Ultra-Wide BandGap Semiconductors (UWBGS)

Dr. Thomas Kazior
Program Manager, MTO
Proposers Day

Ultra-wide bandgap materials – the next revolution in high performance semiconductor technology

October 5, 2023



Part 1

Part 2

Distribution A: Approved for public release; distribution unlimited.

Agenda

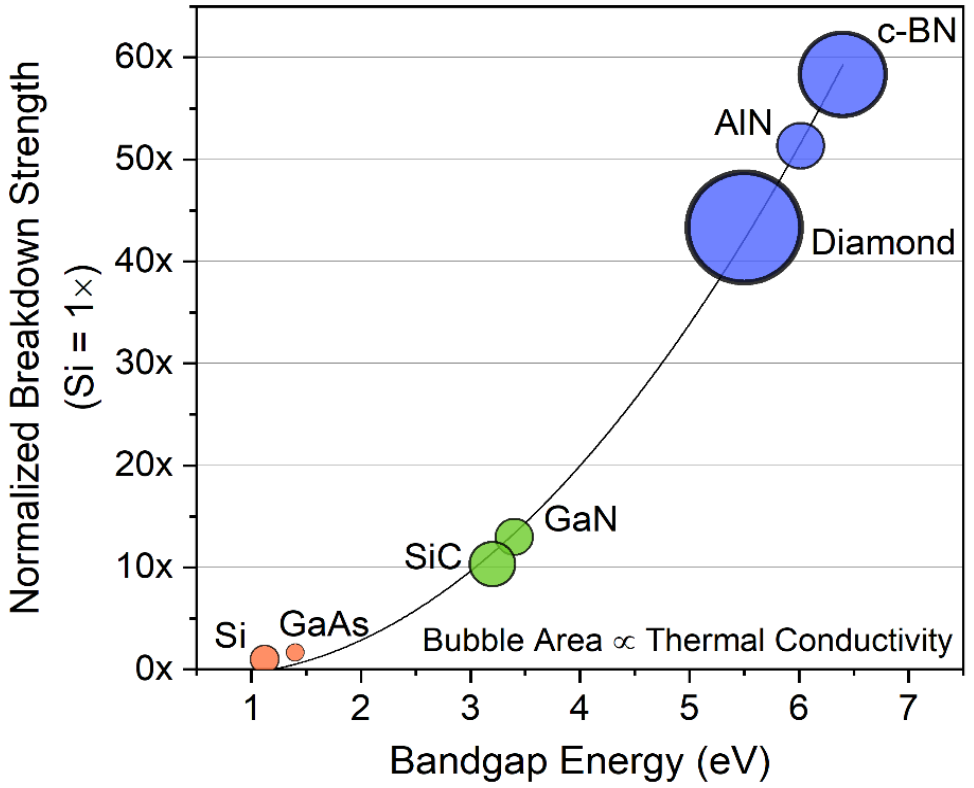
Start (EDT)	Duration	Topic/Speaker
8:30 AM	30 min	**Check-in**
9:00 AM	5 min	**Welcome – Agenda, reminders** Dr. Thomas Kazior, DARPA/MTO Program Manager
9:05 AM	10 min	**Introduction to MTO** Dr. Mark Rosker, DARPA/MTO Director
9:15 AM	30 min	**Program Overview** Dr. Thomas Kazior, DARPA/MTO Program Manager
9:45 AM	30 min	**Challenges and Approaches for P-type and N-type Doping of AlN** Prof. Alan Doolittle, Georgia Institute of Technology
10:15 AM	30 min	**Doping and Low Resistance Contacts on Diamond and c-BN** Prof. Robert Nemanich, Arizona State University
10:45 AM	15 min	**Break**
11:00 AM	20 min	**NRL IV&V Support** Dr. Virginia Wheeler, Materials Research Engineer, Naval Research Laboratory
11:20 AM	30 min	**Contracting Overview** Mr. Lon Wang, DARPA/CMO Contracting Officer
11:50 AM	15 min	**Security Overview** Mr. Joey Gilchrist, DARPA/MTO Program Security Representative
12:05 PM	45 min	**Q&A/Discussion** Dr. Thomas Kazior, DARPA/MTO Program Manager
12:50 PM	70 min	**Lunch Break**
2:00 PM	4 hr	**One-on-One Sessions (by appointment)** Dr. Thomas Kazior, DARPA/MTO Program Manager
6:00 PM	---	**Adjourn**

Part 1

Part 2

Distribution A: Approved for public release; distribution unlimited.

UWBG* materials enable new classes of high performance devices



Source: Naval Research Laboratory

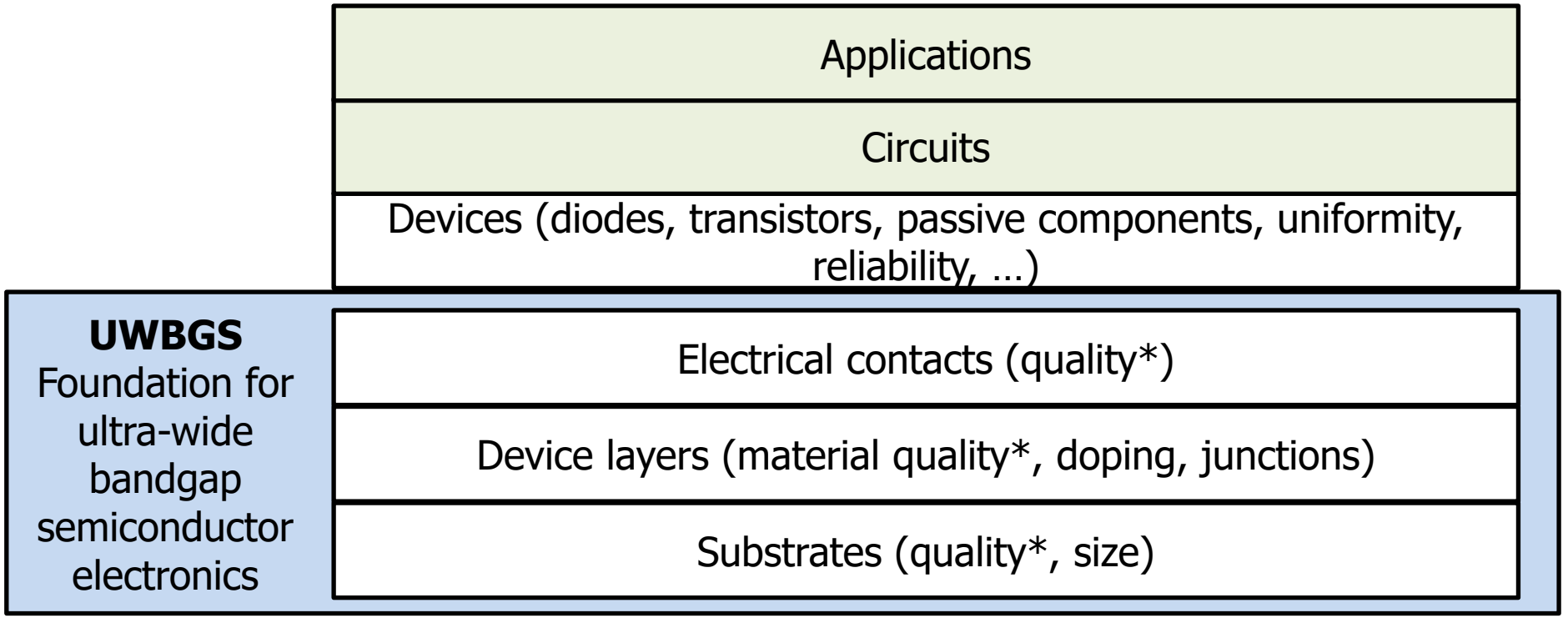
Properties	Potential Applications
High breakdown strength	• RF electronics • Power electronics • High temperature electronics
Good carrier transport electronic properties	
High thermal conductivity	
Large optical bandgap	Deep ultraviolet optoelectronics
Defect quantum spin	Magnetometry

*UWBG = ultra-wide bandgap

Si = silicon
GaAs = gallium arsenide
SiC = silicon carbide
GaN = gallium nitride
AlN = aluminum nitride
c-BN = cubic boron nitride

Distribution A: Approved for public release; distribution unlimited.

Poor quality of UWBG materials and electrical contacts limit performance of UWBG devices



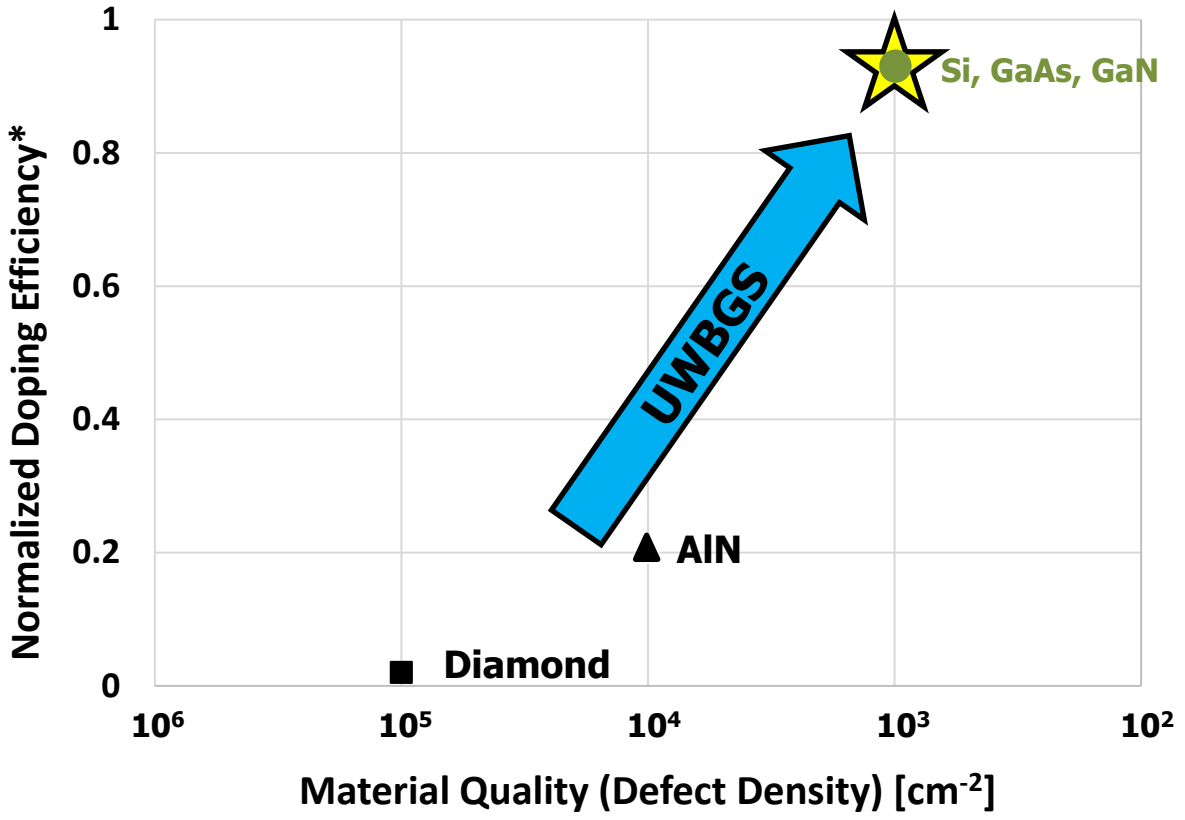
* quality = uniformity, repeatability, low defect density, low contact resistance

Distribution A: Approved for public release; distribution unlimited.

UWBGS Goals

Program Goals

- Enable UWBG applications by developing foundational, high-quality materials and electrical contacts necessary for realization of practical electronics:
  - High quality substrates and device layers
  - High doping efficiency
  - Low resistance contacts



**Measured doping efficiency / max theoretical doping efficiency*
UWBG = ultra-wide bandgap
Si = silicon
GaAs = gallium arsenide
GaN = gallium nitride

Distribution A: Approved for public release; distribution unlimited.

Technical Challenges (TCs)

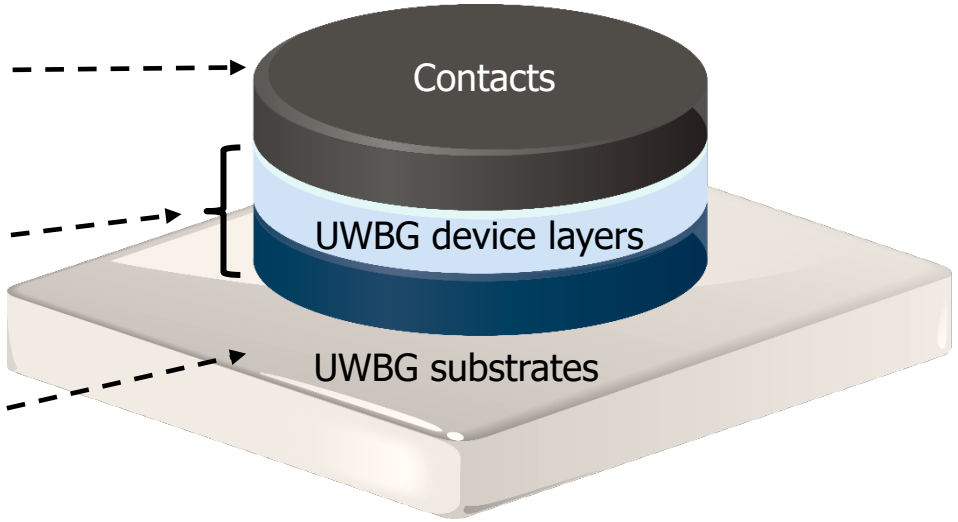
UWBGS Technical Challenges

TC3: Achieving ultra-low resistance electrical contacts to UWBG materials

TC2A: Controlled incorporation of electrically active impurities (dopants) in UWBG materials

TC2B: Creation of low defect and abrupt UWBG homo- and hetero-junctions

TC1: Creation of large area device quality UWBG substrates



UWBG test device (diode)

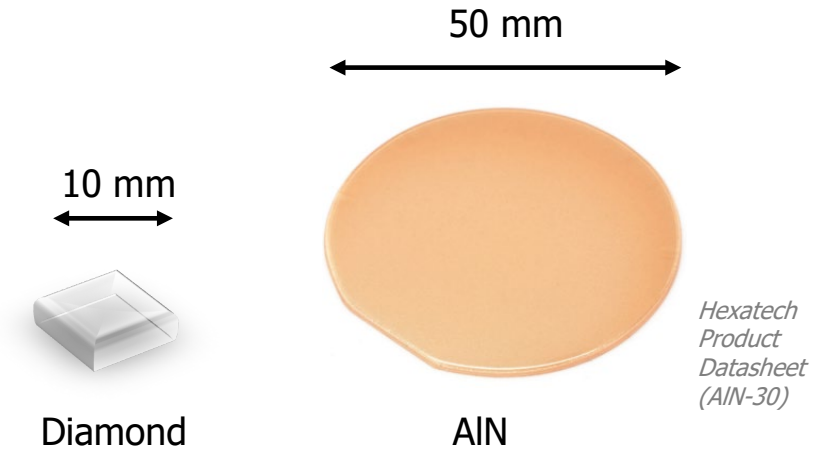
Distribution A: Approved for public release; distribution unlimited.

Technical Challenge 1: Substrates

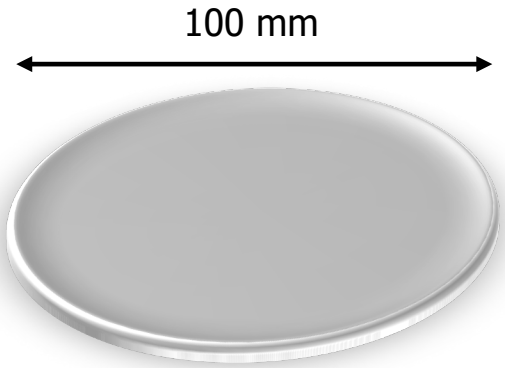
- **Technical Challenge 1:**
  Creation of large area, device quality UWBG substrates

- UWBGS seeks to scale substrate diameter while maintaining low defect density (point defects and dislocations)

- Approaches may include but are not limited to:
  - Bulk growth using physical vapor transport (PVT)
  - Seed expansion techniques such as epitaxial lateral overgrowth
  - Seed tiling
  - Homo- or heteroepitaxial growth processes
  - Innovations in nucleation layers
  - Innovations in defect annihilation techniques/processes
  - Innovations in reactor design, substrate holders, and growth processes/chemistry
  - Innovations in "wafering" (wafer slicing, chemical-mechanical or plasma assisted polishing)



Today



UWGBS Goal

Distribution A: Approved for public release; distribution unlimited.

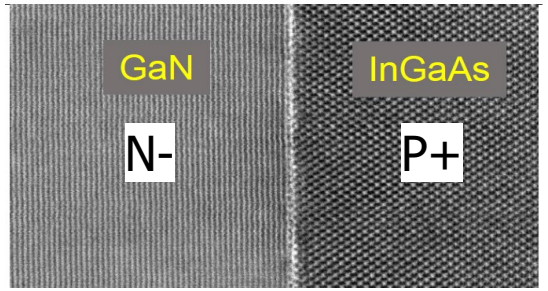
Technical Challenge 2: Device Layers

- **Technical Challenge 2A:** Controlled incorporation of electrically active impurities (dopants) in UWBG materials
- Approaches may include but are not limited to:
  - Novel epitaxial growth chemistry and growth processes
  - Ion implantation
  - Innovations in epitaxial reactor design and substrate holders

- **Technical Challenge 2B:** Creation of low defect and abrupt UWBG homo- and hetero-junctions
- Approaches may include but are not limited to:
  - Layer bonding of dissimilar materials to create novel heterostructures
  - Co-doping to compensate for carriers and create steep doping gradients
  - Innovations in reactor design, substrate holders, and growth processes/chemistry



Source: Shutterstock



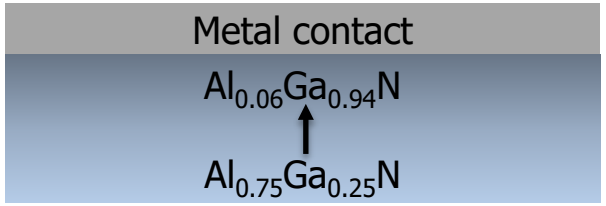
DAPRA Heterogeneous Heterostructures (H2) μE
North Carolina State University

Near ideal bonded p-n junction

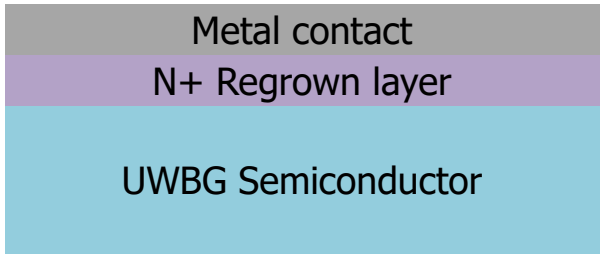
Technical Challenge 3: Electrical Contacts

- **Technical Challenge 3:** Achieving ultra-low resistance electrical contacts to UWBG materials

- Approaches may include but are not limited to:
  - Novel electrical contact processes to add interface materials between contact metals and UWBG material
  - N+ regrown contact layers to reduce barrier to current flow
  - Refractory metals to improve contact robustness



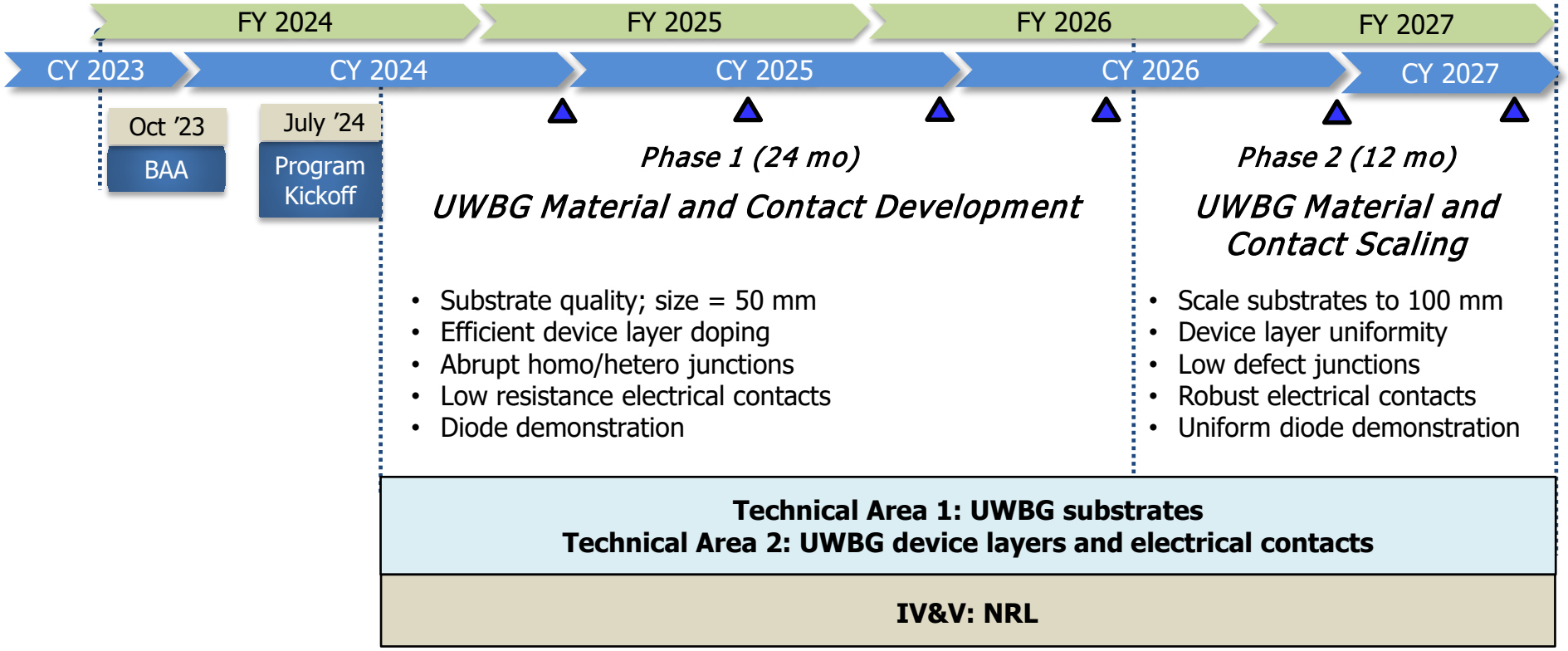
Compositional grading of UWBG materials



Regrown layer

Distribution A: Approved for public release; distribution unlimited.

UWBGS Program Structure and Schedule



Distribution A: Approved for public release; distribution unlimited.

UWBGS TA1 Program Metrics (Substrate)

Metric	Units	SOA	Phase 1	Phase 2
Size (1, 2)	mm	(1)	50	100
Defect density Dislocation (3) Point defects (3, 4)	 $/cm^2$ $/cm^3$	 (1) (1)	 10^3 10^{16}	 10^3 10^{16}
Thermal conductivity (5)	W/m-K	X (1)	0.95X	0.95X
Surface roughness (6)	nm	(1)	0.2	0.2

1. Proposer-defined ultra-wide bandgap material with minimum thermal conductivity of 300 W/m-K, with substrate diameter, defect density, thermal conductivity, and surface roughness based on proposer's baseline material
2. Substrate must be single crystal, 0.5 mm nominal thickness with proposer defined crystal orientation
3. Characterize using performer defined approach such as cathodoluminescence or x-ray topography
4. Point defects include vacancies, interstitials, and impurity atoms
5. Thermal conductivity in vertical and lateral directions at ≤ 100 °C
6. Average surface roughness (Ra) over a 100 µm scan on epi-ready side

Distribution A: Approved for public release; distribution unlimited.

UWBGS TA2 Program Metrics (Device Layer and Contacts)

Metric	Units	SOA	Phase 1	Phase 2
Normalized doping efficiency (1, 2, 3, 4)	--	< 0.2	0.6	0.9
Material non-uniformity (5)	%	50	10	5
Electrical contact resistance (6, 7)	Ω-cm^2	2 x 10^{-3}	2 x 10^{-5}	2 x 10^{-6}
Test diode ideality factor (8)	--	> 2	$\leq$ 1.5	$\leq$ 1.1
Test diode non-uniformity (9)	%	50	10	5
Test diode F_{co} (10)	GHz	40	400	1000

1. Normalized doping efficiency: measured doping efficiency / maximum theoretical doping efficiency for proposer selected UWBG material system
2. Doping efficiency: electrically conducting carriers / incorporated dopant atoms
3. n- and p-type dopants; controllable carrier concentration ranges as low as 10^{16} and up to 10^{19} cm^{-3}, with minimum room temperature thermal conductivity of 50 W/m-K
4. Device layer point defect density (include vacancies, interstitials, and impurity atoms): < 1 x 10^{16}/cm^3
5. Proposer defined; for example, sheet resistivity measured across a minimum of a 25 mm diameter wafer in Phase 1 and a 50 mm diameter wafer in Phase 2; minimum 25 data points per wafer; measured on two or more wafers
6. Contact resistance to both n-type and p-type semiconductors
7. Contact resistance must not degrade (< 5% change in contact resistance) under 1000-hour bias stress test; measured on a minimum of 6 electrical contact test structures; proposer defined bias conditions; bias conditions must reflect a relevant operational environment in a real-world device
8. Proposer defined homo- or hetero-junction diode with breakdown field strength of 4 MV/cm; diode must exhibit abrupt junctions (< 100 nm) with low junction defect density (< 10^{12}/cm^2)
9. Diode electrical characteristics (ideality factor, breakdown voltage, leakage current); measured across minimum 25 mm diameter wafer (Phase 1) and 50 mm diameter wafer (Phase 2), minimum 25 data points /wafer; measured on two or more wafers
10. Diode figure of merit $F_{co} = 1/2\pi R_{on}C_{off}$

Distribution A: Approved for public release; distribution unlimited.

Other Considerations

- Proposers should not propose to more than one Technical Area in a single proposal
- Proposers who wish to propose to both Technical Areas must submit a separate full proposal for each individual Technical Area.
- Proposals for Technical Area 1 must address Technical Challenge 1, and proposals for Technical Area 2 must address Technical Challenges 2A, 2B, and 3
- TA1
  - UWBG materials with thermal conductivities less than 300 W/m-K are not within the scope of this solicitation
- TA2
  - It is expected that, in Phase 2, TA2 performers will need to procure UWBG substrates that meet or exceed the TA1 substrate metrics

Distribution A: Approved for public release; distribution unlimited.

Deliverables

Reports and updates

- Detailed spend plan at program kickoff and execution of subsequent option awards
- Quarterly technical reports
- Monthly technical status updates
- Monthly financial reports including updated expenditures.
- Briefing materials for program kickoff, periodic technical status reviews and program-wide (PI) reviews
- Test data packages for all hardware deliverables

Hardware deliverables:

- **TA1**
  - Interim: Minimum of one substrate every 6 months starting 12 months after kick-off
  - End of Phase: Minimum of five UWBG substrates
- **TA2**
  - Interim: Minimum of one wafer with device layers, test structure, and test devices every 6 months starting 12 months after kick-off
  - End of Phase: Minimum of two wafers with device layers and material, electrical contact resistance and diode test structures
- End of Phase 1 deliverables should be received by government no less than six weeks before end of phase to allow time for IV&V

Distribution A: Approved for public release; distribution unlimited.

Metrology and Test Articles

TA1 (substrate)

- Metrology techniques may include:
  - Defect density: cathodoluminescence or x-ray topography
  - Surface roughness: Atomic force microscopy (AFM)
  - Thermal conductivity: steady state thermoreflectance (SSTR) or laser flash analysis (LFA)

TA2 (device layer and contacts)

- Test articles include:
  - Material test structures
  - Electrical contact test structures
    - Contact resistance measurement
    - 1000-hour bias stress test measured on a minimum of 6 test structures
  - Diodes
    - Homo- or hetero-junction diode with breakdown field strength of 4 MV/cm
    - Measured across minimum 25 mm diameter wafer (Phase 1) and 50 mm diameter wafer (Phase 2)

Independent Verification and Validation (IV&V)

- To ensure consistency in characterization, performers are expected to coordinate with IV&V team to define appropriate test structure and metrology techniques for substrate, device layers, electrical contact, and diode characterization

Distribution A: Approved for public release; distribution unlimited.

Key UWBGS Dates

- **Abstract Due Date:** November 1, 2023 4:00 pm (ET)
- **FAQ Submission Deadline:** December 4, 2023 by 4:00 pm (ET)
- **Proposal Due Date:** December 15, 2023 4:00 pm (ET)
- **Estimated period of performance start:** July 2024

Distribution A: Approved for public release; distribution unlimited.

Agenda

Start (EDT)	Duration	Topic/Speaker
8:30 AM	30 min	**Check-in**
9:00 AM	5 min	**Welcome – Agenda, reminders** Dr. Thomas Kazior, DARPA/MTO Program Manager
9:05 AM	10 min	**Introduction to MTO** Dr. Mark Rosker, DARPA/MTO Director
9:15 AM	30 min	**Program Overview** Dr. Thomas Kazior, DARPA/MTO Program Manager
9:45 AM	30 min	**Challenges and Approaches for P-type and N-type Doping of AlN** Prof. Alan Doolittle, Georgia Institute of Technology
10:15 AM	30 min	**Doping and Low Resistance Contacts on Diamond and c-BN** Prof. Robert Nemanich, Arizona State University
10:45 AM	15 min	**Break**
11:00 AM	20 min	**NRL IV&V Support** Dr. Virginia Wheeler, Materials Research Engineer, Naval Research Laboratory
11:20 AM	30 min	**Contracting Overview** Mr. Lon Wang, DARPA/CMO Contracting Officer
11:50 AM	15 min	**Security Overview** Mr. Joey Gilchrist, DARPA/MTO Program Security Representative
12:05 PM	45 min	**Q&A/Discussion** Dr. Thomas Kazior, DARPA/MTO Program Manager
12:50 PM	70 min	**Lunch Break**
2:00 PM	4 hr	**One-on-One Sessions (by appointment)** Dr. Thomas Kazior, DARPA/MTO Program Manager
6:00 PM	---	**Adjourn**

Distribution A: Approved for public release; distribution unlimited.



www.darpa.mil

Distribution A: Approved for public release; distribution unlimited.

MTO Ultra-Wide BandGap Semiconductors (UWBGS) Proposer's Day Introduction brief

Mark Rosker, MTO Director

Briefing prepared for UWBGS Proposer's Day

05 October 2023



Approved For Public Release; Distribution Unlimited

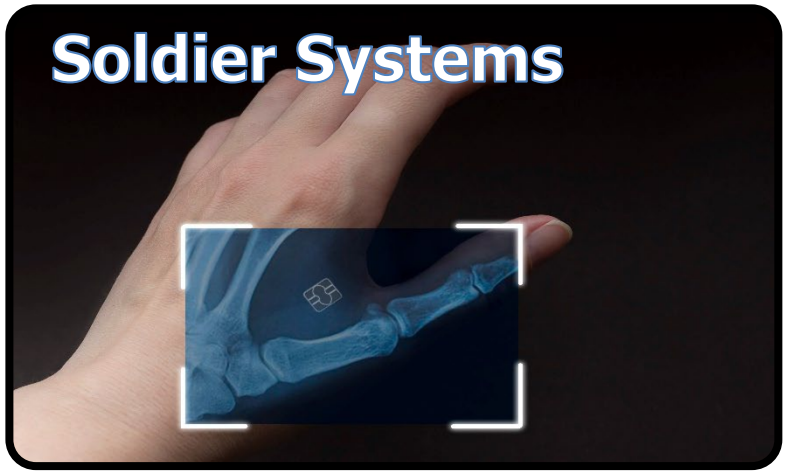
Our mission

High-performance, intelligent microsystems and next-generation components













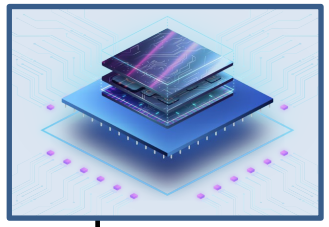
C4ISR: Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
PNT: Positioning, Navigation, and Timing

Electronics Resurgence Initiative (ERI) 2.0 timeline

NGMM Phase 0 BAA
August 2022



ERI Summit 2023
August 22-24 / Seattle, WA



FY22 | FY23 | FY24 | FY25 | FY26 | FY27

Original ERI | **ERI 2.0: Reinventing microsystems manufacturing for a new age**



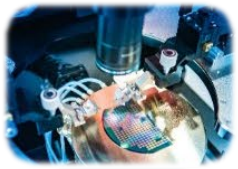
TALK — Securing communications



COMPUTE — Increasing information processing efficiency at the edge



DECIDE — Accelerating innovation in AI hardware



BUILD — Manufacturing complex 3D microsystems



COMPOSE — Optimizing design and test for complex circuits



SECURE — Overcoming security threats across the entire hardware lifecycle



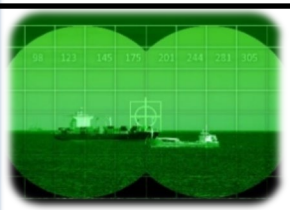
HARDEN — Developing electronics for extreme environments

NGMM: Next-Generation Microelectronics Manufacturing program

UWBGS enables several MTO thrust areas

DISRUPTIVE MICROSYSTEMS

SEE



Gaining an advantage in sensing the physical world

TALK



Securing communications

ACT



Increasing the effectiveness of radiation on target

NAVIGATE



Embedding accurate positioning and timing

EDGE PROCESSING

COMPUTE



Increasing information processing efficiency at the edge

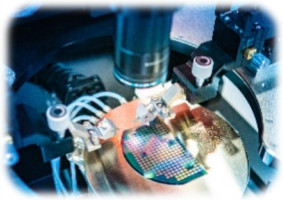
DECIDE



Accelerating innovation in AI hardware

MICROSYSTEMS MANUFACTURE

BUILD



Manufacturing complex 3D microsystems

COMPOSE



Optimizing design and test for complex circuits

SECURE



Overcoming security threats across the entire hardware lifecycle

HARDEN



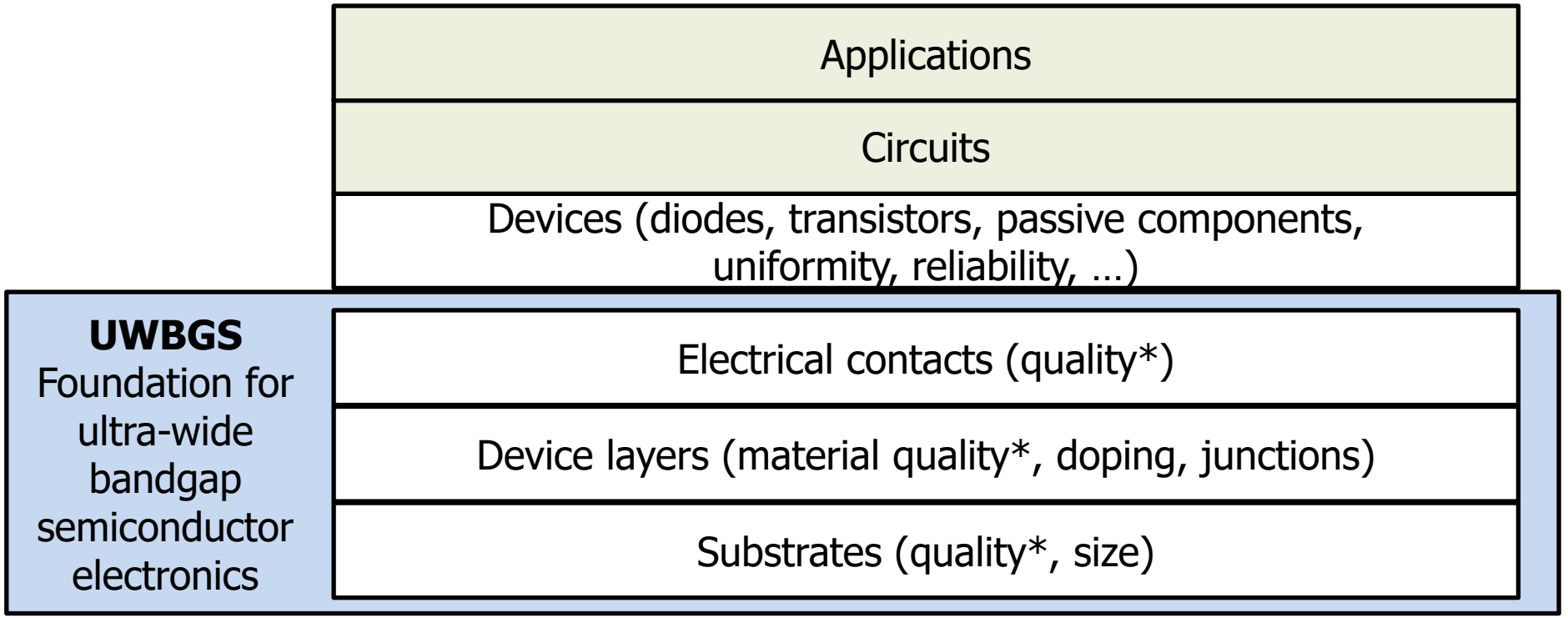
Developing electronics for extreme environments

3D: Three-dimensional
AI: Artificial Intelligence

https://www.darpa.mil/about-us/offices/mto

Approved For Public Release; Distribution Unlimited

To date, poor quality of UWBG materials and electrical contacts has limited performance of UWBG devices



* quality = uniformity, repeatability, low defect density, low contact resistance

Does this sound familiar?

UWBGS: Ultra-wide bandgap semiconductors

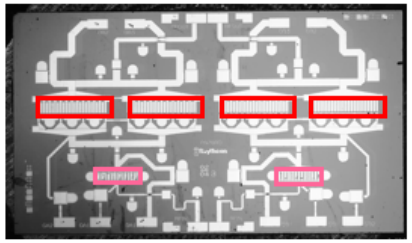
We've been here before…



WBGS RF Devices Enable High Performance Amplifiers

10 W X-band GaAs PHEMT amp

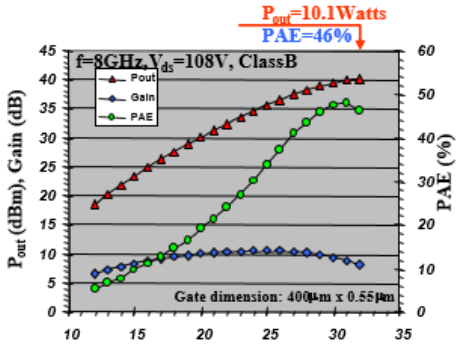
5.7 mm x 3.3 mm



7V @ 75 mA/mm
PAE = 40%
~ 20 mm total output gate periphery
R_{out} ~ 4.6 Ω

Same power at 1/20 the Footprint and >20x impedance

GaN



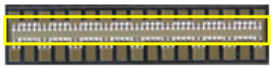
FET:
0.4 mm periphery
Vds = 108 V,
Id = 425 mA/mm,
PAE= 46%
R_{out} = 600 Ω

High impedance enables high efficiency and wide bandwidth

~10x the power in same transistor size

50 W (pulsed) X-band GaN HEMT Device

0.7 mm x 4 mm (~1/2 GaAs output stage)

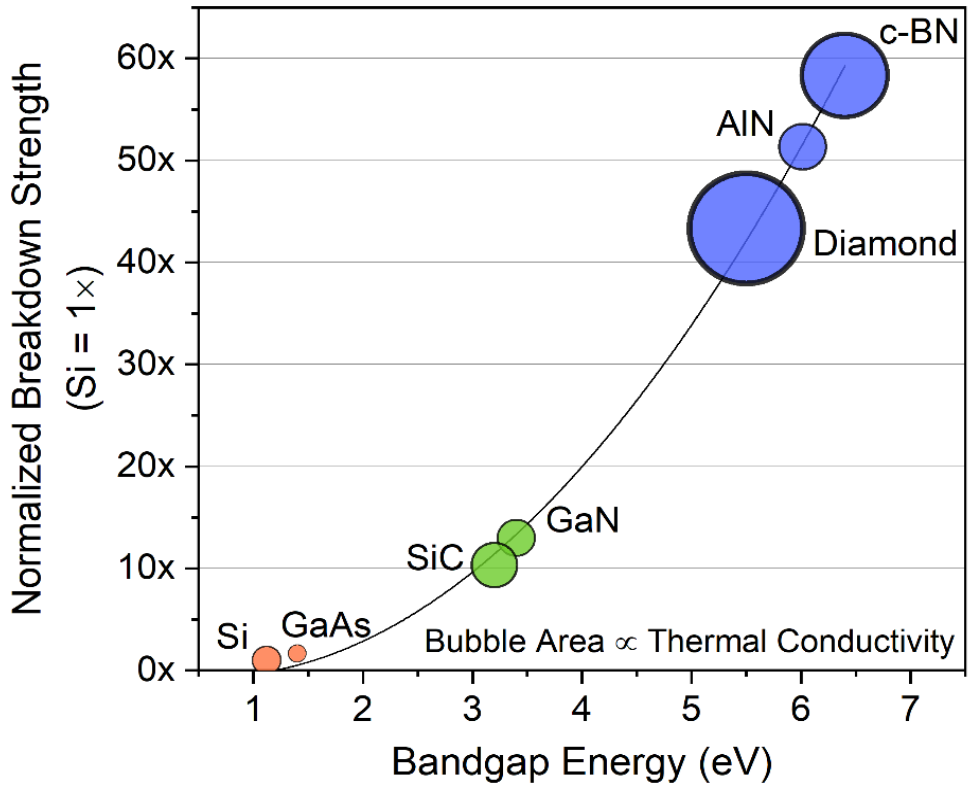


50 V @ 250 mA/mm
PAE = 28%
12 mm periphery
R_{out} ~ 15Ω

Commercial impact expected from superior linearity and efficiency

Source: DARPA / 2005 CS MANTECH conference

UWBG materials **will** enable new classes of high performance devices



Source: Naval Research Laboratory

Properties	Potential Applications
High breakdown strength	• RF electronics • Power electronics • High temperature electronics
Good carrier transport electronic properties	
High thermal conductivity	
Large optical bandgap	Deep ultraviolet optoelectronics
Defect quantum spin	Magnetometry

AlN: Aluminum nitride
c-BN: Cubic boron nitride
GaAs: Gallium arsenide
GaN: Gallium nitride
RF: Radio frequency
Si: Silicon
SiC: Silicon carbide
UWBG: Ultra-wide bandgap



www.darpa.mil

Approved For Public Release; Distribution Unlimited

Georgia Tech

Challenges and Approaches for p-type and n-type Doping of AlN

W. Alan Doolittle, Habib Ahmad, Christopher M. Matthews, Keisuke Motoki, Zachary Engel, and Sangho Lee

Georgia Institute of Technology

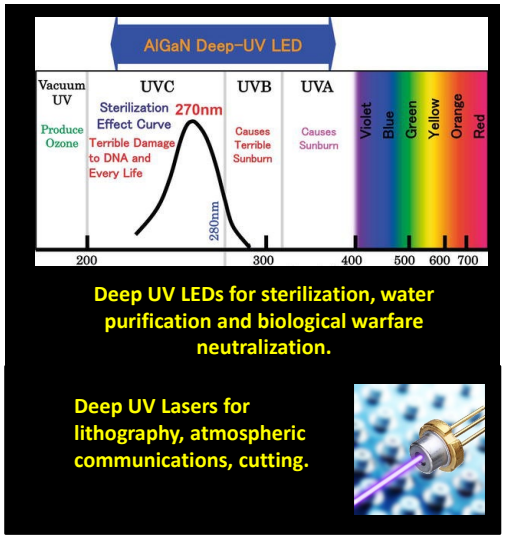
DARPA UWBG Industry Day, October 5th, 2023

Supported by ONR – Lynn Peterson (p-type and contacts)
AFOSR - Dr. Ali Sayir (n-type and characterization) and
DARPA – Ben Griffin (AlScN)









alan.doolittle@ece.gatech.edu
AFOSR AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
ONR Science & Technology
DARPA

Primary References

W. Alan Doolittle, Christopher M. Matthews, Habib Ahmad, Keisuke Motoki, Sangho Lee, Aheli Ghosh, Emily N. Marshall, Amanda L. Tang, Pratyush Manocha, P. Douglas Yoder, "Prospectives for AlN Electronics and Optoelectronics and the Important Role of Alternative Synthesis", APL Perspectives, Appl. Phys. Lett. 123, 070501 (2023)

H. Ahmad, Z. Engel, C. M. Matthews, S. Lee, and W. Alan Doolittle, "Realization of homojunction PN AlN diodes", J. Appl. Phys. 131, 175701 (2022)

H. Ahmad, J. Lindemuth, Z. Engel, C. M. Matthews, K. Motoki, W. Alan Doolittle, "Substantial P-type Conductivity of AlN Achieved via Beryllium Doping," Advanced Materials 33 (42), 2104497, September 2021.

Outline

Background on AlN Doping

- Dopant Impurities
- Compensating Defects

Why Low Temperature Growth? Metal Modulated Epitaxy Explained

- Low Temperature Growth does not mean “low quality”
- Not just “Shuttered Growth”
- Replaces Temperature with Barrier Lowering/Rapid Growth to Accomplish Diffusion Control

New Accomplishments

- **Improved P-type ($p=4.4\times10^{18}$ cm^{-3}, 30 cm^2/V-sec, 0.04 ohm-cm*) bulk conducting AlN**
- **Improved mobility in N-type ($n=3\times10^{18}$ cm^{-3} , 509 cm^2/V-sec, 0.02 ohm-cm*) bulk conducting AlN**
- **Temperature Dependent IV of pin AlN Homojunction diode reveals understanding of defect energies and conduction dominance.**

- **Comments on Contact Issues with AlN**

** When contact resistance is high, Van de Pauw anomalies for AlN result in ~10x lower values than this but are suspect.*

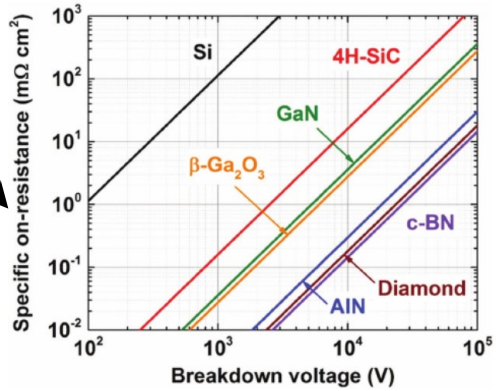
Georgia Tech

Motivation: AlN Ranks in the Top 2 in All Major UWBS Performance Parameters

Material	E_G (eV)	V_{sat} (10^7 cm/s)	E_{crit} @ 10^{16} cm^{-3} (MV)	Thermal Conductivity (W/m-K)	Johnson FOM (10^{12} V/S)	~V_{Break} @ 10 mW cm^2 (V)	Available Substrate?	N-type?	P-type?	Light Emission ?
Si	1.12	1.0	0.3	145	0.48	100	Yes	Yes	Yes	No
SiC	3.26		3.1	**490**		3000	Yes	Yes	Yes	No
GaN	3.45	**1.4**	4.9	253	11	5000	Almost	Yes	Yes	Yes
β-Ga_2O_3	4.8	1.1	10.3	27	18	6000	Yes	Yes	No	No
AlN (Parameter Rank)	**6.1 (#1)**	1.3 (#2)	**15.4 (#1)**	319 (#2)	**32 (#1)**	20,000 (#2)	Yes	**Yes This Work!**	**Yes This Work!**	Yes

Adv. Electron. Mater. 2018, 4, 1600501

- In all performance predictors, AlN is either the best or a close second to other semiconductors with a 2" diameter substrate.
- **The critical electric field of AlN is:**
- **~1.5x Ga_2O_3 (3x if you consider Ga_2O_3 can only use Schottky rectifiers)**
- **~3x GaN**
- **~5x SiC.**
- **Up to now, the major limitation for AlN PIN diodes was the lack of doping. We achieved substantial conductivity with p-type AlN:Be films and n-type AlN:Si films grown via metal modulated epitaxy (MME).**



Georgia Tech

Justifying New Investment: Will it Pay Off in Multiple Applications?

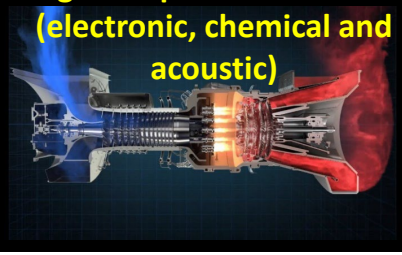
Extreme Environments (radiation and heat)



High Temperature Electronics



High Temperature Sensors (electronic, chemical and acoustic)







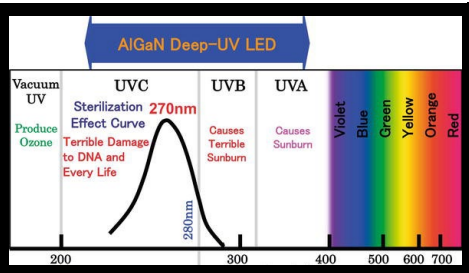
High Voltage switching, protection and distribution

High Power RF



Electrical Applications

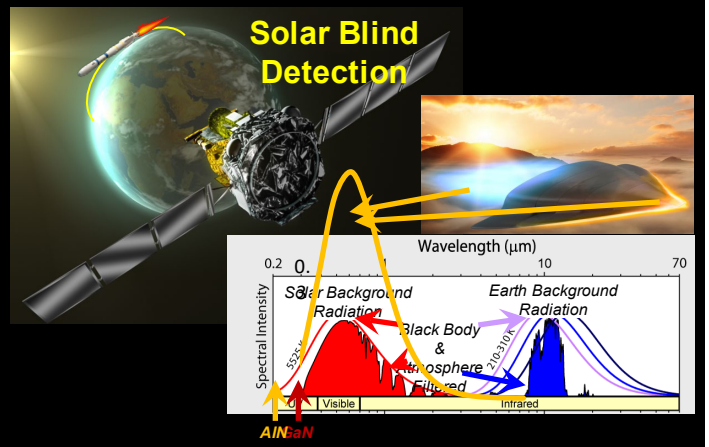
Optical Applications



Deep UV LEDs for sterilization, water purification and biological warfare neutralization.

Deep UV Lasers for lithography, atmospheric communications, cutting.





alan.doolittle@ece.gatech.edu

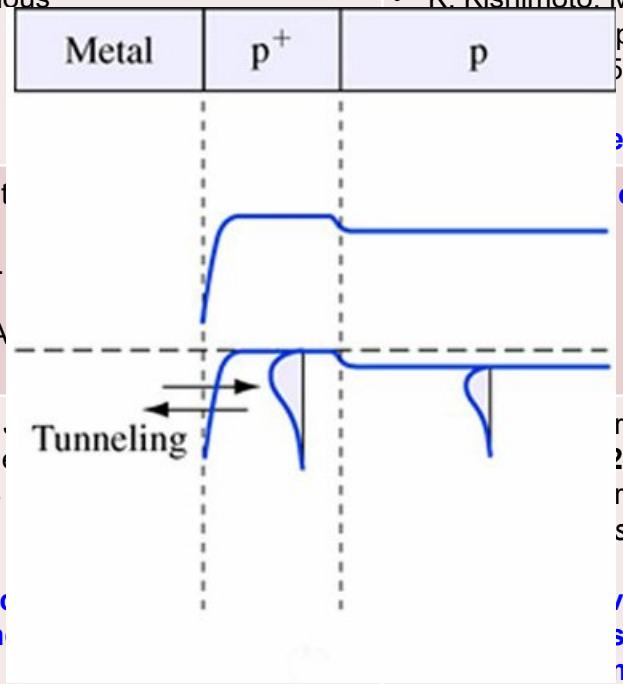
AFOSR AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

ONR Science & Technology

DARPA

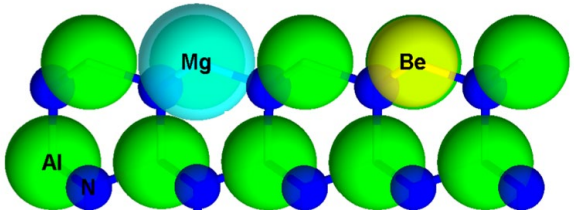
Key Prior AlN Doping and Defect Work

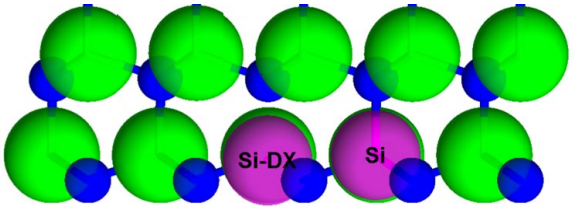
Dopant	Theory	Experimental Surface / Near Surface	Experimental Bulk
Mg p-type	• 580 meV (Y. Zhang et al. *Phys. Rev. B - Condens. Matter Mater. Phys.*, vol. 77, p. 035201, 2008) • 510 meV (K. Nam et al. *Applied Physics Letters,* vol. 83, p. 878, 2003). • 630 meV (Taniyasu et al. Nature, vol. 441, p. 325, 2006)	**No prior success**	**No prior success**
C p-type	Various	• K. Kishimoto, M. Funato, Y. …plied Physics Express …512. **…e Sheet Charges**	**No prior success**
Be p-type	• 220-262 meV F. Mireles et … (7), 3879, 1998. • 330 meV A. Sedhain et al. … vol. 93, p. 141104, 2008 • 340 meV R. Q. Wu et al. A … 152110 , 2007.	**…or success**	**No prior success** **Here: Update: p=4.4x10^{18} cm^{-3}**
Si n-type	• L. Gordon, J. L. Lyons, A. … Physical Review B - Cond… Physics 2014, 89, 085204 • I. Bryan, et al, Appl. Phys. • **Provides key incite into … structures: DX center an…**	…ridge, et al, *Appl.* **…20**, *116*, 172103. …ridge, et al, *Applied* **…s 2021**, *118*, 112104. **…via ion implantation …s not the limitation …mpensation is.**	• M. L. Nakarmi, et al, Applied Physics Letters 2004, 85, 3769. • T. Ive, et al, Applied Phys… 024106. **Here: n=6.1x10^{18} cm^{-3}** • **N ~ 10^{15} cm^{-3} Maximum**
O	• **G. A. Slack, J. Phys. Chem. Solids. 1973, 34, 321 showed O is an important compensating defect forming a DX center and aggravated by Al vacancies**		

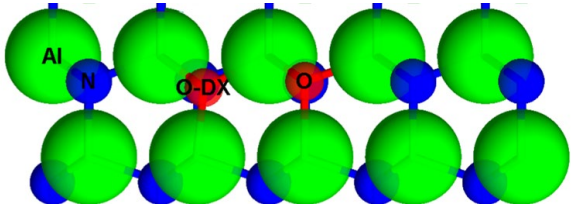


Georgia Tech

Pathway for Doping Success: Takeaway







Use lowest strain element possible (Be).
- Be requires low substrate temperatures to avoid Be runaway.
- Absolutely critical to avoid oxygen (low temperature).
- Oscillate from N-rich to Metal Rich
  - Avoid N-rich to improve crystal quality.
  - Prefer N-rich for chemistry
- Avoid vacancies (low temperature).

- Use Al-rich conditions (avoid Al vacancy that complexes with Si)
- Avoid lattice expansion that aggravates Si c-axis bond breakage that forms the compensating DX center → low temperature.
- Avoid vacancies (low temperature).

- Low Temperature (low outgassing of O and small lattice expansion) environment is critical.

- ***Vacancies, lattice expansion (temperature increases) and O impurities lead to compensation of carriers.***
- ***Vacancy concentrations and thus, compensation, is reduced by many orders of magnitude at low temperature!***

The Science Behind the Heresy

- **Thermal Energy is not required for good epitaxy. Large surface diffusion lengths are!**
  - MBE of epitaxial Aluminum is performed at 100º C or less
  - MBE of epitaxial AlN is performed at 800º C - 1400º C (or more)
  - **Surface Bond Strength Dominates Over Temperature in Epitaxy**

Exponential Dependence
Surface Barriers

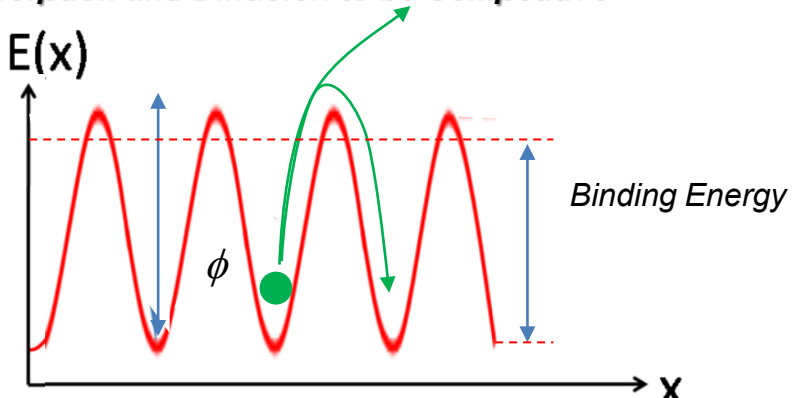
$$\text{Hopping Rate} = \omega e^{-\emptyset/kT}$$

Vibration Frequency
~10^{13} Hz (slightly T dependent)

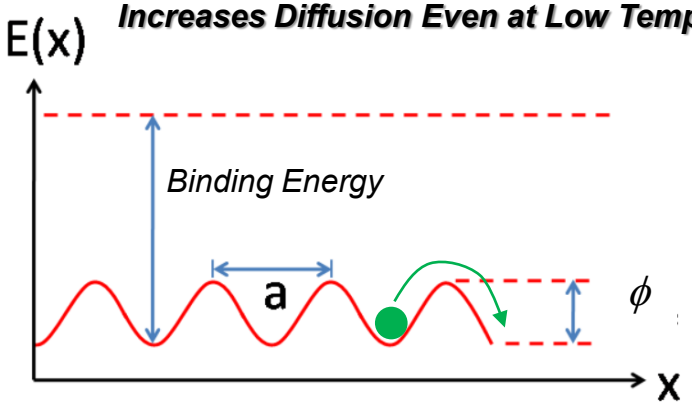
Exponential Dependence
on Temperature

$$\text{Surface Diffusivity} = \underbrace{\left[a^2\left(\frac{\omega}{4}\right)\right]}_{D_o} e^{-\emptyset/kT}$$

***Strong Bonds* in Wide Bandgap Semiconductors Cause Desorption and Diffusion to be Competitive**



Replacing the Strong Bonds in Wide Bandgap Semiconductors with Weak Metal Bonds Increases Diffusion Even at Low Temperatures



The Science Behind the Heresy

CVD Solution: Go to High Temperatures
Byproduct: Enormous vacancy concentrations→
Compensation
$[Vacancies]=[N_{atomic}]e^{-E/kT}$

Exponential Dependence
Surface Barriers

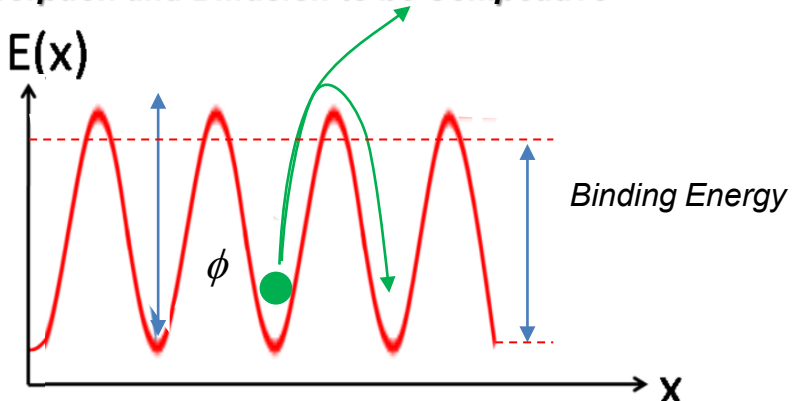
$$\text{Hopping Rate} = \omega e^{-\phi/kT}$$

Vibration Frequency
~10^{13} Hz (slightly T dependent)

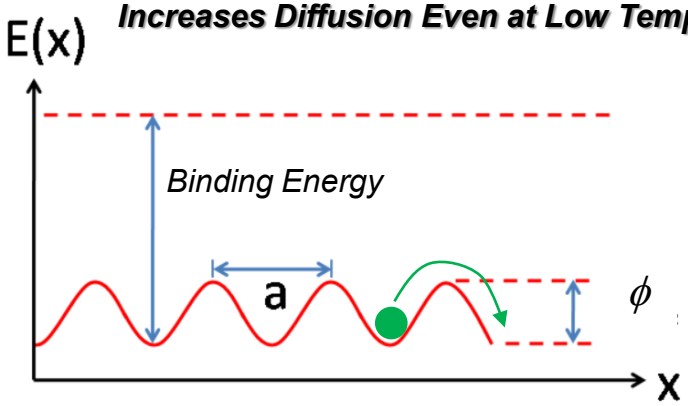
Exponential Dependence
on Temperature

$$\text{Surface Diffusivity} = \underbrace{\left[a^2\left(\frac{\omega}{4}\right)\right]}_{D_o} e^{-\phi/kT}$$

Strong Bonds in Wide Bandgap Semiconductors Cause Desorption and Diffusion to be Competitive

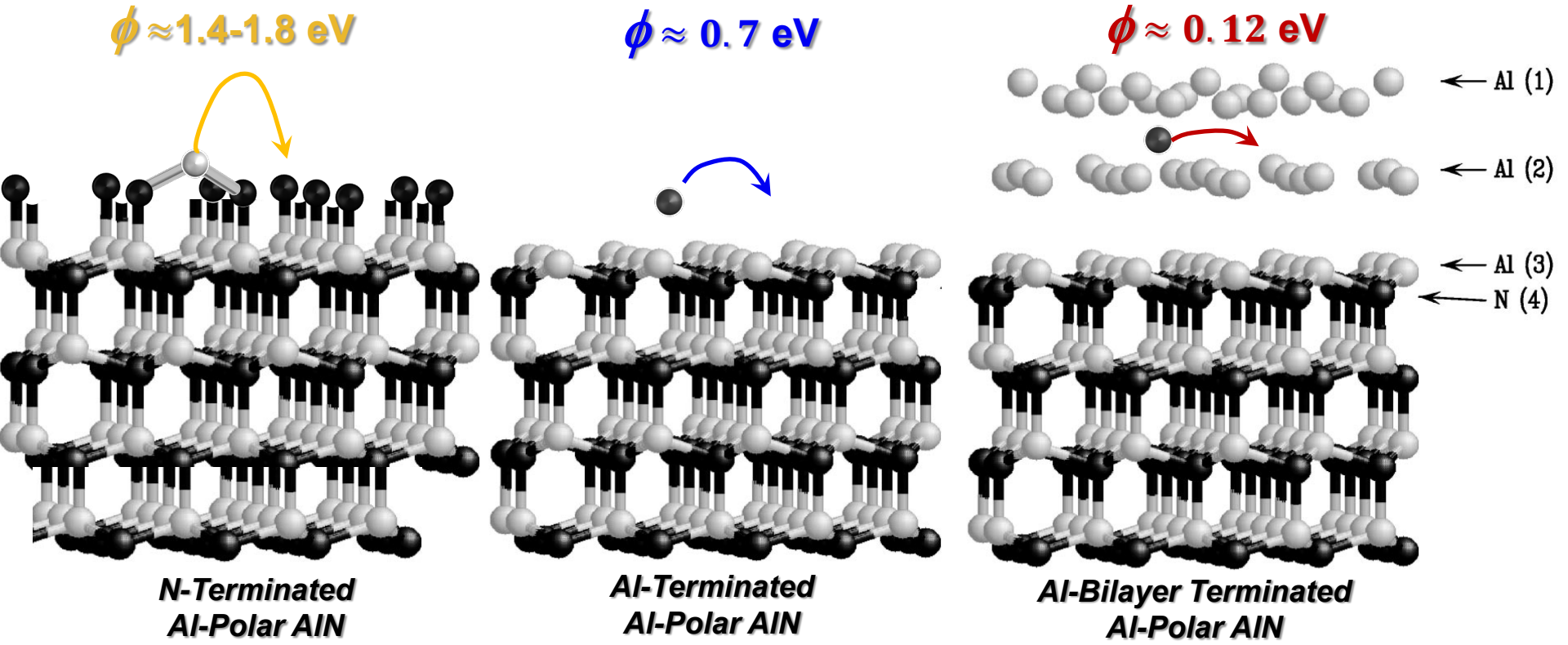


Replacing the Strong Bonds in Wide Bandgap Semiconductors with Weak Metal Bonds Increases Diffusion Even at Low Temperatures



Comparison of Surface Diffusion Barriers on GaN

Metallic bilayers reduce the diffusion barrier significantly.



Modified Images after: C. D. Lee, Y. Dong, R. M. Feenstra, J. E. Northrup, J. Neugebauer, Phys. Rev. B 68, 205317 (2003)

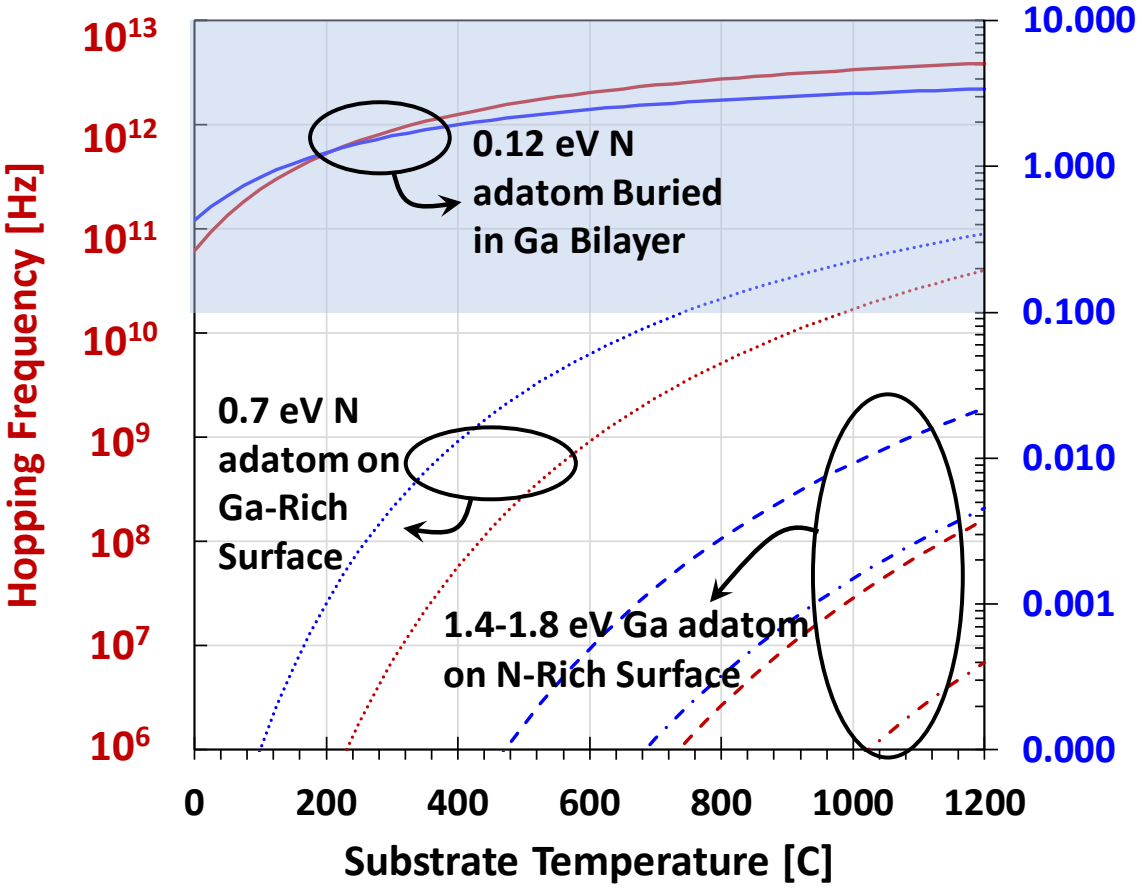
ϕ based on reported values for GaN in:

J. Neugebauer, T. K. Zywietz, M. Scheffler, J.E. Northrup, H. Chen, and R.M. Feenstra, Phys. Rev. Lett. 90(5), 056101 (2003).

J. Neugebauer, T. K. Zywietz, M. Scheffler, and J. E. Northrup, Appl. Surf. Sci 159–160, 355–359 (2000).

The Science Behind the Heresy

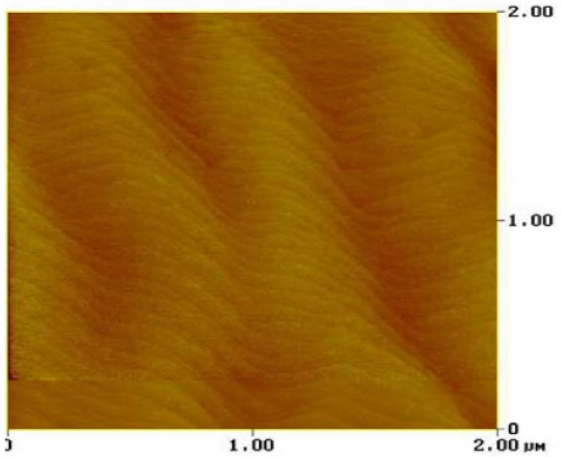
- Adatom diffusion is orders of magnitude faster for metallic surfaces than semiconductor surfaces.
- Diffusion lengths longer than 1 um obtained.*
- Metallic surfaces have several advantages:
  - Adatom diffusion is almost constant with temperature
  - Approaching the "mobility regime" where $\phi/kT \sim 1$
  - Leads to improved control of the epitaxy process especially for ternaries.

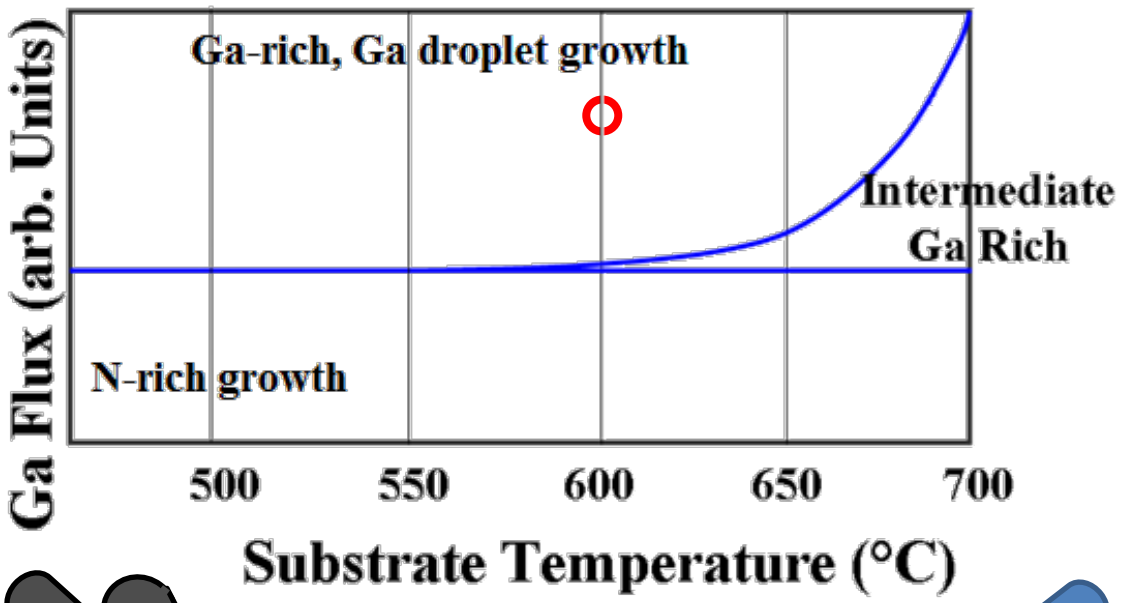


** Hopping rates assume $\omega=10^{13}$ Hz, and ϕ based on reported values in:*
J. Neugebauer, T. K. Zywietz, M. Scheffler, J.E. Northrup, H. Chen, and R.M. Feenstra, Phys. Rev. Lett. 90(5), 056101 (2003).
J. Neugebauer, T. K. Zywietz, M. Scheffler, and J. E. Northrup, Appl. Surf. Sci. 159–160, 355–359 (2000).
Diffusion lengths assume 1 um/hour growth rates which define the time before overgrowth inhibits diffusion.

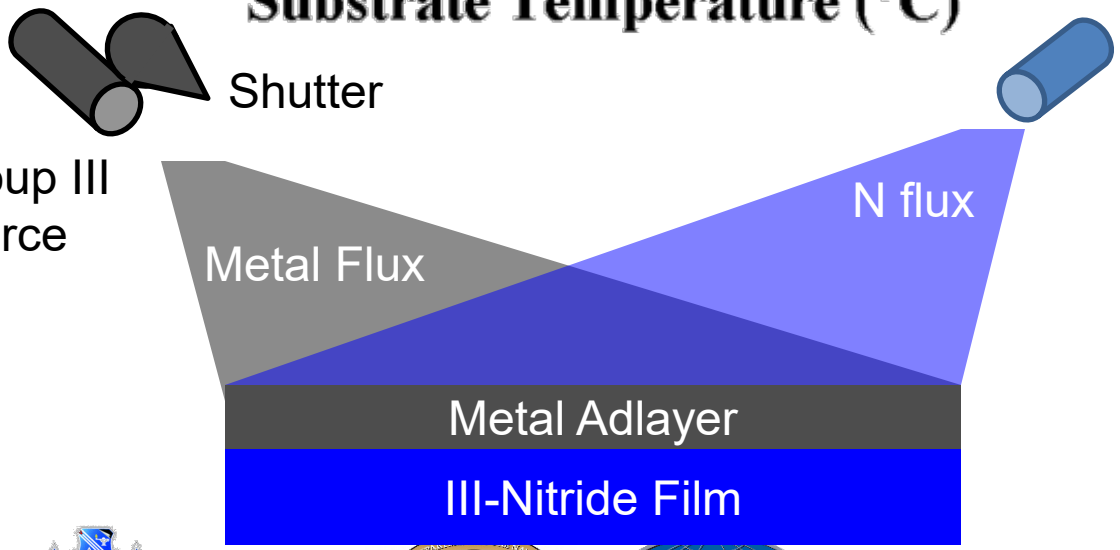
alan.doolittle@ece.gatech.edu

Metal-Modulated Epitaxy

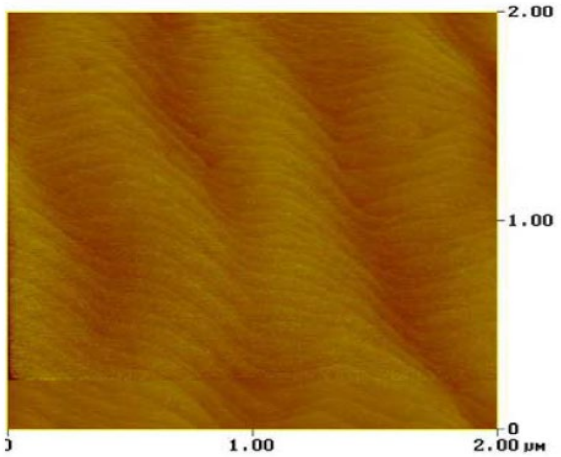




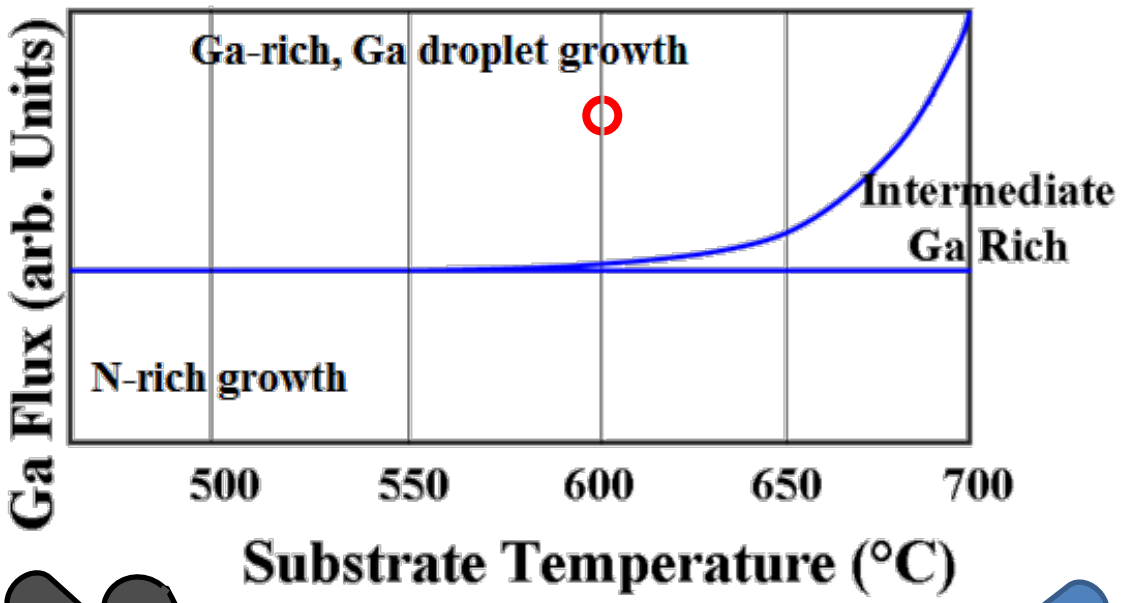
- Extremely metal-rich fluxes (1.3-3x greater than stoichiometric point)
- **T_{sub} ~ 600 °C growth** avoids intermediate regime
- Enhanced adlayer mobility from bilayer
- Consumes droplets into film on shutter close
- **Growth rate up to 10 µm/hour and beyond!**



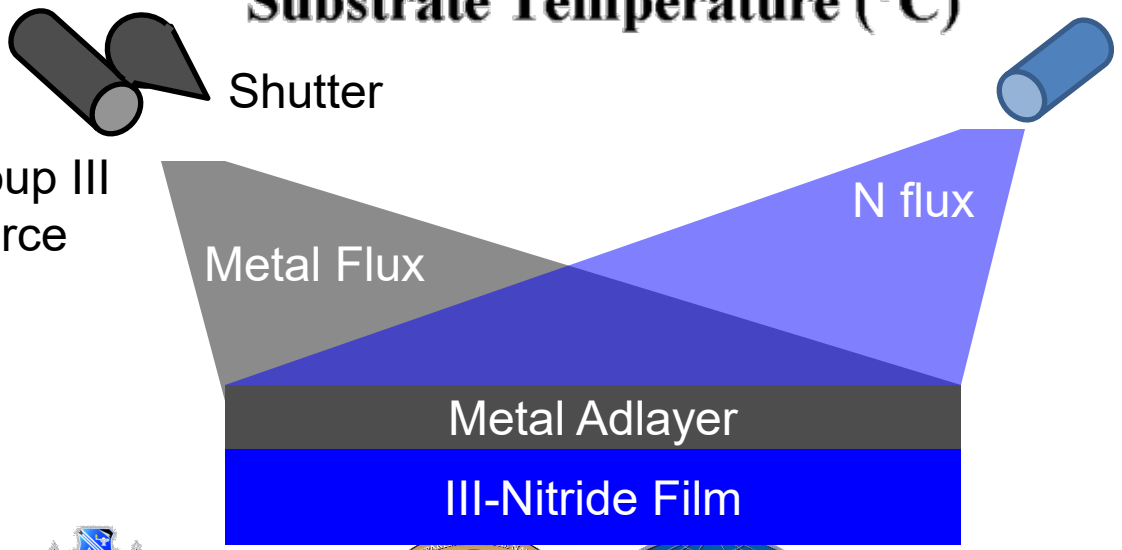
Metal-Modulated Epitaxy



0.19 nm RMS at 600 °C

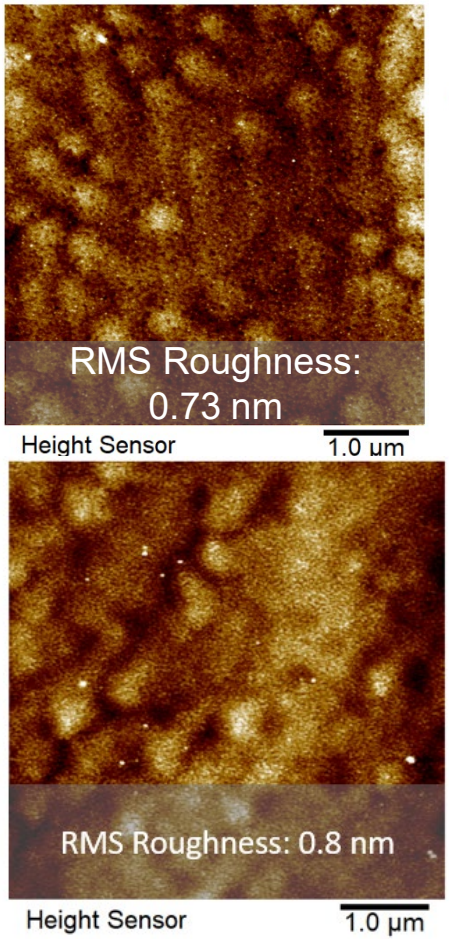


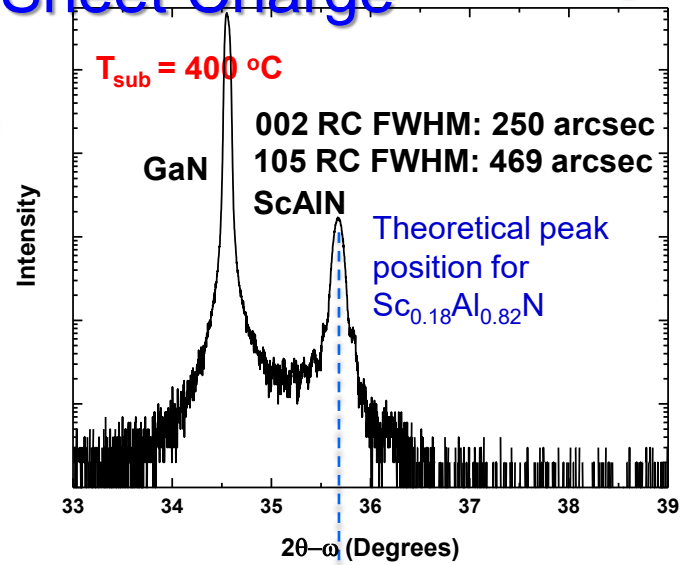
Atomically Smooth Surfaces at Low Substrate Temperature

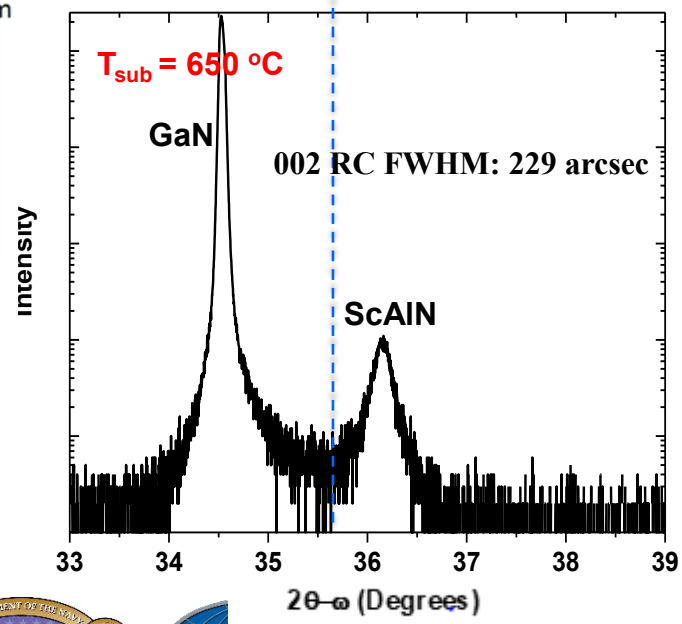


State of the Art AlScN/GaN Sheet Resistance and Experiment Matches Theoretical Sheet Charge

- Proper control of metal buildup allows for the growth of ScAlN under metal rich conditions without loss of phase purity.
- A significant catalytic effect is observed in growth with Sc. A 2-3x increase in growth rate is observed in ScN growth vs AlN.
- Excellent electrical performance is demonstrated, with a sheet charge as high as 5.9×10^{13} cm^{-2} and a sheet resistance as low as 152 Ω/□

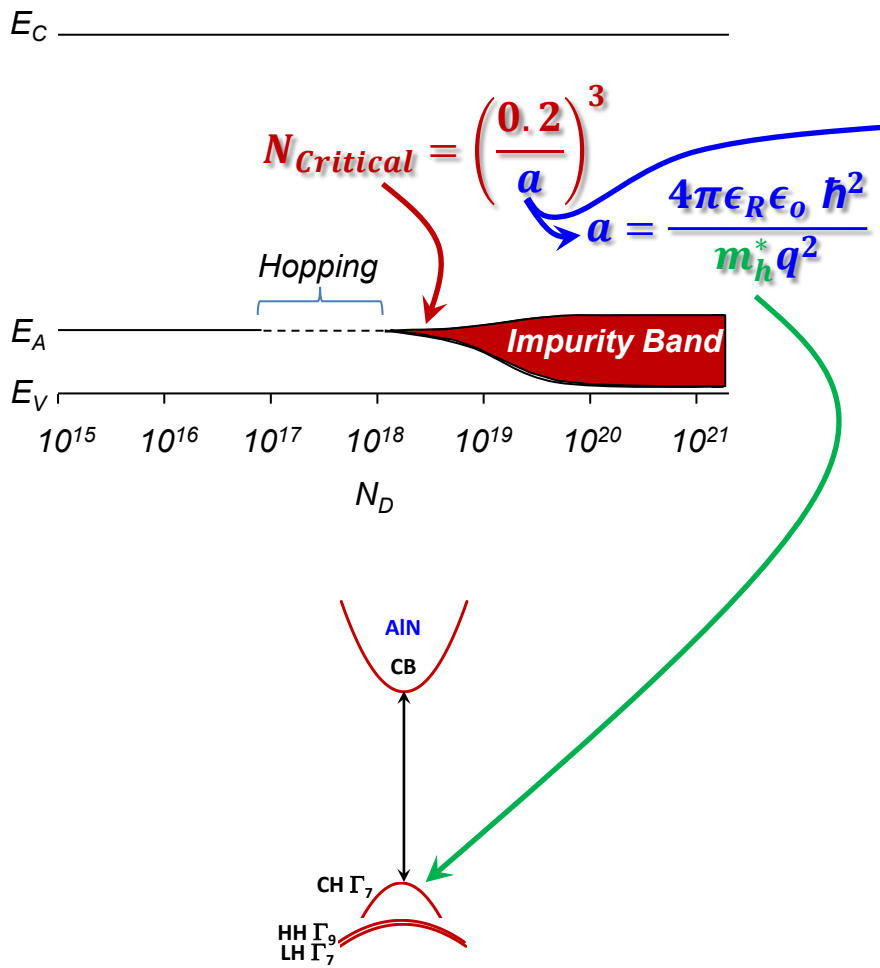


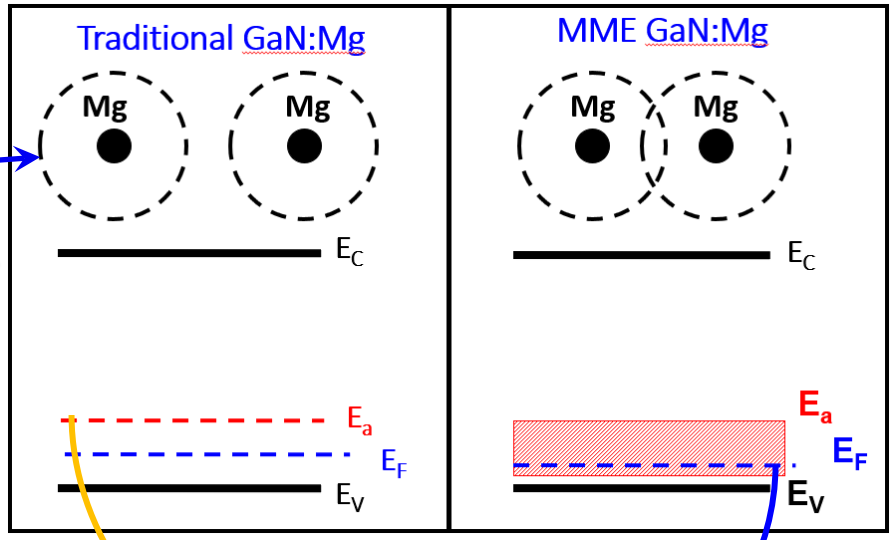


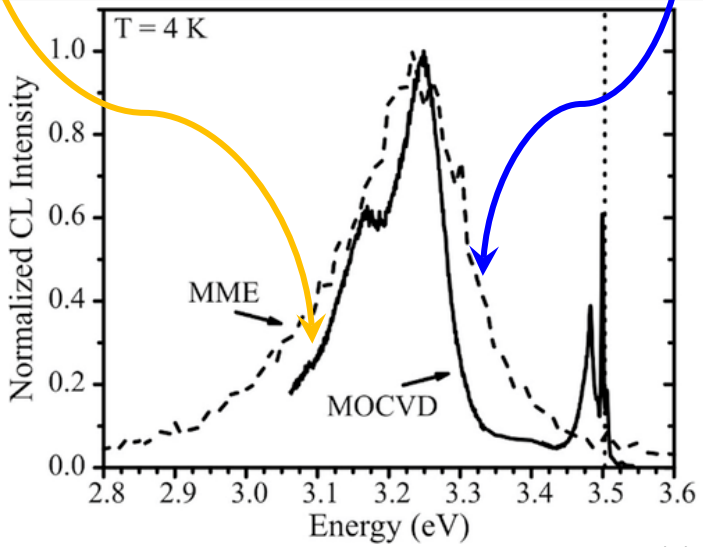


	Sheet Resistance	Mobility	Sheet Charge
20nm ScAlN/GaN HEMT Structure	152 Ω/□	700 cm^2/vs	5.9×10^{13} cm^{-2}

Mechanism: Kinetics of Non-equilibrium Growth Forms Acceptor Impurity Band







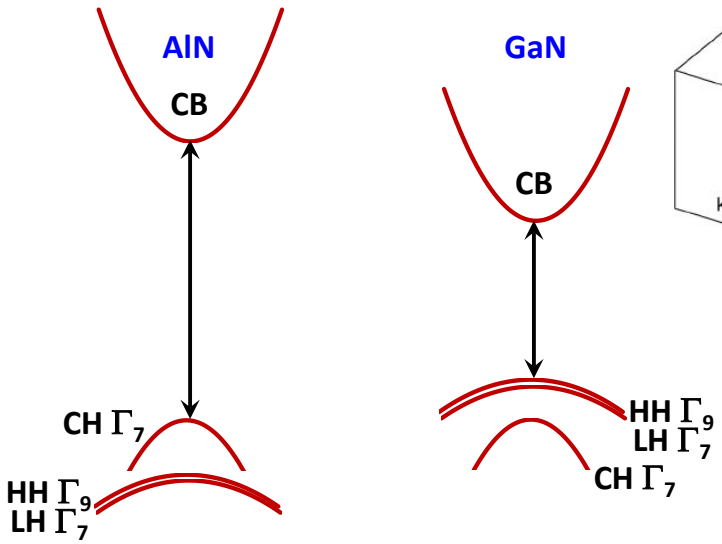
Fischer *and Doolittle* et al. Phys. Status Solidi B, **254** (8), 1600668 (2017)

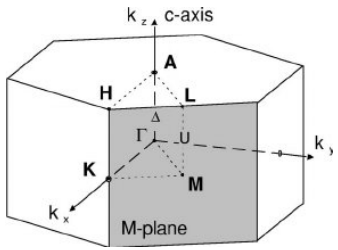
W. Alan Doolittle, C. M. Matthews, H. Ahmad, K. Motoki, S. Lee, A. Ghosh, E. N. Marshall, A. L. Tang, P. Manocha, P. D. Yoder, APL Perspectives, Appl. Phys. Lett. 123, 070501 (2023)

AlN Has Anomalous Valence Band Structure

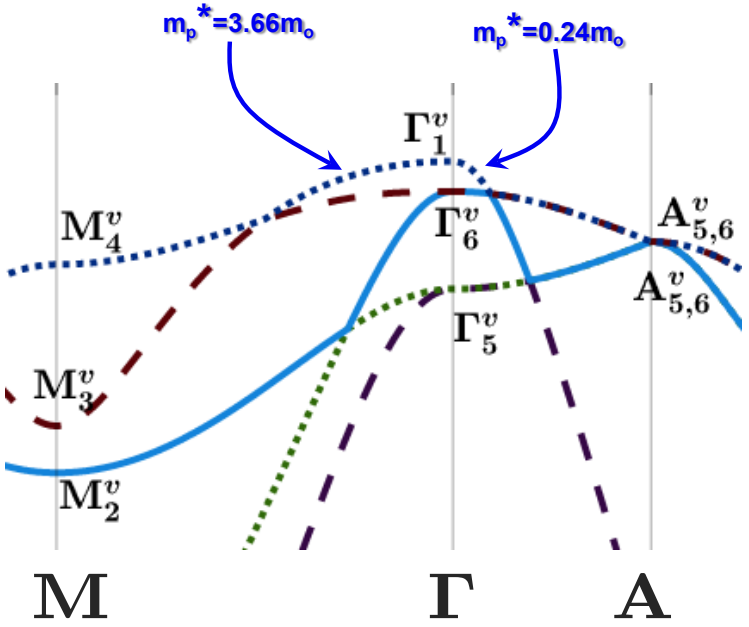
Georgia Tech

- **In contrast to GaN, the highest-lying valence band in AlN is the split-off band, which exhibits smaller effective mass.**
  - **Vertical devices (m_p*=0.24m_o)**
  - **Lateral device (m_p*=3.66m_o)**
- **Results: 0.04 ohm-cm p-type AlN**





DFT Valence Band Structure
(Compliments of Doug Yoder, Ga Tech)



GaN	AlN
μ~1-3 cm^2/V-sec @ p~4x10^{18} cm^{-3}	**μ=30 cm^2/V-sec** @ p=4.4x10^{18} cm^{-3}
$m^*_p \approx 0.8\ m_o$	$m^*_p \approx 0.24\ m_o$
$N_{critical} \approx 4 \times 10^{19}$ cm^{-3}	$N_{critical} \approx 1.2 \times 10^{18}$ cm^{-3}

W. Alan Doolittle, C. M. Matthews, H. Ahmad, K. Motoki, S. Lee, A. Ghosh, E. N. Marshall, A. L. Tang, P. Manocha, P. D. Yoder, APL Perspectives, Appl. Phys. Lett. 123, 070501 (2023)

alan.doolittle@ece.gatech.edu

Growth of Homojunction MME AlN PIN Diode

Georgia Tech

p-contact

200 nm MME AlN:Be 7×10^{18} cm^{-3} at **Tsub=700 °C**

Corresponding hole concentration 1×10^{18} cm^{-3}

200 nm MME AlN:Si 5×10^{17} cm^{-3} at **Tsub=800 °C**

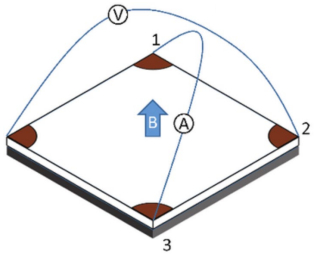
Corresponding electron concentration was unmeasurable by Hall

Corresponding electron concentration 5×10^{17} cm^{-3}

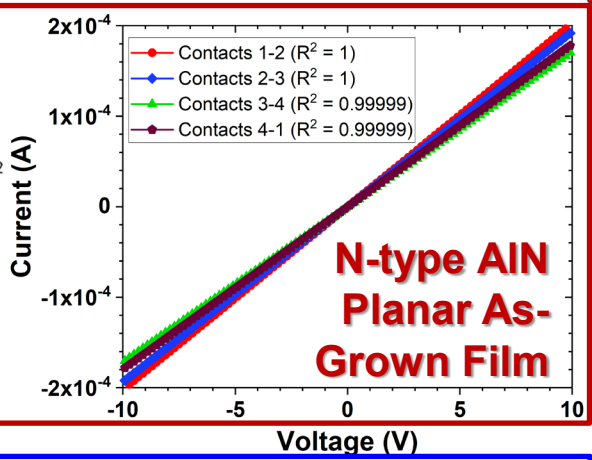
n-contact

1 µm MME AlN:Si 8×10^{18} cm^{-3} at **Tsub=800 °C**

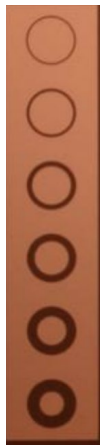
MSES HVPE AlN on sapphire substrate



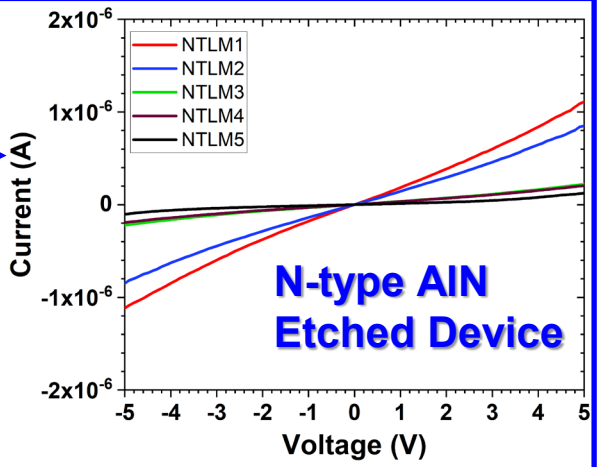
1x1 cm^2 AlN



N-type AlN Planar As-Grown Film



TLM ~10's um

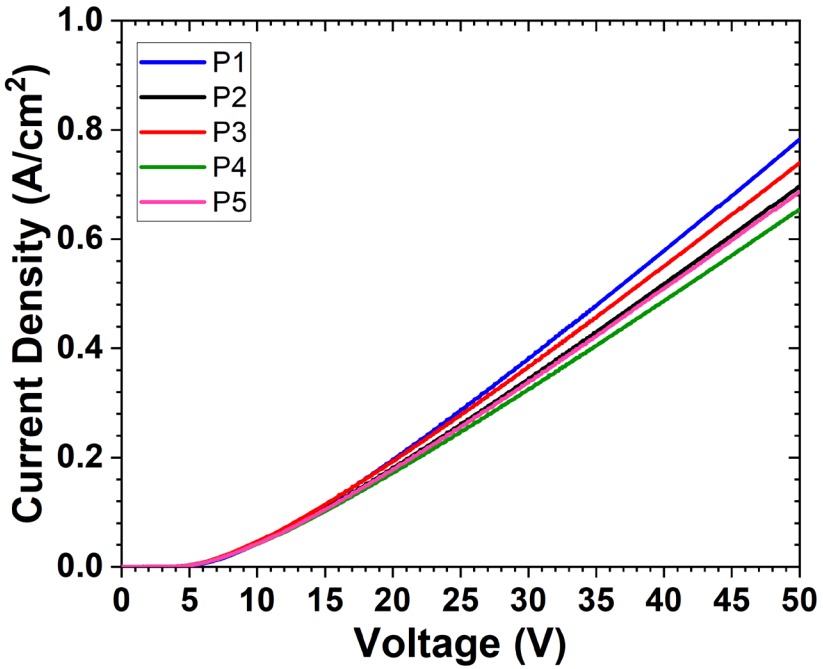


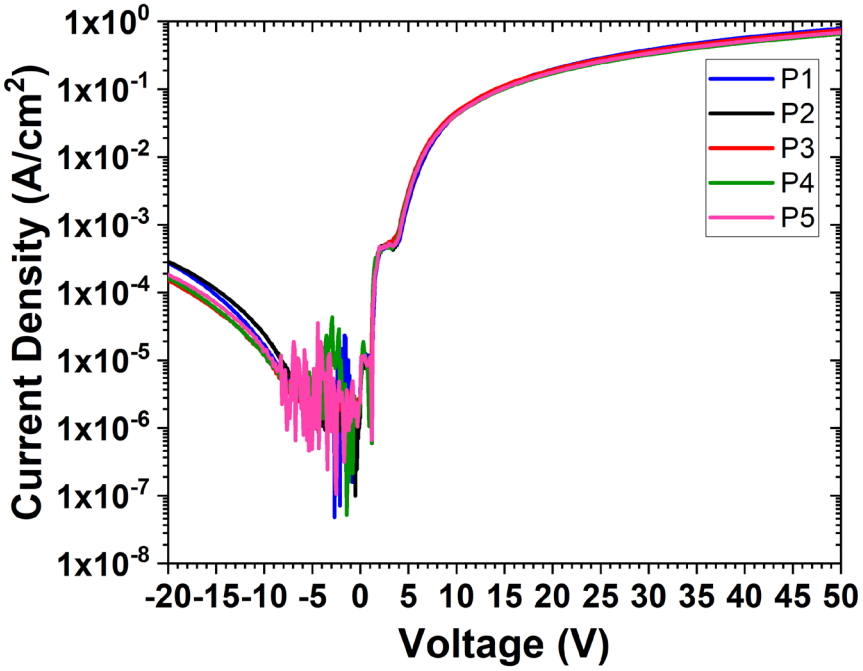
N-type AlN Etched Device

- **The current levels of plasma etched n-type AlN:Si contacts in the PIN diode are lower by 2-3 orders of magnitude than contacts to as grown material.**
- Presumably due to difficulty in making contacts to the plasma damaged AlN films.
- Introduces high series resistance into the device.

First-ever AlN Homojunction Diodes

- ~6-7 orders of magnitude small reverse to large forward rectification is achieved.
- We achieved a nearly ideal turn-on voltage of ~6V for a 6.1 eV semiconductor.
- A high series resistance is also evident by the current density tail on the semilog plot.
- This high series resistance is attributed to the high etched/damaged N-contacts resistance.
- Contacts improvement will further improve the performance of these devices.

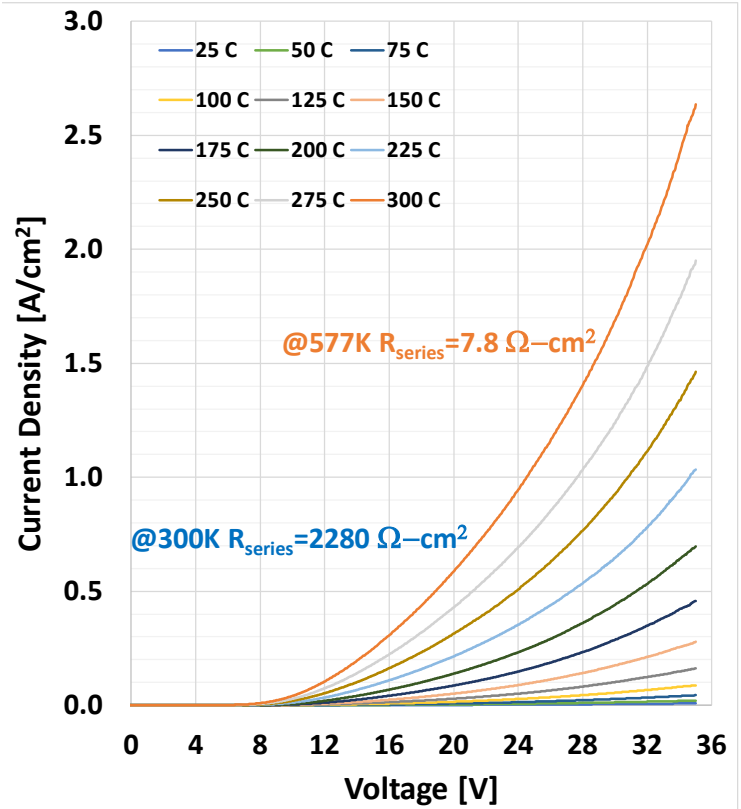


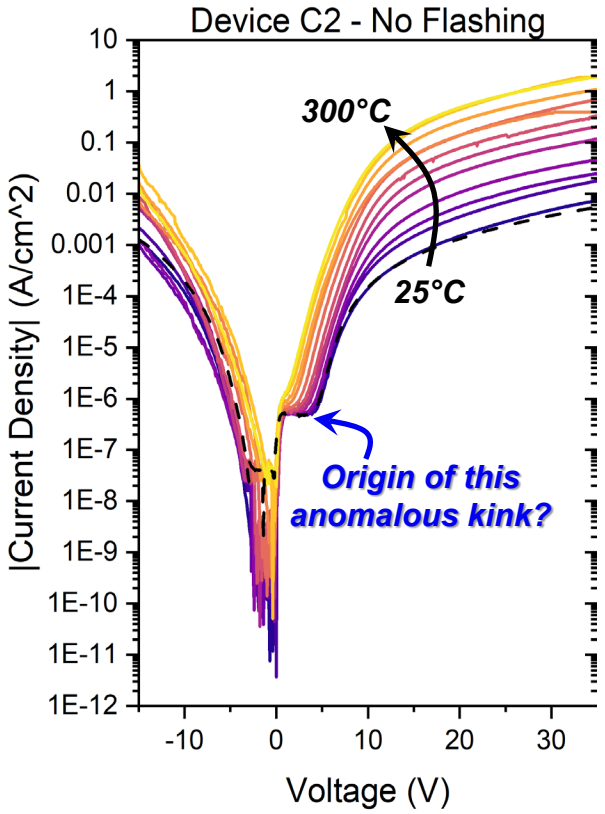


H. Ahmad, Z. Engel, C. M. Matthews, S. Lee, and W. Alan Doolittle, J. Appl. Phys. 131, 175701 (2022)

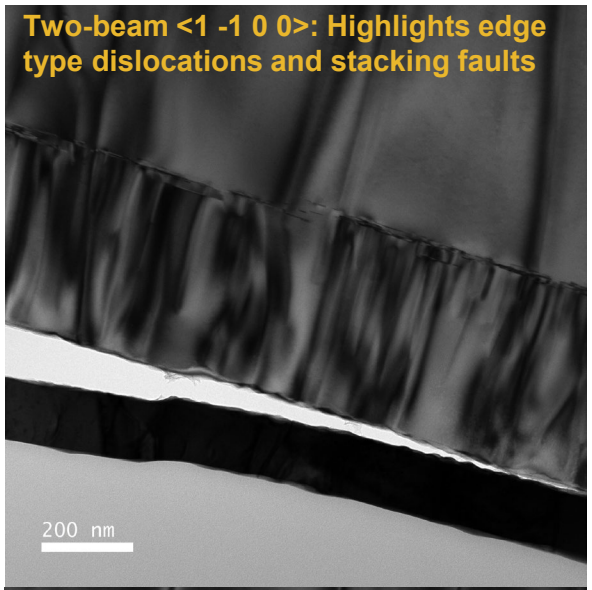
Current-Voltage-Temperature Study Shows improved Performance at ~575ºK

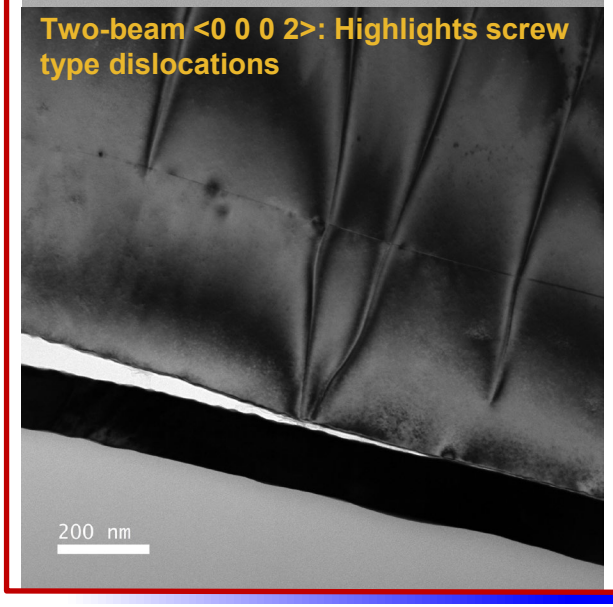
- Diodes show improved IV at higher temperature
  - Series resistance dominates IV but reduces by 70x
  - Exponential IV after turn on
- Current Density is greater than 2.8 A/cm^2



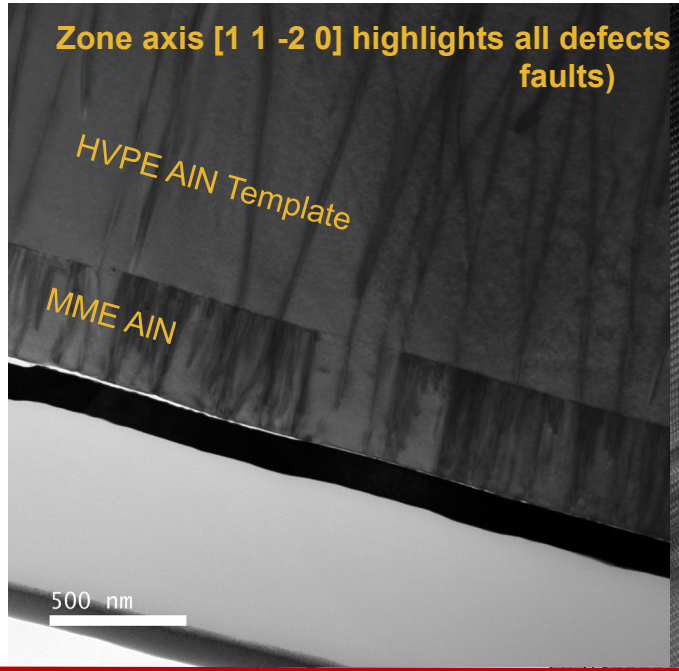


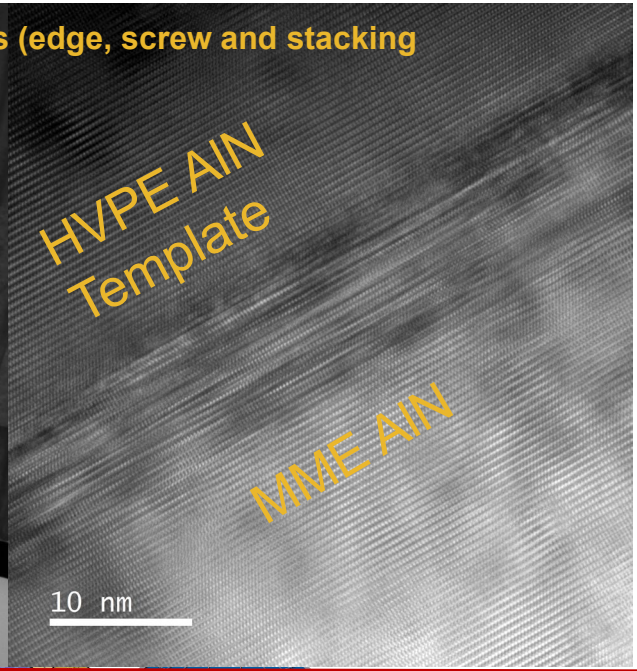
Initial Growths: Source of and Solution for Non-Ideal IV





Al-Oxide related contamination result in interfacial stacking faults and edge dislocations lowering crystal quality

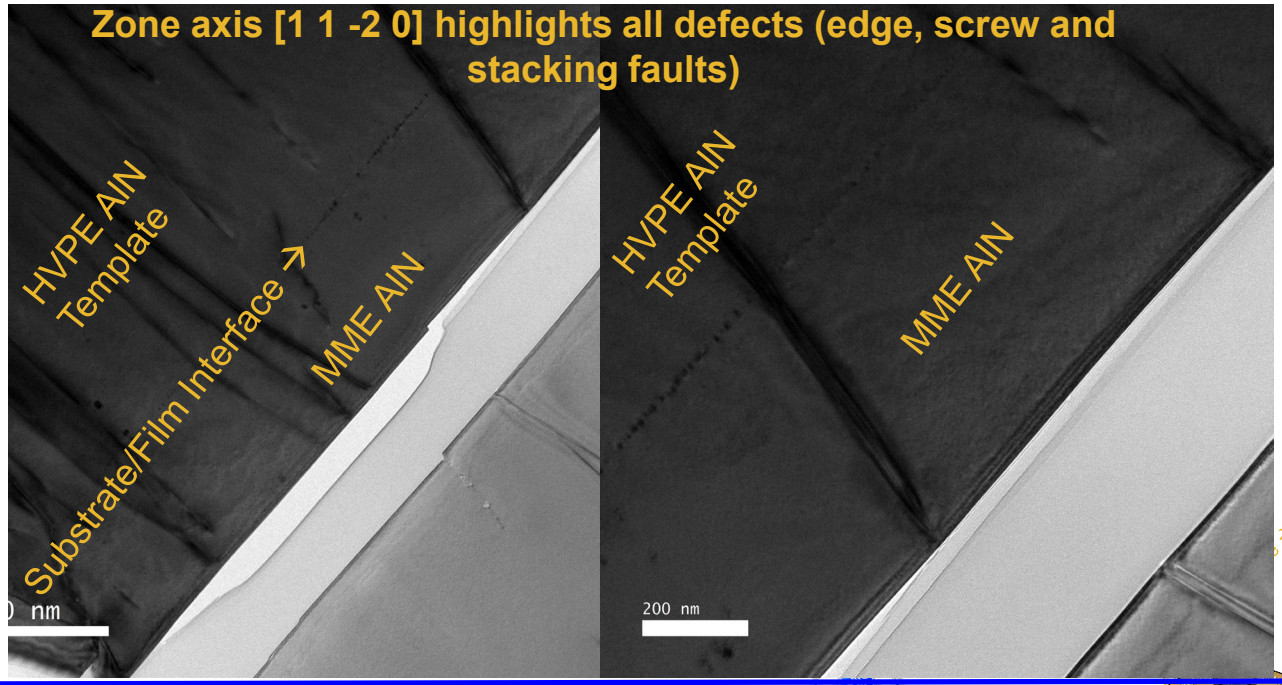


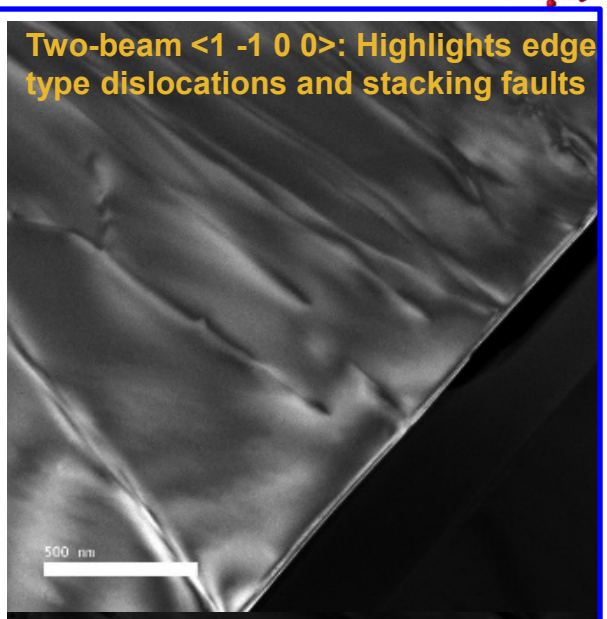


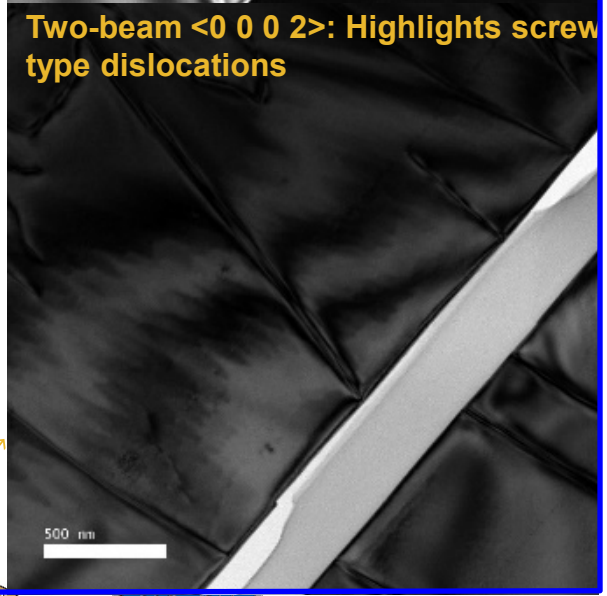
Improved Growths: Solution for Non-Ideal IV

Georgia Tech

Flashing removes all oxygen related stacking faults and results in duplication of the template's crystal quality



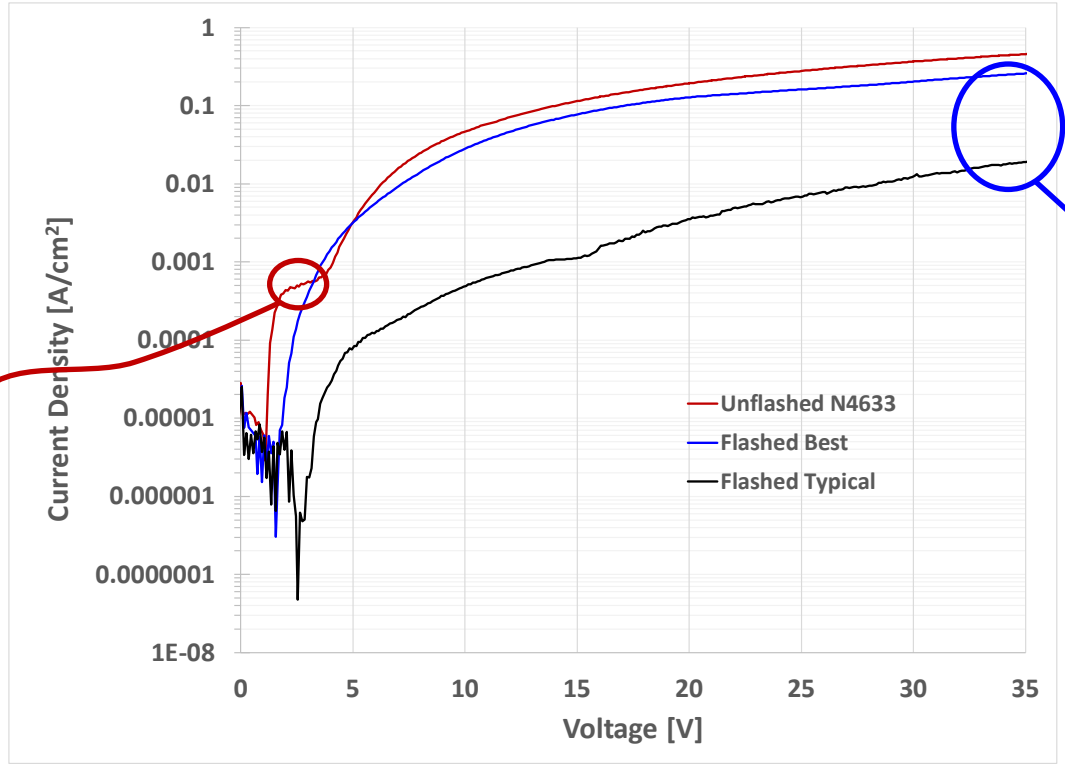


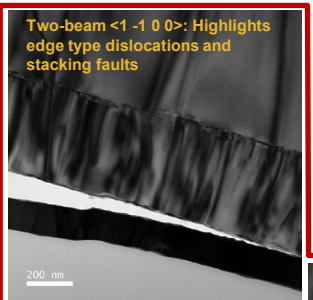


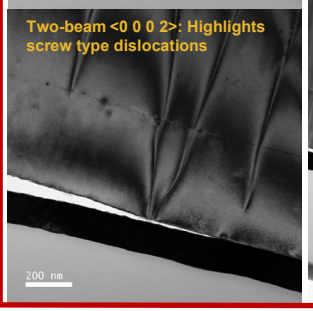
Source of and Solution for Non-Ideal IV

Georgia Tech

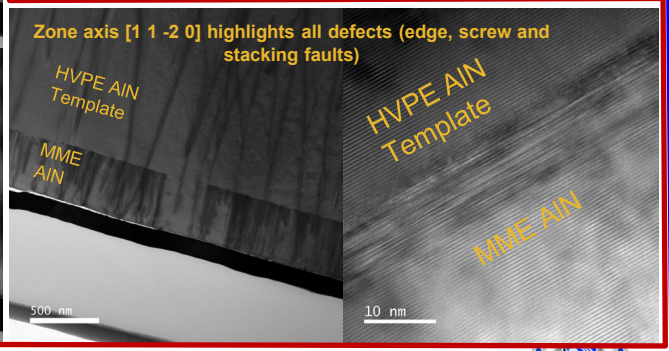
- **Metallic aluminum cleaning drastically reduces defect density.**
  - **Virtually eliminates stacking faults and thus, edge dislocations.**
  - **No increase in screw dislocations**
  - **Improved forward IV**



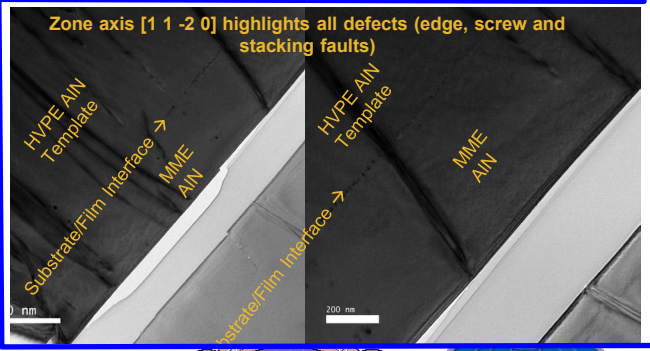


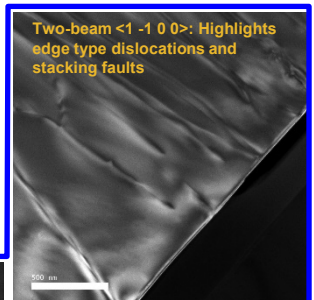


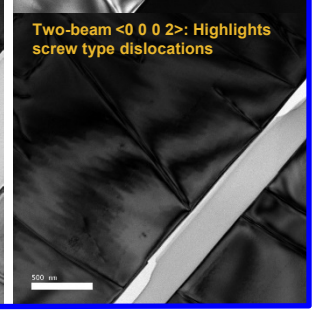
Al-Oxide related contamination results in interfacial stacking faults and edge dislocations lowering crystal quality



Flashing removes all oxygen related stacking faults and results in duplication of the template's crystal quality



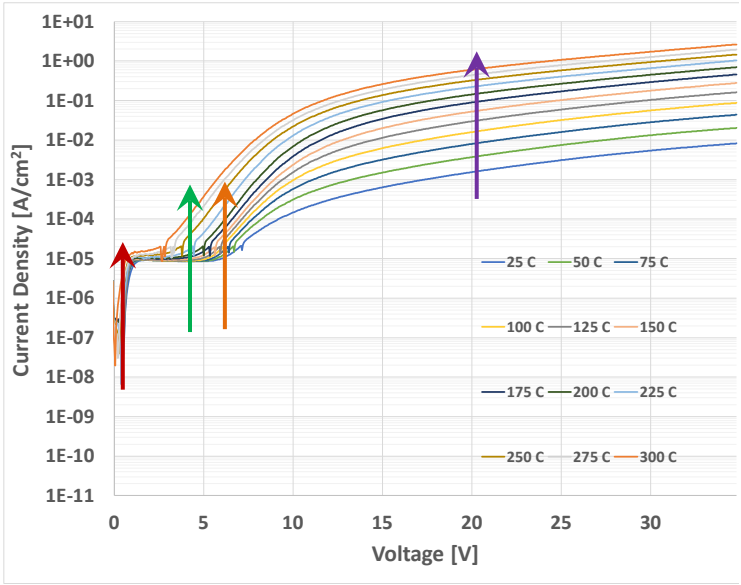


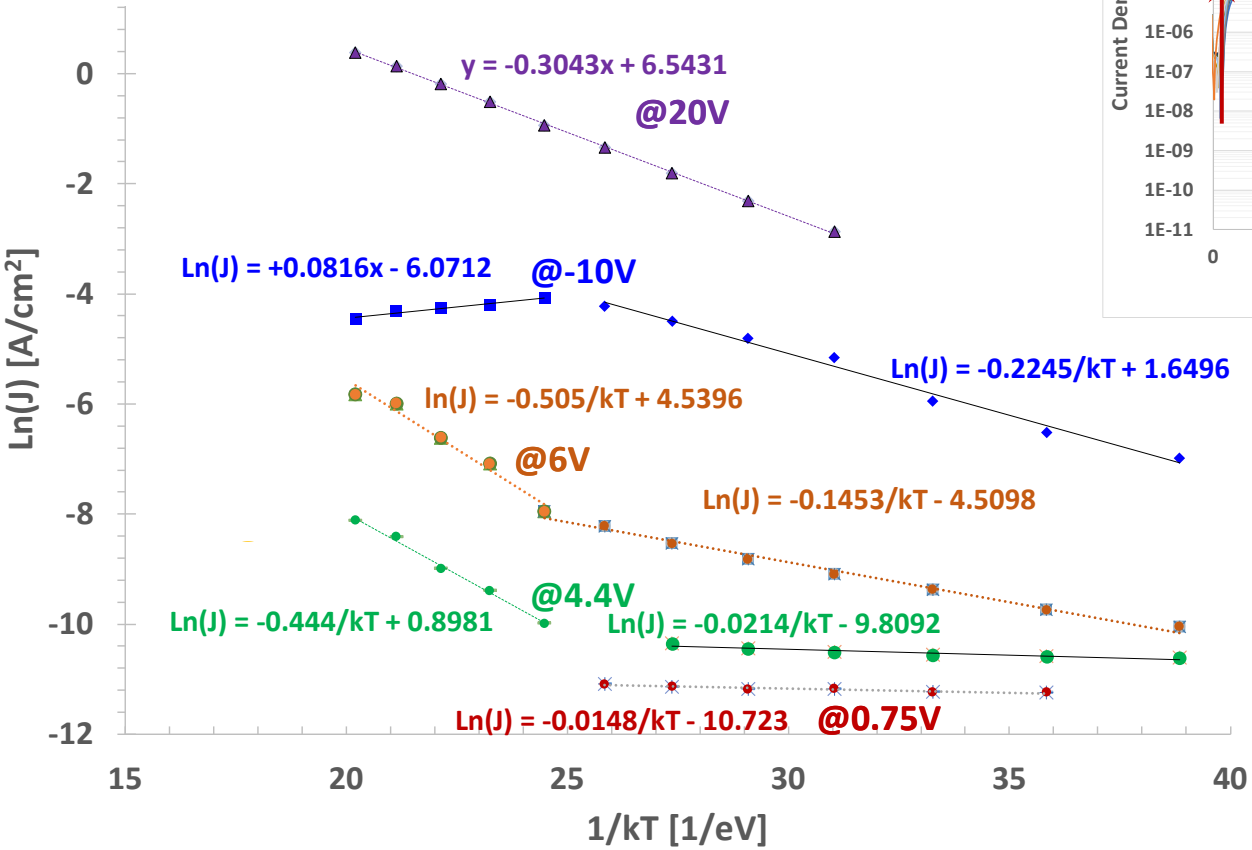


alan.doolittle@ece.gatech.edu

Current-Voltage-Temperature Study Shows Improved Performance at ~575ºK

- Dominant current mechanisms:
  - Possibly tunneling at low voltage
  - Thermionic via defect/impurity character around turn on
    - Two separate activation energies below and above 200º C
  - Series resistance E_A=0.3 eV

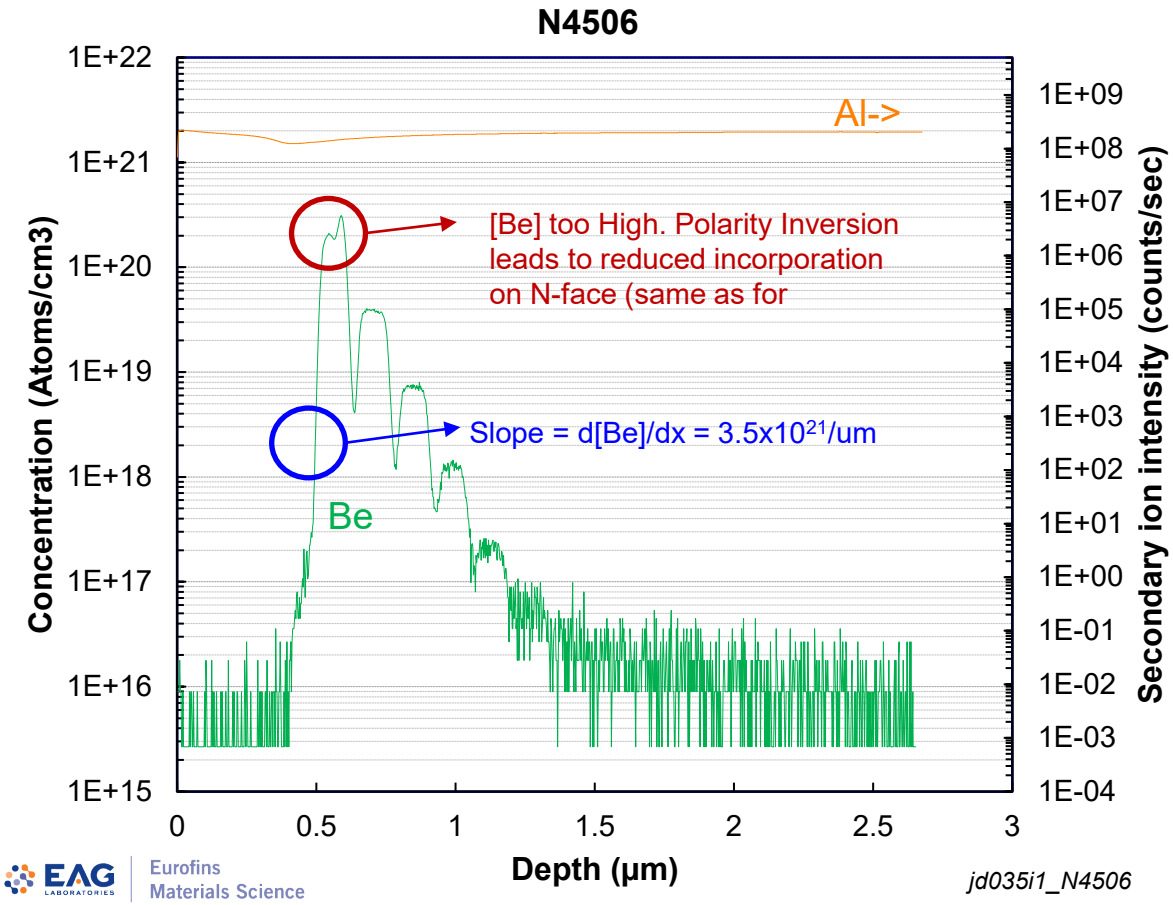




alan.doolittle@ece.gatech.edu

Be Solubility and Abrupt Profile Control

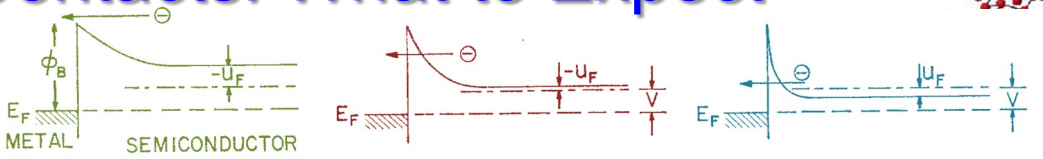
- Be solubility in AlN seems to be ~10^{20} cm^{-3}
- Be can be accurately placed with no surface accumulation for MME (not true for MBE)
- Similar (slightly higher) values expected for Si (solubility limit not yet reached)

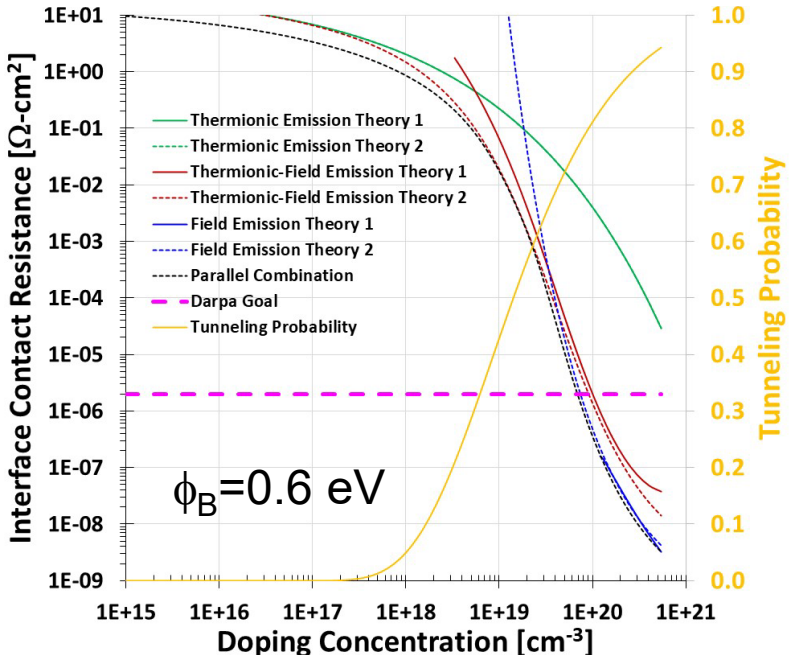


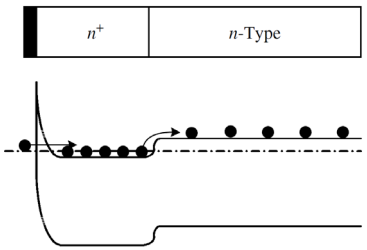
alan.doolittle@ece.gatech.edu

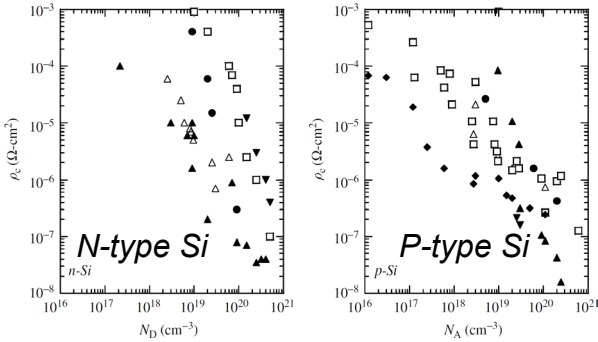
Modeling AlN Contacts: What to Expect

- Planar transistor ohmic contacts are more straight forward than quasi-vertical devices.
- Plasma etched contacts are atrocious and may offer a clue as to what is making the doping work.
- Electron Affinity Model (EAM) is a guide and not always valid.
  - Predicts difficulty for n-type AlN since AlN has an electron affinity <2 eV.
  - The measured AlN electron affinity has not been measured in doped AlN.
  - Surface oxides complicate the known values of the electron affinity.
- Contacts (Ti for example) often introduce a n+ region to facilitate Thermionic-Field Emission
- In practice, Field-Emission is not reached in many wide bandgaps (requires >10^{20} cm^{-3} doping).
- Literature reports of UWBG Contact Resistance < 10^{-6} Ω-cm^2 are questionable and can only be possible with non-standard means.





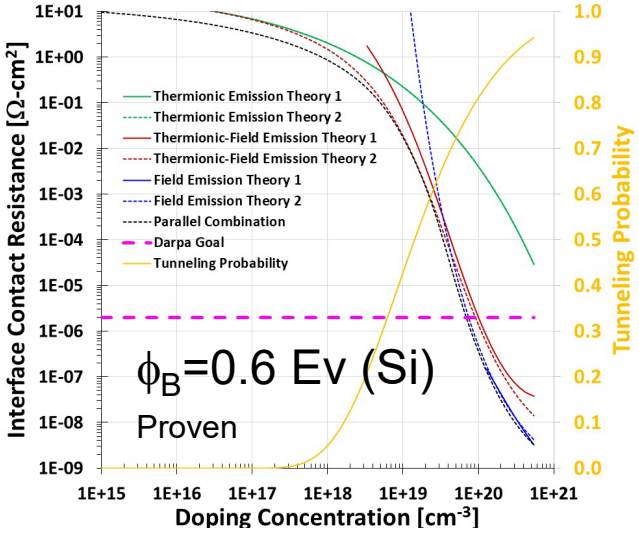


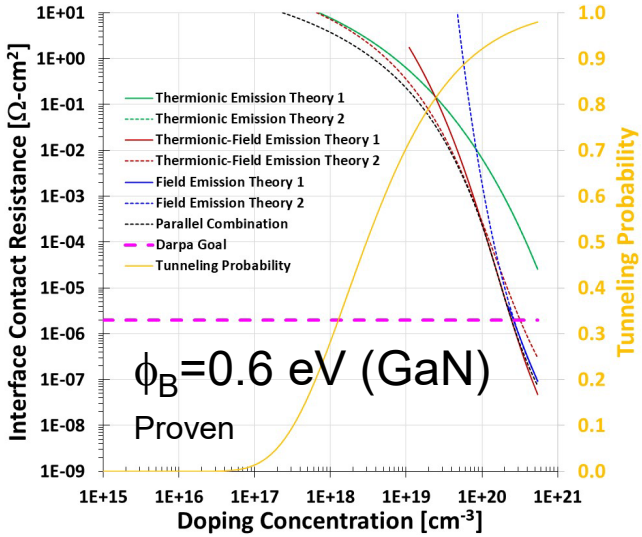


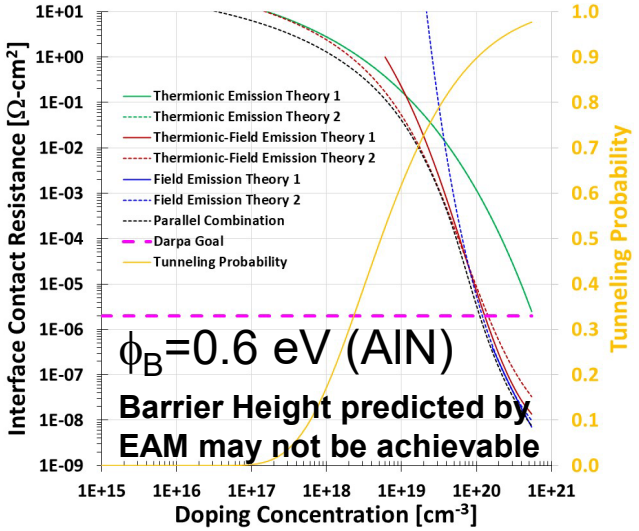
Si images after Schroeder

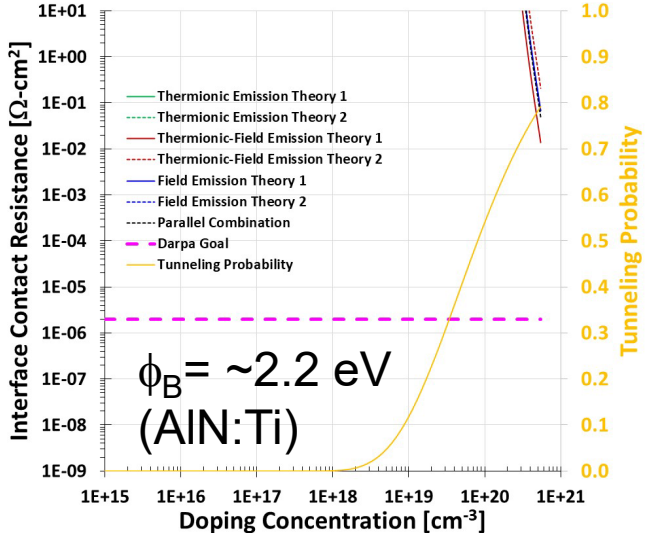
Modeling AlN Contacts: To Achieve DARPA Goals, High Doping and Non-Standard Approaches are Likely to Be Needed

- Doping and barrier height dominates over other all other material parameters when determining contact resistance.
- As bandgap increases, the EAM suggests DARPA goal is challenging.
- Solutions exist but require non-standard approaches.





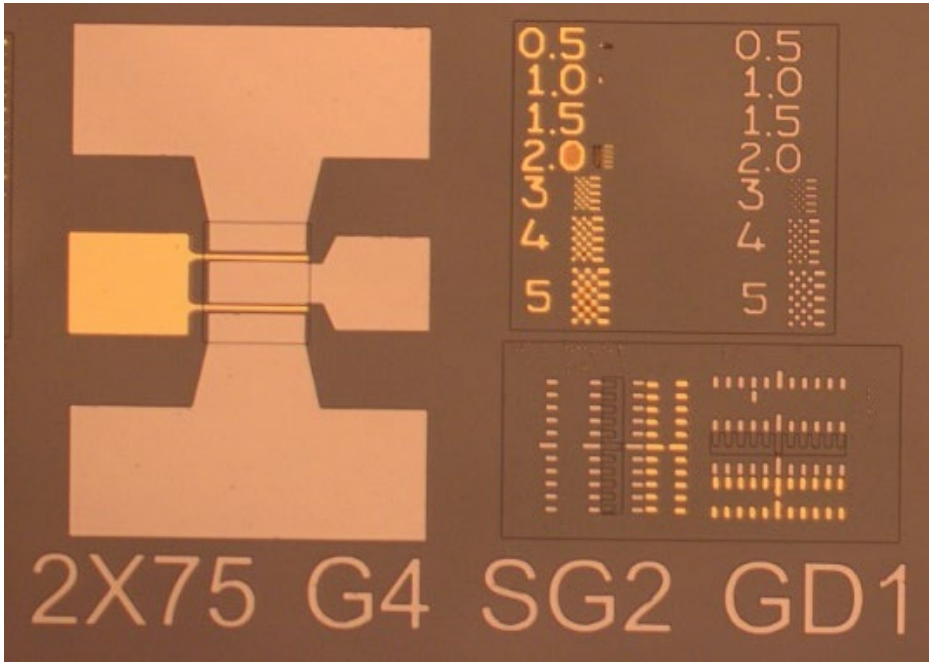




alan.doolittle@ece.gatech.edu

Progress Toward an AlN Transistor

- **New contact strategies being addressed**
  - **356 mA/mm for n-type AlN @ 10V**
  - **37 mA/mm for p-type AlN @ 30V**
- **Fabrication limited not fundamentally limited**

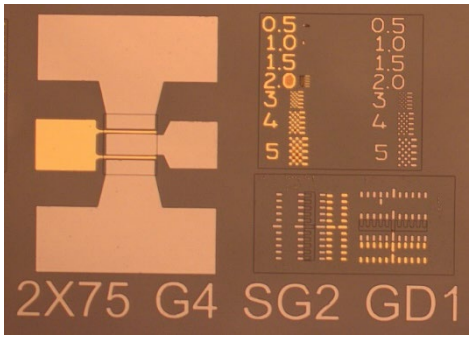


Georgia Tech

Summary

Conclusions

- Low temperatures are a viable option for synthesis of AlN devices
  - Less thermal expansion limits DX centers
  - Lower outgassing of compensating impurities
  - Compatible with dopants that can lower strain and decrease interstitial formation



- Device quality and State-of-the-Art Devices have been produced
  - p-type AlN – $p=4.4\times10^{18}$ cm^{-3}!
  - First AlN PIN Diodes!
  - 6000x improvement in n-type AlN
  - $n= 1\times10^{15}$ cm^{-3} → 6×10^{18} cm^{-3}!
- The Electron Affinity Model predicts difficulty for good ohmic contacts to UWBGS
- But creative solutions exist…

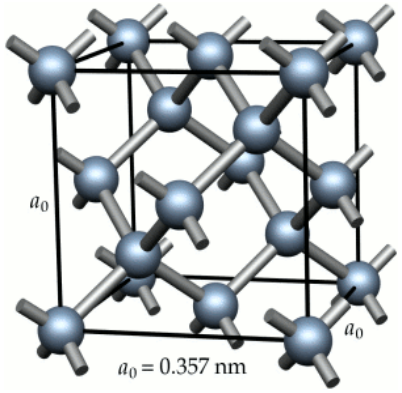
Doping and Low Resistance Contacts on Diamond and c-BN

Robert J. Nemanich, Franz A. Koeck, Terry Alford, Stephen Goodnick, David Smith, Trevor Thornton

Arizona State University

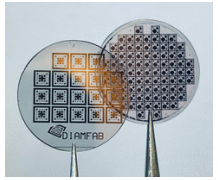
In collaboration with Northrop Grumman Corp.

Diamond Cubic

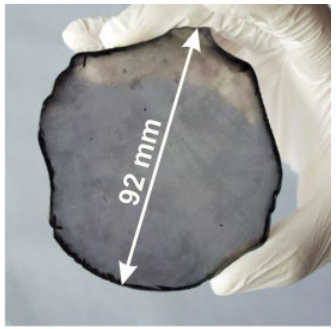


- sp^3 bonded carbon
- C – 6e
- Diamond Cubic

  a = 3.57 Å

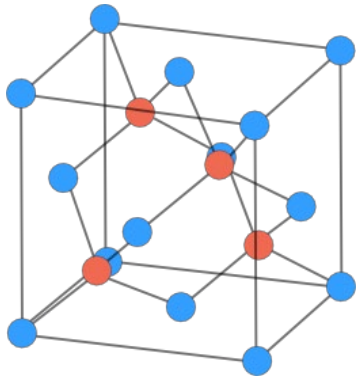


DiamFab



Augsburg Univ.

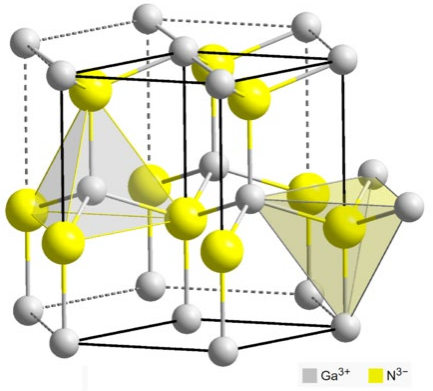
Cubic Boron Nitride (c-BN)



- sp^3 bonded BN
- B - 5e; N – 7e
- Zinc Blende

  a = 3.62 Å[2]

Wurtzite AlN ($B_xAl_{1-x}N$)



- sp^3 bonded Al-N
- Al - 13e; N – 7e
- Wurtzite structure
- a = 3.11 Å
- c = 4.93 Å



HexaTech
50 mm

G. L. Doll, J. A. Sell, C. A. Taylor II, and R. Clarke, Phys. Rev. B, **43**, 6816 (1991).

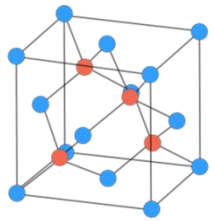
Wide Bandgap Properties

		Si	4H-SiC	GaN	Ga_2O_3	Diamond	c-BN	AlN
Bandgap	Eg (eV)	1.1	3.3	3.4	4.8	5.5	6.4	6.2
Electron Mobility	μ (cm^2 V^{-1} s^{-1})	1450	950	1200	300	4500	800	400
Hole Mobility	μ (cm^2 V^{-1} s^{-1})	430	120	200	<100?	3800	200	<100?
Electron Saturation vel	v_s (x 10^7 cm/s)	1.0	2.0	2.5		1.5		
Hole Saturation vel	v_s (x 10^7 cm/s)	0.4	1.0	1.7		1.1		
Breakdown Field	E_b (MV cm^{-1})	0.3	2.5	3.3	8	10	>10	>10
Rel. Diel. Constant	ε	11.8	9.7	9.0	10	5.5	7.1	8.5
Thermal Conductivity	W cm^{-1} K^{-1}	1.5	4.9	2.3	0.2	22 (30 for ^{12}C)	13	3.2

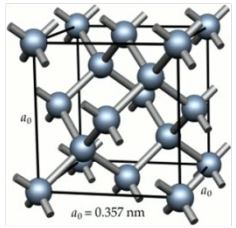
Wide Bandgap Semiconductor Properties



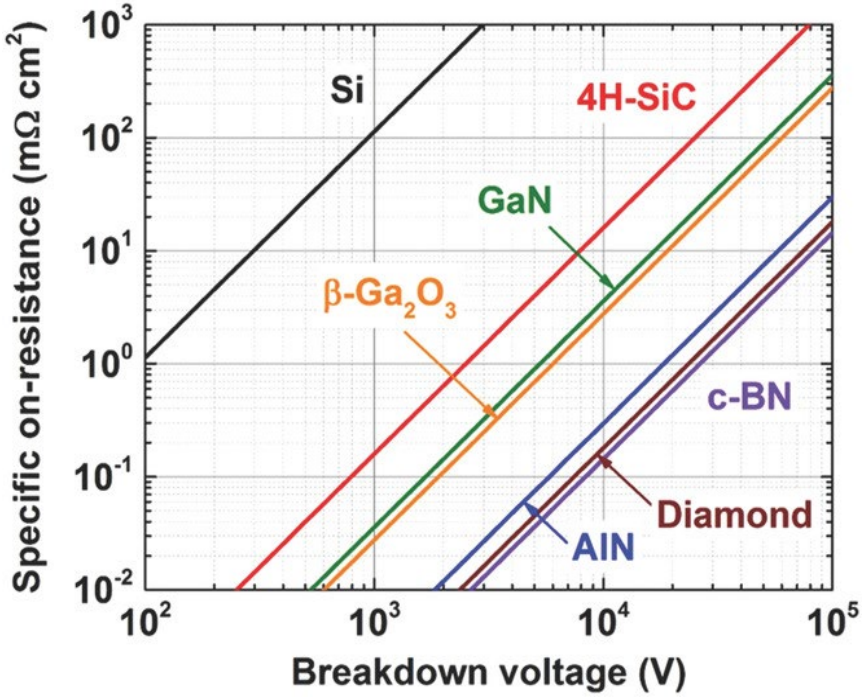
Wurtzite AlN

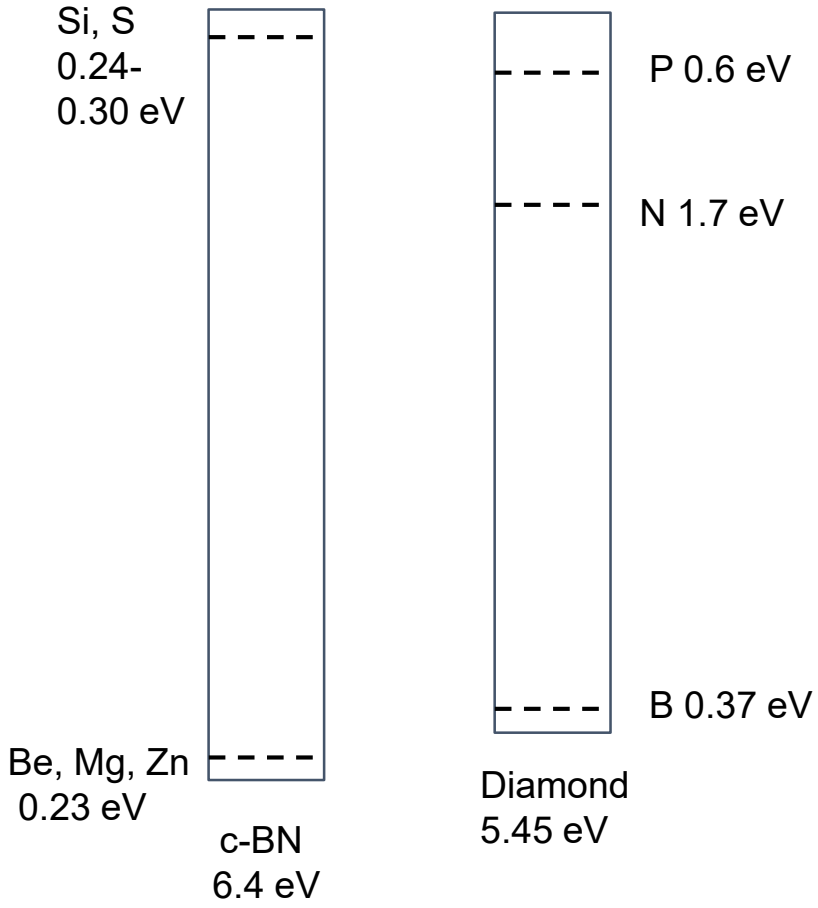


Cubic boron nitride (c-BN)



Diamond Cubic



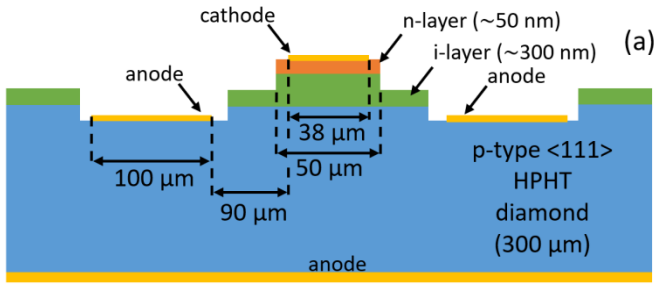


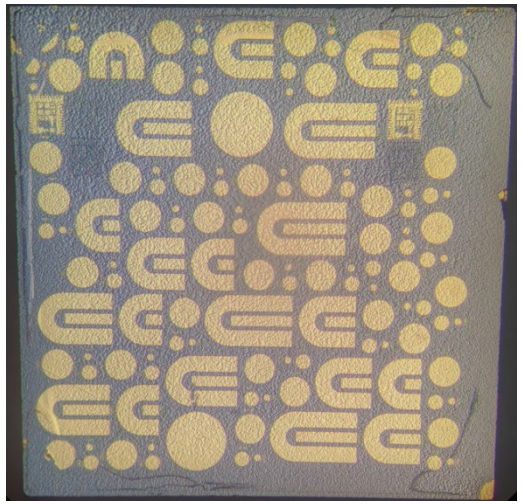
Interface character:
cubic/hexagonal,
covalent/ionic,
polar/non-polar

J. Tsao et al., Adv. Electron. Mater. 2017, 1600501. DOI: 10.1002/aelm.201600501

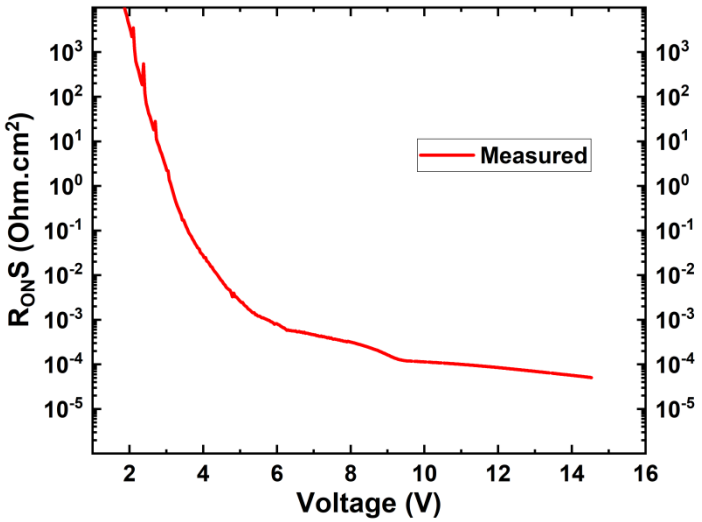
Diamond for High Power Applications

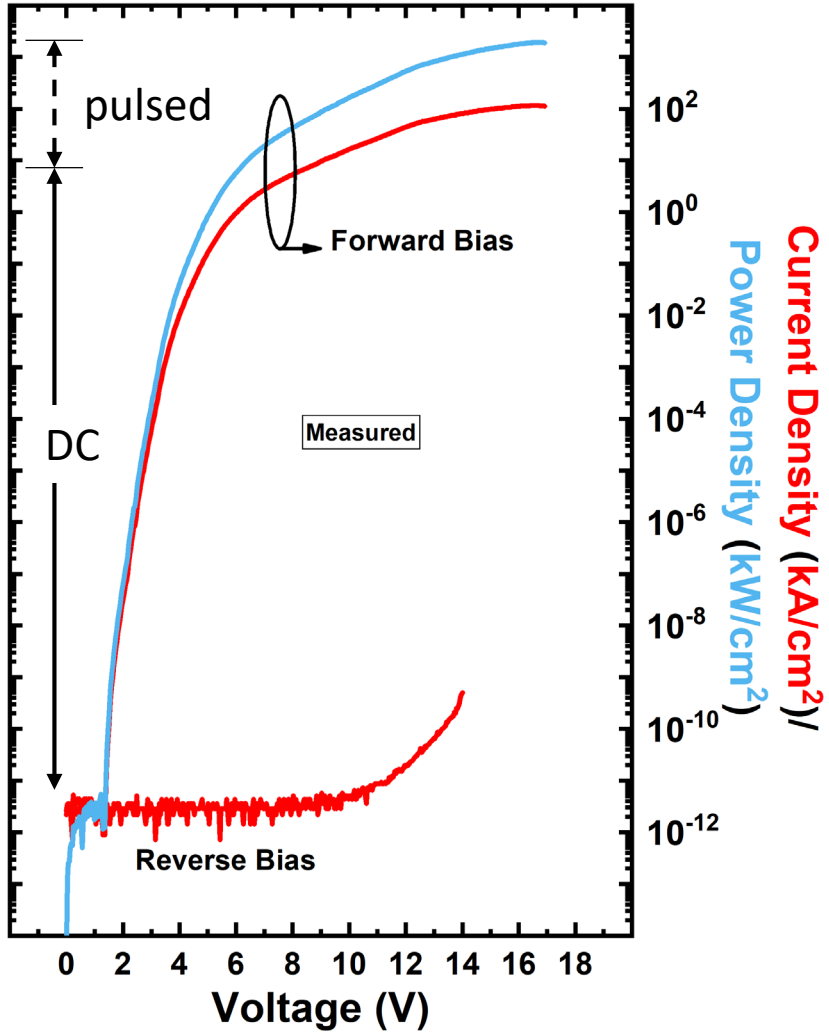
Pseudo-Vertical Diamond SPIND





- $I_{MAX} = \sim 1.35\ A$
- $J_{MAX} = \sim 116\ kA/cm^2$
- $I_{ON/OFF} = 6 \times 10^{12}$
- Maximum Power = $\sim 1.9\ MW/cm^2$
- Minimum $R_{ON}S$ $= \sim 5 \times 10^{-5} \Omega.cm^2$



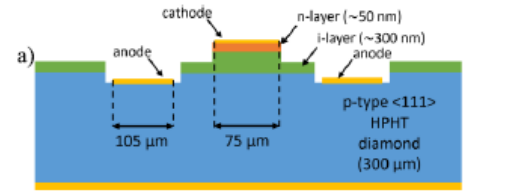


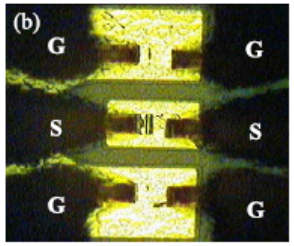
H. Surdi et al., IEEE Trans. Elect. Dev. 69, 254 (2022)

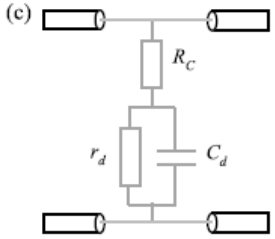
RF Characterization of Diamond Schottky p-i-n Diodes for Receiver Protector Applications

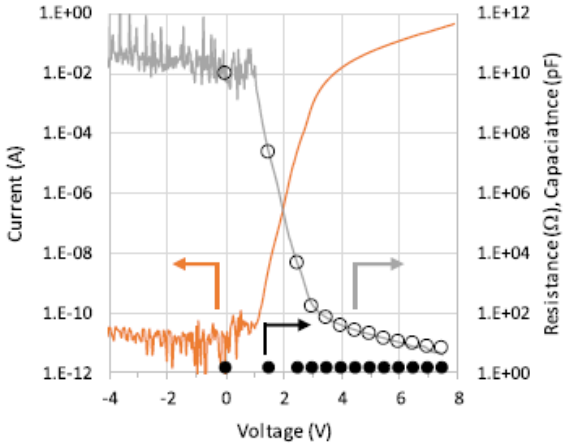
Harshad Surdi, Mohammad Faizan Ahmad, Franz Koeck, Robert J. Nemanich, Stephen Goodnick , and Trevor J. Thornton

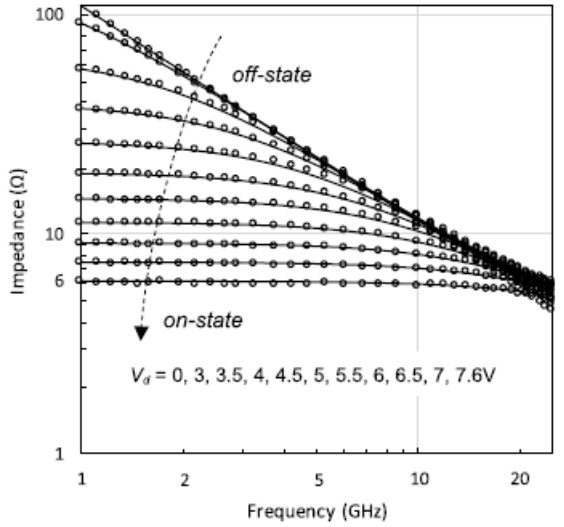
IEEE Microwave and Wireless Components Letters 30, 1141 (2020)









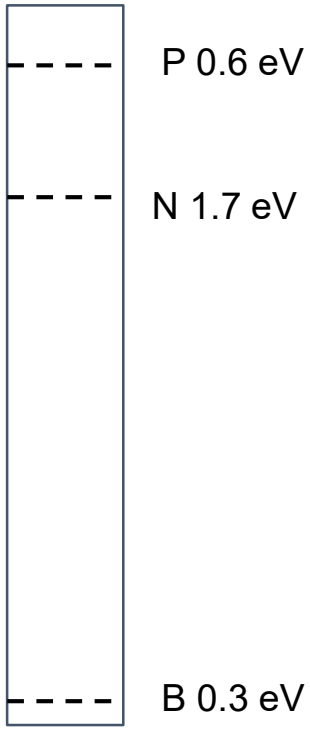


COMPARISON OF P-I-N DIODE LIMITERS USING DIFFERENT MATERIAL SYSTEMS

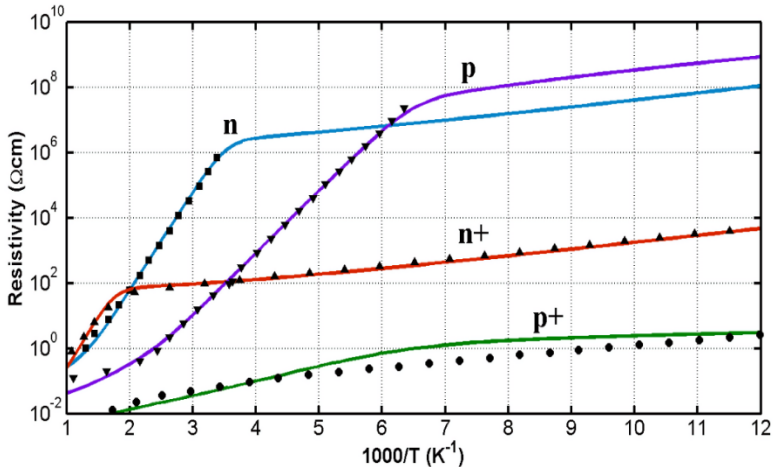
Ref.	Material System	Thermal Conductivity (W/cm-K)	Frequency (GHz)	Insertion Loss (dB)	Maximum Return Loss (dB)
[14]	Silicon	1.5	8 - 18	< 2	> 40
[15]	GaAs	0.46	10	0.8	25
This work	Diamond	30	1	0.3	19

Substitutional Doping:
n-type Diamond using Phosphorus

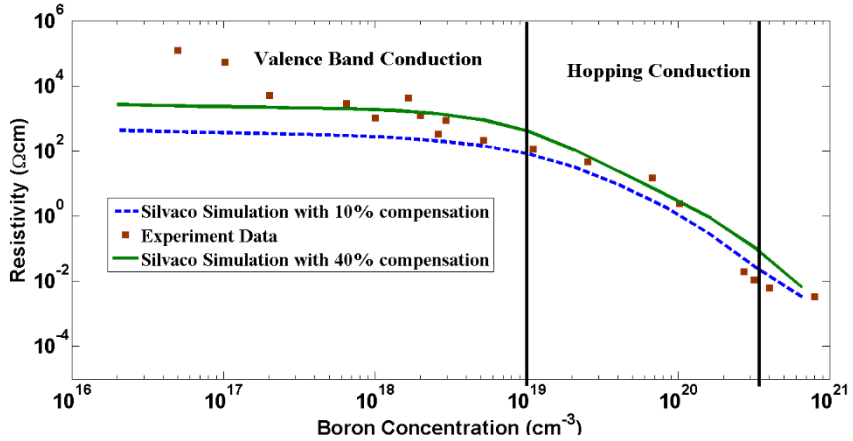
Diamond Doping

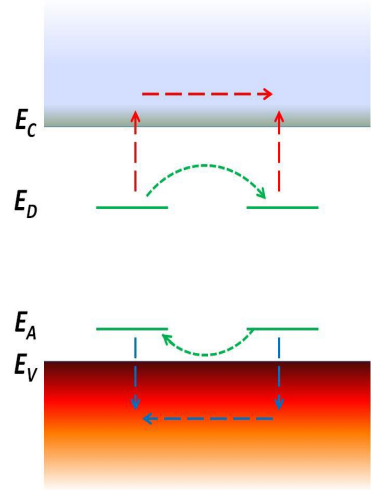


Diamond Bandgap 5.45 eV



1×10^{18} cm^{-3}
1×10^{18} cm^{-3}
8×10^{19} cm^{-3}
2×10^{20} cm^{-3}

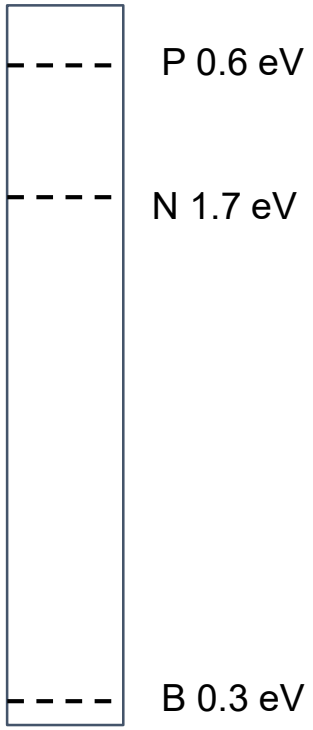




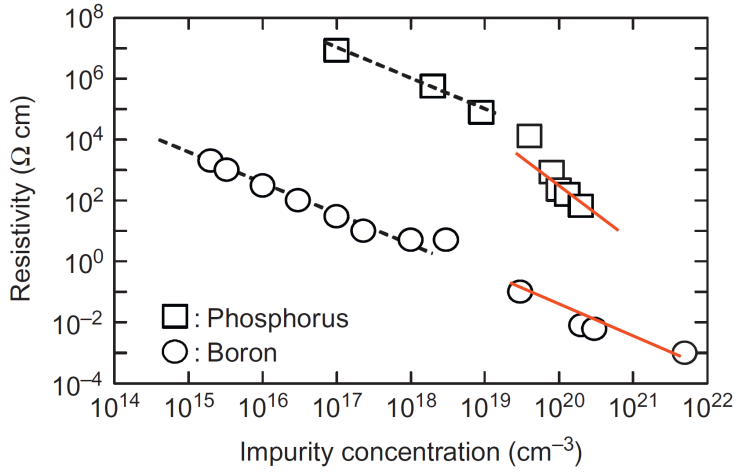
P-doping nearest neighbor hopping
B-doping variable range hopping

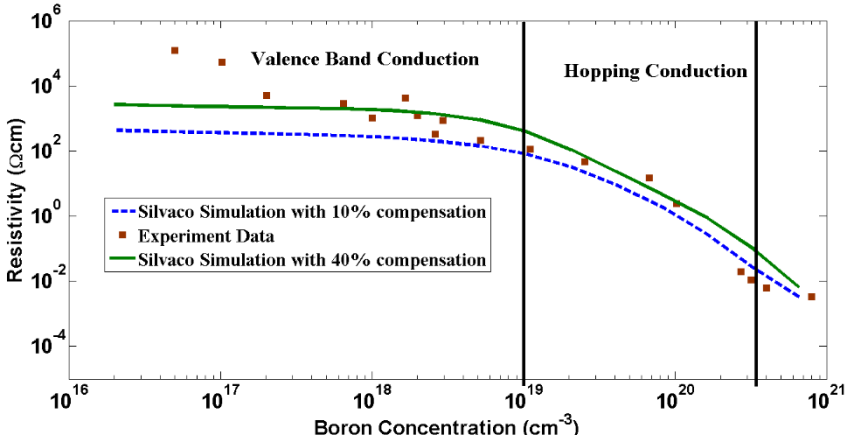
*K. Oyama, et al, APL **94**, 152109 (2009)
Hathwar et al., J. Appl. Phys. 119, 225703 (2016)

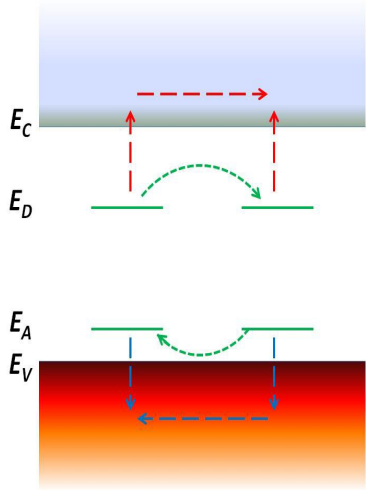
Diamond Doping



Diamond Bandgap 5.45 eV



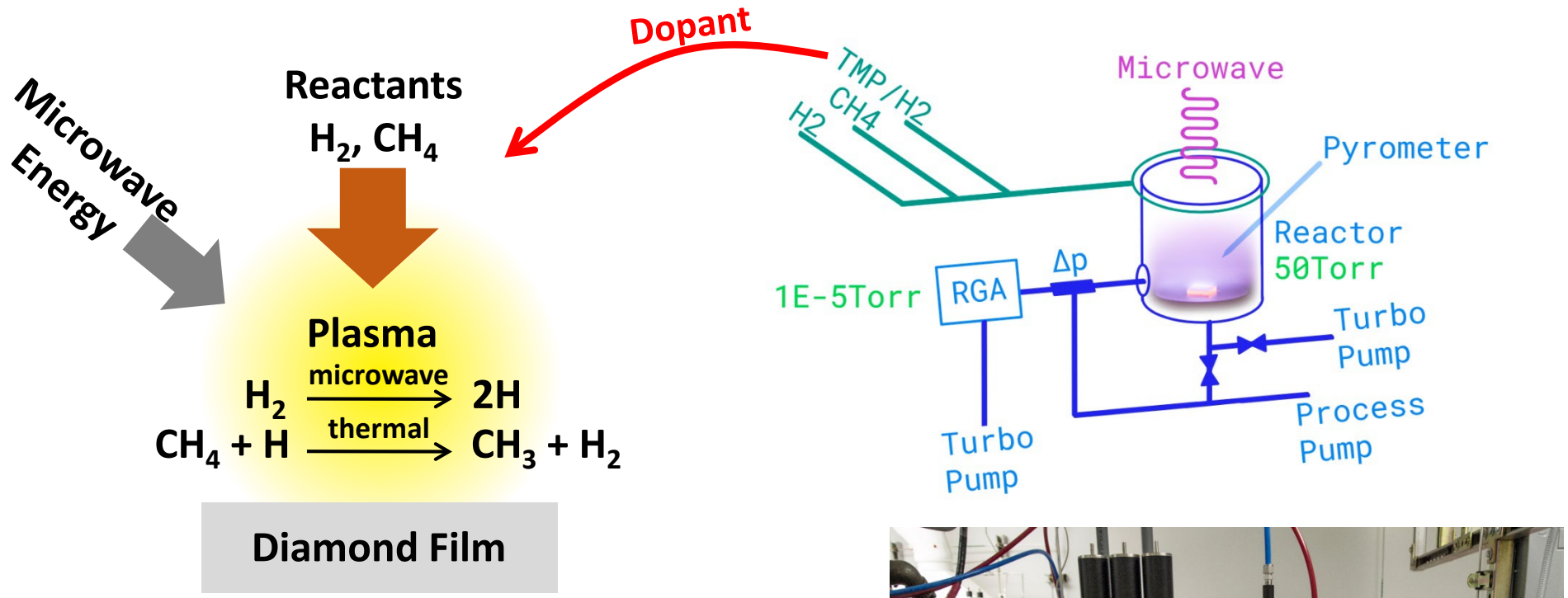


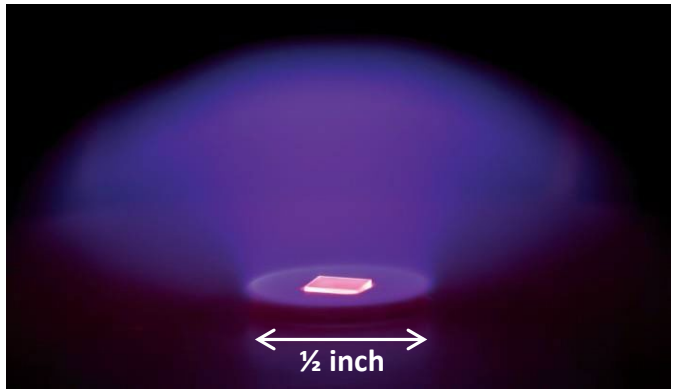


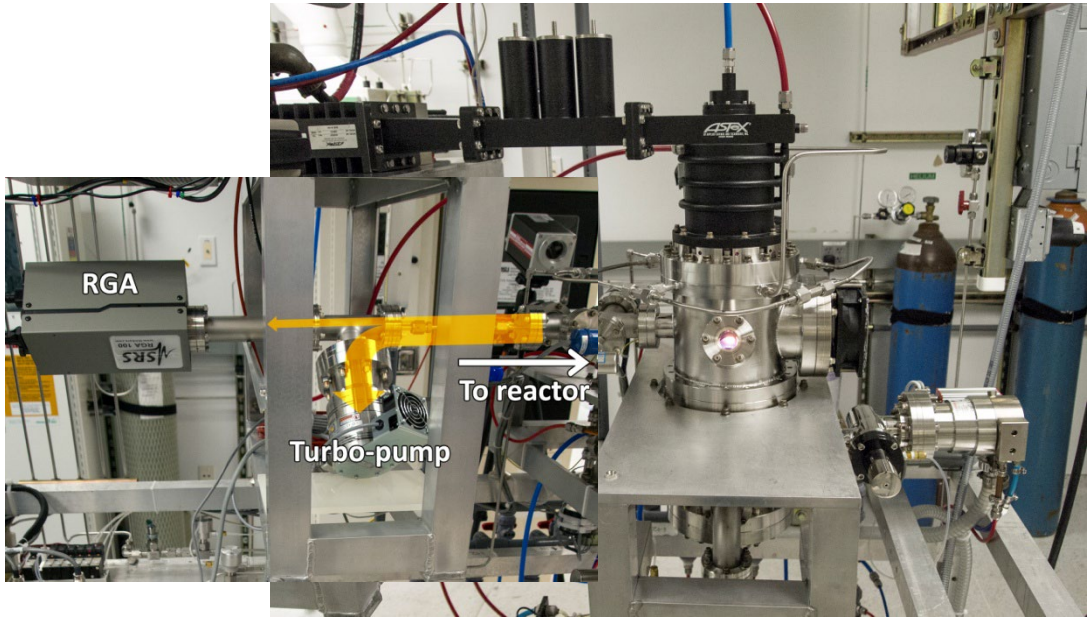
P-doping nearest neighbor hopping
B-doping variable range hopping

H. Kato et al., Diam Relat Mater. 27, 19 (2012)
Hathwar et al., J. Appl. Phys. 119, 225703 (2016)

Materials Enabled by Plasma Enhanced Chemical Vapor Deposition (PECVD)







Microwave plasma enhanced CVD for n-type, phosphorus doped diamond

Growth Challenges:

- **Separate control of temperature and plasma power (sample holder design*)**
- **Control the active species at the surface (in situ RGA)**
- **Reduce impurities (compensation)**
- **Surface morphology:**

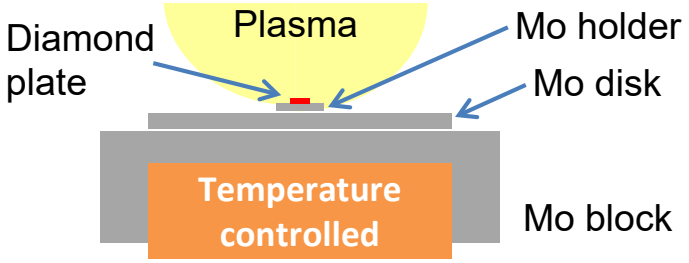
  Starting surface

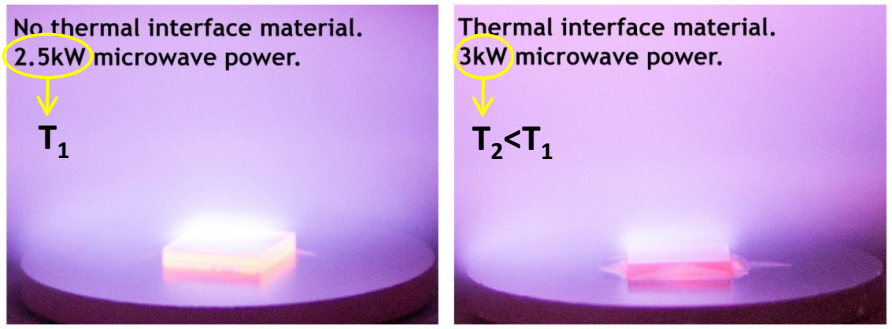
  Step flow growth (off axis sample)

Approach:

***In situ* RGA, pyrometer, and OES**

***Ex situ* SIMS, optical microscopy, TEM**

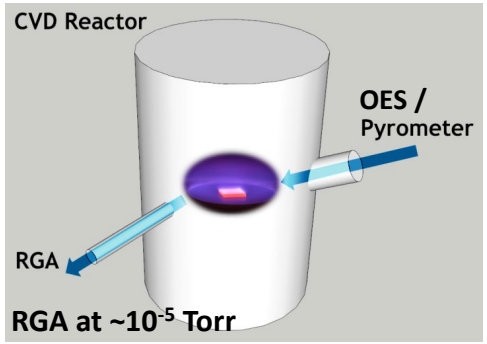




Separate plasma power and substrate temperature (T_n).

*Koeck, Franz A., and Robert J. Nemanich. "Sample stage/holder for improved thermal and gas flow control at elevated growth temperatures." U.S. Patent 10,704,160, issued July 7, 2020.

Materials Enabled by Plasma Enhanced Chemical Vapor Deposition (PECVD)

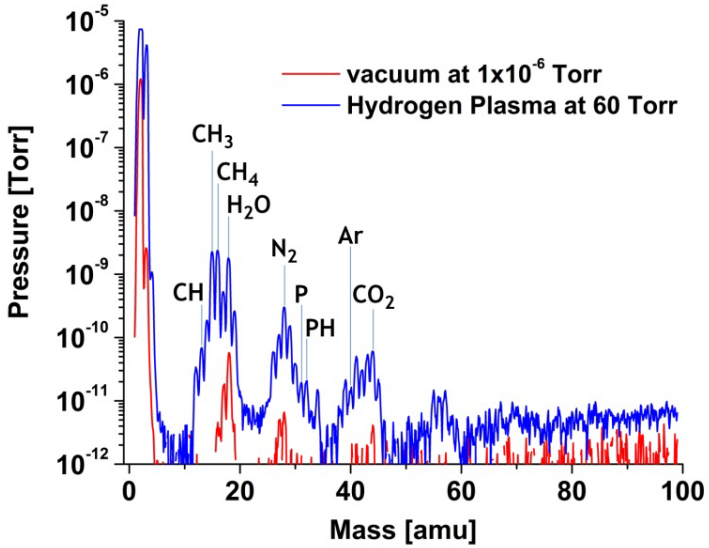


Establishing impurity background levels (N)

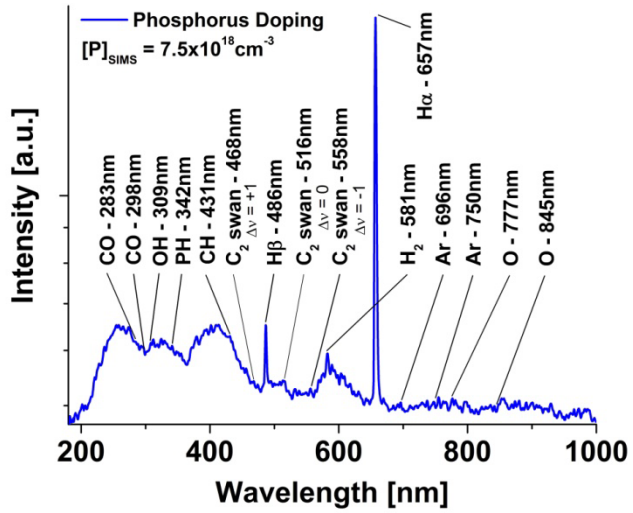
Fast response (~second) for time resolved characterization of growth species ↔ comparison with OES

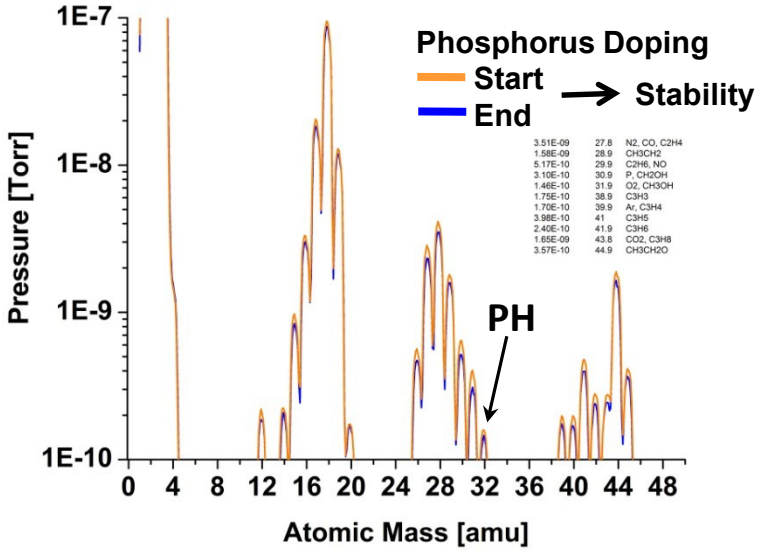
Important for controlling the doping gradient /profile

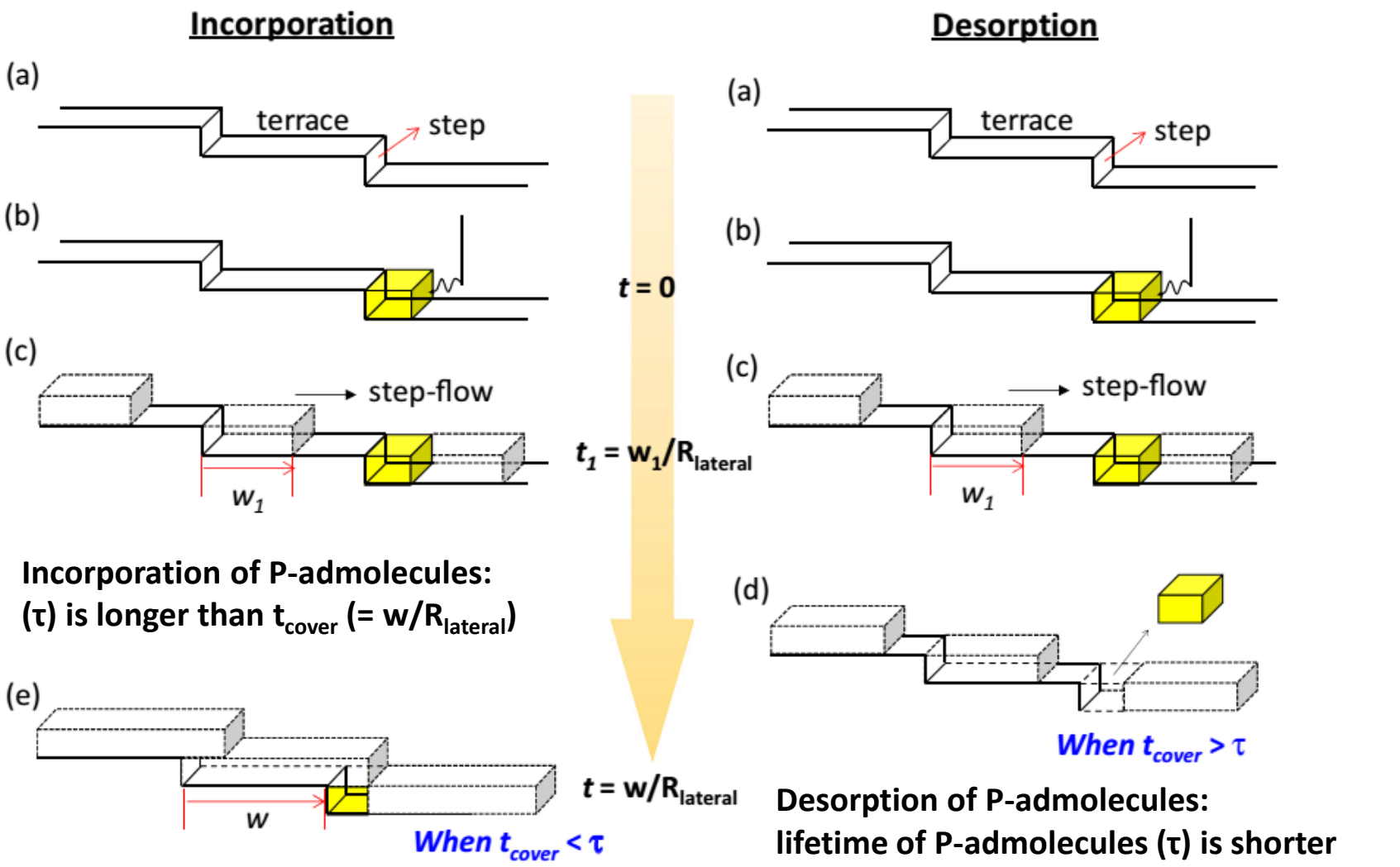
In situ characterization for PECVD



Optical Emission Spectroscopy (OES)





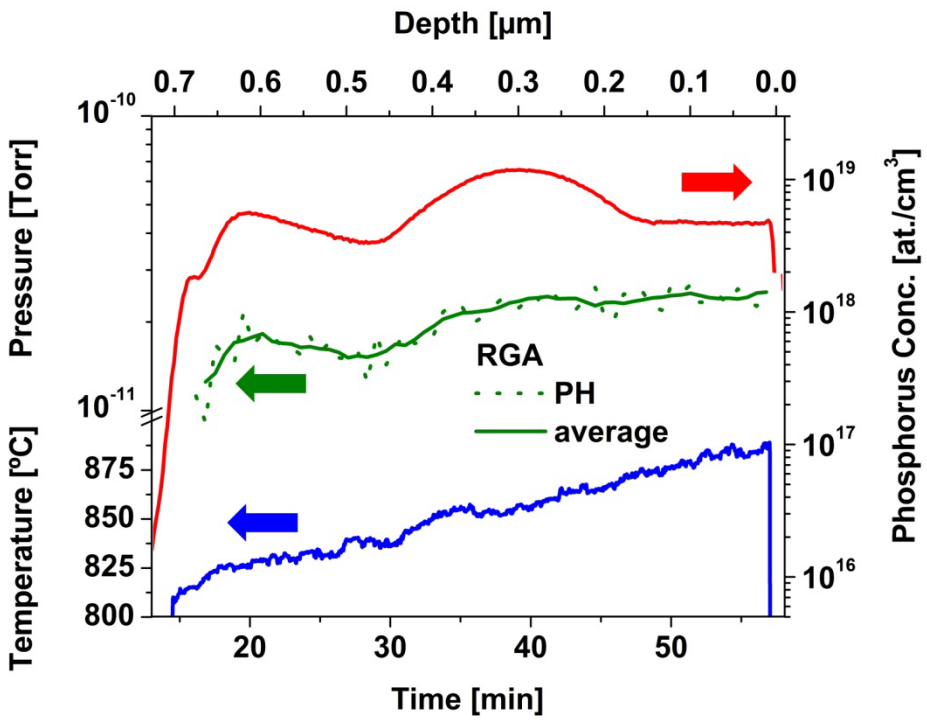


Incorporation of P-admolecules:
(τ) is longer than t_{cover} (= $w/R_{lateral}$)

Desorption of P-admolecules:
lifetime of P-admolecules (τ) is shorter than time required for terrace overgrowth (t_{cover})

S. Ohmagari et al. / Journal of Crystal Growth 479 (2017) 52–58

Controlled P-Doping with Plasma Enhanced CVD



Phosphorus doped diamond growth was characterized In situ by

pyrometer for growth temperature
RGA (OES) for gas chemistry characterization (PH)

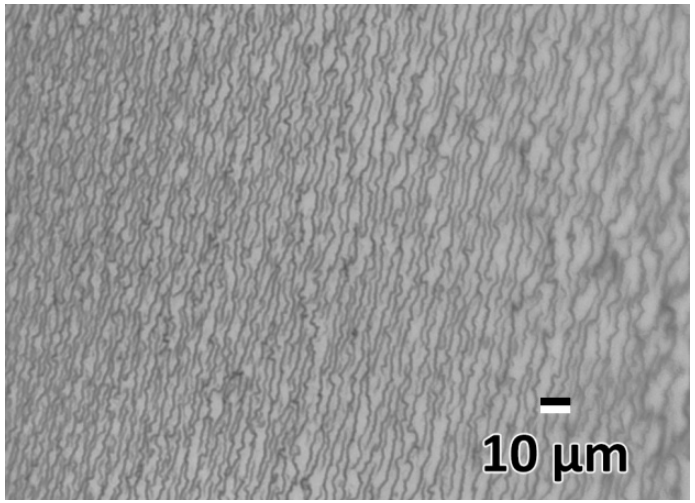
and SIMS was performed to evaluate the phosphorus doping concentration.

Substrate: IIa CVD (111) plate
Phosphorus doping source:
200ppm trimethylphosphine (TMP) in H_2

Correlation of the phosphorus doping concentration to
the growth temperature (Pyrometer)
doping species (PH)

How do surface properties affect the phosphorus incorporation?

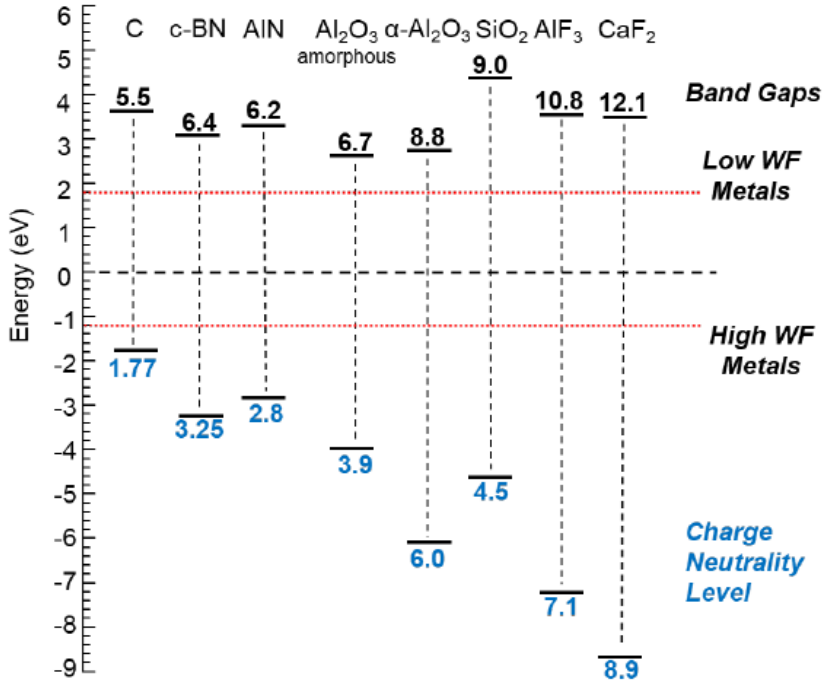
What phenomena drive a step-flow growth mode?

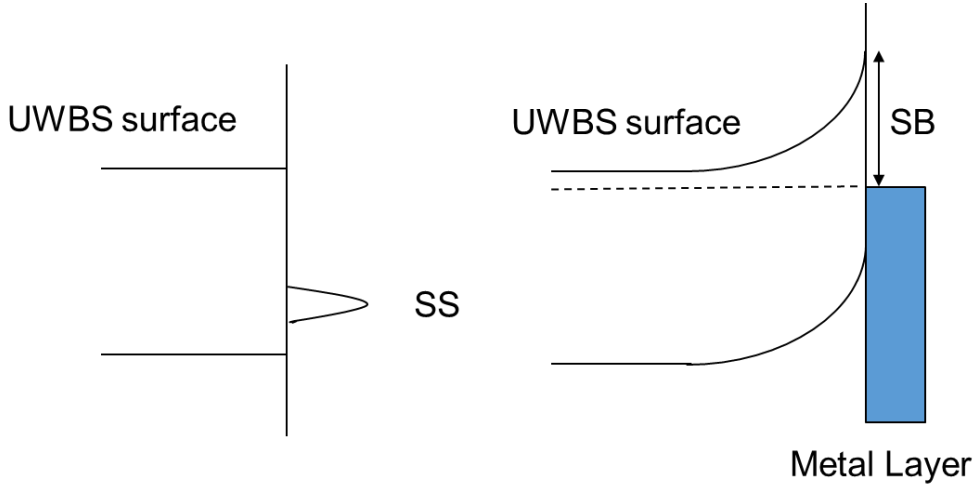


Optical microscopy identifies a step-flow growth mode.

Electrical Contacts to P-doped Diamond

Electron Contacts to UWBS

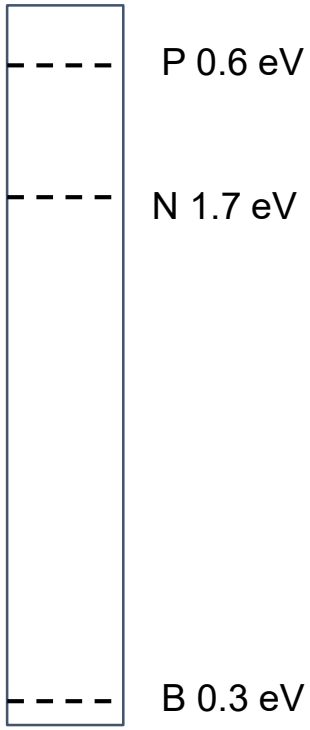




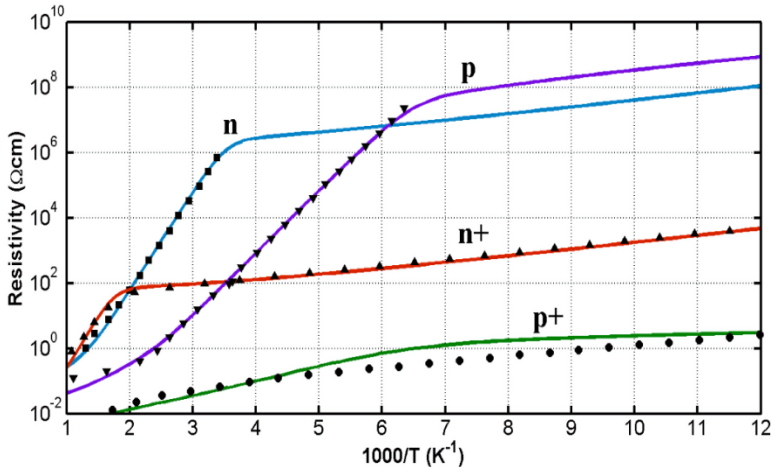
Low work function contacts to n-type UWBS is complicated

Surface states (or CNL) on diamond and AlN (and c-BN) can pin the interface Fermi level providing a large Schottky barrier that limits electron injection.

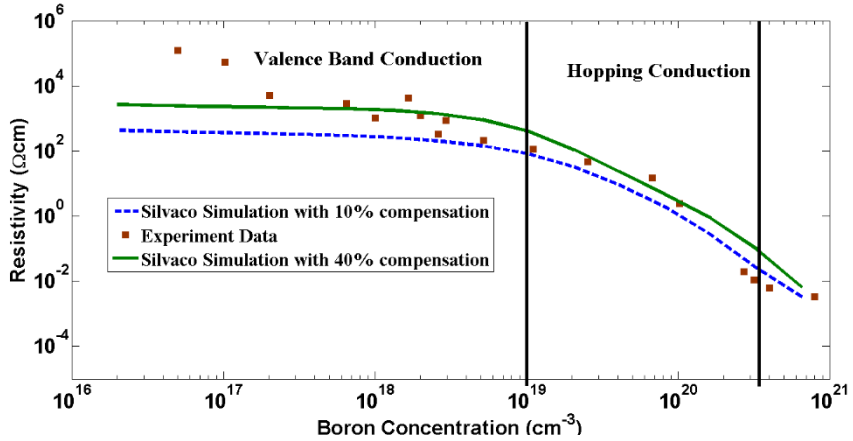
Diamond Doping

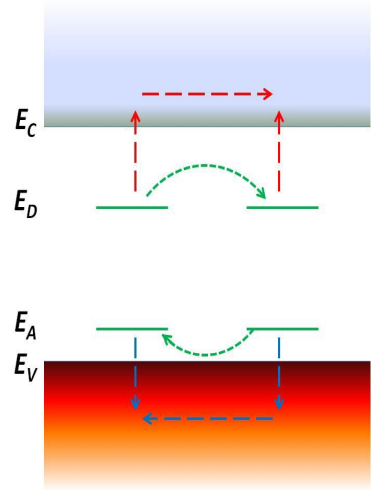


Diamond Bandgap 5.45 eV



1×10^{18} cm^{-3}
1×10^{18} cm^{-3}
8×10^{19} cm^{-3}
2×10^{20} cm^{-3}

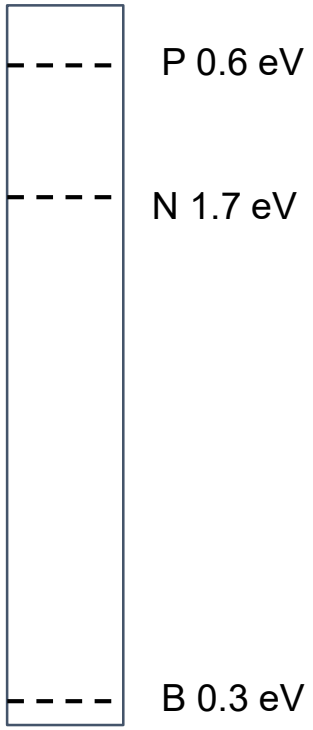




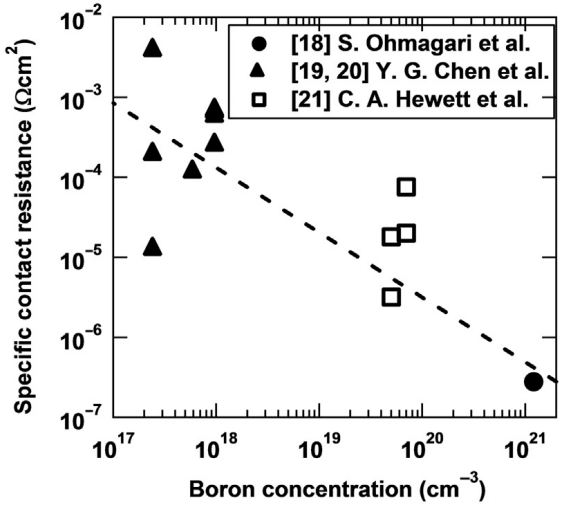
P-doping nearest neighbor hopping
B-doping variable range hopping

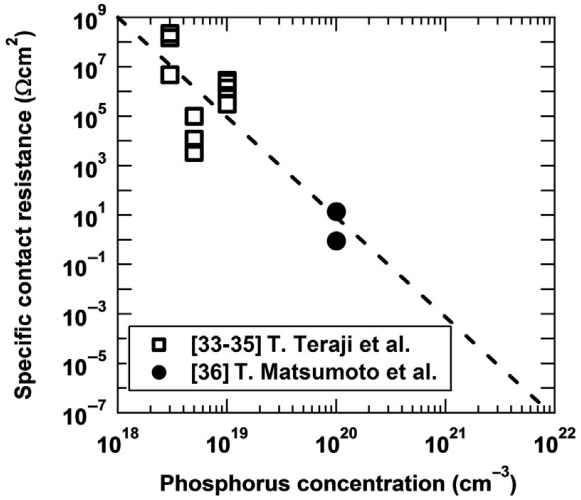
*K. Oyama, et al, APL **94**, 152109 (2009)
Hathwar et al., J. Appl. Phys. 119, 225703 (2016)

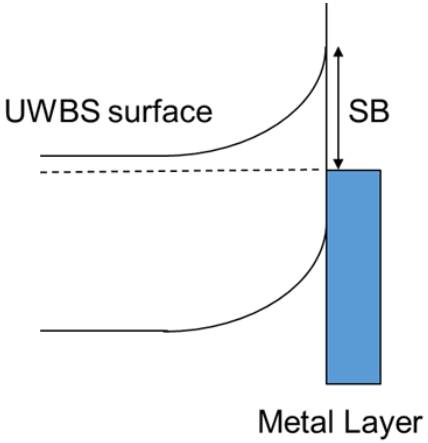
Diamond Contacts



Diamond Bandgap 5.45 eV

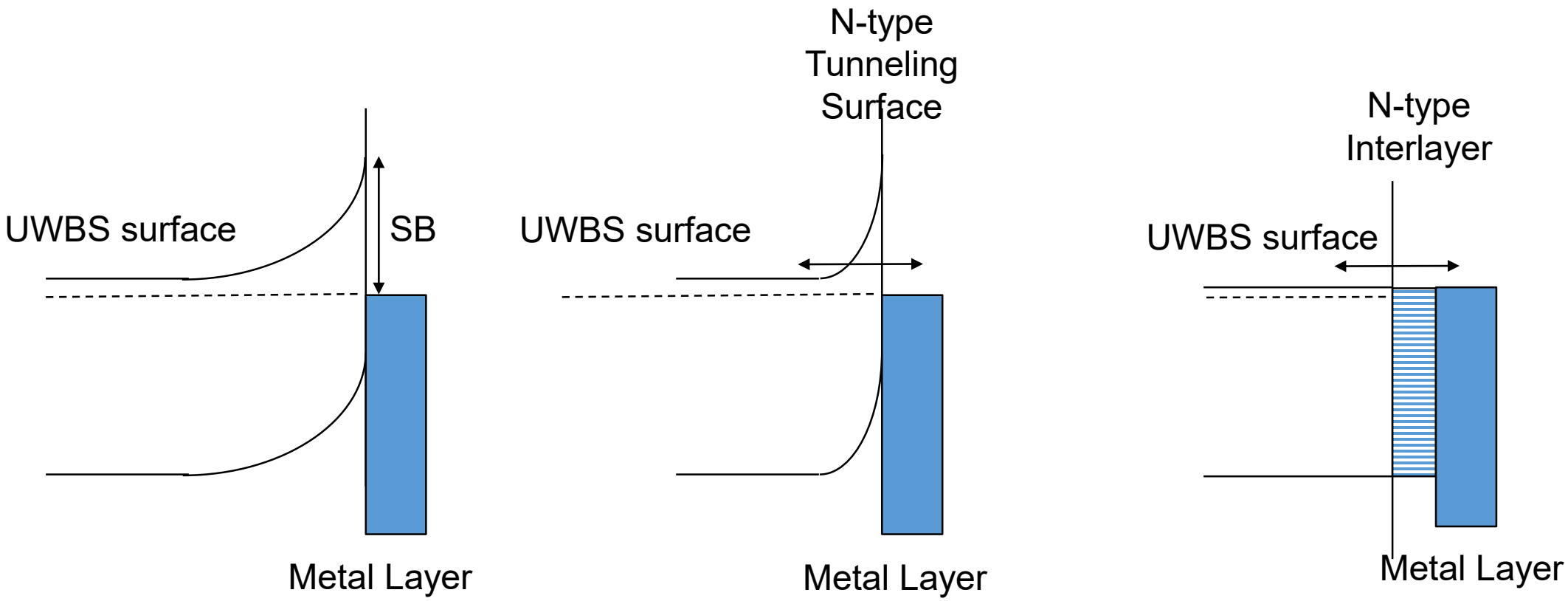






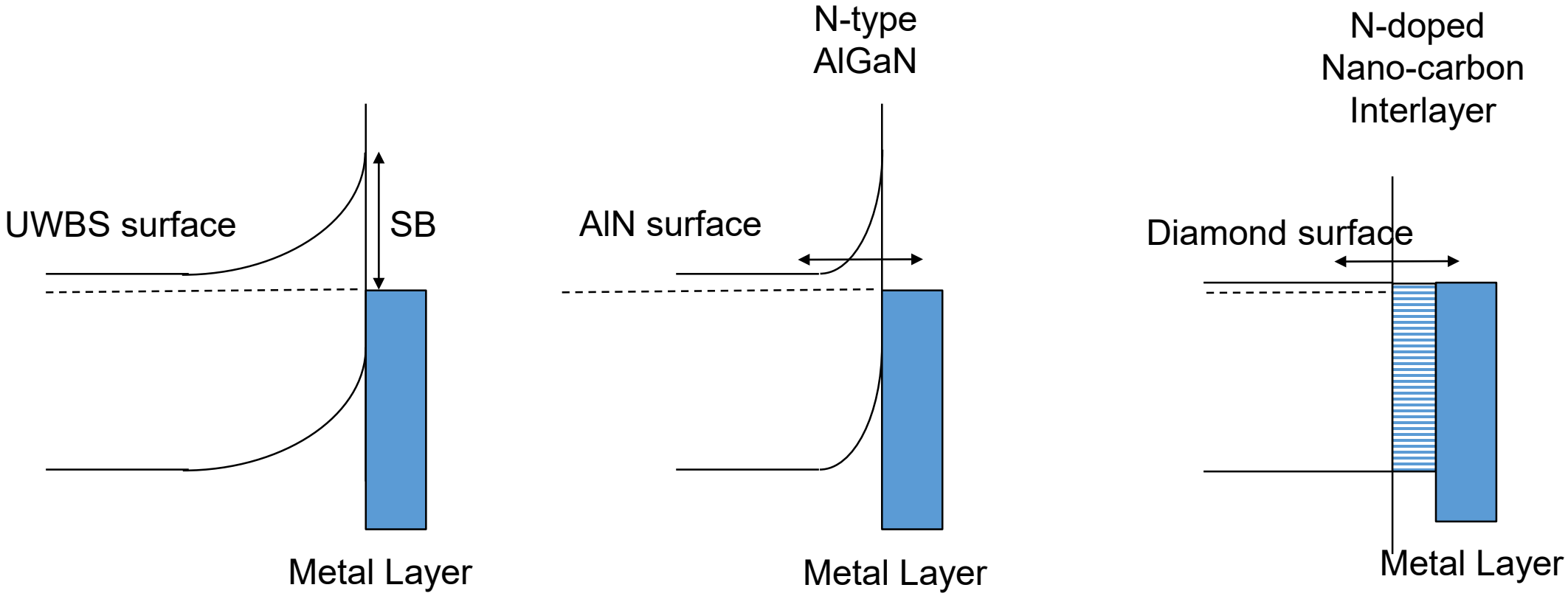
T. Matsumoto, Ch 4.2 Schottky and ohmic contacts on diamond, *Power Electronics Device Applications of Diamond Semiconductors,* (2018).

Electron Contacts to UWBS



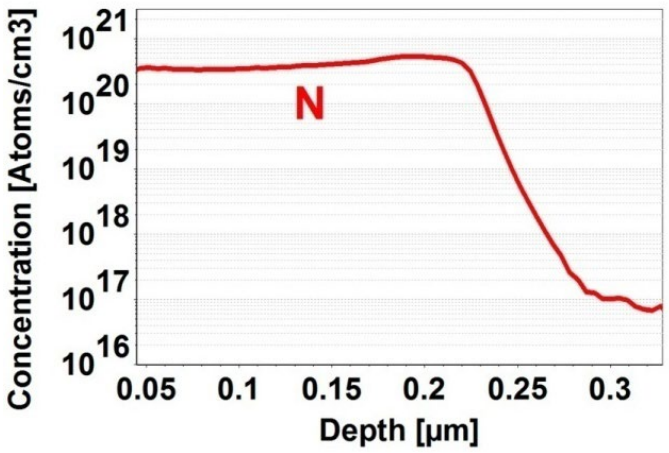
Low work function contacts to n-type UWBS is complicated

Electron Contacts to UWBS

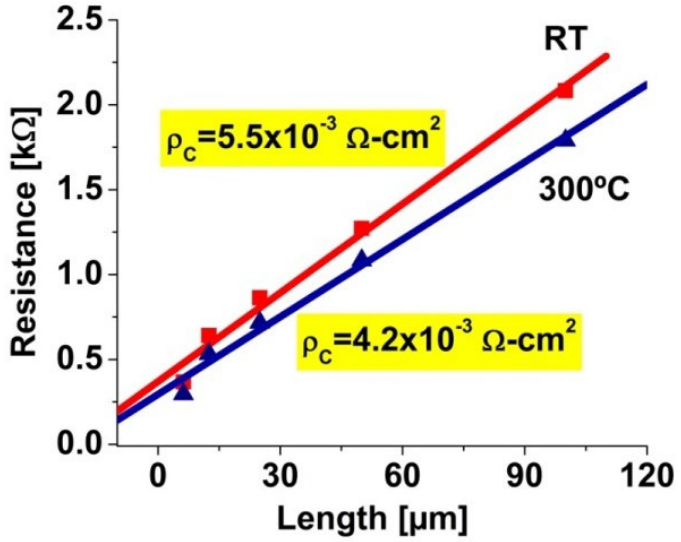


Low work function contacts to n-type UWBS is complicated

SIMS



TLM



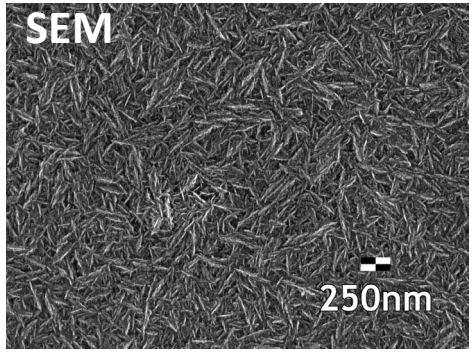
Nanostructured Carbon Contact Layers

- Nanostructured carbon (nanoC) layer
  Dedicated PECVD

Growth Parameters

Parameter	Growth
Hydrogen [sccm]	5
Methane [sccm]	20
Nitrogen [sccm]	100
Argon [sccm]	10
µ-wave [W]	900
Pressure [torr]	20
Pyrometer [°C]	900
Time [min]	20

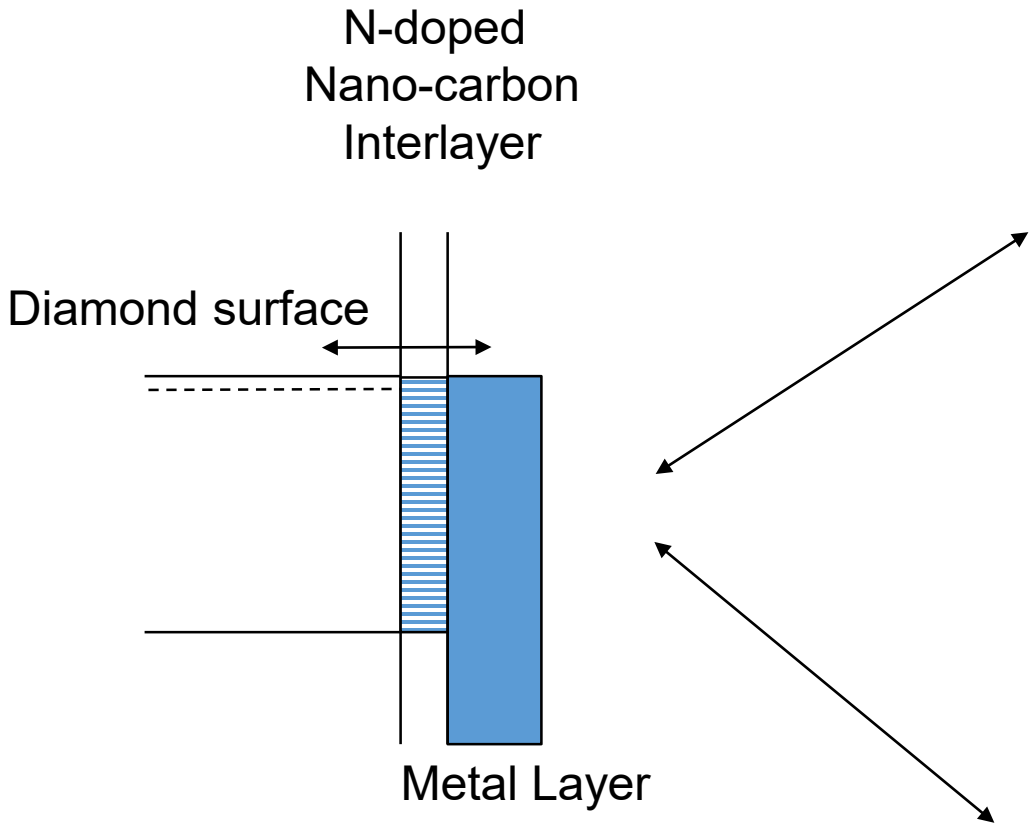
Film Morphology

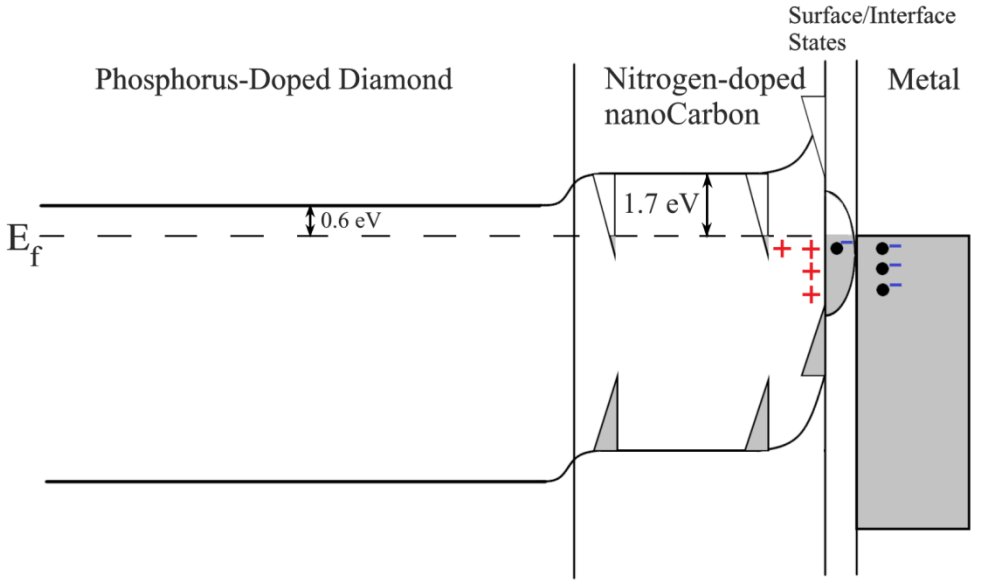


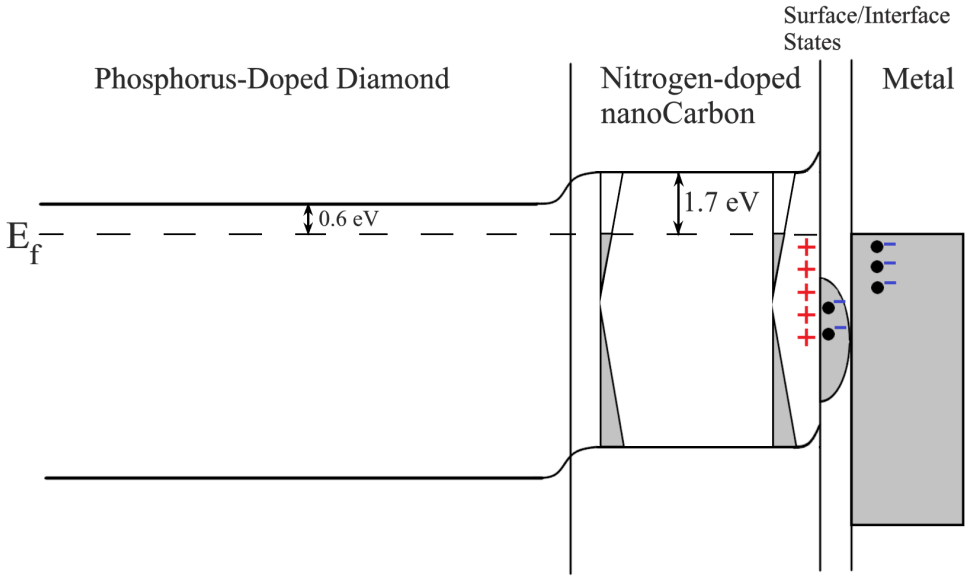
Argon chemistry for re-nucleation process.
Significant nitrogen addition.

- Nitrogen incorporation (SIMS) >$3x10^{20}$ cm^{-3}
- Nanostructured carbon layer with a thickness of ~200nm.
- TLM characterization to derive contact resistance for Ti/Pt/Au metallurgy
- Contact resistivity of ~10^{-3} Ω cm^2 suitable for devices.

Electron Contacts to UWBS

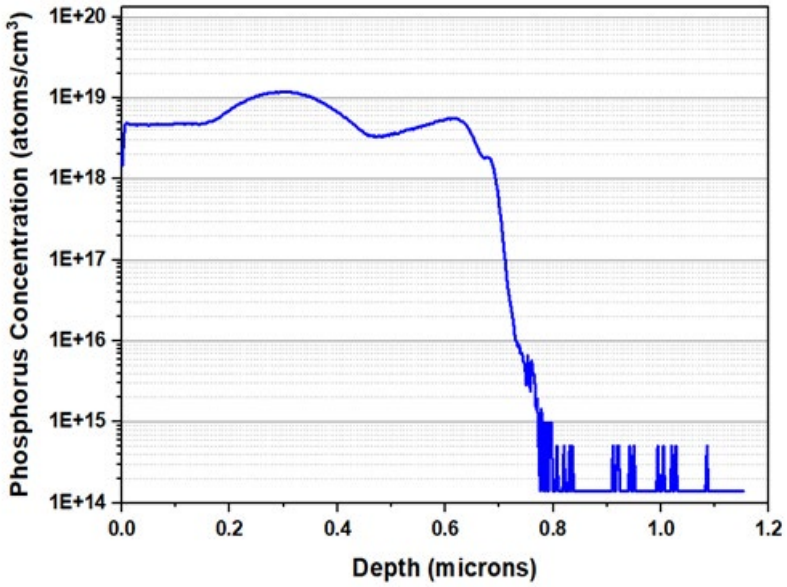




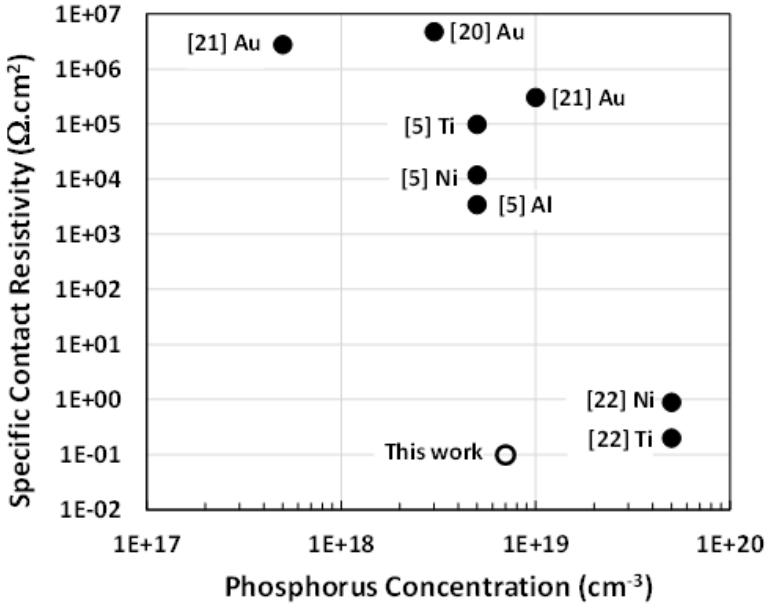


Low work function contacts to n-type UWBS is complicated

Electron Contacts to UWBS



SIMS profile showing phosphorus concentration in diamond film.

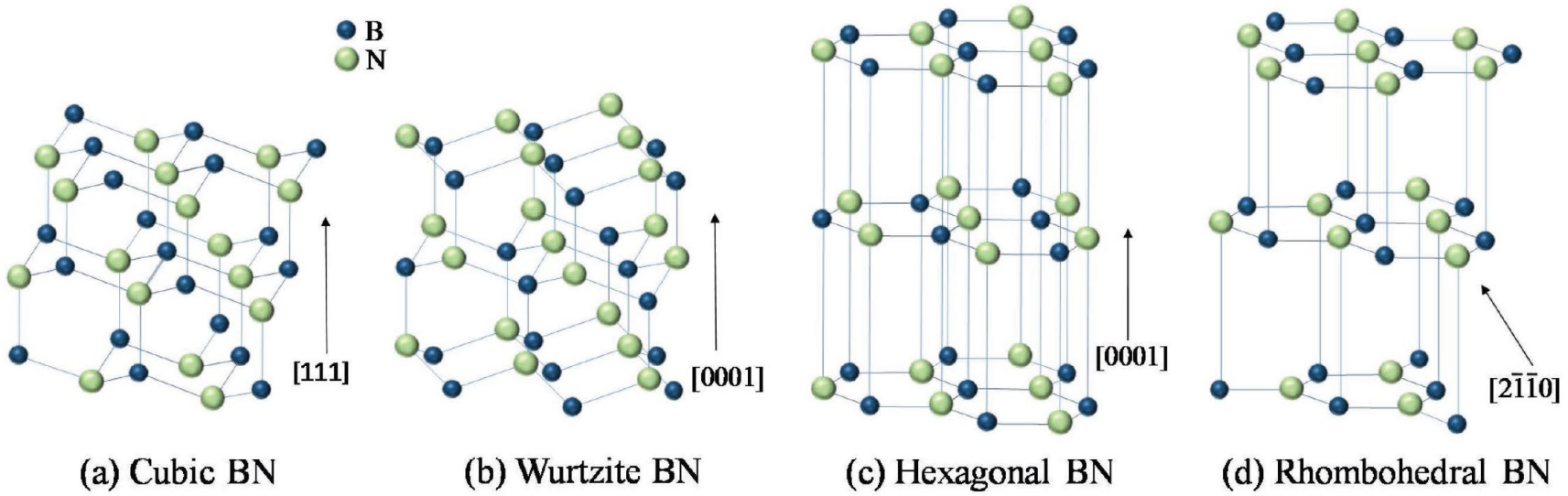


Comparing the specific contact resistivity for moderately P-doped diamond films

[5] Teraji et al, JJAP L1096 (1999)
[20] Teraji et al, APL 1303 (2000)
[21] Teraji et al, JJAP L882 (2003)
[21] Takemasa et al, ECS Trans, 491 (2014)

Plasma Enhanced CVD of c-BN

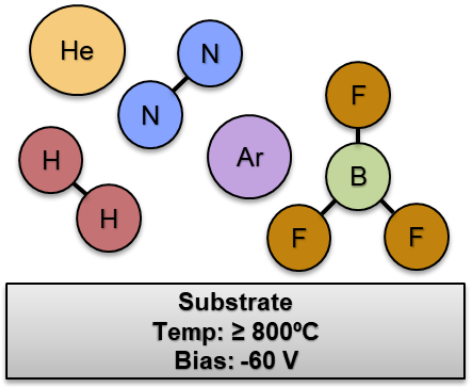
Boron Nitride Crystalline Phases

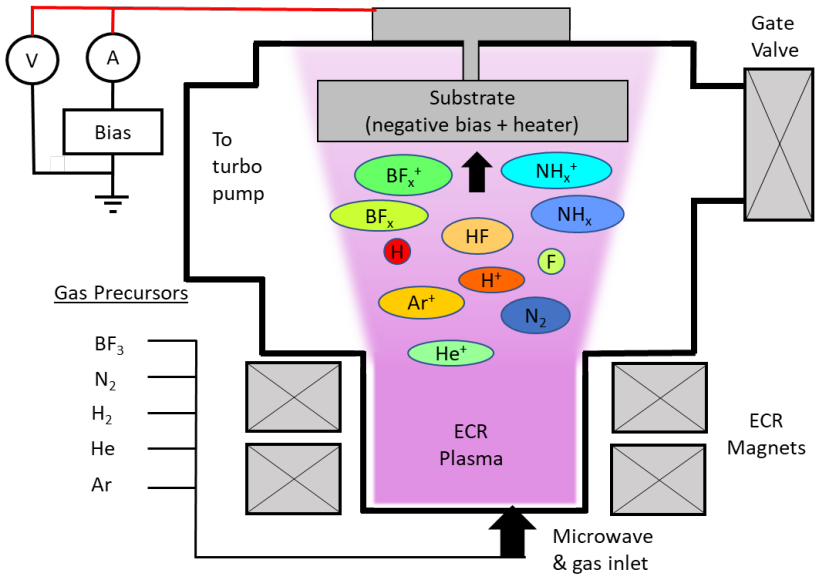


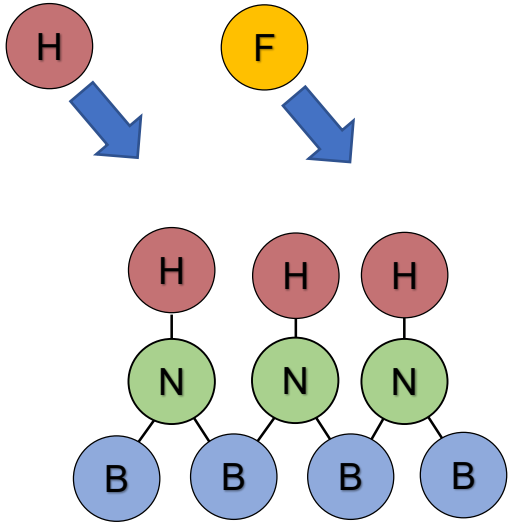
Density (gm/cm^3)-	3.48	3.47	2.2	2.26
Bonding	sp^3	sp^3	sp^2	sp^2

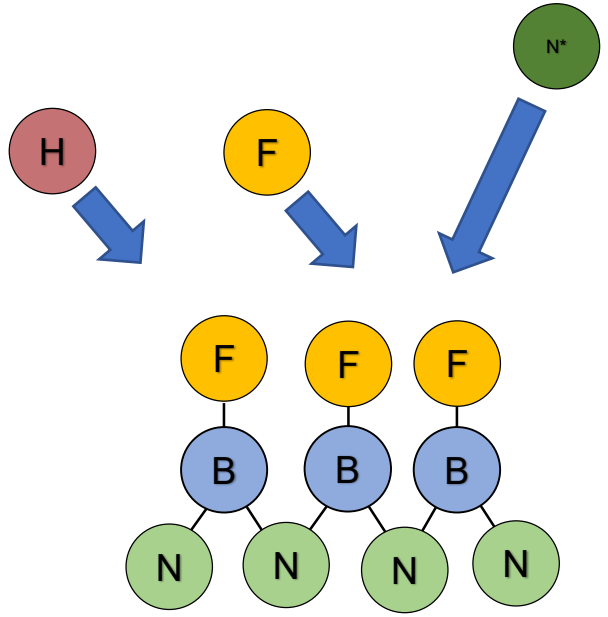
N. Izyumskaya et al., Adv. Electron. Mater. 3, 1600485 (2017)

c-BN Growth









- H or F proposed for abstraction of H from N surface sites.
- H or F plus impinging ions proposed to abstract F from B surface sites.

Nucleation of Epitaxial c-BN

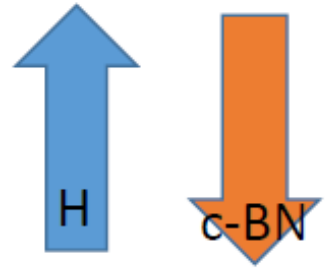
Precursors → **Plasma** → **Surface**

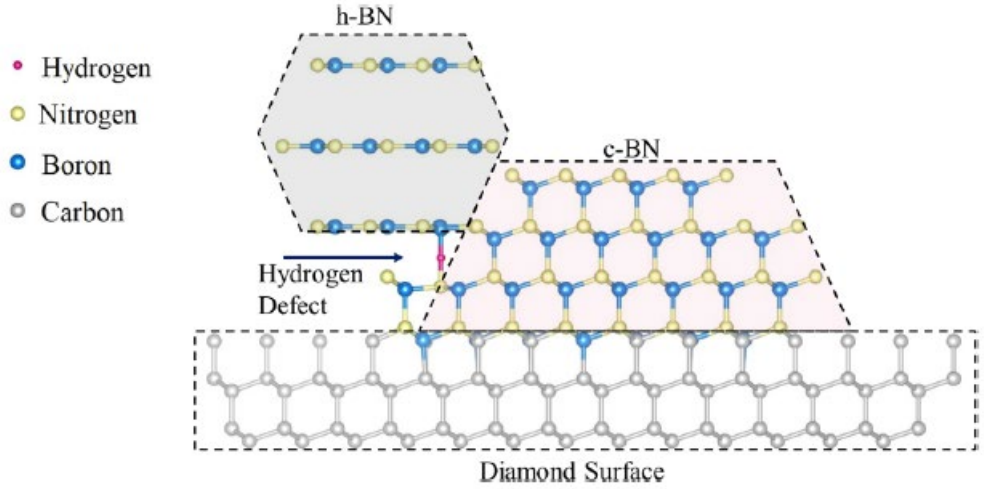
Ratio of H_2 to BF_3 is critical to the deposition of c-BN or h-BN

$$\text{Balanced: } 1.5H_2 + BF_3 + N_2 \rightleftarrows BF_x + NH_x + HF \rightleftarrows BN_{(s)} + (x+1)HF,$$

$$\text{Excess } H_2\text{: } 2H_2 + BF_3 + N_2 \rightleftarrows BF_x + NH_x + HF \rightleftarrows BN_{(s)} + (x+1)HF + H,$$

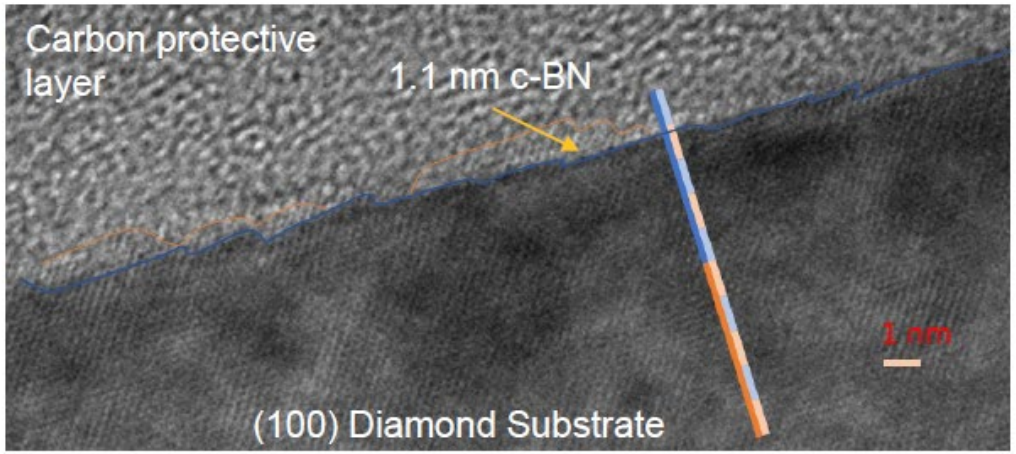
$$\text{Limited } H_2\text{: } 1H_2 + BF_3 + N_2 \rightleftarrows BF_x + NH_x + HF \rightleftarrows BN_{(s)} + (x+1)HF + F.$$





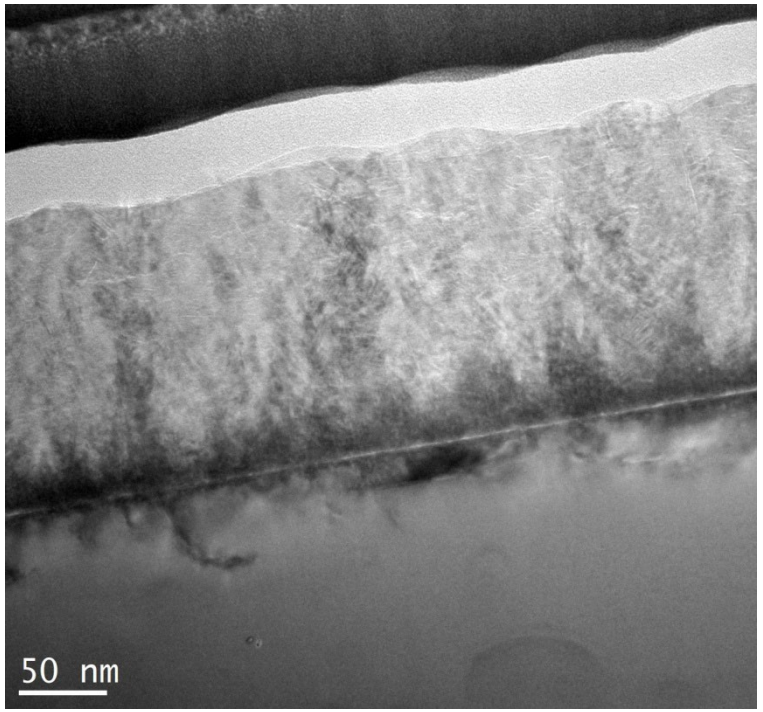
Hydrogen defects → h-BN

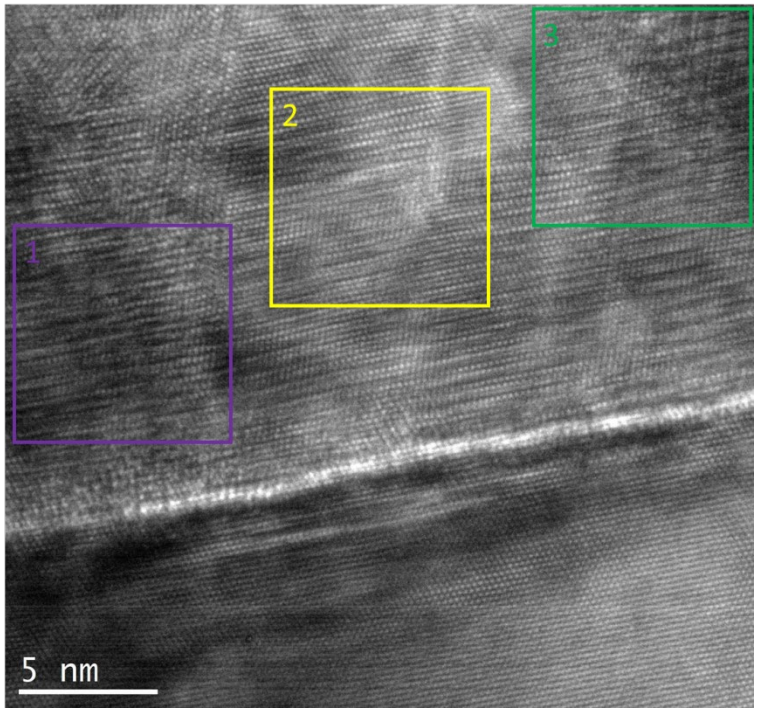
Transmission Electron Microscopy (TEM) Image

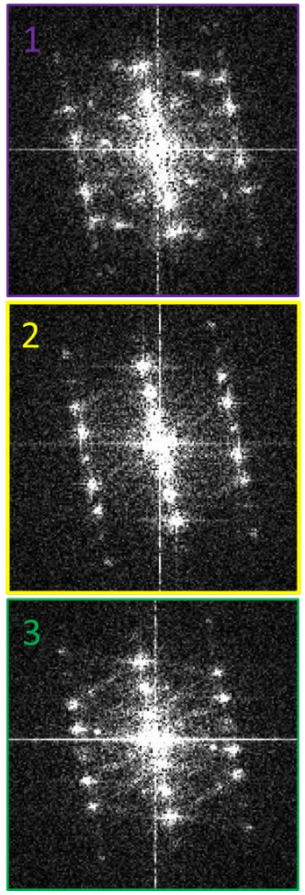


J. Brown, et al., J. Appl. Phys 133, 215303 (2023)

c-BN / w-BN – Diamond (111)

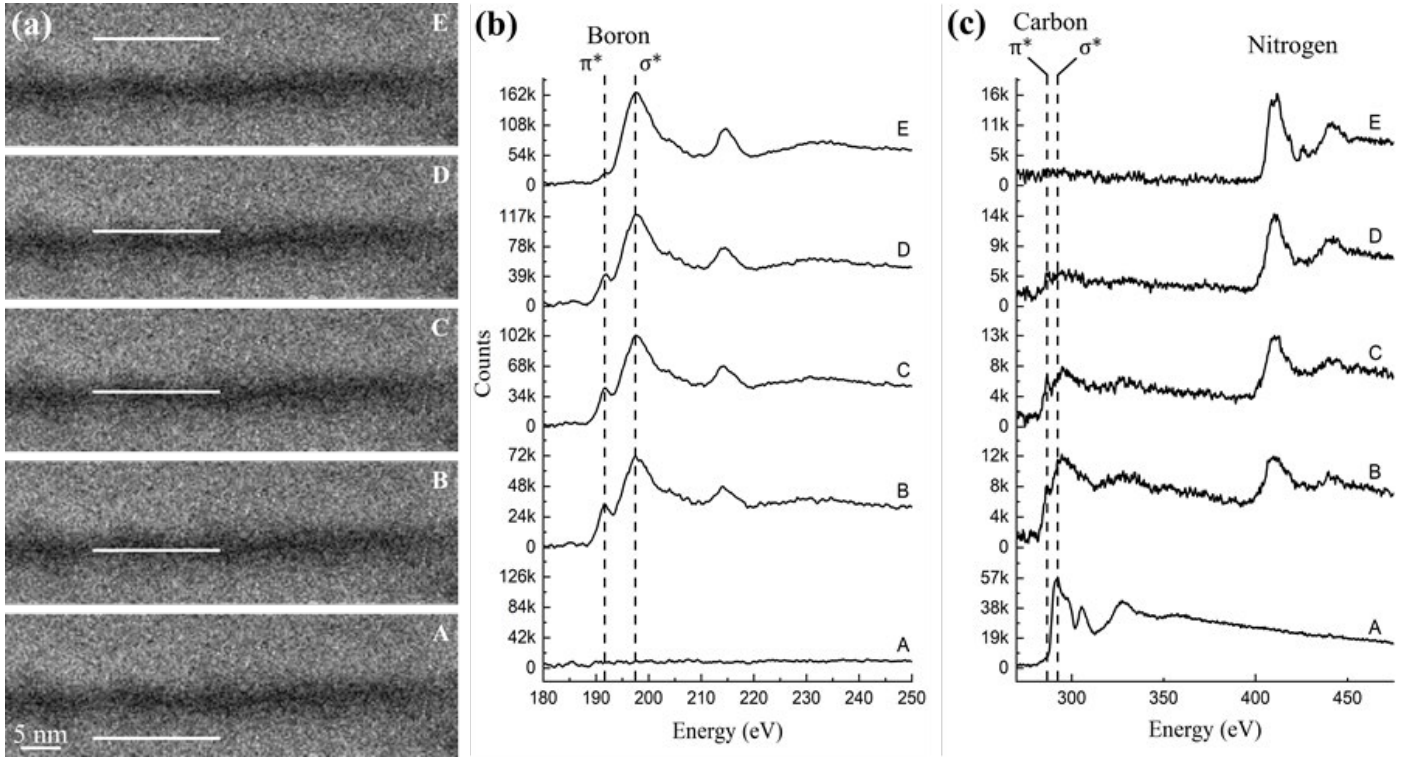




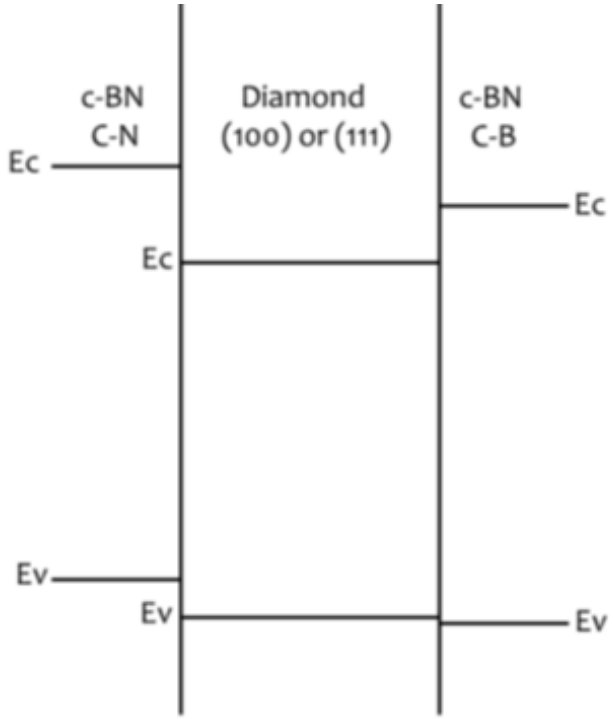


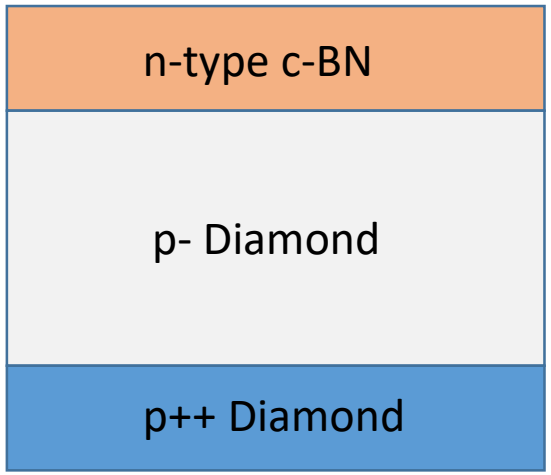
BN film thickness ~ 160 nm

EELS at BN – Diamond Interface



c-BN – Diamond PIN







D. Zhao, et al, RSC Adv. 9, 8435-8443 (2019). DOI:10.1039/c9ra00784a

Summary and Status

- **Substitutional doping and hopping conduction enables PiN diodes.**
- **In situ characterization for real time control of n-type doping in diamond.**
- **Contact strategy including doping and nano carbon interlayer.**
- **Synthesis of c-BN epitaxy through control of gas phase precursors and plasma conditions.**
  - **Synthesis of both cubic and hexagonal BN (control of precursors).**
- **P-i-N diode proposed with p-diamond and n-type c-BN.**

Funding Acknowledgment

- **Department of Energy through the ULTRA Energy Frontier Research Center (ULTRA EFRC)**
- **DARPA – through Northrop Grumman seedling project**
- **NSF/DARPA – Electrons in Diamond project**

U.S. NAVAL RESEARCH LABORATORY

NRL IV&V Capabilities

Ginger Wheeler

Eric Jin, James Champlain, Andrew Lang, Brian Downey, David Meyer

UWBG Proposer Day

Oct. 5th, 2023

U.S. NAVAL RESEARCH LABORATORY

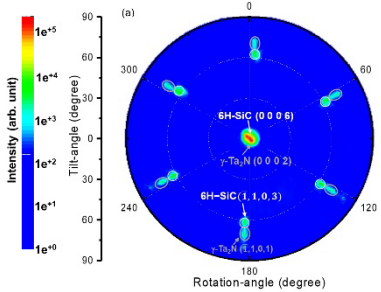
Evaluation for UWBG Program

Overview of Capabilities:

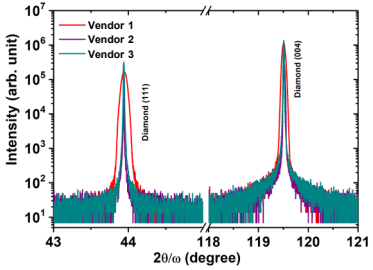
- X-ray diffraction to determine substrate orientation and offcut
- Chemical etching to determine dislocation density
- X-ray topography to determine extended defect/dislocation density and resulting strain fields
- Photoluminescence to identify the presence and density of point defects
- Raman spectroscopy to identify the presence of subsurface damage and uniformity of strain
- Transmission electron microscopy to identify extended and point defects, lattice constants, and chemical information from EELS/EDX
- X-ray photoelectron spectroscopy detect any surface impurities, stoichiometry of layers, band offsets, etc.
- Atomic force microscopy to determine surface roughness and topography
- Wafer curvature measurements to determine substrate bow
- Steady-state thermoreflectance and/or laser flash analysis to determine thermal conductivity
- Contactless sheet resistance measurements to determine electrical resistivity
- C-V, I-V, Hall electrical measurements to measure sheet resistance, carrier concentrations/dopant efficiency, interface trap densities, breakdown voltage, etc.
- Small signal RF measurements to measure diode figure of merits

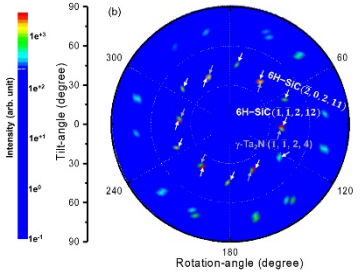
U.S. NAVAL RESEARCH LABORATORY

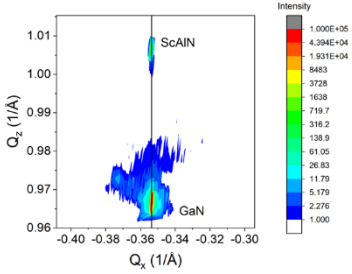
Material Structure-Property Characterization

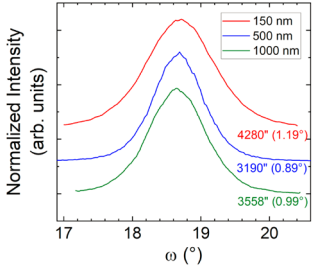












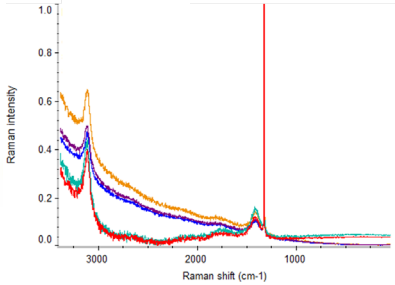
Rigaku 9 kW monochromated SmartLab Diffractometer with rotating copper anode

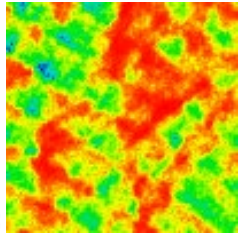
- High resolution rocking curve measurements (12 arcsec resolution)
- Rocking curve X/Y wafer maps
- Offcut and offcut maps
- Wafer scale measurements

Thermal Fischer DXR Raman System

- 532 and 455 nm lasers
- High resolution stage mapping – ideal spatial resolution 0.5um
- Confocal depth resolution 1.7um

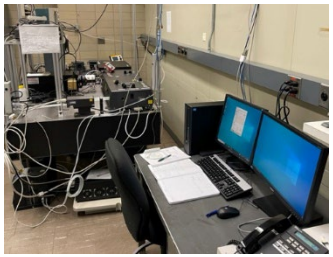


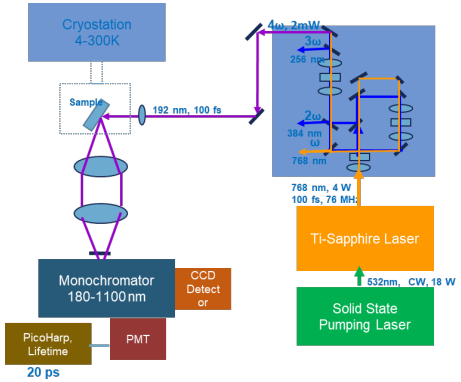


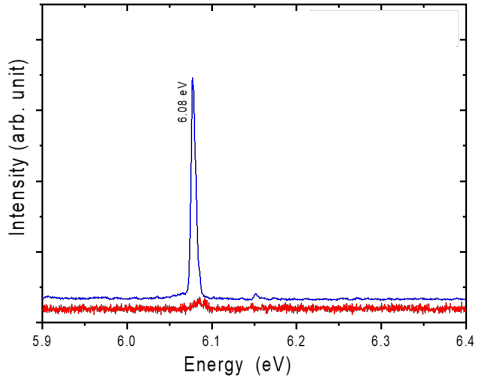


U.S. NAVAL RESEARCH LABORATORY

Material Structure-Property Characterization





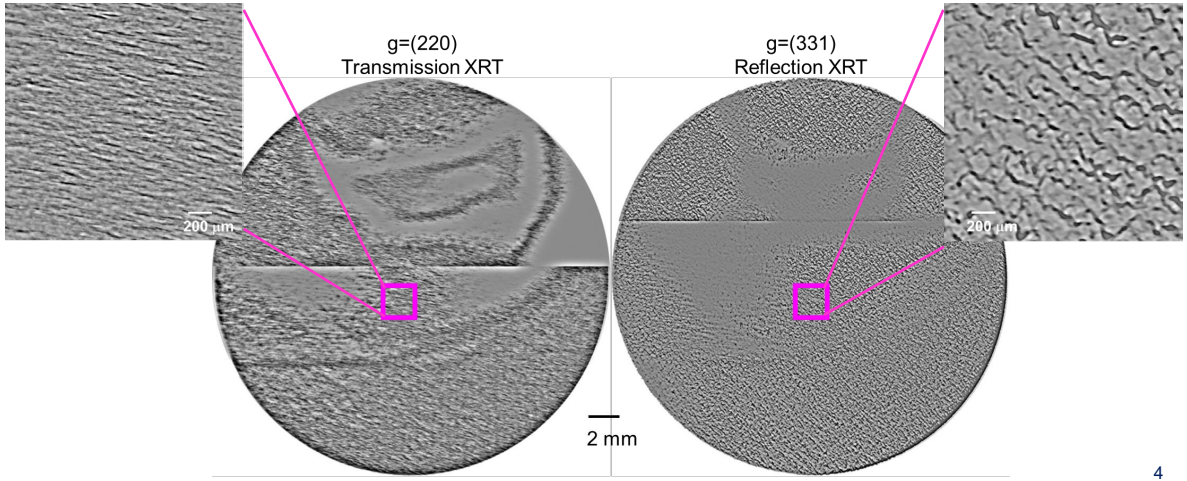


Coherent Deep UV photoluminescence system

- 192 nm lower resolution achieved via 4th harmonic
- Identify band edge and mid gap defects in UWBG materials
- Quantification can be done but must careful calibrate and run system
- Can use CL for comparison and different depth of defects

High resolution X-ray topography measurements (N. Mahadik)

- Transmission geometry using Mo Kα radiation
- Reflection geometry using Cu Kα radiation – pentration depth 15μm
- Lattice curvature and dislocations can be mapped



Material Structure-Property Characterization

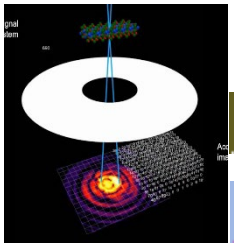
Nion UltraSTEM 200X

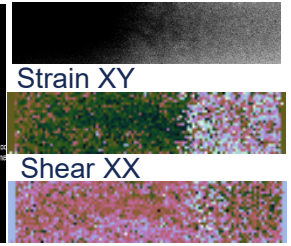
- Aberration-corrected dedicated STEM w/ <100 pm resolution
- Single atom composition - EDS
- Plasmon and core-shell spectroscopy - EELS
- Merlin EELS detector w/ 4x sensitivity
- *in situ* experiments – heating, electrical biasing, wet cell, electrochemical
- Dark-field atomic image simulations

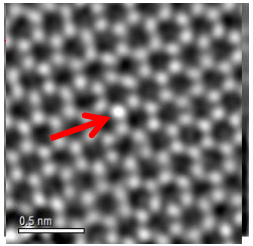


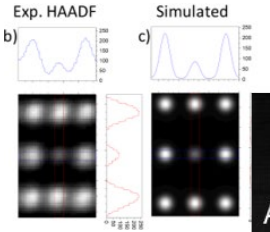
JEOL 2200FS

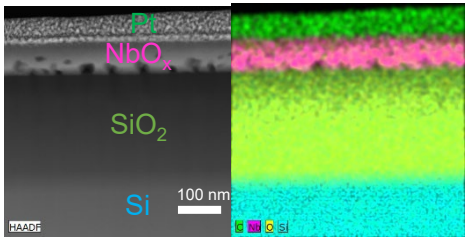
- 4D-STEM – 2D diffraction × XY raster w/ strain & shear
- OneView 4k × 4k camera at 25 Hz imaging
- 3D electron tomography at ~1 nm^3 voxels
- EDS and EELS spectroscopy

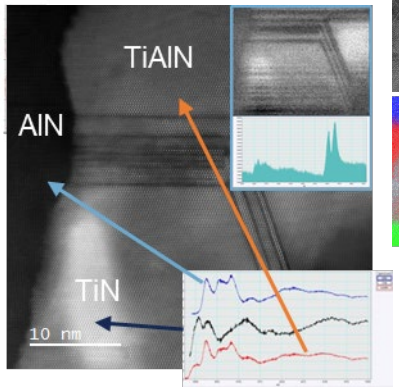


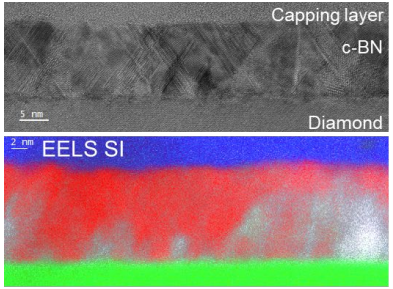






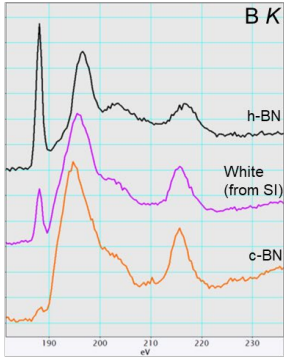


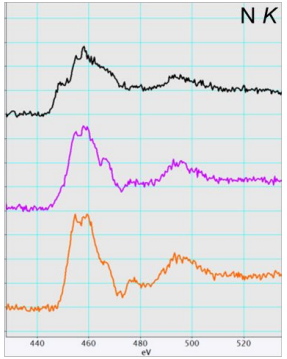




Blue: Capping layer
Green: sp^3 Carbon

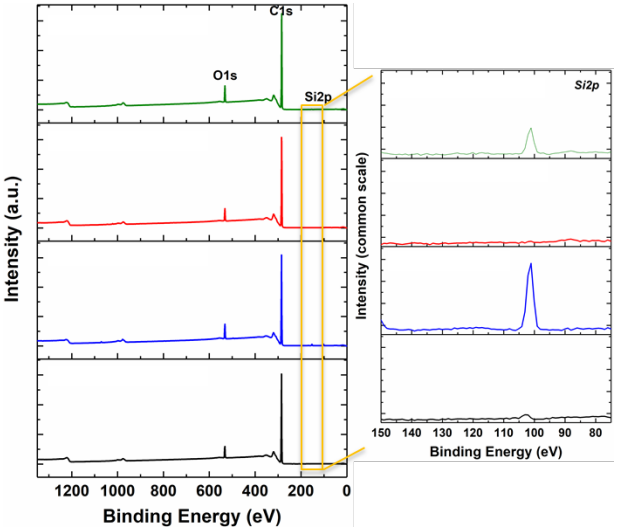
Red: pure sp^3 BN
White: presence of 191.3 eV peak in cBN





U.S. NAVAL RESEARCH LABORATORY

Material Structure-Property Characterization





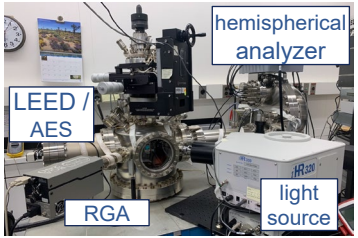


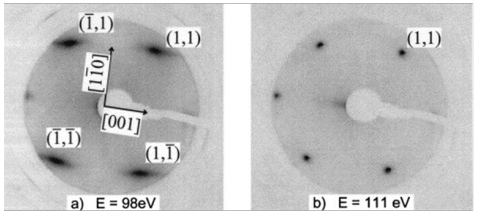
Multiple XPS Systems – Nexsa and Theta Probe

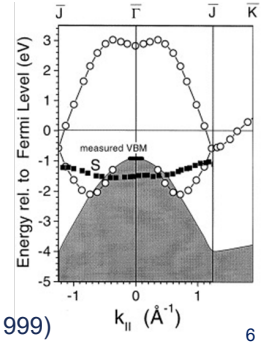
- Up to 4” wafer capability
- Angle-resolve without tilt for mapping
- Monoatomic and cluster ion sources for depth profiling
- UPS capabilities

Two Custom In-house Surface Science Chambers

- XPS, UPS, IPE , SEES, LEED, AES
- Electron affinity, band offsets
- Simultaneous chemical and structural analysis



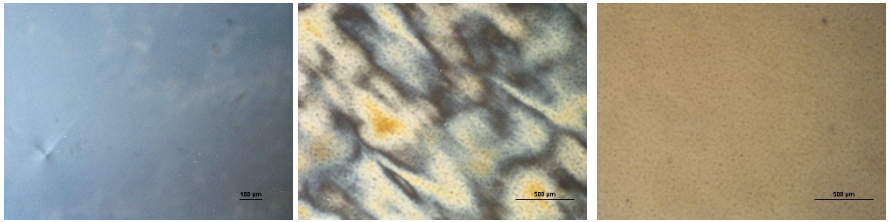




Maier, F, et al. *Surf. Sci.* **443(3)** 177-185 (1999)

Material Structure-Property Characterization

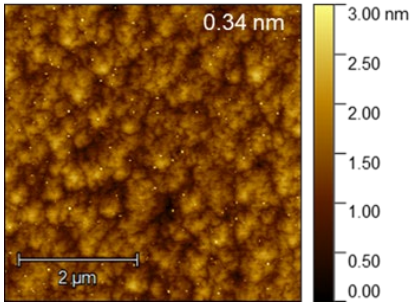
Diamond substrates



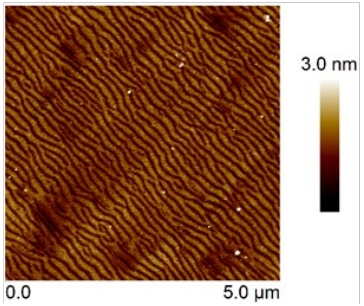
Nikon Optical Microscopy

- Differential interference contrast imaging possible
- Polarization options included
- Fluorescence filter for color center detection

MBE AlN/bulk AlN



Diamond substrate



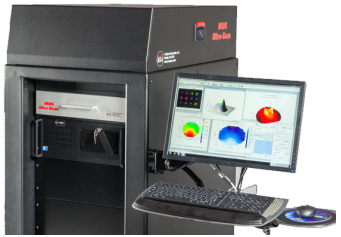


Bruker Dimension AFM with both Icon and FastScan Heads

- Tapping and contact modes available
- Upto 90 µm^2 scans over 150 mm wafer scale
- Local I-V and piezoelectric measurements possible

kSA MOS UltraScan wafer curvature mapping

- 1”-8” wafer size capability
- 1 µm XY stage resolution
- 4 × 10^{-5} m^{-1} curvature resolution and 2 m to 50 km radius of curvature range
- 0.32 MPa stress accuracy/resolution
- Can compare with white light profilometry (Zygo measurements)



U.S. NAVAL RESEARCH LABORATORY

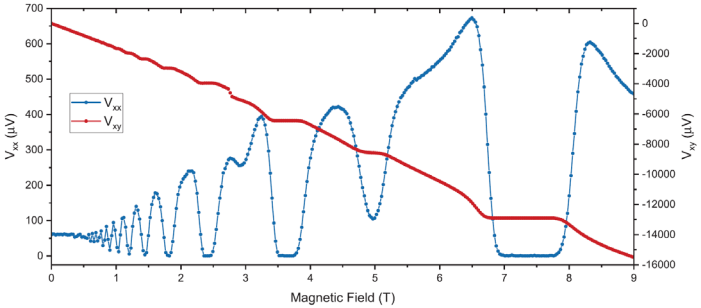
Physical Properties Measurement System (PPMS)

Quantum Design DynaCool PPMS

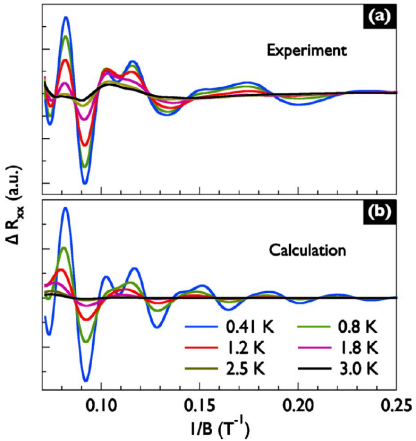
- Cryogen-free, 9 T magnet, temperature range 1.8-400 K
- AC and DC resistance capabilities; van der Pauw Hall transport; angle-dependent B field measurements
- Measure quantum materials, exotic low-temperature effects
- Working to upgrade for RF measurements



GaAs 2DEG (Palmstrom group, UCSB)



STO (UCSB, S.Mack NRL)

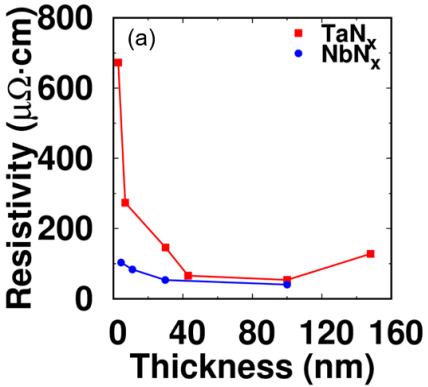


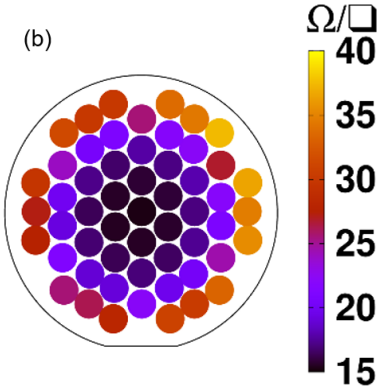
Electrical Characterization – wafer scale



LEI Contactless Measurement System

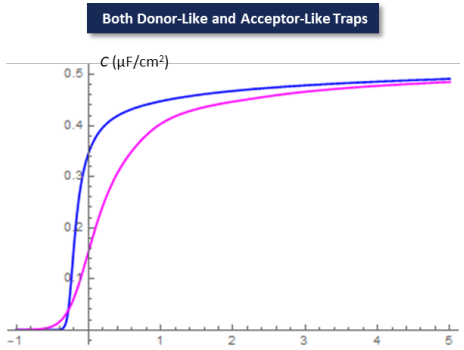
- Up to 6” wafer mapping
- Fast, Non-destructive sheet resistance measurements

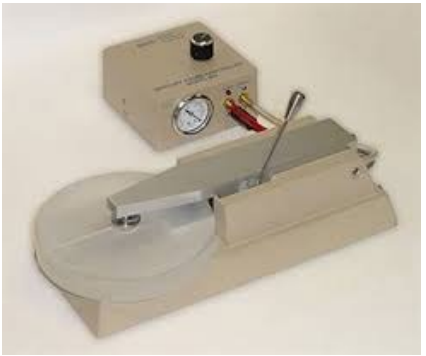




MDC 802B-150 Mercury CV Probe

- Up to 6” wafers and partial wafers
- Schottky and MOS C-V characterization for epilayer diagnostics such as carrier concentration, HEMT evaluation, thickness, and dielectric constants
- 100Hz to 1 MHz

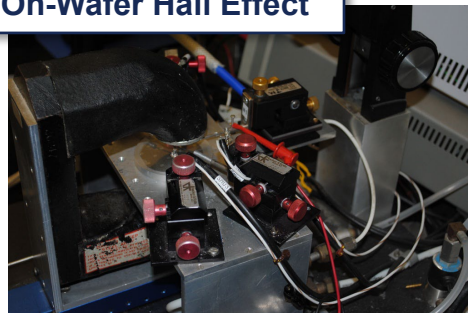




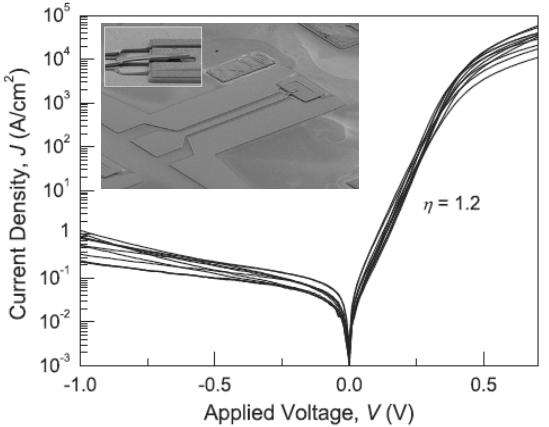
U.S. NAVAL RESEARCH LABORATORY

Electrical Characterization/Diode Qualification

On-Wafer Hall Effect

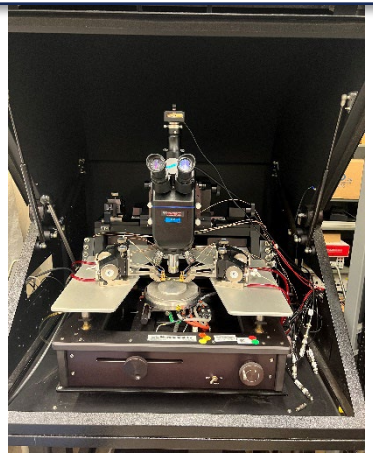


- Room temperature carrier density and mobility measurement



J. G. Champlain, R. Magno, D. Park, H. S. Newman, and J. B. Boos, "High-Frequency, 6.2 Å *pN* Heterojunction Diodes," *Solid-State Electronics*, vol **67**, pp. 105-108 (2012)

400 °C DC IV/CV Probe Station w/ Light Enclosure



Keithley 4200A-SCS Parameter Analyzer



Capabilities

- 4 IV SMUs
- CV up to 10 MHz
- UV light
- Dual-tip Kelvin probes for removal of probe resistance

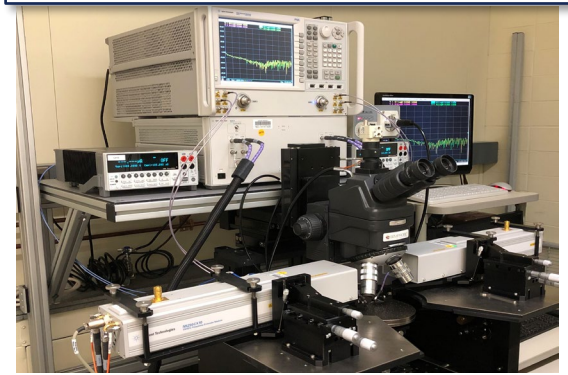
Evaluation

- Contact and sheet resistance extraction (TLM/CTLM)
- Diode ideality factor extraction
- Built-in potential, diode series resistance estimation
- Geometric analysis of IV behavior

U.S. NAVAL RESEARCH LABORATORY

Electrical Characterization/Diode Qualification

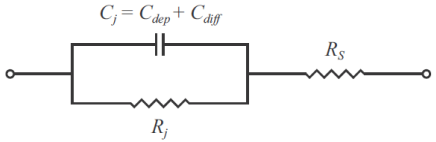
Multiple Small-Signal RF Characterization Systems





- Small-signal model extraction
  - Series resistance (R_S), junction resistance (R_j) and capacitance (C_j)
- RC-cutoff frequency (f_{RC}) calculation and analysis

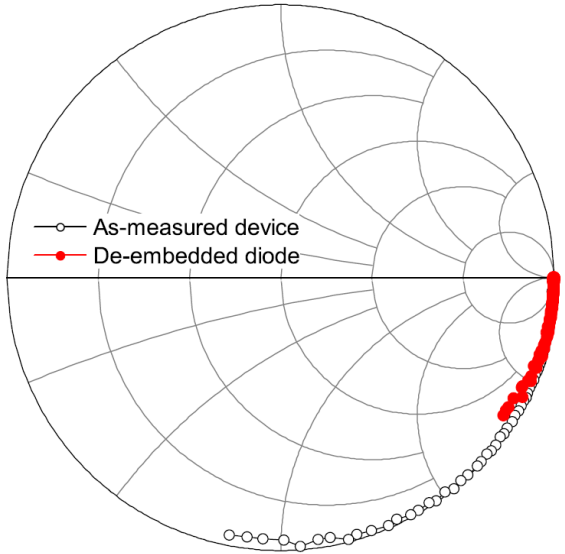
Diode Small-Signal Model



$$f_{RC} = \frac{1}{2\pi R_S C_j}$$

Capabilities

- S-parameter measurement
- W-band (75-110 GHz) frequency extenders
- Keysight ADS circuit modeling



$f_{measure}$ = 10 MHz - 40 GHz

J. G. Champlain, R. Magno, D. Park, H. S. Newman, and J. B. Boos, "High-Frequency, 6.2 Å *pN* Heterojunction Diodes," *Solid-State Electronics*, vol **67**, pp. 105-108 (2012)

U.S. NAVAL RESEARCH LABORATORY

Summary

- Lots of fundamental material and electrical characterization capabilities – many are wafer scale or can be mapped
- Significant experience in characterizing WBG and UWBG materials and devices
- Happy to discuss additional characterization techniques as needed or short loop characterization

Virginia (Ginger) Wheeler

virginia.wheeler@nrl.navy.mil

UWBGS
HR001123S0051

Proposers Day

October 5, 2023

Lon Wang
Contracting Officer
DARPA Contracts Management Office

Distribution Statement A. Approved for Public Release; Distribution Unlimited.

Proposers Day Disclaimer

- **Lots of information is made available to potential proposers to clarify program goals/objectives and proposal preparation instructions - those things that are stipulated in the BAA**

However:

- Only the information/instructions in the BAA counts
- Proposals will only be evaluated in accordance with the instructions provided in the BAA
- Any response provided by the Government in the FAQ that's different than what is provided in the BAA will be made formal by an amendment to the BAA
  - Such responses will make note of an impending BAA amendment

<u>Only a duly authorized Contracting Officer may obligate the Government</u>

Distribution Statement A. Approved for Public Release; Distribution Unlimited.

BAA Overview

- **BAAs allow for a variety of technical solutions**
  - The BAA defines the problem set, the proposer defines the solution (and SOW)
  - Allows for multiple award instrument types:

    - Procurement Contract or Other Transaction
    - Anticipated Funding Type: 6.2 (Applied Research)
      - ➢Restricted research for for-profit team members (prime or subcontractor)
      - ➢Fundamental research for universities (prime and subcontractor)

- **Attachment 3 to BAA: General MTO Controlled Unclassified Information (CUI) Guide**

- **DARPA Scientific Review Process**
  - Proposals are evaluated on individual merit and relevance as it relates to the stated research goals/objectives rather than against one another
  - Selections will be made to proposers whose proposals are determined to be most advantageous to the Government, all factors considered, including potential contributions to research program and availability of funding

  - ➢**Government may select for negotiation all, some, one, or none of the proposals received**
  - ➢**Government may accept proposals in their entirety or select only portions thereof**
  - ➢**Government may elect to establish portions of proposal as options**

Distribution Statement A. Approved for Public Release; Distribution Unlimited.

BAA Process/Timeline

1. **BAA published: 29 September 2023**
2. **Proposers Day: 5 October 2023**
3. **Abstracts Due: 1 November 2023**
4. **Frequently Asked Questions: 4 December 2023**
5. **Proposals Due: 15 December 2023**
6. **Proposals are reviewed for BAA compliance**
   Noncompliant proposals are not reviewed (and cannot be selected)
7. **Government conducts Scientific Review Process**
   Clarification requests may be sent to various proposers
8. **Government sends out notification letters: ~ 2 January**
9. **Contracts negotiated & awarded (performance start): ~ July 2024**
   (can assume 1 July 2024 for Pricing)

See BAA for complete date/time information

Monitor SAM.gov for any BAA amendment(s)

Distribution Statement A. Approved for Public Release; Distribution Unlimited.

Eligibility Issues

- All interested/qualified sources may respond subject to the parameters outlined in BAA
- Foreign participants/resources may participate to the extent allowed by applicable Security Regulations, Export Control Laws, Non-Disclosure Agreements, etc.
- FFRDCs and Government entities:
  - Are not prohibited by the BAA from proposing
  - Are, however, subject to applicable direct competition limitations
  - Are, however, required to demonstrate eligibility (sponsor letter)
  - ➢ The burden to prove eligibility for all such team members rests with the proposer and all elements of a proposal (tech and cost, prime and subs – even FFRDC team members) must be included in the prime's submission
  - ➢ Government entities/FFRDCs interested in participating in the UWBGS program or proposing to this BAA should first contact the Technical Point of Contact (POC) listed in Part I prior to the Abstract due date listed in Part I to discuss eligibility.
- Real and/or Perceived Conflicts of Interest:
  - Identify any conflict/s
  - If any are identified, a mitigation plan must be included

Distribution Statement A. Approved for Public Release; Distribution Unlimited.

Proposal Abstracts (1 of 2)

- **Abstracts are highly encouraged:**
  1. They minimize unnecessary effort in proposal preparation and review
  2. They reduce the potential expense of preparing an out of scope proposal

- **The abstract provides a synopsis of the proposed project (tech and budget)**

- **Government will reply by letter with one of two possible responses:**
  1. Encourage full proposal, and may provide feedback
  2. Discourage full proposal, and will provide rationale

  - DARPA will not communicate further (verbally or in writing)

- **Regardless of DARPA's response to an abstract, proposers may submit a full proposal**

  - DARPA will review all full proposals submitted without regard to abstract recommendation/feedback

Distribution Statement A. Approved for Public Release; Distribution Unlimited.

Proposal Abstracts (2 of 2)

- **Abstracts (Unclassified) must include the following components:**
  - Cover Sheet
  - Innovative Claims
  - Technical Approach
  - Deliverables
  - Cost and Schedule

Max of 4 pages

- **The total page limit does not include the cover sheet (required) or a submission letter (optional)**

- **All pages marked "UNCLASSIFIED//FOR OFFICIAL USE ONLY"** (in header and footer)

- **Submit ONLY to the DARPA BAA Website (https://baa.darpa.mil)**

Full Proposal Ground Rules

- **KEY POINTS:**
  - **Each proposal must address all technical challenges– address all phases and metrics. Proposers can propose to multiple TAs but each must be a separate proposal.**
  - **Submit unclassified proposals ONLY to the DARPA BAA Website (https://baa.darpa.mil)**
    - **Click "Finalize Full Proposal" button (otherwise you have not submitted)**
  - **Submit classified proposals (or classified parts of otherwise unclassified proposals) to DARPA per "Security Information" section of the BAA**
    - Do not submit classified proposals/information to the DARPA BAA Website
    - If unsure, please ask questions (well before the proposal due date)

Propose to the program (goals, objectives, metrics, schedule, deliverables) the BAA has defined, not to the program you desire

Distribution Statement A. Approved for Public Release; Distribution Unlimited.

Full Proposal Preparation

- **Volume 1: Technical/Management Proposal**
  - Be mindful of the page limitations (Sec II: 20 pages)
  - Be sure to respond to all 11 of the required "Detailed Proposal Information" items

    - Technical Approach – is the centerpiece of the technical proposal

    - Statement of Work – Organize Phase, then by Tasks. Define all tasks (what you are doing, not how you are doing it) and deliverables (data, software, and material items, as applicable)

    ➢ Keep an eye out for proposal preparation guidance in the "Funding Opportunity Description" as well

- **Volume 2: Cost Proposal**
  - No page limitations
  - Fully detailed cost build-ups/estimates (Prime & Subcontractors)(All instrument types)
    - Summary Cost Build-up: By phase and performer fiscal year
    - Detailed Cost Build-up: By phase, technical task, and month
    - See Note 4 (this is new to all DARPA BAAs): DARPA Standard Cost Proposal Spreadsheet
  - All necessary supporting information (BoE, BoM, vendor quotes, rate agreements, etc.)
  - Subcontractor proposals are required (to include SOW)
  - No Rough Order of Magnitudes (ROMs)

Distribution Statement A. Approved for Public Release; Distribution Unlimited.

Full Proposal Preparation

Volume 2: Cost Proposal

Note 4 – DARPA Standard Cost Proposal Spreadsheet

The Government requires that proposers use the provided MS Excel™ DARPA Standard Cost Proposal Spreadsheet in the development of their cost proposals. A customized cost proposal spreadsheet may be an attachment to this solicitation. If not, the spreadsheet can be found on the DARPA website at http://www.darpa.mil/work-with-us/contract-management (under "Resources" on the right-hand side of the webpage). All tabs and tables in the cost proposal spreadsheet should be developed in an editable format with calculation formulas intact to allow traceability of the cost proposal. This cost proposal spreadsheet should be used by the prime organization and all subcontractors. In addition to using the cost proposal spreadsheet, the cost proposal still must include all other items required in this announcement that are not covered by the editable spreadsheet. Subcontractor cost proposal spreadsheets may be submitted directly to the Government by the proposed subcontractor via e-mail to the address in Part I of this solicitation. Using the provided cost proposal spreadsheet will assist the Government in a rapid analysis of your proposed costs and, if your proposal is selected for a potential award, speed up the negotiation and award execution process.

- **Do not make changes that are specifically prohibited by the instructions**
- **Questions are welcomed. Please direct them to costproposal@darpa.mil**

Distribution Statement A. Approved for Public Release; Distribution Unlimited.

Data Rights

- **Government desires as few restrictions as possible - however….**

- **If asserting less than Unlimited Rights (e.g., Restrictions):**
  - Provide and justify basis of assertions using the prescribed format
  - Explain how each item will be used to support the proposed research project
  - Explain how the Government will be able to reach its program goals (including technology transition)

✓The proposer (prime) must submit a Data Rights Cert covering the entire team (prime and subcontractors), as applicable

✓Provide a Data Rights Cert no matter the instrument type being proposed

✓This information is assessed during evaluations (barriers to transition)

Distribution Statement A. Approved for Public Release; Distribution Unlimited.

Pitfalls That Delay Proposal Review or Result in Non-Conforming

- **Failure to submit proposal on time - noncompliant!**
  - Proposal due date and BAA closing date are the same – so, late is late!
- **Failure to submit using the correct mechanism - noncompliant!**
  - Unclassified proposals (for procurement contract or OT) ONLY to DARPA BAA website
  - Classified proposals/information ONLY per "Security Information" section of the BAA
- **Failure to submit both proposal volumes - noncompliant!**
  - OT proposals must also include a full cost volume (Cost Realism is an evaluation criterion for all proposals)
  - OT proposals must also include a detailed list of payment milestones (Milestone Plan)
- **Pages beyond the page limitation (tech prop) - pages will not be reviewed** (or could result in being deemed noncompliant!)
- **ROM/s instead of full subcontract cost proposal/s - noncompliant!**
  - "I didn't have time to get the subcontract proposal/s" will not change the outcome
  - "My subcontractor/s would not give me a proposal" will not change the outcome
- **Missing FFRDC or Government Entity cost proposal – noncompliant!**

Distribution Statement A. Approved for Public Release; Distribution Unlimited.

Communications

- **Prior to Receipt of Proposals (Solicitation Phase): No restrictions, however Gov't (PM/PCO) shall not dictate solutions or transfer technology**
  - ➢ Typically handled through the FAQ
- **After Receipt of Proposals/Prior to Selections (Scientific Review Phase): Limited to Contracting Officer or BAA Coordinator (with approval) to address clarifications requested by the review team**
  - ➢ Proposal cannot be changed in response to clarification requests
- **After Selection/Prior to Award (Negotiation Phase): Negotiations are conducted by the Contracting Officer**
  - ➢ PM and/or COR typically tasked with finalizing the SOW (with PI)
  - ➢ PM and/or COR typically involved in any technical discussions (i.e., partial selection discussions)
  - ➢ Pre-award costs will not be reimbursed unless a pre-award cost agreement is negotiated prior to award
- **Informal Feedback Sessions (Post Selection): May be requested/provided once the selection(s) are made**
  - – If made on a timely basis (~1 wk after letter), all requests will be accepted

Distribution Statement A. Approved for Public Release; Distribution Unlimited.

Referenced Links

- http://www.darpa.mil/work-with-us/contract-management#SolicitationContracting
  (General DARPA contract management information)
  (DARPA Standard Cost Proposal Spreadsheet)

- http://www.darpa.mil/work-with-us/additional-baa
  (general BAA info pertaining to all instrument types)

- http://www.darpa.mil/work-with-us/procurementcontracts
  (info pertaining to contracts)

- https://acquisitioninnovation.darpa.mil/
  (info pertaining to OTs)

- http://www.darpa.mil/work-with-us/reps-certs
  (DARPA-specific reps and certs for all instrument types)
  (Note August 2020 version of 52.204-24)(Similar is required for OTs as well)

Distribution Statement A. Approved for Public Release; Distribution Unlimited.

MTO Security Briefing for Ultra Wide Bandgap Semiconductors (UWBGS)

MTO PSR – Joey Gilchrist

MTO PSO – James Persons

5 October 2023



DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited

Unplanned Interruptions

- Teleconference attendees should remain on the line
  - In cases with interruptions stay on the line and a notice will be sent for attendees once the interruption has been resolved (Evacuation, Fire Alarm etc.)

DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited

Meeting Level

This meeting is for:

UWBGS Proposer's Day

This Zoom meeting is at:

UNCLASSIFIED LEVEL

- Classified discussions are prohibited!

DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited

COMMUNICATIONS

- All Questions & Answers (Q&A) **MUST** go through the BAA IN-BOX
  - Individual folders will be setup for Security and Technical
  - BAA Coordinator will file questions in the appropriate folders
  - Folders will be reviewed each day and questions answered as time permits
  - **DO NOT** go direct with MTO Security
  - BAA Coordinator will provide Frequently Asked Questions List (FAQs) as directed by the PM

DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited

Submissions (Follow the BAA Guidance)

- Address for mailing Unclassified & Collateral Classified
  - Defense Advanced Research Projects Agency Address
    ATTN: Program Security Officer, MTO
    Reference: HR001123S0013
    675 N Randolph St, Arlington, VA 22203

- All Unclassified Proposals **must** be submitted through the BAAT:
    - DARPA BAA Website (https://baa.darpa.mil) IAW Section IV.C.2. of the BAA.
  - Classified Proposals
    - MAILING (Provide a Tracking #) or HAND-CARRIED (Arrival Notification)
      - Must notify us through the BAA IN-BOX if your submitting classified

- Forward the BAA to your Security Team and **inform** your Security Team on what you are planning to do:
  - Classified submission
  - Classified systems you intend to use
  - Classified spaces you intend to use

DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited

CLASSIFIED Submissions

- Proposers choosing to submit classified information from other collateral classified sources (i.e., sources other than DARPA) must ensure:

  - (1) they have **permission** from an authorized individual at the cognizant Government agency (e.g., Contracting Officer, Program Manager)

  - (2) the proposal is **marked in accordance** with the source Security Classification Guide (SCG) from which the material is derived

  - (3) the source **SCG is submitted** along with the proposal

DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited

CUI Compliance

- COMPLIANCE WITH CONTROLLED UNCLASSIFIED INFORMATION (CUI)
  - MANDATED
  - NATIONAL INSTITUTE of STANDARDS & TECHNOLOGY (NIST) Special Publication (SP) 800-171 “Protecting Controlled Unclassified Information in Non-Federal Information Systems and Organizations
- CUI Markings
  - Marked appropriately in accordance with DoDI 5200.48.
  - CUI needs to be identified and protected, please mark your proposals accordingly

DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited

ANY QUESTIONS?

Thank you for your time☺



DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited

Ultra Wide Bandgap Semiconductors (UWBGS)

Proposers Day Recording:

https://www.youtube.com/watch?v=wCLROJEibfg