

Heterogeneous Integration of Diamond Electronics: Transistors, Diodes and Packaging

Aris Christou

**Mechanical Engineering Department
and Materials Science and Engineering
CALCE Electronic Products Center
*University of Maryland, College Park, MD***

•

**IMAPS HITEC Conference
KEYNOTE PRESENTATION April 16, 2025**



Outline

Diamond Material Background and Materials Science

CVD Growth of Epitaxial Diamond

Defects in Diamond

The doping problem

Fabrication of Field Effect Transistors and Results.

Advanced Diamond Transistor Structures

UMD Delta Doped FETS

Diamond in Advanced Packaging

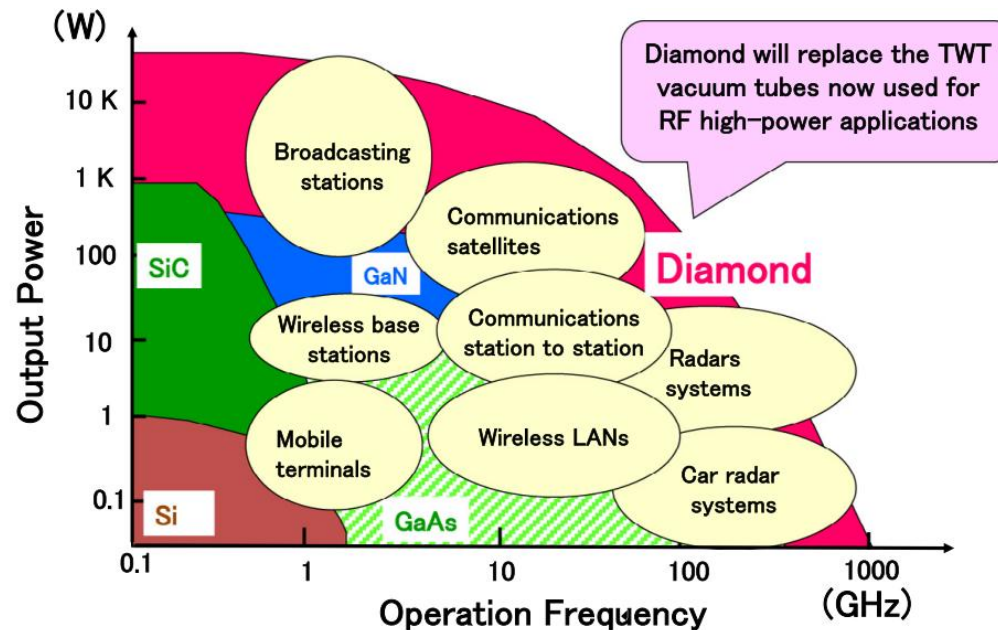
Summary of Remaining Issues

Diamond and the Ultra-Wide Bandgap Semiconductors

2025 Joint HITEC/CICMT/APPE Conference, Albuquerque, New Mexico, April 14-17, 2025



- Semiconductors with bandgaps exceeding those of GaN and SiC
 - Candidate materials include β -Ga₂O₃ and **Diamond**
- Combination of materials parameters points to diamond for highest power AND highest frequency demands



M. Kasu, in "CVD Diamond for Electronic Devices and Sensors", Ed. R. Sussmann, Wiley and Sons

Z. Guo, et al., *Appl. Phys. Lett.* 100, 113503 (2012).

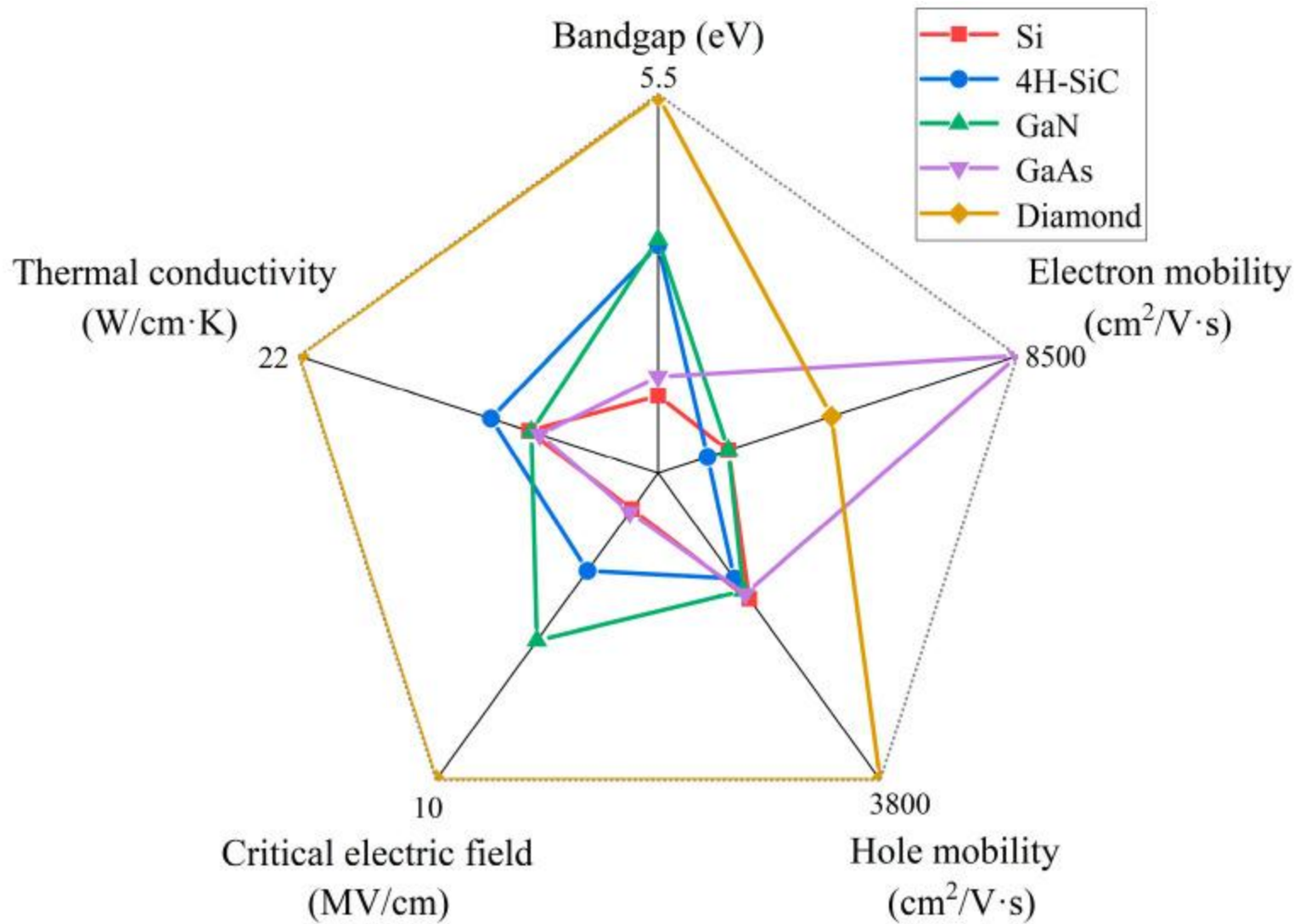
T.P. Chow, *Microelect. Eng.* 83, 112 (2006).

M. Higashiwaki, et al., *Appl. Phys. Lett.* 100, 013504 (2012).

M. Kasu, et al., *Diam. Relat. Mater.* 16, 1010 (2007).

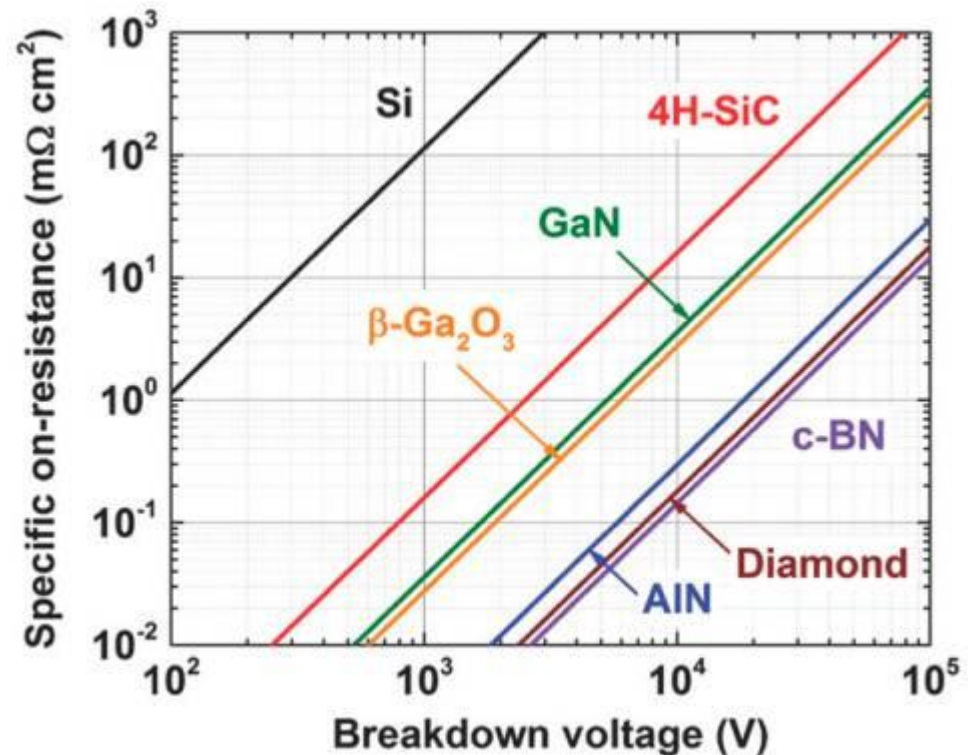


A. JAMES CLARK
SCHOOL OF ENGINEERING



Diamond Comparison to Si, SiC, GaN

- Diamond is (theoretically) best candidate for next-gen **High Power Microwave Applications, as well as High Temperature Electronics**
- Reliability Limitations have not been determined.
 - CVD Diamond compatibility allows production of heterojunction devices (HEMTs)
 - Current efforts have not reached theoretical limits

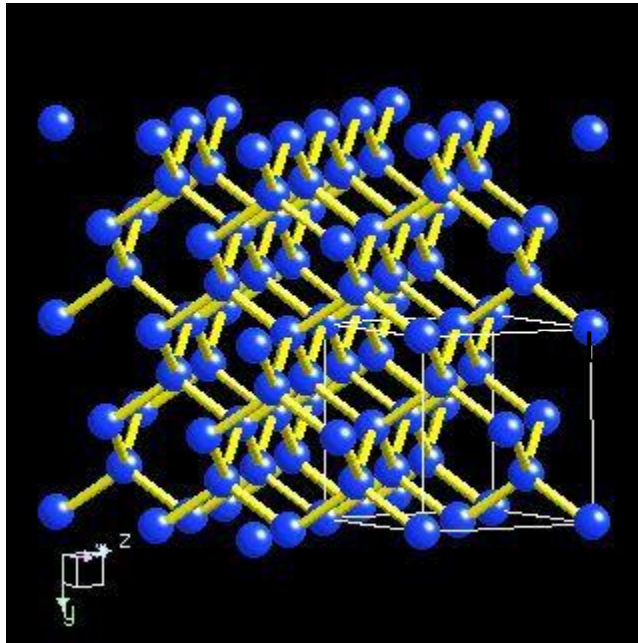




Atomic structure of diamond

2025 Joint HITEC/CICM/APPE Conferences | Albuquerque, New Mexico | April 14-17, 2025

- atomic density $1.76 \times 10^{23} \text{ cm}^{-3}$ (record high)
- cubic lattice parameter $a = 3.56 \text{ \AA}$
- interatomic distance $1.54 \text{ \AA}$



Remarkable properties of diamond are result of

- light atom ($Z=6$)
- short and strong covalent bonding (3D vs 2D for graphite).

Christou

Debye temperature $T_D = 1860 \text{ K}$

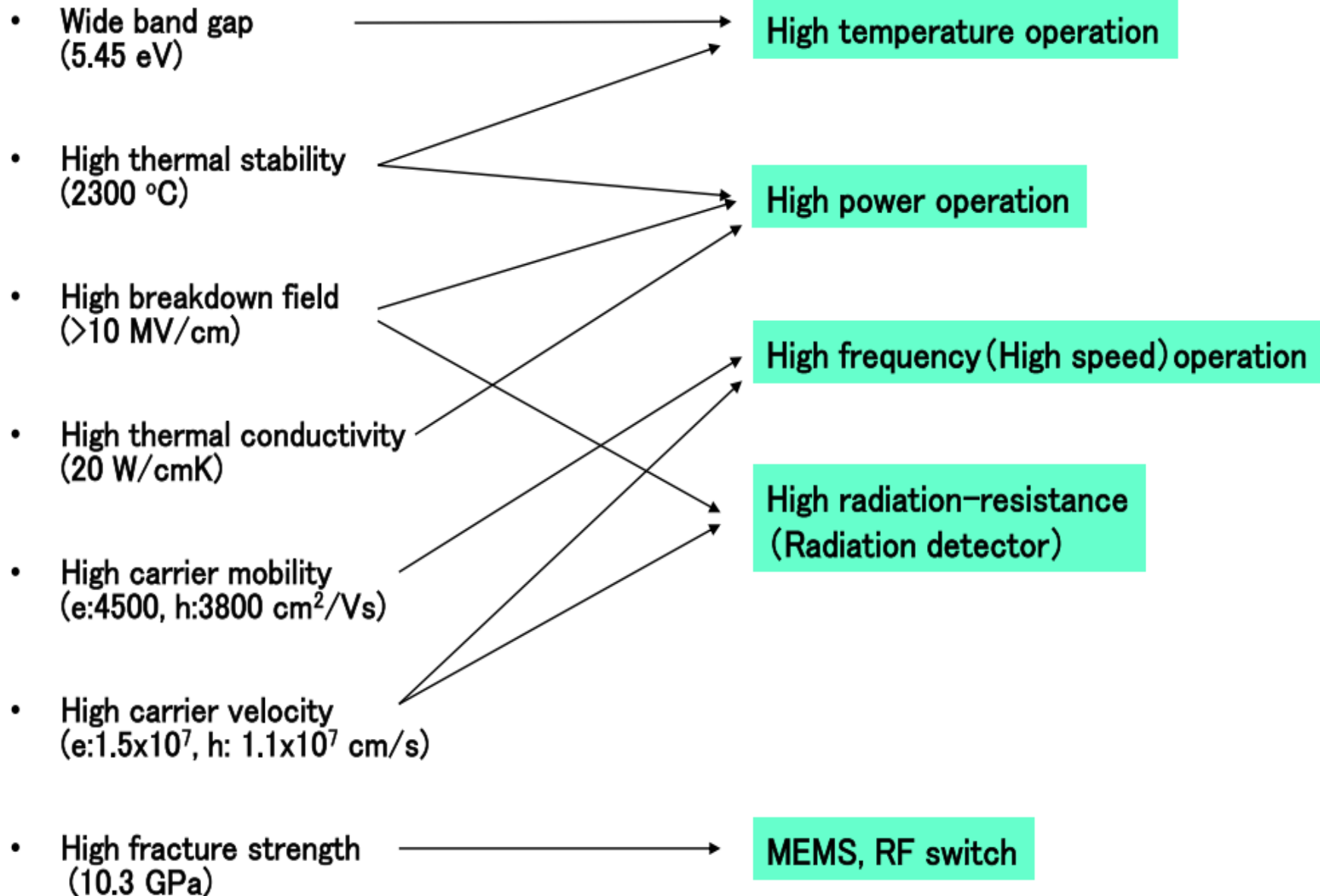
→ $T = 300 \text{ K}$ is low temperature for diamond.

Displacement energy of atom from lattice $\approx 43 \text{ eV}$

→ radiation hardness.



A. JAMES CLARK
SCHOOL OF ENGINEERING



Diamond Substrates

Classification of Diamond Crystals Based on type and Amount of Impurities

Type II: Low nitrogen concentration, usually $<10^{17} \text{ cm}^{-3}$.

Type IIa: Very low boron and nitrogen concentration. Purest available, used as gemstones. Used as substrates for n-type devices.

Type IIb: Boron concentration is higher than nitrogen. Used as substrates for p-type devices.

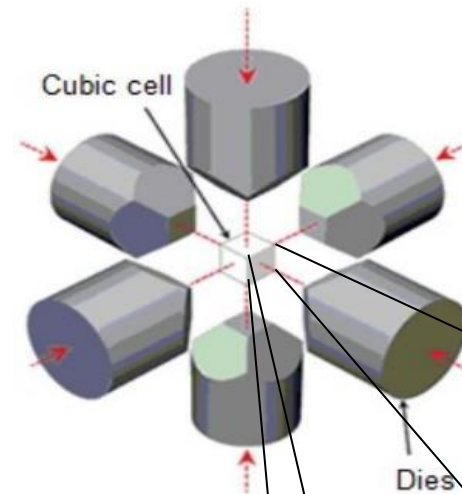
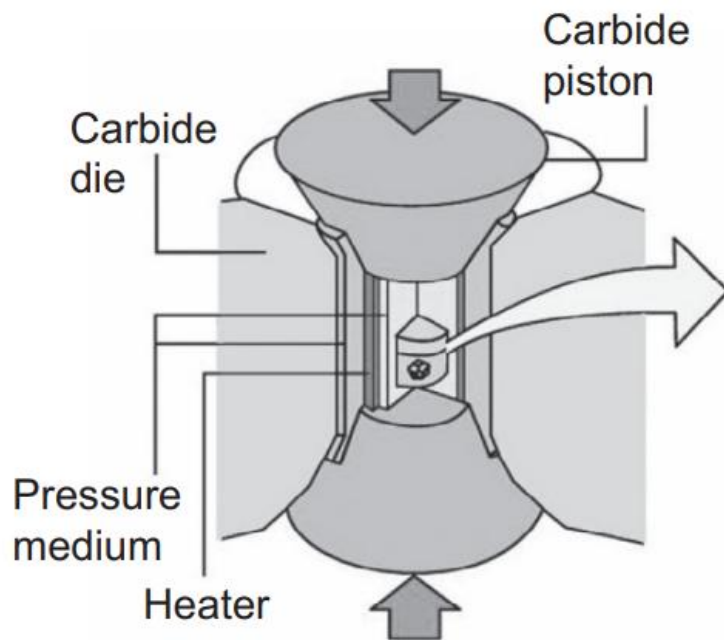
Type I: High nitrogen concentration as measured by IR spectroscopy (0.3%-0.5%)

- Type Ia: N atoms are in C substitutional sites and congregate as C-N.
- Type Ib: N replace C atoms, but do not cluster (HPHT diamond substrates are mainly Ib).

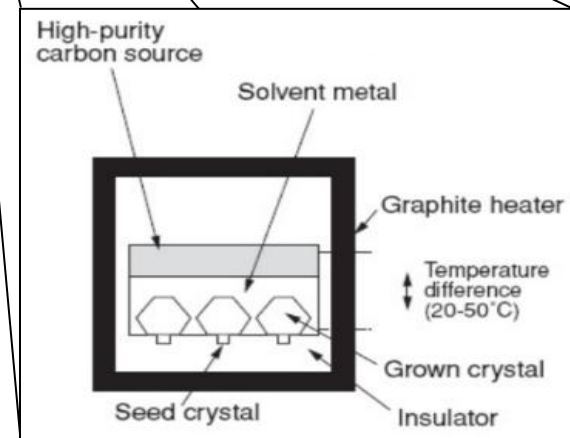


Bulk Diamond Substrates Are Available

- High Pressure High Temperature (HPHT) (100) Type IIb substrates



Can be Polished to Less than 0.3 nm surface roughness



UMD Deposition of Diamond Epitaxy Microwave plasma CVD systems

2.45 GHz and 915 MHz

Parallel processes:

- Etching (sp_2 , sp_3 :orbital hybridization)
- Co-deposition (sp_2 , sp_3)

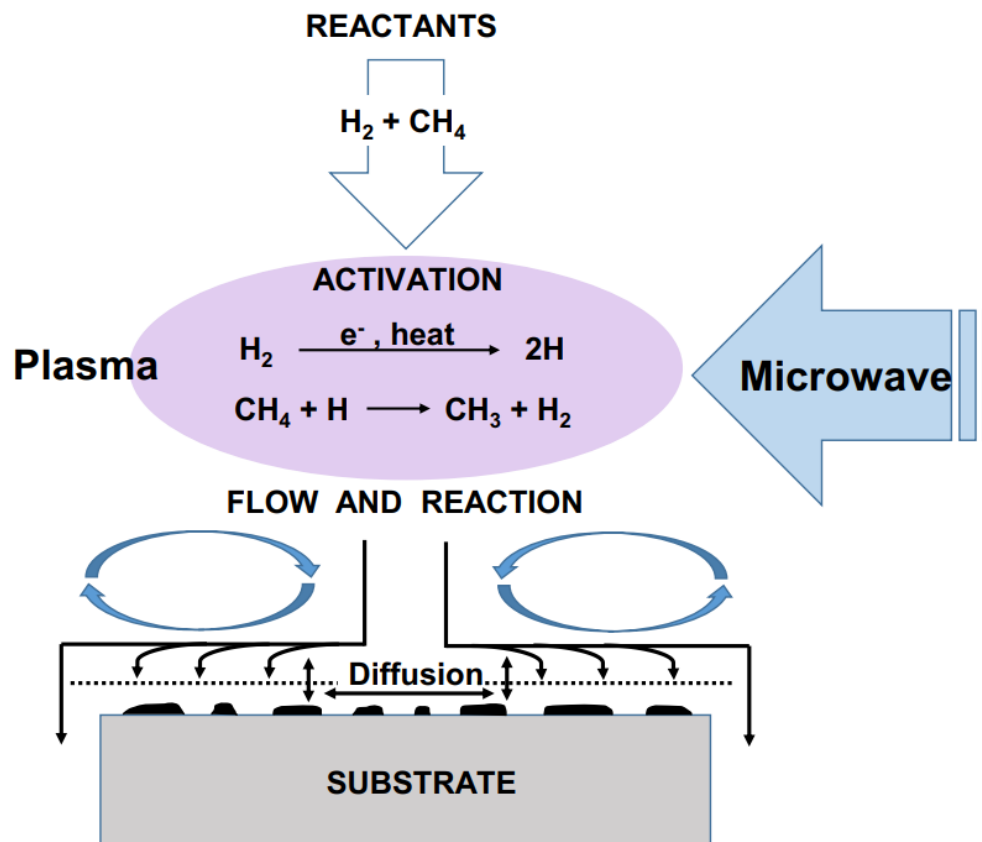
► Dominating product - diamond

Methods of gas activation

- Hot filament
- DC arc jet
- DC plasma
- Laser plasma
- Oxygen-acetylene flame
- Microwave plasma*

*realized at Euclid, Jim

Butler



Any physical process creating atomic hydrogen and CH_x radicals potentially is able to produce diamond.

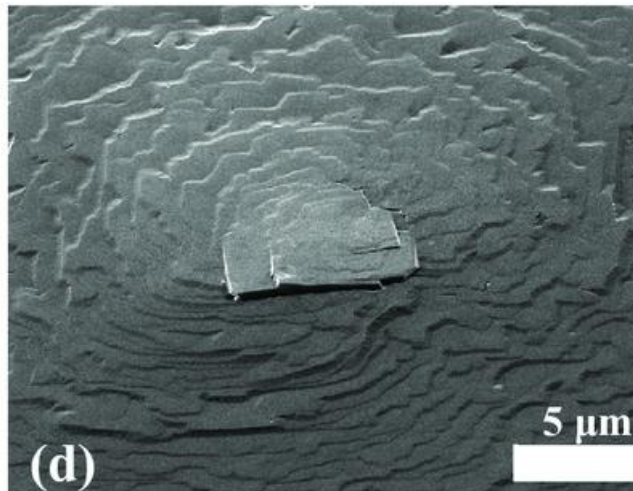
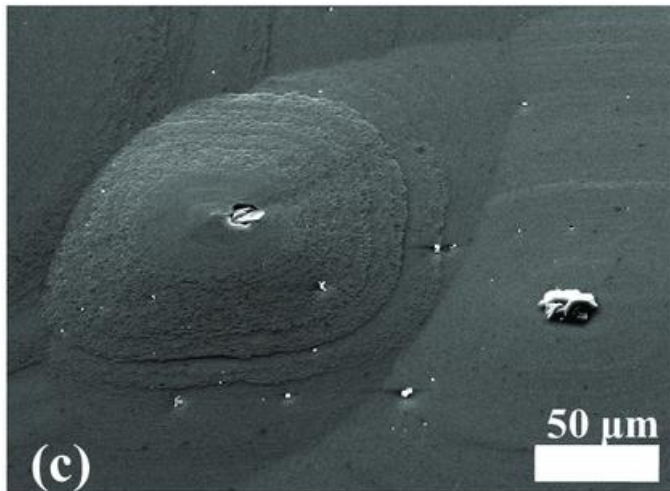
Deposition of Diamond Epitaxy

Microwave plasma CVD systems

2.45 GHz and 915 MHz

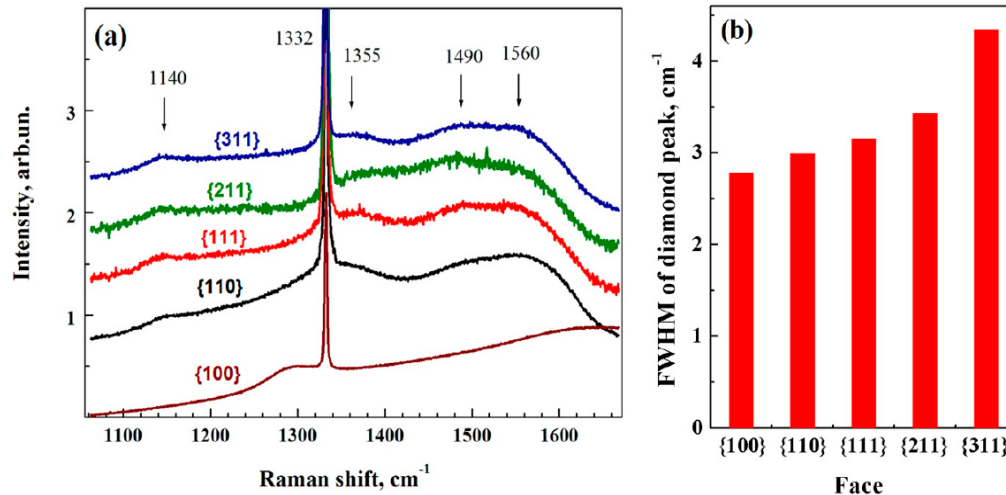
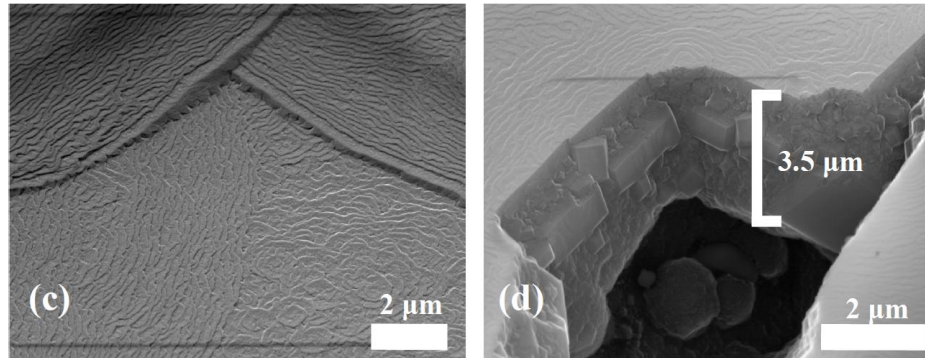
The most successful method for CVD diamond owing to:

- the availability of standard 2.45 GHz components to build the CVD reactor;
- wide experience in microwave plasma surface processing, especially in microelectronics;
- Large deposition area with MW plasma at 915 MHz (plasma size scales with MW wavelength: $\lambda=12$ cm for 2.45 GHz and $\lambda=32$ cm for 915 MHz)
- **Killer Defect: The hillock which can generate polycrystalline regions.**



SEM images after 70-min growth on a single-crystal HPHT substrate: (c) stepped growth and formation of a hillock on the {100} face; (d) generation of a polycrystalline aggregate on the top of a hillock on the {100} face;

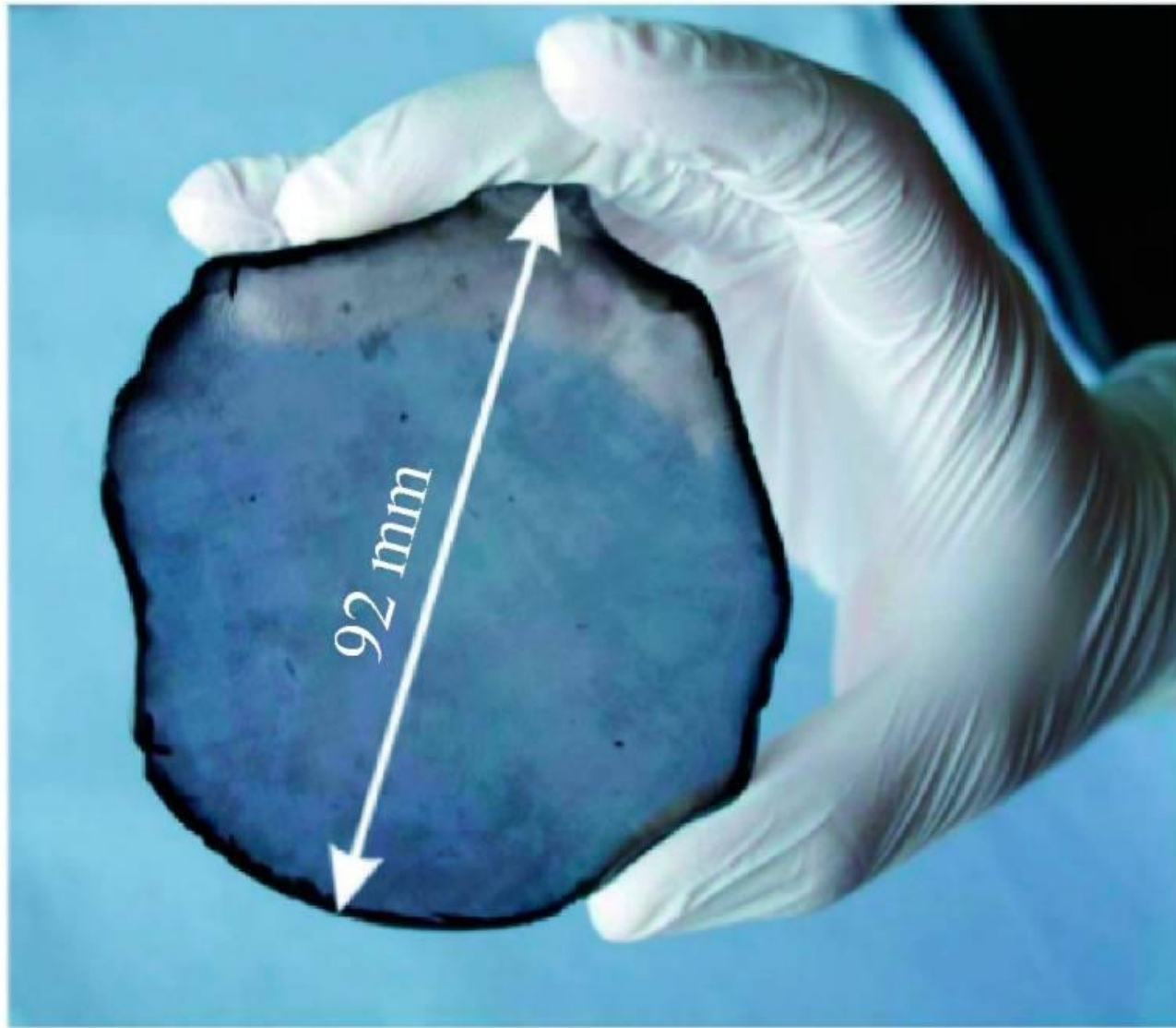
Diamond deposition after 5 min growth on HPHT diamond on the [100] face and view at perpendicular to the face [100]



Raman spectra after 5 min growth on different faces. The bands at 1290 and 1650 cm^{-1} on the [100] are due to photoluminescence of the H3 defect center.

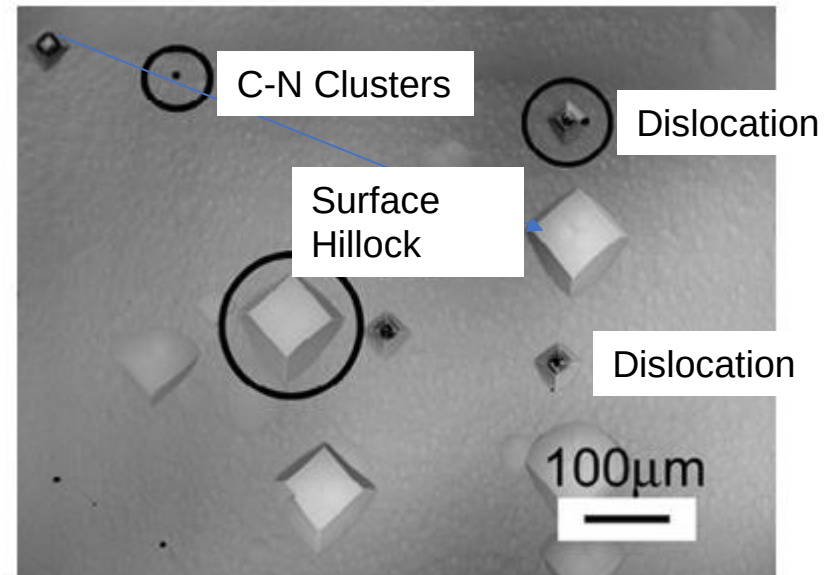
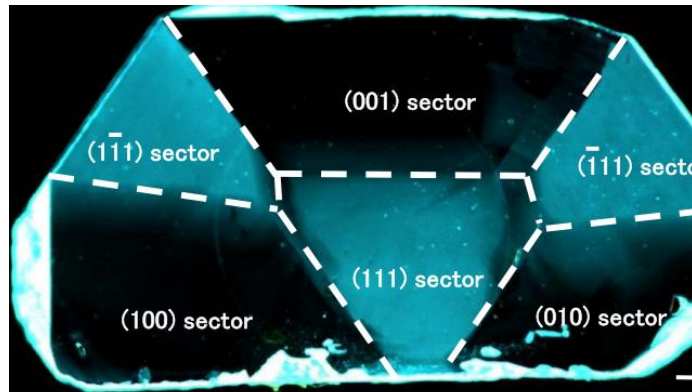
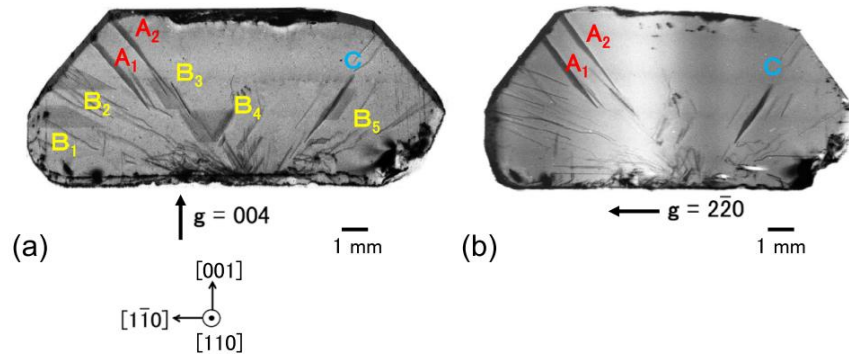
Summary of Impact of Defects on Diamond Properties

- **Mechanical Properties:** Increase hardness, lower toughness, and lower fracture resistance.
- **Optical Properties:** defects can lead to color centers and luminescence.
- **Electrical Properties:** defects can affect conductivity and doping.
- **Thermal Properties:** defects can lower thermal conductivity.



Defects in (001) CVD Diamond on HPHT Substrate

- Surface Hillocks
- Termination of dislocations.
- Stacking faults (A, B)
- C-N clusters



UV Light excited
photoluminescence image of
(110) diamond

Reprinted from A. Tallaire, Elsevier Science, 2008
and S. Musuya, 2016, Japan Soc of Applied Physics

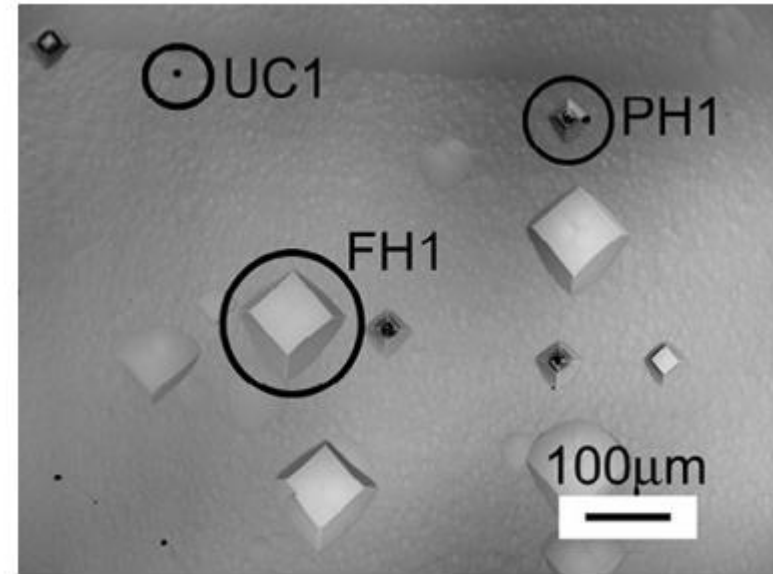
Types of Defects in CVD Diamonds

• **Intrinsic Defects:**

- **Vacancies**: Missing carbon atoms in the lattice.
- **Interstitials**: Extra carbon atoms in the lattice.
- **Dislocations**: Line defects in the crystal structure.

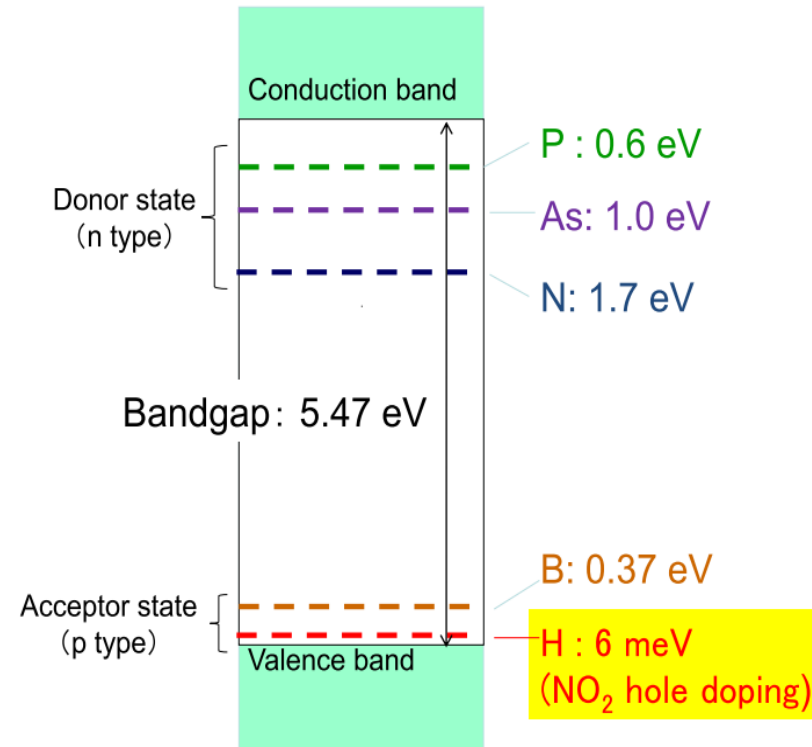
• **Impurities:**

- **Nitrogen**: Common impurity in natural diamonds, can also be present in CVD diamonds.
- **Other impurities**



Active Diamond Electronics: Substitutional Doping is a Problem

- All dopants are deep in bandgap
 - Boron - p-type - 0.37 eV
 - Phosphorous - n-type - 0.6 eV
 - Nitrogen - n-type - 1.7 eV
 - Issue:
 - Since substitutional doping is problematic, must go to high temperatures, greater than 300 K
 - High carrier concentrations only at $T > 300\text{ }^{\circ}\text{C}$
 - But mobility is limited by defect scattering
- Partial ionization occurs,
limiting number of carriers.

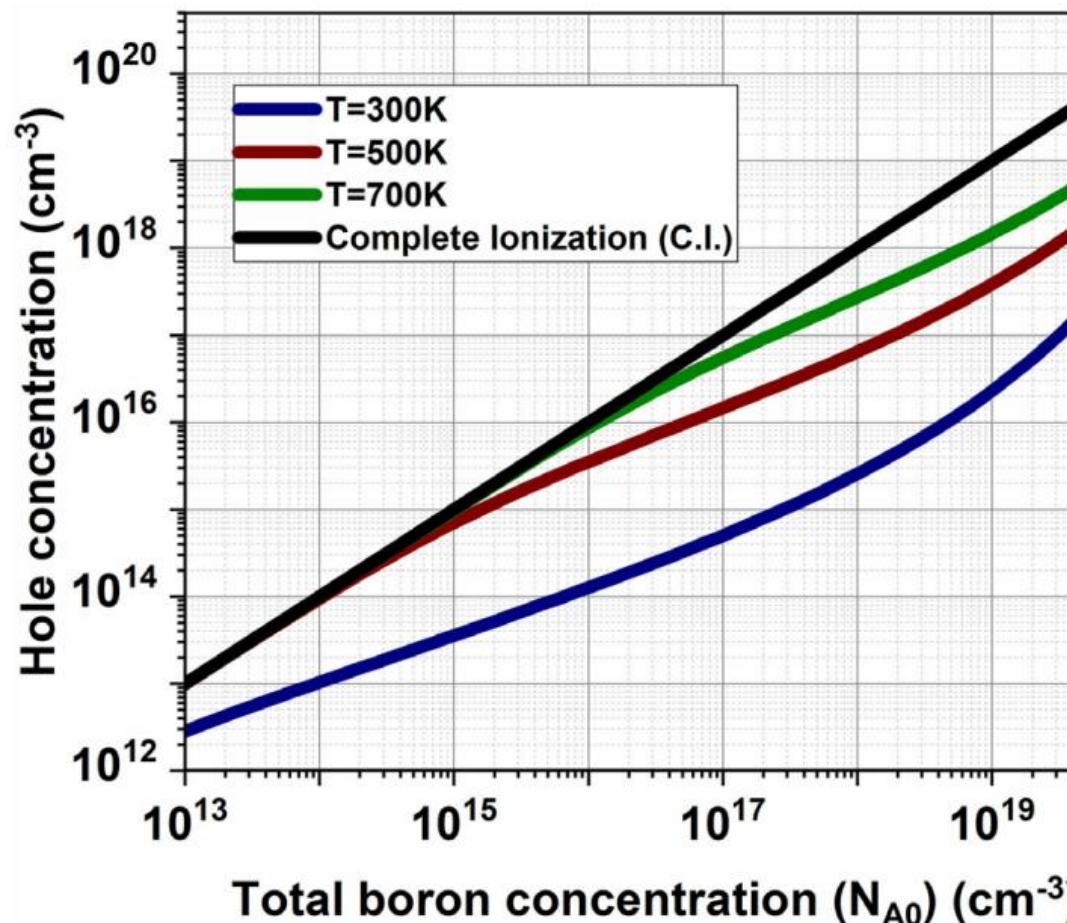


Donor and acceptor levels in diamond



Hole Concentration and Donor Compensation

Partial ionization occurs, limiting number of carriers.



Boron activation is further limited by donor compensation



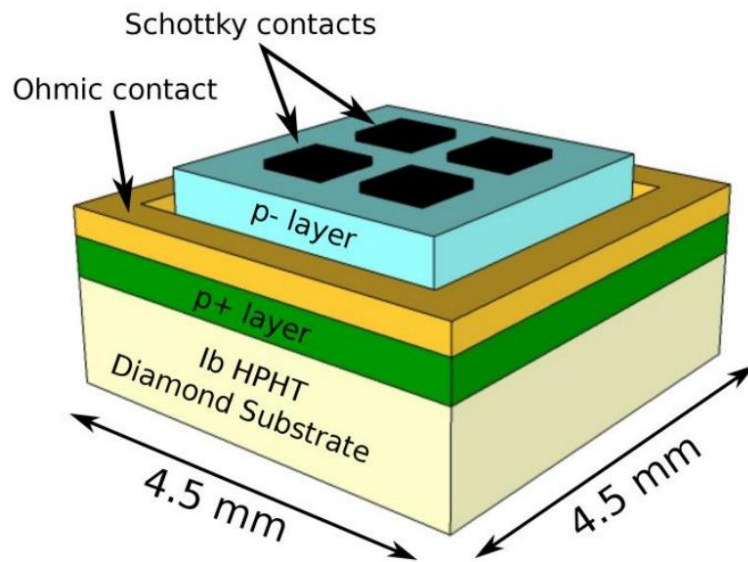
Diamond Power Electronics: Benchmarking with SiC

Explanation of dopant problem

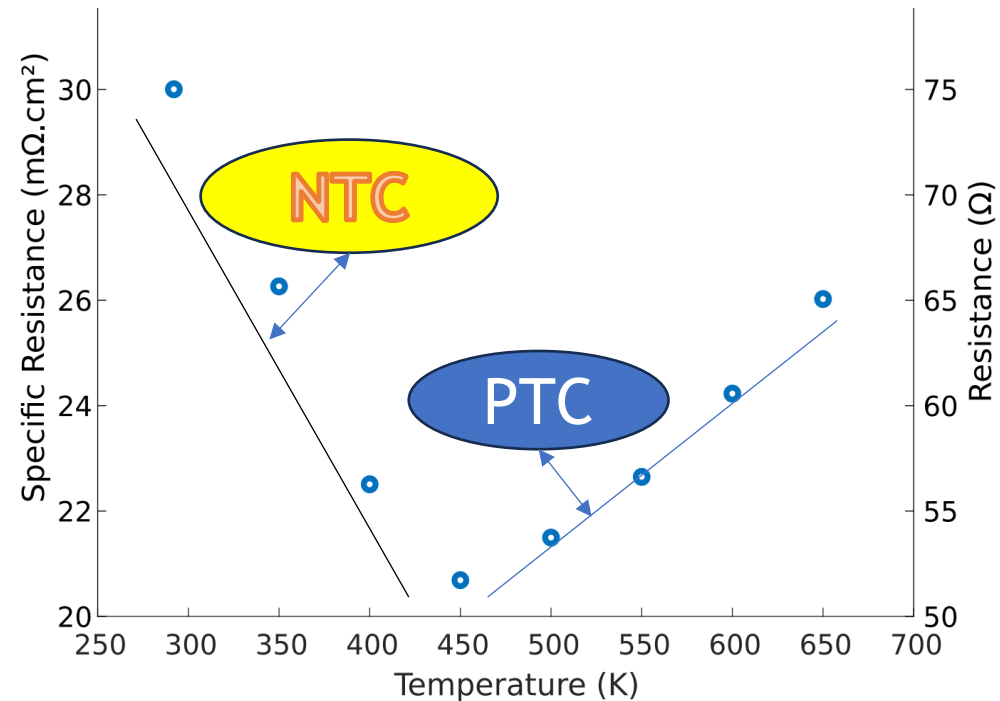


Diamond Power Electronics: Benchmarking with SiC

Incomplete Ionization of p dopants and n dopants. Leads to both NTC (α) and PTC. The on-state resistance is minimized at high temperatures.



$$P_{cond}(T) = R_{ON}(T) \times I_{load}^2 \times (1 - \alpha)$$

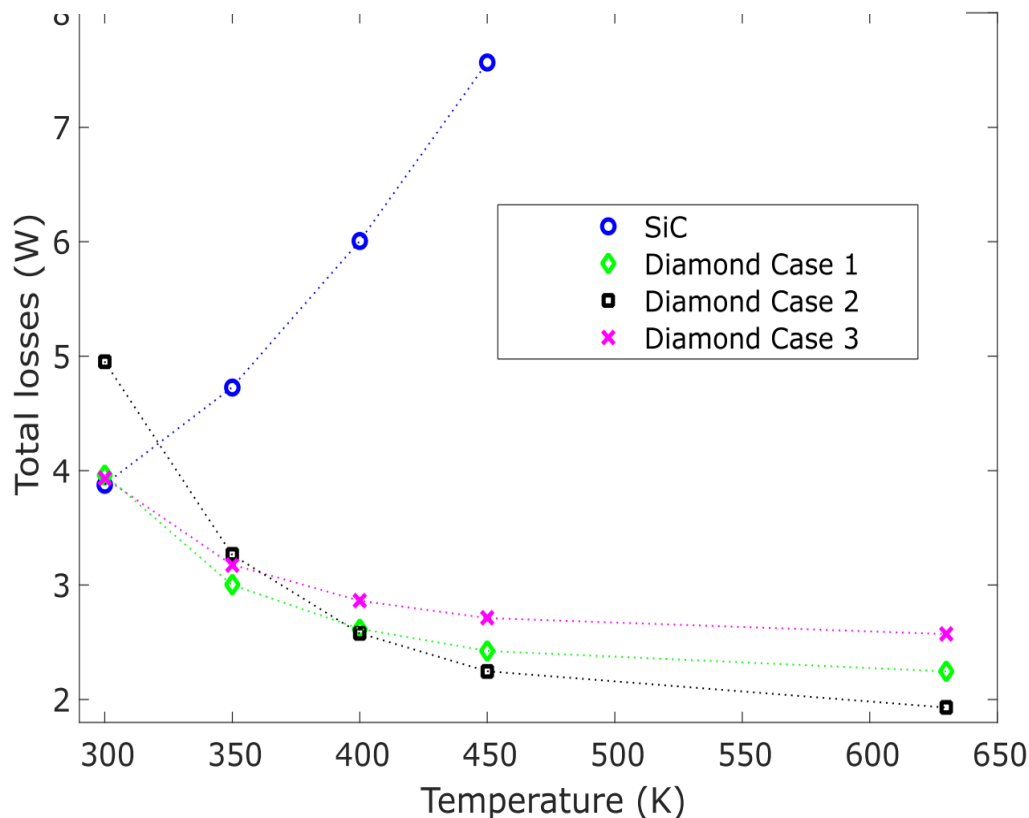


On state resistance as a function of junction temperature

Estimated Total Losses of Diamond vs SiC devices

- SiC devices requires tradeoff between decrease of converter volume (heat sink volume) and increase in operating temperature.
- For diamond electronics, you may decrease converter volume and resistive semiconductor losses by increasing temperature.

$$P_{cond}(T) = R_{ON}(T) \times I_{load}^2 \times (1 - \alpha)$$

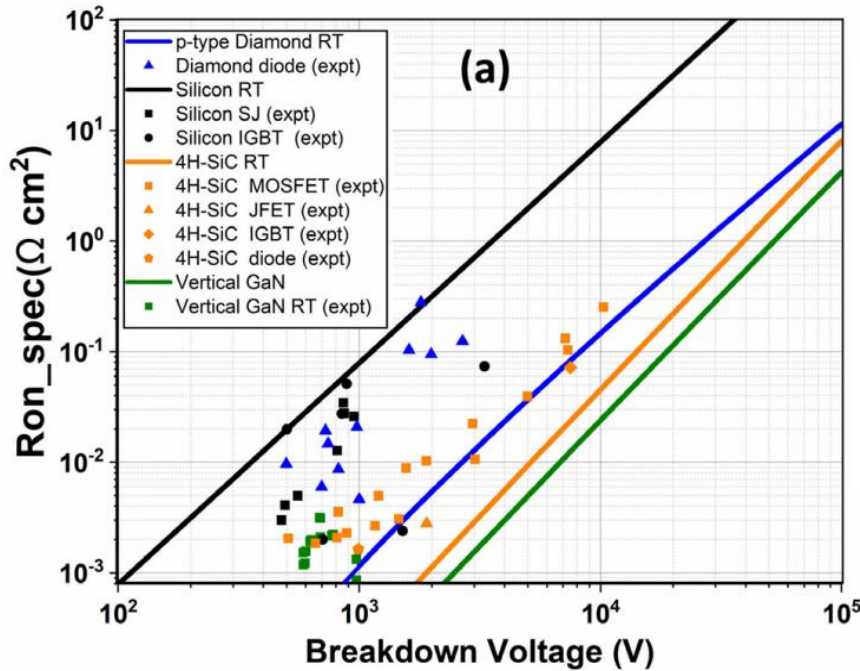


Total losses of SiC and Diamond Schottky Diodes as a function of junction temperature. Losses decrease at elevated temperatures.

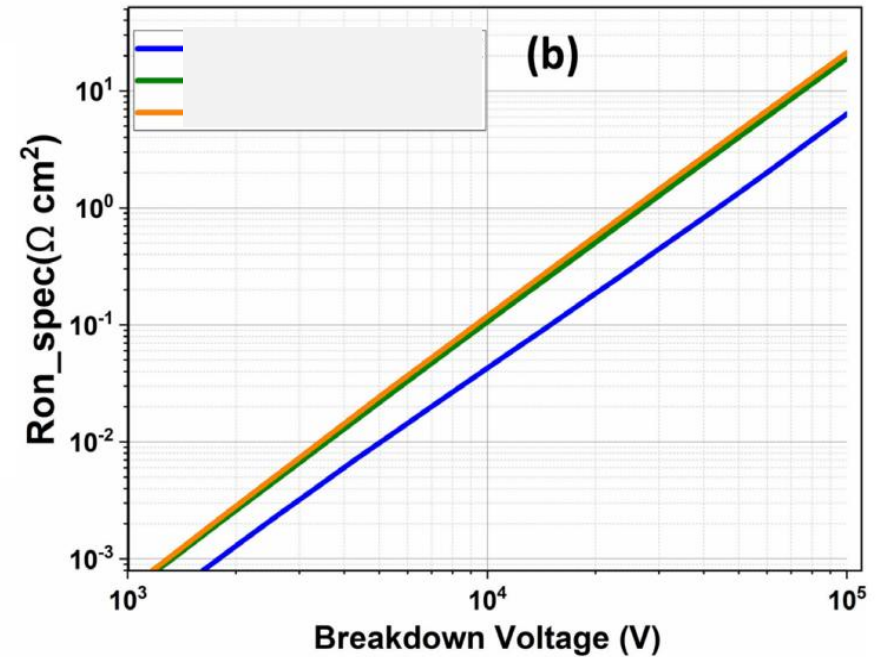


R_{on} vs BV at RT and HT

T= Room Temp



T= HT (450 C)



Vertical $R_{on-spec}$ versus BV and comparison with experimental results at RT and HT (450C). Calculated lines are at punch through limit. Note p-diamond (boron doped) shows lower R_{on} at higher BV for HT.



Solving the Dopant problem

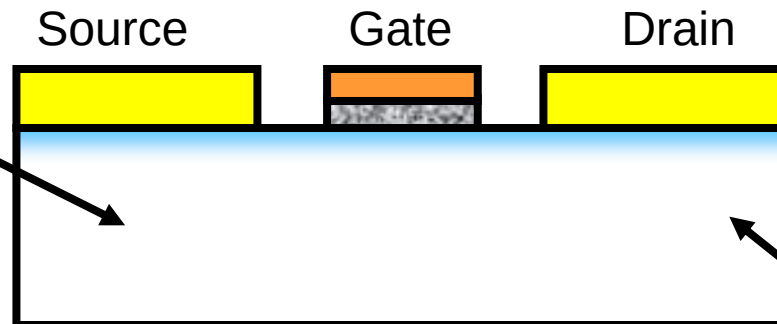
Two Dimensional Diamond Channels

- **Hydrogen-termination** (usually accomplished via exposure to hydrogen plasma) has been found to create a **C-H surface dipole layer** that reduces the carrier ionization energy by nearly 1.5 eV, followed by NO_2 and O_3 doping.
- Alternative is **2D doping via the delta doping approach** developed for Compound Semiconductors. Accomplished by ion implantation or stepped CVD growth.

Advantage of diamond

High breakdown
field 10 MV/cm

Low dielectric
constant 5.7

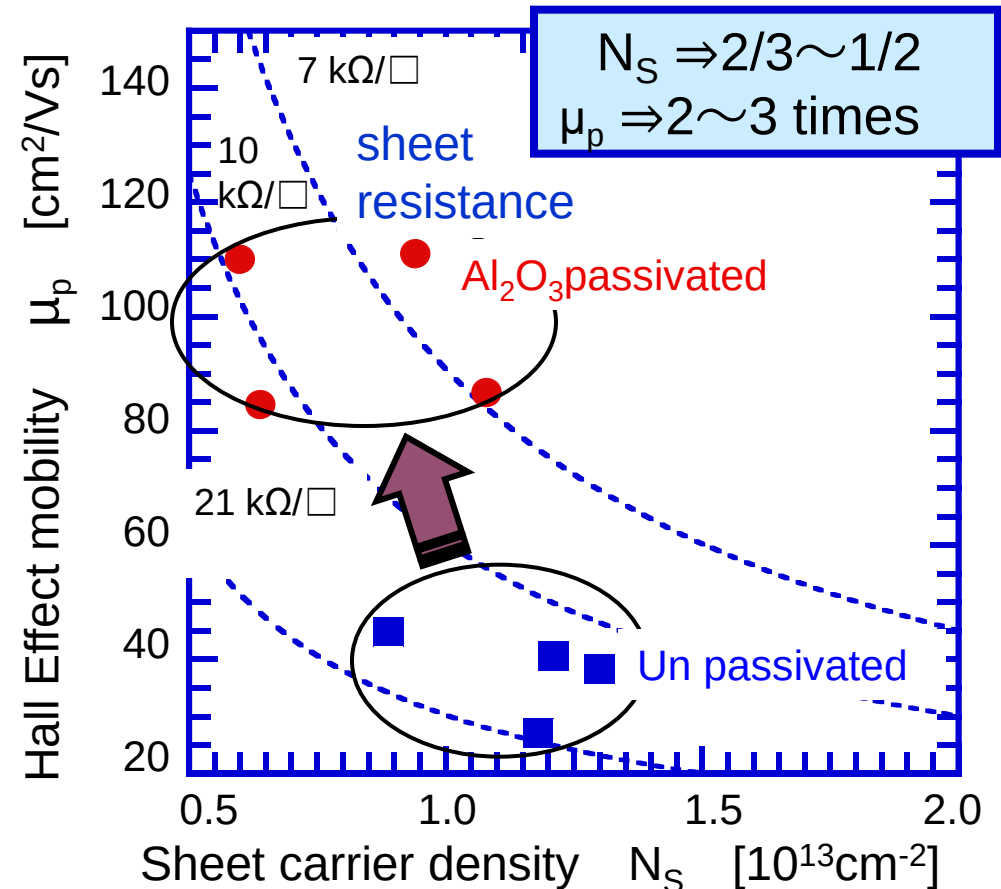
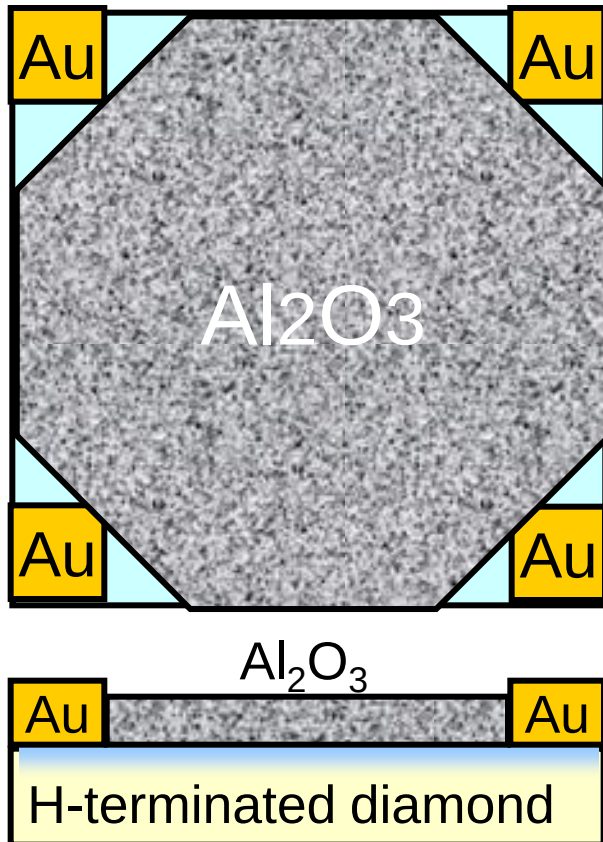


Advantage of diamond

Highest thermal
conductivity
22 W/cm·K

Passivation is Necessary

Van der Pauw measurement

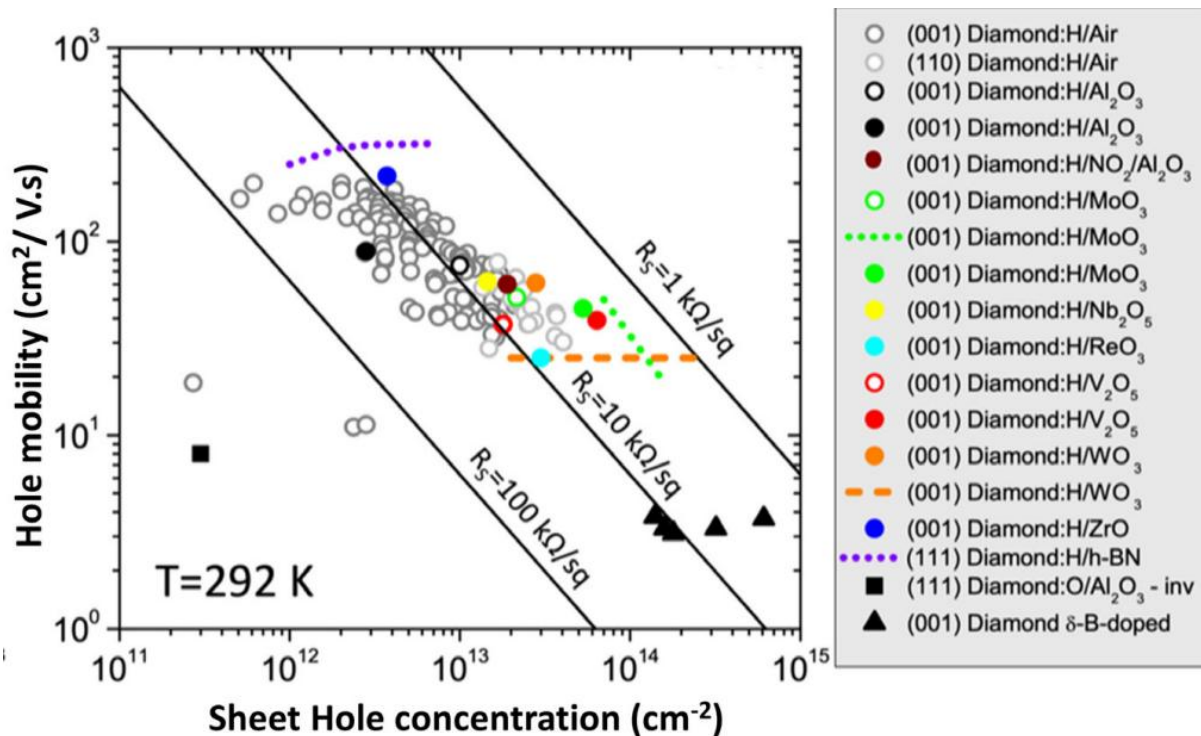


Mobility increases after dielectric passivation

Hall Mobility vs Temperature for Bulk Diamond

Gray Circles in (b) is Hall Mobility for H-terminated FETS

- Elevated temperatures and Hall mobility data of doped diamond via H/Air, H/Al₂O₃ and H/other dielectrics and delta -B-doping



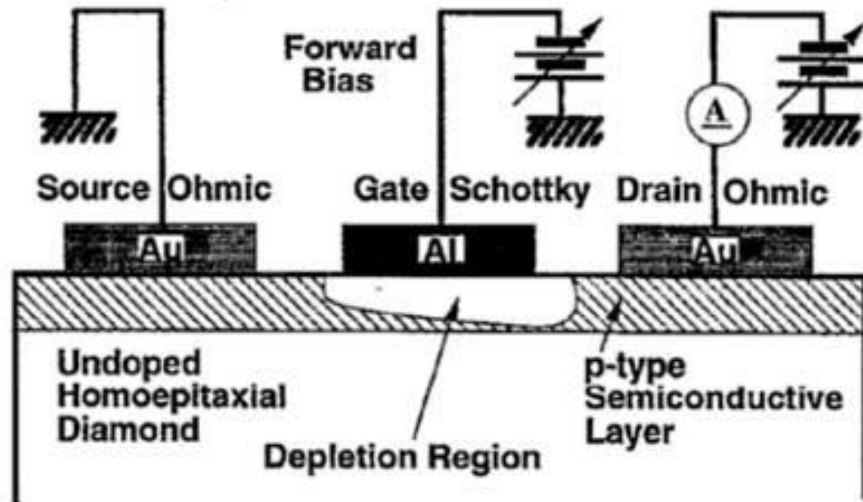
N Donato et al 2020 J. Phys. D: Appl. Phys. 53 093001

- Available Doping Windows for Doping of Diamond Devices, n-type refers to phosphorous

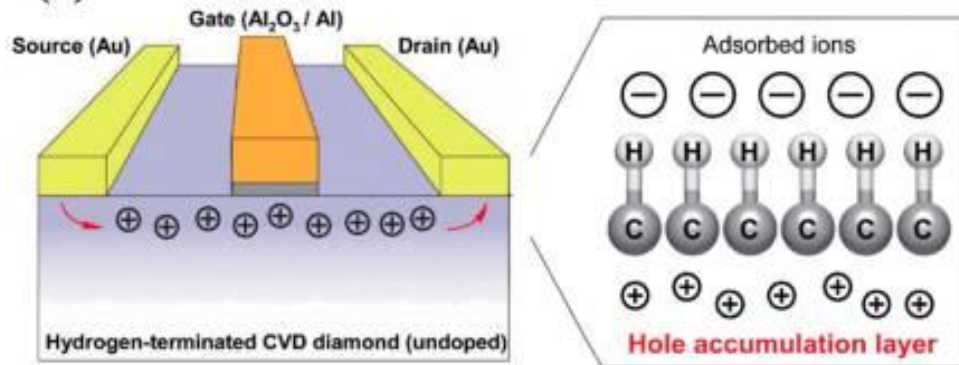
	Available	
	Min	Max
n-type doping concentration	$\approx 3 \times 10^{15} \text{ cm}^{-3}$	$\approx 8 \times 10^{19} \text{ cm}^{-3}$
n-type layer thickness	$< 100 \text{ nm}$	$\approx 5 \text{ } \mu\text{m}$
p-type doping concentration	$\approx 1 \times 10^{15} \text{ cm}^{-3}$	$> 1 \times 10^{21} \text{ cm}^{-3}$
p-type layer thickness	$< 10 \text{ nm}$	$\approx 100 \text{ } \mu\text{m}$



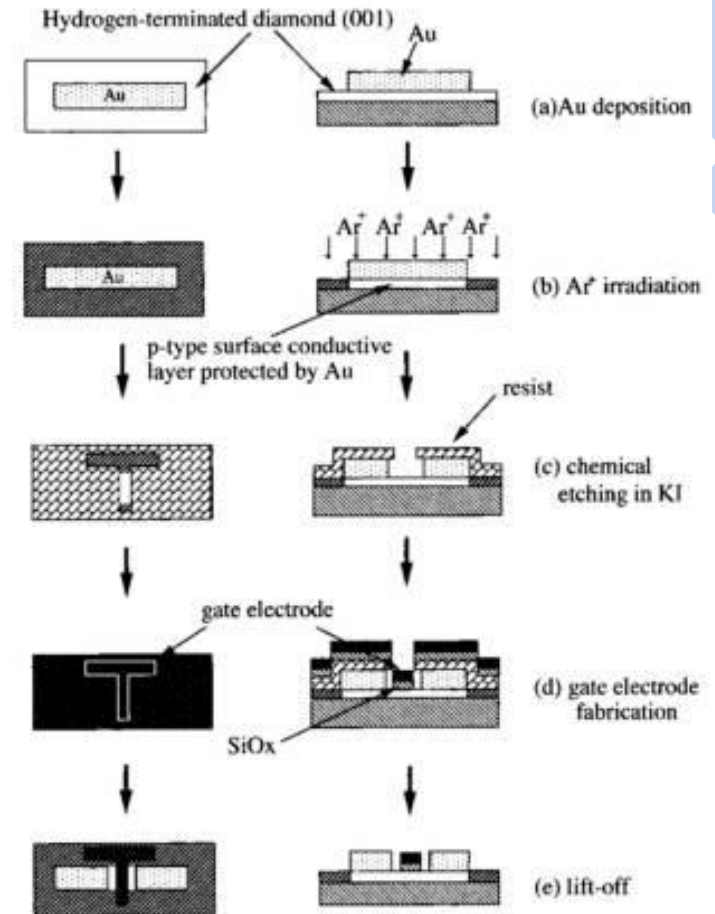
(a)



(c)

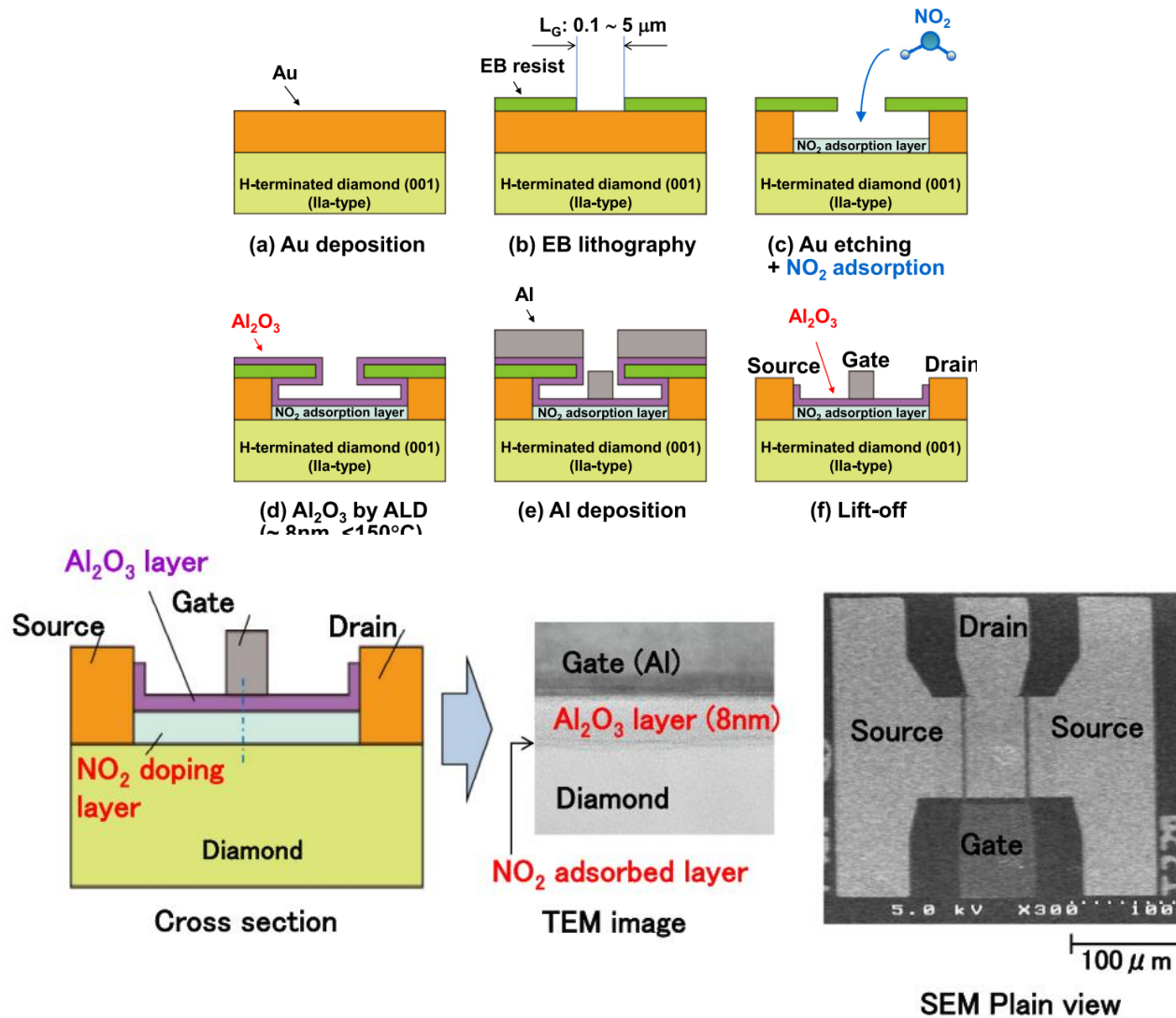


(b)



In the 1990s, H. Kawarada et al. [168] at Waseda University first reported a MESFET based on a H-terminated diamond, as shown First hydrogen-terminated normally-off MESFET devices [168]. (b) Process Flow of hydrogen terminal MOSFETs [171]. (c) Hydrogen terminal MOSFETs with an Al_2O_3 gate dielectric layer [173].

UMD Diamond Field Effect Transistor Fabrication Process



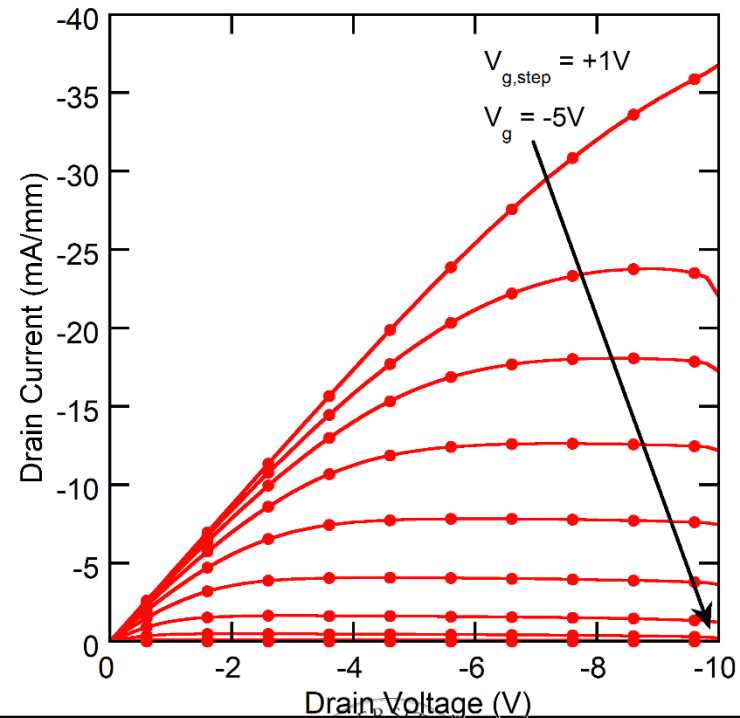
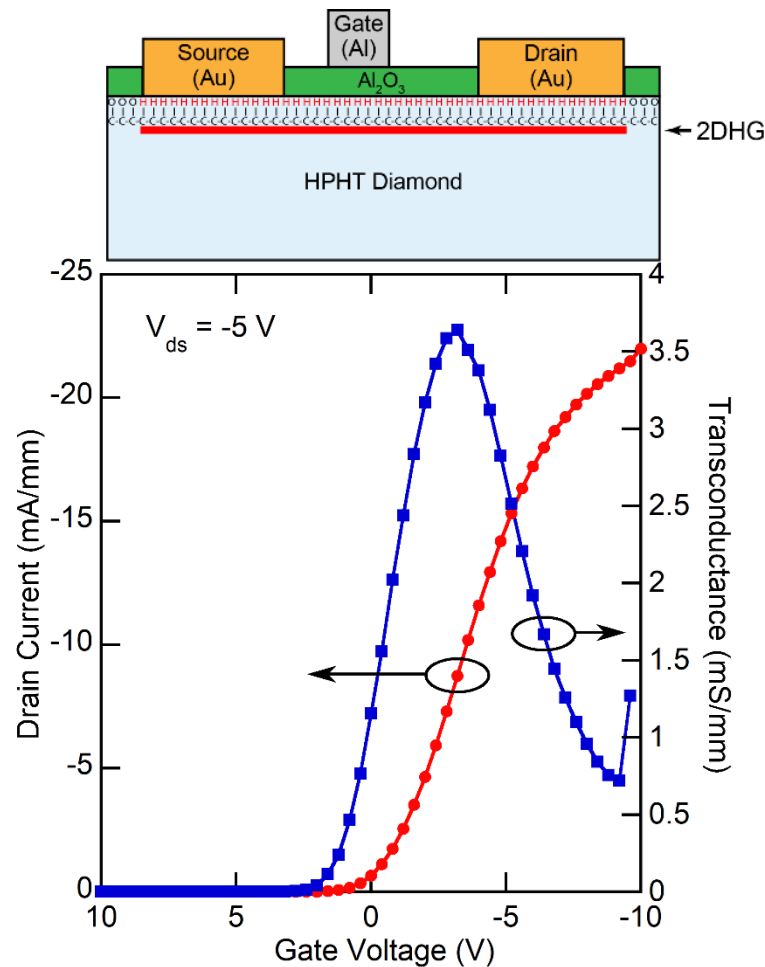
- ✓ NO_2 exposure to H-terminated surface $\rightarrow$ High current
- ✓ Passivation of Al_2O_3 layer $\rightarrow$ Thermal stability



UMD/ Al_2O_3 /H-Diamond FET Stability in Air

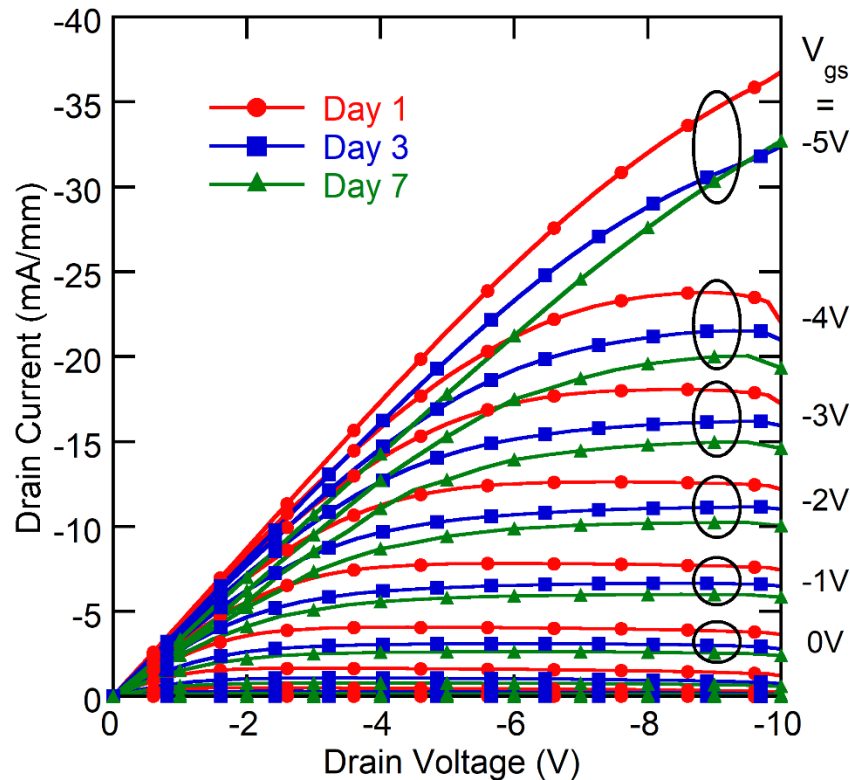
- 25 nm Al_2O_3 dielectric/p-dopant (H surface)

Parameter	Value
V_t	-0.80 V
$g_{m,\max}$	3.64 mS/mm
$I_{\text{off}} (V_{\text{ds}} = +10 \text{ V})$	$8.23 \times 10^{-4} \text{ mA/mm}$
$I_{\text{ds,max}}$	-36.8 mA/mm
R_{on}	$230 \Omega \cdot \text{mm}$



Al₂O₃ /H-Diamond FET Stability in Air

- UMD Devices are relatively stable in air with small shifts in transfer characteristics



Over 7600 hours:

$R_{on} \uparrow 54 \Omega \cdot \text{mm}$ (27%)

$I_{dsmax} \downarrow 4 \text{ mA/mm}$ (11%)

No significant transfer characteristic changes

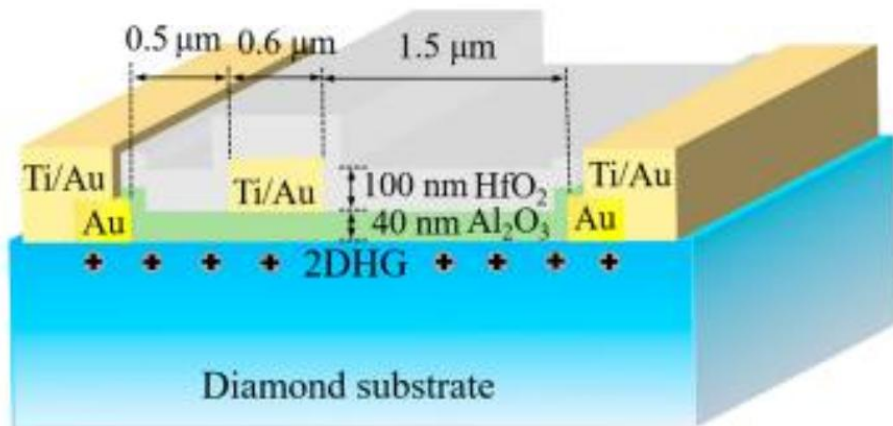
$V_t: -0.8 \rightarrow -0.76 \text{ V}$

$g_{m,max}: 3.6 \rightarrow 3.5 \text{ mS/mm}$

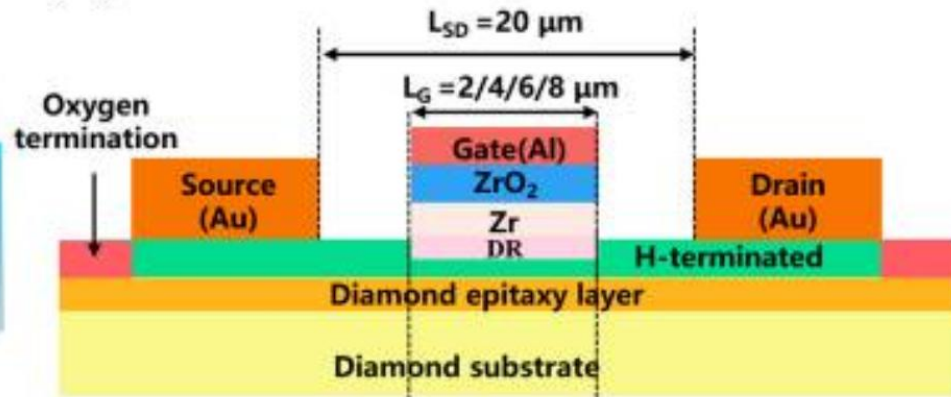


Diamond MOSFETs with Hi-k Dielectrics

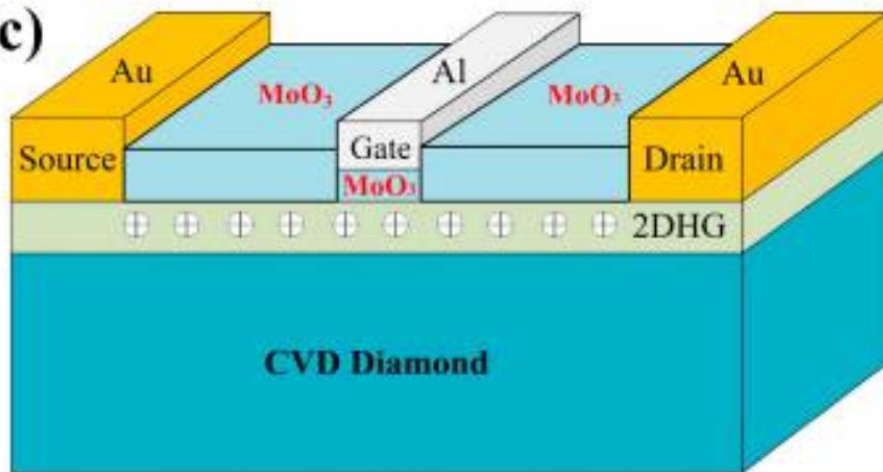
(a)



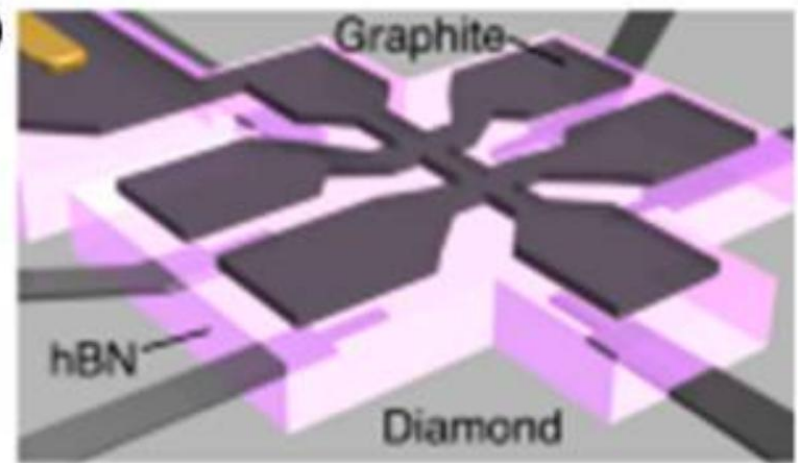
(b)



(c)



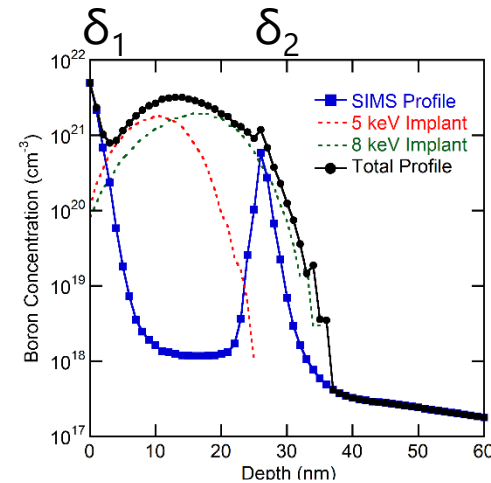
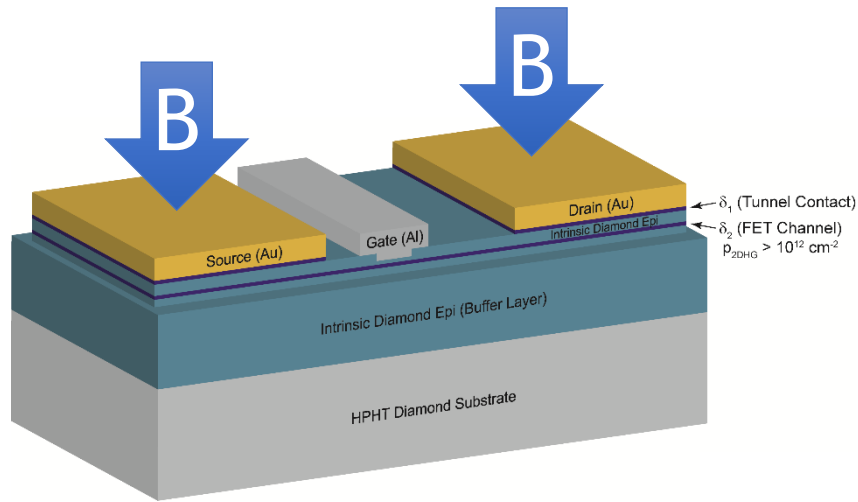
(d)



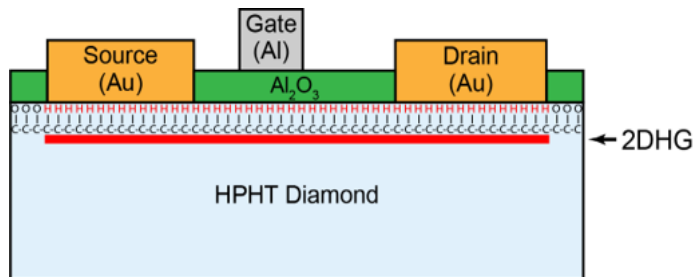
UMD FET-Processing for Delta-Doped Diamond and H Terminated FETs

2025 Joint H-TEC/Clewin/PNE Conferences | Albuquerque, New Mexico | April 14-17, 2025

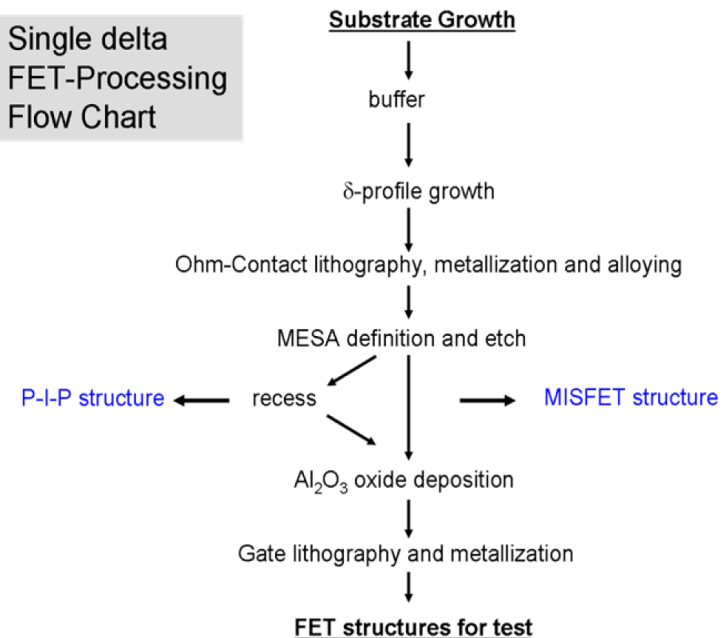
Self-aligned B⁺ implantation and Ti/Pt/Au deposition for contact to delta layers



Energy (keV)	B Dose (cm ⁻²)
5	2x10 ¹⁵
8	3x10 ¹⁵



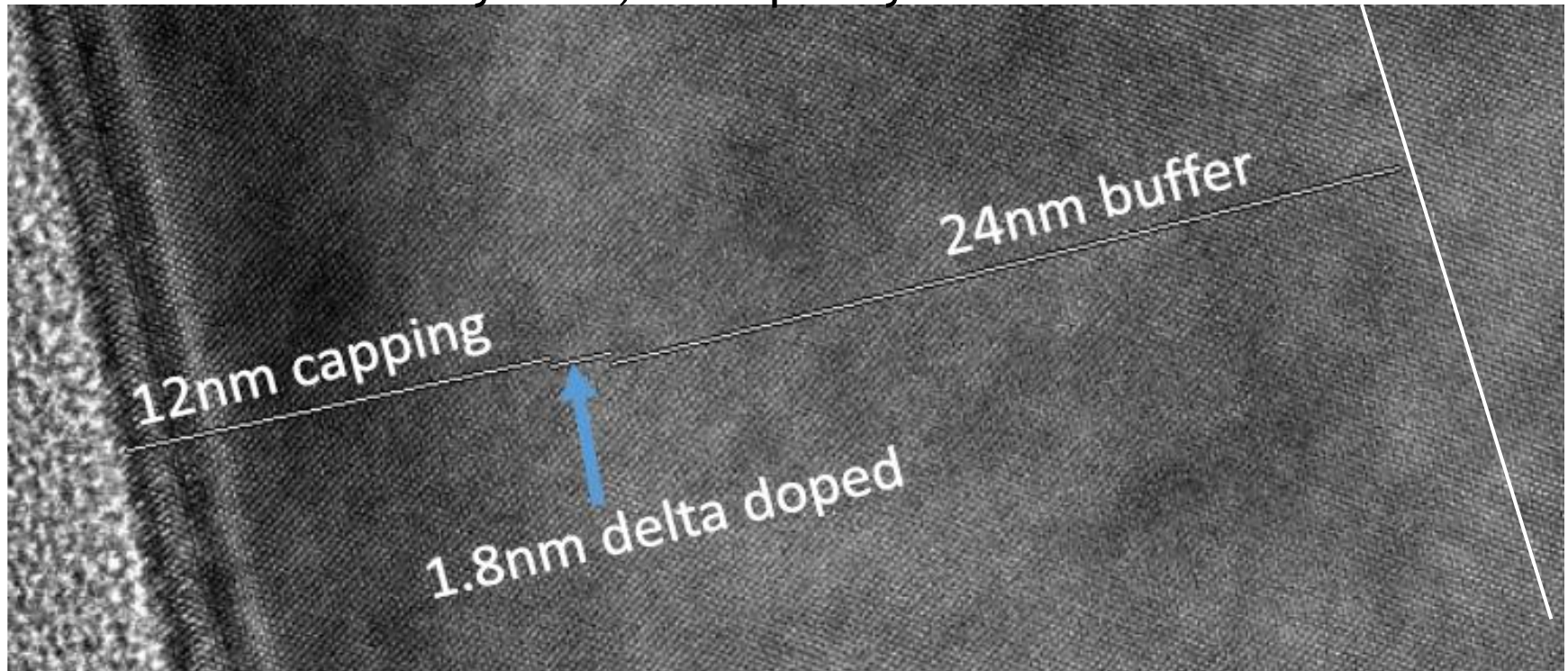
Single delta
FET-Processing
Flow Chart



TEM X-Section of CVD and Delta Layers

Interfaces are barely seen, full epitaxy

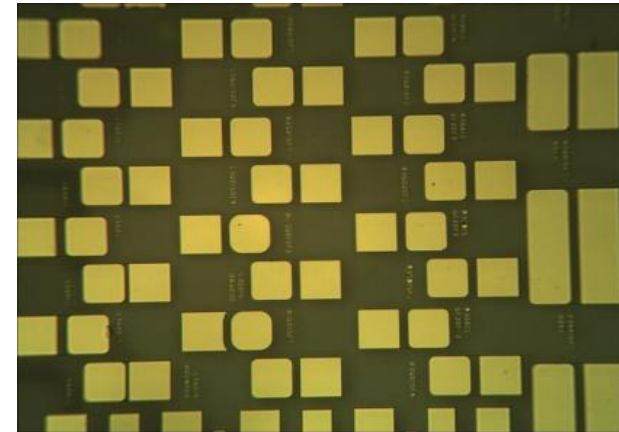
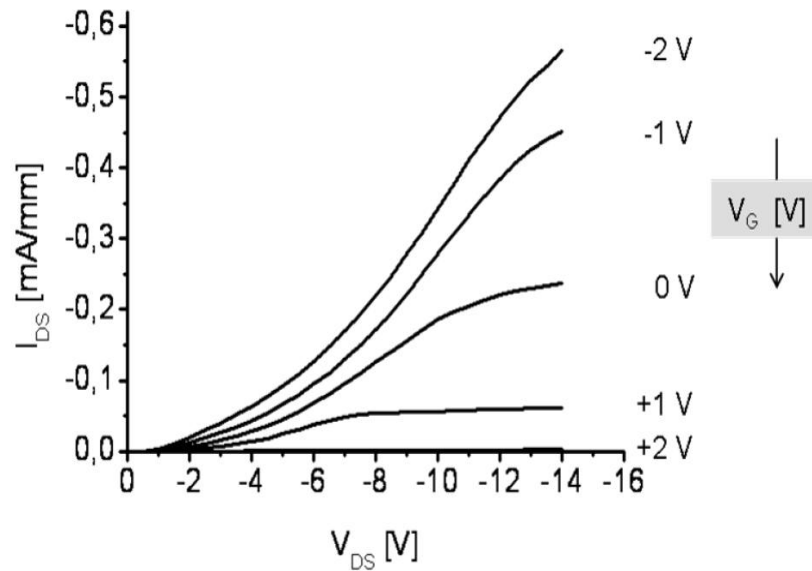
substrate



CVD deposition



Delta Doped Diamond MESFET FABRICATION



Ti/Pt/Au Ohmics

TLM Measurement for sheet resistance and contact resistance

DC Characteristics of transistor with delta doped layers.

Maximum current density of 0.5 mA/mm

Maximum transconductance of 0.3 mS/mm

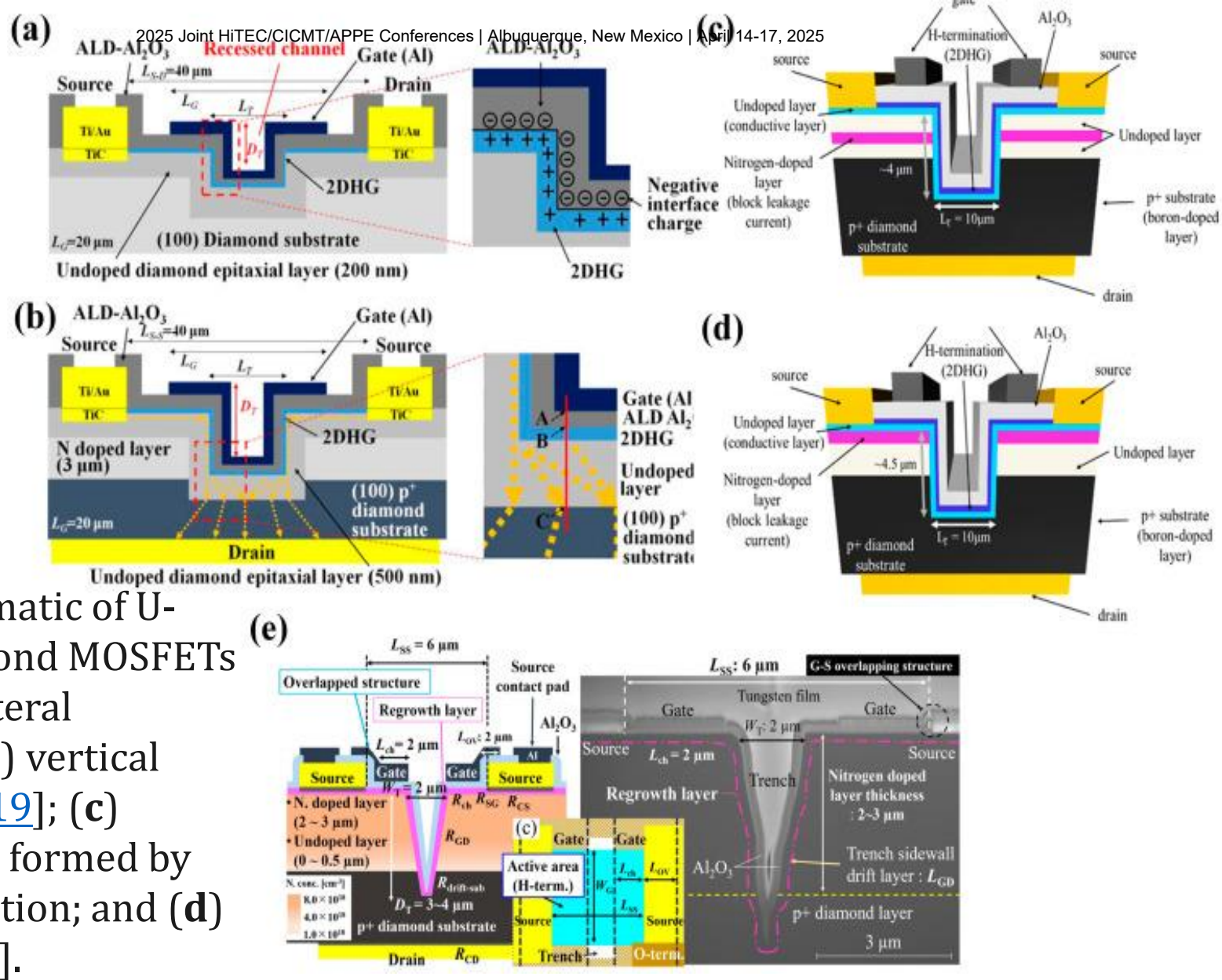
Gate modulation was possible in both enhancement (negative gate bias) and depletion mode



Other Structures: VMOSFETs, BJTs, JFETs, and So On

In addition to the conventional FET structure, vertical MOS field-effect transistors (VMOSFETs), bipolar junction transistors (BJTs) and junction field-effect transistors (JFETs), which are common in power devices, are also applied in diamond devices.

The vertical structure is typical in power devices which can increase the length of the drift region in the vertical direction to achieve higher current density. This is beneficial to reduce the chip area, and at the same time has enhanced channel control and smaller parasitic capacitance.



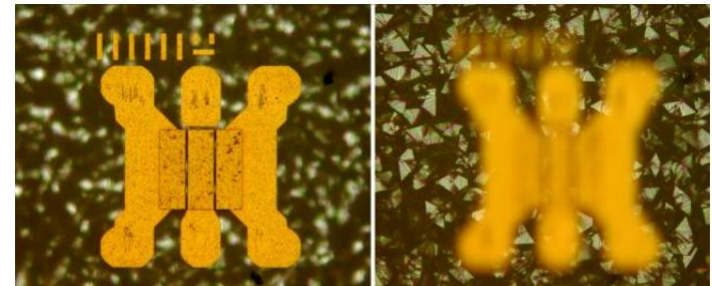
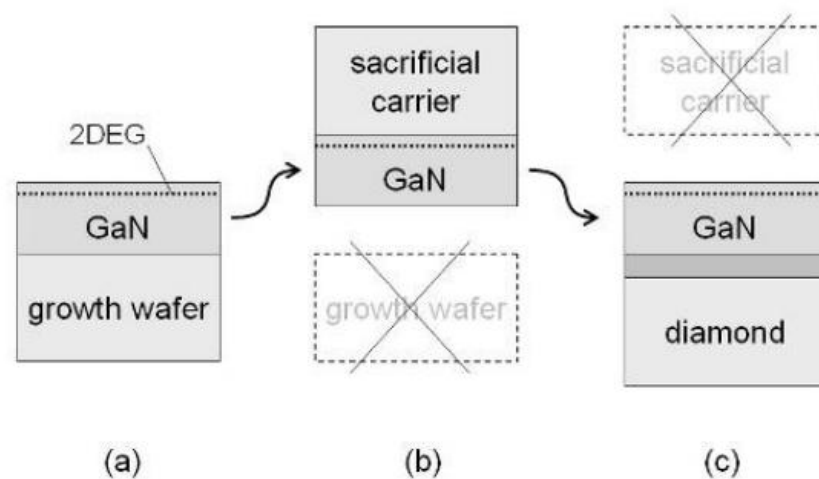
Device schematic of U-trench diamond MOSFETs with a (a) lateral structure; (b) vertical structure [219]; (c) barrier layer formed by ion implantation; and (d) epitaxy [220].

36 (e) Device schematic of vertical V-trench diamond MOSFETs with a highly concentrated N-diffusion barrier layer [221].

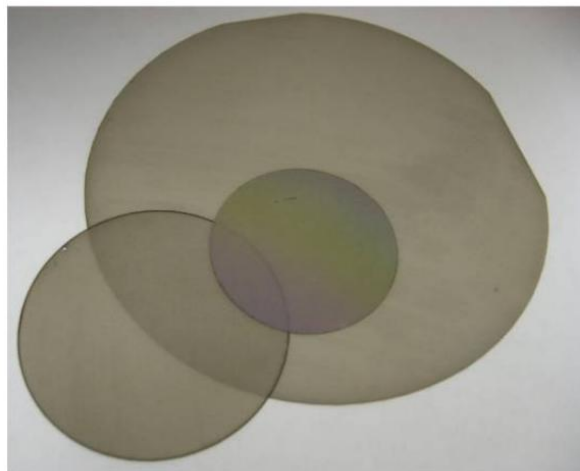
Heteroepitaxy of GaN on Diamond

- Accomplished via GaN transfer and wafer bonding, at the expense of thermal resistance degradation.

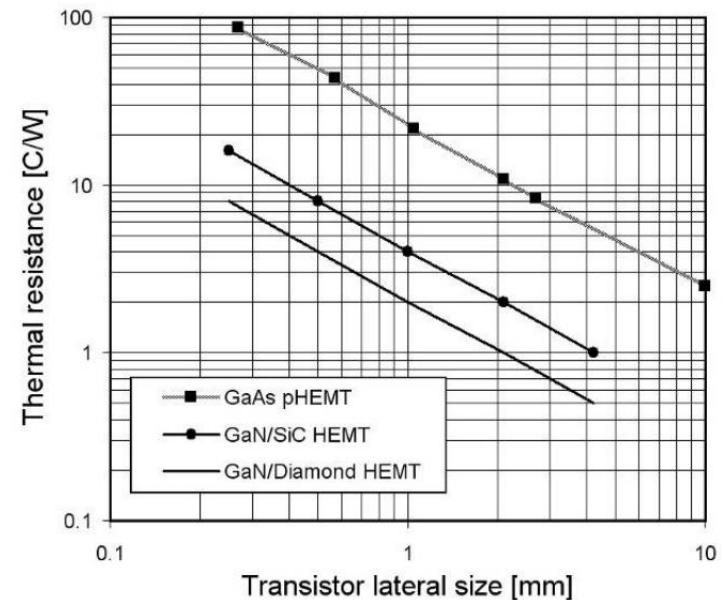
GaN Epi Layers on Diamond Substrate



2x150 micron HEMT with focus on back of diamond wafer (diamond is transparent)



GaN on diamond, 4 inch diameter



GaN-on-diamond Field-Effect Transistors: from Wafers to Amplifier Modules

D. I. Babić¹, Q. Diduck¹, P. Yenigalla¹, A. Schreiber¹, D. Francis¹, F. Faili¹, F. Ejeckam¹, J. G. Felbinger², L. F. Eastman²

¹Group4 Labs, Inc., 13500 Stevenson Place, Suite 207, Fremont, CA 94539, USA

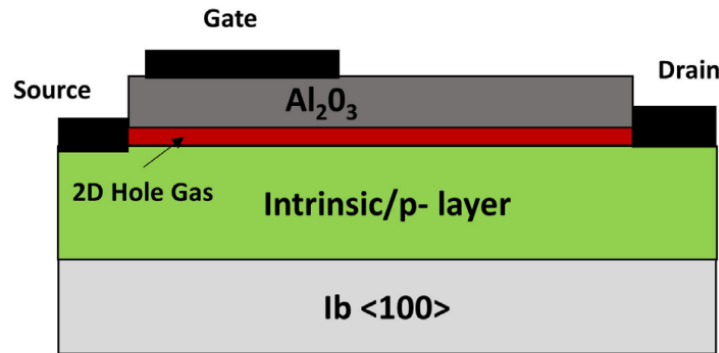
²Cornell University School of Electrical and Computer Engineering, Ithaca, NY 14853, USA

Phone: (408) 398-2484 Fax: (408) 689-9674 E-mail: dubravko.babic@group4labs.com

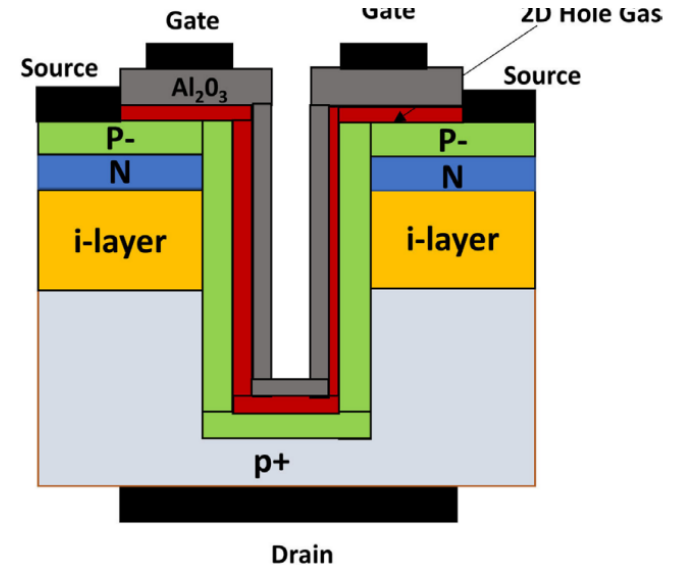


A. JAMES CLARK
SCHOOL OF ENGINEERING

State of the Art Parameters and Schematic of Lateral and Vertical HFET



Lateral HFET



Vertical HFET

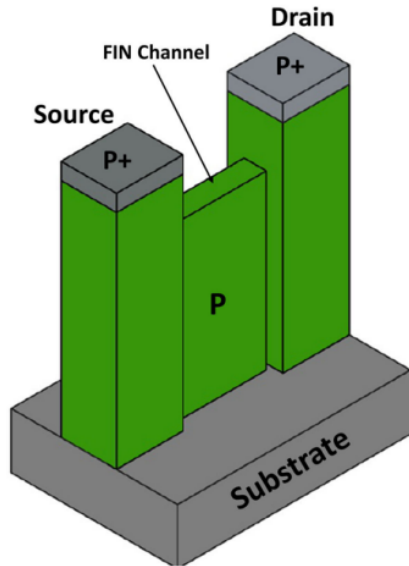
Breakdown Voltage > 2kV at T=300K

Current Density > 1.3 A/mm at 300K

> 3 kV at T=300K

> 2 A/mm at
T=600K (UMD)

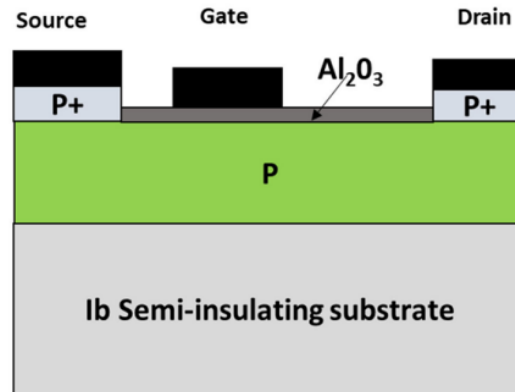
Vertical Fin-FET



Fin channel allows for normally-OFF operation.

BV measurements are not reported. However, gate and drain overlap limits the max BV
Max observed drain current is limited to 838 nA for $V_{GS} = V_{DS} = -16$ V at $T = 300$ K and $29 \mu\text{A}$ at 450 K [130]

Lateral Deep depletion MOSFET

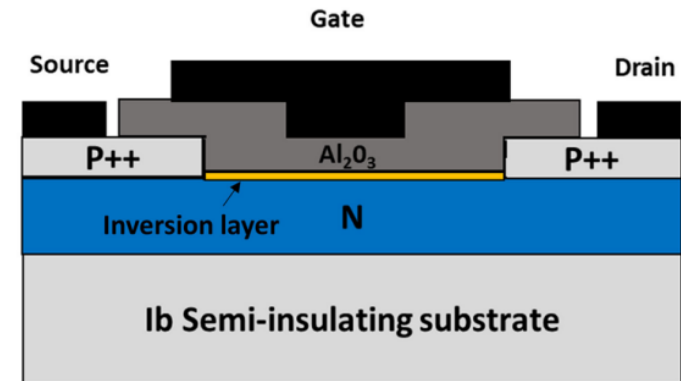


Normally-ON.

HT operation increases the current and reduces the threshold voltage
Scaling of the R_{on_spec} and BV is an issue

Field plates are needed to improve the BV
Current density is limited by the incomplete ionization at RT

Lateral inversion mode MOSFET



Normally-OFF

Low interface mobility
High density of traps

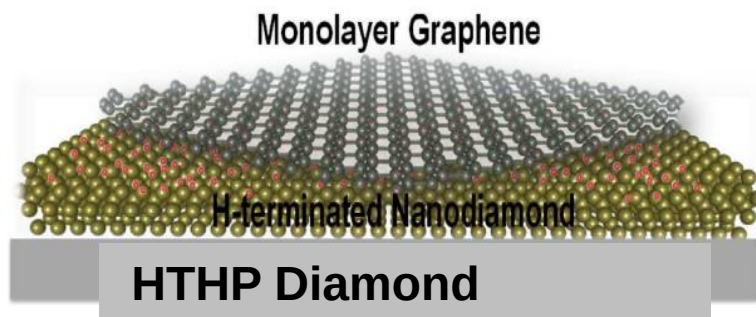
Low BV
First proof of concept

RECENT ADVANCES BASED ON GRAPHENE 2D LAYERS

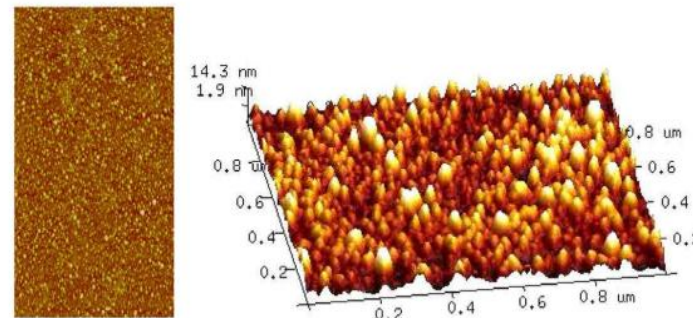
Nano-diamond replaces epi
diamond.

Is there anything to be gained by
adding a graphene layer?

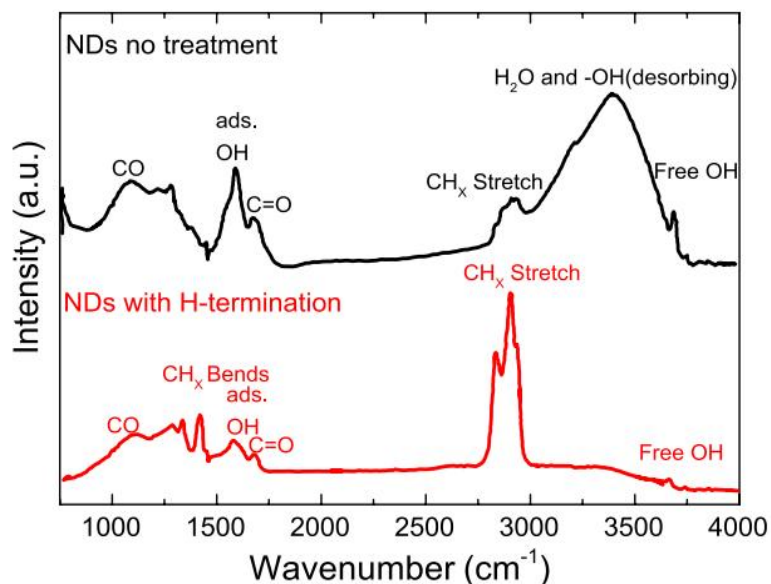


a)  H

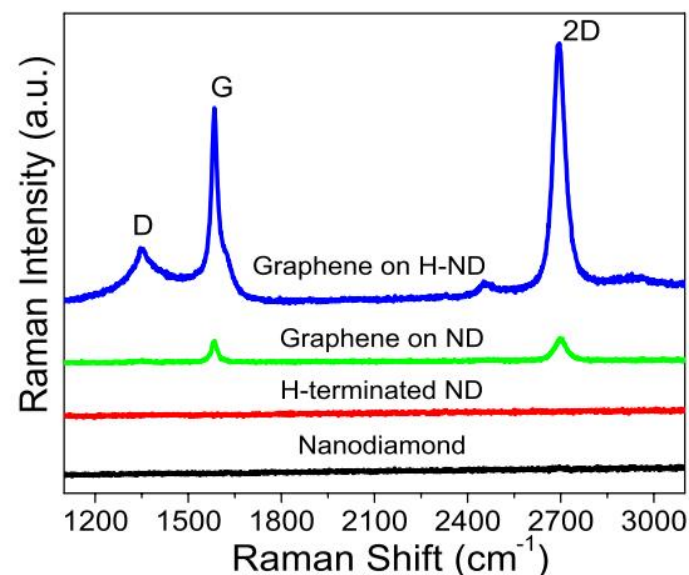
b)



c) 1000 1500 2000 2500 3000 3500 4000



d)

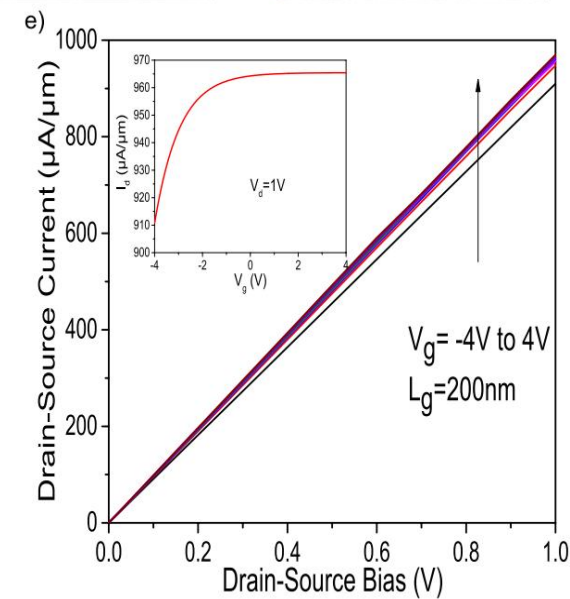
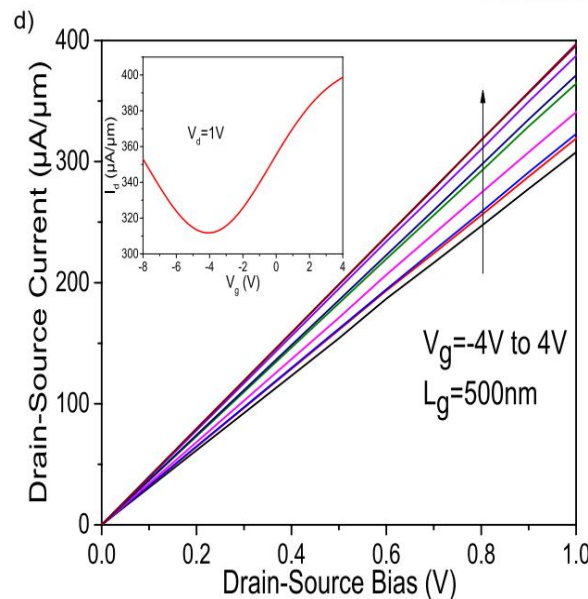
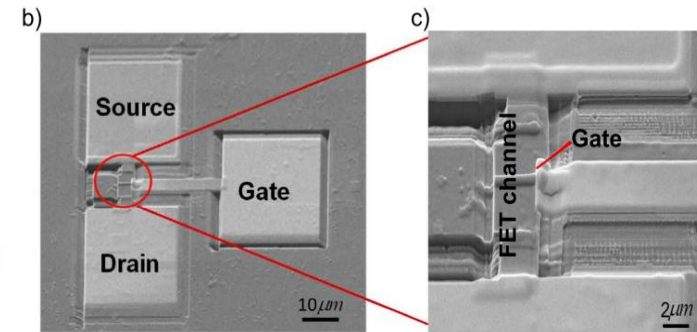
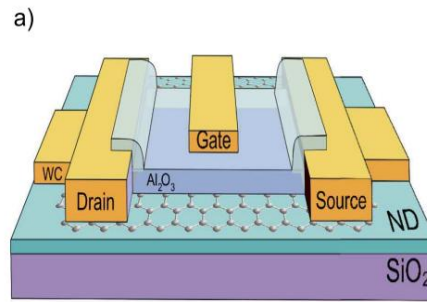
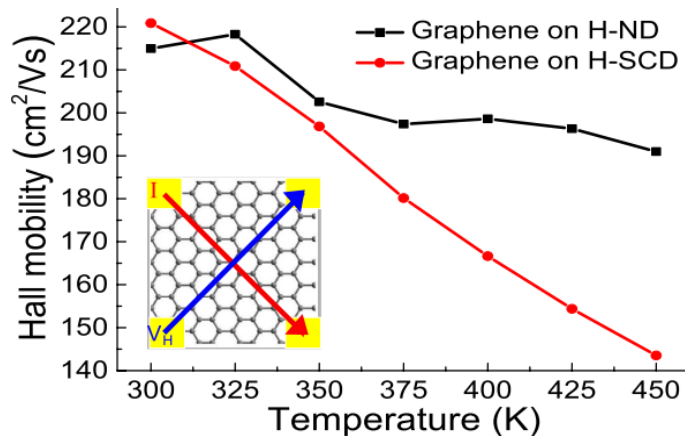


The Graphene/Hydrogen terminated diamond heterostructure
 (a) schematic view, (b) AFM images, (c) FTIR spectra of diamond



Graphene-Diamond Field Effect Transistor

Output characteristics of 500 nm and 200 nm gate length Graphene/diamond FET at $V_{ds} = -1$ V.





Summary

Processing of state of the art high temperature diamond FETs has successfully shown that diamond can be used for active devices.

- Diamond substrates with p-channel formed by H-termination and delta-doping gives excellent high temperature discrete devices.
- DIAMOND TRANSISTORS ON DIAMOND HEAT SINKS READY FOR SPECIAL HIGH TEMPERATURE HIGH RADIATION ENVIRONMENTS. Advantage is the reduction of on state resistance at temperatures up to 450C.



Current Status and Future Directions

	Challenge	Current status	Breakthroughs and future prospective
Material	Wafer size	<1 inch	>2 inches
	Cost	>400\$ per <1 inch wafer	Dependent on the BV (see discussion below (i))
	Defects	High dislocation density	Lower dislocation density for increasing wafer size
	Interface quality	Medium-high interface states and defect density compared to Si devices	Optimized annealing techniques for improving the quality
	Doping	p-type with boron (deep acceptor level), lack of reliable n-type	Lower activation energy dopant species, new conduction mechanisms
Devices	High BV and current FETs	~2 kV for lateral technologies	>10 kV, >10 A for vertical technologies, high transconductance, low threshold voltage, low R_{on_spec} transistors
	High-power p-type SBDs	>1 kV, >5A	Improve the BV (field terminations, thick and high-quality drift region, etc) without affecting the ON state current (target >10 kV, >10 A)
	N-type FET	Not available	Development of techniques for low-resistive n-type layers
	Leakage current	–Dominated by defects –Limiting factor for high BV	Improve material quality
	Lifetime	<10 ns	>100 ns
	Termination	Not optimized and may lead to TDDB	New solution for high-voltage passivation
	Fast switching	Limited to diodes	>100 V ns ⁻¹
	Novel device structures	N/A	Super junctions, floating islands, new techniques
Packaging	HT packaging	N/A	Unique packaging technique for HT operation (i.e. 175 °C for 10 kV, >200 °C for 3 kV)
	Ultra-high voltage packaging	N/A	New passivation methods, secondary passivation techniques, etc
Reliability	Ageing	No ageing tests have been conducted so far	Lifetime of diamond devices is still an open issue
	Yield	N/A	Improve the repeatability and reproducibility of devices

Acknowledgements

Graduate Students: David I. Shahin and Aayush Thapa,
Brett Setera

Undergraduates: Alexander Yuan, Aaron Aaronson

Valuable input from Kiran Kumar Kovi, Ilya Ponomarev,
James E. Butler

Euclid TechLabs, Gaithersburg, MD

FUNDING SOURCES: NSF, DOD, NRL

