Diamond for Power Devices

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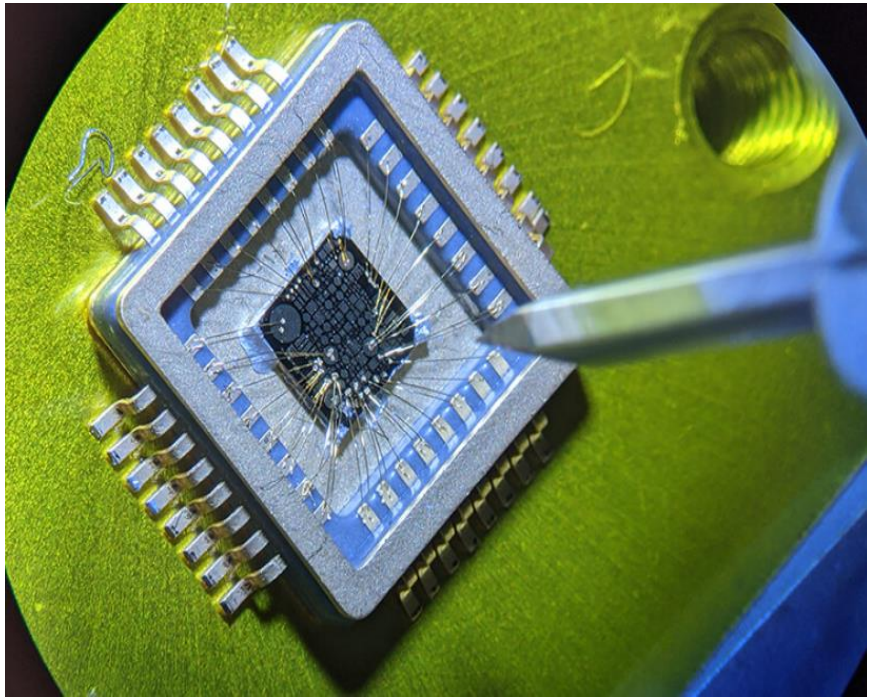
Introduction

The growing electrification of the transportation fleet, and the rapid adoption of renewable energy, is driving a need for new high-performance power electronics.

Electric vehicle charging stations, AC/DC power converters, electric motor drives, solid-state circuit breakers, and solid-state transformers are examples of power electronics products with large and growing markets.

Advent Diamond is developing power electronics components with diamond, the ultimate high temperature and power material.

Diamond’s very high mobility, ultra-high breakdown electric field, and the highest thermal conductivity of any bulk semiconductor material promises outstanding performance for diamond high power devices



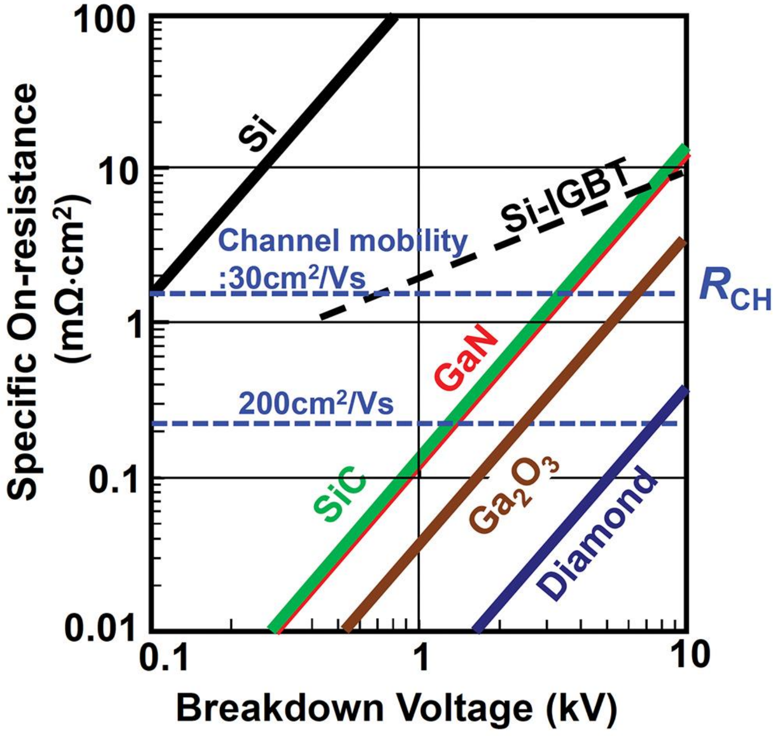
Performance metrics and FOM

Comparison with Alternatives

Property	Units	Si	GaAs	4H-SiC	GaN	AlN	Ga_2O_3	Diamond
Bandgap	eV	1.1	1.43	3.23	3.4	6	4.9	5.5
Saturated drift velocity	10^7 cm/s	1	1	2.1	1.4	1.3	1.1	2.3
Electron mobility	$cm^2/V\text{-}s$	1,240	4,167	980	1,000	426	153	7,300
Hole mobility	$cm^2/V\text{-}s$	480	400	120	11			5,300
Breakdown field	MV/cm	0.3	0.4	3.1	4.95	15.4	10.3	13
Thermal conductivity	W/cm-K	1.45	0.55	3.7	2.53	3.19	0.22	22.9
Thermal Exp. Coefficient	$10^{-6}K^{-1}$	2.6	5.8	2.8	3.2	4.6	8.3	1
Relative Permittivity		11.9	12.9	9.7	10.4	10.1	10	5.7

- Baliga's Figure of Merit (BFOM) and its significance
- On-resistance Vs Breakdown voltage trade-offs
- Other relevant metrics like thermal management, current density, switching speed

Breakdown Voltage Vs ON-Resistance



- We are searching for a material whose characteristics are very close to the right bottom corner of the plot.
- We want to design a device which can be operated at high voltages but offers very low ON resistance

Limitations of BFOM

- Neglects Thermal conductivity of a material
- Ignores Surface conduction mechanisms
- It prioritizes conduction losses
- Diamond's incomplete dopant ionization significantly degrades its practical electrical performance compared to theoretical predictions from Baliga's FOM

Diamond Specific Considerations

For diamond devices, modified figures of merit must account for:

- Ultra-high thermal conductivity (>2200W/mK) enabling superior heat dissipation.
- Critical electric field (>10 MV/cm) allowing thinner drift layers.
- Negative temperature coefficient (NTC) of forward resistance

A comprehensive factor could be:

$$Q_{F2} = \frac{\lambda E_c}{R_{ON,sp}}$$

Diamond Specific Considerations

Table 1: Comparison of Quality Factors for Power Semiconductors

Material	Q_{F2} (Normalized)	E_c (MV/cm)	λ (W/mK)
Silicon	1	0.3	150
4H-SiC	4.63	3.18	370
GaN	0.71	3.5	100
Diamond	14.6	20	2200

System-Level Metrics

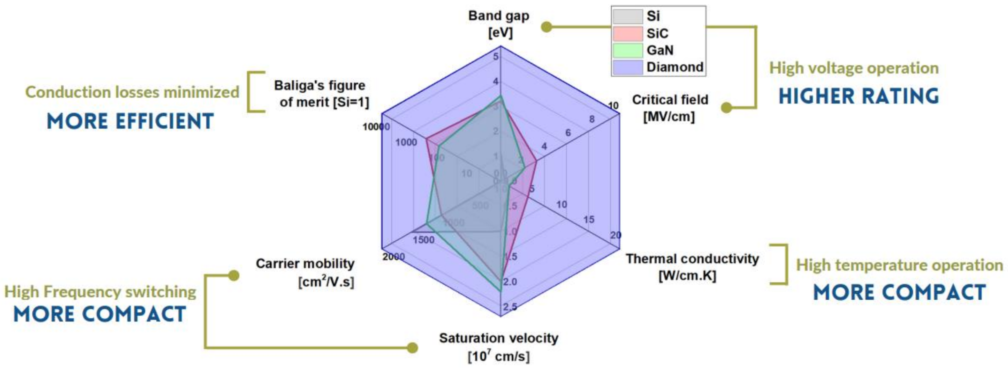
Additional critical parameters for diamond devices include:

- **Gate charge (QG) density**: <10 nC/cm2 for RF applications.
- **Switching frequency potential**: >100 GHz for optimized structures.
- **Maximum junction temperature (Tjmax)**: >450 K operational capability.

The combination of QF2, QG, and Tjmax provides a complete framework for evaluating diamond power devices against traditional semiconductors like SiC and GaN. Diamond's unique negative temperature coefficient of resistance fundamentally changes thermal management considerations compared to other wide bandgap materials.

Case Study Diamond vs SiC

- Both SiC and Diamond materials offer significant advantages over traditional silicon, but diamond exhibits several superior intrinsic properties that position it as a next-generation material for demanding power applications.



For example, a 1200 V SiC MOSFET requires a thicker drift layer than a diamond device, increasing costs and size. Diamond's thermal conductivity also reduces cooling requirements, enhancing system reliability.

$$d = \mathrm{V} / Ec$$

Material Properties Comparision

- Diamond’s thermal conductivity is more than five times higher than that of SiC,
- Its breakdown electric field is also more than three times greater, allowing for thinner drift layers and higher voltage operation.
- The wider bandgap of diamond supports higher temperature and voltage operation.

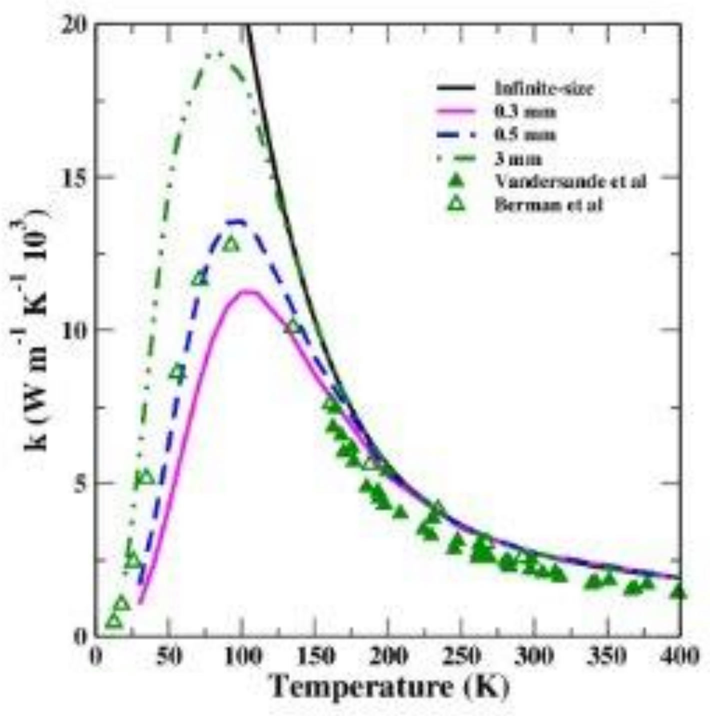
Table 2: Comparison of Key Material Properties of SiC and Diamond

Property	SiC	Diamond
Thermal Conductivity (W/mK)	370	2200
Breakdown Electric Field (MV/cm)	3.18	10
Bandgap Energy (eV)	3.26	5.5
Carrier Mobility (cm^2/Vs)	980	1800

Device and System Implications

- **Higher efficiency**: Diamond devices can cut energy loss by a factor of three compared to SiC, and allow for up to a fourfold reduction in die.
- **Thermal management**: The high thermal conductivity reduces the need for bulky cooling systems, enabling more compact and reliable designs.
- **High-temperature operation**: Diamond devices can operate at temperatures exceeding 300◦C, with improved forward resistance at elevated temperatures, mitigating thermal runaway risks.
- **Switching performance**: Higher carrier mobility and breakdown field support faster switching and higher voltage ratings.

Device and System Implications



- **Thicker samples** (e.g., 3 mm) achieve higher peak k values (up to nearly 20,000 Wm−1K−1), while thinner samples (0.3 mm, 0.5 mm) exhibit lower peaks.
- **High temperature behaviour**: Above 100 K, k decreases for all samples and converges toward similar values as temperature approaches 400K. This is due to increased phonon-phonon scattering, which dominates at higher temperatures.

Device and System Implications

- Diamond’s extremely high thermal conductivity, especially at low and moderate temperatures, is a critical advantage for power electronics. This property enables efficient heat dissipation, reducing the risk of thermal runaway and supporting high-power, high-temperature operation in diamond-based semiconductor devices.
- However, for thin-film or miniaturized diamond components, boundary scattering can significantly reduce k at lower temperatures, which must be considered in device design.

Table 3: Summary of Key Features from the Thermal Conductivity Graph

Sample/Curve	Peak k ($W\,m^{-1}\,K^{-1}$)	Peak Temp (K)	Low-T Lim	High-T Lim 400 K
Infinite-size	~20,000	~80	Highest	~2,000
3 mm	~18,000	~90	Lower	~2,000
0.5 mm	~13,000	~100	Lower	~2,000
0.3 mm	~11,000	~110	Lowest	~2,000

Power Electronic Applications

1. Schottky PIN Diodes
2. High – Temperature Performance
3. High Power RF systems
4. Renewable Energy Infrastructure
5. EV industry

Schottky PIN Diodes

Diamond Schottky PIN diodes combine Schottky and PIN structures for enhanced performance.

- **Structure:** Metal/p+-i-n+ configuration with 2-5 μm intrinsic layer
- Low forward voltage drop (1.5V @ 100A/cm2)
- Ultra-fast switching (<5ns recovery time)
- High power handling (10kW/mm2 at 1GHz)

The key distinguishing feature is that the n-layer becomes fully depleted by the top metal contact, causing the device to operate as a high-speed Schottky rectifier rather than a traditional PIN diode

High Temperature Performance

Diamond devices exhibit superior thermal characteristics:

- Stable operation upto 500K (227°C) with negative on resistance temperature coefficient.
- 3 times lower thermal resistance when compared to SiC (0.5 K·mm/W vs 1.5 K·mm/W).
- 85% efficiency maintenance at 300°C vs 40% for SiC counterparts.

Table 4: Temperature-Dependent Performance Comparison

Parameter	Diamond	SiC	GaN
Max Operating Temp (°C)	300	200	150
Thermal Conductivity (W/mK)	2200	370	130
Power Loss @ 200°C (W/mm)	15	45	60

Applications

- **High-Power RF Systems:**
  - Radar receiver protectors with >30dB power rejection
  - 5G basestation amplifiers (24-40GHz bands)
- **Renewable Energy Infrastructure:**
  - 10kV solar inverter modules with 99.3% efficiency
  - Solid-state transformers for wind farms
- **Transportation Electrification:**
  - 350kWEVfastchargers with 50% size reduction
  - All-electric aircraft power distributio

EV Charging Infrastructure

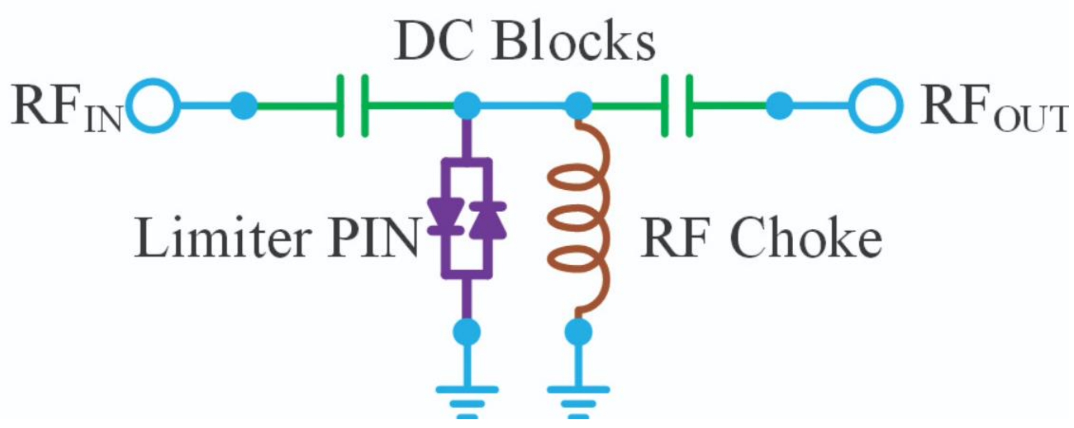
Blue Diamond Garden Centres deployment (2023-2024)

- System specs:
  - – 300+ charge points (22-350kW) across 28 locations.
  - – 4×ultra-rapid 350kW chargers per site.
- Performance metrics:
  - – 150,000 kWh delivered (500,000+ electric miles).
  - – 47,000 kg CO_2 offset through renewable charging.
  - – 98.5% charger uptime maintained.
- Technical advantages:
  - – 40%reduction in cooling system size vs SiC-based chargers
  - – 15%higher peak efficiency (96.2% vs 83.5%)

The diamond-enabled chargers demonstrate 50% faster charge cycles compared to conventional systems while maintaining junction temperatures 60°C lower than SiC solutions under comparable loads

A case study: RF Diodes

- Receiver protector circuits are crucial in radar and RF communication systems where high-power signals threaten critical failure or damage to sensitive receiver components and subsystems.
- Successful receiver protection involves the reflection of large amplitude input signals while exhibiting negligible insertion loss for low amplitude signals.
- The antiparallel or back-to-back configuration allows for reflection of both large positive and negative voltage swings.



RF Diode Developments

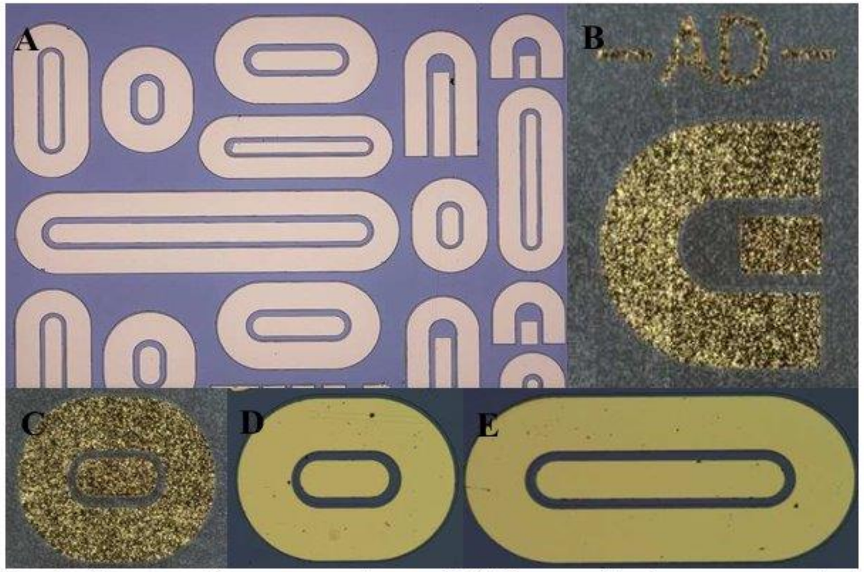


Fig.2. Shows A) an overview of different diodes geometries and areas. B-E) closeups of individual diodes on two different substrate types

- The use of diamond as both our substrate and thin film material enables superior specifications for RF diodes used in receiver protect circuits by leveraging the fundamental properties of diamond.
- Advancements in boron and phosphorus doped diamond thin film growth has facilitated the demonstration of an array of diamond devices.
- A major advantage of diamond devices is the exceptional thermal conductivity of greater than 20 W/(cmK), exceeding that of SiC and GaN.

Device Structures

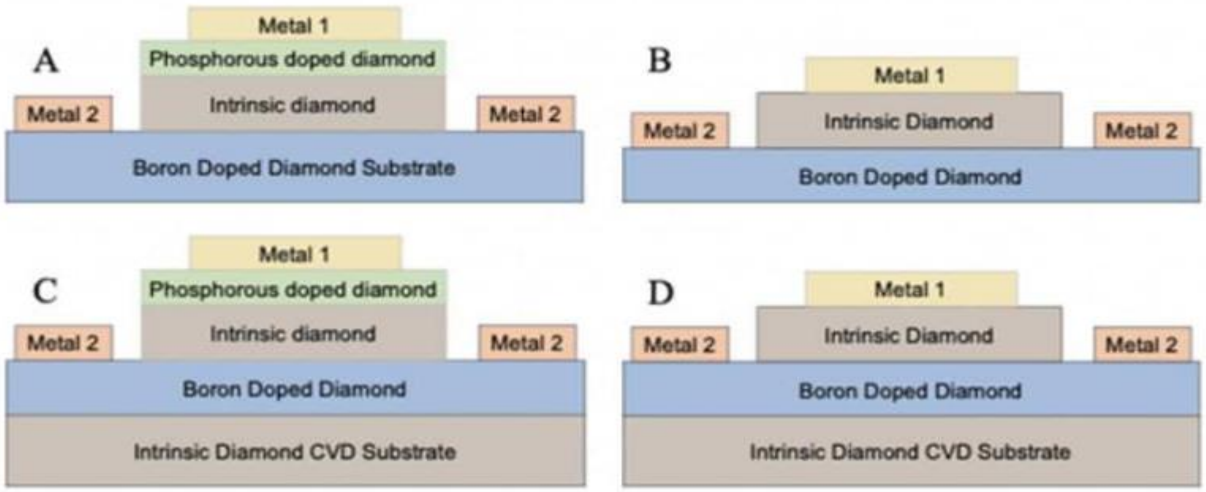


Figure 4: Cross-sectional view of a diamond RF diode.

Diamond RF diodes use boron-doped HPHT or CVD-grown intrinsic substrates. Intrinsic substrates enable device isolation for complex circuits, such as back-to back diode configurations.

Goals of the study

The first major goal was to replicate previous work on <111> HPHT diamond substrates with structure 1A.

The second goal in this work was to show that equivalent devices could be fabricated on intrinsic CVD substrates as shown in structure 1C and 1D.

The limitation of boron doped substrates is that every diode on the substrate will have a common anode, making it difficult to create the isolation between devices needed to connect two diodes back-to-back without shorting

Three distinct samples were fabricated with an array of co-planar strip-line diodes with varying areas and geometries.

labeled AD1, AD2, and AD3 which used structures 1A, 1A, and 1C

Structures Comparision

Table 5: Comparison of Diode Structures

Sample #	**Diode #**	**Diode Characteristics**				
		ssr (Ω)	C_{off} (pF)	C_{off}/A (nF/cm^2)	R*A (mΩ·cm^2)	*FOM (GHz)*
AD1	C	2.2	5.6	17.2	0.71	13
	F	4.6	2.68	17.3	0.72	12.7
	G	8.8	1.43	17.2	0.73	12.7
AD2	C	3.6	5.63	16.8	1.21	7.8
	F	4.2	2.74	16.8	0.69	13.8
	G	6.5	1.42	16.5	0.56	16.5
AD3	C	6.4	6.70	19.0	2.20	3.7
	F	10.2	3.15	19.2	1.68	4.9
	G	15.1	1.72	19.1	1.36	6.1

Results

The study demonstrated successful fabrication of RF diodes with the goal of further optimization of device structures and exploration of power devices.

shown comparable small signal resistance values, off capacitance, and figure of merit values as those achieved on <111> substrates for <100> substrates.

The second goal was to achieve similar diode behavior using an intrinsic CVD grown substrate with a thin film boron layer instead of a boron doped HPHT substrate.

Table I. shows the differences in figure of merit values between these two structural variations (samples AD2 and AD3). For diode G, the smallest in area of all the diodes, the FOM value drops close to three times as a function of substrate.

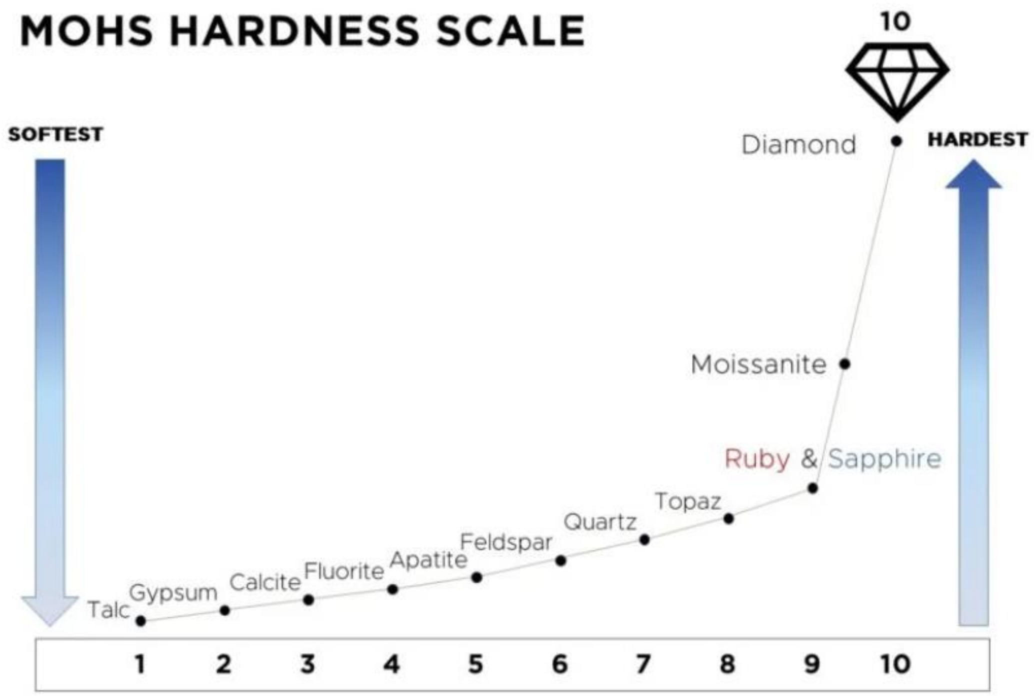
This can be most likely attributed to current crowding in the thin film boron doped layer of sample AD3. Whereas, the current within AD2 is not restricted to a thin film layer, but is free to flow withing the entire bulk of the substrate.

Samples AD1 and AD2 are both identical HPHT structures with the key difference being the metal selected for the metal contact to the phosphorous doped region. Table I, shows there is a clear correlation between metal selection and small signal resistance values, which lead to changes in the FOM value.

Challenges

1. Material Processing Challenges
2. Doping and Junction Formation
3. Commercial Manufacturing Ecosystem
4. Stability and Reliability Concerns

Material Processing Challenges



Diamond’s exceptional hardness (Mohs scale 10) creates fundamental manufacturing hurdles:

- Wafer processing: Conventional diamond wire slicing ineffective, requiring advanced techniques like laser ablation or plasma etching
- Substrate limitations: Current production limited to 2-inch wafers, with Orbray targeting 4-inch substrates by 2026.
- Thinning challenges: Achieving sub-200 μm thickness while maintaining crystal integrity remains problematic.

Doping and Junction Formation

Key technical barriers in device fabrication:

- **n-type doping:** Phosphorus doping yields carrier concentrations$<10^{17}$ cm−3 at room temperature
- **Activation energy**: Boron acceptors require>0.37eV, leading to incomplete ionization below 150◦C
- **Junction limitations:** PIN diodes exhibit high turn-on voltage (4.5V) compared to Si/SiC counterpart

Commercial Manufacturing Ecosystem

Current industry status and challenges:

- **Limited infrastructure:** <5 global suppliers for electronic-grade CVD diamond substrates
- **Process maturity:** Diamond device yield remains <60% vs >95% for SiC
- **Cost factors:** Substrate costs currently 50-100 × higher than equivalent SiC wafers

Stability and Reliability Concerns

Long-term operational challenges:

- **Surface degradation:** Hydrogen-terminated devices show 15% performance loss after 1000h at 300◦C
- **Current leakage:** Unwanted conduction paths observed in 30% of test devices
- **Thermal cycling:** >1000 cycles between-55◦C and 300◦C induces contact delamination

Future Work

Future work should focus on developing novel device architectures that can fully exploit diamond's unique material properties:

• Diamond MOSFETs and IGBTs: Building upon current diode technologies to develop more complex transistor structures with optimized doping profiles and gate configurations.

• Diamond RF transistors: Further refinement of the diamond transistors demonstrated by the University of Glasgow with improved enhancement-mode operation and higher on-current.

• Monolithic integration: Development of all-diamond power modules and integrated circuits to eliminate interface issues and maximize thermal performance.

• 2DHG-based devices: Advanced hydrogen-terminated diamond field-effect transistors leveraging the two-dimensional hole gas for improved performance.

Material Growth and Processing

Improving the quality, uniformity, and scalability of diamond growth processes remains crucial:

• Large-area substrates: Scaling from current 2-inch wafers to 4-inch and eventually 6-inch substrates for industrial viability

• Doping advancements: Developing new techniques for higher concentration, more uniform n-type doping beyond the current phosphorus limitation of 10^{17} cm−3

• Defect reduction: Methods to minimize dislocations and other crystalline defects that limit breakdown voltage below theoretical limits

• Surface passivation: Novel approaches for stable device termination and passivation to prevent performance degradation, particularly for hydrogen-terminated surfaces

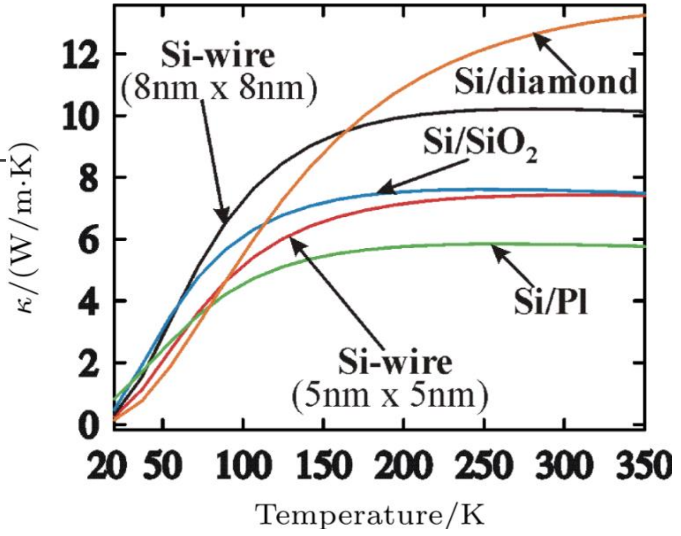
Thermal Management and Packaging

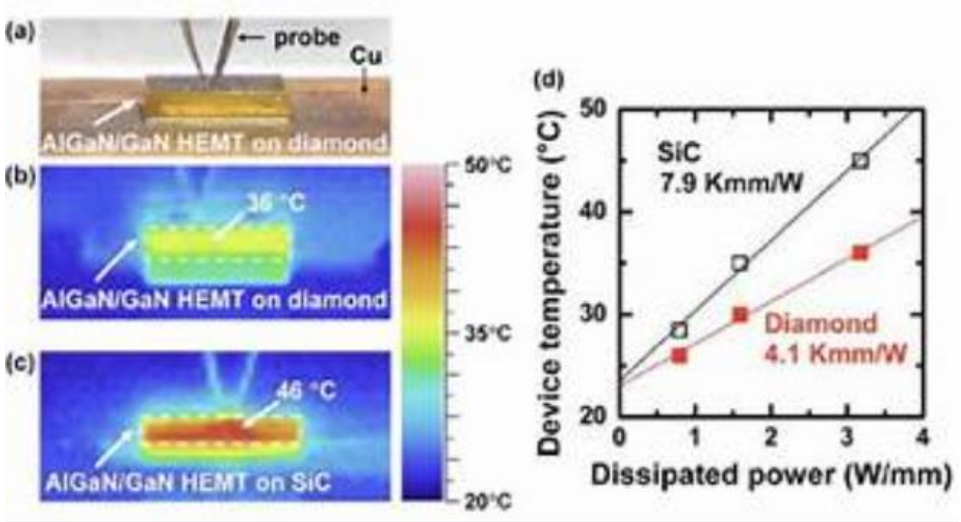
Research on packaging technologies specifically designed for diamond's unique thermal properties:

- Diamond-optimized packages: Development of packaging solutions that can fully utilize diamond's superior thermal conductivity

- High-temperature interconnects: Advanced metallization schemes and bonding techniques for reliable operation above 300 °C

- Direct cooling interfaces: Novel thermal interface materials and cooling systems optimized for diamond's thermal properties





Reliability and Long-term Performance

Comprehensive studies to address diamond's reliability challenges:

• Accelerated lifetime testing: Protocols for predicting long-term reliability under extreme operating conditions

• Failure mechanism analysis: Investigation of degradation and failure modes specific to diamond power devices

• Thermal cycling performance: Evaluation of device and package integrity through extensive thermal cycling from cryogenic to high temperatures

Application-Specific Development

- **Ultra-fast EV charging**: Diamond-based power modules specifically optimized for 350+ kW charging systems with minimized cooling requirements.
- **High-power RF applications**: Receiver protector circuits with >50 dBm input power handling and <0.3 dB insertion loss for radar and satellite communications. The rollout of 5G and development of 6G networks require high-frequency, high-power RF devices. Diamond's thermal conductivity (5x higher than cop per) and high electron mobility enable stable operation in 5G base stations and amplifiers, driving demand.
- **Grid-scale power conversion**: Diamond-based solid-state transformers for renewable energy integration with multi-kilovolt capability
- **Quantum technology integration:** Combining diamond power electronics with NV-center quantum sensors for novel applications. Diamond substrates are gaining traction in quantum computing. Diamond's lattice structure supports nitrogen-vacancy centers for quantum sensing, driving R&D investment.

Commercialization and Cost Reduction

Strategies to bridge the gap between laboratory demonstrations and commercial viability:

• Manufacturing scalability: Development of high-throughput fabrication processes with improved yield (>85%) and uniformity

• Cost reduction pathways: Process optimizations to reduce the current 50 100× cost premium over SiC devices

• Industry standards: Establishment of testing and qualification standards specific to diamond power devices

• Device-system co-design: Optimization of power electronic systems to fully leverage diamond’s unique characteristics rather than simple component re placement

Conclusion

- Diamond semiconductors represent a breakthrough in electronic material science, offering unparalleled performance for both power and RF applications.
- The exceptional intrinsic properties of diamond—extremely high thermal conductivity, ultra-wide bandgap, high carrier mobilities, and a breakdown electric field an order of magnitude greater than silicon—render it ideally suited for next-generation electronics.
- Despite these advances, substantial challenges remain. Device fabrication, particularly ohmic contact formation and n-type doping, is still an active area of research. Furthermore, the high cost of synthetic diamond substrates and limited commercial availability restrict scalability.
- Nonetheless, ongoing collaborative work across academic institutions, startups like Advent Diamond, and global semiconductor research centers is rapidly pushing the boundaries. If current trends in fabrication optimization, cost reduction, and device integration continue, diamond is well poised to become the corner stone of high-density, high-efficiency, and thermally robust electronic systems.

“The hardest material on earth may just be the key to the softest energy footprint.”

THANK YOU !