Neutron Detection Signatures at Zero Bias in Novel Semiconducting Boron Carbide Containing Pyridine Polymers

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SUMMARY

Novel and more unconventional semiconductor devices based on boron carbide were formed by Plasma-enhanced chemical vapor deposition (PECVD) of closo-1,2-dicarbadodecaborane (ortho-carborane; 1,2-$B_{10}C_2H_{12}$) in the presence of the aromatic compound pyridine (Py) and on n-type Si.

Three types of boron carbides made into heterojunction diodes with silicon for this study, each one made out of a different boron carbide film, are (i) pure boron carbide films, (ii) boron carbide films with a pyridine concentration roughly proportional to the icosahedral carborane moieties, (iii) boron carbide films with a relatively high pyridine concentration of ten times the pyridine (Py) concentration relative to the icosahedral carborane (BC) moieties.

The neutron capture generated pulses from these heterojunction diodes were obtained at zero bias voltage, although without the signatures of complete charge collection expected boron neutron capture generated electron hole pair production. These results, nonetheless, suggest that modifications to boron carbide may result in better neutron voltaic materials with linking groups chosen from family of aromatic compounds that stretch between borazine ($B_3N_3H_6$) and benzene that point the way to a whole family of future studies that may ultimately lead to boron carbides better suited to low power and low flux neutron detection.

STRUCTURAL MODELS

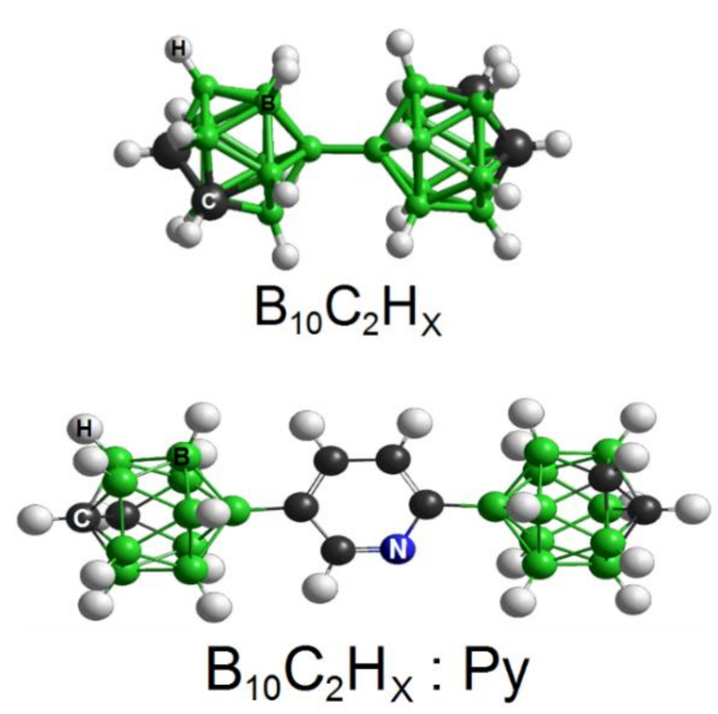
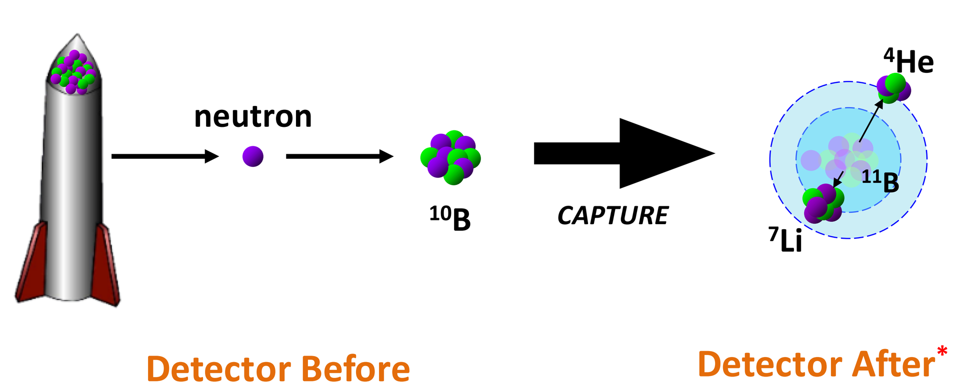


Figure 1. Structural models. Top: Boron Carbide. Bottom: Boron Carbide with aromatic pyridine.

The addition of nitrogen may marginally increase neutron capture cross-sections at the very high neutron energies where the strong boron capture cross-section falls sharply, without leading to an increase in cross-sections to hard X-ray or gamma radiation being similarly a low Z element.

NEUTRON CAPTURE BY ^{10}B ATOM



*** Helium-4 and Lithium-7 stop within 5 microns in most materials.**

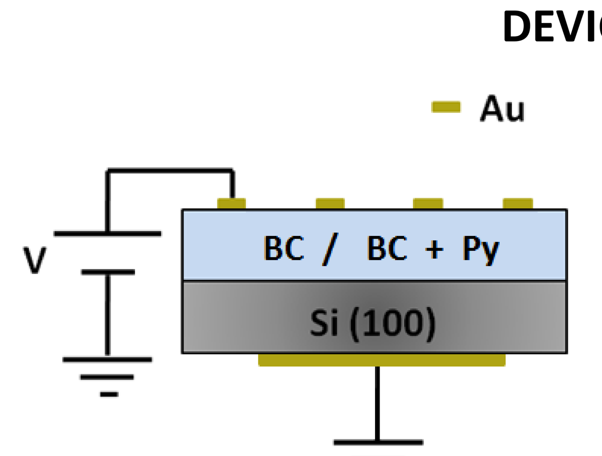
The basis for neutron detection involving boron is $^{10}B(n,\alpha)^7Li$ neutron capture that results in:

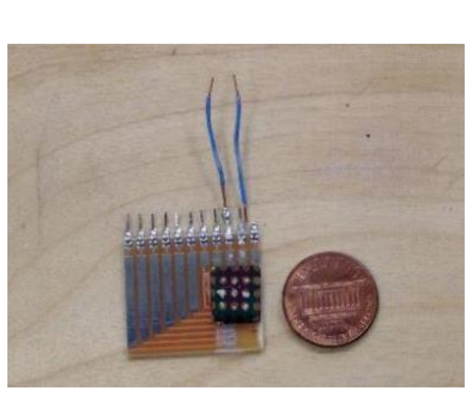
$$^{10}B + n \rightarrow {}^{7}Li\ (0.84\ MeV) + {}^{4}He\ (1.47\ MeV) + \gamma\ (0.48\ MeV)$$

$$^{10}B + n \rightarrow {}^{7}Li\ (1.02\ MeV) + {}^{4}He\ (1.78\ MeV)$$

with 94 and 6% probability respectively and yields the large kinetic energies listed in parentheses

DEVICES





CURRENT-VOLTAGE CHARACTERISTICS

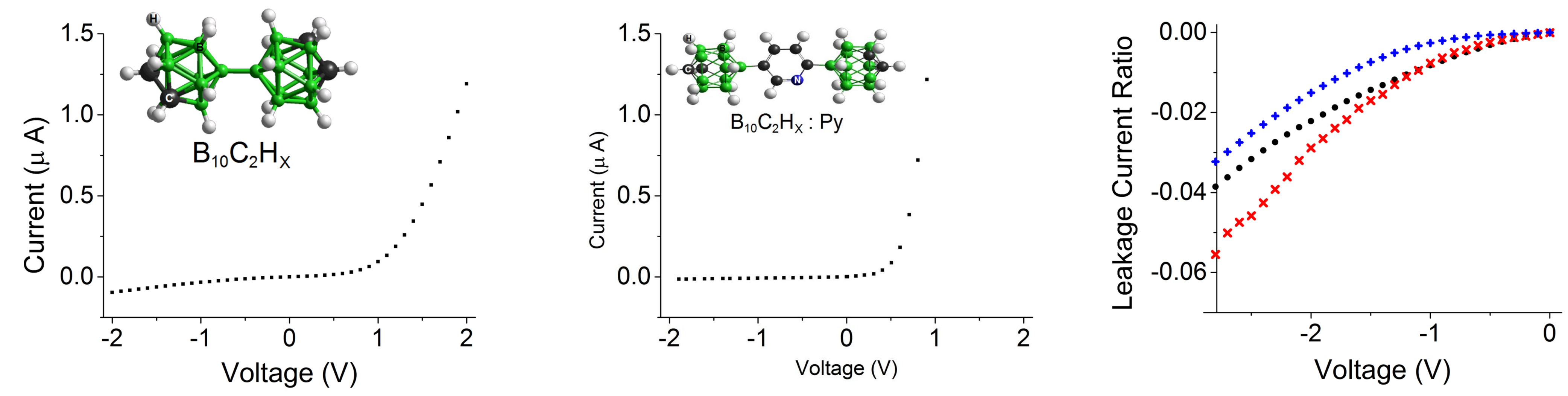


Figure 2. Left: I-V curve of $B_{10}C_2H_X$. Center: I-V curve of $B_{10}C_2H_X$:Py. Right: Reverse bias current normalized to the 3 V forward bias current (Black: $B_{10}C_2H_X$, Red: $B_{10}C_2H_X$:Py ratio about 1:3, Blue: $B_{10}C_2H_X$:Py ratio about 1:10).

The I-V characteristic curves for the heterojunction diodes exhibit strong rectification. The reverse bias normalized leakage currents are largely unperturbed with increasing pyridine inclusion. The devices are largely gamma insensitive and yet neutron voltaic properties of these boron carbides is demonstrated.

NEUTRON DETECTION

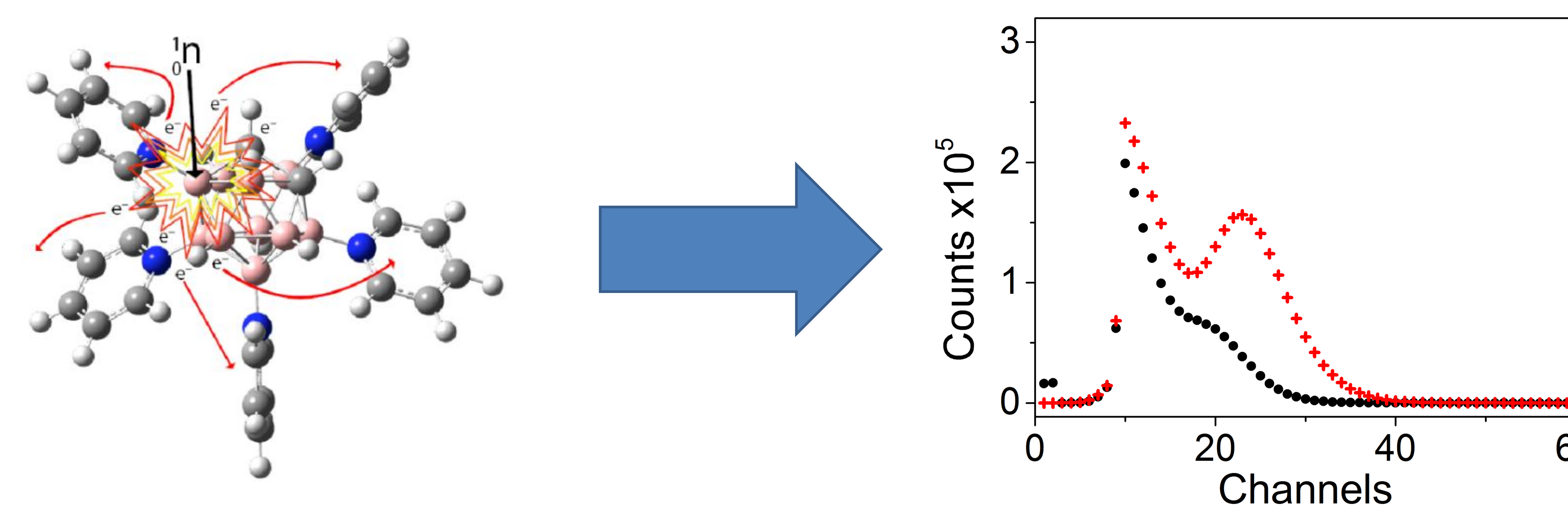


Figure 3. Left: Schematic neutron capture on Boron Carbide. Right: Experimental neutron pulse height spectra of $B_{10}C_2H_X$ (black filled circles) and $B_{10}C_2H_X$:Py (red plus symbols) at zero bias.

What is key to the general motivation behind this work is that the devices exhibit neutron capture generated pulses obtained from these heterojunction diodes at zero applied bias, as seen in Figure 3. The pulse height spectra for boron carbide with a heavy inclusion of pyridine BC:Py10 (concentration 1:10) does show the signature improved electron hole separation, and thus better charge collection, as might occur in very thin films of the boron containing semiconductor even at higher reverse bias (but without any reverse bias). There may even be some marginal improvements in the overage pulse collection.

COMPARATION TO OTHER MATERIALS

Detector type	Semiconducting ^{10}BC	^{3}He tube / ^{3}He array	GEM/ MicroMegas	Scintillator	** Other semi-conductors
Voltage (V)	~0	~ 10^3	~ 10^3	~1 to ~ 10^3	~1 to ~ 10^2
*** Minimum power demand (W)**	10^{-6} to 10^{-3}	~10^0	~10^0	10^{-6} to ~10^0	10^{-6} to 10^{-3}
Maximum thermal neutron detection efficiency (%)	70	70	>50	90	70 (bulk) 5 to potentially 20? (conversion)
Detector thickness for 50% efficiency	<10^{-3}	10^{-1}	10^{-1}	10^{-3} to 10^{-1}	10^{-3} to 10^{-2}
Capital cost/unit active area	Very low/low	Running out of ^{3}He	Low	Moderate	High

CONCLUSION

Boron carbide films formed with pyridine linking groups leads to improved charge collection after neutron capture while remaining insensitive to gamma radiation. This demonstrates that boron carbide neutron detection can be improved by the incorporation of pyridine or similar groups that enhance electron-hole separation and, possibly, better carrier mobilities and total charge collection. The data presented here suggest that further improvements in neutron detection efficiency to nonthermal neutrons, by even small increases in the fast neutron absorption cross may be possible. **Therefore, modifications to boron carbide may result in better neutron voltaic materials.**

WHAT NEXT?

One approach to improve neutron detection efficiency, as suggested by the results here, would be modification of a semiconducting boron carbide through the incorporation of other moieties chosen from the family of aromatic compounds that stretches from borazine ($B_3N_3H_6$) to benzene, including more amino, amido and borane (boron and nitrogen moieties) substitutions on the aromatic functionality, so that the overall boron and nitrogen content per unit volume is enhanced. The extended electron-hole lifetimes characteristic of polypyridines and polypyridine multidentate ligands may not extend to all possible aromatic linking groups, but will certainly be apparent in a number of such more boron-rich alternatives. **This present work points the way to a whole family of future studies that may ultimately lead to boron carbides better suited to low power and low flux neutron detection.**

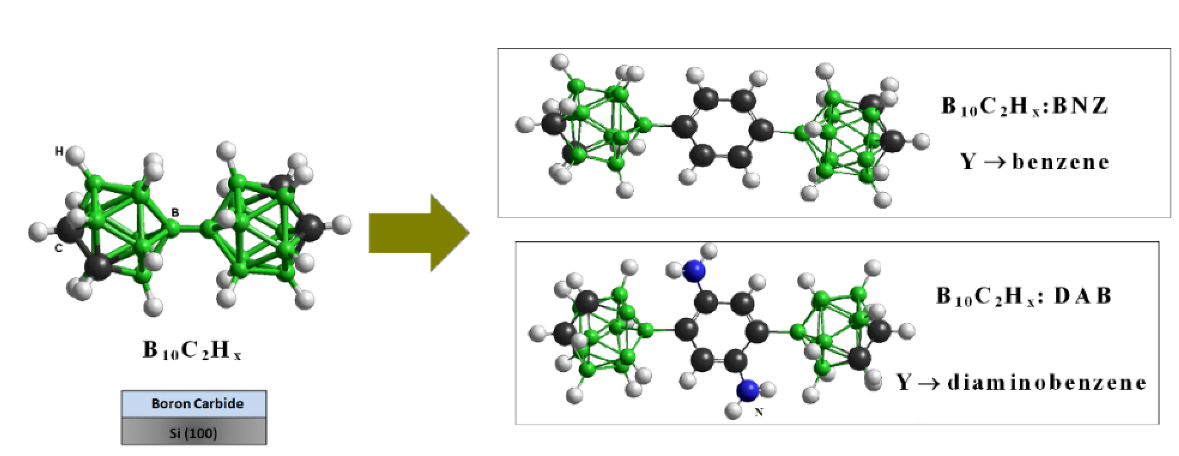


Figure 4. Structural models of $B_{10}C_2H_X$: Y.