Advancement in radiation hard metal/semiconductor diode material technology for space power applications

R.D. Vispute, Adeel Chaudhry, and Austin Stallworth

Blue Wave Semiconductors, Inc. Baltimore MD USA

Introduction

High radiation resistance and high efficiency photovoltaics integrated with bypass and string diodes are very important for power generator modules operating in high radiation orbits such as Geosynchronous Earth Orbit (GEO) or in a Low Earth Orbit (LEO), or in a Medium Earth Orbit (MEO). The solar arrays require radiation hardened, high temperature, and high voltage discrete diodes for solar cell bypass protection and string blocking operations. Furthermore, high temperature and high voltage solar cell bypass and string diodes are necessary to handle larger solar cells (>30cm^2) and flex blankets, where bypass diodes may experience extreme temperatures.

Radiation-resistant Wide Band Gap bypass and string diodes are proposed for space solar panels to serve as a protection mechanism that allows the panel to continue producing power when one of its cell strings is shaded or damaged while operating in space.

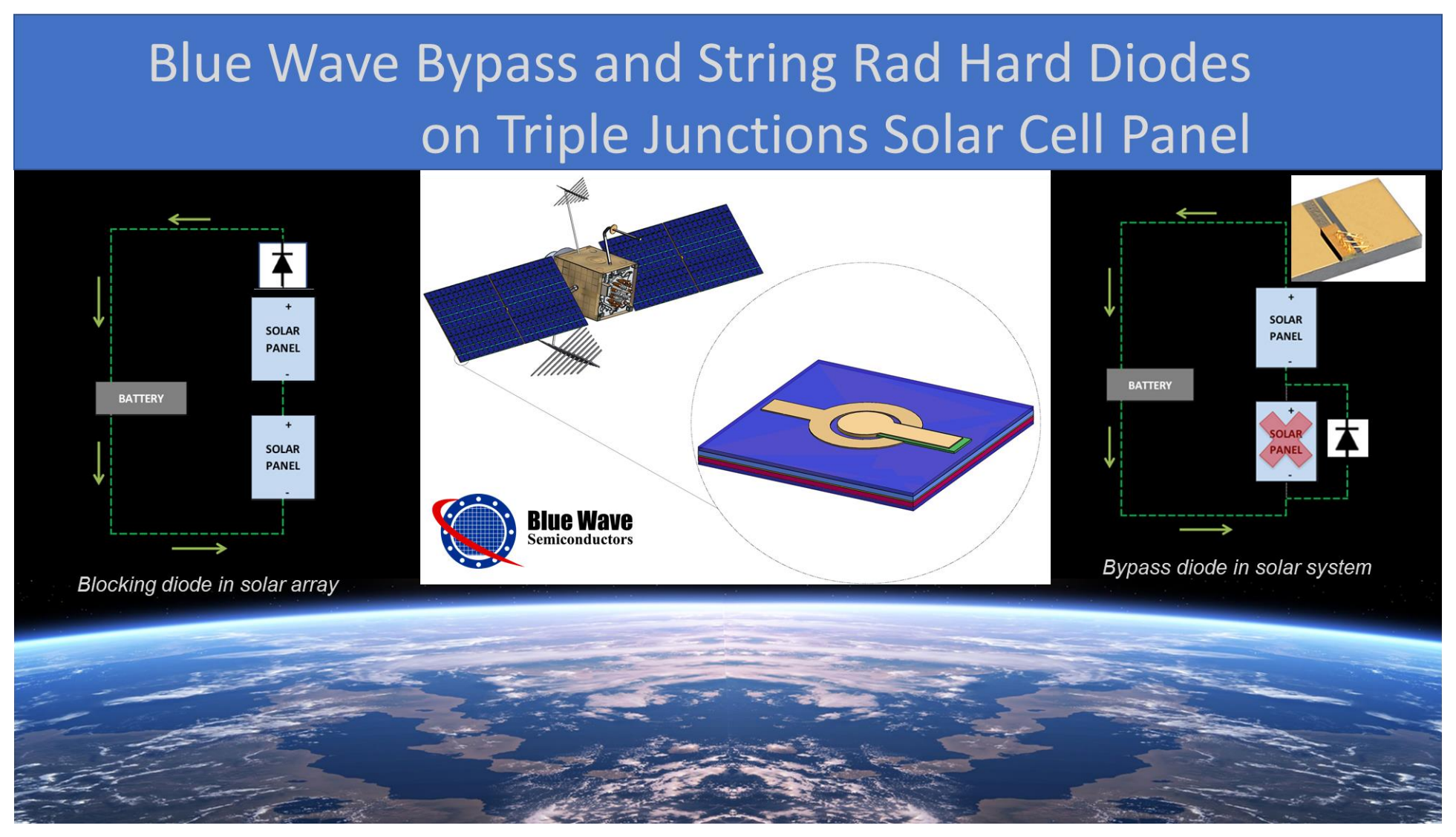


Table I: Properties of Wide Bandgap Materials for Electronic Devices

Properties	Si	4H-SiC	GaAs	GaN	Diamond
Energy Gap (eV)	1.12	3.26	1.43	3.50	5.47
Electron Mobility (cm^2/Vs)	1400	900	8500	1250	2800
Hole Mobility (cm^2/Vs)	600	100	400	200	1900
Breakdown Field (V/cm) x 10^6	0.3	3.0	0.4	3.0	10
Thermal Conductivity (W/cm°C)	1.5	4.9	0.5	1.3	200
Saturation Drift Velocity (cm/s x10^7)	1.0	2.7	2.0	2.7	2.7
Relative Dielectric Constant	11.8	9.7	12.8	9.5	5.7

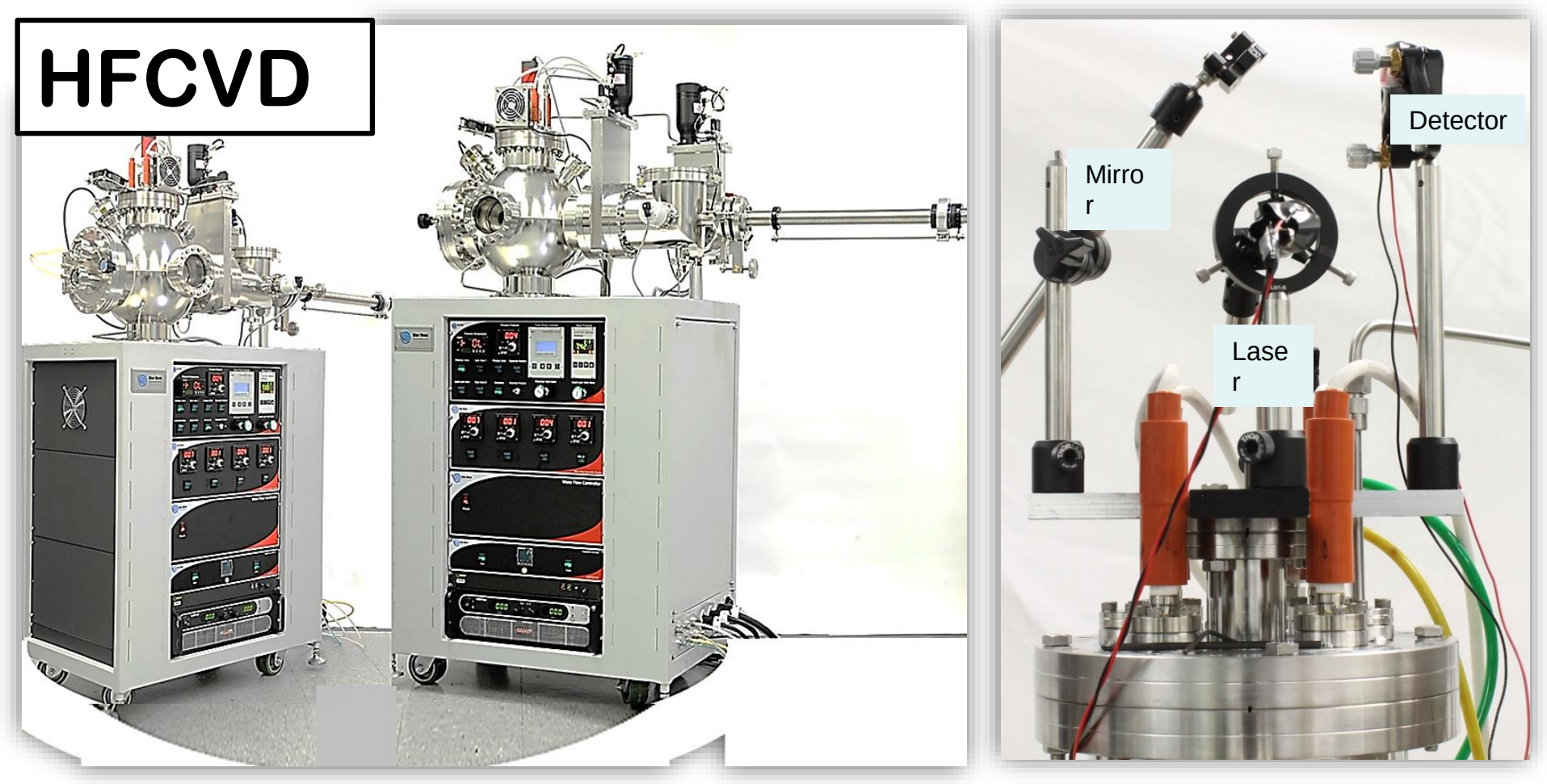
Project Goals

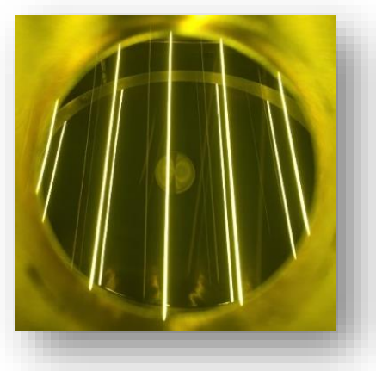
- ☐ Proto-type rectifying diamond and SiC schottky or p-n junction diodes.
- ☐ Optimize device design and diode characteristics needed for space solar cell panel integration
- ☐ Develop strategy for implementing these devices on cell (solderable on cell) for space panels
- ☐ Achieve desirable electrical characteristics (turn on voltage, power density, reverse leakage currents, blocking voltage, effects of temperatures and radiation on devices) in Diamond, SiC and Si diodes with rad hard packing concepts
- ☐ Integration of prototype and successful diodes coupling with high efficiency solar cells or panels to produce highest possible power density.

Methods

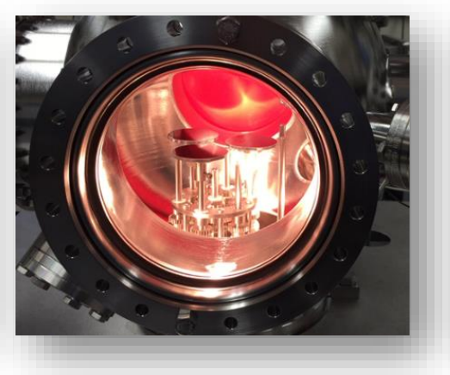
- ☐ CVD Diamond, SiC, and Diamond and Oxide Passivated Si Diodes (Ref. 1-7), integrate with high efficiency Solar cell and Panels.
- ☐ Primary metric for improvement: Diamond Schottky diodes, SiC schottky diodes, PN junctions, packaging
- ☐ Secondary metric for improvement: Manufacturing processes-PVD and CVD, Processing conditions, Radiation testing.
- ☐ Implement advances in diamond, SiC, and Si technologies with protective layers from Rad hard coatings via PVD and CVD processes
- ☐ Integrate innovative device approaches with triple junction solar cell
- ☐ Demonstrate diamond and SiC integrated devices for space power electronics.

Experimental



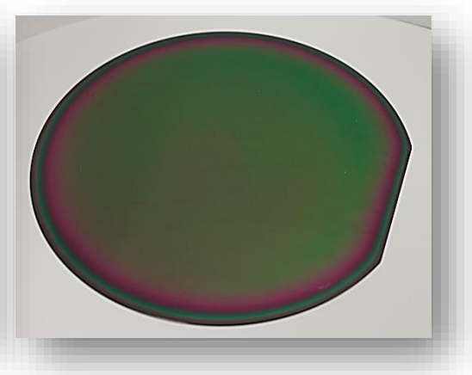


HFCVD



Substrate Carousel

Nanodiamond film/4" Si



Nanodiamond film/ 6" Si

In-situ Monitoring of CVD diamond layers

As the CVD diamond film starts to grow the laser reflectance decreases, until the nucleation layer is continuous on the substrate. After that laser reflectance starts to increase and oscillations can be measured. SEM measurements were conducted to confirm the film thickness measurements using LRI. Using this approach, CVD diamond active layers for our diode fabrication are under development.

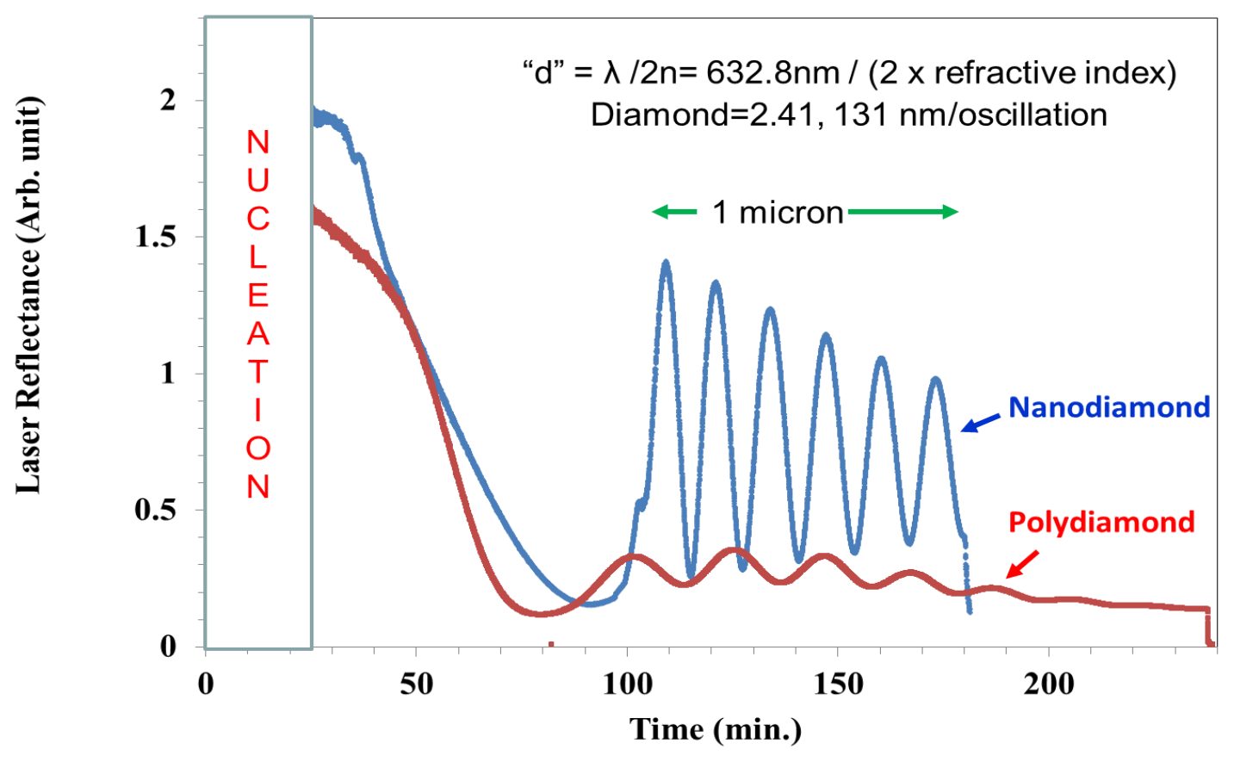
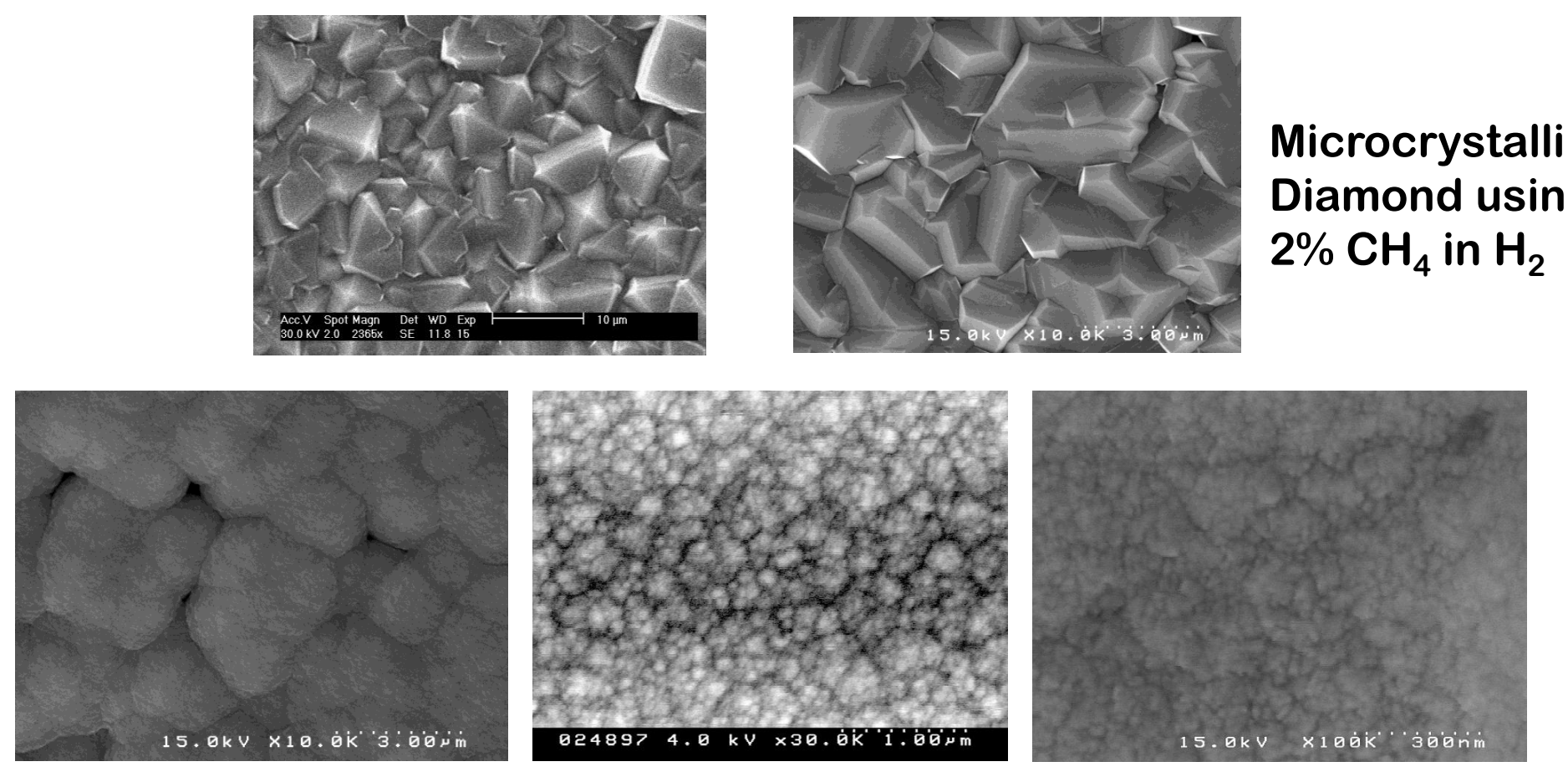


Fig. 1 Blue Wave HFCVD Laser Reflectivity Measurement



Microcrystalline Diamond using 2% CH_4 in H_2

Transition towards nano With Filament Temp=2250C

Nanodiamond (Ar-rich conditions)

Fig. 2. Grain size of nanodiamond films are controlled with Ar/H2 gas mixing

Results

Diode Fabrication

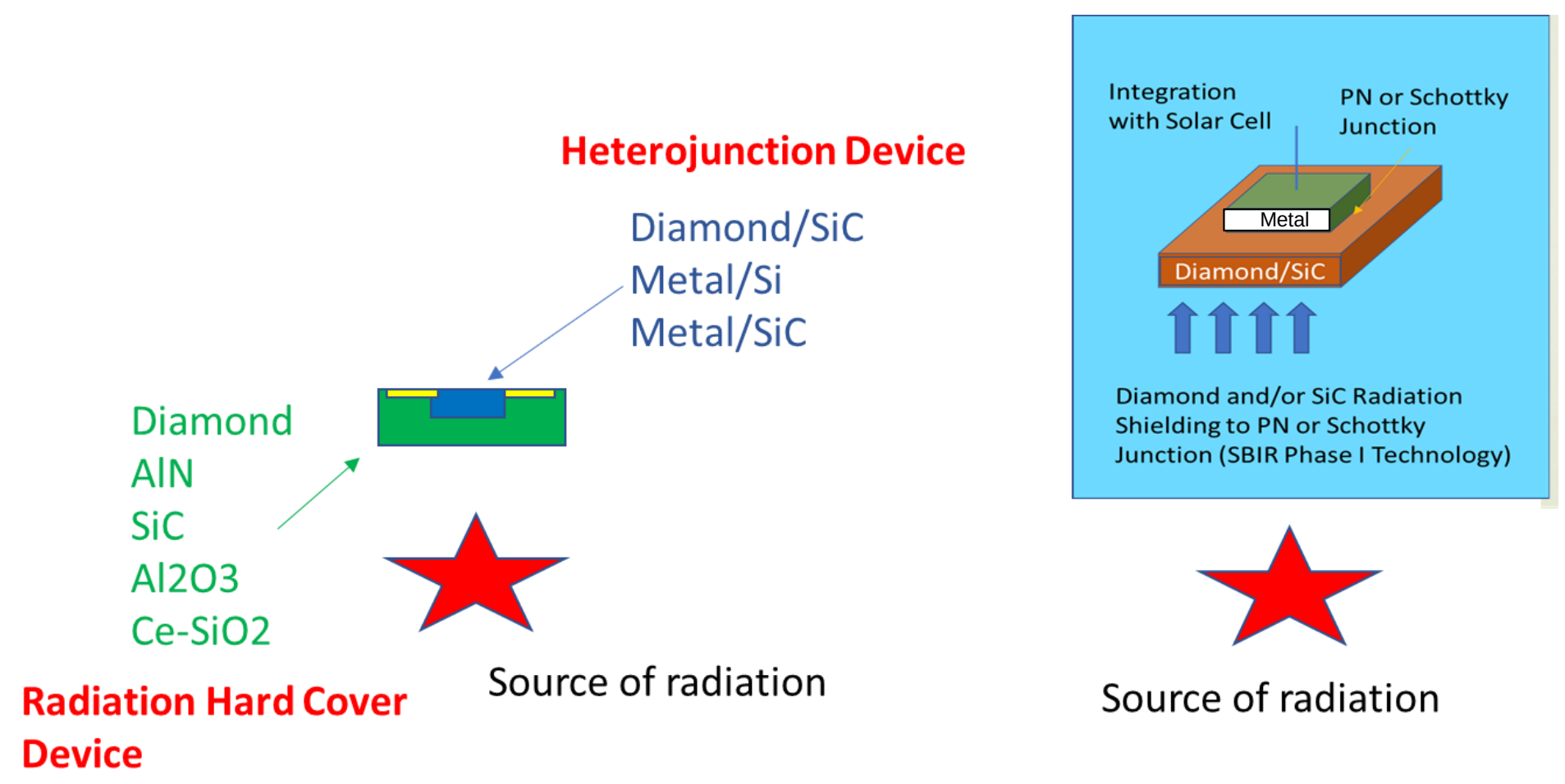


Fig. 3. Picturization of importance of radiation hard diodes for space solar cell operating in harsh environment. About 100-200-micron thick diamond or SiC can easily protect device junction from radiation exposure.

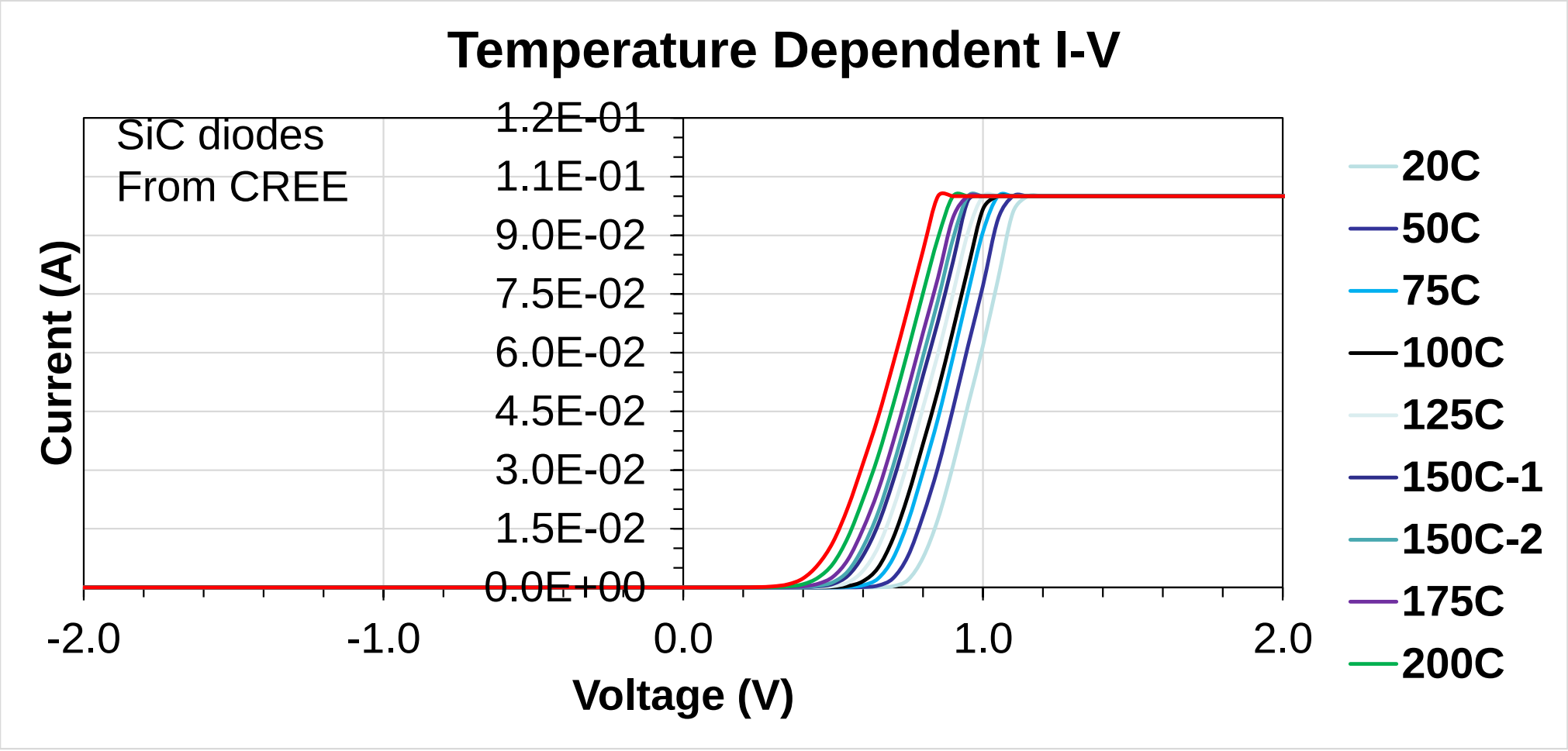


Fig. 4. Forward characteristics of fabricated SiC diodes at high temperatures.

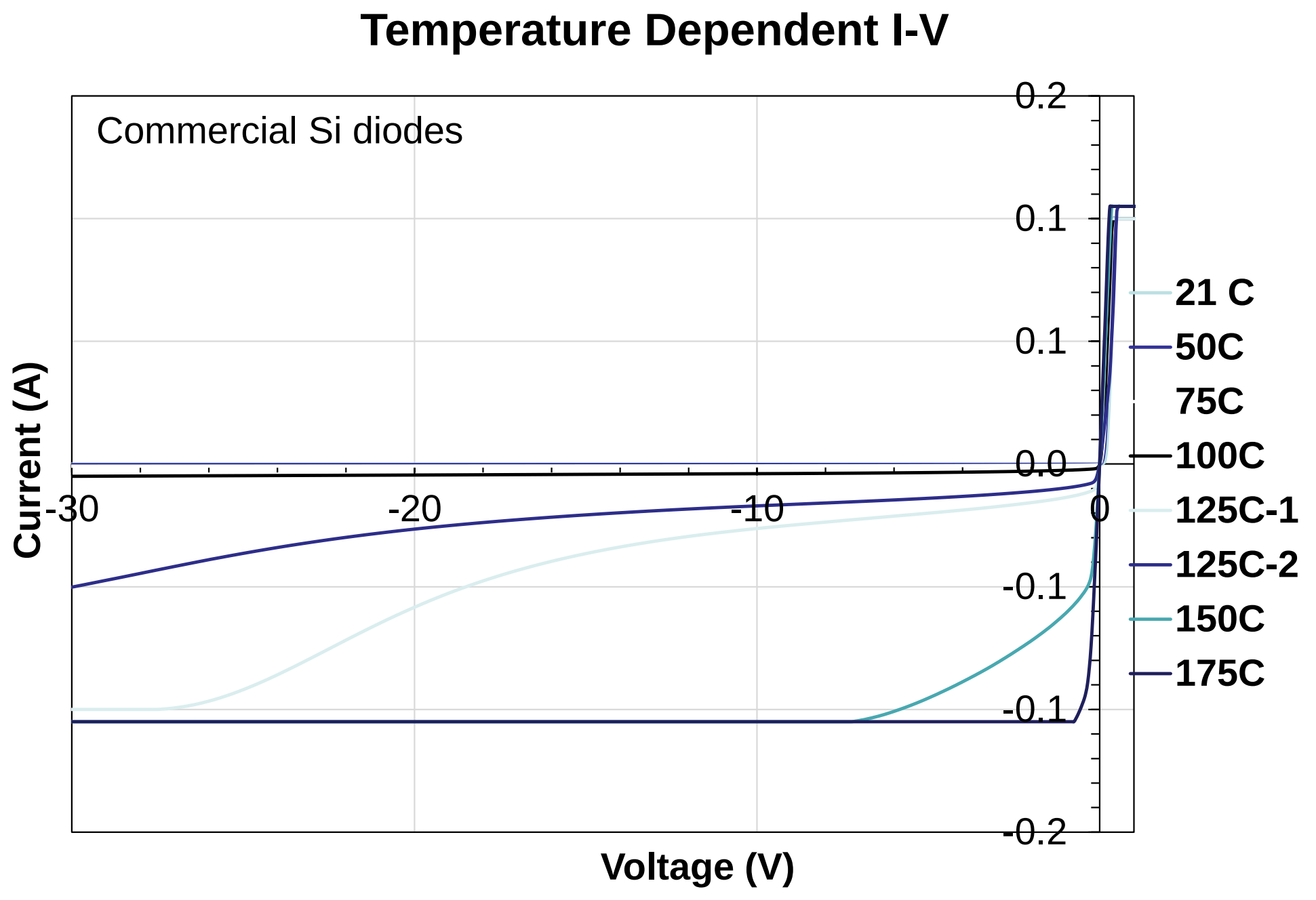


Fig. 5 Forward characteristics of fabricated Si diodes at high temperatures.

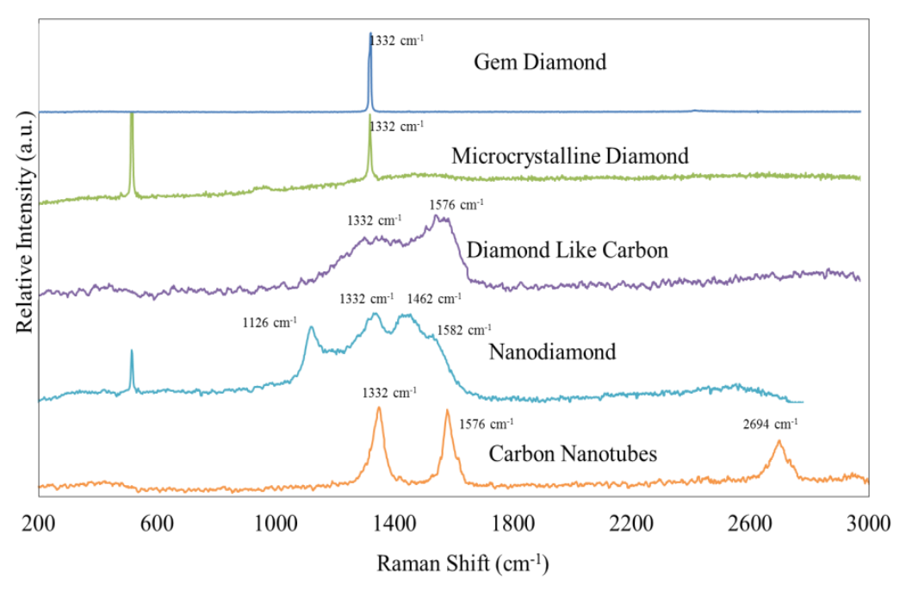


Fig. 6. Raman of various forms of carbon including diamond.

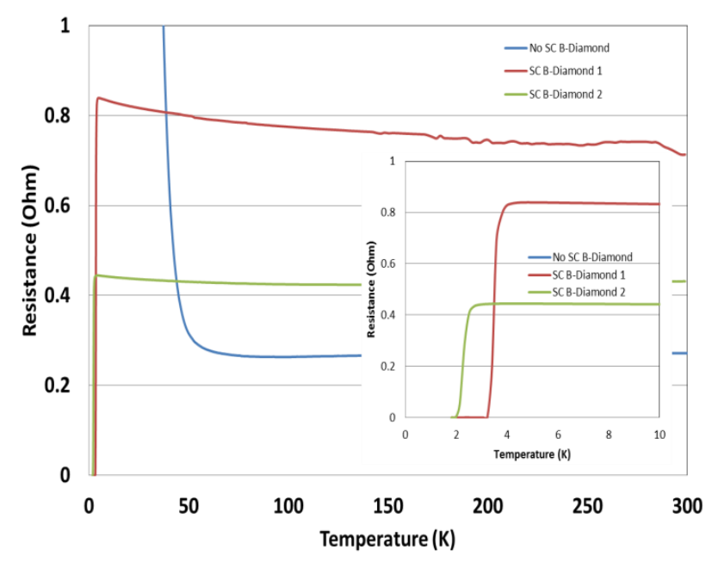
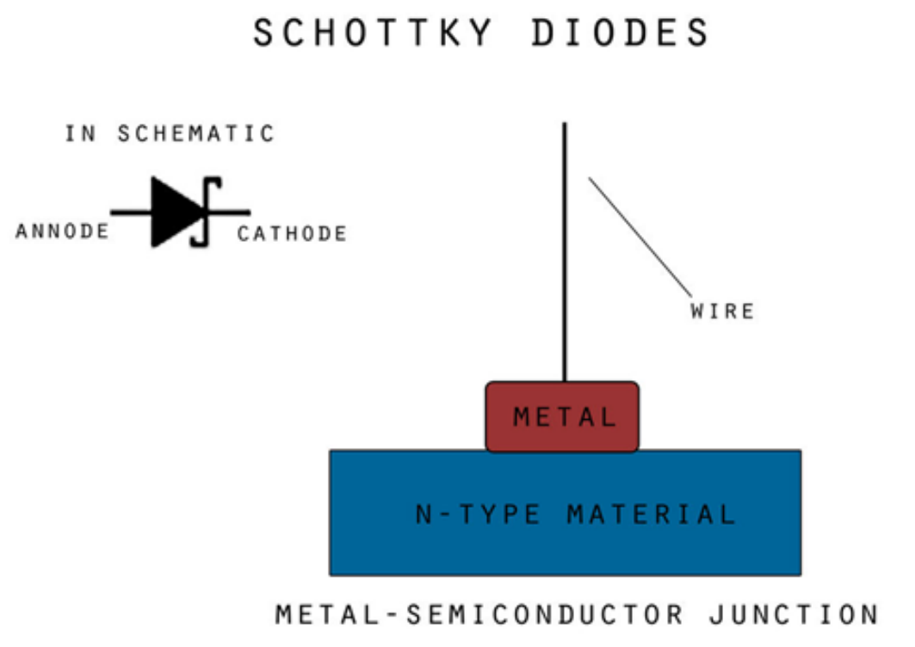


Fig. 7. Resistance Vs Temperature data for boron-doped CVD diamond film. This indicate that boron doping can be used for development of conductive to semiconductive to insulating diamond layer for diodes.

Devices under Fabrication



Device 1) Metal/Diamond
Device 2) Diamond/SiC
Device 3) Metal/SiC

Fig. 8. Schematics of diodes under fabrication from various metals-Semiconductors Rad Hard Materials.

Results

Literature/Reference Data

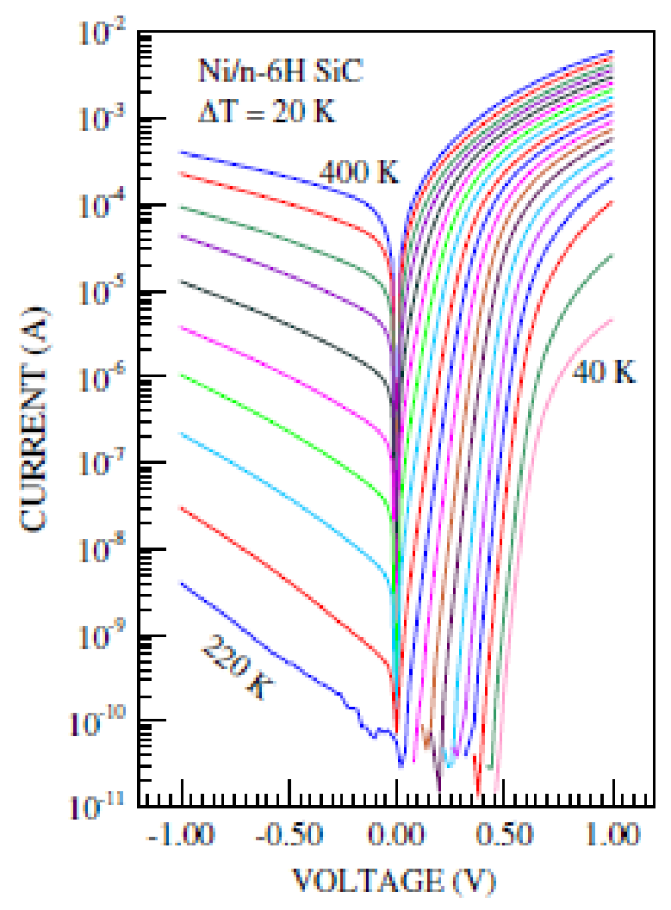


Fig. 9 I-V of Ni/n6H-SiC Schottky diode in the measurement temperature range of 40-400K [Ref. Kadir Ejderha et al. [1]].

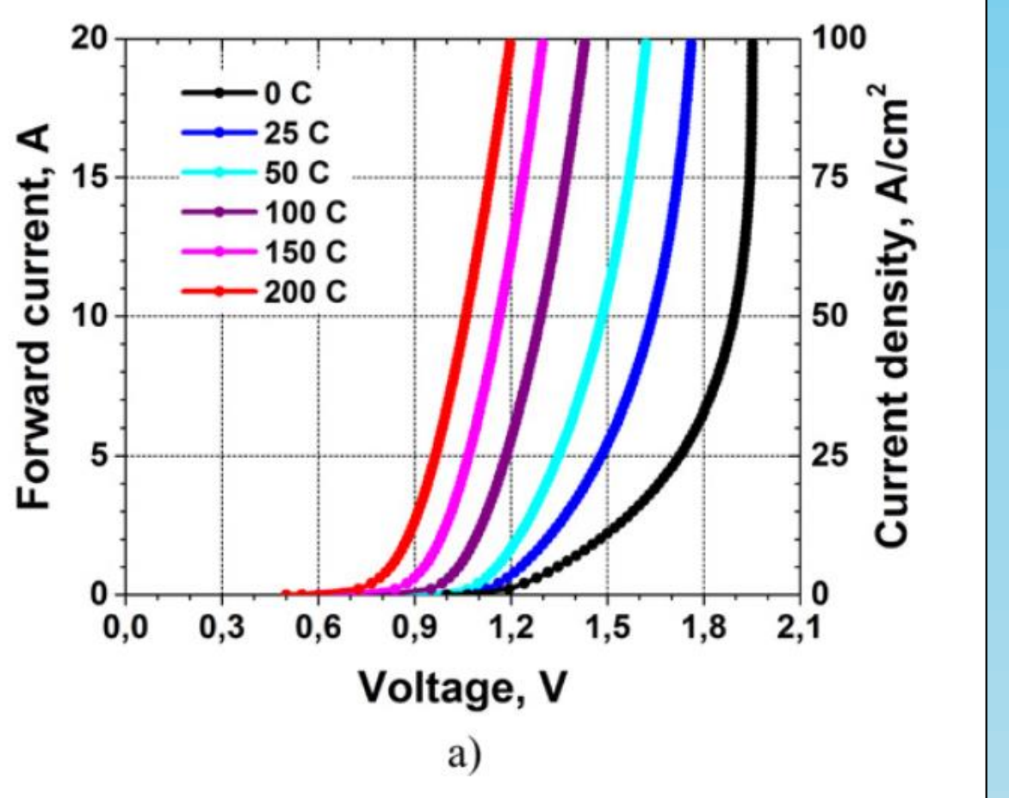


Fig. 5 Forward characteristics of fabricated thin diamond diodes at different temperatures [Ref. V.S. Bormashov et al. [3]].

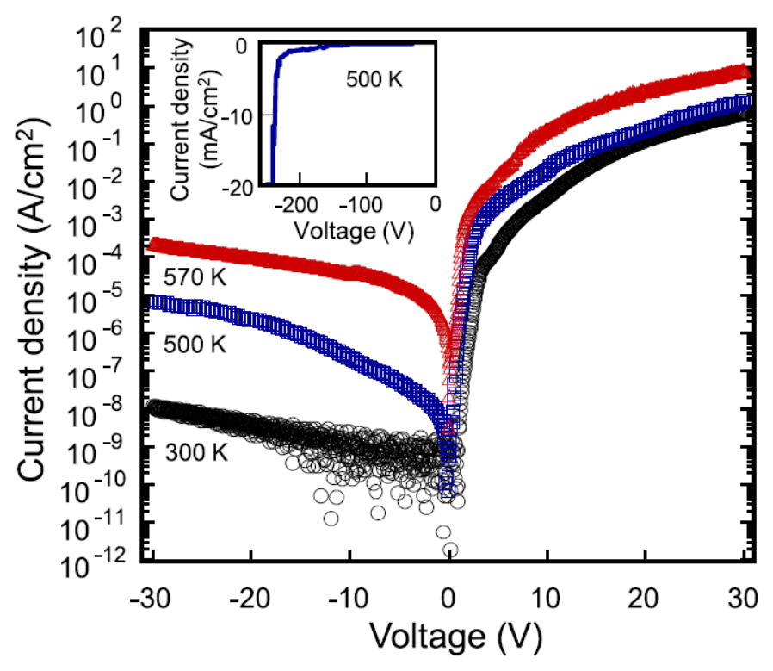


Fig. 10. *I-V* characteristics of the *n*-NCD/*p*-SiC diode measured at Tm=300, 500, and 570 K [M. Gato et al.[5]]

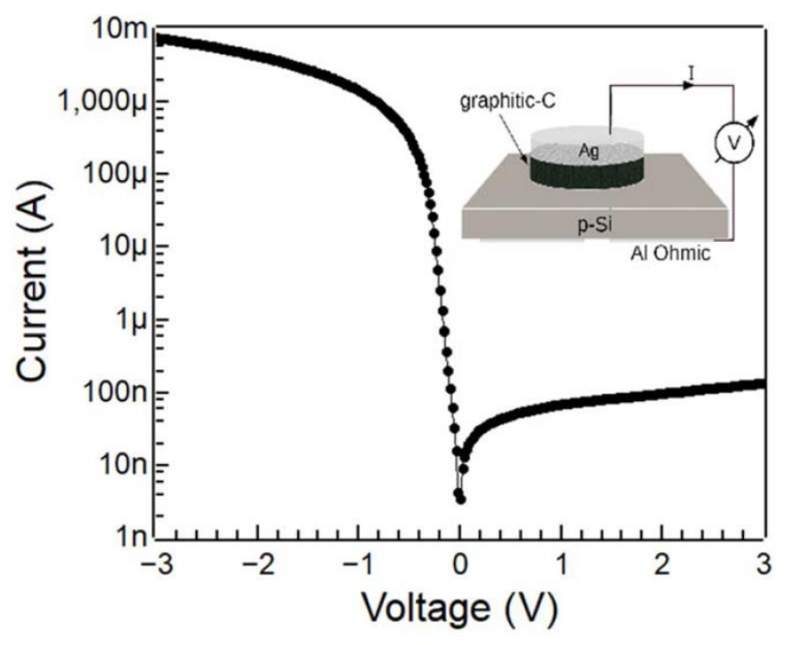


Fig. 11 Room temperature I–V characteristics of an energetically deposited C/p-type Si junction. The inset shows the structure of the device and the measurement circuit [H.V. Pham et al. [7]]

Conclusions

Advancements in spacecraft solar array technologies require radiation hard, high temperature discrete diodes for solar cell protection. To achieve this objective, wide band gap semiconductor diode technology is ideal for this application. We are fabricating and investigating wide band gap heterostructure diode technology that will be radiation hard, capable of handling high temperature, high power, and reliable to integrate in space power solar cell technologies.

Acknowledgement

This research is supported by AFRL SBIR Phase I contract #FA9453-19-P-0588.

References

1. Kadir Ejderha, Abdulkerim Karabulut, Nurettin Turkan, Abdulmecit Turut, "The Characteristic Parameters of Ni/n-6H-SiC Devices Over a Wide Measurement Temperature Range," Silicon, 9:395-401, (2017).
2. D. Mukherjee, L.N. Alves, M. Neto, F.J. Oliveira, R.F. Silva, J.C. Mendes, "Fabrication and characterization of n-SiC / p-diamond heterojunctions"
3. V.S. Bormashov, S.A. Terentiev, S.G. Buga, S.A. Tarelkin, A.P. Volkov, D.V. Teteruk, N.V. Kornilov, M.S. Kuznetsov, V.D. Blank, "Thin large area vertical Schottky barrier diamond diodes with low on-resistance made by ion-beam assisted lift-off technique," Diamond & Related Materials 75: 78-84, (2017)
4. Richard Patterson, Ahmad Hammoud, Malik Elbuluk, Scott Gerber, "Performance of Various Types of Diodes at Cryogenic Temperatures," NASA Electronic Parts and Packaging Program
5. Masaki Goto, Ryo Amano, Naotaka Shimoda, Yoshimine Kato, and Kungen Teii, "Rectification properties of n-type nanocrystalline diamond heterojunctions to p-type silicon carbide at high temperatures," Applied Physics Letters 104, 153113 (2014)
6. A. Vescan, Member, IEEE, I. Daumiller, P. Gluche, Student Member, IEEE, W. Ebert, and E. Kohn, Member, IEEE, "Very High Temperature Operation of Diamond Schottky Diode," IEEE Electron Device Letters, Vol. 18, NO. 11, 556-558, November (1997)
7. Hung V Pham, Phuong Yen Le, Hiep N Tran, Thomas J Raeber, Mohammad Saleh N Alnassar, Anthony S Holland and Jim G Partridge, "Temperature dependent electrical characteristics of rectifying graphitic contacts to p-type silicon," Semicond. Sci. Technol. 34 015003 (5pp), 1-5 (2019)