"Development of Ion Beam Nuclear Transmutation Doping (IBNTD) for Novel Electronics in Extreme Conditions"

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Collaborative Research Opportunities
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Development of IBNTD for electronics under extreme conditions.

- We hope to create novel wide bandgap devices using Ion Beam Nuclear Transmutation Doping (IBNTD). These devices may be used as rugged high power switches, and high current/low noise amplifiers. Diamond in itself represents a “Holy Grail” for electrical applications due to its very high thermal conductivity and excellent electrical characteristics.

- We also hope to develop devices that can convert the enormous energy from high-energy nuclear particles (α^{2+},β^{-},β^{+}, γ particles) into useful electricity and thus harness the enormous energy still contained in “spent” nuclear fuel. Developing these direct energy conversion (DEC) devices would significantly reduce conversion inefficiencies.

- To create a radiation-rugged devices that can withstand high particle beam fluxes (e.g. outer space, and nuclear engineering sensors).

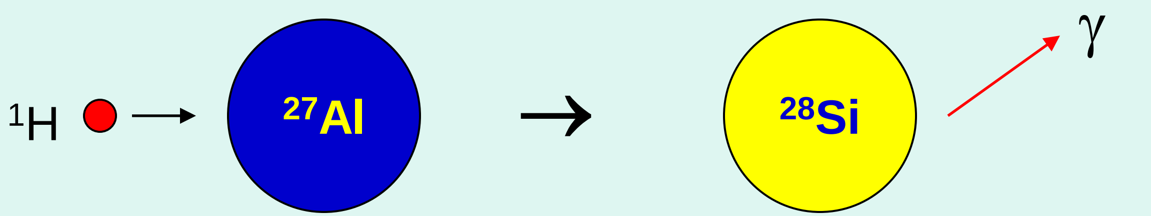
- *Reference:* “A novel method to dope diamond - Ion Beam Nuclear Transmutation Doping (IBNTD),” M.G. Pravica, N.A. Guardala and J.L. Price, *Diamond and Related Materials,* **18**, pp. 846-849 (2009)

- *US Patent* 7,795,120: “Doping wide band gap semiconductors using proton induced transmutation.”

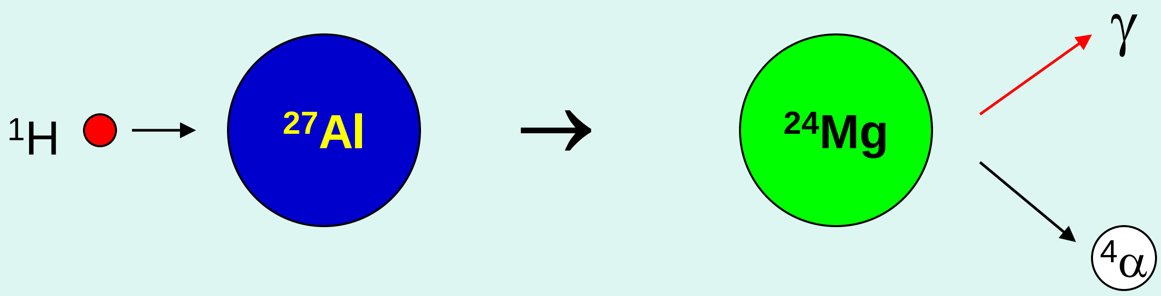
Nuclear Transmutation via proton capture (true alchemy)

H							He
Li	Be	B	C	N	O	F	Ne
Na	Mg	Al	Si	P	S	Cl	Ar
		Ga	Ge	As			
		In	Sn	Sb			

$^{1}H + {}^{27}Al \rightarrow {}^{28}Si + \gamma$ $\quad E_R = 992$ keV

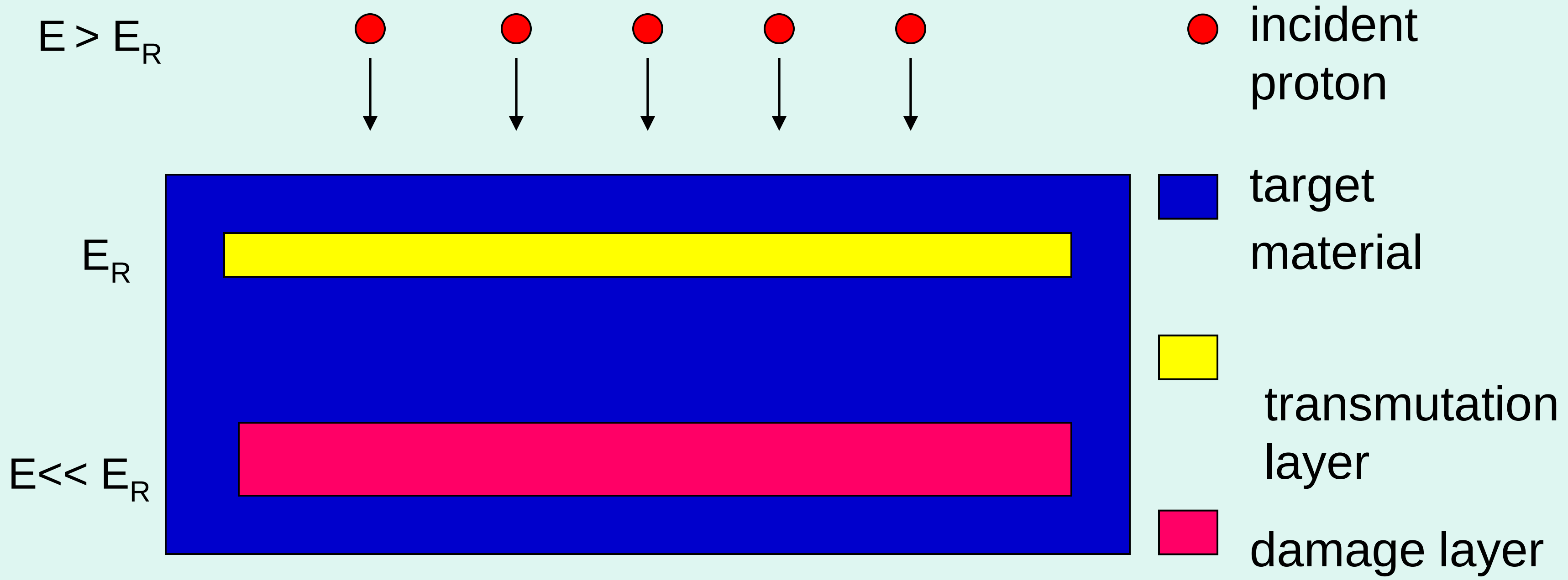


$^{1}H + {}^{27}Al \rightarrow {}^{24}Mg + {}^{4}\alpha + \gamma$ $\quad E_R = 1183$ keV



Ion Beam Nuclear Transmutation Doping (IBNTD)

- Charged beam provides control of areal deposition
- Resonance energy requirement provides depth control via material's dE/dx

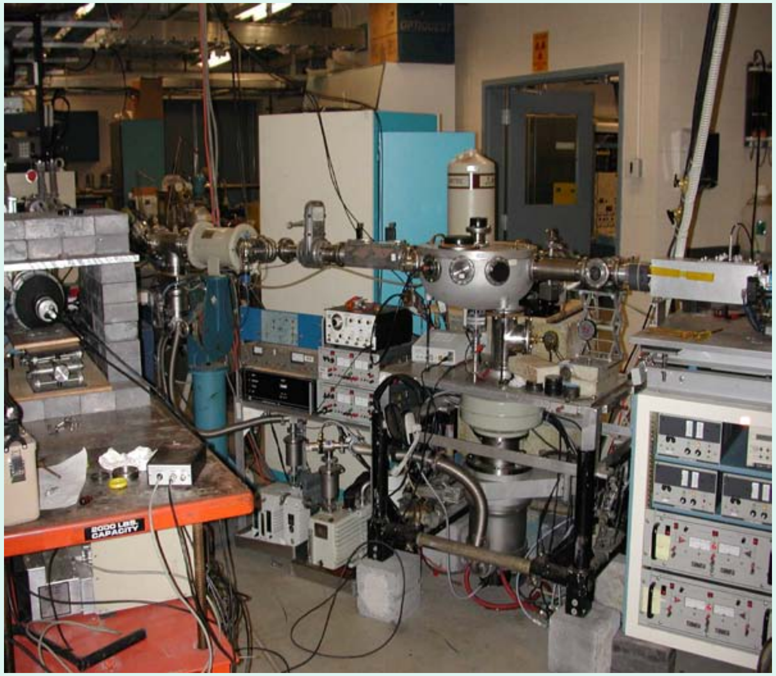


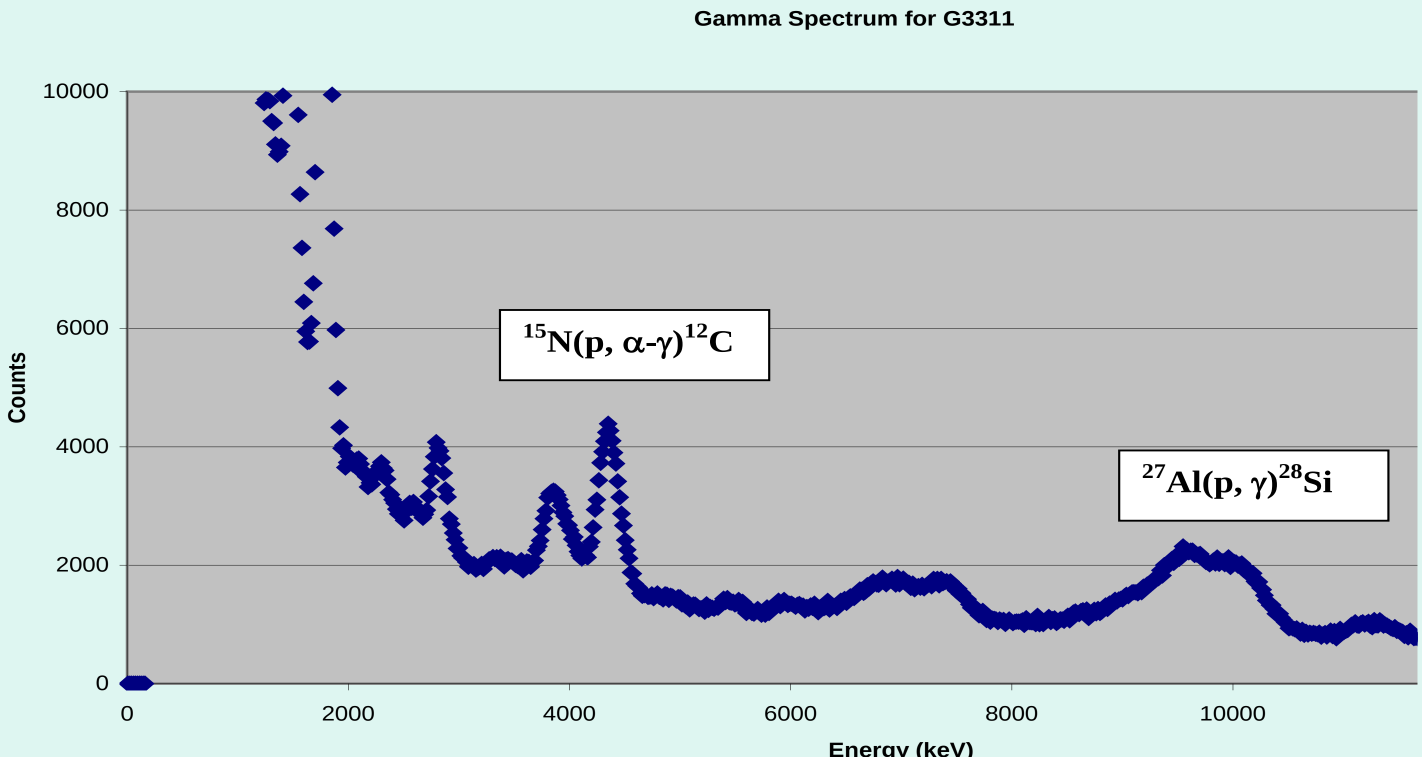
Approach

N- and p-type doping of diamond, $Al_{1-x}Ga_xN$, GaN, AlN, SiC, AlAs, BN, GaP and Al_2O_3 can be accomplished by transmuting host nuclei using various resonant reactions at different energies (only a select few of many are listed here):

$^{1}H + ^{27}Al \rightarrow ^{28}Si + \gamma$	E_R = 992, 1368 keV	n-type
$^{1}H + ^{27}Al \rightarrow ^{24}Mg + ^{4}\alpha + \gamma$	E_R = 1183 keV	p-type
$^{1}H + ^{15}N \rightarrow ^{12}C + ^{4}\alpha + \gamma$	E_R = 897, 3000 keV	p-type
$^{1}H + ^{30}Si \rightarrow ^{31}P + \gamma$	E_R = 620 keV	n-type
$^{1}H + ^{31}P \rightarrow ^{32}S + \gamma$	E_R = 1251 keV	n-type
$^{1}H + ^{31}P \rightarrow ^{28}Si + ^{4}\alpha + \gamma$	E_R = 1521 keV	p-type
$^{1}H + ^{13}C \rightarrow ^{14}N + \gamma$	E_R = 1748 keV	n-type
$^{1}H + ^{13}C \rightarrow ^{10}B + ^{4}\alpha$	E_R = 720, 1740 keV	p-type

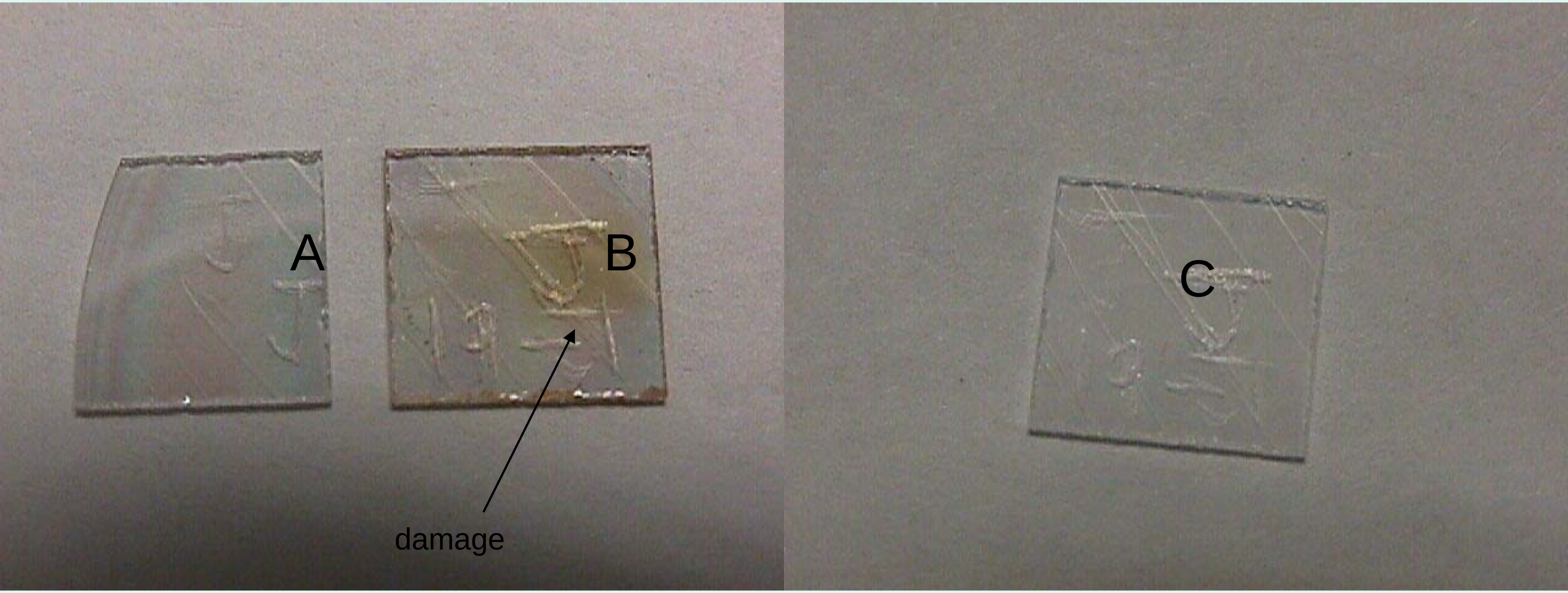
Positive ion facility at the Naval Surface Warfare Center, Carderock (NEC-9SDH2 Tandem Pelletron)





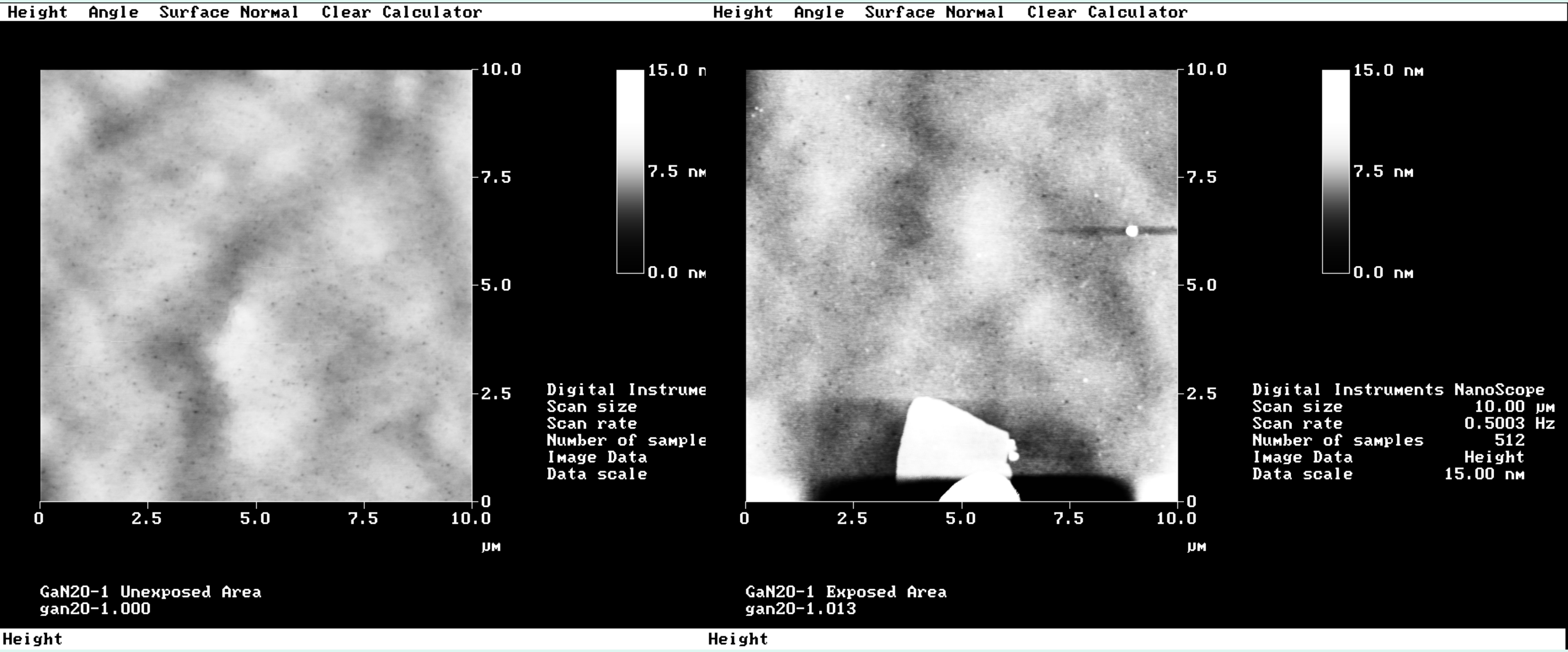
- Accumulated gamma ray spectrum.
  - –Accumulated during the “transmutation” of aluminum to silicon.
    - 993 keV proton beam.
    - $Al_{0.3}Ga_{0.7}N$/Sapphire.
  - –High energy gammas seen only for Al → Si reaction.
  - –Evidence of nitrogen transmutation to carbon

AlGaN sample images.



A: Unirradiated AlGan B: Irradiated sample 19-1 C: Sample 19-1 after annealing

AFM images of AlGaN surface.



AFM shows minimal damage due to irradiation of AlGaN

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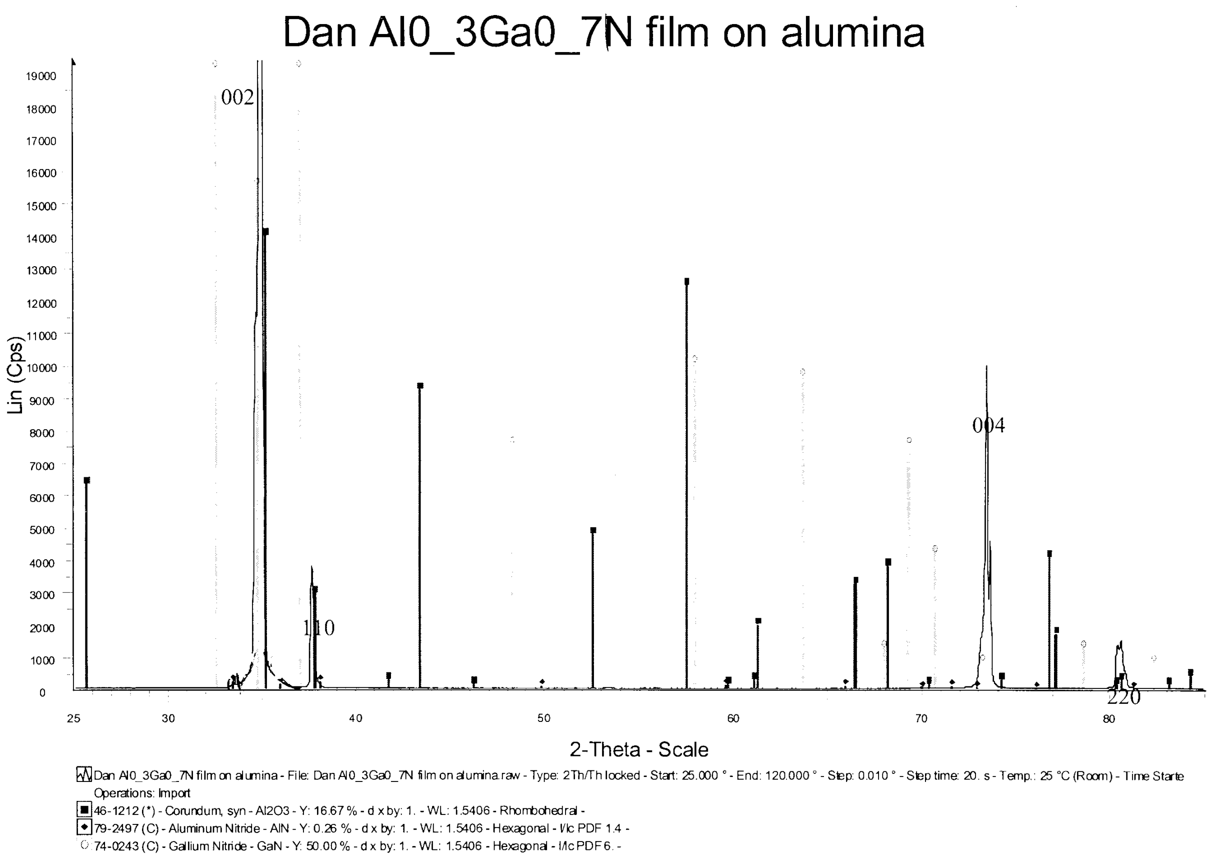
X-ray Diffraction Data on Doped AlGaN sample showing evidence for substitutional doping.

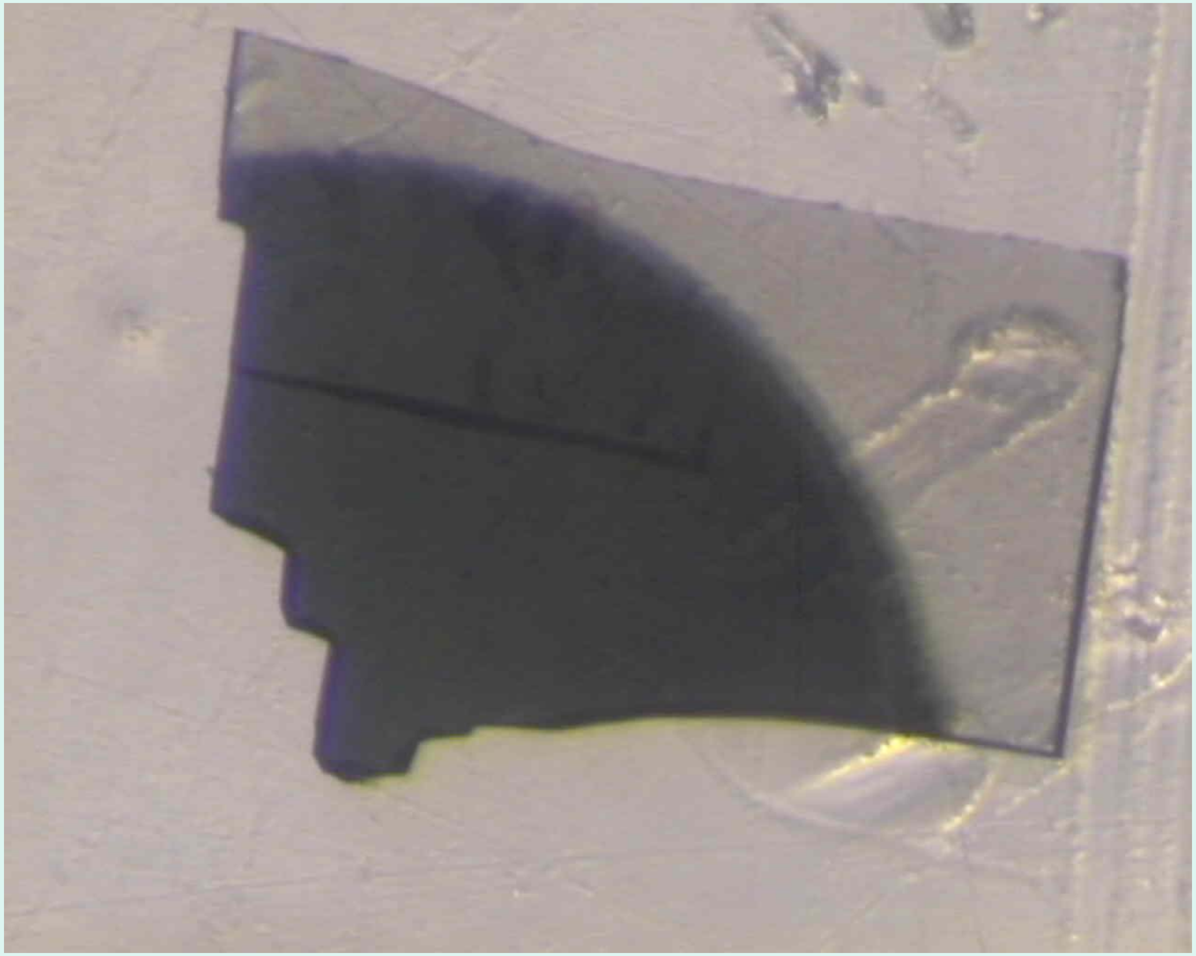


Doping of Diamond

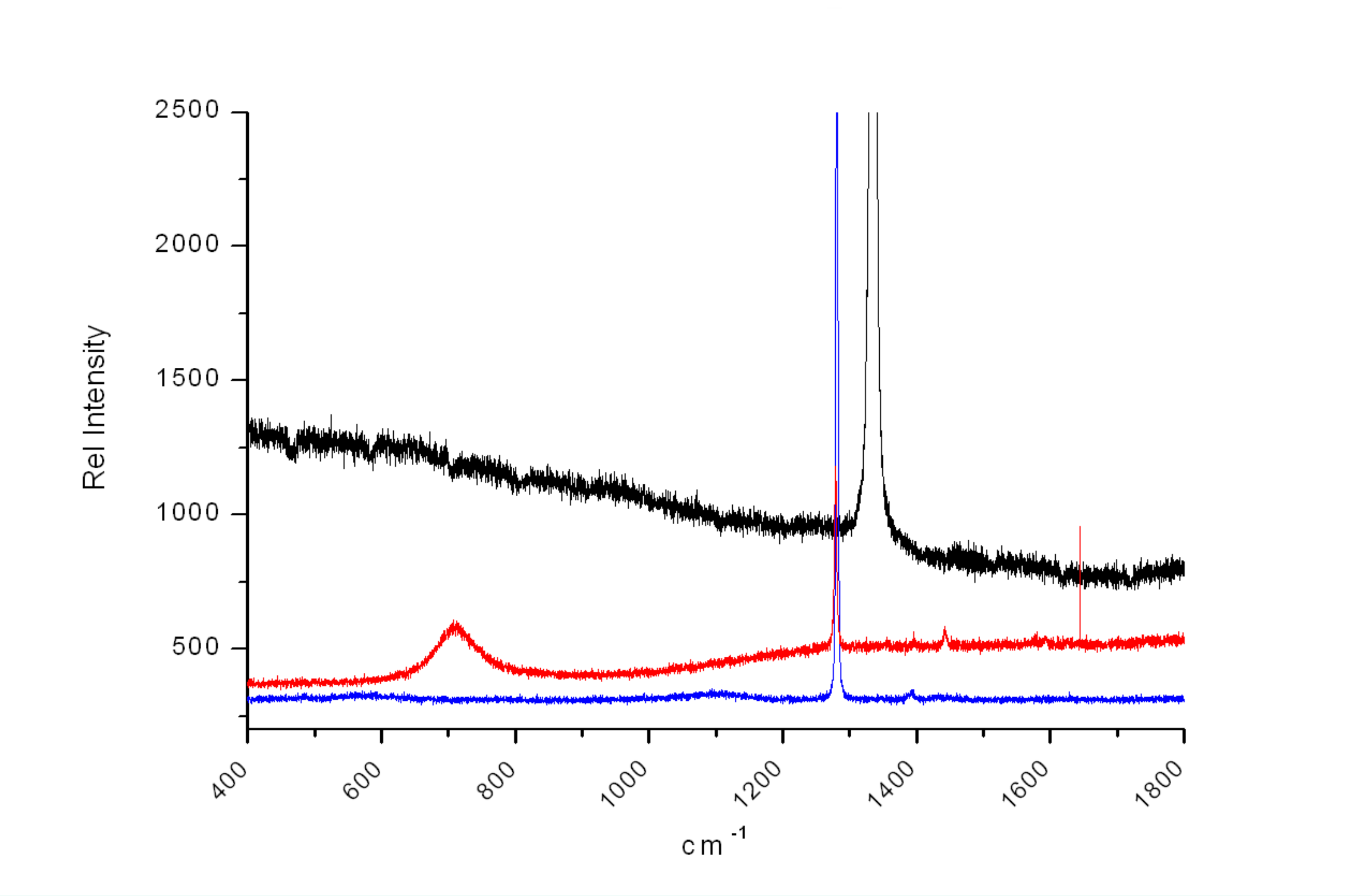
- We chose the $^{1}H + ^{13}C \rightarrow ^{14}N + \gamma$ nuclear reaction with E_R = 1748 keV to dope enriched diamond n-type. Though there are issues with using nitrogen as a dopant material for diamond due to the deep level (1.7eV) of the nitrogen donors within the nitrogen gap , we chose this reaction as it is strong (high cross section of ~320 mbarns) and has a narrow resonance width (~75eV) to demonstrate our novel technique.
- We used the positive ion accelerator facility at NSWCCD to produce ~ 1μA of protons at an energy of 1.90 MeV (1keV) for ~44 hours.
- We estimate a dopant concentration of 5.7×10^{14} dopants/cc within a 22nm layer after an 8-hour day of continuous bombardment which is within the range of detection by a number of spectroscopic methods.
- Nuclear transmutation was immediately observed to occur with bombardment using a 5”x5” CsI scintillation crystal and associated counting electronics.

^{13}C-diamond doped via IBNTD.

Virgin sample was initially made via CVD by Jim Butler of NRL for David Schiferl and Bob Sander of LANL.



Raman spectra of natural diamond, virgin ^{13}C, and doped ^{13}C. Potential evidence of subtitutional doping via IBNTD.



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Advantages of the IBNTD method

- Wide bandgap semiconductors are very rugged electronic materials that can withstand high radiation damage suffer less from the effects of noise (due to their large bandgap energies. Devices made from these materials can create and withstand high voltages and currents.
- Doped layers are10's of nanometers depending on the nuclear reaction resonance width and the width of the proton beam allow for very narrow and concentrated pn junctions at any depth desired within the host crystal.
- The these properties may allow for the creation of highly compact devices that can in principle very efficiently collect/convert energy released into the device by high energy particles.
- With large energies being deposited into the device, there is great potential of self-annealing.
- Enabling technology for use in high temperature, high voltage, and high frequency electronics.
- A major hurdle in the doping/fabrication of wide-band gap devices will be overcome.

Future Plans

- We will endeavor to find the optimum reaction/substrate parameters to create ideal conditions for IBNTD.
- We will seek to further determine the level of substitutional vs. interstitial doping.
- We will fabricate devices utilizing this doping method.

Summary

- We have demonstrated a novel method of doping challenging wide bandgap materials using high energy (MeV or greater) protons to induce nuclear transmutation.
- Our rugged samples suffer relatively little from the bombardment (except perhaps end of range damage which can be likely annealed or polished away).
- We suggest the possibility of doping very narrow layers (order of 10nm). Due to the very narrow resonance reaction widths (typically the order of 100eVs or less), the primary factor driving the dopant layer thickness pertains to the proton beam width (order of 1keV).

Acknowledgements

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- We wish to thank Dr. Jim Butler of the ONR for creating the ^{13}C-enriched diamond films and Drs. David Schiferl and Robert K. Sander from LANL (C-PCS division) for giving us permission to use the leftover pieces.
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