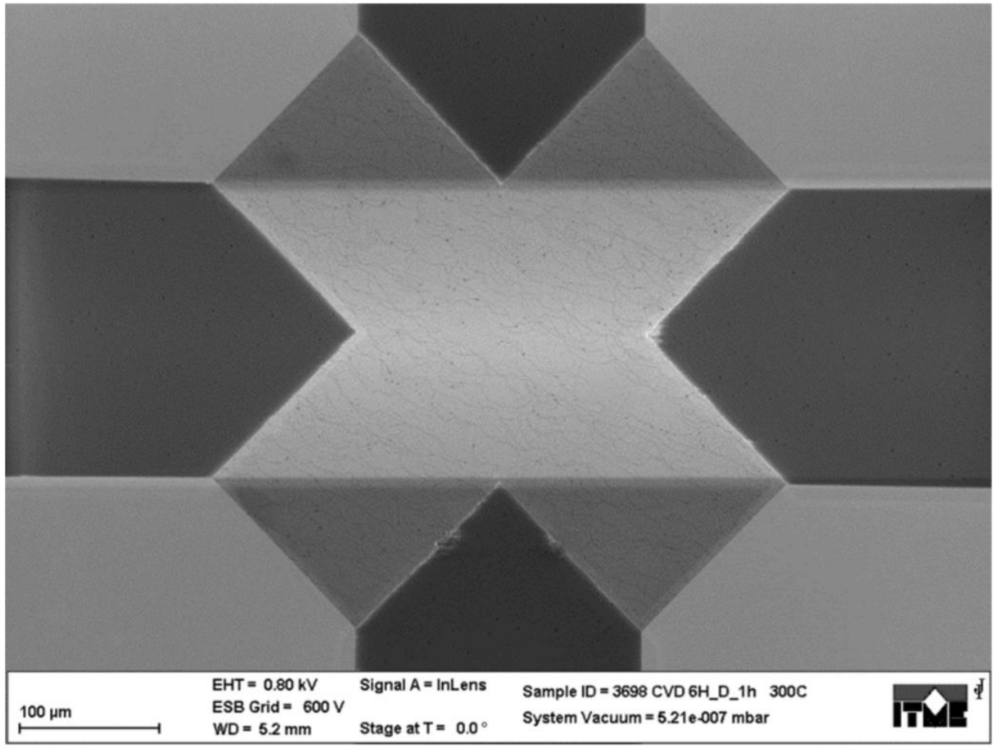
Principle of operation: classical Hall effect

Configuration: van der Pauw

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

Total dimensions: 1.4 mm x 1.4 mm

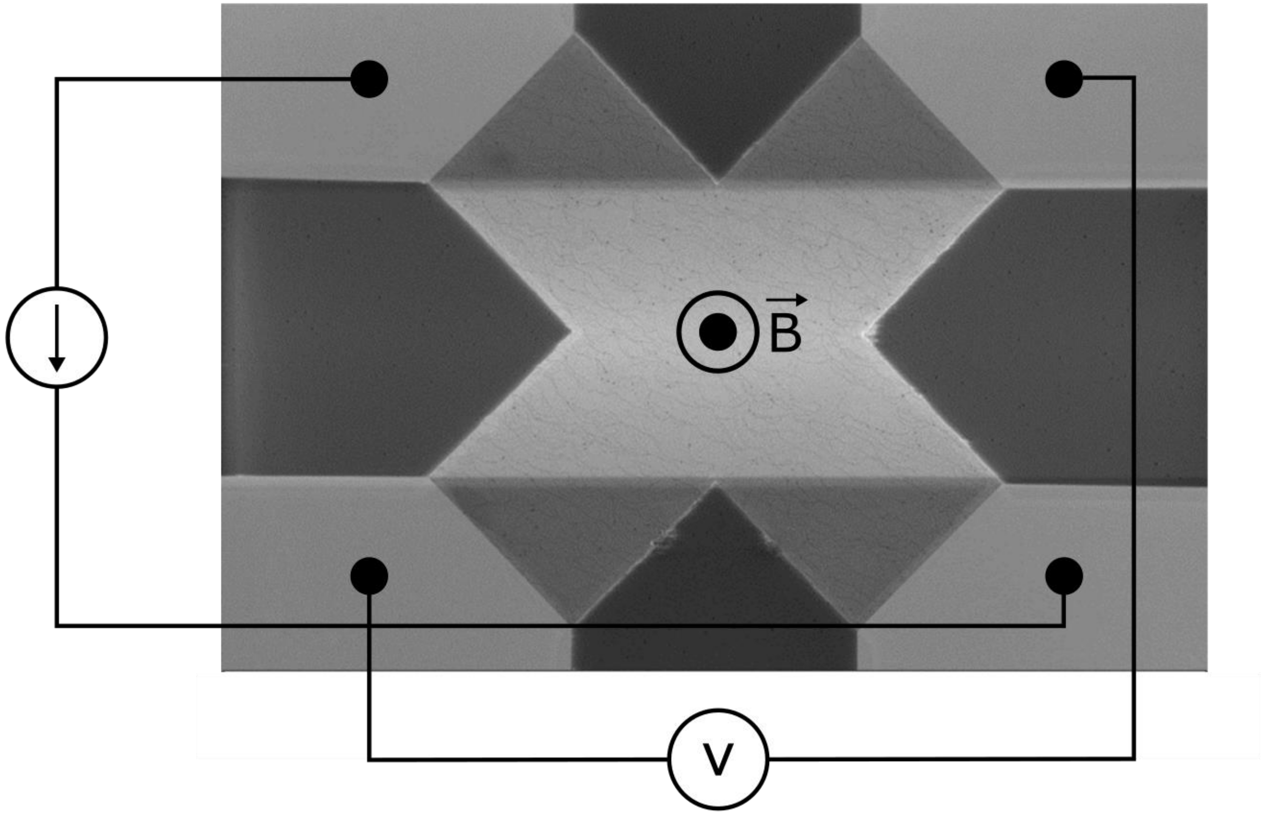


doi.org/10.1016/j.carbon.2018.07.049

Defect-engineered two-dimensional graphene-on-silicon-carbide platform for high-temperature magnetic diagnostics in modern fusion reactors

Input: direct current

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



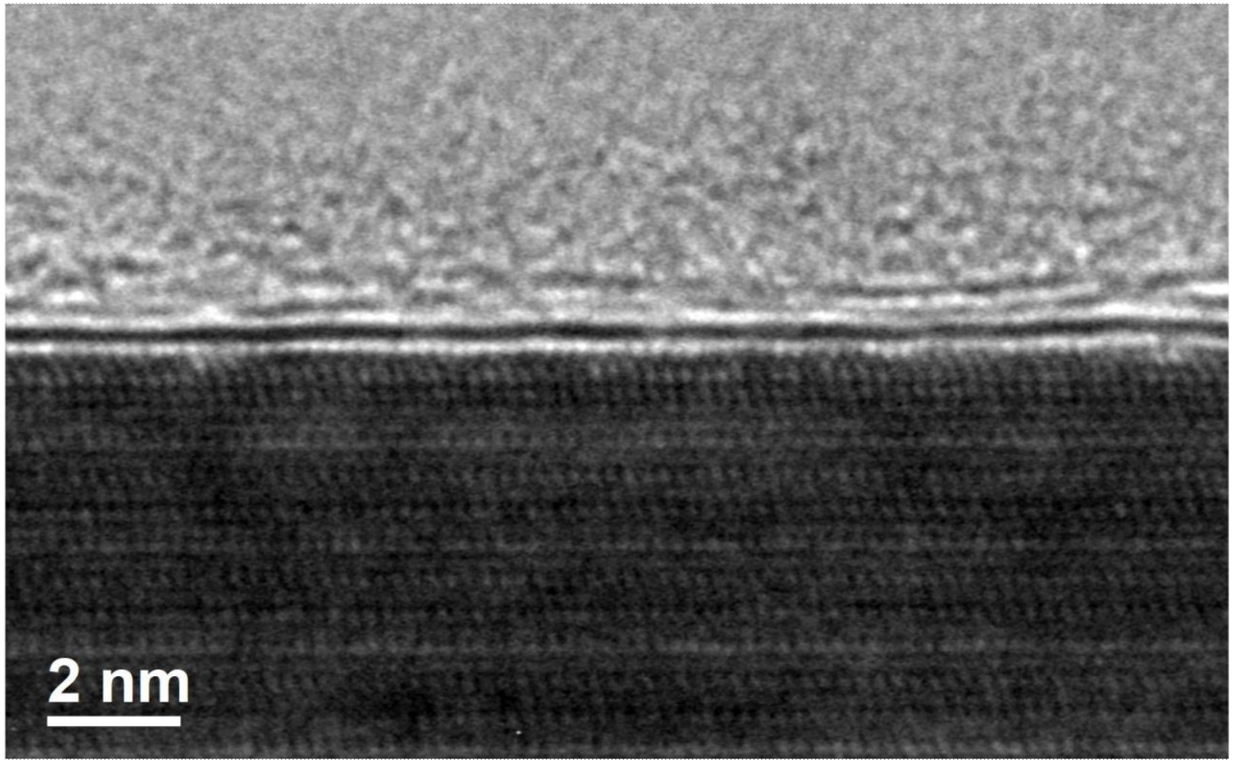
Defect-engineered two-dimensional graphene-on-silicon-carbide platform for high-temperature magnetic diagnostics in modern fusion reactors

Passivation: aluminum oxide

Process: atomic layer deposition

Precursors: TMA and DI

Purpose: environmental protection



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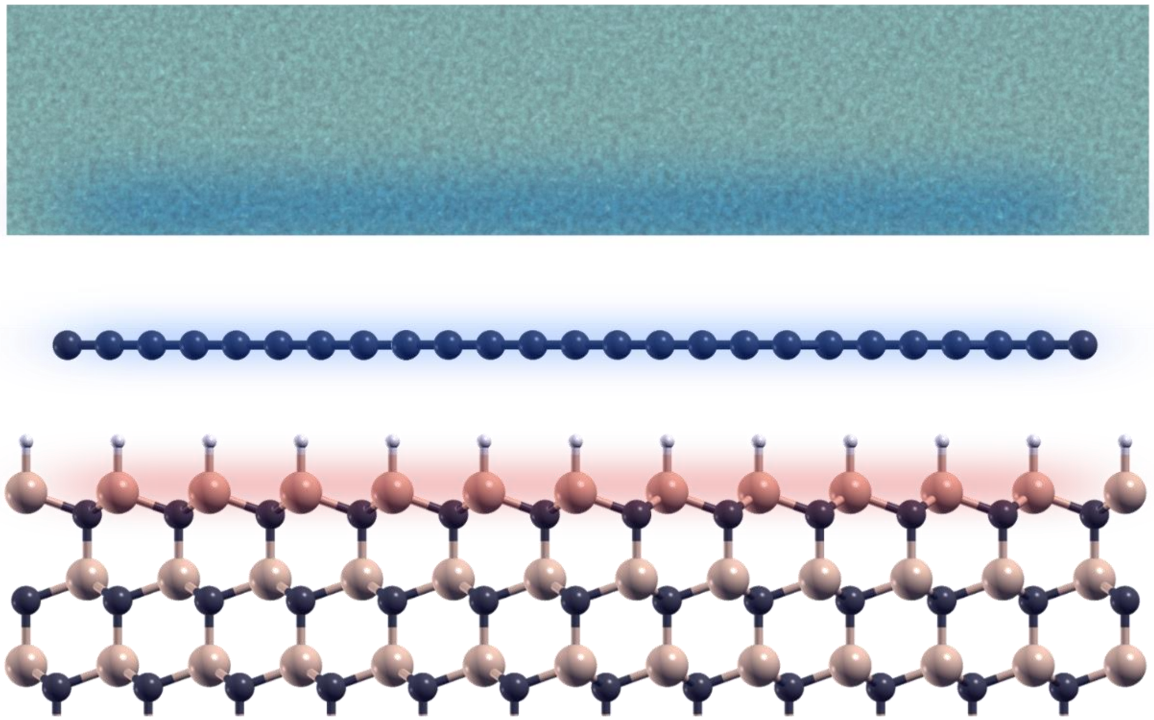
100-nm *a*-Al2O3: excess positive charge

Polarization effect: negative

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

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



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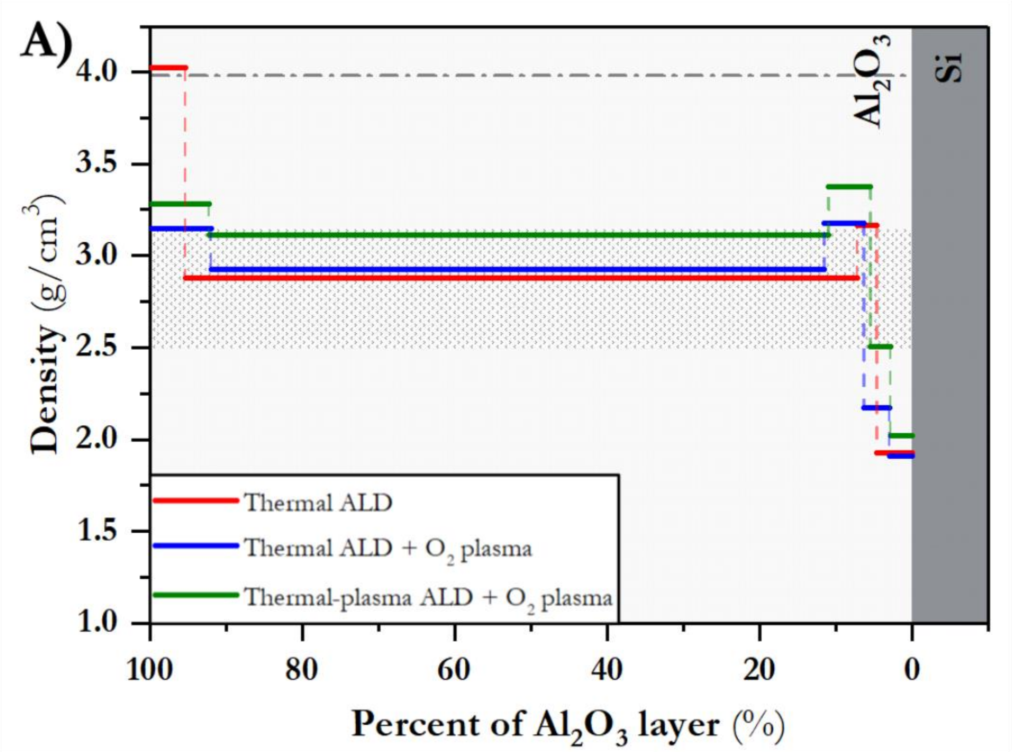

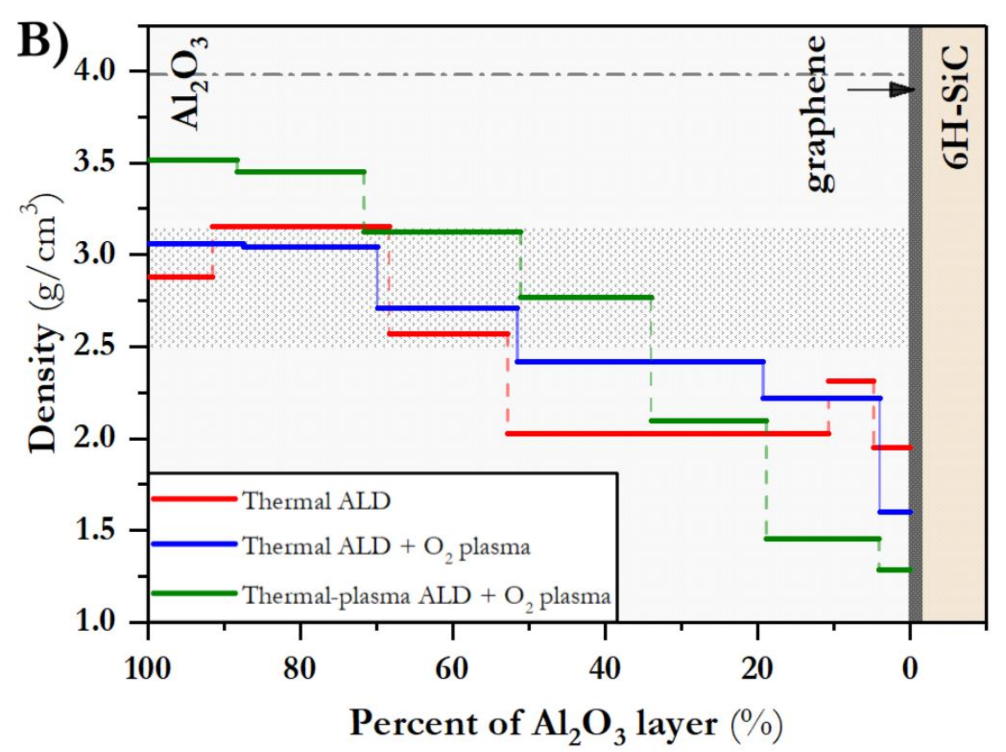

doi.org/10.1021/acsaelm.3c01627

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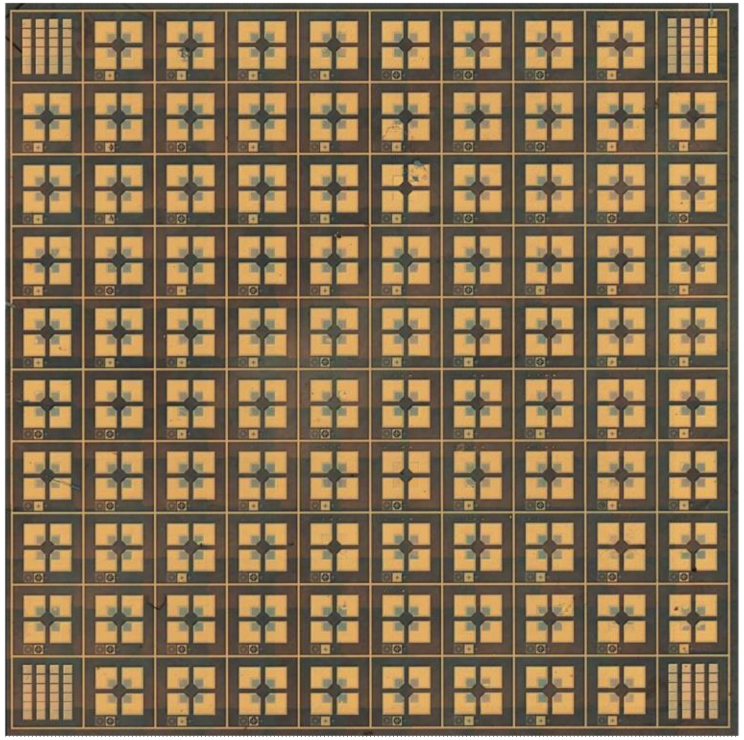

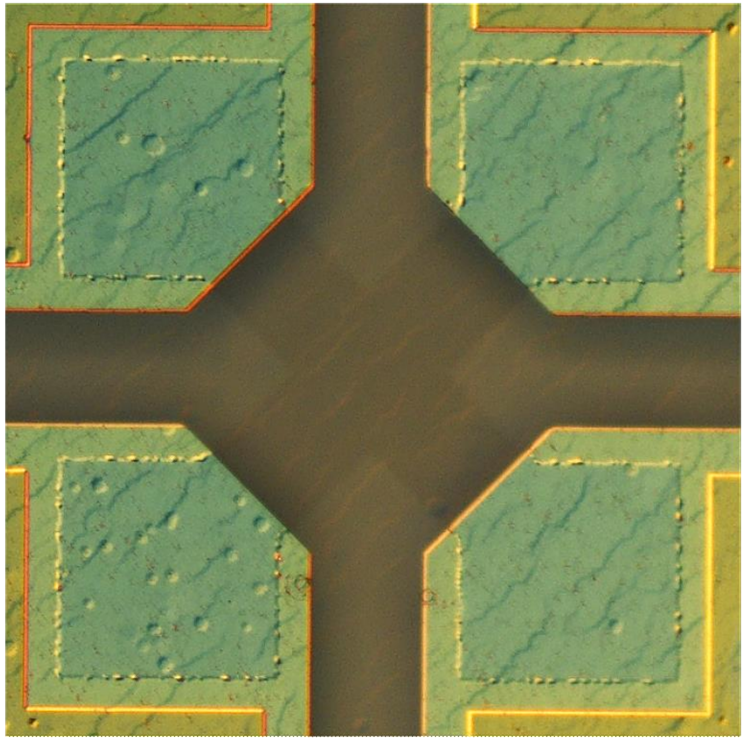

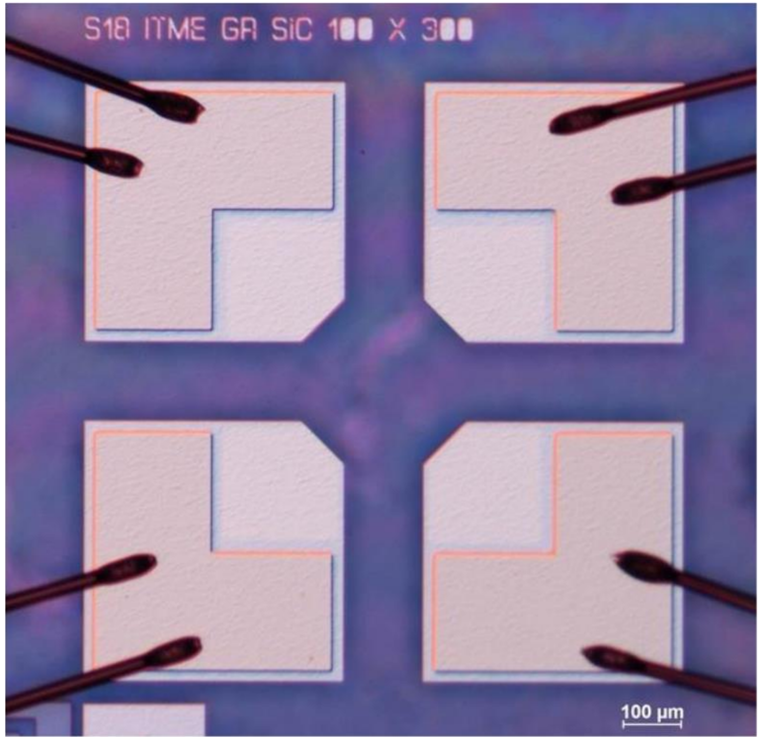

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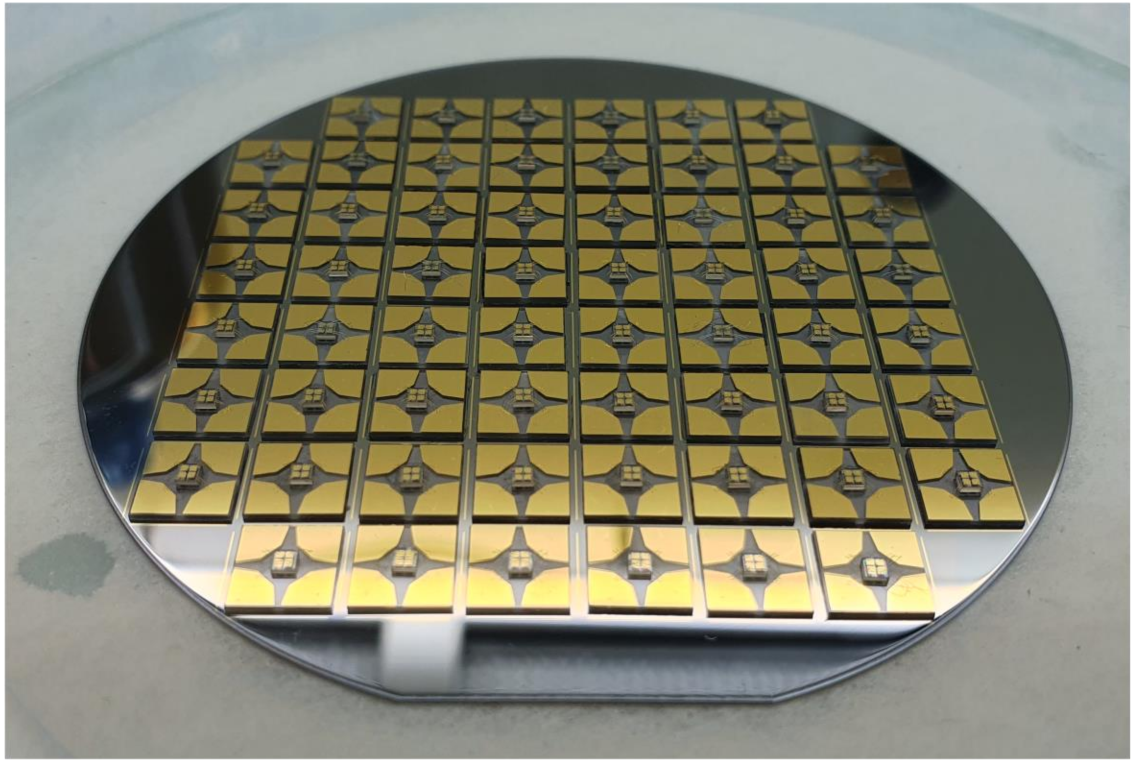
Defect-engineered two-dimensional graphene-on-silicon-carbide platform for high-temperature magnetic diagnostics in modern fusion reactors

Mounting: custom holders

Feed current: < 10 mA

Magnetic induction: 0.55 T

Temperatures: up to 770 K (497 °C)



10.1109/TED.2019.2915632

Defect-engineered two-dimensional graphene-on-silicon-carbide platform for high-temperature magnetic diagnostics in modern fusion reactors

Motivation

Graphene on Silicon Carbide

Magnetic Field Detection

Extreme Temperatures (Defect Engineering)

Neutron Radiation

Defect-engineered two-dimensional graphene-on-silicon-carbide platform for high-temperature magnetic diagnostics in modern fusion reactors

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

Expressed in: V/AT

Inversely proportional to: hole density

Polytype dependent: Yes

Defect-engineered two-dimensional graphene-on-silicon-carbide platform for high-temperature magnetic diagnostics in modern fusion reactors

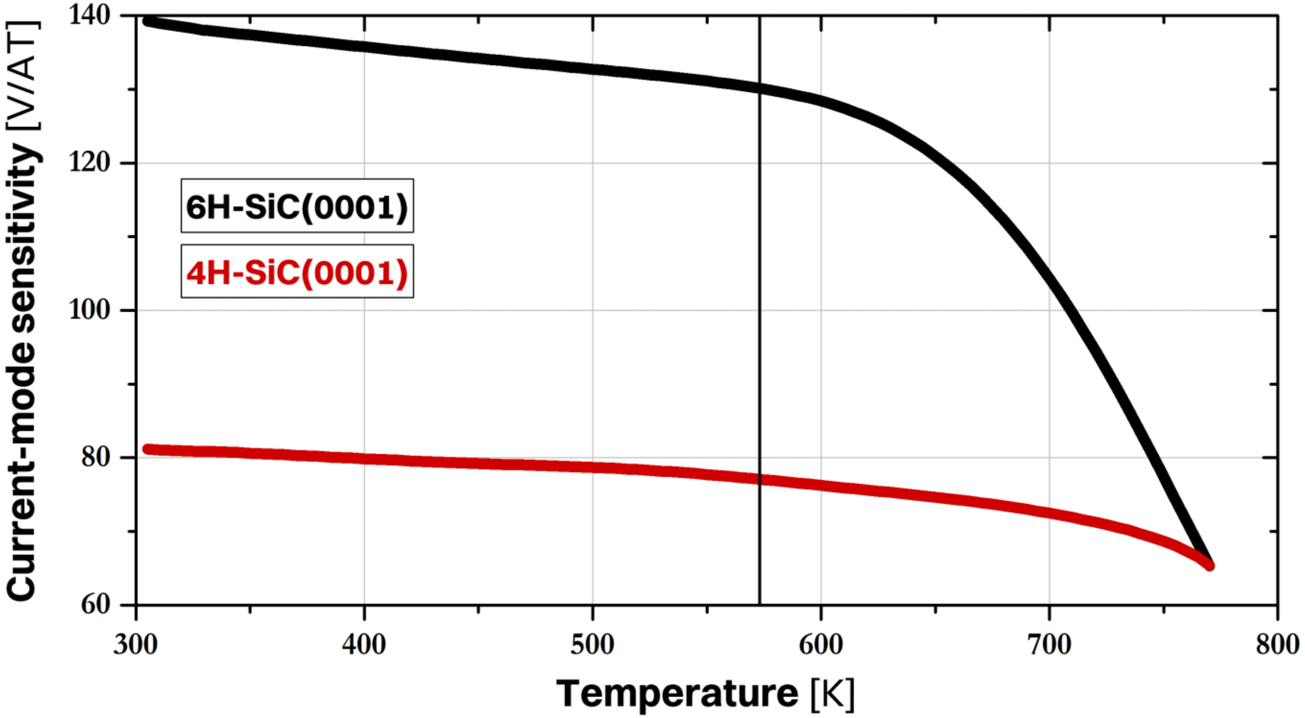
Two platforms: 6H-SiC and 4H-SiC

Two levels of sensitivity:

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

Start temperature: RT

End temperature: 770 K (497 °C)



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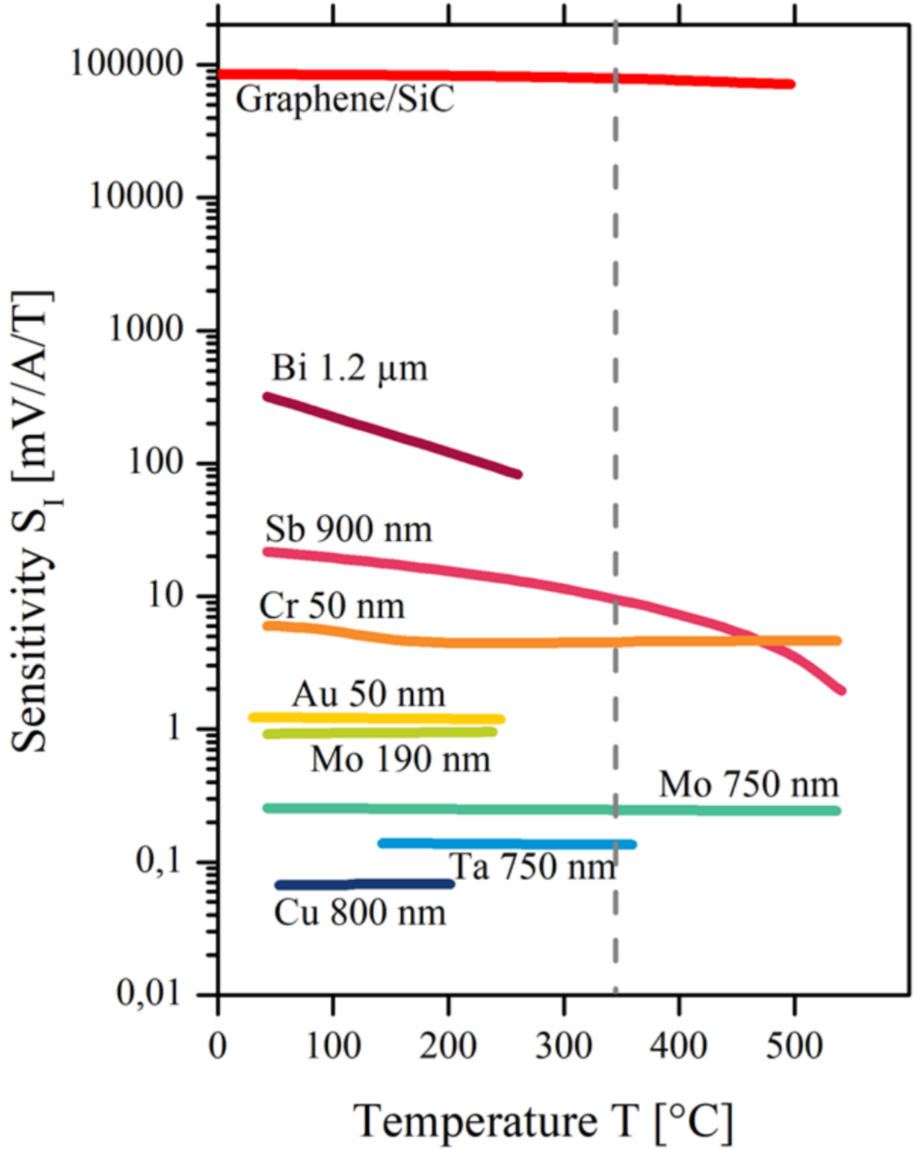
Alternative platforms: Bi, Sb, Cr, Au, Mo, Ta, Cu

Sensitivities: 0.1 mV/AT - 100 mV/AT

Start temperature: 50 °C

End temperature: 770 K (497 °C)

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



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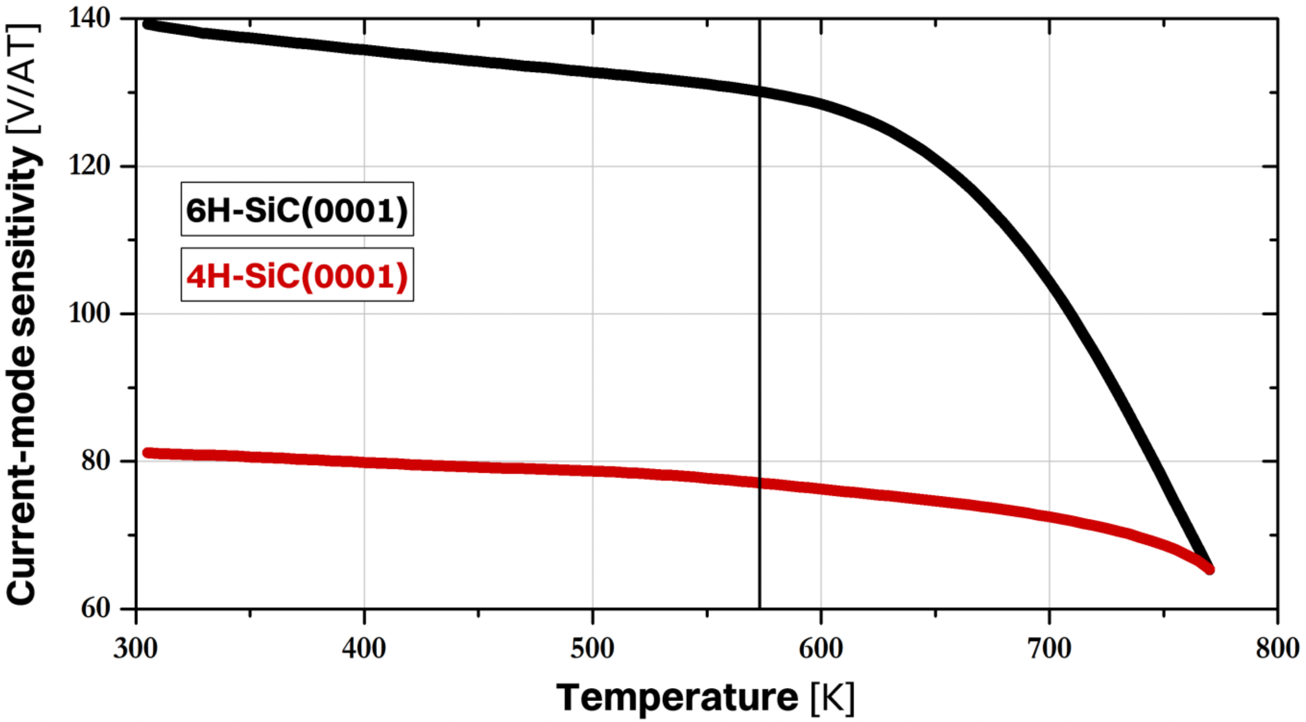
Down-bending: >573 K (300 °C)

Physical degradation: No

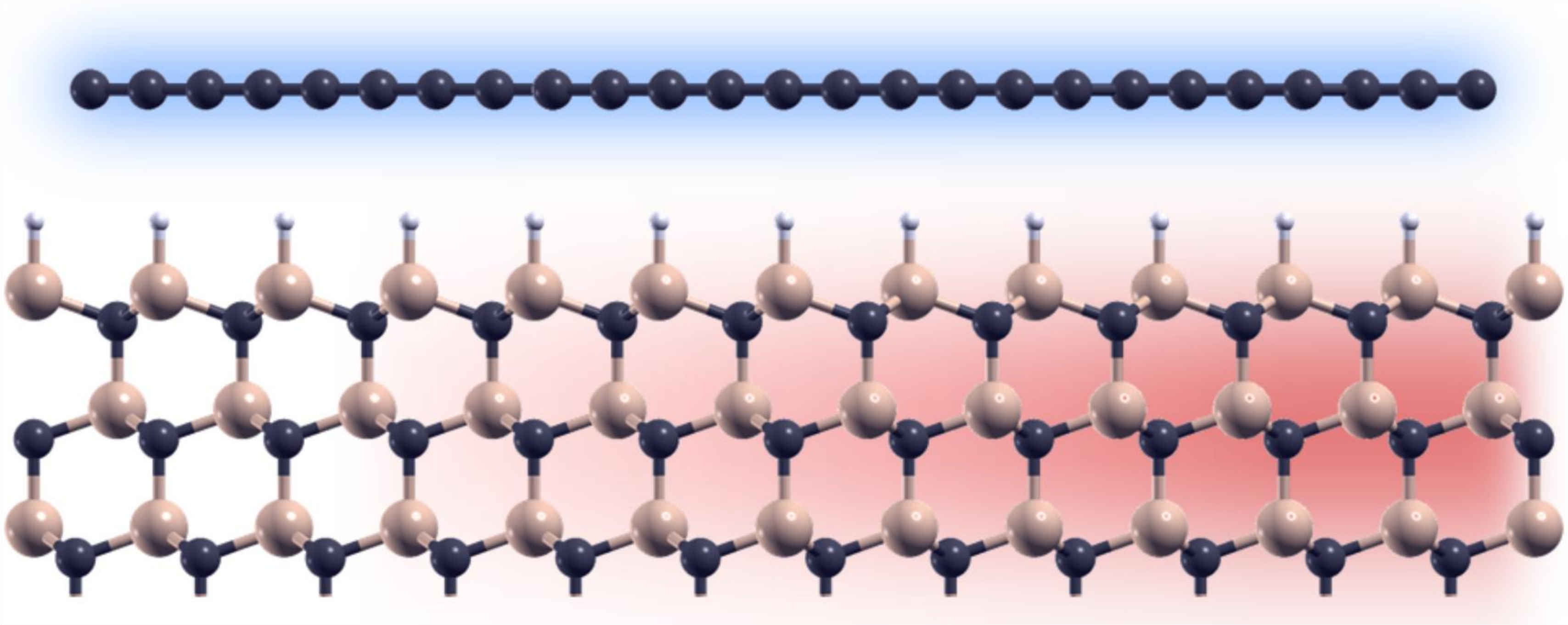
Fully reversible: Yes

Possible hallmark: Yes



Defect-engineered two-dimensional graphene-on-silicon-carbide platform for high-temperature magnetic diagnostics 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)



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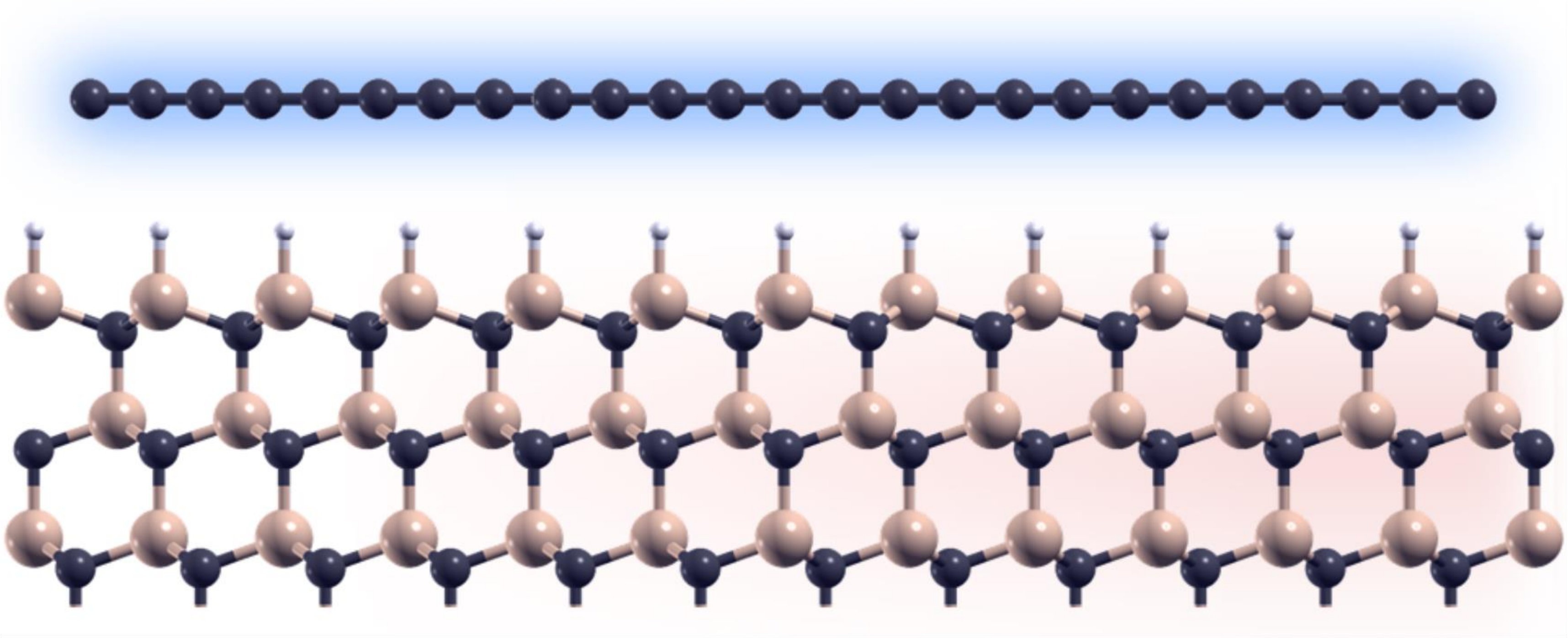

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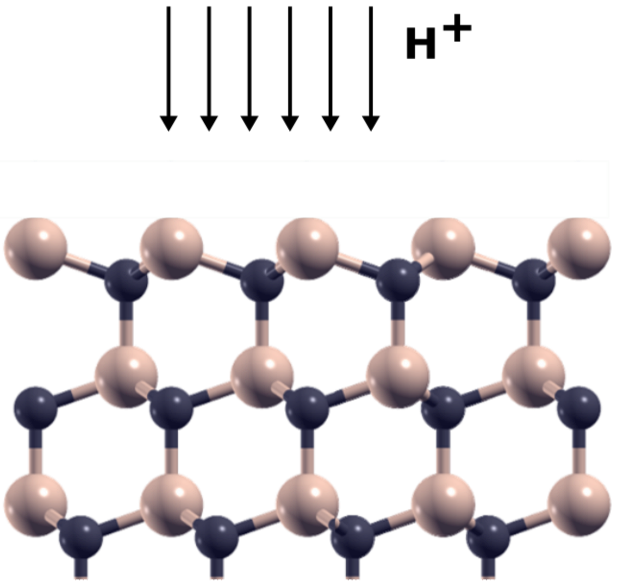
As revealed by High-Resolution Photo-Induced Transient Spectroscopy (**HRPITS**)

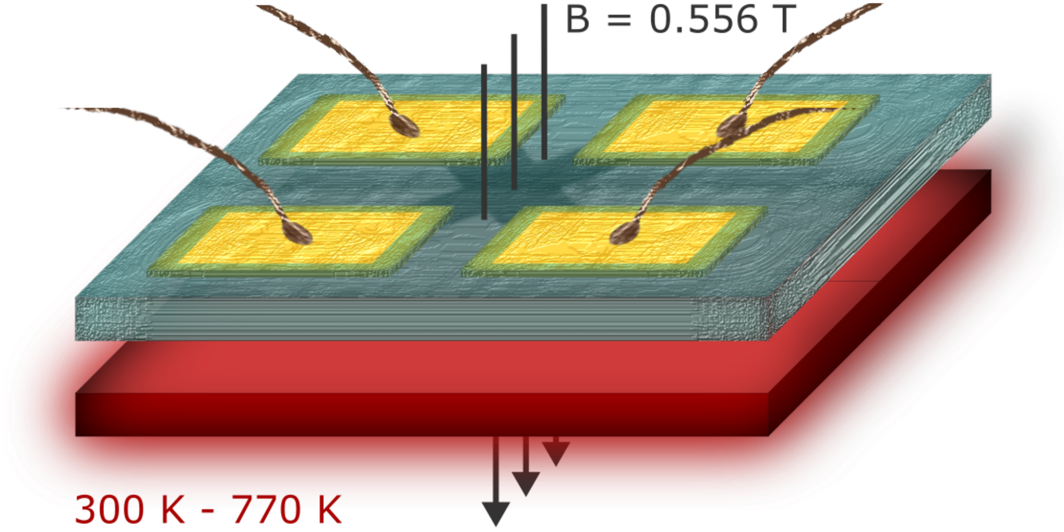
SI vanadium-compensated 6H-SiC has 9 trap levels

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

Defect-engineered two-dimensional graphene-on-silicon-carbide platform for high-temperature magnetic diagnostics in modern fusion reactors

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





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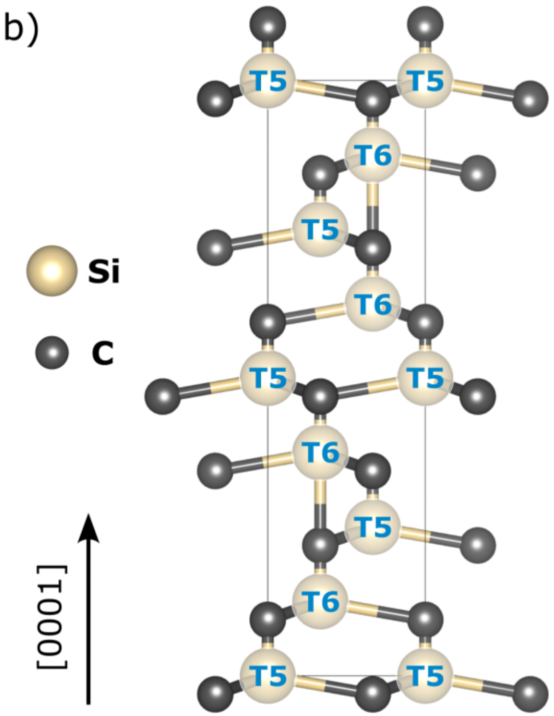
Pre-epitaxial bombardment: H^+ ions

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

b)



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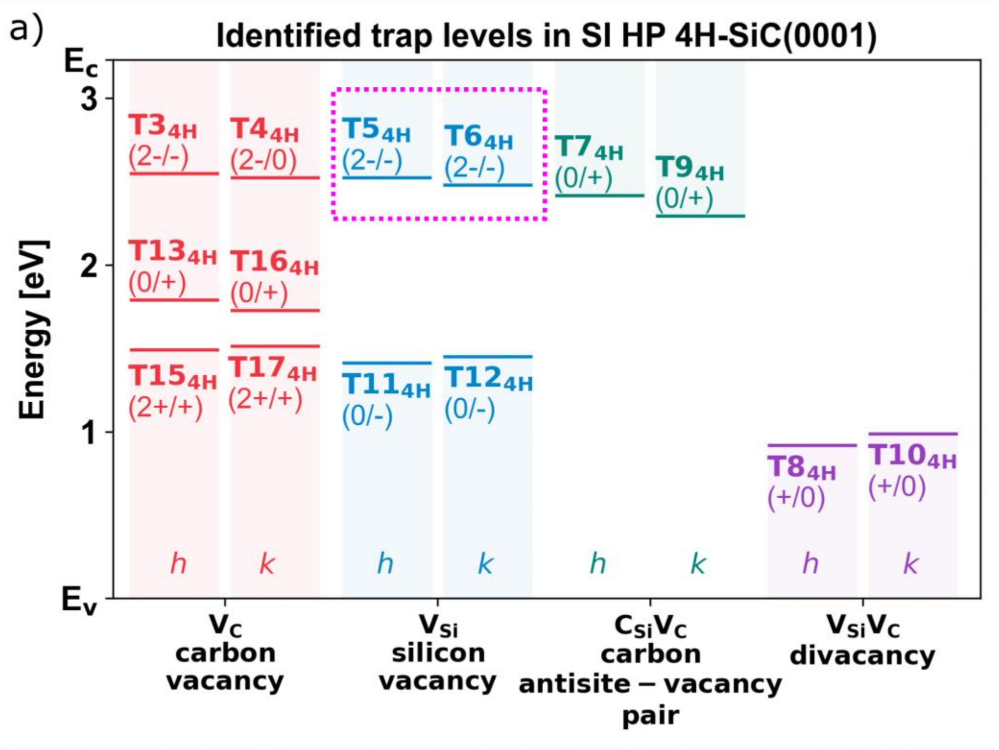

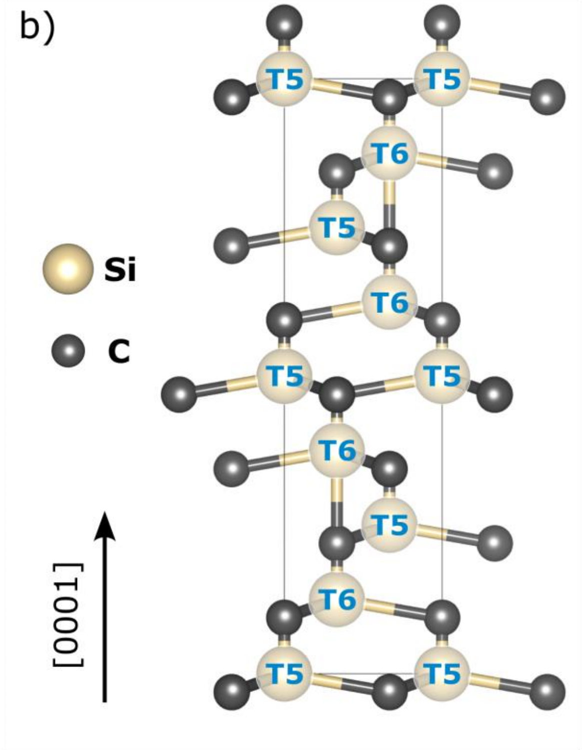

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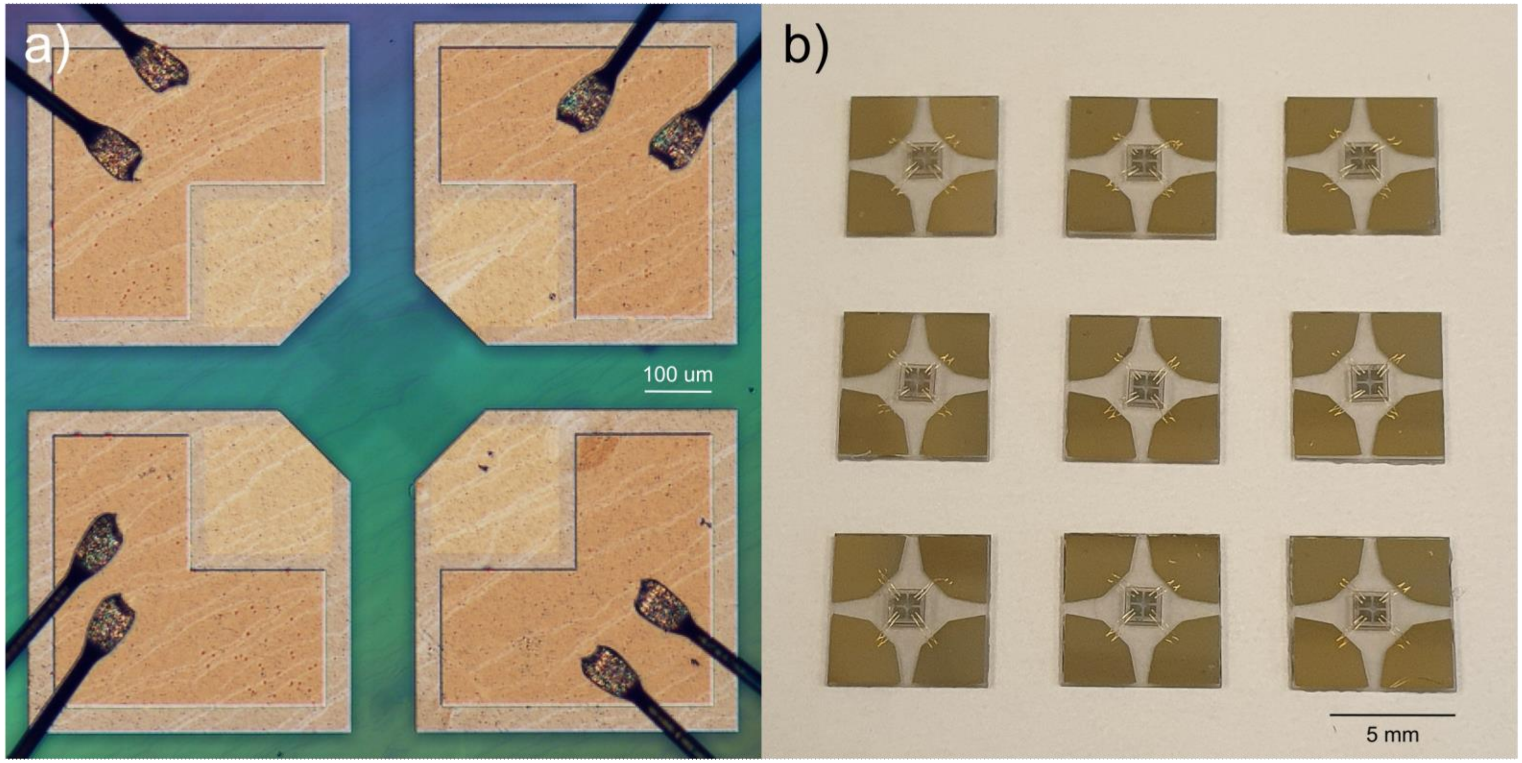


10.1109/LED.2024.3436050

Defect-engineered two-dimensional graphene-on-silicon-carbide platform for high-temperature magnetic diagnostics in modern fusion reactors

Platform: 4H-SiC

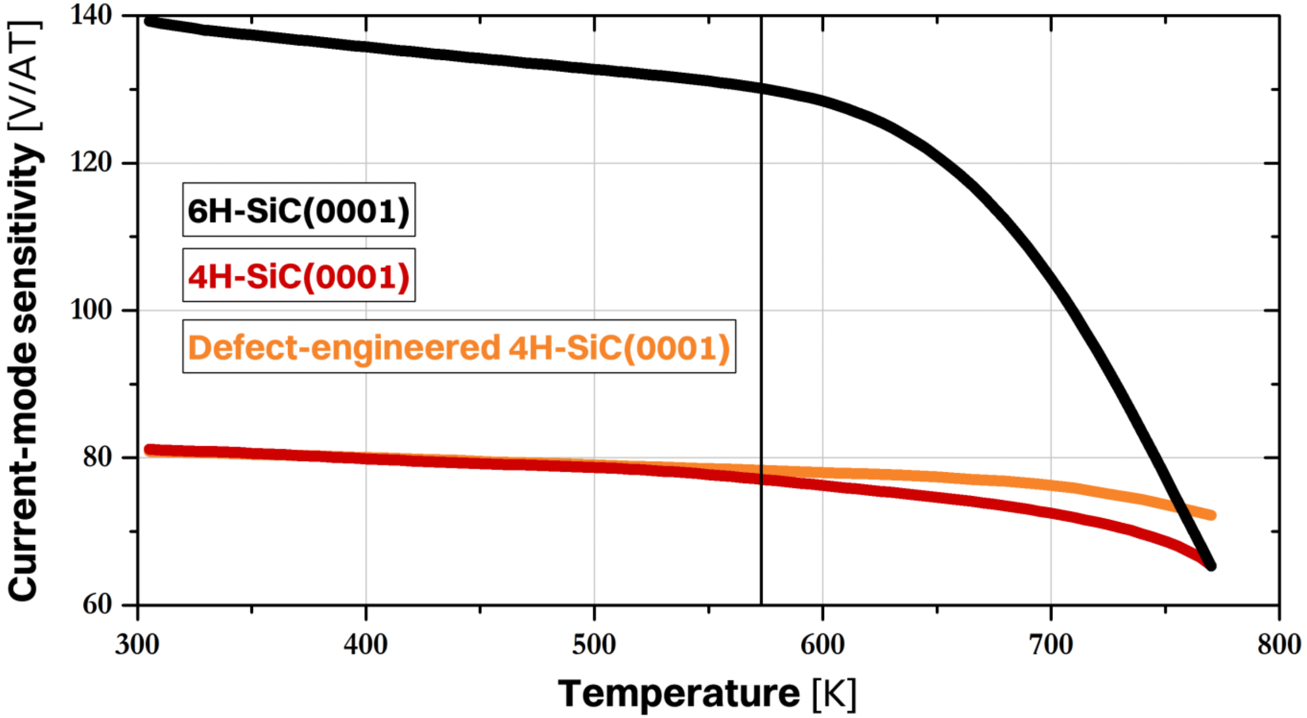
Type: Ion-implanted

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

End temperature: **770 K (497 °C)**

Advantages: more linear,

less dispersed



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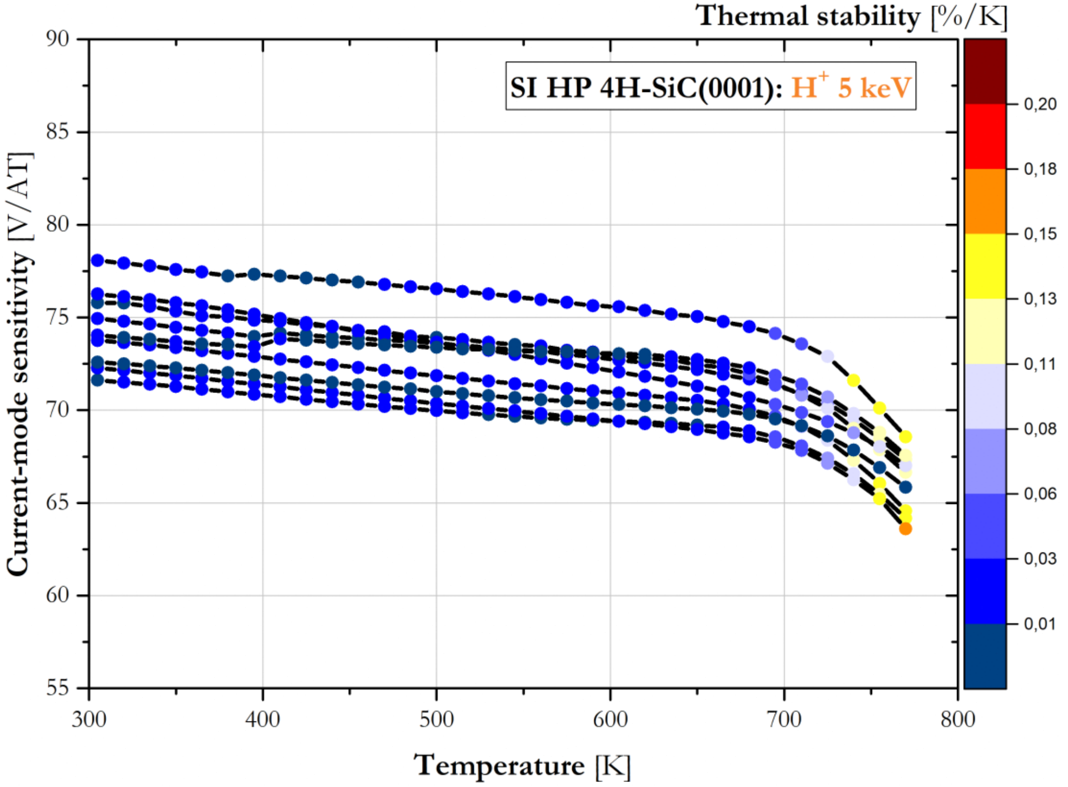

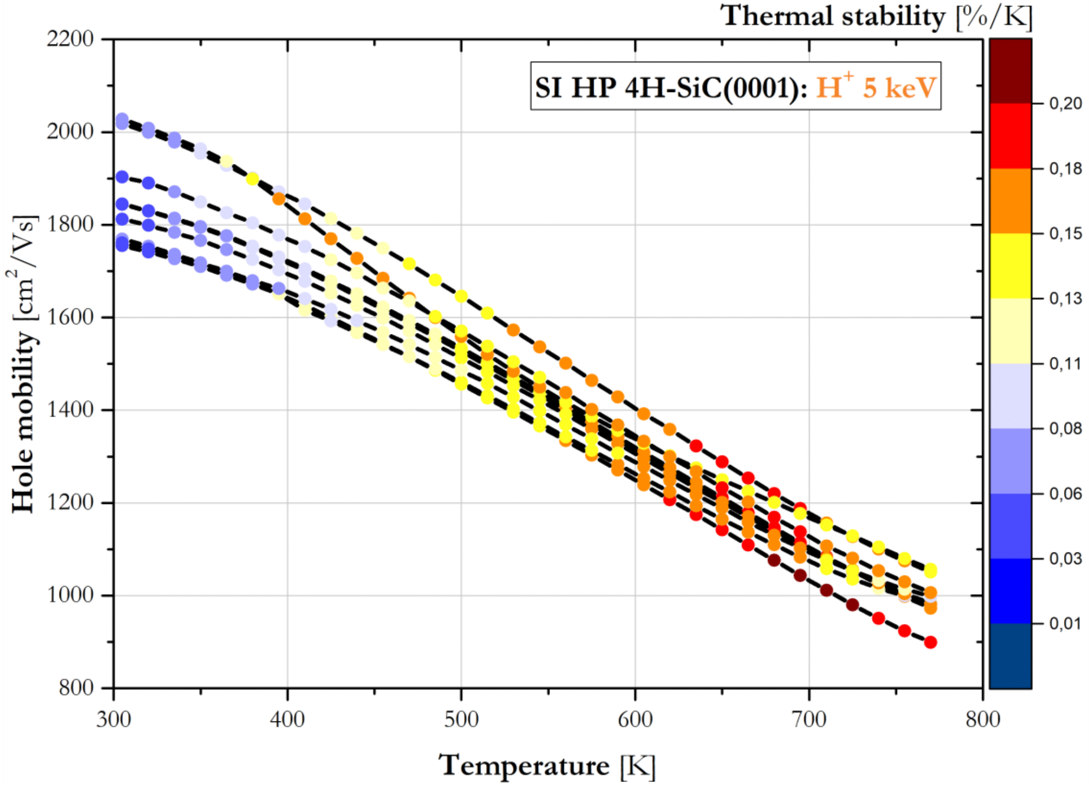

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Expected fast neutron doses:

ITER: E16 - E18 cm^{-2}

DEMO: E16 - E22 cm^{-2}

Investigated fast neutron doses:

E16	E17	E18	E19	E20	E21	E22

Defect-engineered two-dimensional graphene-on-silicon-carbide platform for high-temperature magnetic diagnostics in modern fusion reactors

Completed but not yet published:

Fast neutron fluence of **2.0 E17** cm^{-2} (peak at 1-2 MeV) Exposure time: **7 days**

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

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

Defect-engineered two-dimensional graphene-on-silicon-carbide platform for high-temperature magnetic diagnostics in modern fusion reactors

MARIA reactor: fast neutron (1-2 MeV) fluence of 2.0 E17 cm^{-2}

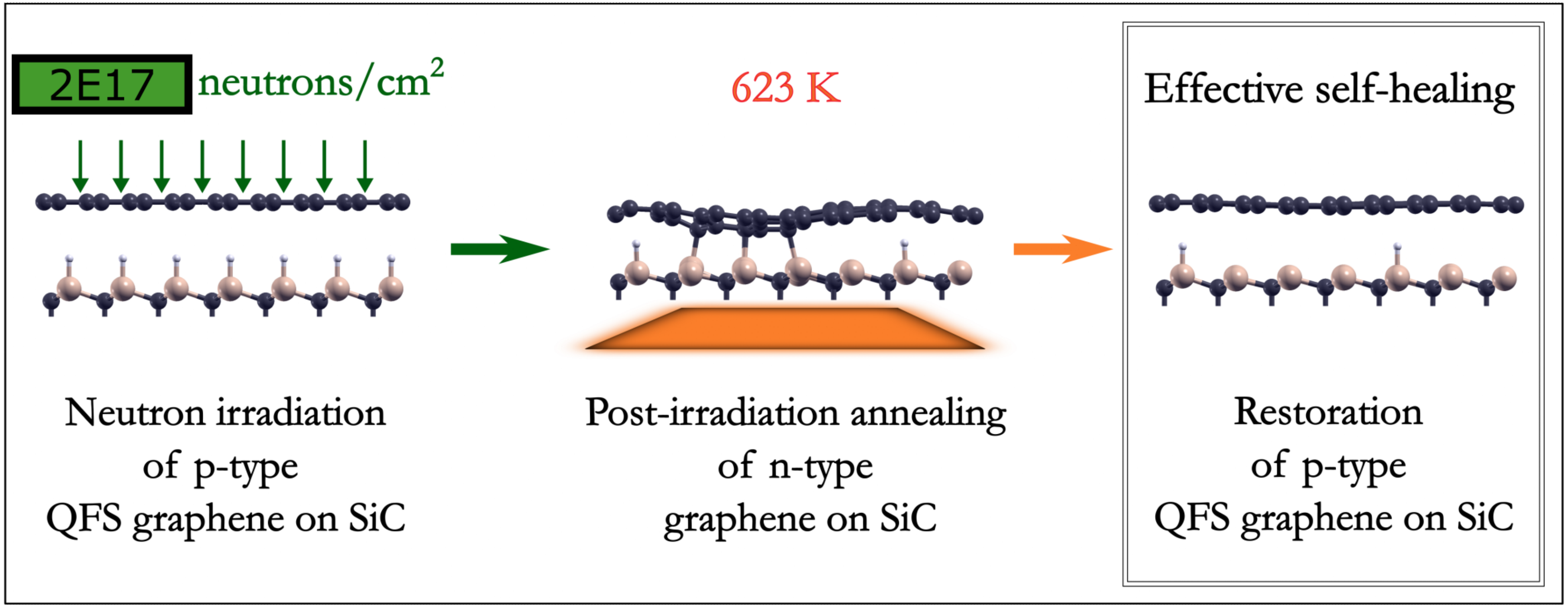
Estimated defect density: 3.1 E10 cm^{-2}

MARIA reactor: fast neutron fluence (1-2 MeV) of 2.0 E18 cm^{-2}

Estimated defect density: 1.3 E11 cm^{-2}

It takes **millions of neutrons** to introduce **1 defect in graphene**

Defect-engineered two-dimensional graphene-on-silicon-carbide platform for high-temperature magnetic diagnostics in modern fusion reactors



Summary & Conclusions

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

Additional modification: low-energy ion implantation

Competitive advantages:

- operates **up to 770 K** (497 °C)
- largely resistant to neutron irradiation (self-healing effect **at least up to 2.0 E17**)

Potential application: magnetic diagnostics and plasma control in fusion reactors

Defect-engineered two-dimensional graphene-on-silicon-carbide platform for high-temperature magnetic diagnostics in modern fusion reactors

THANK YOU FOR YOUR ATTENTION!

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