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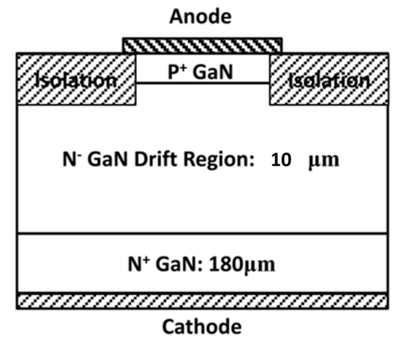

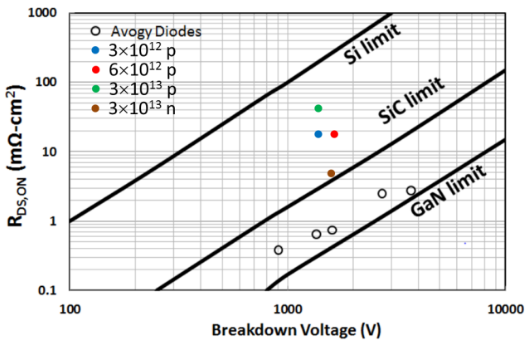

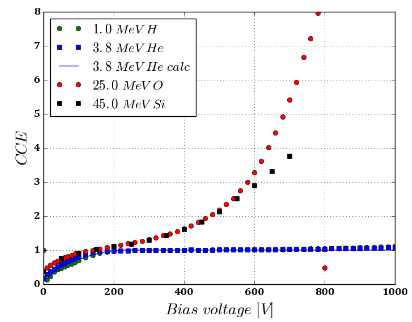

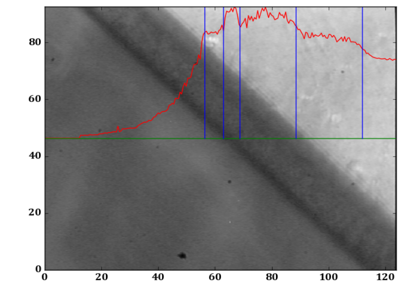

Nuclear microprobe investigation of the effects of ionization and displacement damage in vertical, high voltage GaN diodes

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U.S. DEPARTMENT OF ENERGY   NNSA National Nuclear Security Administration

Outline

- What is power electronics and why GaN?
- Basic radiation effects on electronics
- IBIC as a tool to measure displacement damage
- Charge collection efficiency as function of ion species and energy (charge multiplication)
- Charge collection efficiency as function of damage (an unexpected discovery)
- Effect of edge termination rings (desired and undesired)
- Summary

What is power electronics?

Power electronics is the application of solid-state electronics to control and conversion of electric power.
Among them rectifiers, inverters, AC-AC and DC-DC converters.
Power diodes – power MOSFETs- IGBTs – and other devices.

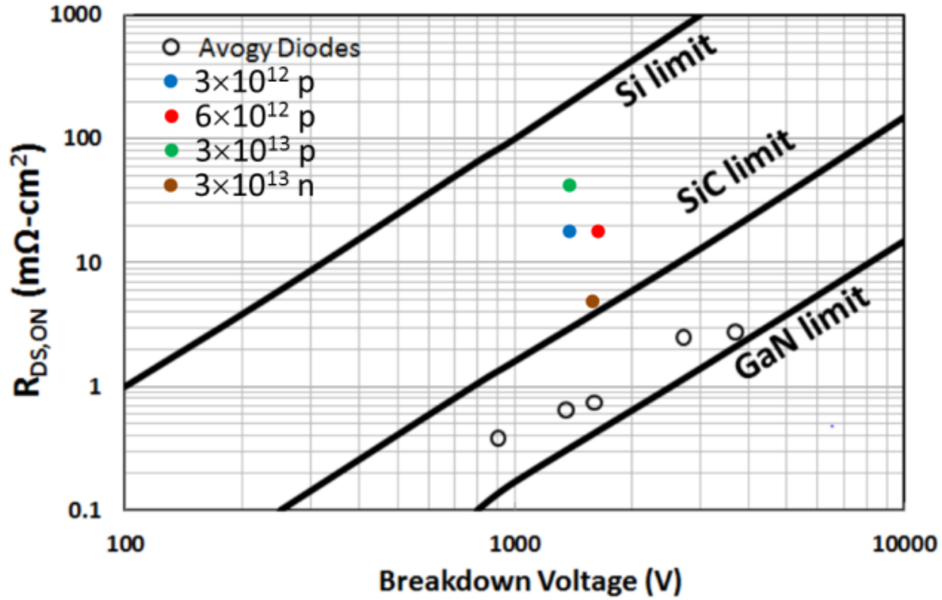
From electronics (computer, phones) to automotive to aviation to weapons.


Why GaN?

Requirements of power devices:

- High break-down voltage
- High current drive
- High efficiency
- Temperature extremes
- Vibration
- <u>Radiation</u>

Unipolar figure of merit

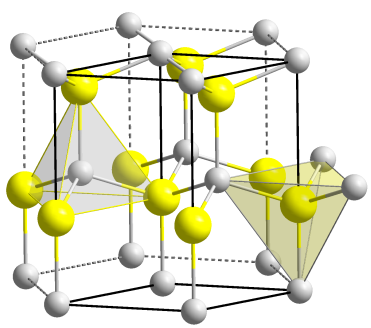


M. P. King et al., IEEE TNS 62(6), 2912 (2015)

Today's devices: Si

Future : SiC, GaN, AlGaN

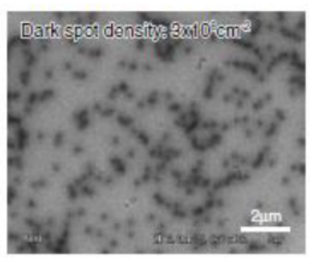
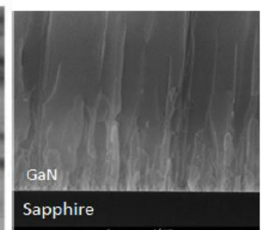
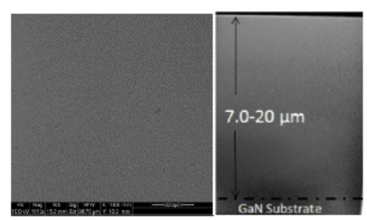
GaN



bandgap - 3.4 eV, e-h energy – 8.9 eV, cohesive energy ~ 9 eV, melting point > 2500 C, break down field > 3 MeV/cm,

Why are not GaN devices widespread?

Large threading dislocation density on Si, SiC, and sapphire substrates, lack of high quality GaN substrates recently.

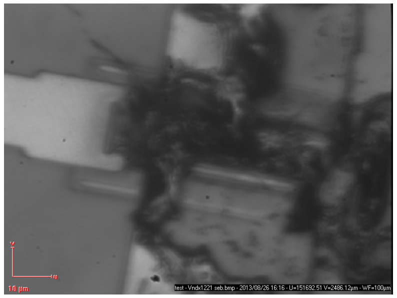
Attributes	GaN on Si	GaN on SiC	GaN on Bulk-GaN
Defect Density (cm^{-2})	10^9	$5x10^8$	10^3 to 10^6
Lattice Mismatch, %	17	3.5	0
CTE Mismatch, %	54	25	0
Layer Thickness (μm)	< 5	< 10	> 50
Breakdown Voltage (V)	< 1000	< 2000	> 5000
OFF State Leakage	High	High	Low
Device Types	Lateral	Lateral	Vertical and Lateral
Microscopy and Growth			

From Robert Kaplar, SNL

Basic radiation effects on electronics

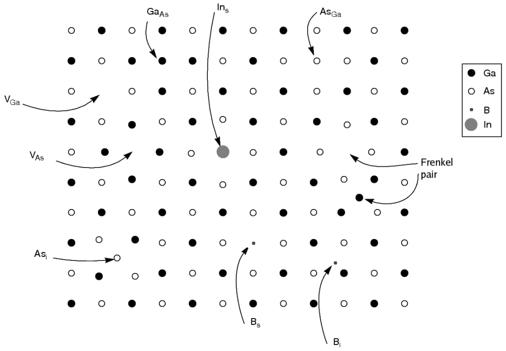
Ionization

- e-h pairs created
- Carrier movement in electric field creates photocurrent (Gunn theorem)
- Single Event Effects
- Charge multiplication (avalanche)



Displacement damage

- Atoms are removed from lattice sites
- Defects can trap carriers
- Increases SRH recombination
- Trapped charge reduces apparent doping level, distorts energy bands
- Increased leakage current



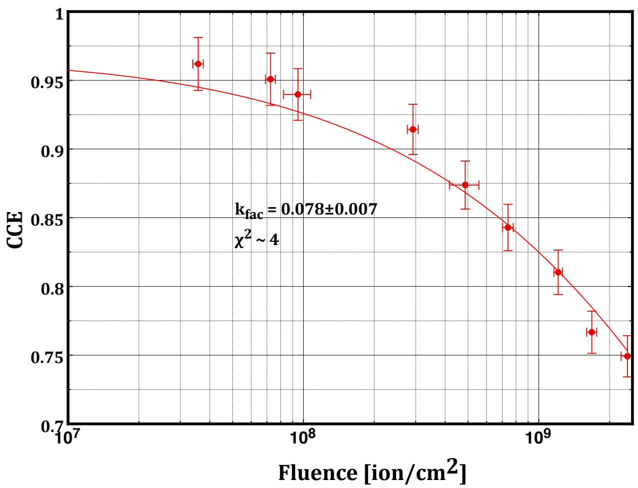
IBIC to measure effect of displacement damage

Charge collection efficiency $$CCE = \frac{Q_{induced}}{Q_{created}}$$

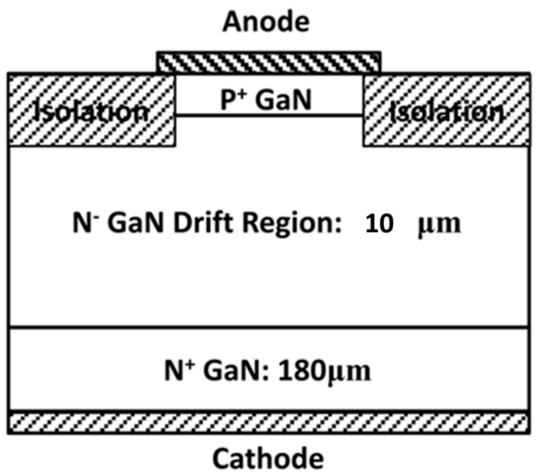
Carriers moving in electric field can be captured by defects created by displacement damage and recombine. For relatively low damage:

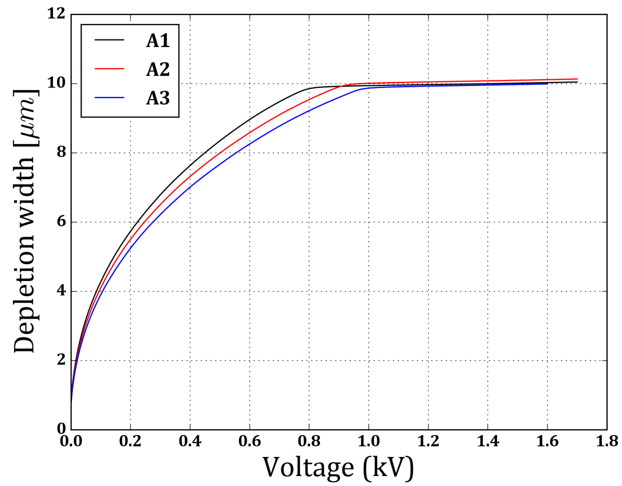
$$CCE(\Phi) = 1 - k \cdot \Phi$$

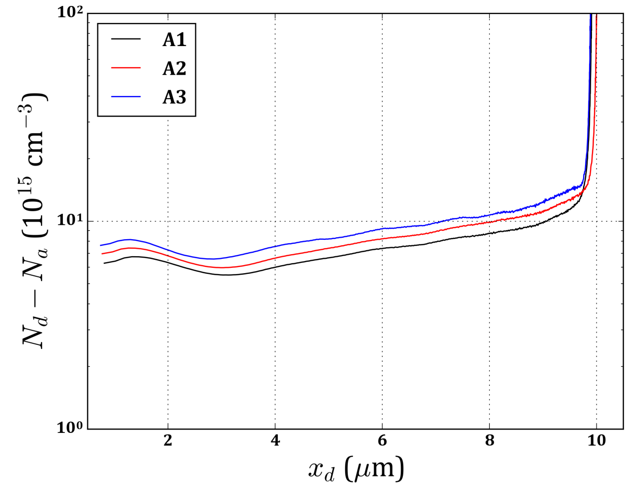
k, the damage factor is a complicated function of number of defects, their depth distribution, capture cross sections, ionization profile, and electric field. For detailed discussion see previous presentation by Prof. Vittone.



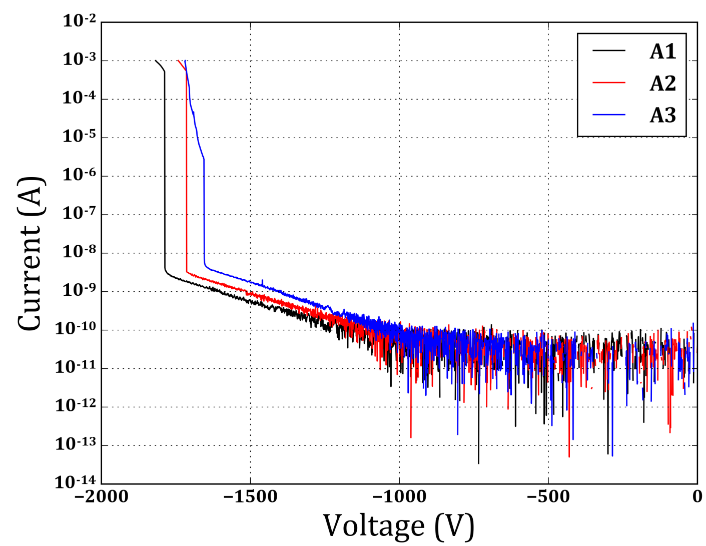
The device used in the experiments





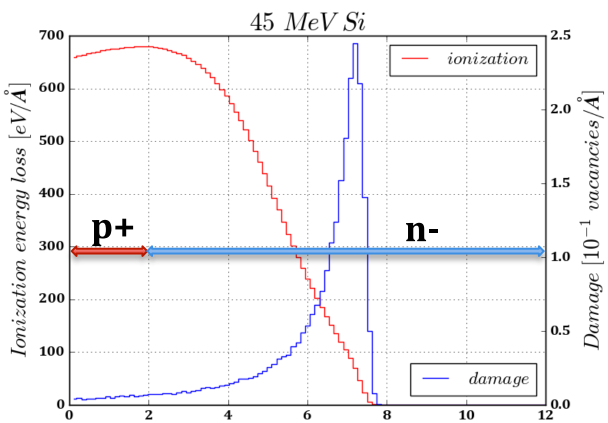


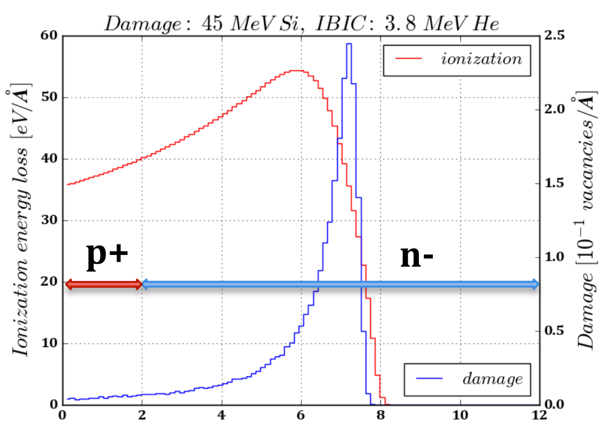
- Doping density ~ 10^{16} dopant/cm^3
- Fully depleted to 10 µm at ~ 800 V
- Non destructive breakdown ~ 1700 V
- Edge termination guard rings (not shown) to improve breakdown performance



Irradiation conditions

- **Energies and species: 1 MeV H, 3.8 MeV He, 25 MeV O, and 45 MeV Si**
- **All deposit their energy in the top 6 µm in front of the damage peak at 6 µm. Electrons have to go through the damaged layer, but the holes not**
- **Bias curves with large area scan, damage studies 50x50 µm² spots**
  - **Damage analysis with the damaging ion in the same spot**
  - **Different spots damaged with heavy ions with different fluences, analyzed by light ions**

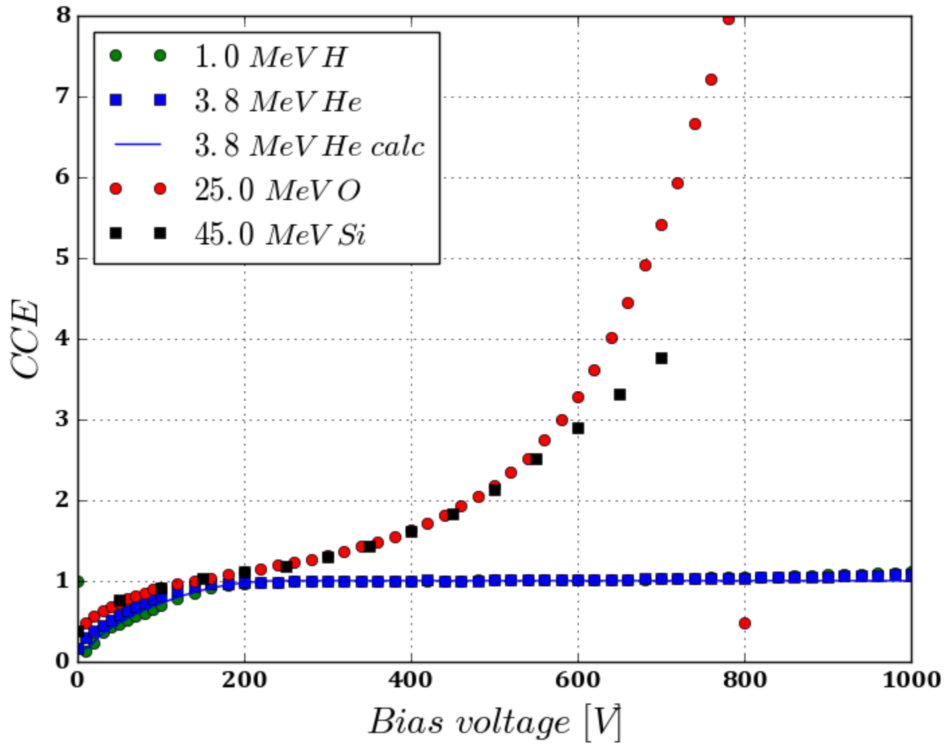


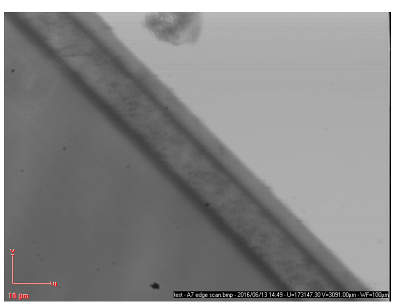


Very short carrier lifetimes

$$CCE(V) = \frac{\int_0^{w(V)} S_e(x)\,dx}{E_{ionization}}$$

CCE vs. bias





Light ions:

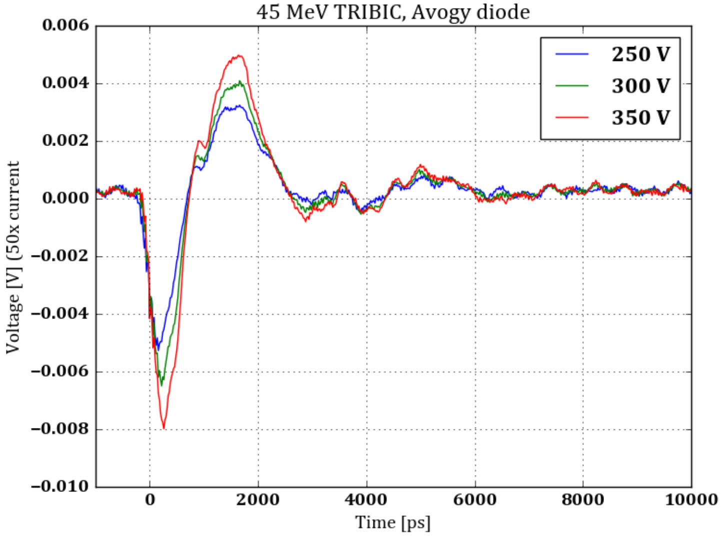
- **CCE follows theoretical prediction**

Heavy ions:

- **CCE exponentially increases above 200 V exceeding 100% several times**
- **Charge multiplication (avalanche)**
- **Catastrophic, destructive breakdown ~700-800 V**
- **Short circuit or leakage current increased several orders of magnitude**

For heavy ions the dense plasma compresses the electric field at the end of the n- layer creating much higher field than in DC mode.

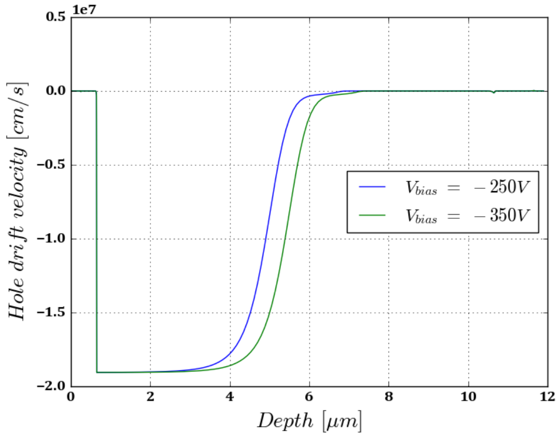
TRIBIC to show avalanche

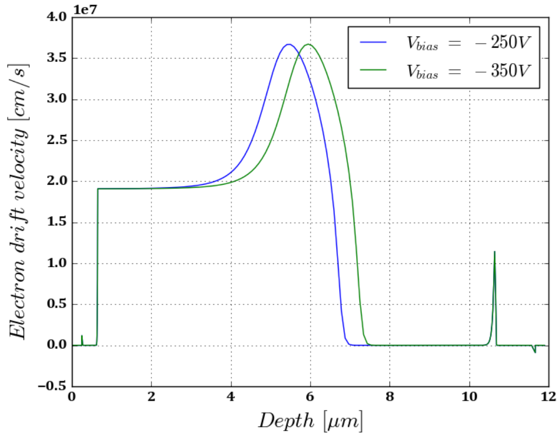


Gunn theorem

$$i = -q \cdot \vec{v}_d \cdot \frac{\partial \vec{E}}{\partial V} = -\frac{q \cdot \vec{v}_d}{w}$$

If v_d is saturated the maximum transient current can increase only if charge multiplication occurs. TCAD simulation* shows that both electron and hole drift velocities are saturated even at 250 V.

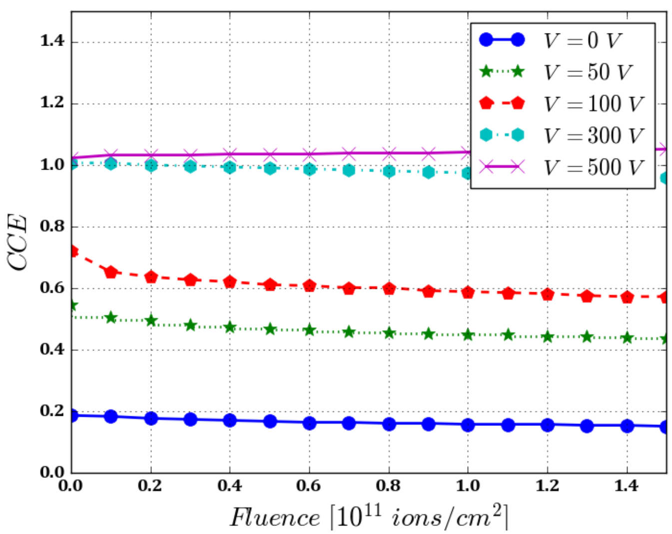




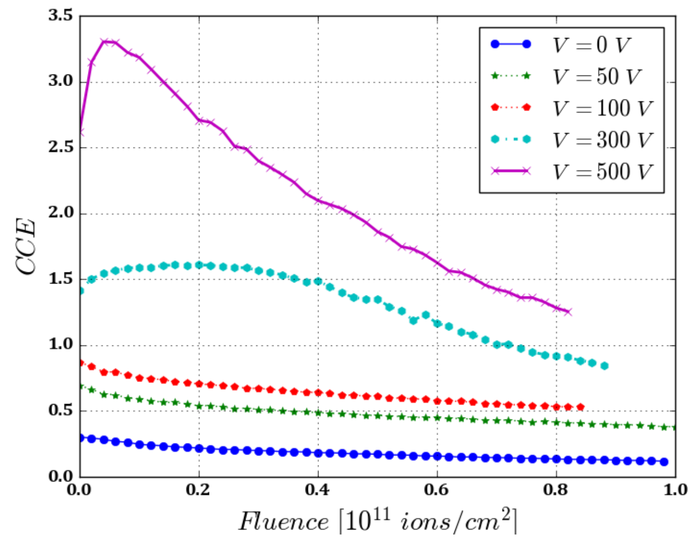
***Courtesy of J.R. Dickerson, SNL**

CCE as function of fluence

3.8 MeV He



25 MeV O

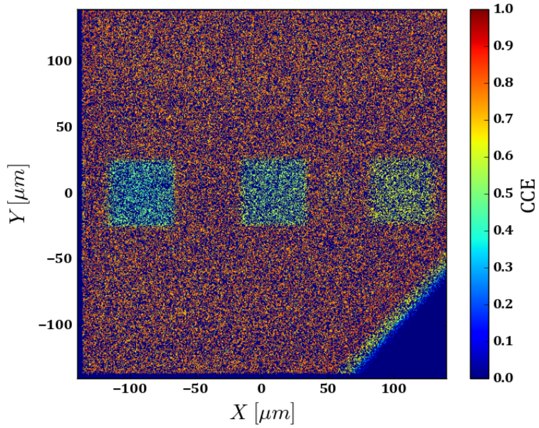


Expected behavior, CCE degradation with fluence at low bias, almost not change at high bias

Expected behavior at low bias, but surprise at higher bias values. CCE increases with damage at first before it starts increasing. The charge multiplication is amplified by the damage.

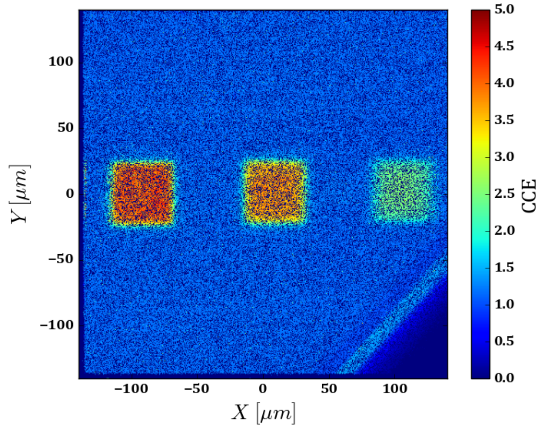
45 MeV Si damage measured with 3.8 MeV He

100 V

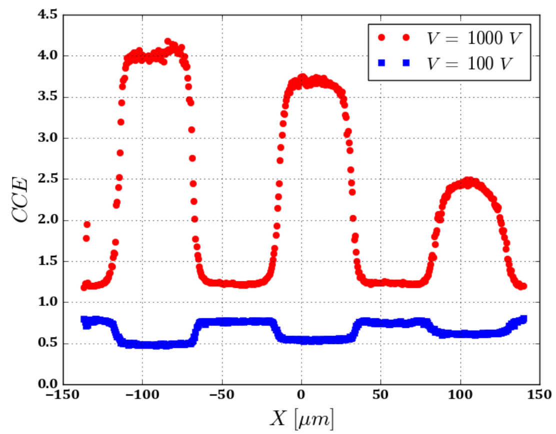


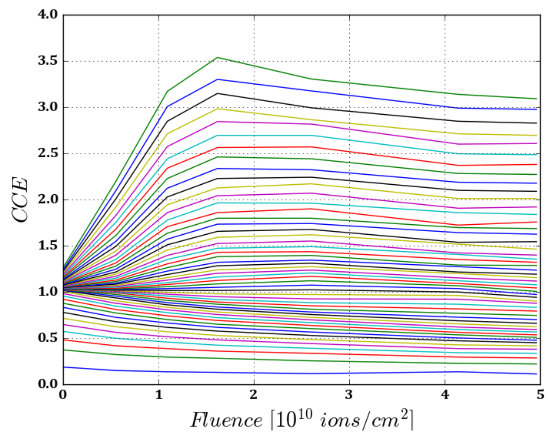
damage

1000 V



damage

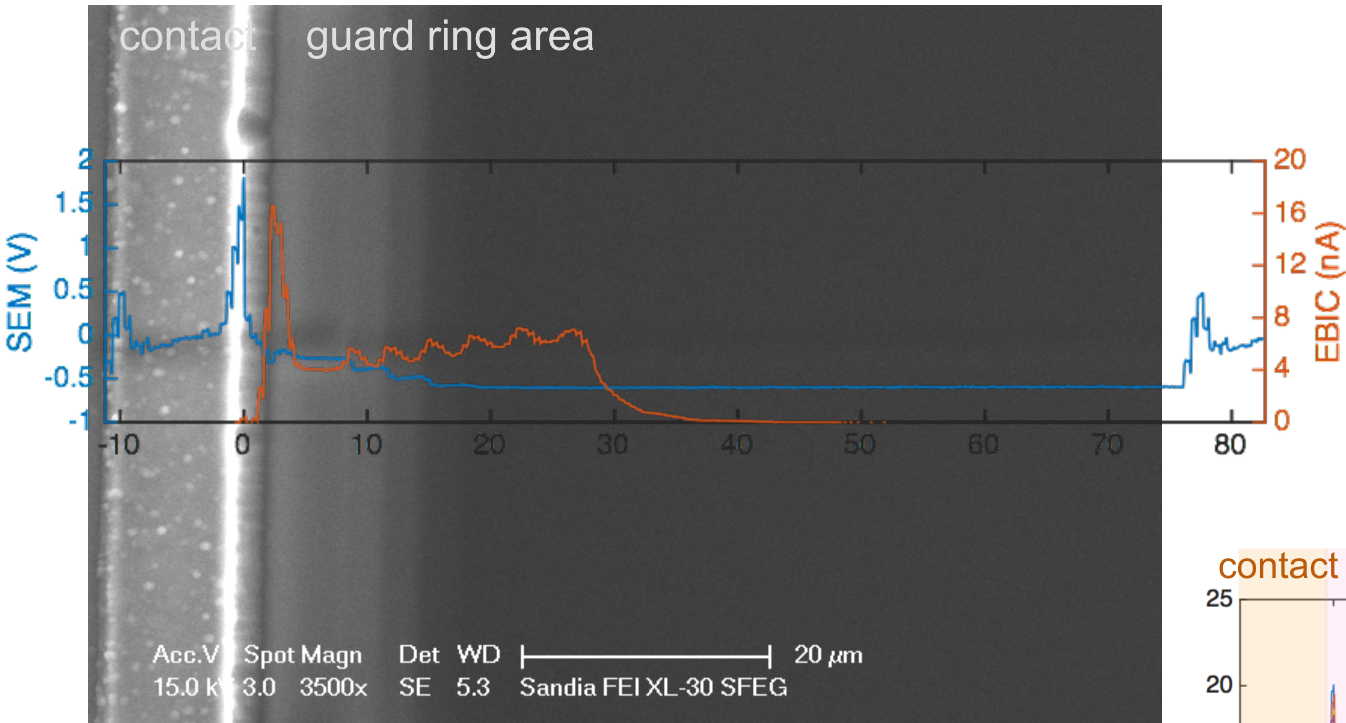




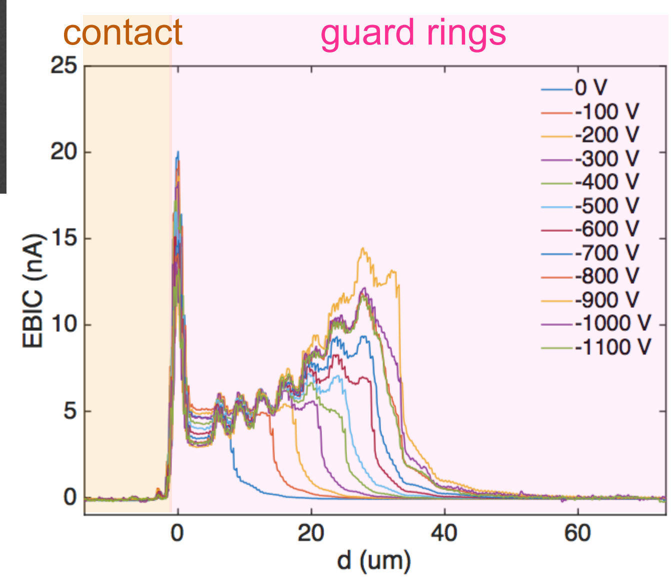
In undamaged diode there is very little charge multiplication/ avalanche with He beam.
It seems that the moderate damage increases the probability of avalanche locally before the CCE starts decreasing with damage.
Possible explanations:

- **Carriers are trapped in defects in the bandgap. It takes less energy to raise them into the conduction band.**
- **Trapped charge creates higher local field in damaged areas that can reach avalanche threshold.**
- **Clustering bends the bands, which allows easier tunneling from the valance to conduction band.**

Edge termination with guard rings



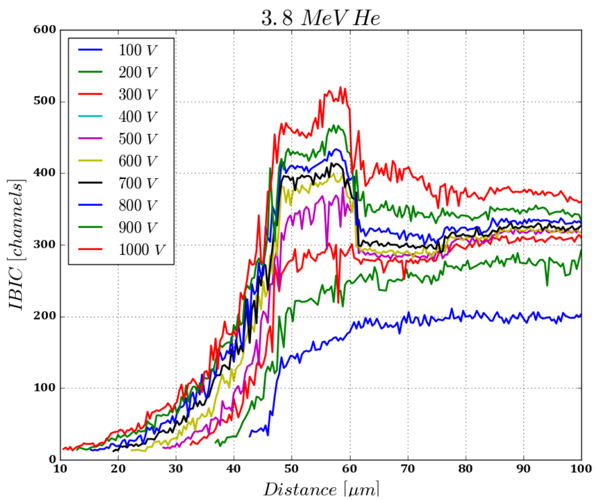
As the bias voltage increases more rings are turned on.

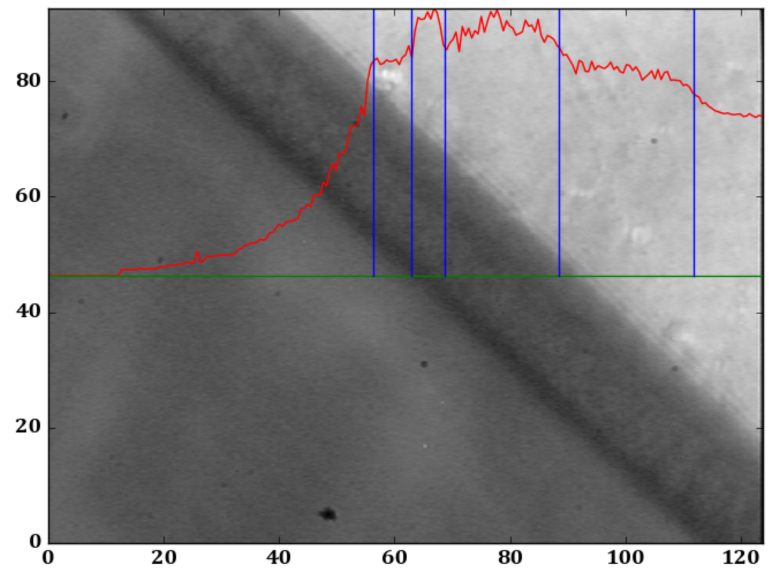


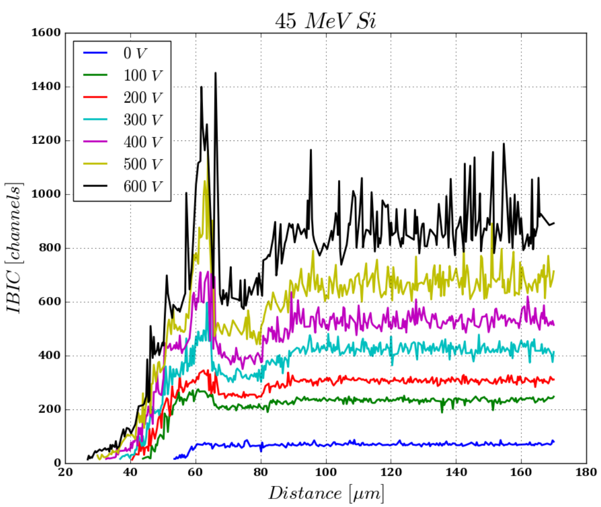
Edge termination guards rings are designed to spread the high electric field at the edge of the junction and improve breakdown performance.

Courtesy of Kim Collins, SNL, CA

Avalanche in the guard ring area







The guard rings seem to work, the electric field increases faster in the guard ring area than in the contact (larger charge multiplication). While in DC operation the guard rings help improve the breakdown performance under ion irradiation they increase the chance of destructive breakdown.

Summary

- In GAN vertical diodes that have a breakdown voltage of 1700 V we found that high energy heavy ion irradiation triggered avalanches at biases as low as 300 V.
- Light ions (H, He) had very little charge multiplication at even 1000 V.
- Displacement damage caused significant local enhancement in charge multiplication for even light ions up to a certain damage level. After this damage level the CCE started to decrease as expected.
- The edge termination design worked as the electric field spread to the guard ring but it became so high that avalanche developed at higher voltages even with light ions under the guard rings.

Thank you for your attention!

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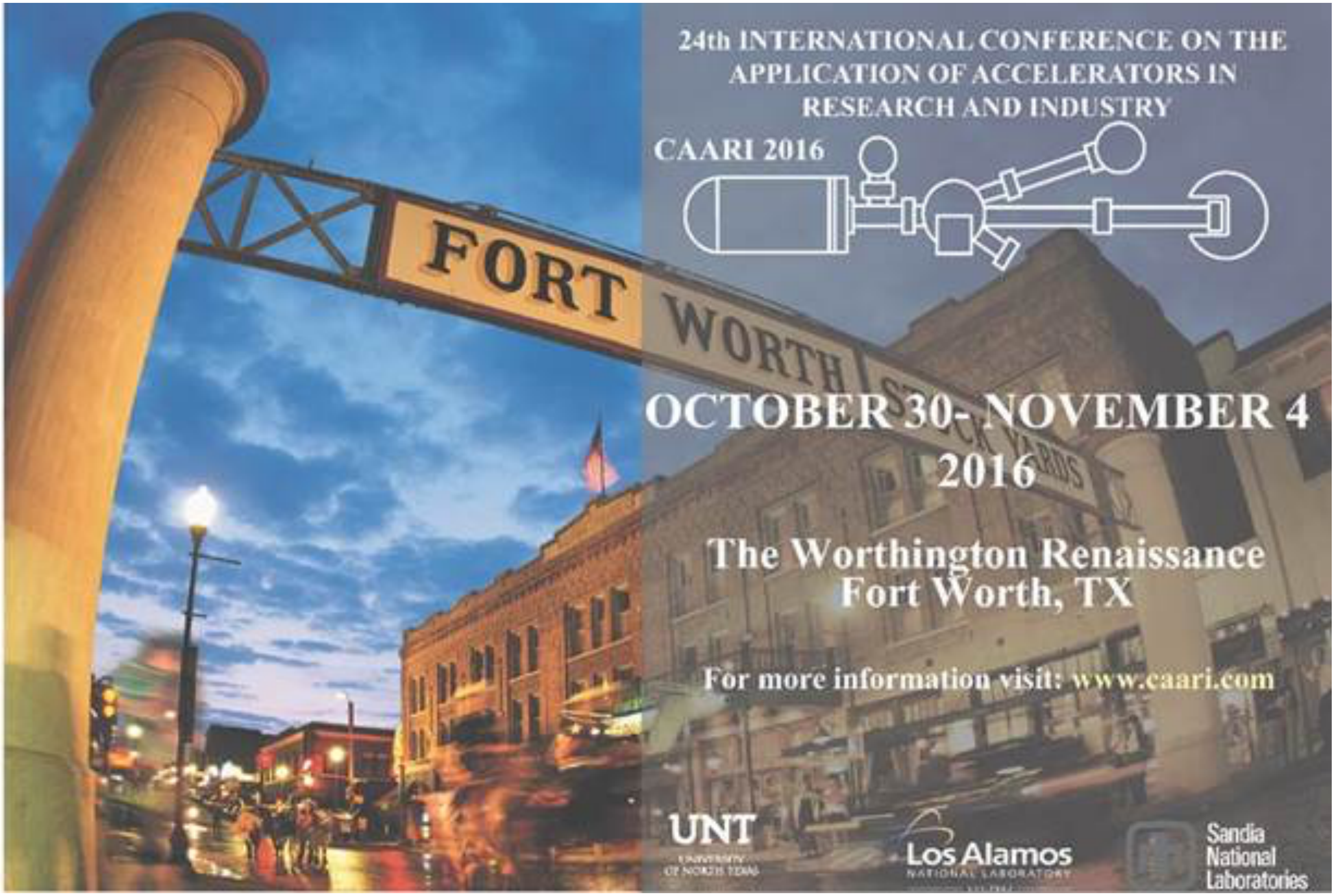
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