Advancing Diamond Semiconductor Technology: High-Temperature Devices for Power Conversion Applications

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Outline

1) Introduction to diamond and current bottlenecks

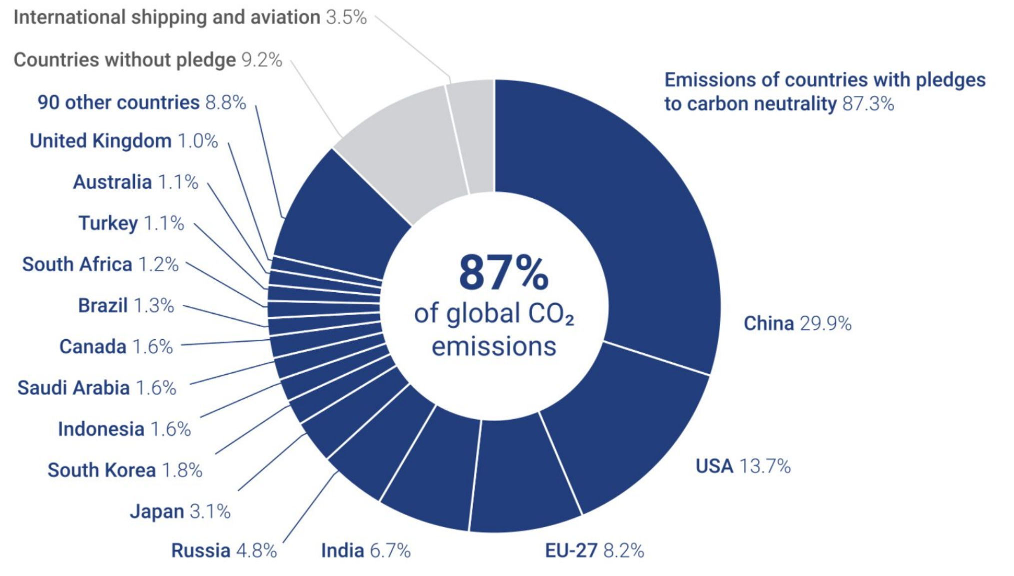
2) Progress on Diamond Hole FETS

3) Method for p type doping and ohmic contact formation

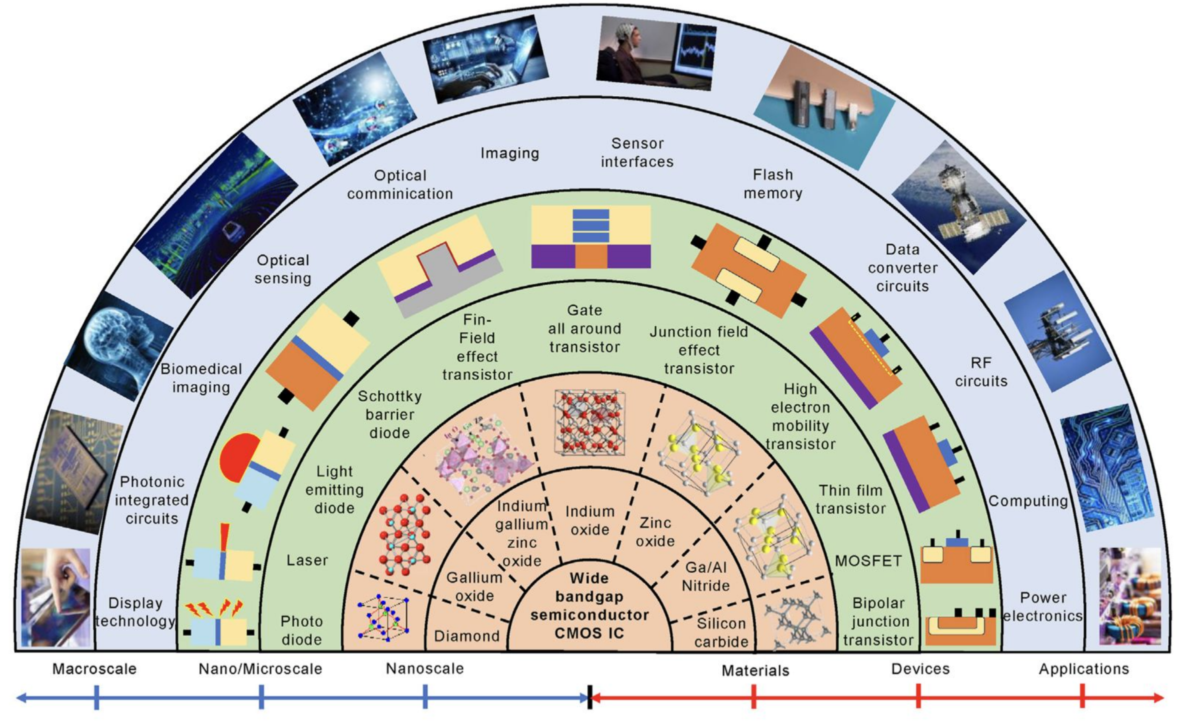
Need for wide bandgap semiconductors

Global emissions and carbon neutrality pledges

The 131 countries which have pledged to become carbon neutral account for 87% of global CO_2 emissions.

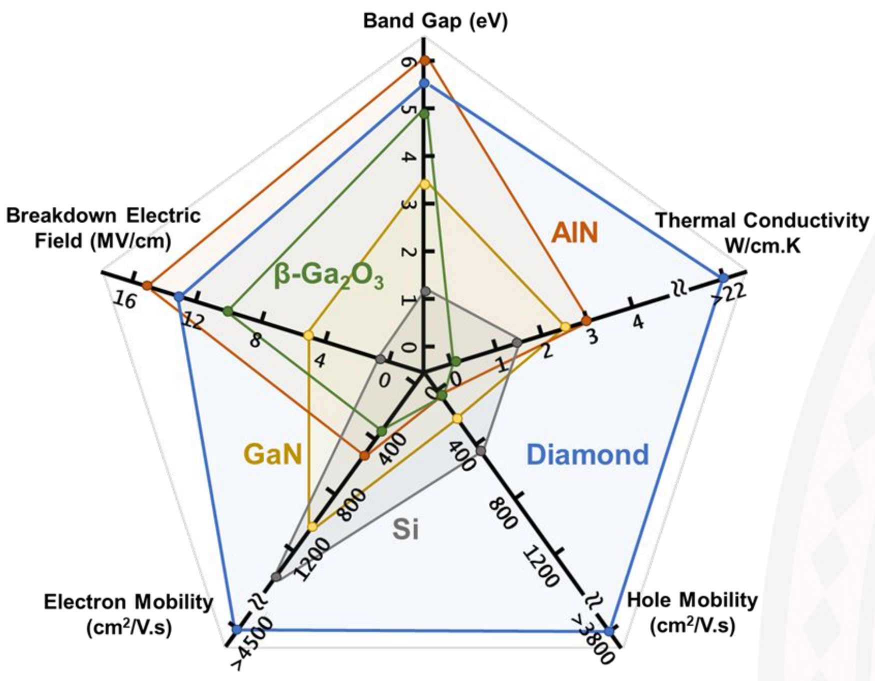


https://factsonclimate.org/infographics/emission-pledges



https://doi.org/10.1016/j.chip.2023.100072

Diamond: An ultra wide bandgap material



K. Woo et al 2024 J. Phys. Mater. 7 022003

❖Activation energy for boron is 0.37 eV. Difficulty to get high hole concentration for bulk transport at RT.

Hydrogen terminated diamond

❖ Hydrogen termination enables the formation of a conductive channel

❖ Surface band bending is due to transfer of electrons from valence band in diamond to empty surface acceptor states

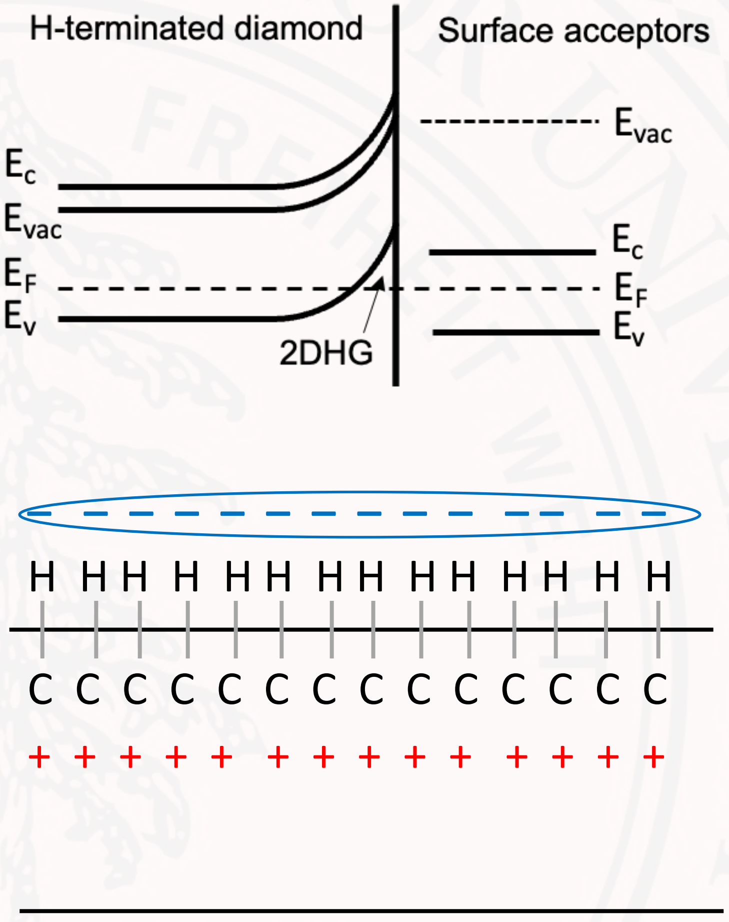
❖ The lowest unoccupied level of surface acceptors should be below the VBM of diamond

❖ H-terminated diamond exhibits a negative electron affinity (-1.3 eV)

❖ Surface acceptors include air, water, NO_2, metal oxides etc.

❖ Channel extremely sensitive to environment

Transfer doping model*



H-terminated diamond

*Crawford, Kevin G.etc.. "Thermally Stable, High Performance Transfer Doping of Diamond Using Transition Metal Oxides." Scientific Reports8, no. 1 (2018).

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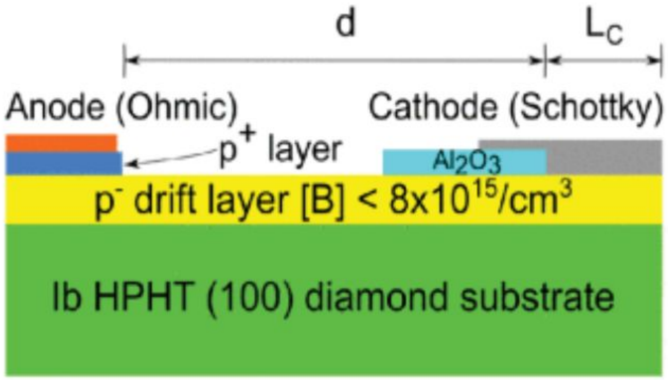
State of the art Diamond Power Devices

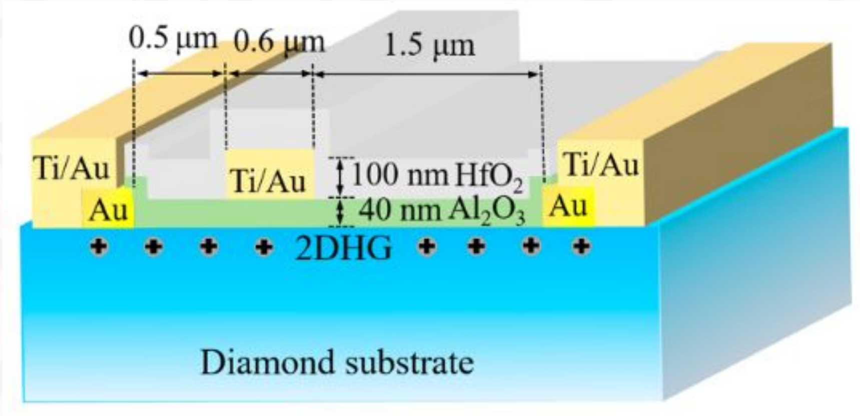
Schottky Barrier Diodes



Ron,sp 534 Ω cm^2, Vbv 5612 V

Z. Han and C. Bayram, *IEEE Electron Device Letters* (2023)

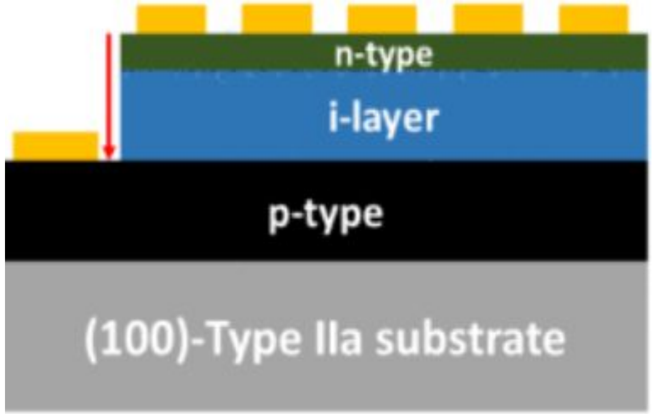
2DHG Hole FETS



Ron,sp 31.9 mΩ cm^2, Vbv 2 kV

Y. Kitabayashi *et al.*, "Normally-Off C–H Diamond MOSFETs With Partial C–O Channel Achieving 2-kV Breakdown Voltage," in *IEEE Electron Device Letters* (2017)

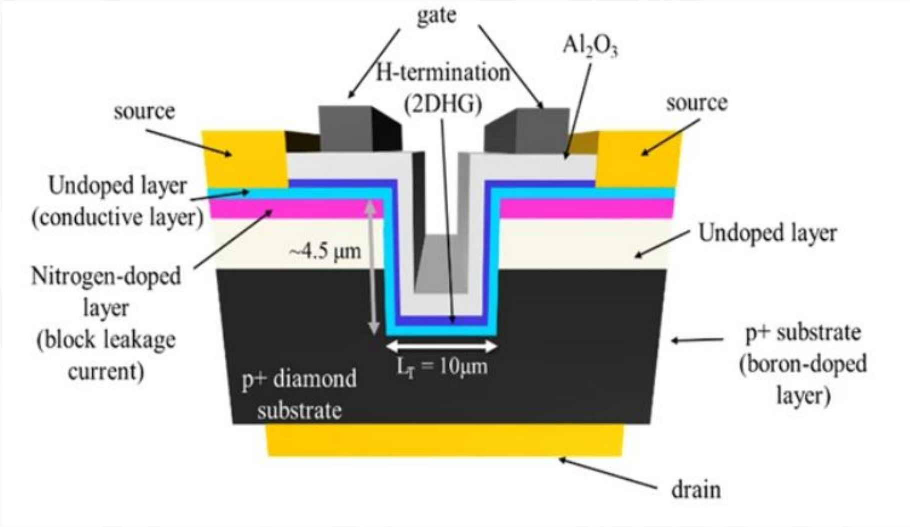
PIN Diodes



Ron,sp 0.25 Ω cm^2, Vbv 1 kV

M. Dutta, et. al. "High Voltage Diodes in Diamond Using (100)- and (111)- Substrates," in *IEEE Electron Device Letters* (2017)

Vertical MOSFET (using 2DHG)



Ron,sp 41 mΩ cm^2, Vbv 300 V, Emax

Oi, N., Inaba, M., Okubo, S. *et al.* Vertical-type two-dimensional hole gas diamond metal oxide semiconductor field-effect transistors. *Sci Rep* 8, 10660 (2018).

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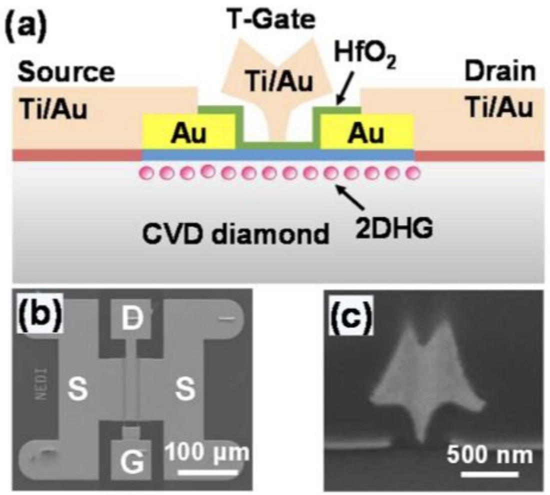
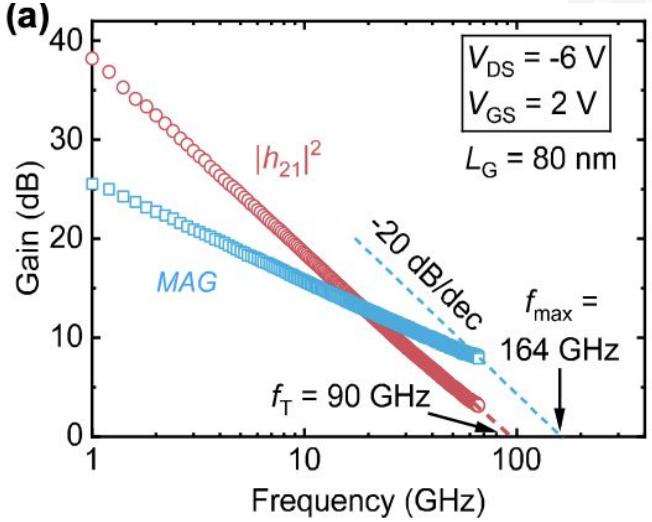
State of the art diamond RF peformance

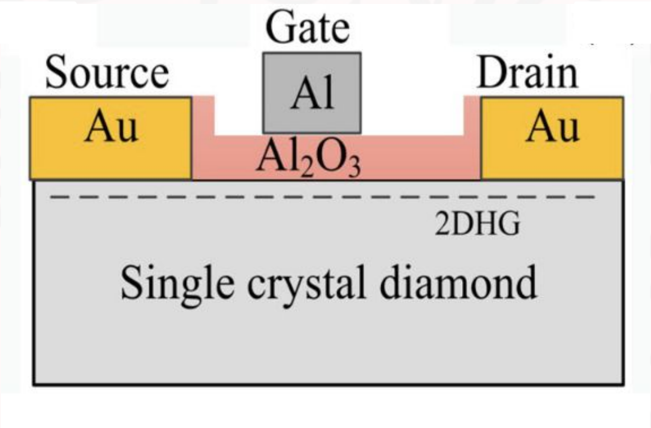
Small signal performance

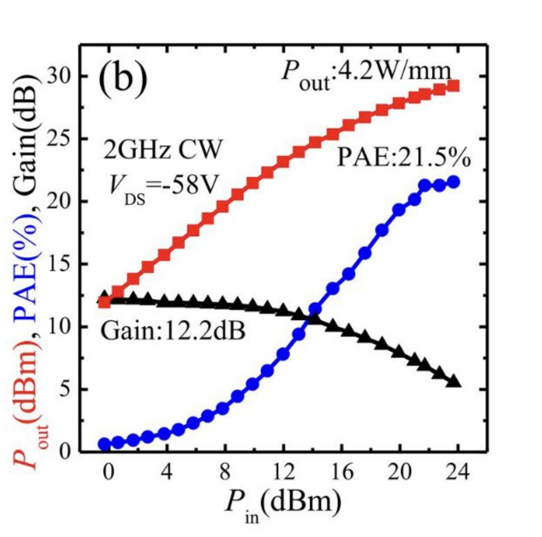


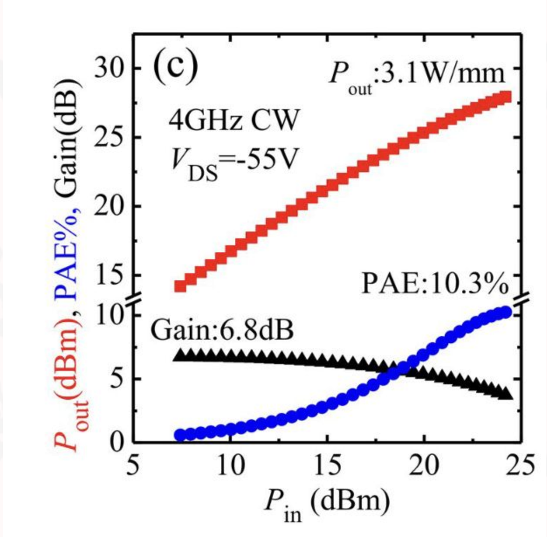


X. Yu *et al.*,*2024 IEEE International Electron Devices Meeting (IEDM)*.

Large signal performance



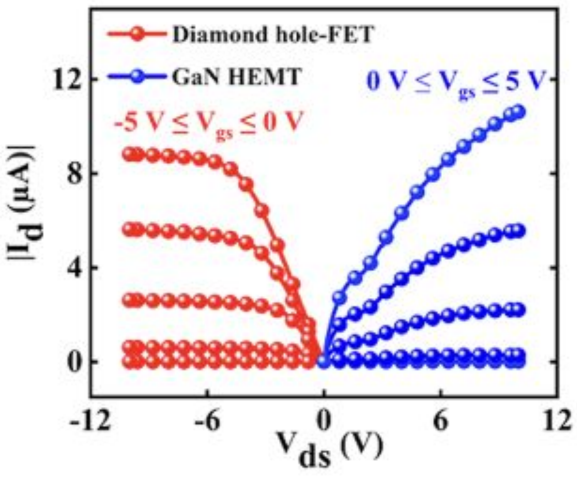


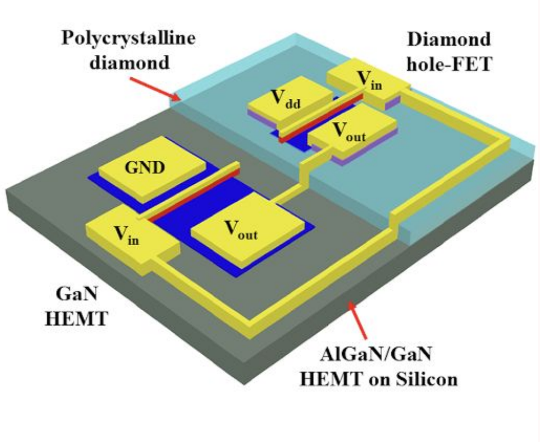


Yu, C. et al.,*Functional Diamond*, 2(1), 2022

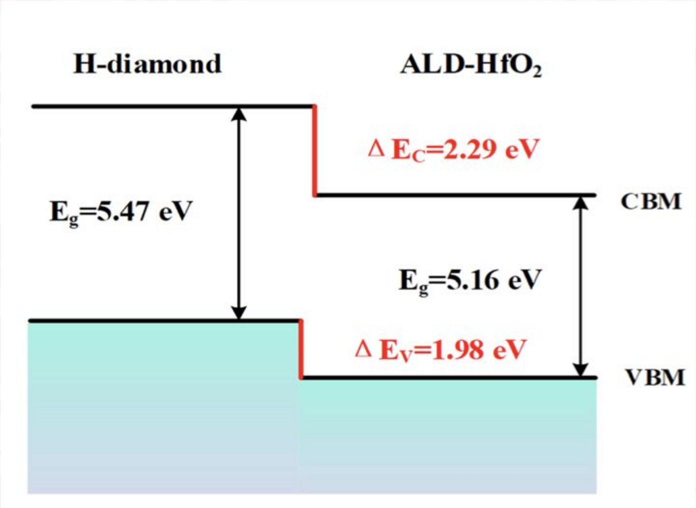
Need for surface passivation

- H-terminated diamond surface needs to be passivated to preserve 2DHG under harsh conditions.
- Dielectrics like Al_2O_3,HfO_2, ZrO_2 are widely used as the gate dielectric for H-Diamond FETs.
- C. Ren et al. demonstrated Al_2O_3/H-diamond FET with max drain current of 12 mA/mm.
- HfO_2 is a widely used dielectric due to high breakdown field and large band offsets (ΔE_c=2.29 eV and ΔE_v=1.98 eV)* w.r.t. H-diamond.





C. Ren et al., ACS Appl.Electron.Mater.2021, 3, 4418−4423



*Z. Ren et al., AIP Advances **11**, 035041 (2021)

Factors limiting performance of H-diamond FETs

❑ High contact resistance	Reduces RF gain, output power
❑ Surface channel instability	Leads to threshold voltage and RF instability
❑ High trap density at dielectric/diamond interface	Reduced transconductance, RF dispersion
❑ Gate dielectric quality	Gate leakage, reduced breakdown performance, reliability degradation
❑ Quality of diamond substrates	Low mobility, degrade RF performance

Current Work on H diamond FETs

- Study of ALD grown HfO_2 as a dielectric
- Thermal stability of H diamond FETS fabricated with ALD grown HfO_2
- Short channel FETs for RF Applications

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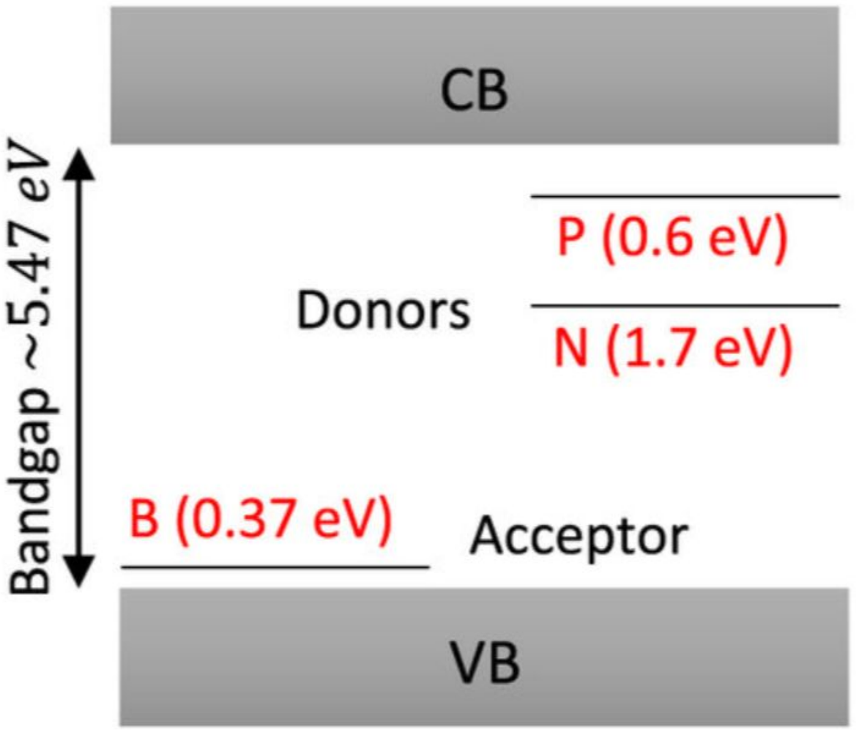
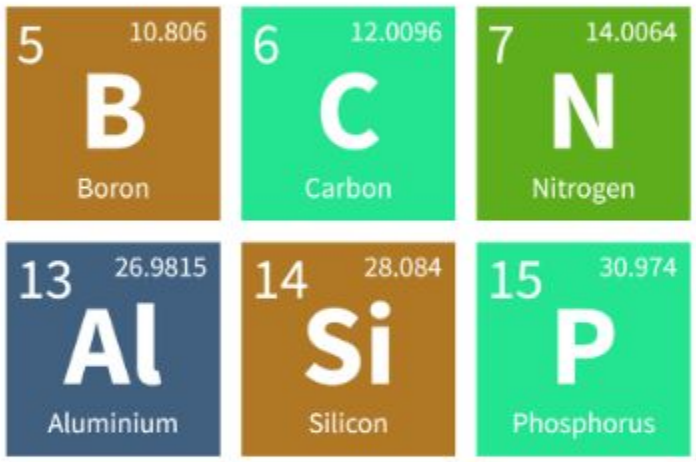
P Type Doping in Diamond

P type doping in diamond is much easier

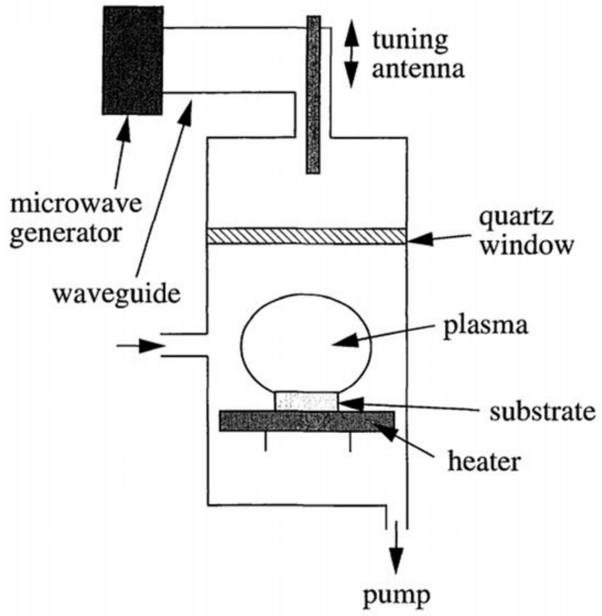




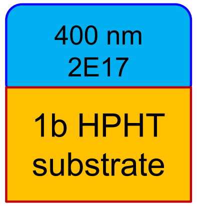
- Lower activation energy
- **Good lattice compatibility - limited distortion**
- Valence band structure supports hole transport
- **Low compensation** — few competing defects for acceptors

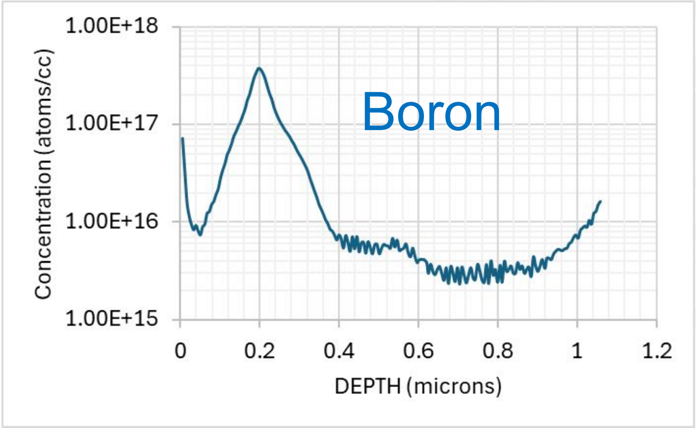
P Type Doping in Diamond via Growth

Microwave plasma CVD



SIMS





Current State:

1) Thick free-standing boron doped CVD diamond with B concentration > **10^{20} B atoms/cm^3**

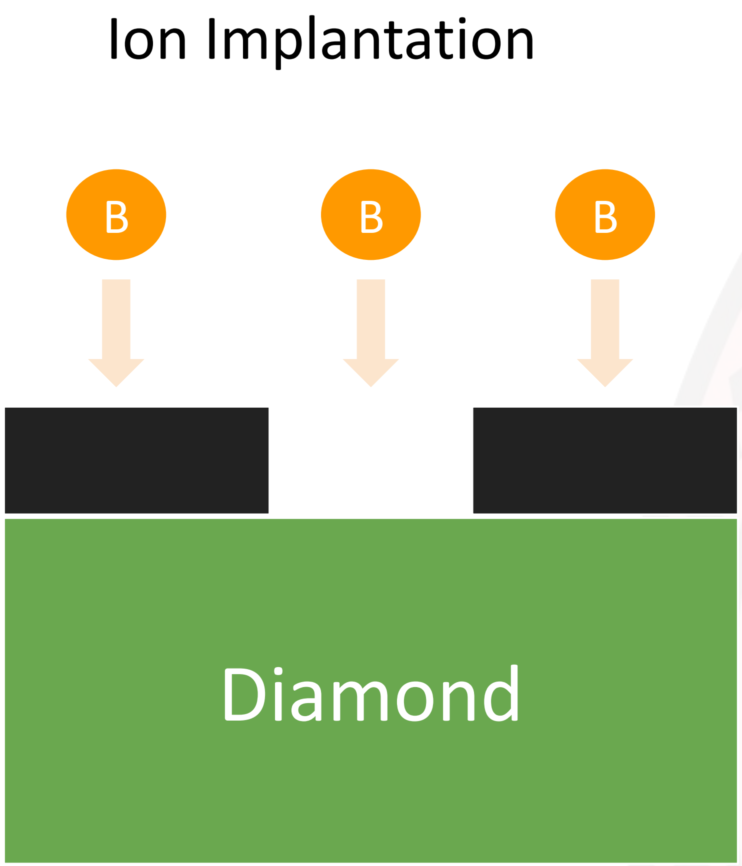
1) Low to medium boron doped epi-layers (10^{17}-10^{18} B atoms/cm^3) **(Our Group's Work)**

Difficulties: regrown interface in **selective doping**, dislocation formation, slow growth

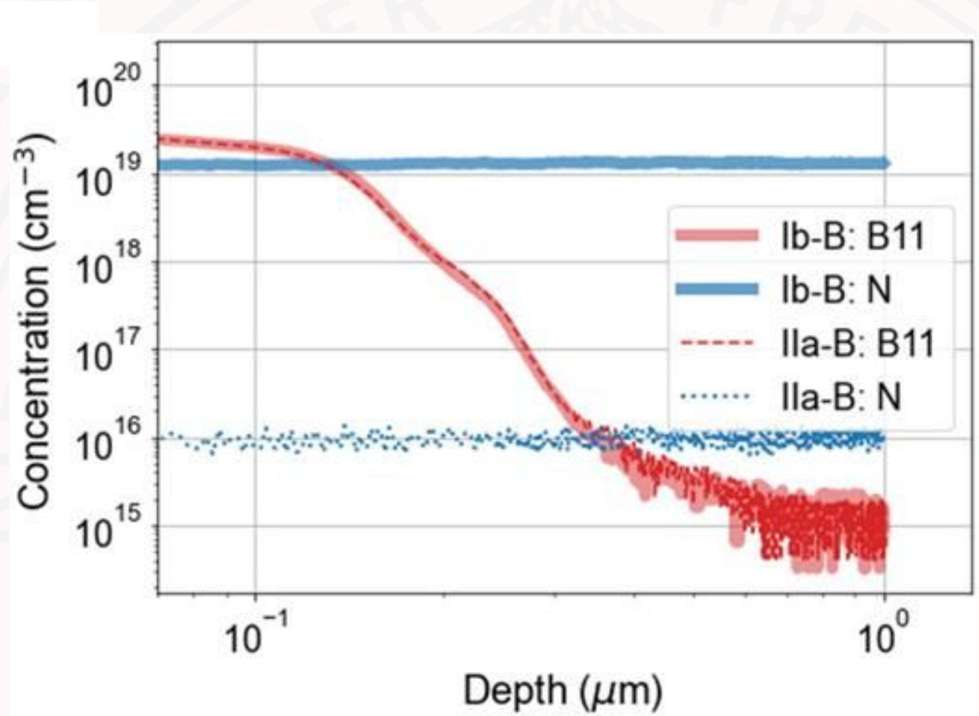
Question: Can we use a non growth based method for achieving selective doping in diamond?

1. Mesples-Carrère et al, Diamond and Related Materials, 2024
2. Araujo, D., et al, Applied Physics Letters 118.5 (2021).

Selective P Type Doping in Diamond via Implantation



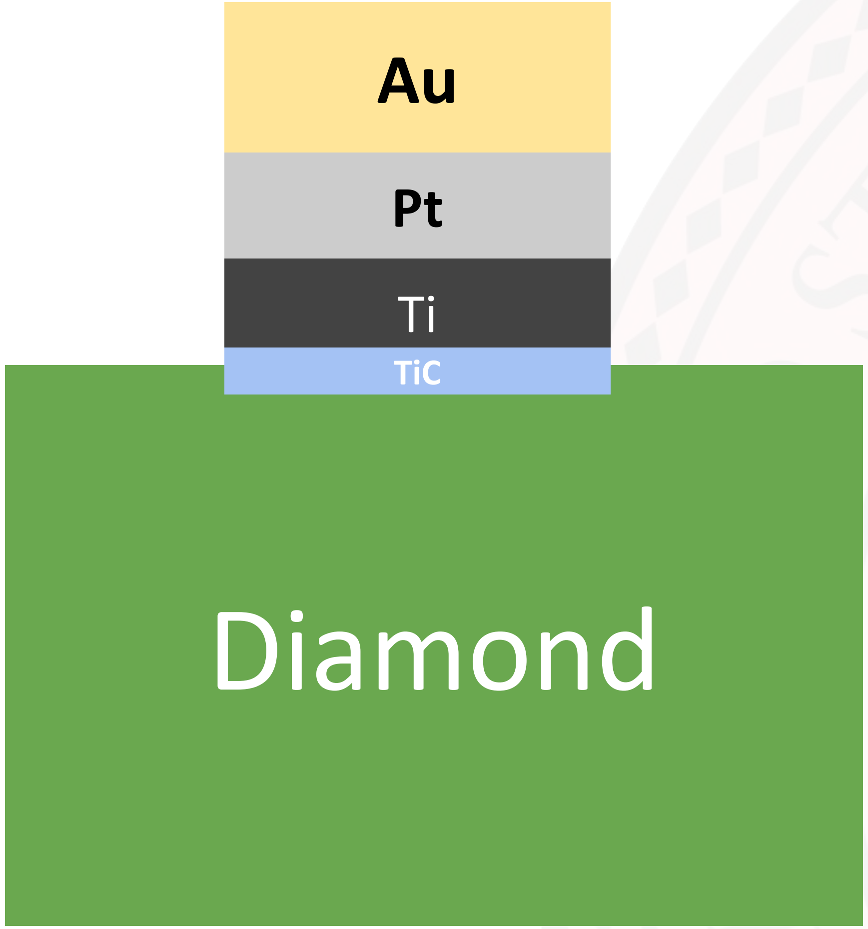
Current State: B concentration of 10^{19}-10^{20} atoms/ cm^3, ~100-200 nm thick, hall mobility ~100 $cm^2V^{-1}s^{-1}$



Difficulties: surface graphitization, boron incorporation into crystal lattice and activation, boron diffusion

1) Yasushi Hoshino and Yuhei Seki *J. Phys. D: Appl. Phys* (2025)
2) Woo, Kelly, et al. *Applied Physics Letters* (2022).

Ohmic Contact Formation



- ❖ Oxygen terminated diamond
- ❖ Lightly p-type diamond

Current Work on P Type Doping

- Study of novel methods to introduce boron into the diamond lattice
- Hall measurement and surface quality analysis of boron doped samples
- Use of doping methods as a means of reducing ohmic contact resistance

Conclusions

- Potential of diamond for RF and high power applications
- Study and progress on diamond hole FETs
- Exploration of methods for boron doping and ohmic contact formation for diamond devices

Acknowledgements

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Thank you very much

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Bio Presentation- Devansh Saraswat

Devansh Saraswat

Email: sdevansh@stanford.edu

- Born in Kanpur, India.
- Graduated from IIT Kanpur in 2019 with a Bachelor's degree in Materials Science and Engineering and a Minor in Electrical Engineering.
- In 2018, I did a research Internship at Max Planck Institute for Solid State Research in Stuttgart, Germany. Performed electrical characterization of thin film transistors on organic semiconductors.
- Master's degree at Cornell University (2019-2021). Worked on Schottky Barrier Diodes on Ga_2O_3 for high power applications.
- Started my PhD program at Stanford University in Fall 2021.
- Focus on diamond-based device fabrication and characterization
- Graduate in 2027
- Outside the lab, I like playing tennis and going on hikes.

Bio Presentation – Nishita Sinha

email: nsinha17@stanford.edu

- ❖ Fourth year PhD student in Electrical Engineering
- ❖ Undergraduate degree from Harvard University in Physics
- ❖ **Research focuses:** physics-based understanding of p-type doping in GaN, p-type doping and ohmic contact formation in diamond
- ❖ **Other interests:** Science communication, understanding microgrids and the grid to chip power conversion pathway, and rock climbing