MEGAWATT SOLID-STATE ELECTRONICS

Development of GaN Power Devices

•University of Florida:	Device Design/Simulation (In Collaboration with Sandia) Process Development Device Fabrication (In Collaboration with Sandia) Improved GaN Materials Novel Gate Dielectrics Characterization
•SRI	High Field Transport Device Design
•MCNC	Packaging Commercialization

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Objectives

Develop the Technology Base for GaN-Based Electrical Switches at Power Levels Well Above 1 MW

- 25 kV Stand-Off Voltage
- 2 kA Conducting Current
- Forward Voltage Drop < 2% of Rated Voltage
- 50 kHz Operating Frequency

Applications :

: More Efficient Transmission and Distribution of Electric Power, as part of EPRI's Flexible AC Transmission Systems (FACTS) Concept

: Single-Pulse Switching in the Sub-Systems of Hybrid-Electric Combat Vehicles (DARPA/DOD)

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CONCEPT

- Low Power MOSFET + Thyristor ® GTO Thyristor
- GTO + Power Diodes + Packaging ® Inverter Module
- Approach is to Make Devices in Parallel with Materials Development, Modelling and Package Development

ACHIEVEMENTS

Previous:

- GaN D-Mode MOSFET
- AlGaN/GaN Thyristor Processing
- AlGaN Schottky Rectifiers with V_{RB} = 4.3 kV, FOM

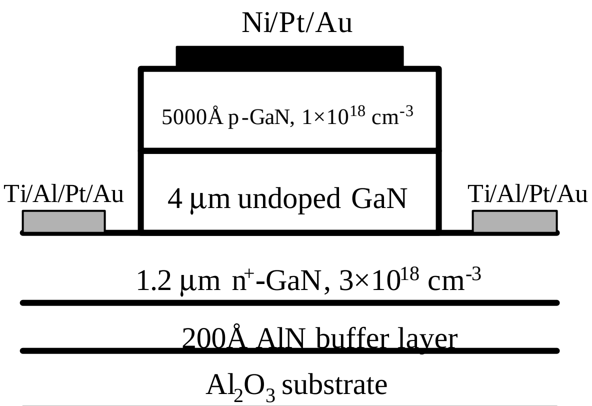
$$\left(V_{RB}\right)^2 / R_{ON} = \leq 55\ MW \cdot cm^2$$

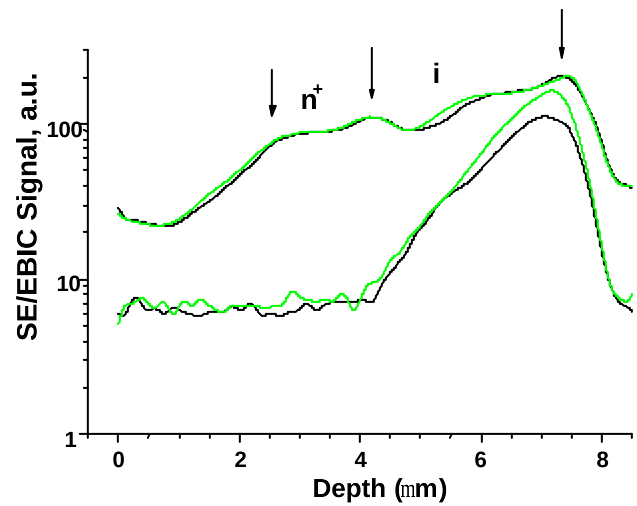
- Process Modules (W contacts, Dry Etching, Implant Doping, Etch Damage, Isolation
- Free Standing GaN Substrates By Several Methods
- Initial Packaging Results
- High Field Transport Theory

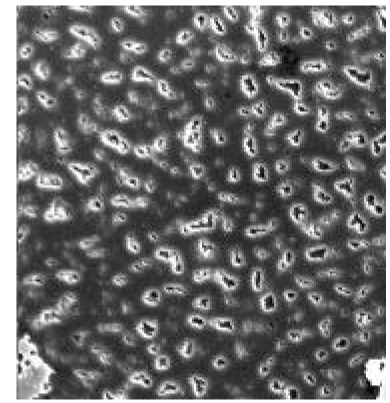
Achievements This Period

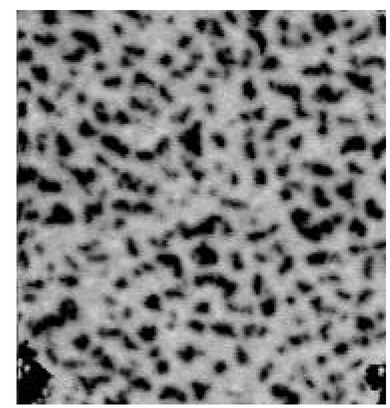
- GaN Schottky Rectifiers with V_{RB} = ~8.8 kV, FOM ~200 MW·cm^{-2}
- AlGaN Schottky Rectifiers with V_{RB} = 9.7 kV, FOM 245 MW·cm^{-2}
- Temperature dependence of V_{RB} in Schottky rectifiers
- Improved Understanding of Implantation for Doping of GaN
- Materials Characterization (bulk and epi GaN)
- High field transport theory
- Prospects for Commercialization

P-I-N Rectifier Material Characterization

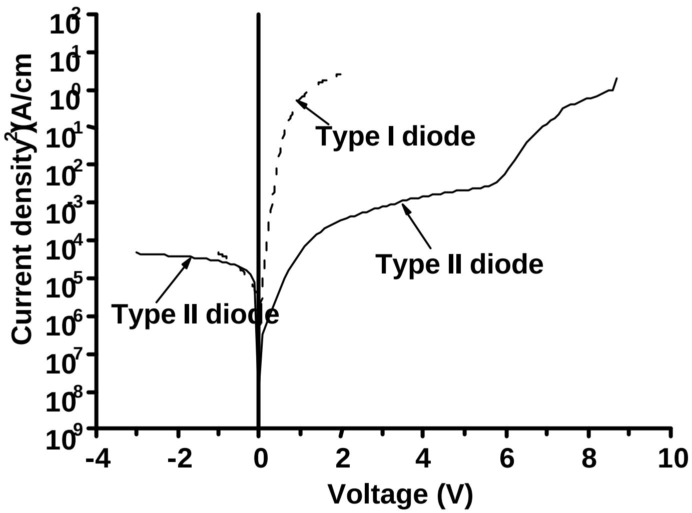








P-I-N Rectifier Material Characterization (continued)



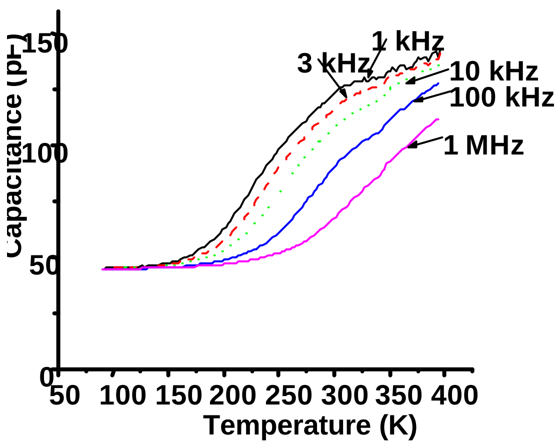
Type I Diodes

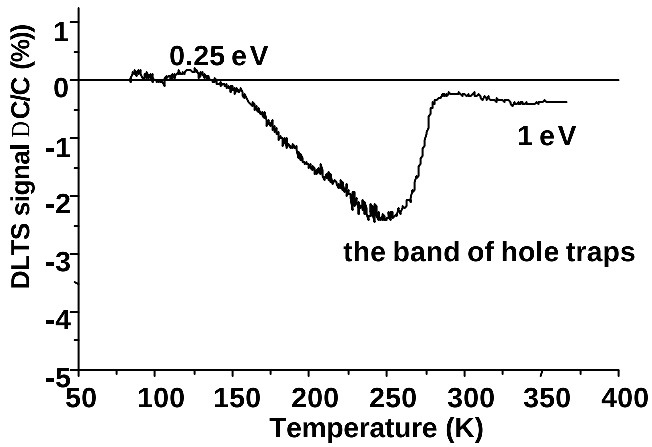
- Hole diffusion length 0.7-0.8μm
- Lot of recombination, non-uniformity
- $\geq 10^3 cm^{-2}$ defects which provide bright contrast in EBIC images of cleaved diodes
- n $\sim 10^{16} cm^{-3}$, $N_T \sim 10^{16} cm^{-3}$

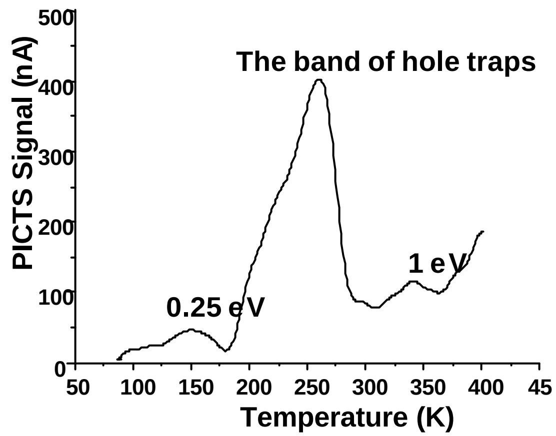
Type II Diodes

- Hole diffusion length 0.5μm
- Lot of recombination, non-uniformity
- Varying compensation ratio of donors near dislocations, relative to matrix
- n $< 10^{14} cm^{-3}$, $N_T \sim 10^{16} cm^{-3}$

Deep Traps in p-i-n Rectifiers



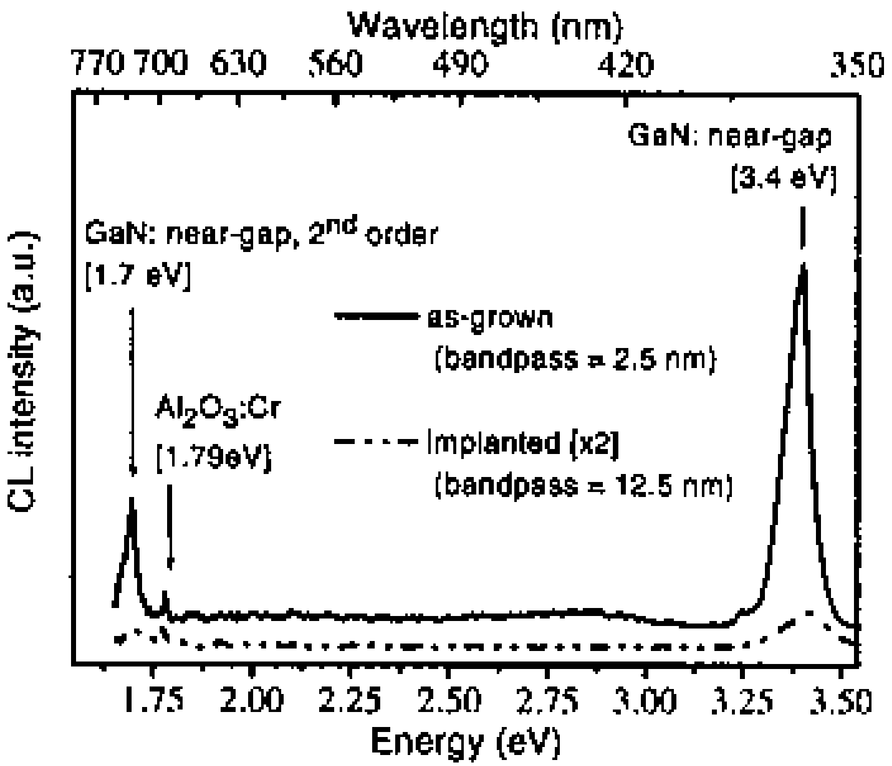




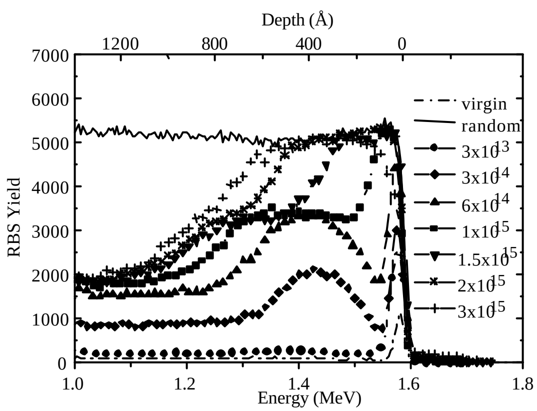
Surface Disordering and Nitrogen Loss During Ion Implantation

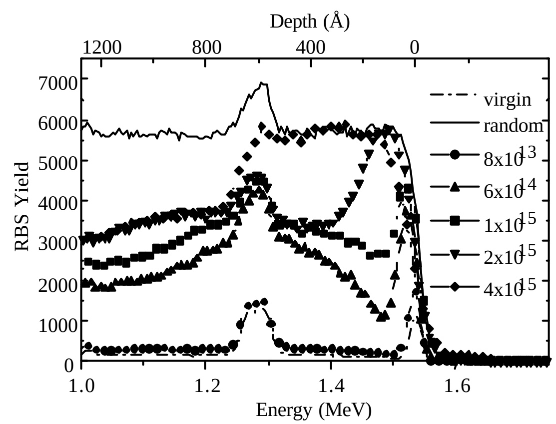
Table II. Implant conditions used in this study.

Ion	Energy (keV)	Implantation Temperature (°C)	Beam Flux (10^{12} $cm^{-2}s^{-1}$)
^{12}C	40	-196	14
^{12}C	40	20	14
^{16}O	50	-196	19
^{16}O	50	20	19
^{28}Si	60	20	16
^{63}Cu	130	20	9.4
^{107}Ag	200	20	0.6
^{197}Au	100	-196	14
^{197}Au	100	20	14
^{197}Au	300	-196	3.1
^{197}Au	300	20	4.4
^{197}Au	300	550	3.1
^{197}Au	900	-196	31
^{197}Au	2000	20	5
^{197}Au	2000	-196	5



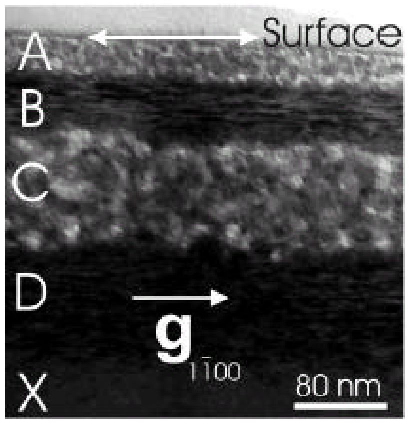
Surface Disordering and Nitrogen Loss

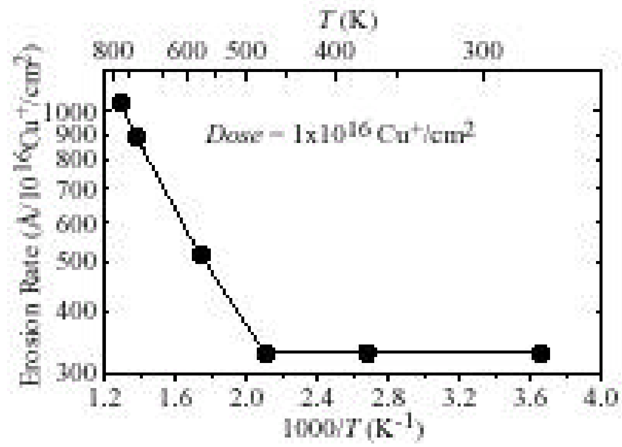


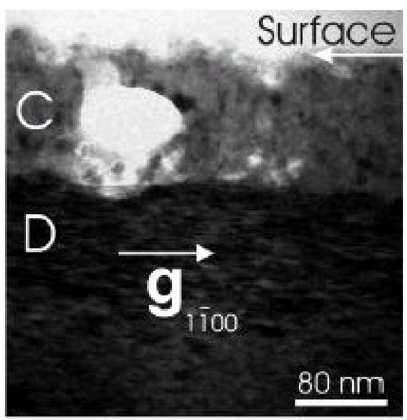


- •Capping with SiN_x does not eliminate surface disordering but prevents some loss of N_2
- •Complete decomposition of near-surface and formation of Ga droplets on preamorphized GaN annealed above 400^{o}C
- •The surface disorder is in addition to the bulk damage. Amorphization nucleates first at surface under all conditions.

Heavy Dose Implantation in GaN (Basic Studies)

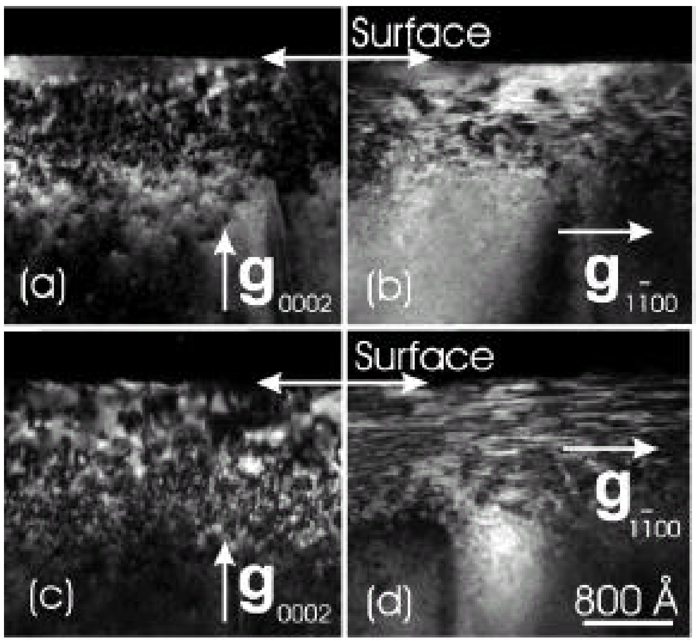


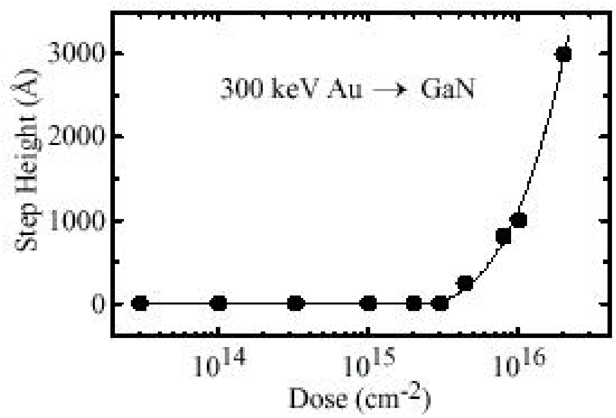




- Amorphized bulk regions cannot be recrystallized (become poly)
- Amorphous surface regions decompose, even at 500^{o}C
- Elevated temperature reimplantation erodes the initially damaged material (Probably because the N_2-deficient region is easily sputtered)

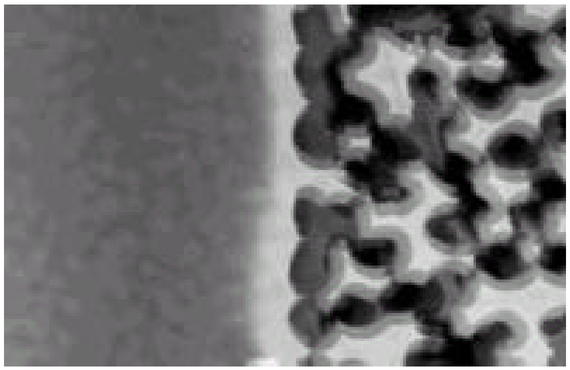
Single Elevated Temperature Implantation of GaN





- Damage buildup and amorphization are suppressed at elevated temperatures (550°C)
- As dose increases, point defects agglomerate, leading to planar defects
- High dose implantation at elevated temperature complicated by surface erosion

Re-Implantation of Light Ions in Amorphized GaN



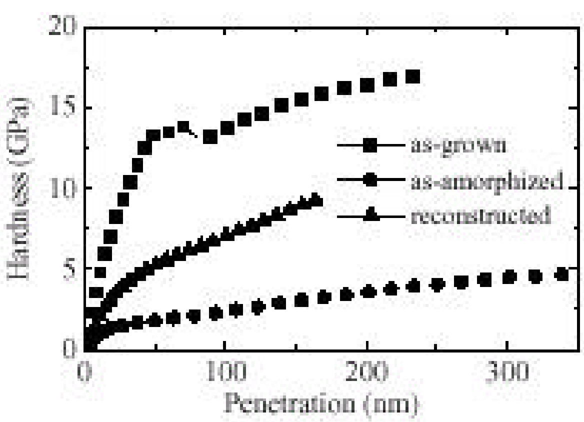


Table I. The values of hardness, *H*, and Young's modulus, *E*, at a plastic penetration depth of 100 nm for the three GaN samples from Figure 2.

GaN sample	*H* (GPa)	*E* (GPa)
As-grown	14.0	233
As-amorphized	2.4	65
Light-ion re-irradiated	7.0	99

Table II. The values of the nuclear (E_n) and electronic (E_n) energy loss of 600 keV H and 2.5 MeV Si ions implanted into GaN.

Ion	E_n (eV A^{-1})	E_n (eV A^{-1})
600 keV ^{1}H	9.4 x 10^{-3}	10.7
2.5 MeV ^{28}Si	8.1	279.4

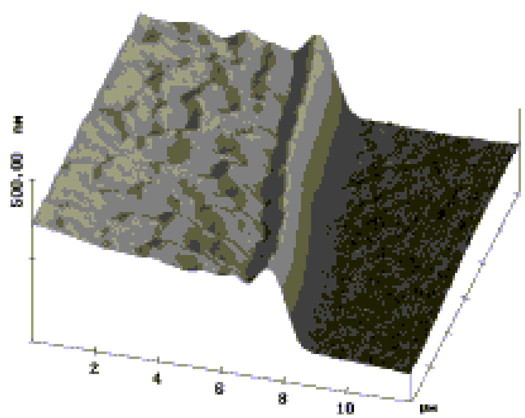
Light Ion Re-Implantation of n-GaN

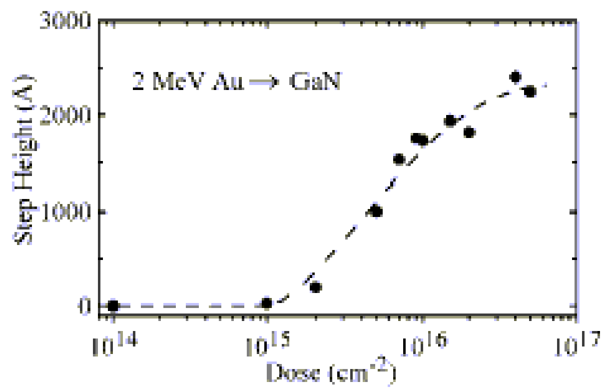
- Increases Material Density
- Suppresses decomposition during annealing
- Increases hardness and Young's Modulus
- Decrease in visible light absorption

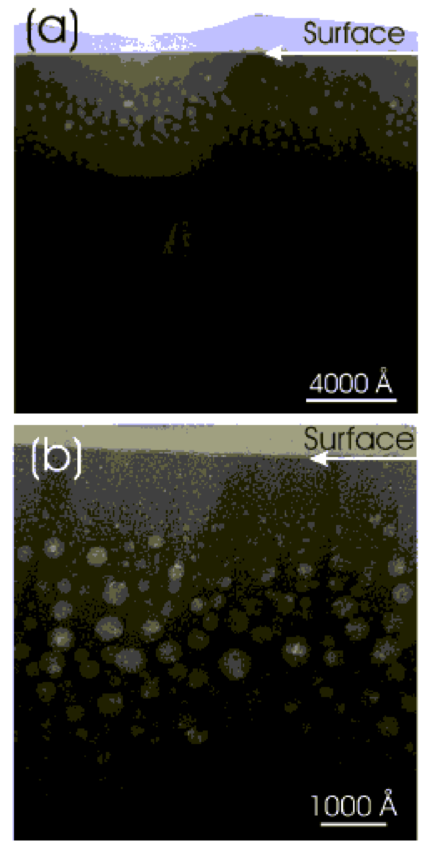
Ion Implantation Induced Porosity of GaN

To demonstrate worse-case scenario

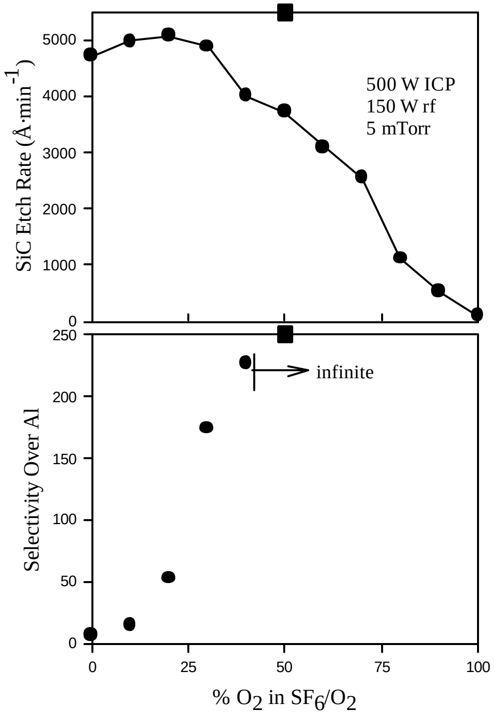
: 2 MeV Au^+
: LN_2 temperature
: beam flux $5x10^{12} cm^2 \cdot s^{-1}$
: dose 10^{14}-$5x10^{16}$ cm^{-3}

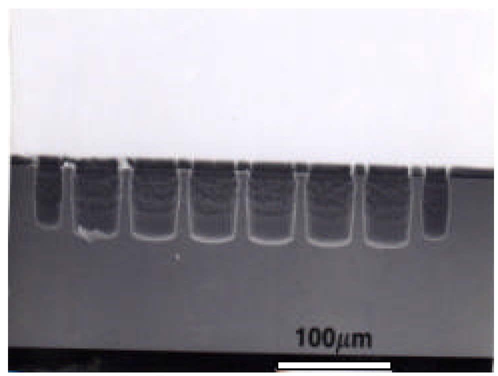


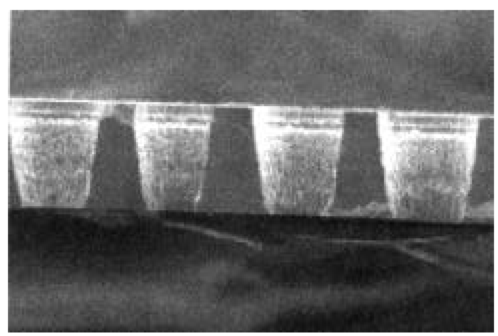


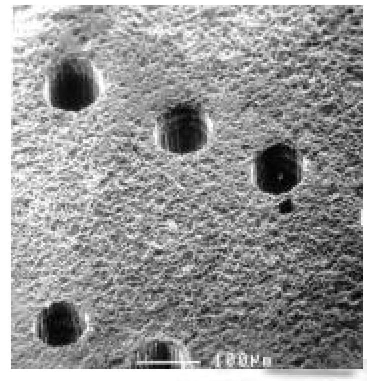


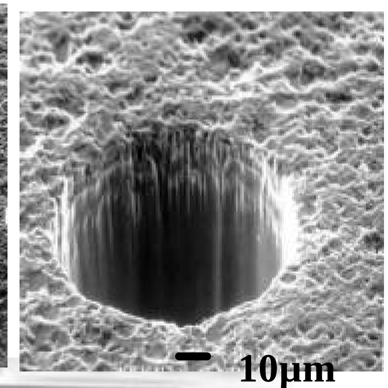
Deep Etching of SiC

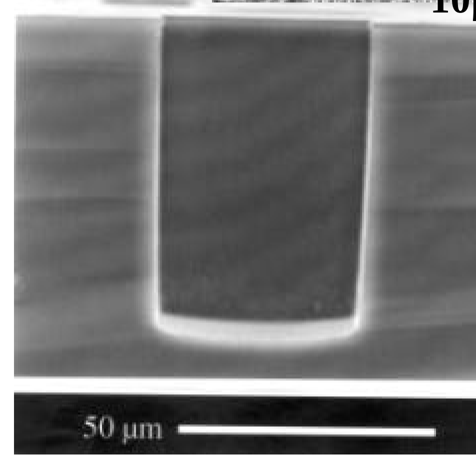












Future Work

Rectifiers

-More detailed measurements of switching characteristics of high breakdown GaN and AlGaN devices
-Continue to optimize edge termination/surface passivation
-Stability at 300°C under bias
-Measure V_{RB} versus diode size
-Vertical devices on bulk material

Thyristors

-Post mortem of second attempt (measure minority carrier diffusion length, trap levels in the stand-off layer)
-New wafer incorporating all relevant device/materials feedback (process)