Diamond Power Semiconductor Devices

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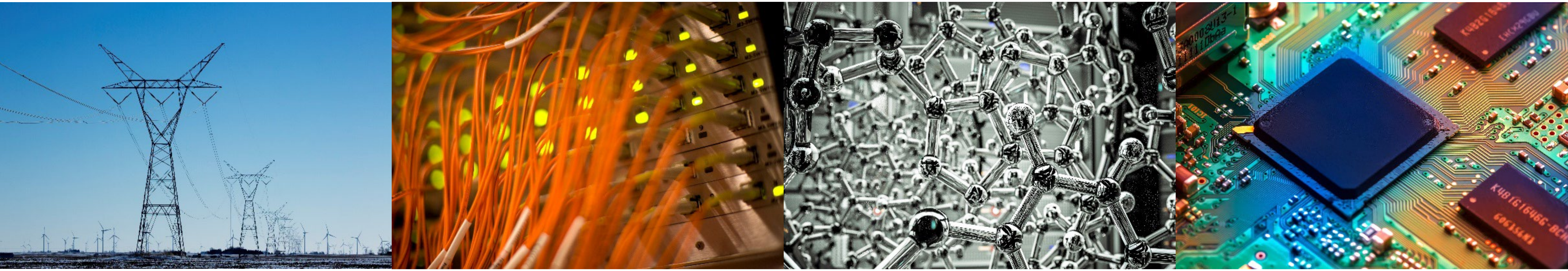


Evolving Wide Bandgap Materials and Device Technology for Advanced Switching, Microwave and Grid Applications

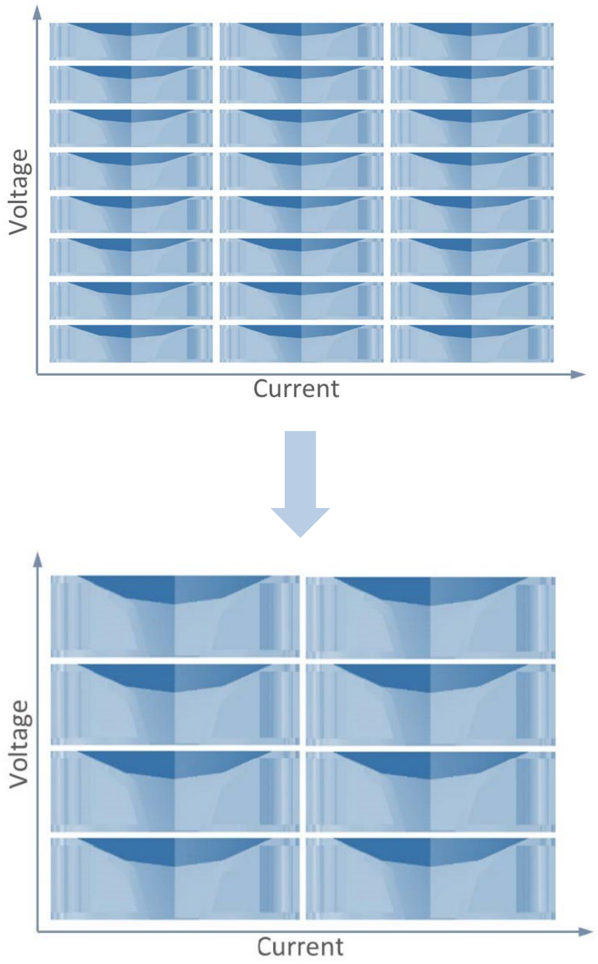
Nov 8th, 2024, Virtual

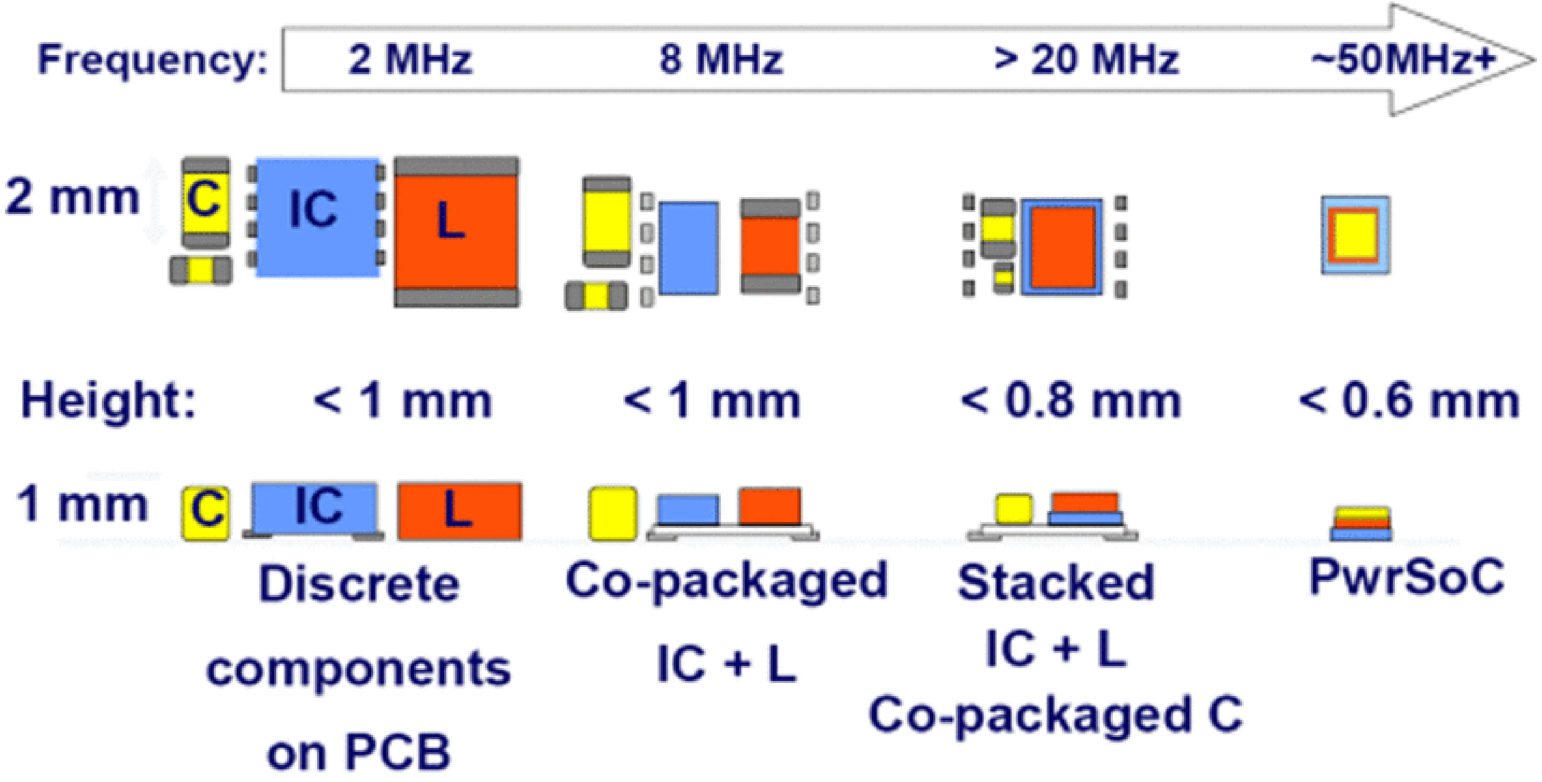
ILLINOIS
Electrical & Computer Engineering
COLLEGE OF ENGINEERING

Contents

- Introduction & Motivation
- Diamond Schottky Power Diodes
- Diamond Photoconductive Switches
- Conclusion & Future work

Motivation: higher voltage, current, and speed discrete devices



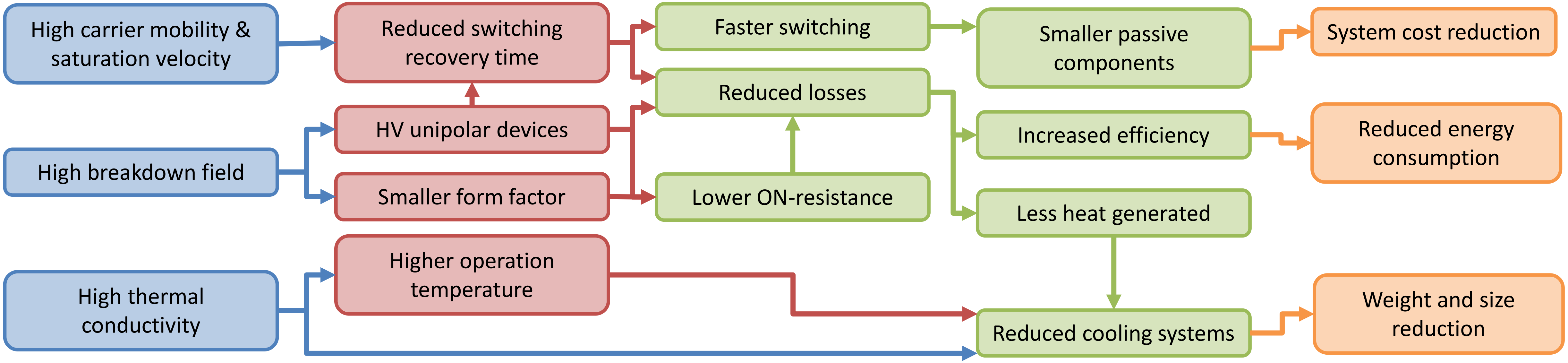


- ❖ Improve/simplify circuit realization with fewer higher voltage/current devices/modules
- ❖ Reduce energy storage requirements and passive component sizes

C. Ó. Mathúna, N. Wang, S. Kulkarni and S. Roy, "Review of Integrated Magnetics for Power Supply on Chip (PwrSoC)," in *IEEE Transactions on Power Electronics*, vol. 27, no. 11, pp. 4799-4816, Nov. 2012

Ultra-Wide-Bandgap semiconductors: diamond's material advantages

Si	4H-SiC	GaN	β-Ga_2O_3	AlN	Diamond



High carrier mobility & saturation velocity

High breakdown field

High thermal conductivity

Reduced switching recovery time

HV unipolar devices

Smaller form factor

Higher operation temperature

Faster switching

Reduced losses

Lower ON-resistance

Smaller passive components

Increased efficiency

Less heat generated

Reduced cooling systems

System cost reduction

Reduced energy consumption

Weight and size reduction

Donato, N., et al. "Diamond Power Devices: State of the Art, Modelling, Figures of Merit and Future Perspective." Journal of Physics., vol. 53, no. 9, 2020

Diamond power devices: performance advantages & key applications

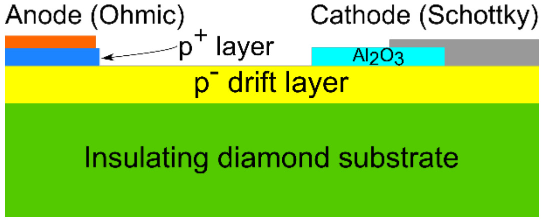
Next-Gen diamond devices

Application | **Diamond Devices** | **Performance Benefits** | **Prototype Diamond Devices**

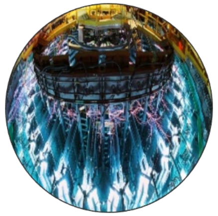
High voltage:
HVDC/UHVDC

Unipolar diodes
& transistors

Higher BV
Faster switching



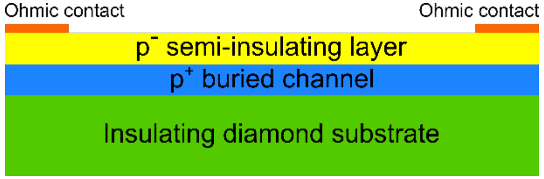
5 kV Lateral SBDs



Fast actuation:
Grid-protection
Pulsed power

Photo switches

Longer lifetime
High slew rates



Buried channel PCSS

Donato, N., et al. “Diamond Power Devices: State of the Art, Modelling, Figures of Merit and Future Perspective.” Journal of Physics., vol. 53, no. 9, 2020
Chow T P, Omura I, Higashiwaki M, Kawarada H and Pala V 2017 Smart power devices and ICs using GaAs and wide and extreme bandgap semiconductors IEEE Trans. Electron Devices 64 856–73

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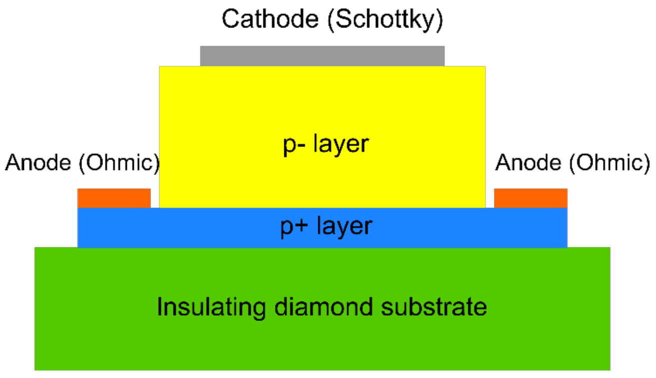
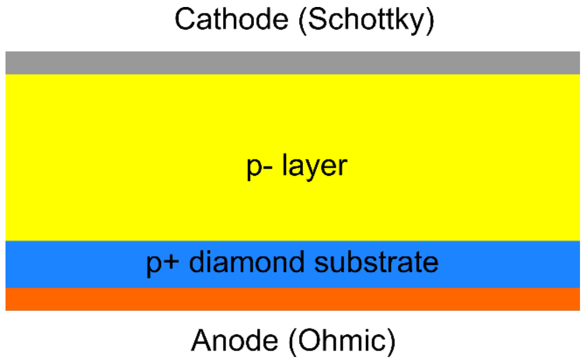
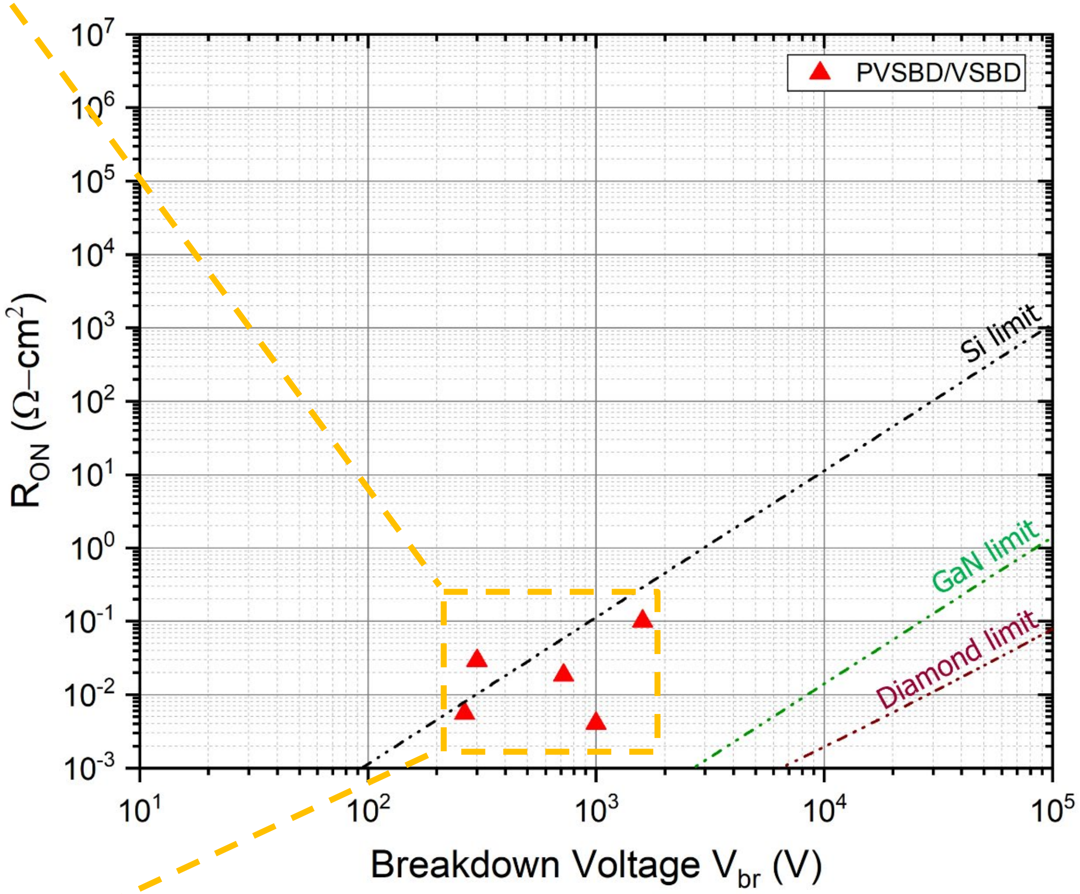
Diamond Schottky barrier diodes: vertical vs. Lateral



Pseudo-vertical SBDs



Vertical SBDs



Challenges for PVSBD/VSBD:

- Breakdown voltage scales with epitaxial layer thickness
- PVSBD: Deep dry etching of diamond is difficult & creates processing issues
- VSBD: Difficult to grow heavily doped substrate; high defect densities

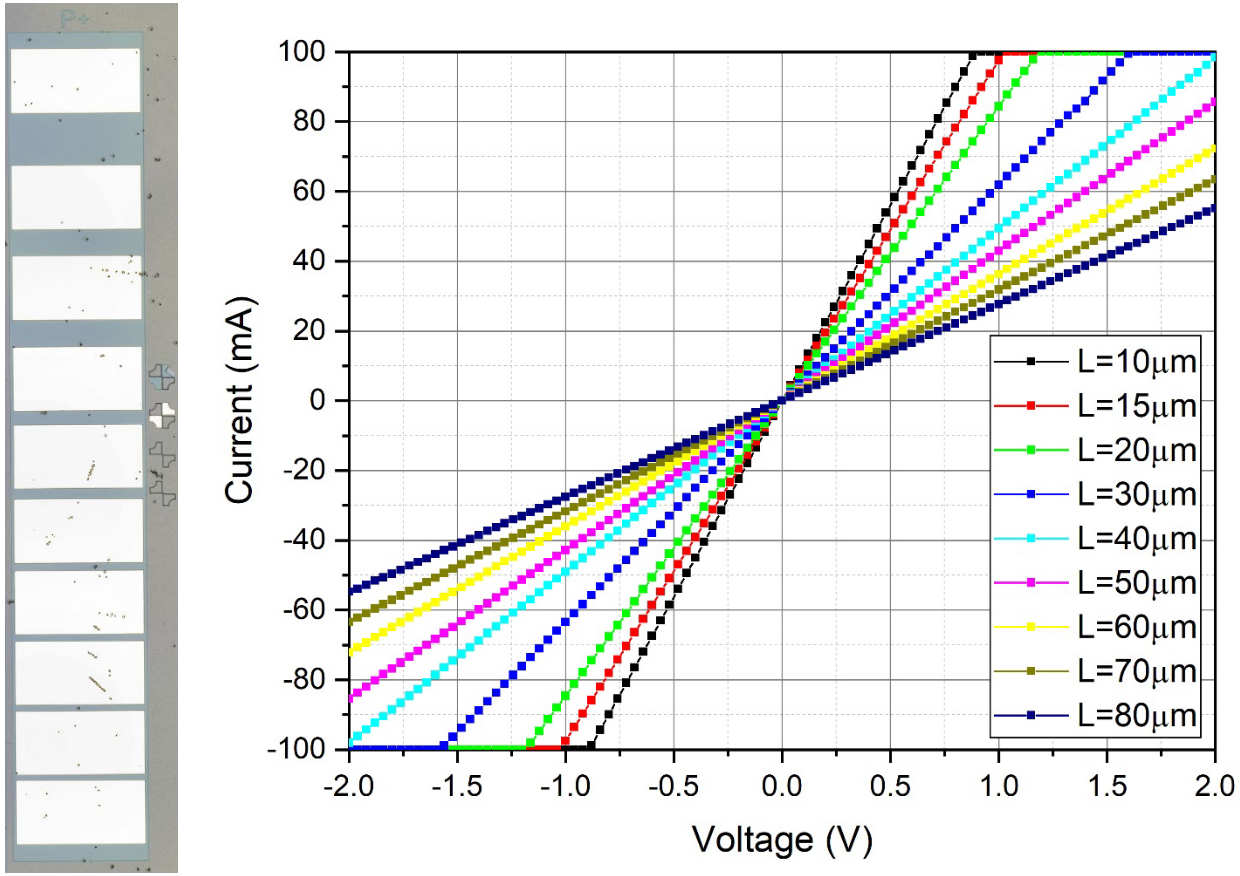
Solution for >5kV operations:

- Lateral SBD:
  - ✓ Scalability of BV
  - ✓ Does not require thick epitaxial layers

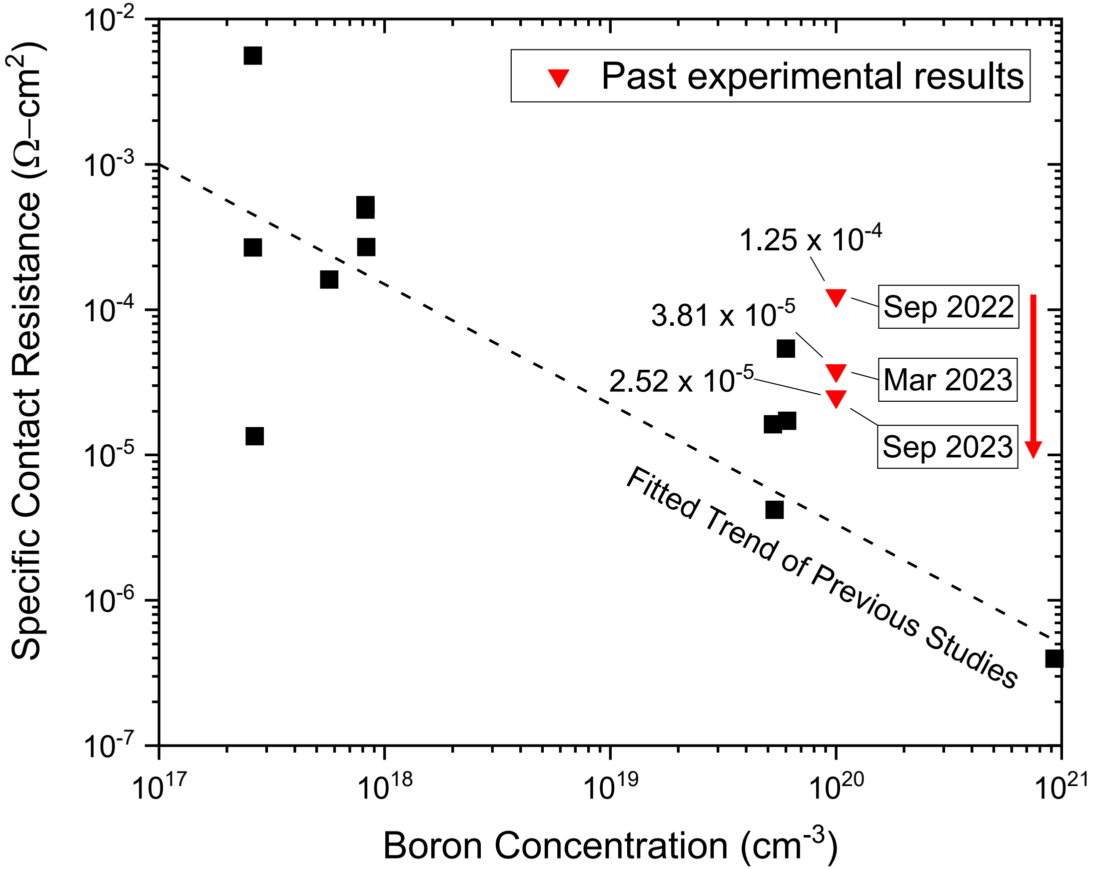
A. Traoré, P. Muret, A. Fiori, D. Eon, E. Gheeraert, and J. Pernot, Appl Phys Lett 104, (2014)
J. Wang, G. Shao, Q. Li, G. Chen, X. Yan, Z. Song, Y. Wang, R. Wang, W. Wang, S. Fan, and H.X. Wang, IEEE Trans Electron Devices 69, 6231 (2022)
H. Umezawa, S.I. Shikata, and T. Funaki, in Jpn J Appl Phys (Japan Society of Applied Physics, 2014)
K. Ikeda, H. Umezawa, N. Tatsumi, K. Ramanujam, and S. ichi Shikata, Diam Relat Mater 18, 292 (2009)
R. Kumaresan, H. Umezawa, N. Tatsumi, K. Ikeda, and S. Shikata, Diam Relat Mater 18, 299 (2009)

G. Chicot, D. Eon, and N. Rouger, Diam Relat Mater 69, 68 (2016).
Y. Kato, T. Teraji, T. Matsumoto, N. Tokuda, and H. Umezawa, in Power Electronics Device Applications of Diamond Semiconductors (Elsevier, 2018), pp. 219–294.
J. Achard, F. Silva, R. Issaoui, O. Brinza, A. Tallaire, H. Schneider, K. Isoird, H. Ding, S. Koné, M.A. Pinault, F. Jomard, and A. Gicquel, Diam Relat Mater 20, 145 (2011).
A. Toros, M. Kiss, T. Graziosi, S. Mi, R. Berrazouane, M. Naamoun, J. Vukajlovic Plestina, P. Gallo, and N. Quack, Diam Relat Mater 108, (2020).

Ohmic contact on P^+ boron-doped diamond

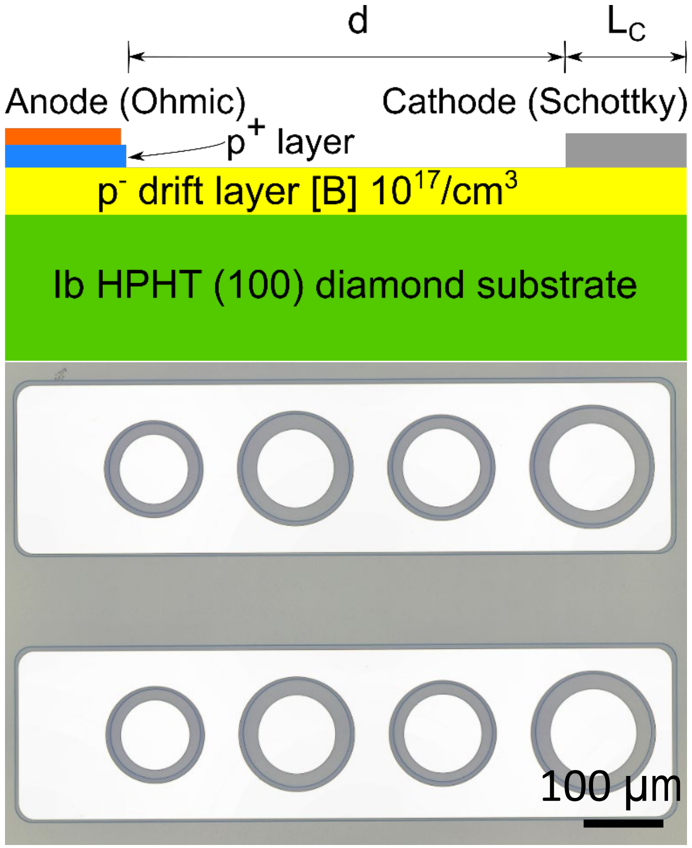


(Left) Optical microscope image of linear TLM patterns; (Right) *I-V* measurements from TLM patterns

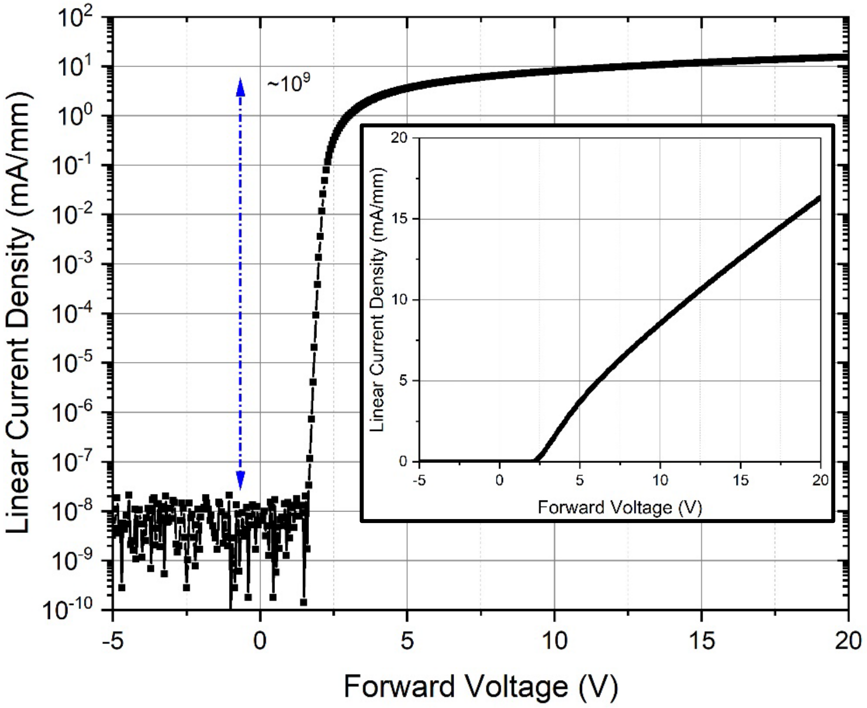


Summary of past experimental results, showing the progress in reducing specific contact resistance

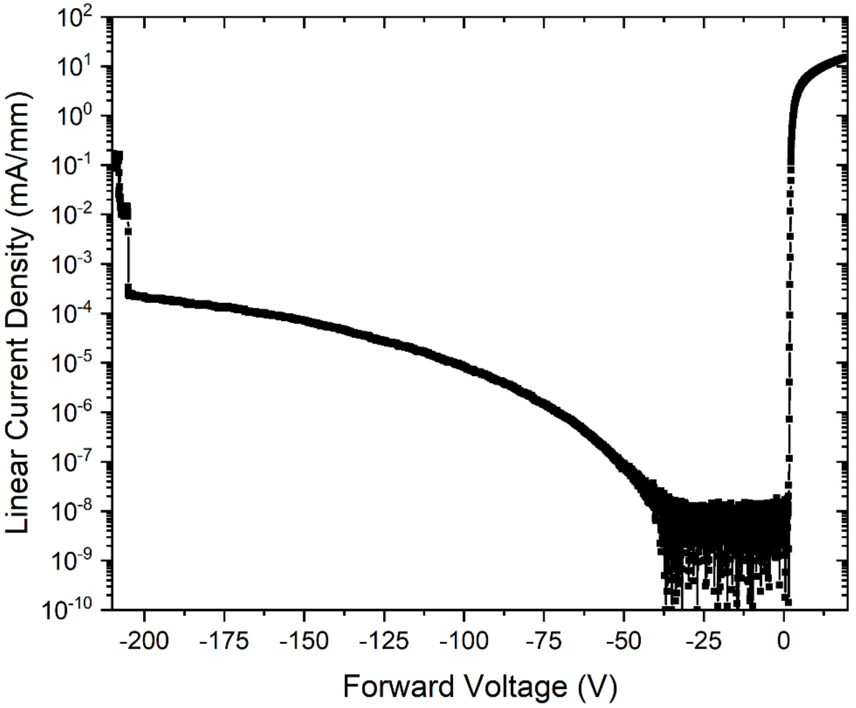
Schottky contact on P^- boron-doped diamond



Cross-section schematic (Top) and top-view microscope image (Right) of lateral Schottky diodes

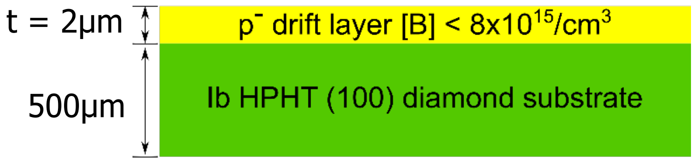


I-V characteristics of lateral Schottky diodes at room temperature in semi-log and linear scales

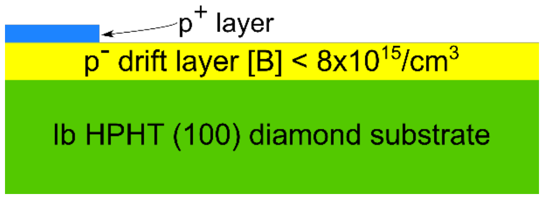


- Mo-diamond Schottky contacts are fabricated
- Diode Ideality factor ≤ 1.20
- Rectifying ratio over 10^9
- Peak electric field ≥ 4 MV/cm

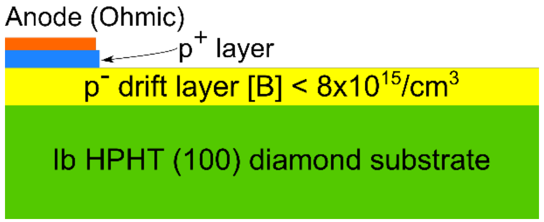
4.6 kV Diamond p-type lateral SBDs: Fabrication process



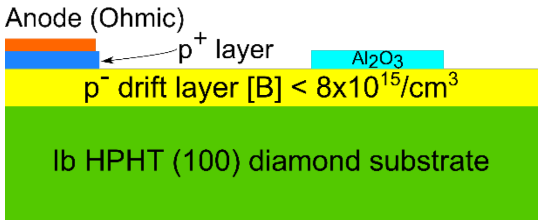
(a) P^- epitaxial growth



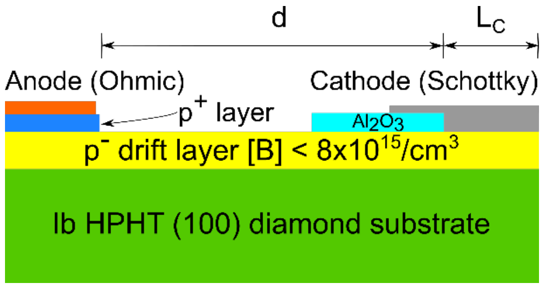
(b) P^+ selective growth



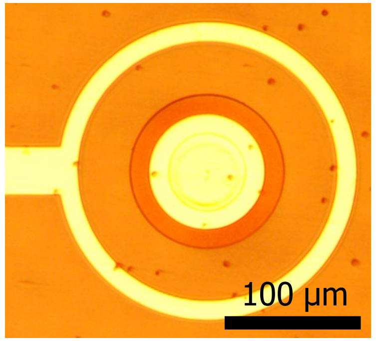
(c) Ohmic contacts deposition



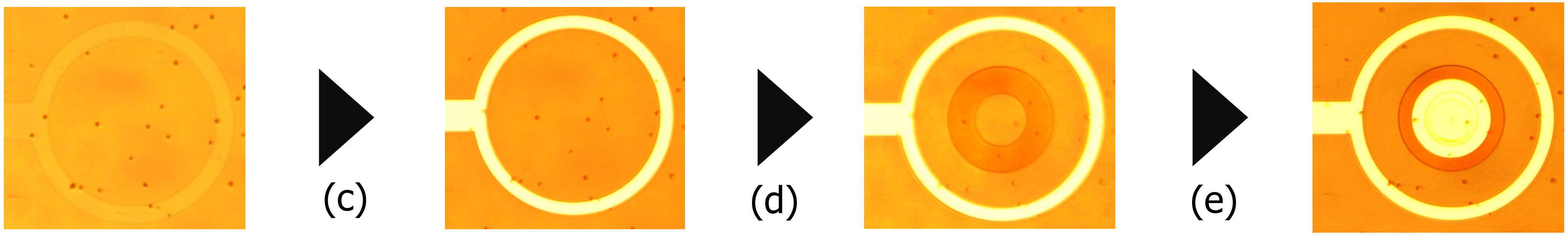
(d) Al_2O_3 field plates formation



(e) Schottky contacts deposition

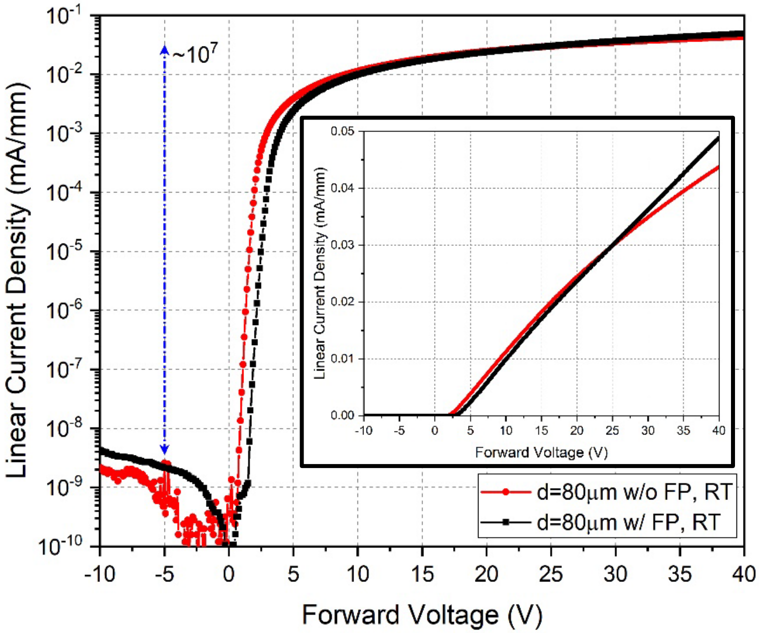


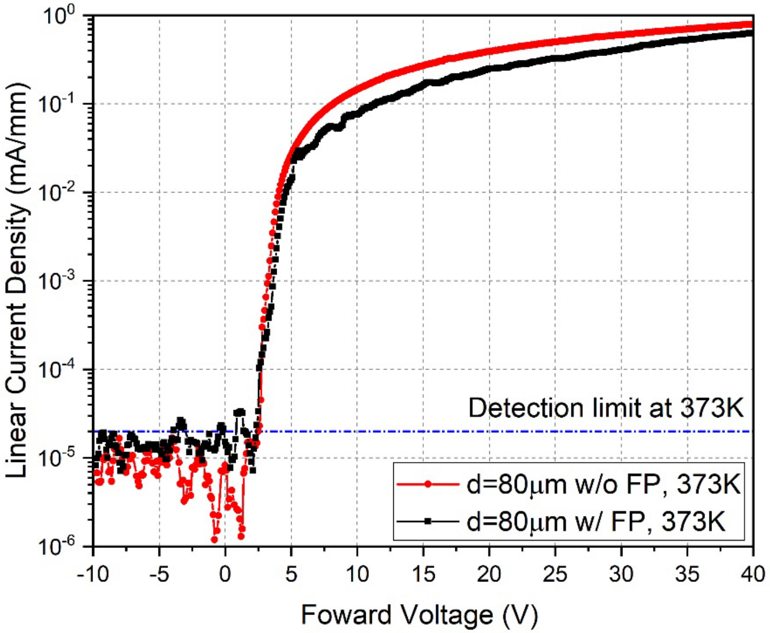
(f) Microscope image of an SBD

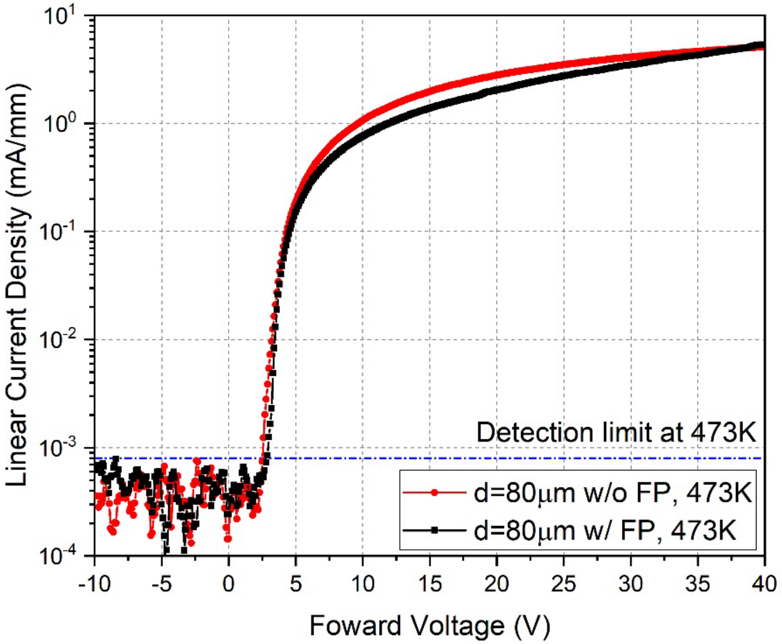


*Z. Han and C. Bayram, "Diamond p-Type Lateral Schottky Barrier Diodes With High Breakdown Voltage (4612 V at 0.01 mA/Mm)," in IEEE Electron Device Letters, vol. 44, no. 10, pp. 1692-1695, Oct. 2023, doi: 10.1109/LED.2023.3310910.

Diamond p-type lateral SBDs: Forward *I-V* characteristics





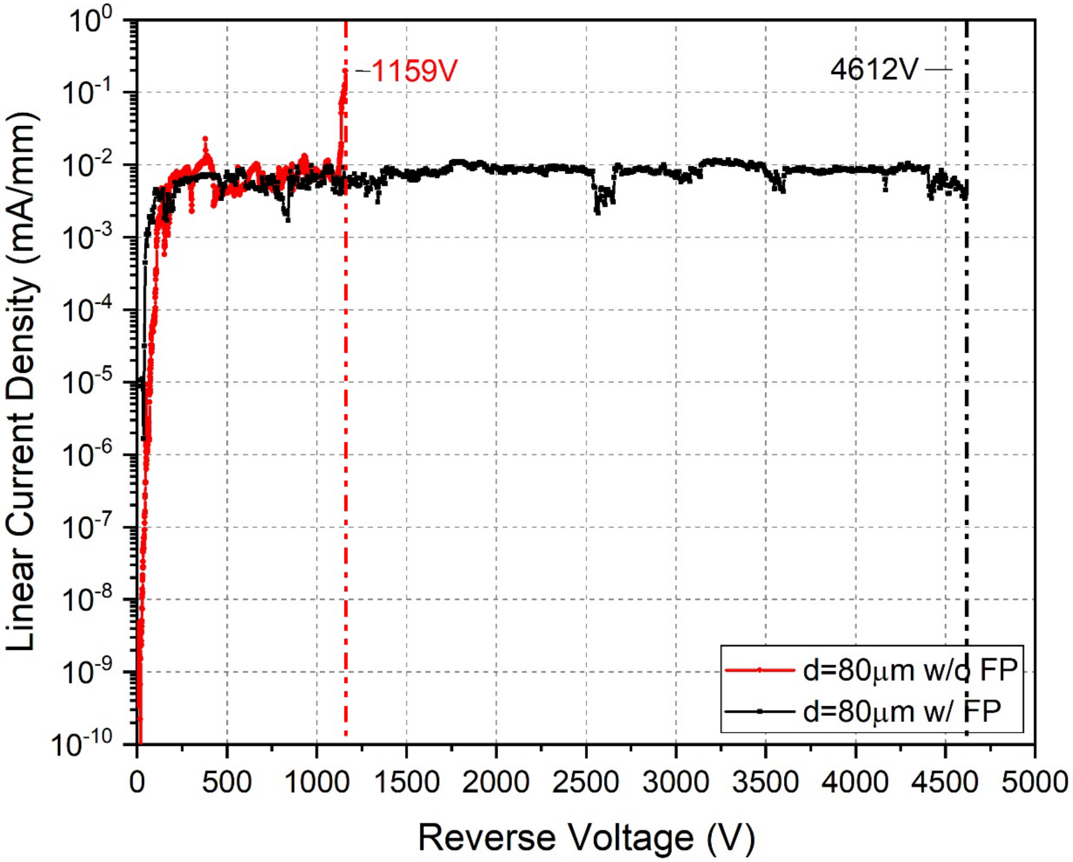


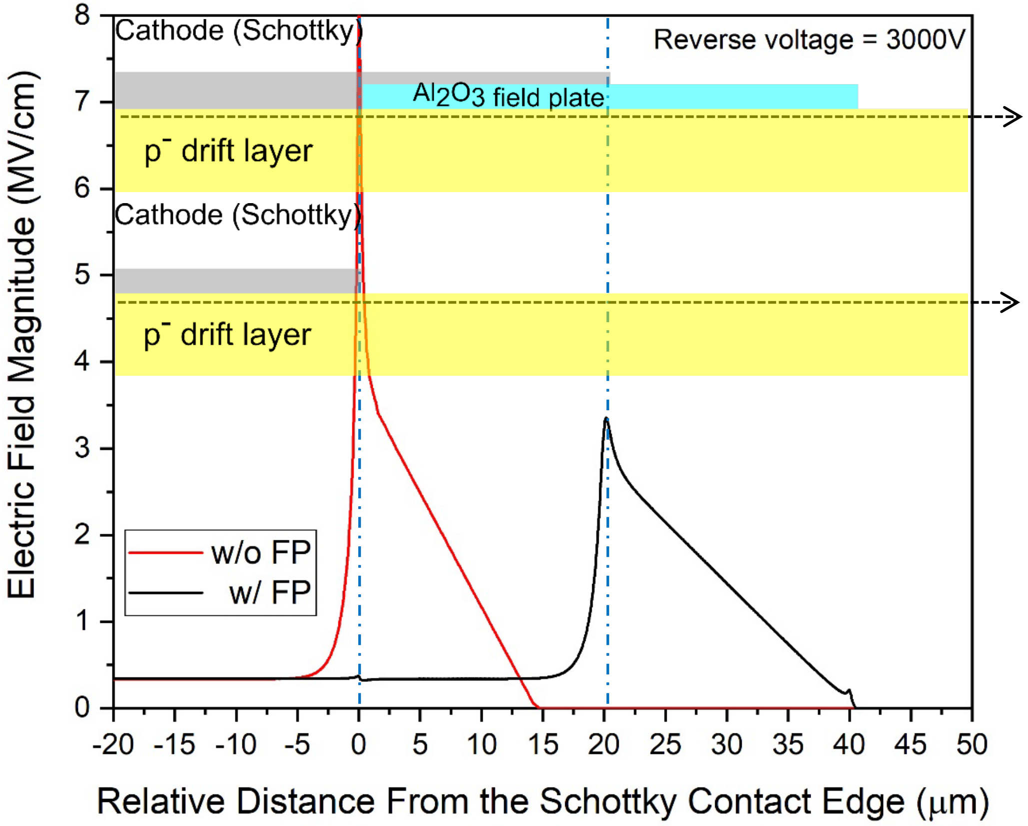
Forward current density at 40V, 300K:
- 0.044 mA/mm w/o FP
- 0.049 mA/mm w/ FP

Forward current density at 40V, 373K:
- 0.79 mA/mm w/o FP
- 0.64 mA/mm w/ FP

Forward current density at 40V, 473K:
- 5.39 mA/mm w/o FP
- 5.09 mA/mm w/ FP

Diamond p-type lateral SBDs: Reverse *I-V* characteristics





With the Al_2O_3 FP added, breakdown voltage improved from 1159V to over 4612V (limit of setup)

TCAD Simulation predicts a 56% reduction in peak electric field with the Al_2O_3field plate added

Summary & Benchmark

Performance goal

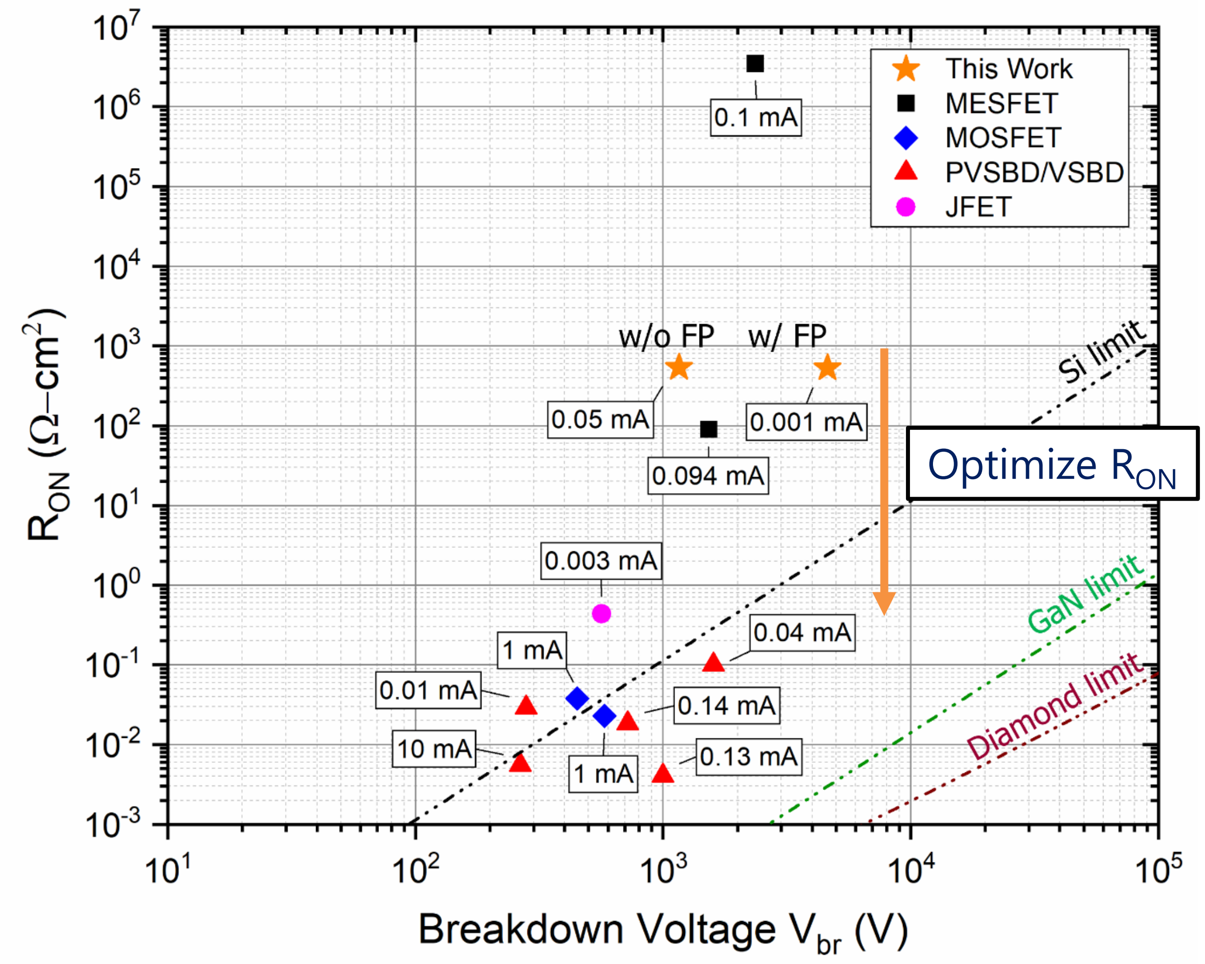
- ❖ 5kV diamond power diodes

Approach

- ❖ Lateral Schottky diodes
- ❖ Contact regrowth
- ❖ Edge termination

Results

- ❖ >4.6kV breakdown voltage
- ❖ Low contact resistance
- ❖ Improved performance at high temperature conditions



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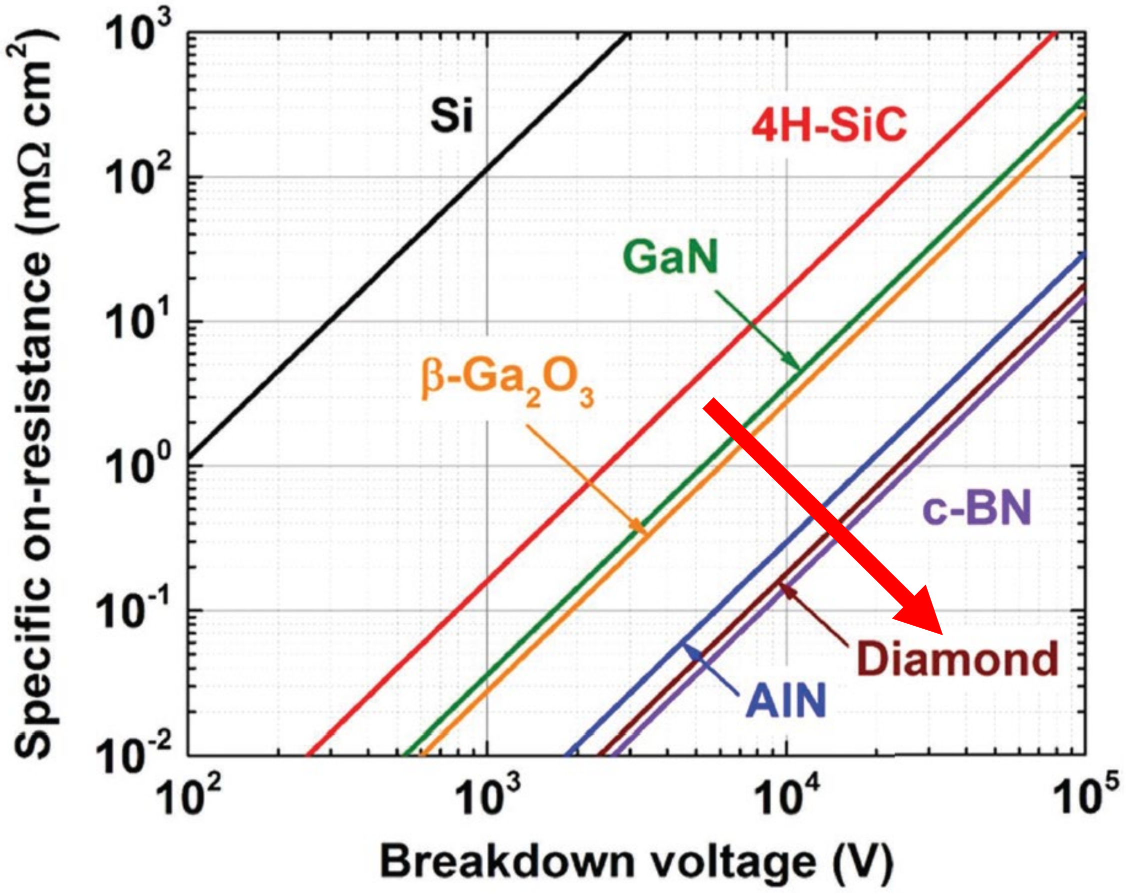
Reaching diamond’s material limit with novel power devices

How to reach BFOM limits of UWBG materials?



Contours of constant Baliga figure-of-merit (BFOM)

Challenges for reaching diamond’s limit:

- Poor dopant incorporation efficiency at room temperature
- P-type boron activation energy: 0.38 eV from valence band maximum
- N-type phosphorous activation energy: 0.57 eV from conduction band minimum

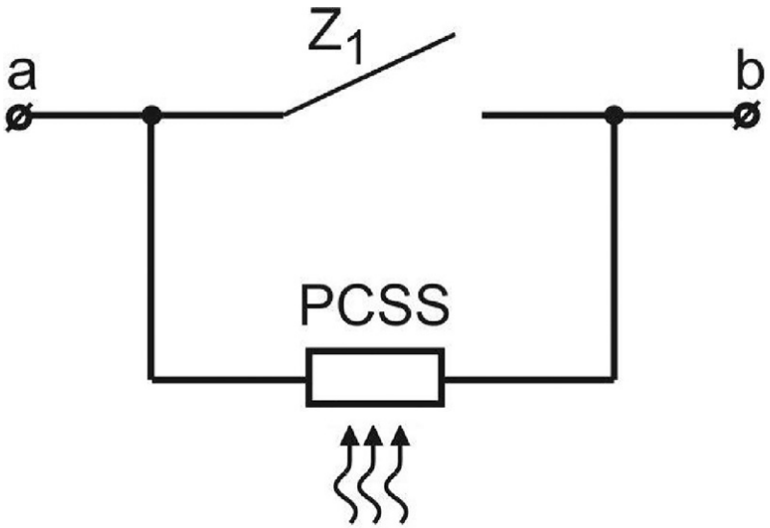
Solutions for reaching low on-resistance:

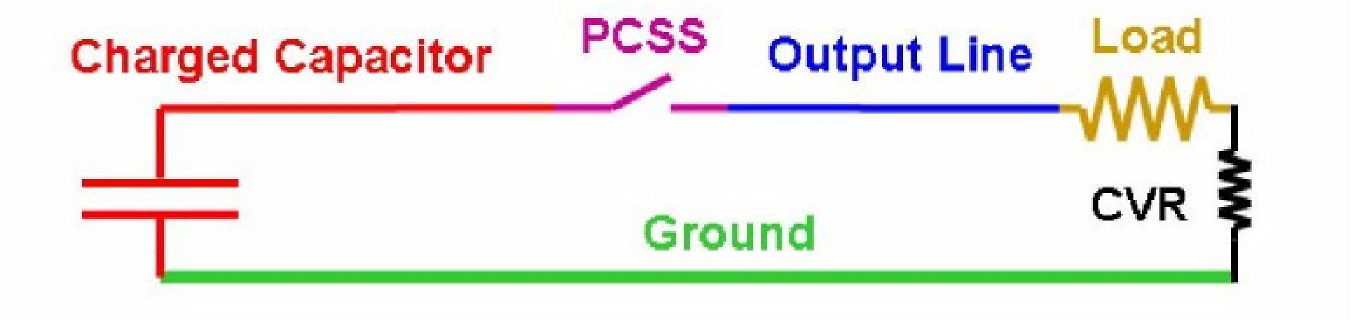
- Introduce extrinsic carriers through optical excitations
  - ✓ Bipolar conduction
  - ✓ High carrier mobility due to the lack of impurity scattering
  - ✓ Fast response (~ns) and high voltage packaging

M. W. Geis *et al.*, “Progress toward diamond Power Field-Effect transistors,” *Physica Status Solidi A-applications and Materials Science*, vol. 215, no. 22, p. 1800681, Nov. 2018.

Photoconductive semiconductor switches (PCSS)

- PCSS utilize photoconductivity for switching between on / off state
- Application: **Hybrid power switch**, **Trigger generators**, **Power grid protection** etc.





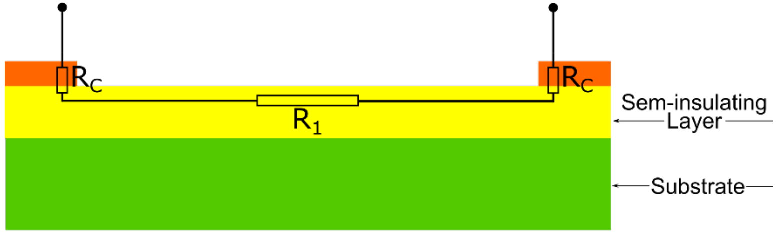
PCSS application in a hybrid power switch

PCSS application in a capacitive discharger pulser

- E. Majda-Zdancewicz, M. Suproniuk, M. Pawłowski, and M. Wierzbowski, “Current state of photoconductive semiconductor switch engineering,” Opto-electronics Review, vol. 26, no. 2, pp. 92–102, May 2018.
- F. Zutavern et al., Fiber-Optic controlled PCSS triggers for high voltage pulsed power switches. 2005.

Buried channel PCSS concept: theory

(a)



- Effective circuit model of **(a)** conventional PCSS without the buried channel and **(b)** buried channel PCSS.
- Current density distribution in logarithmic scale based on TCAD simulation inside **(c)** a conventional PCSS and **(d)** a buried channel PCSS under the same condition as **(c)**.

Equivalent circuit model:

- Conventional PCSS:

$$R_{conventional} = 2R_C + R_1$$

- Buried channel PCSS:

$$R_{buried\ channel} = 2R_C + \frac{R_1(2R_2 + R_{3)}}{R_1 + 2R_2 + R_3}$$

✓ Lower on-resistance thanks to the low-resistivity channel

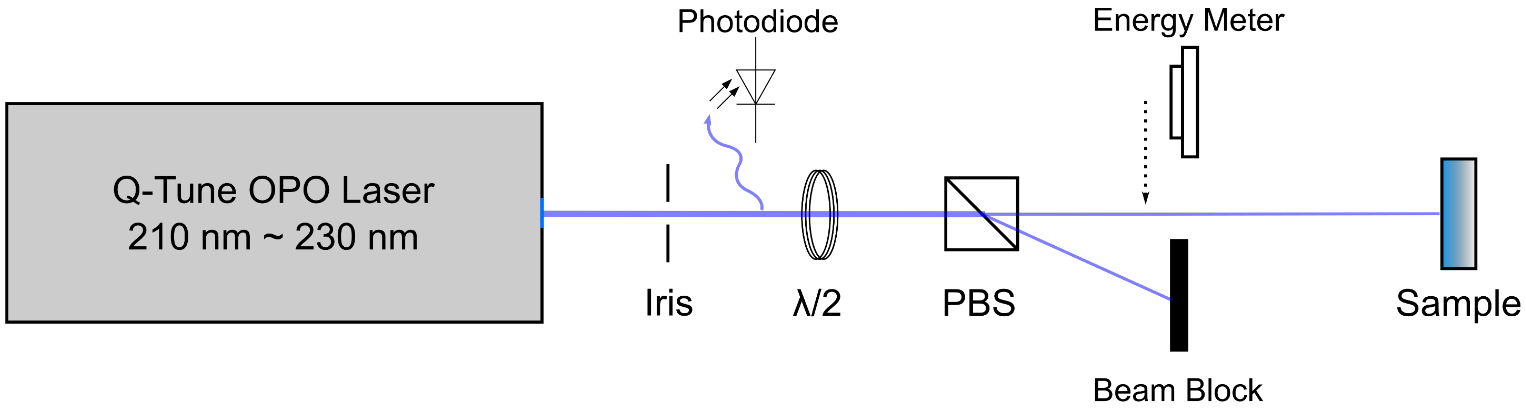
✓ During ON-state, most current flows through the buried channel

Buried channel PCSS: experiment

Type IIa HPHT Diamond substrate

500 μm thickness

Buried channel PCSS: measurement setup

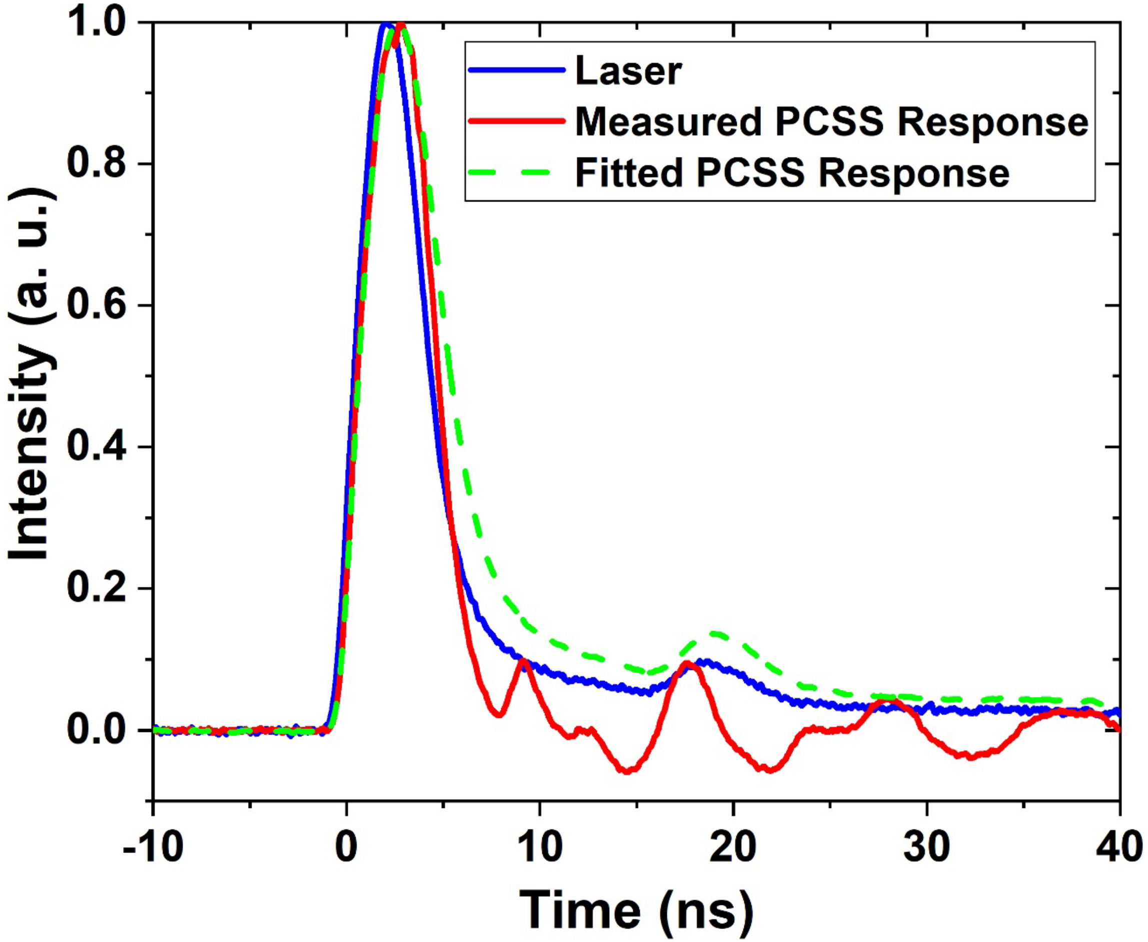


<u>Optical setup used to measure the PCSS device performance</u>

- OPO: optical parametric oscillator
- λ/2: half-wave plate
- PBS: polarizing beam splitter

<u>Electrical setup used to measure the PCSS device performance</u>

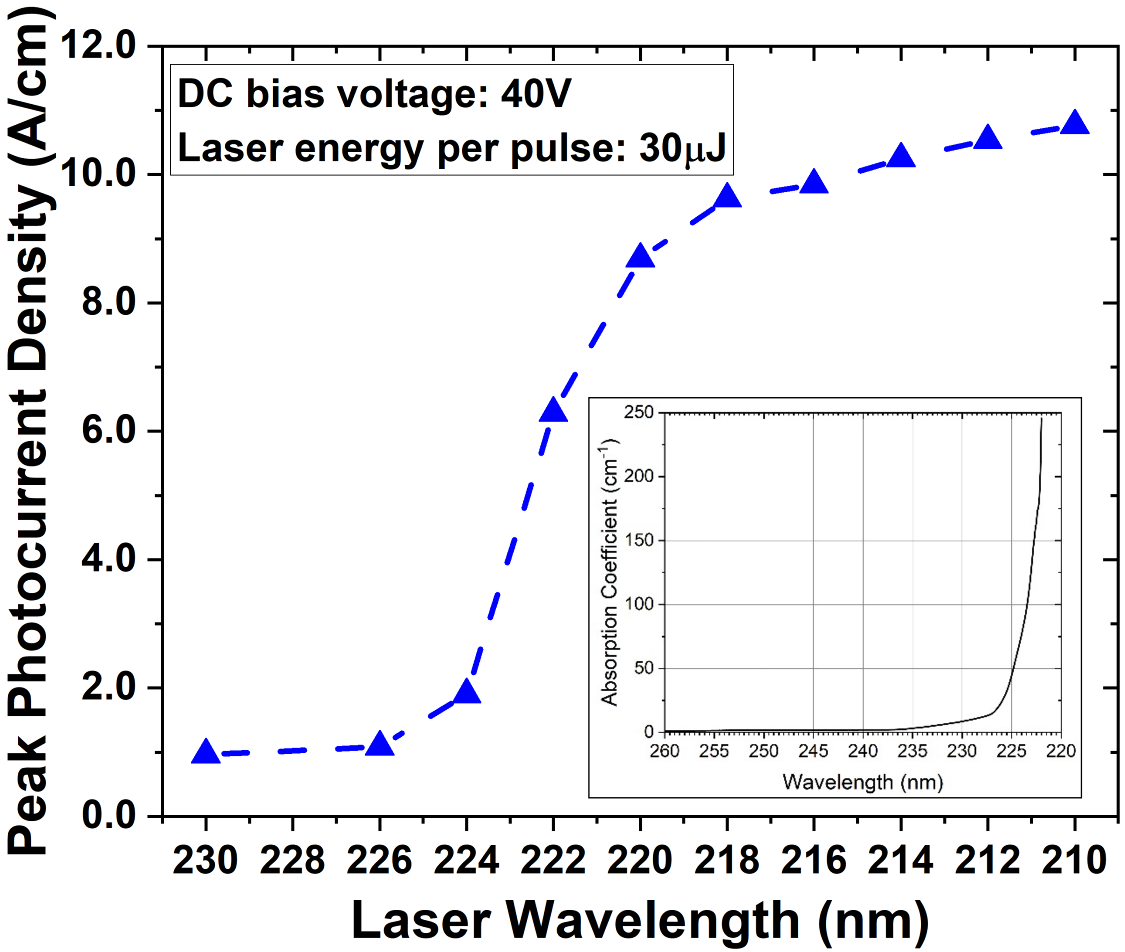
Photo response: rise/fall time & carrier lifetime



- Laser spectral range: 210 nm - 230 nm
- Spectral width: < 0.1 nm
- Laser pulse width: 4 ns
- Repetition rate: 10 Hz

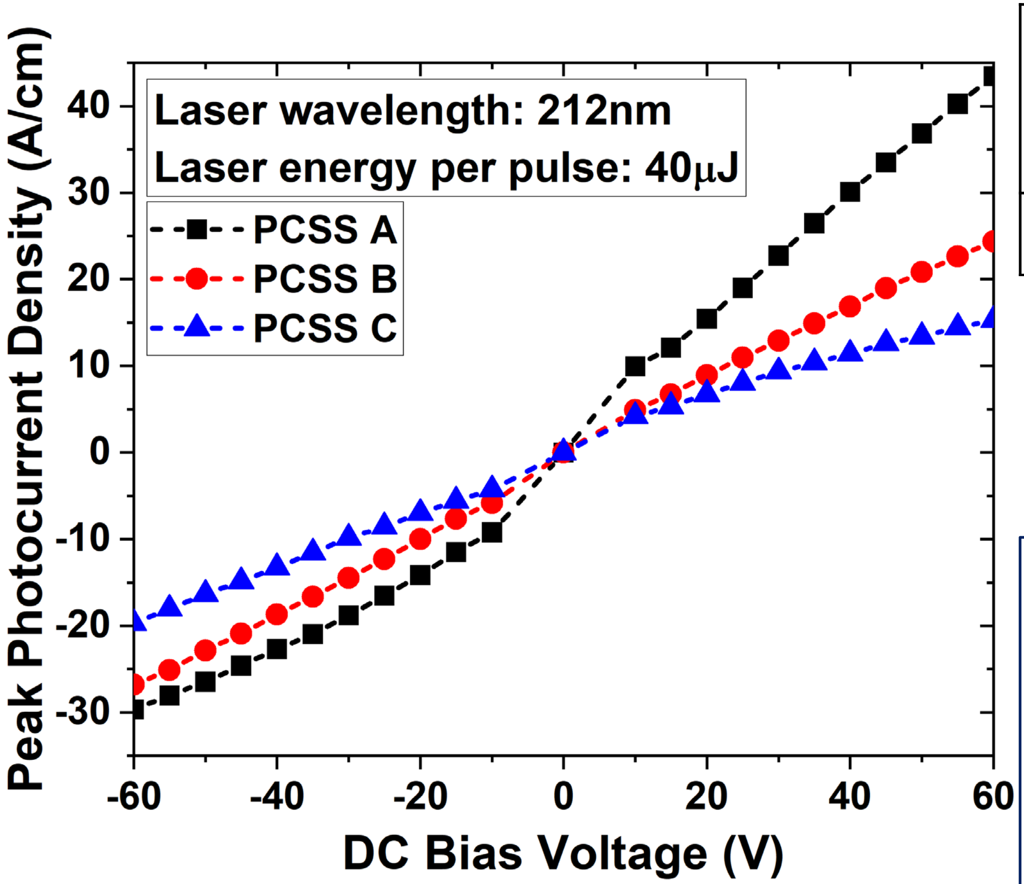
- ➢ Estimated carrier lifetime in PCSS: τ ≈ 0.5 ns
- ➢ PCSS response follows closely with optical trigger signal, promising high slew rate when bias voltage is scaled up

Photo response: wavelength dependent characteristics



- ➢ Photocurrent increases significantly above diamond's bandgap (< 226 nm)
- ➢ Finding: above-bandgap excitations are advantageous for lateral diamond PCSS

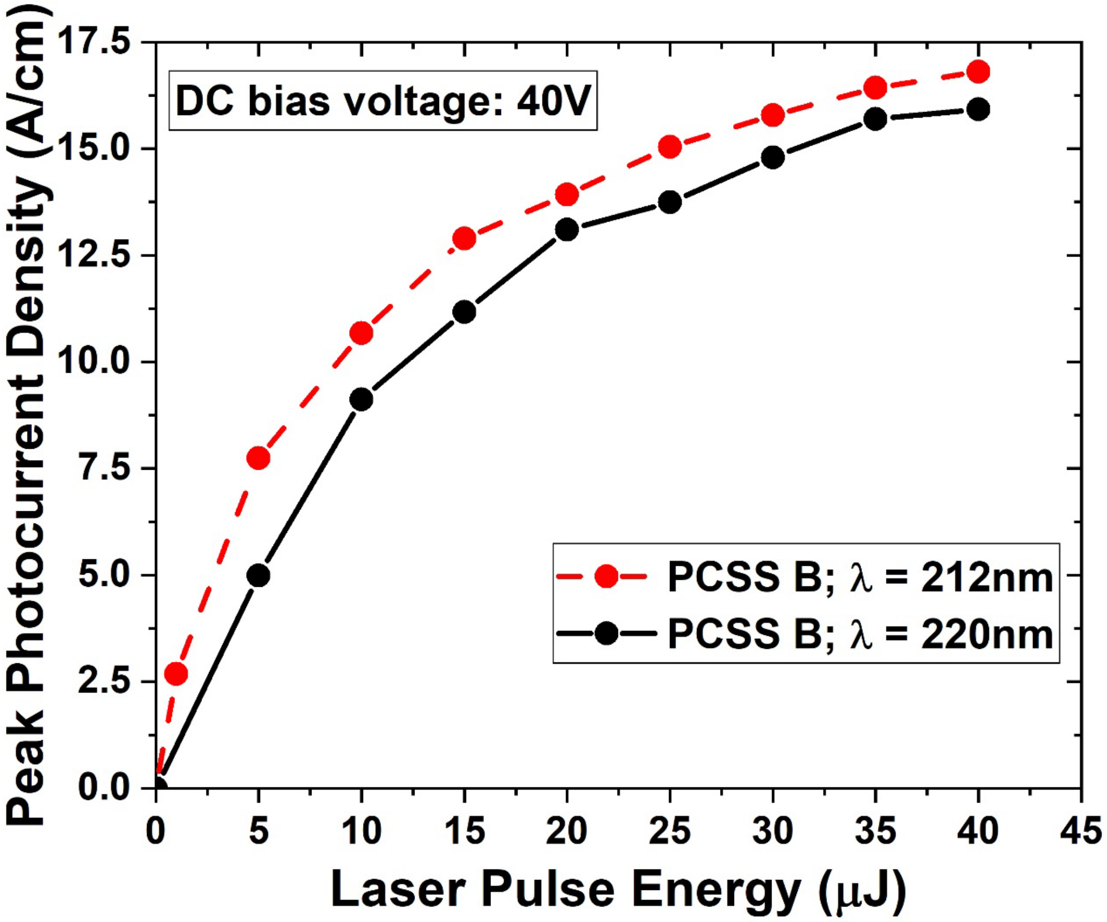
Photo response: voltage-current characteristics



#	Spacing (μm)	R_{OFF} (GΩ)	R_{ON} (Ω)	$\frac{R_{OFF}}{R_{ON}}$	Peak *J* (A/cm)	Normalized Responsivity (mA-cm/W-kV)
A	8	0.24	72.1	3.3×10^6	43.5	3.55

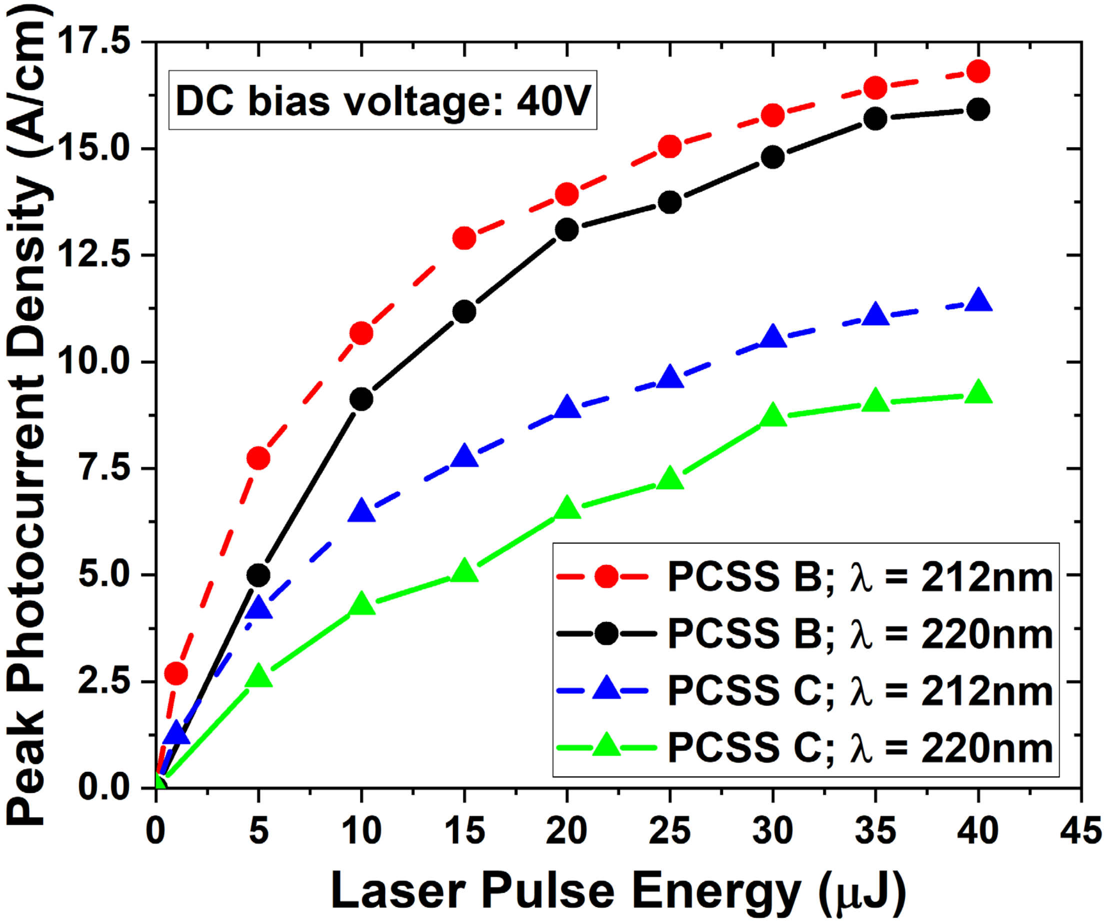
- ✓ Highest current density achieved: **43.5 A/cm** at 60 V
- ✓ Highest Responsivity achieved: **130 mA/W** at 60 V
- ✓ Highest on/off ratio achieved: **3.3×10^{11}** at 60 V
- ✓ No current saturation observed in all devices
- ✓ Linear *I-V* characteristics for +/- bias

Photo response: optical power dependent characteristics



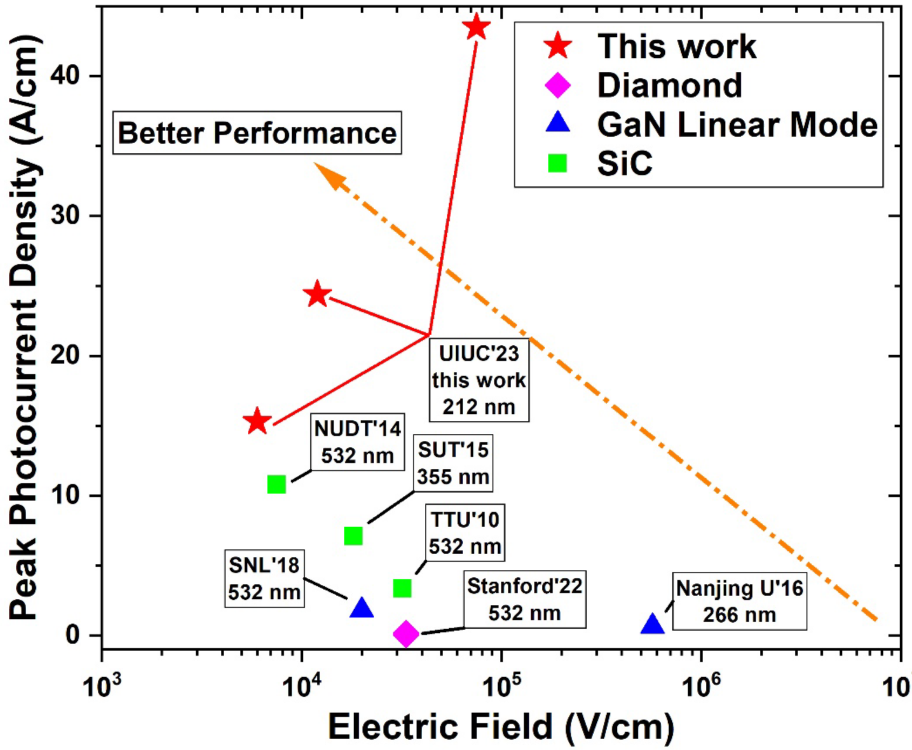
- At 212 nm and 220 nm, photocurrent saturates at high optical power due to invariant resistances in contacts and the buried channel
- Invariant resistance in PCSS B: **113 Ω**

Photo response: optical power dependent characteristics

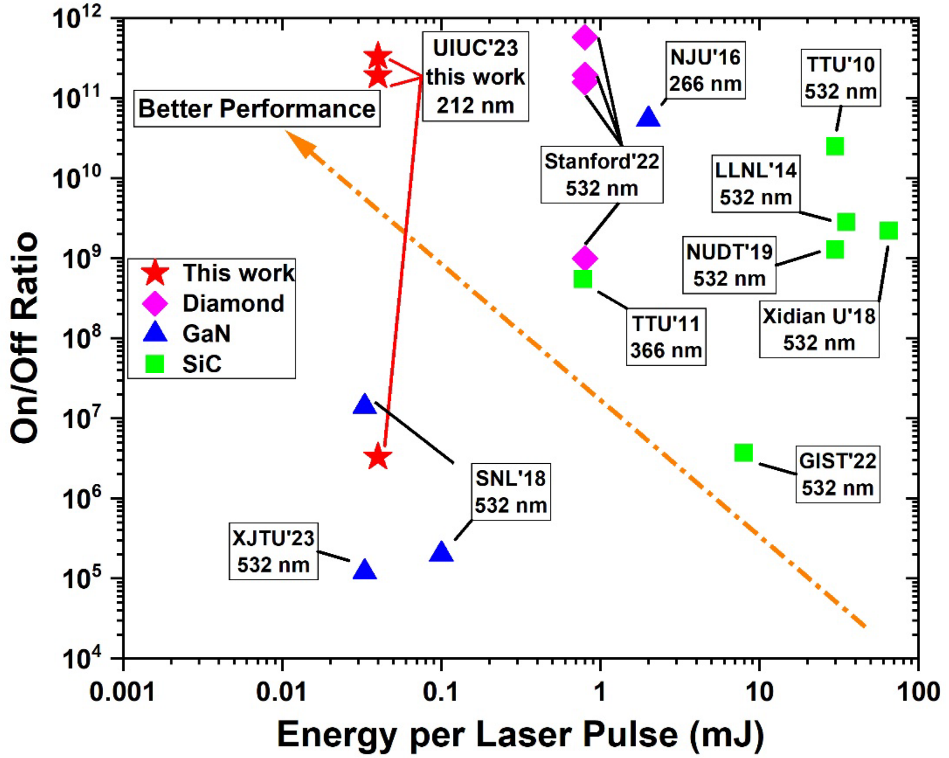


- At 212 nm and 220 nm, photocurrent saturates at high optical power due to invariant resistances in contacts and the buried channel
- Invariant resistance in PCSS B: **113 Ω**
- Invariant resistance in PCSS C: **154 Ω**
- Calculated resistances predict that between **91%** to **93%** of current conduction is through the buried channel

Summary & Benchmark



Benchmark of PCSS in terms of photocurrent density vs. lateral E-field



Benchmark of PCSS in terms of on/off ratio vs. energy per laser pulse

- ✓ **High current density** in linear mode at low optical power & electric field
- ✓ **~ns rise/fall time** and **> 10^{11} on/off ratio**

[1] K. Woo, M. Malakoutian, B. A. Reeves, S. Chowdhury, Appl Phys Lett 2022, 120. [2] C. James, C. Hettler, J. Dickens, IEEE Trans Electron Devices 2011, 58, 508. [3] J. S. Sullivan, Appl Phys Lett 2014, 104, 172106. [4] P. Cao, W. Huang, H. Guo, Y. Zhang, IEEE Trans Electron Devices 2018, 65, 2047. [5] P. H. Choi, Y. P. Kim, M.-S. Kim, J. Ryu, S.-H. Baek, S.-M. Hong, S. Lee, J.-H. Jang, IEEE Access 2022, 10, 109558. [6] Q. Wu, T. Xun, Y. Zhao, H. Yang, W. Huang, IEEE Trans Electron Devices 2019, 66, 1837. [7] L. Wang, T. Xun, H. Yang, J. Liu, Y. Zhang, Review of Scientific Instruments 2014, 85, 044703. [8] C. James, C. Hettler, J. Dickens, in 2009 IEEE Pulsed Power Conference, IEEE, 2009, pp. 283–286. [9] Z. Hemmat, R. Faez, S. Amiri, in The 6th Power Electronics, Drive Systems & Technologies Conference (PEDSTC2015), IEEE, 2015, pp. 253–256. [10] X. Yang, Y. Yang, L. Hu, J. Liu, X. Duan, J. Huang, X. Li, W. Liu, IEEE Photonics Technology Letters 2023, 35, 69. [11] A. D. Koehler, T. J. Anderson, A. Khachatrian, A. Nath, M. J. Tadjer, S. P. Buchner, K. D. Hobart, F. J. Kub, ECS Journal of Solid State Science and Technology 2017, 6, S3099. [12] Y. Chen, H. Lu, D. Chen, F. Ren, R. Zhang, Y. Zheng, physica status solidi c 2016, 13, 374.

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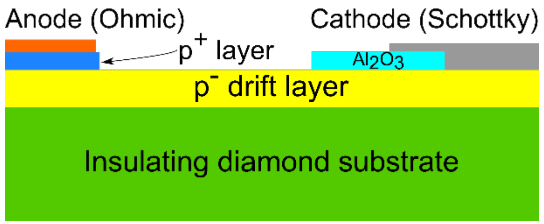
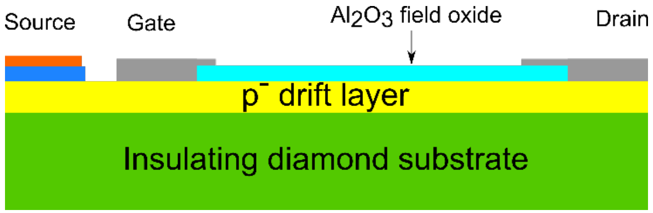
Conclusion & future work

High voltage:
HVDC/UHVDC



Lateral SBDs

- 5kV BV
- Stable at high temperature



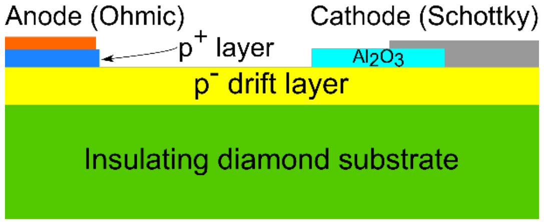
Reverse-blocking MESFETs

- Current work
- 10kV BV
- Low gate leakage

Can Bayram, and Zhuoran Han BIDIRECTIONAL DIAMOND DEVICES (UIUC2023-082-01(PRO))

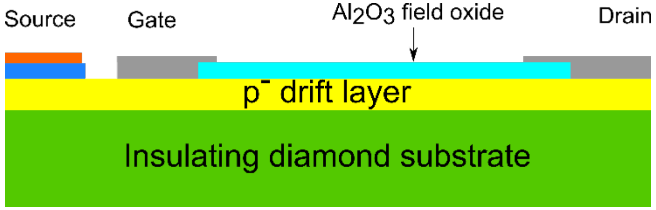
Conclusion & future work

High voltage:
HVDC/UHVDC



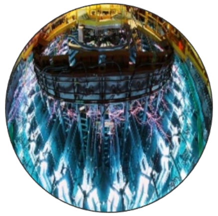
Lateral SBDs

- 5kV BV
- Stable at high temperature

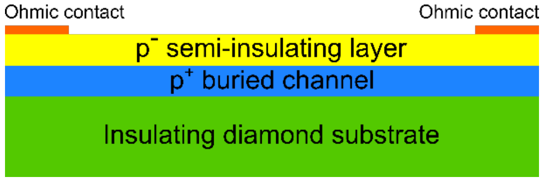


Reverse-blocking MESFETs

- Current work
- 10kV BV
- Low gate leakage



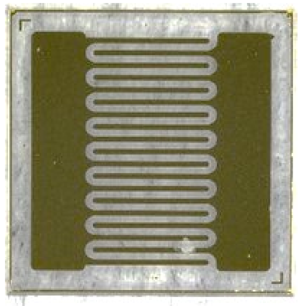
Fast switching:
Grid-protection

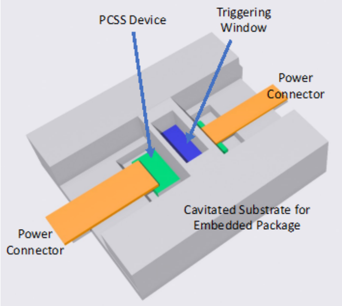


Buried channel PCSS

- 43.5A/cm current density
- $>10^{11}$ on/off ratio

Scale-up





- Slew rate: ≥ 500 V/ns, ≥ 200 A/ns
- 20 kV BV
- ≥ 5 A per die

Can Bayram, Jae Kwon Lee, Andrey Mironov, and Zhuoran Han LIGHT-TRIGGERED DIAMOND SWITCHES (Application No.: 63/530,434)
Can Bayram, and Zhuoran Han bidirectional diamond devices (Application No.: 63/609,000)
Can Bayram, Jae Kwon Lee, and Zhuoran Han buried channel photoconductive switch (Application No.: 63/531,298)

Acknowledgements

Our work is partially supported by

- Coherent / II-VI Foundation
- Advanced Research Projects Agency–Energy (ARPA-E), under award number DE-AR0001846
- Office of Naval Research (ONR), under award number 13235235
- Applied Research Institute (ARI) / Silicon Crossroads Microelectronics Commons (SCMC) Hub
- University of Illinois Urbana-Champaign ECE Distinguished Research Fellowship
- University of Illinois Urbana-Champaign ECE Promise of Excellence Fellowship
- Andrew T. Yang Research and Entrepreneurship Award
- Nick and Katherine Holonyak Jr. Outstanding Research Award
- SPIE Optics and Photonics Scholarship

Publications & patents

❖ Journal Papers:

- Z. Han, J. Lee, S. Messing, T. Reboli, A. Mironov, and C. Bayram, **“Buried Channel Diamond Photoconductive Switch with High Above-Bandgap Responsivity,” (2024),** *IEEE Electron Device Letters (Top downloaded article)*
- Z. Han, and C. Bayram, **“Diamond p-type Lateral Schottky Barrier Diodes with High Breakdown Voltage (> 4.6 kV at 0.01 mA/mm),” (2023),** *IEEE Electron Device Letters (Top downloaded article)*
- J. Lee, C. Bayram, and J.P. Leburton, **“High Field Transport in (Ultra) Wide Bandgap Semiconductors: Diamond Versus Cubic GaN,” (2024),** *IEEE Transactions on Electron Devices (Top downloaded article)*

❖ Patents:

- Can Bayram, Jae Kwon Lee, Andrey Mironov, and Zhuoran Han **LIGHT-TRIGGERED DIAMOND SWITCHES** (Application No.: 63/530,434)
- Can Bayram, and Zhuoran Han **BIDIRECTIONAL DIAMOND DEVICES** (Application No.: 63/609,000)
- Can Bayram, Jae Kwon Lee, and Zhuoran Han **BURIED CHANNEL PHOTOCONDUCTIVE SWITCH** (Application No.: 63/531,298)

Thank you!