Diamond Diode Devices

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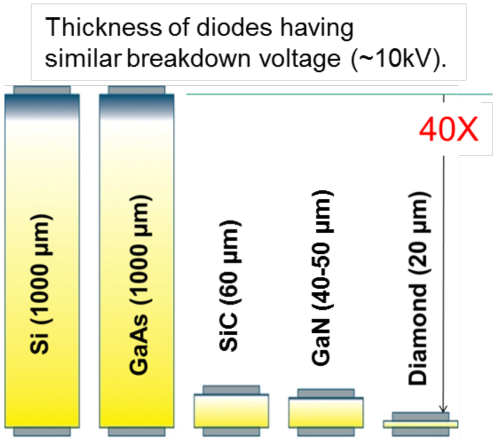
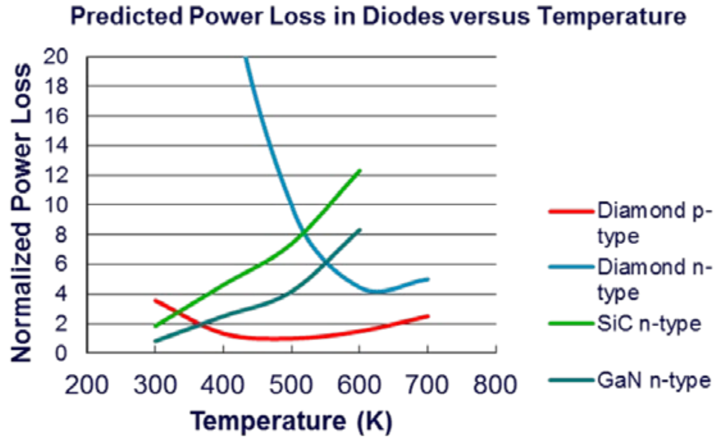
Diamond Diode Devices

- The long term goal is development of diamond diodes and transistors capable of operating at high temperatures, higher voltages and higher power switching levels as compared to other wide bandgap electronics.
- At high operating temperatures above 100°C diamond electronics are expected to operate with lower power losses as compared to silicon, SiC and GaN. Thermal conductivity is the other key advantage.

Property	Si	GaAs	6H-SiC	4H-SiC	GaN	Diamond
Bandgap, E_g (eV)	1.12	1.43	3.03	3.26	3.45	5.45
Electric Breakdown Field, E_c (kV/cm)	300	400	3000	3000	4900	10000-13000
Thermal Conductivity, λ (W/cm·K)	1.5	0.55	3.7	3.7	2.5	22





Comparison of diodes designed to flow the same current and block the same high reverse bias voltage.

Year 1 Seeding Project: Diamond diodes

Year 2 Project Objective: Diamond diode with a forward rated current of 10 A and a reverse bias breakdown of 1200 V.

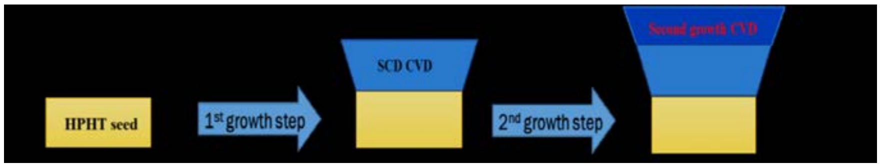
Year 3 Project Objective: Diamond diode with a forward current of 10 A and a reverse bias breakdown of 10kV.

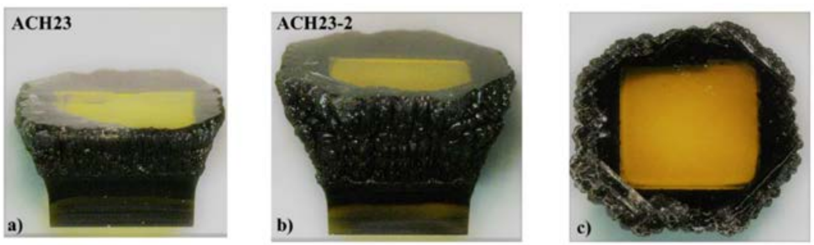
Team

- Michigan State University (MSU) & Fraunhofer USA Center for Coatings and Diamond Technologies (CCD)
- Personnel:
  - Timothy Grotjohn (PI) – Semiconductor devices, diamond processing and synthesis
  - Timothy Hogan – Electronic materials and devices characterization to high T
  - Thomas Schuelke – IC manufacturing, materials testing
  - Jes Asmussen – Plasma-assisted CVD reactor design, diamond synthesis
  - Chuan Wang – Al_2O_3 deposition
  - John Albrecht - Semiconductor device simulation
  - Fang Peng – Switching and double pulse testing of diodes
  - Steve Zajac, Amanda Charris, Ayan Bhattacharya, Wesley Spain, Jinshui Miao, Tommy Sereseroz, Hulong Zeng, Ujjwal Karki– MSU students
  - Michael Becker, Aaron Hardy, Robert Rechenberg – Fraunhofer personnel
- Fraunhofer CCD and MSU have combined facilities on the MSU campus with diamond synthesis and processing capabilities including diamond synthesis, diamond doping during epitaxial growth, plasma-assisted etching, metallization, diamond cutting by laser, diamond polishing, and optical and electronic characterization of diamond material and devices.
- MSU and Fraunhofer CCD have combined activities on the R&D of diamond technology. Fraunhofer CCD also has a focus on prototyping of products and transition of technology to industry.

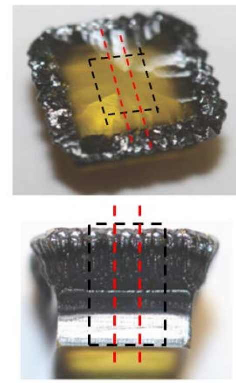
Diamond Diode Devices

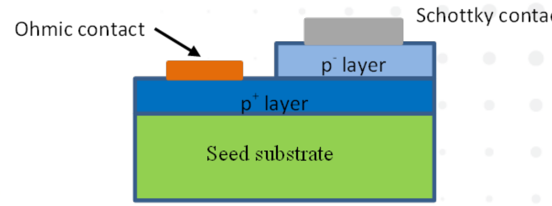
- Substrate Development/Improvement
  - Substrates developed with essentially no killer defects.
  - Develop of process for creating substrates with dislocation defect densities of low 10^3 cm^{-2} (Etch pit density)

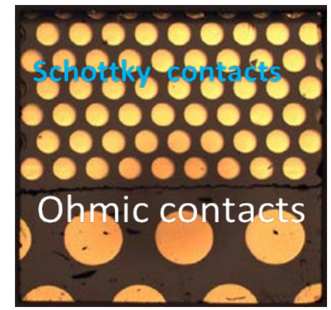




Sample 184
1.35 mm thick layer



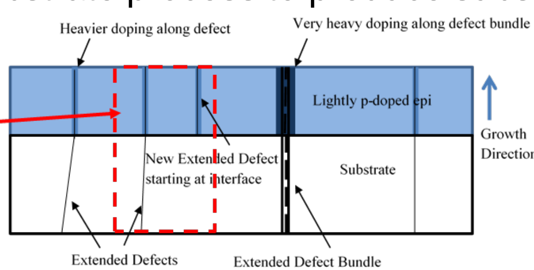


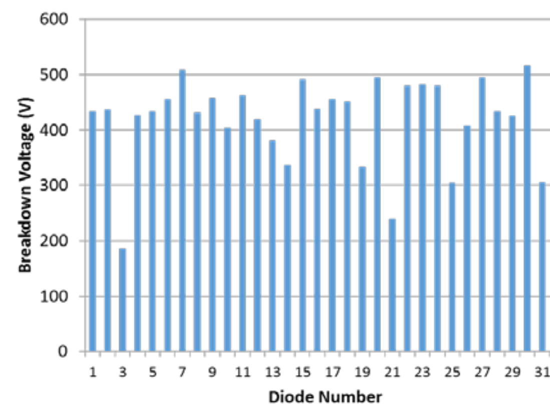


Diodes fabricated on flipped substrate

- Use a flipped substrate process to produce substrates

Cut out vertical substrate and flip on its side.



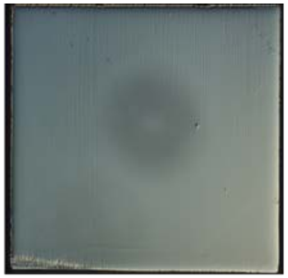


All the diodes worked

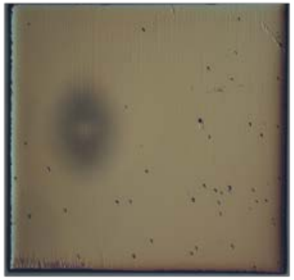
Diamond Diode Devices

3rd Year Accomplishments

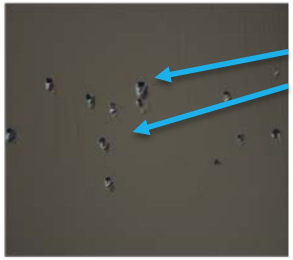
- Developed a process to create thick (300 µm) boron doped substrates with resistivity less than 0.1 Ω–cm. (Boron doping $10^{19} – 10^{20}$ cm^{-3})
- Reduced the particle and soot problem during p^+ diamond growth.



25x, DIC, **After 1st deposition**

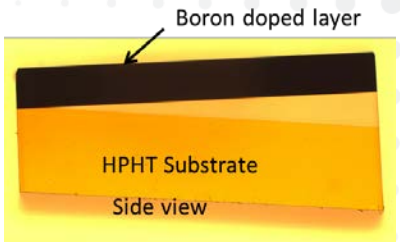


25x, DIC, **After 2nd deposition**



100x

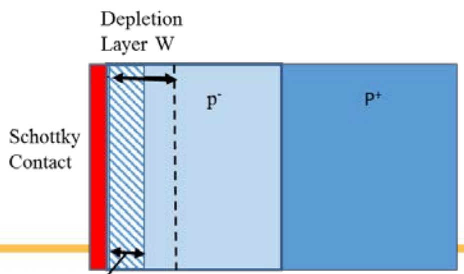
Particles thought to cause these defects



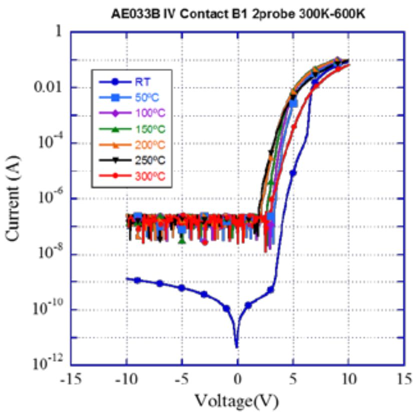
Improved process with no visible defects

100X

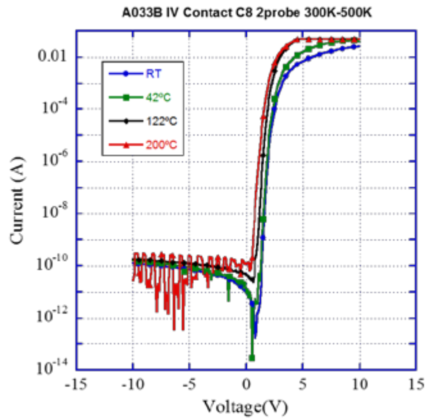
- Developed a better understanding of hydrogen passivation during the p^- layer growth. Reduced the hydrogen passivation problem.
  – Achieved room temperature mobility of 1900 cm^2/V-sec with doping of 10^{16} cm^{-3} of boron
  – Compensation level of less than 4 ppb (~10^{14}-10^{15} cm^{-3})
  – Boron doping levels from $10^{16} – 10^{18}$ cm^{-3}



Region of more defects, passivation by hydrogen, deep traps



Before Anneal



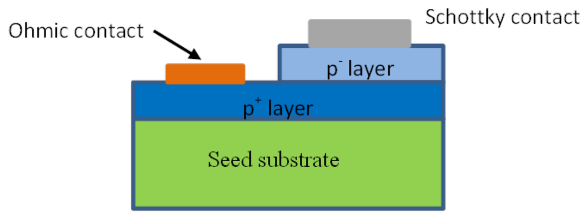
After Anneal at 800°C

Improvement by reducing hydrogen passivation

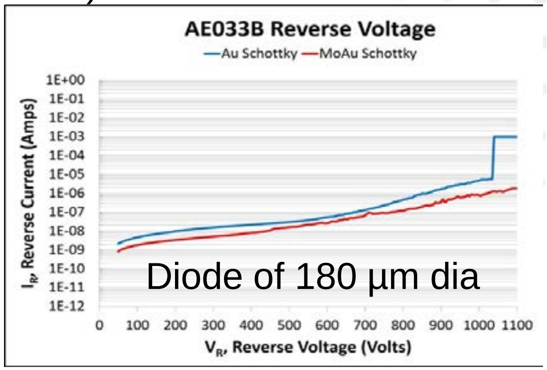
Diamond Diode Devices

3rd Year Accomplishments

Achieved breakdown voltages in excess of 1000 V. Achieved breakdown field strength of ~ 3-4 MV/cm. The dominate mechanism in reverse bias is leakage (not avalanche breakdown) at this time.

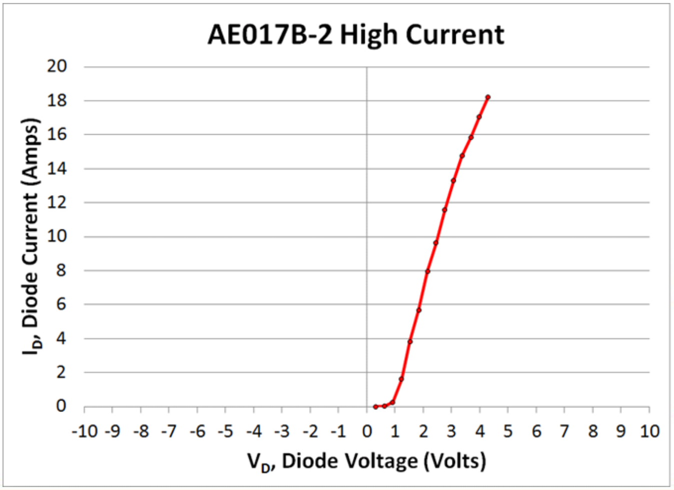


Example of reverse bias current with two different Schottky metals

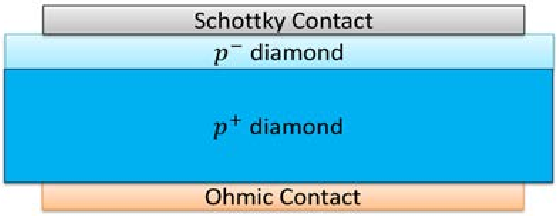


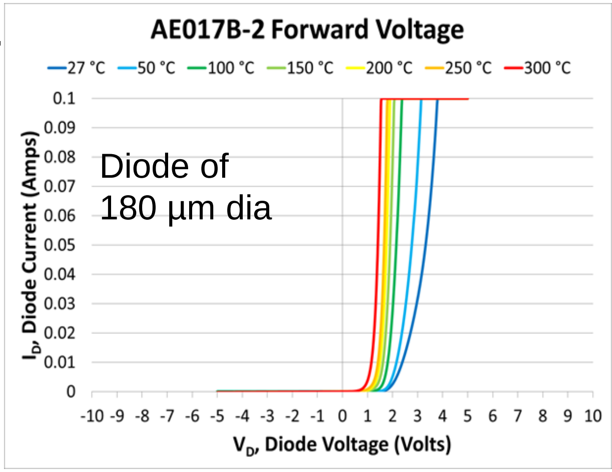
The current status of Schottky diodes

- With diameter generally 150-500 µm the current density is 100-900 A/cm^2
- A larger Schottky diode (area ~2 mm^2) demonstrated a current of 18 A.



18 A current flow in 2 mm^2 diode 900 A/cm^2

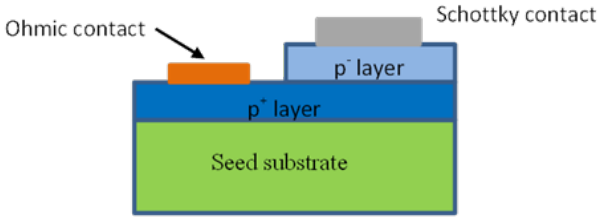


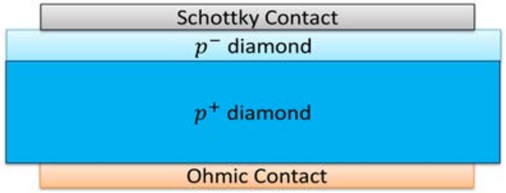


Temperature dependence of current

Diamond Diode Fabrication

Process Step	Critical Issues
1. Start with high quality substrate	-Low dislocation defect density across an area of 2-5 mm^2 (dislocation density ~ low 10^3 cm^{-2})
2. Prepare the substrate surface for doped epi-layer growth	-Preferred off-cut angle from (100) crystallographic plane (~3°) -Removal of polishing damage layer with RIE -Surface cleaning
3. Deposition of p^+ epi-layer or grow p^+ substrate on starting substrate	-Low resistance and low defect diamond needed (resistivity less than 0.1 Ω-cm)
4. Deposition of p^- epi-layer	-Controlled boron doping level -Low compensation by impurities -Controlled layer thickness
5. Form ohmic and Schottky contacts	Ohmic contacts resistance (~10^{-4} Ω–cm^2)

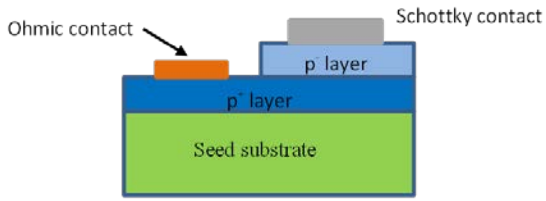


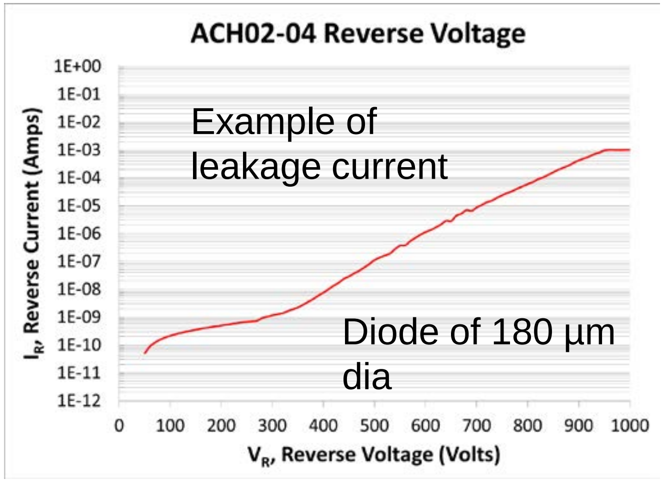


Diamond Diode Devices

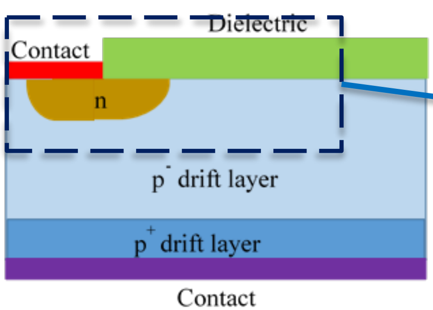
Project End Goals
3-6 months remain

- Reduce the leakage current. Reduce the dislocation defects from the p^+ layer (& p- layer) deposition layers. Improve the Schottky contacts. Reduce compensation < 1 ppb
- Achieve 3-10 kV breakdown voltages with sufficiently low leakage.

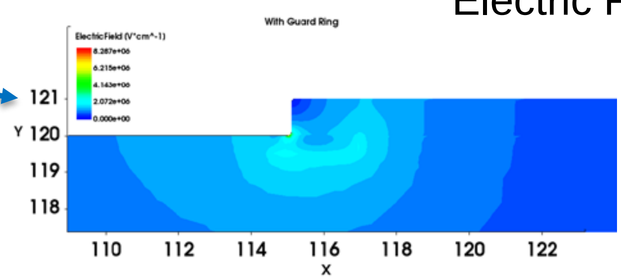




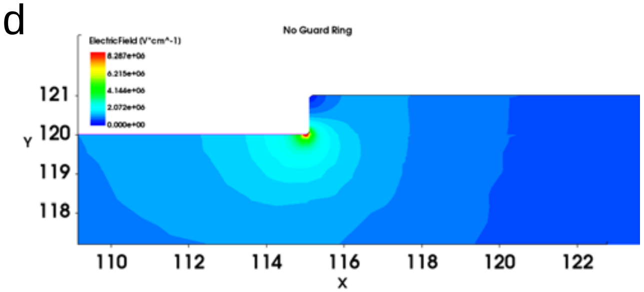
- Implement a guard ring process (n-type doping) to achieve higher breakdown voltages. (Phosphorus doping for n-type). Use an earlier developed (year 1) selective growth process. Simulations and experiments underway.



Electric Field



With Guard Ring



Without Guard Ring

Diamond Diode Devices

- Increase area of high quality regions of substrates to achieve 10 A diodes

V (volts)	W (μm)	N_A (cm^{-3})	J	R_{on} (100 C)	Area for 10 A with 5 Volts drop
1000	3.8	2.3×10^{16}	484 A/cm^2	0.0021 Ω-cm^2	0.004 cm^2 (0.7 mm dia)
3000	11.4	7.7×10^{15}	54 A/cm^2	0.019 Ω-cm^2	0.038 cm^2 (2mm X 2mm)
5000	19	4.6×10^{15}	38 A/cm^2	0.026 Ω-cm^2	0.052 cm^2 (2.3 mm X 2.3 mm)
10000	38	2.3×10^{15}	9 A/cm^2	0.11 Ω-cm^2	0.2 cm^2 (4.5 mm X 4.5 mm)

- Dynamic testing of diodes
  - Packaging is underway of diamond diodes
  - Double pulse test circuit established. Measurement technique being tested now with purchased SiC diodes.

- Demonstration planned of switching of the diamond diodes designed for 10 A and multi-kV in a switching test at 5 A and 3-5kV at a switching frequency of greater than 40 kHz.

Technology-to-Market

- Preliminary manufacturing cost model
- First target market selected (high temperature applications)
  - Engaging potential users to understand target applications and markets
- Next stage funding received
  - Doping and defects in diamond for electronics, National Science Foundation, September 2016 – August 2020
  - Development of single crystal diamond wafers, Army Phase I SBIR subcontract, July – December 2016.
  - Vertical growth technique for diamond substrates, Army Phase I SBIR subcontract, Sept. – February 2017.
  - Diamond for rf electronics, Massachusetts Institute of Technology – Lincoln Laboratories, Oct. 2014 – Sept. 2017
  - Total ~ $1.3M
- Additional activities
  - Oct 2016: Organized high temperature electronics workshop (MSU)
  - Dec 2016: ARPA-E iMatSci booth at MRS Fall meeting
  - Feb 2017: Organized diamond electronics workshop (ARL sponsored)

Manufacturing Cost Model

(0) Grow Substrate Crystal / Produce Plates

(1) Substrate Preparation

(2) p⁺ Epi Layer Growth (contact substrate)

(3) p⁻ Epi Layer Growth (drift layer)

(4) Substrate Separation

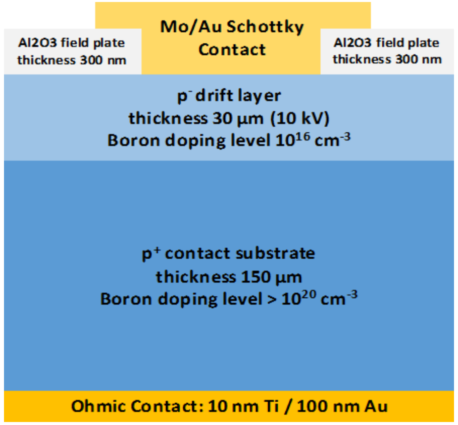
(5) Field Plate Structure

(6) Schottky Contacts

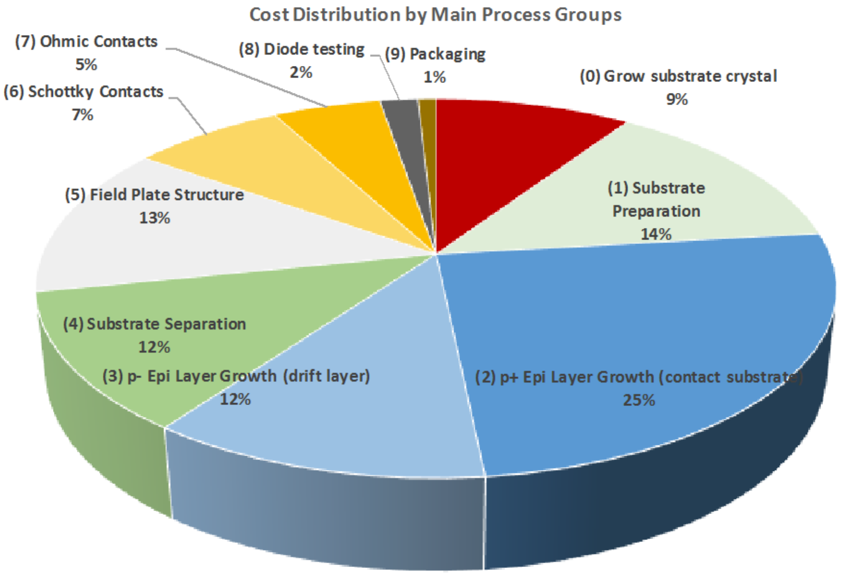
(7) Ohmic Contacts

(8) Testing

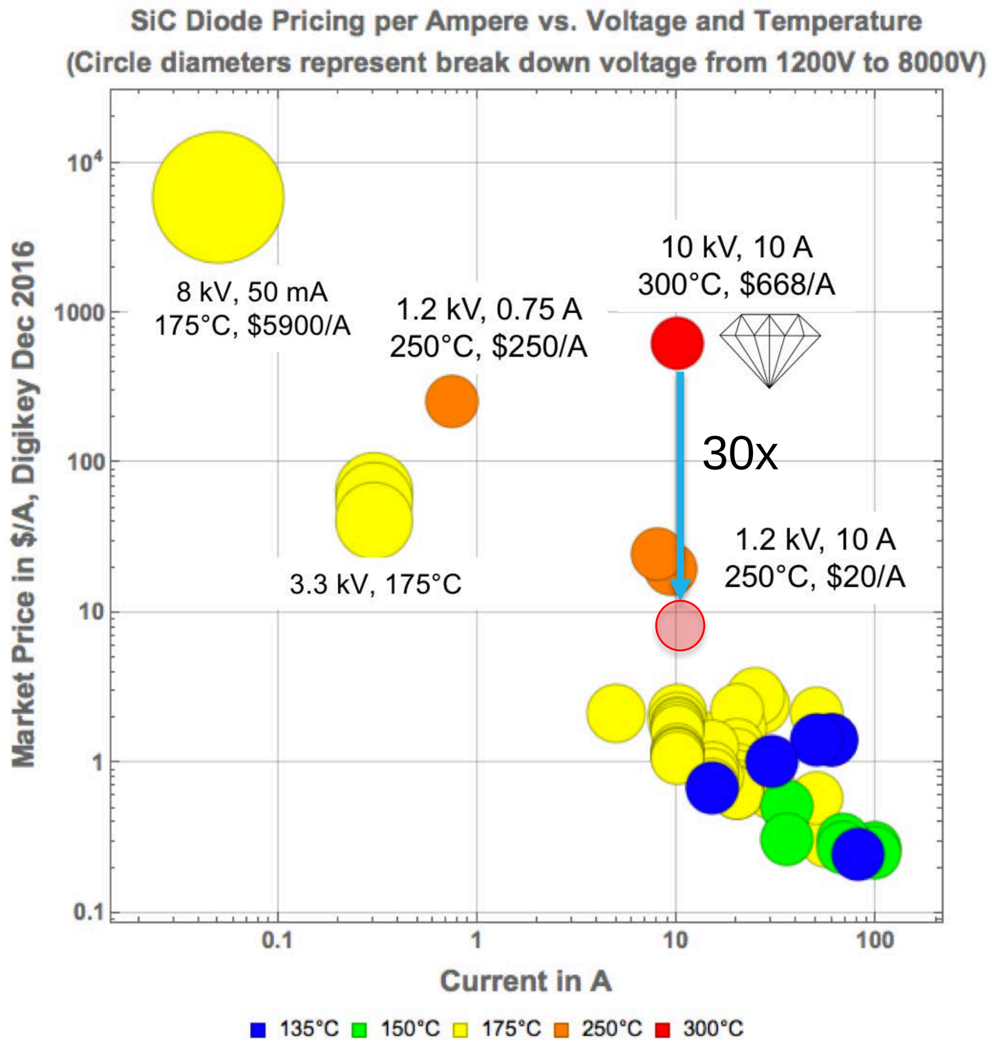
(9) Packaging



- \$668 / A
- 10 kV, 10 A, >300°C, 200 A/cm^2
- "Single device processing" on flipped plates 1.5 x 3.5 mm^2 = 5.25 mm^2



Diamond Diode vs. Market Place



- $668 / A with Single device on flipped plate 1.5 x 3.5 mm^2 = 5.25 mm^2
- ~$7 / A with a 1” diameter wafer.
- Real potential for cost reduction lies in using **larger substrates** (wafers).
- → Yield is the next challenge

- **First Target for Diamond:**
  High Temperature & Voltage

Conclusions

- Substrates with minimal killer defects and dislocation defect densities of ~10^3 cm^{-2} achieved
- p^-, p^+ and n-type epitaxial layers of diamond have been deposited and their properties studied and improved
- Semiconductor device simulations have been used to help design diamond diodes to meet the specification of multiple kV and 10A. Materials models have been implemented in the simulation tools
- Small area diodes without a field plate have been demonstrated with breakdown voltages of > 1100 V and 100's A/cm^2
- A larger area diamond diode with 18 A of current (900 A/cm^2) with less than 5 voltages forward voltage drop has been demonstrated
- Future goals are to make larger area high quality substrates with lower compensation and lower dislocation defect densities, and to add edge termination to the Schottky contact regions to reduce electric field
- With these advances the goals/outcomes of this diamond diode SWITCHES program project (multiple kV & 10A) will continue to advance and be achieved.