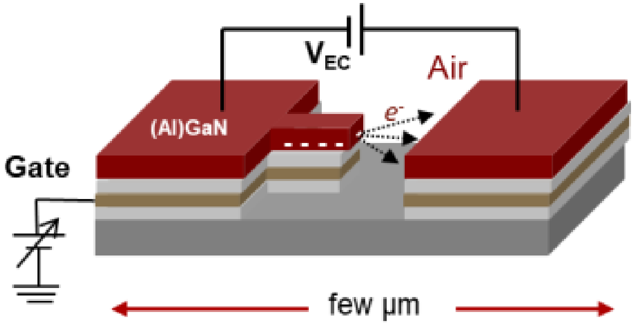
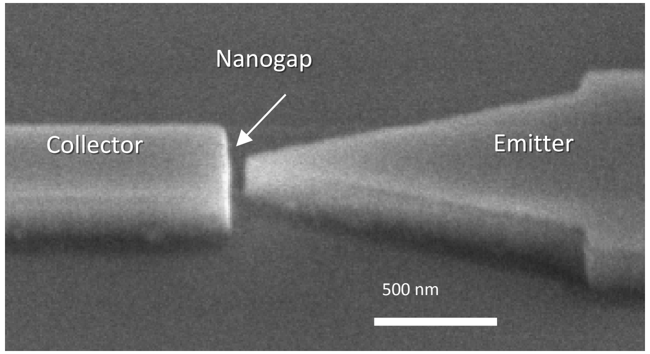
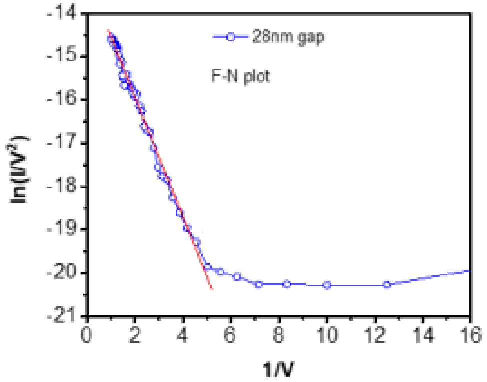
SAND2022-2452C







Proton irradiation effects on GaN nanoscale vacuum electron diodes

Keshab R. Sapkota[1*], George Vizkelethy[2], George T. Wang[2]

[1]Center for Integrated Nanotechnologies, Sandia National Laboratories, Albuquerque, NM, USA

[2]Sandia National Laboratories, Albuquerque, NM, USA

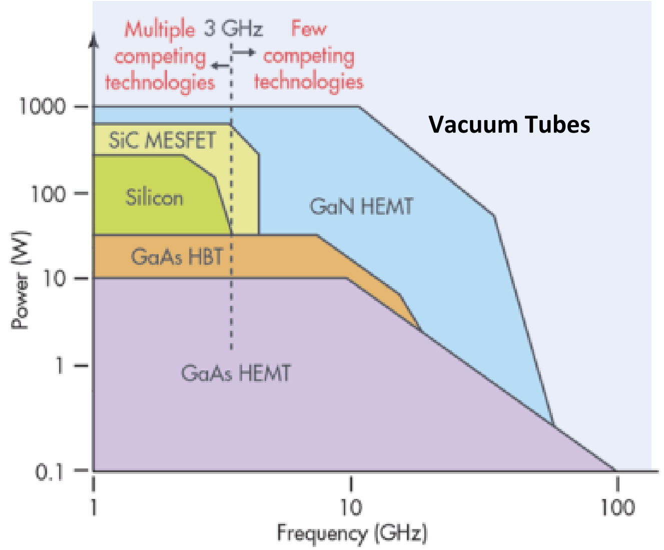
*krsapko@sandia.gov

Supported by the Laboratory Directed Research and Development program at Sandia National Laboratories, a multi-program laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Vacuum Devices – Still Around!

- Solid state devices began to replace vacuum tubes more than 60 years ago
- But vacuum electron devices have distinct advantages and are still in limited use!
  - **Communication:** Radar, RF broadcasting
  - **NASA:** Satellite communications, Electronics for space missions
  - **Industry:** Industrial RF heating, THz technologies, Microwave electronic applications

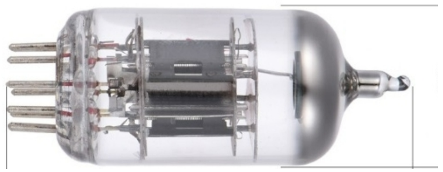
High power, high frequency



Source: http://www.electronicdesign.com/power/optimize-power-scheme-these-transient-times

Advantages of vacuum electron devices

- **Ballistic transport in vacuum channel:**
- **No heat generation** during electron transport in vacuum
- **No dielectric breakdown** (Dielectric strength = 10^{18}V/m)
- Operation in **harsh environments (radiation, temperature)**: no junction, vacuum channel unaffected
- As a result, vacuum devices can operate at **higher frequencies & power** than solid-state semiconductor devices

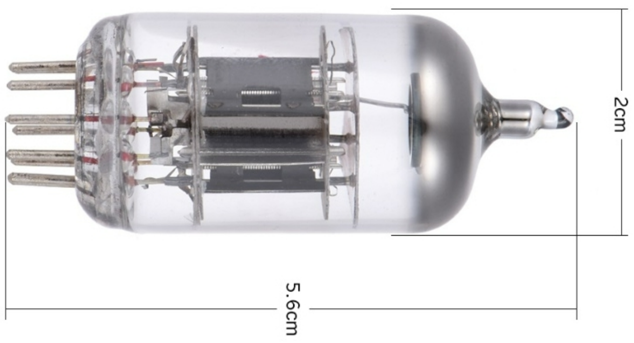


Drawbacks of vacuum tubes: Size, cost, reliability, energy efficiency, integration, vacuum requirement

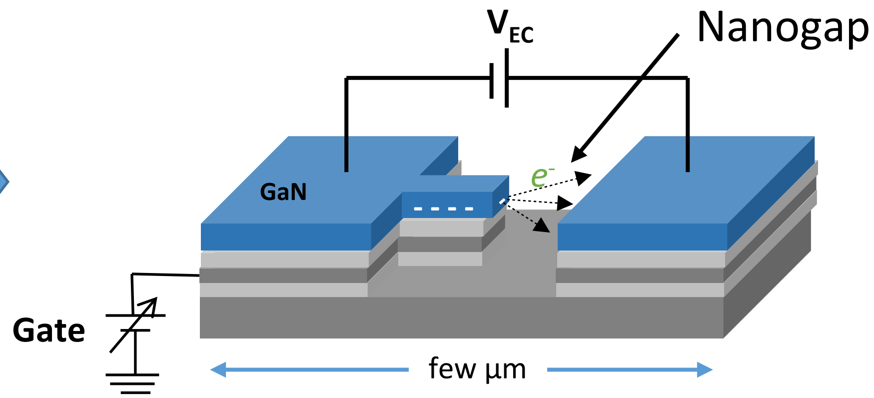
Solid-State, Vacuum-Free "Vacuum" Electronics

- ✓ Electron transport in air is vacuum-like if nanogap << λ_e (~ 500 nm)
- ✓ Nanogap field emitters can operate in air and can be used for "vacuum" electronics

Needs Vacuum



Works in Air !



Nanogap << λ_e (electron mean free path)

Solid state "vacuum" nanoelectronics integrates advantages of vacuum devices and semiconductor nanofabrication

GaN: Superior Platform for Vacuum Nanoelectronics

Sandia National Laboratories

Major Challenges for Vacuum Nanoelectronics

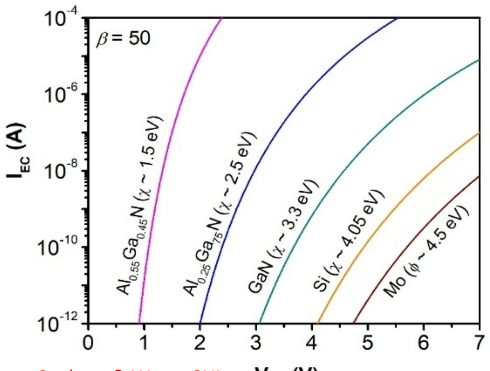
1. Difficult to get low voltage field emission

Fowler-Nordheim (FN) equation

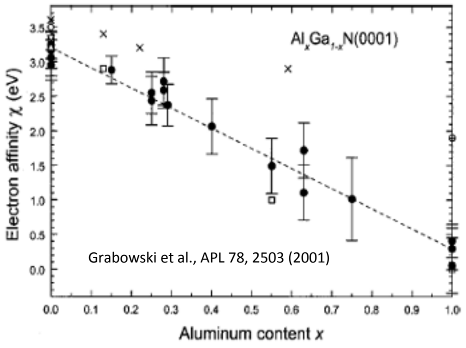
$$J = A\left(\frac{\beta^2 V^2}{\phi d^2}\right)\exp\left(-\frac{B\phi^{3/2}d}{\beta V}\right)$$

φ ➔ work function;
$\varphi \sim \chi$ (electron affinity) for n-doped semiconductor

GaN: low χ ➔ Low voltage field emission



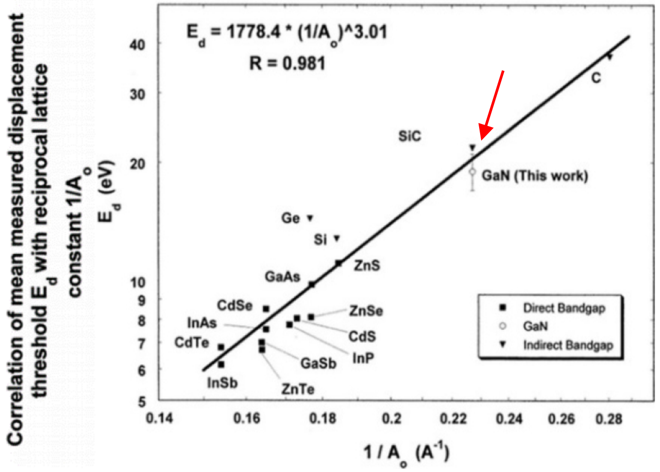
Sapkota & Wang, SNL



2. Device degradation/chemical instability

GaN has significantly higher bond strength

- ✓ Sputtering resistance and low degradation
- ✓ Chemical stability
- ✓ Operable at high temperature
- ✓ Radiation hardness

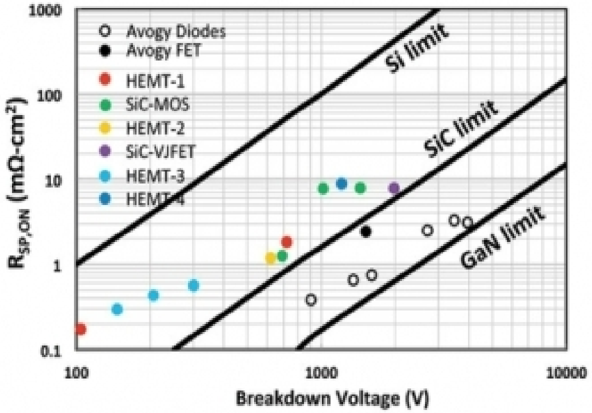


Source: Nedelcescu et al., IEEE Nuclear Science (2002)

3. High Power Operation

GaN has High Breakdown Field

- ✓ High power operation
- ✓ High frequency operation



Source: https://compoundsemiconductor.net/article/98990

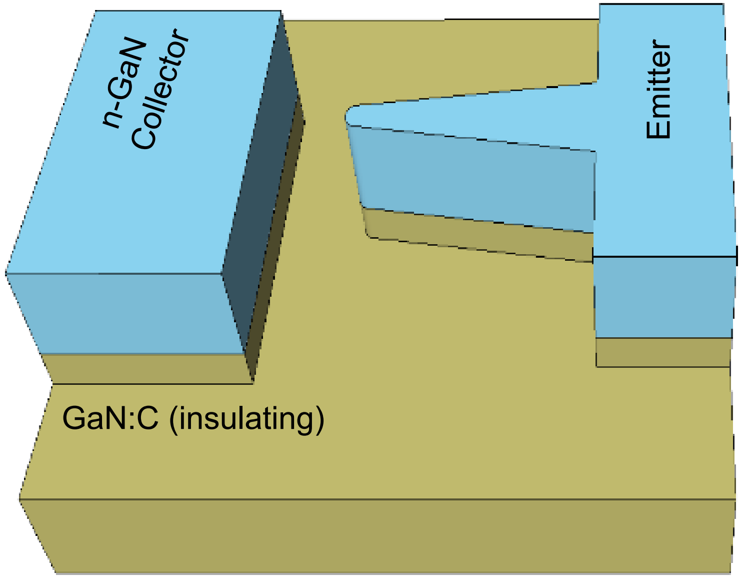
Nanofabrication of GaN Lateral Field Emission (FE) Structures

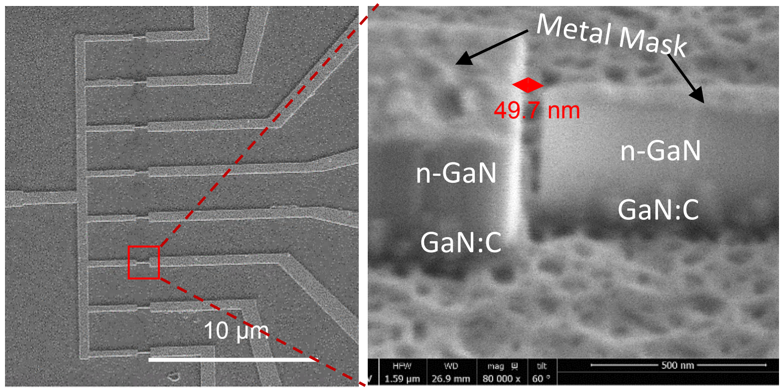
III-N top-down fabrication process

Electron Beam Lithography → Dry Etching (ICP/RIE) → Wet Etching (KOH based)

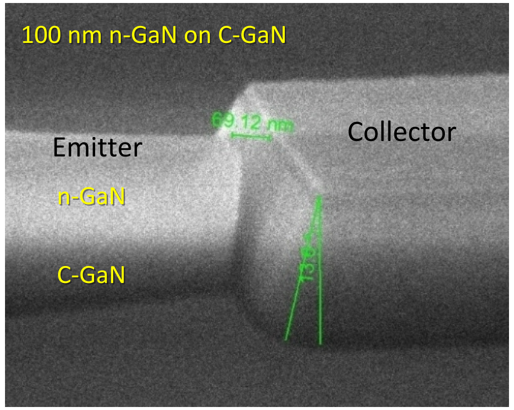
From knowledge of KOH wet etching of GaN:

- Orient collector // to m-plane to avoid microfacet protrusions
- Limit wet etch time to reduce wedge retraction effect
- consider dependence of wet etch on doping and composition

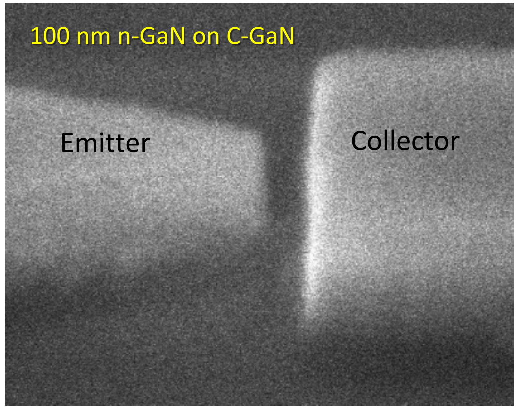




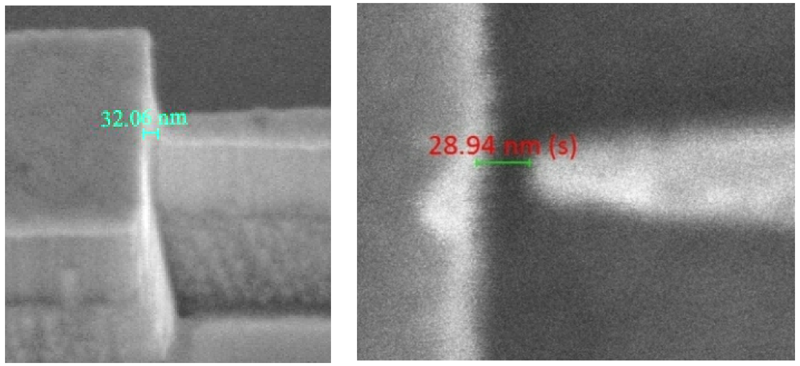
Epilayer designs: 200 nm n-GaN (doping ~5E18) on 2 µm GaN:C



ICP dry etch: **Angled side walls – variable gap size, possible shorting at bottom, sidewall damage**



+ AZ400K wet etch: **Vertical side walls, cleared gap, remove sidewall damage, smoother m-face collector**



GaN structures down to ~30 nm gaps and ~20 nm wide emitters

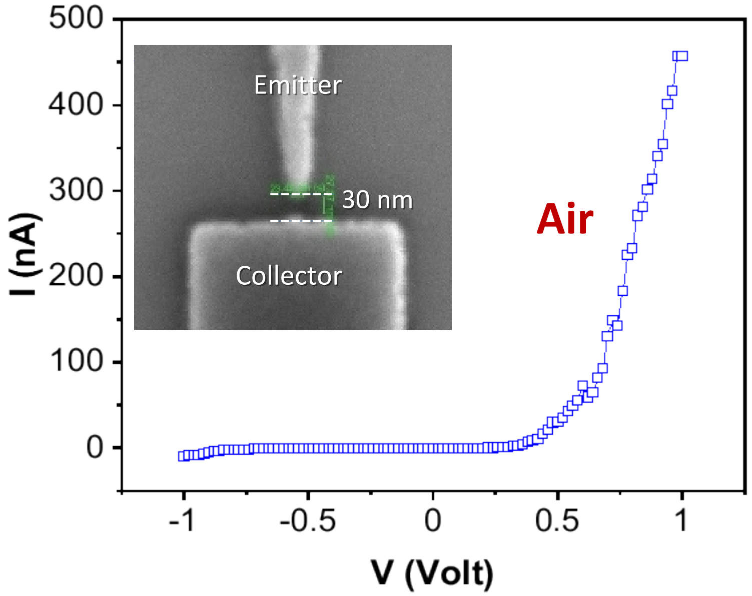
Working GaN Field Emission Devices

Successful field emission (FE) in air with low turn on voltage and high emission current!

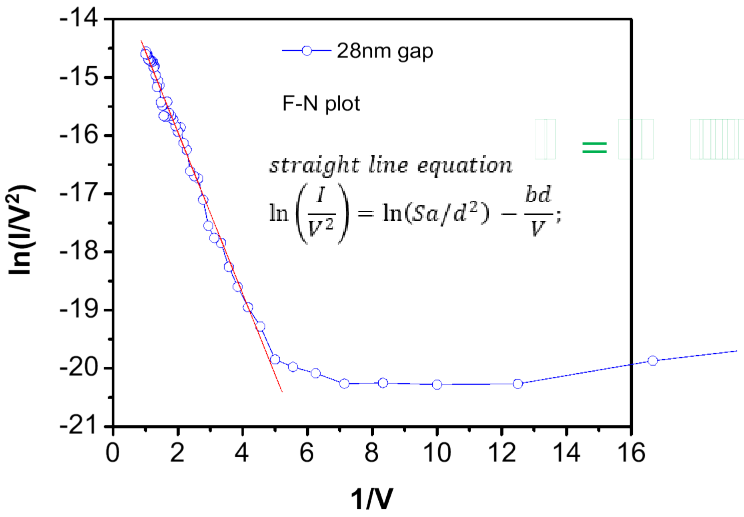
Field emission is diode-like for sharp emitter and flat collector (expected)

Device Geometry:

Gap = 30 nm, Emitter r_{tip} ~ 17nm



IV measurement: **Diode** characteristics



Fowler-Nordheim (FN) test for field emission

Very low turn on and very high FE current!

Effect of Emitter Size on Field Emission

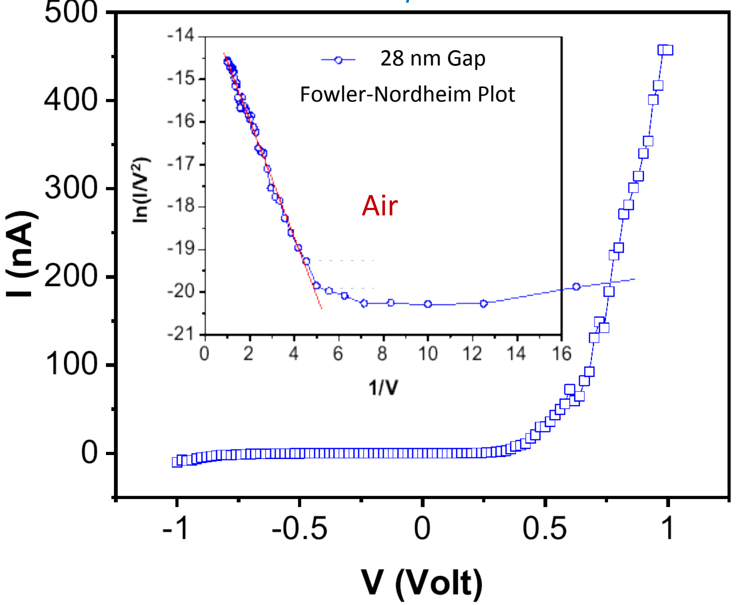
Sharper emitter is desired for low voltage field emission

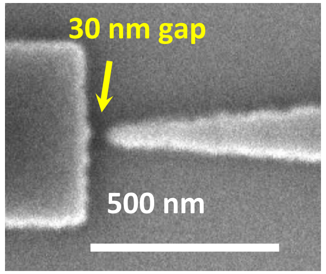
- Increases field enhancement
- Reduces the device turn on voltage

$$J = A\left(\frac{\beta^2 V^2}{\phi d^2}\right)\exp\left(-\frac{B\phi^{3/2}d}{\beta V}\right)$$

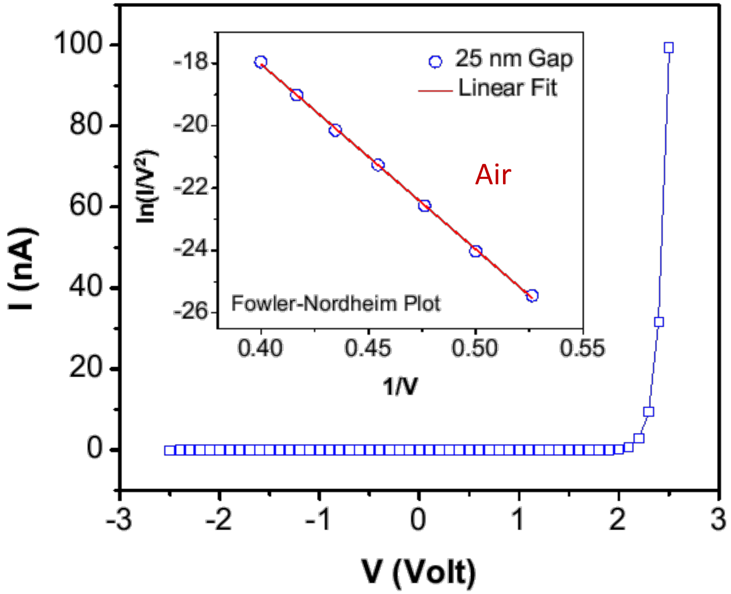
β ➔ Field enhancement factor, depends on geometry

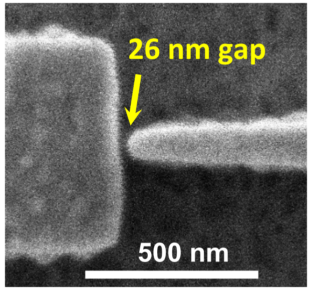
Emitter r_{tip} = 17 nm





Emitter r_{tip} = 31 nm





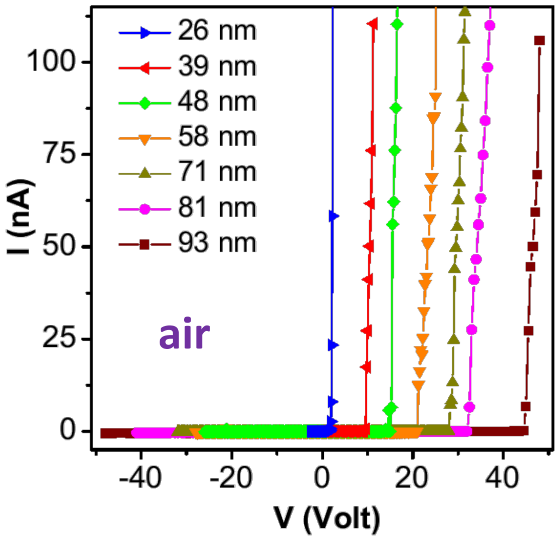
- Field enhancement factor (β) = 920
- Turn on voltage = 0.24 V @ 50pA

- Field enhancement factor (β) = 32
- Turn on voltage = 1.9 V @ 50pA

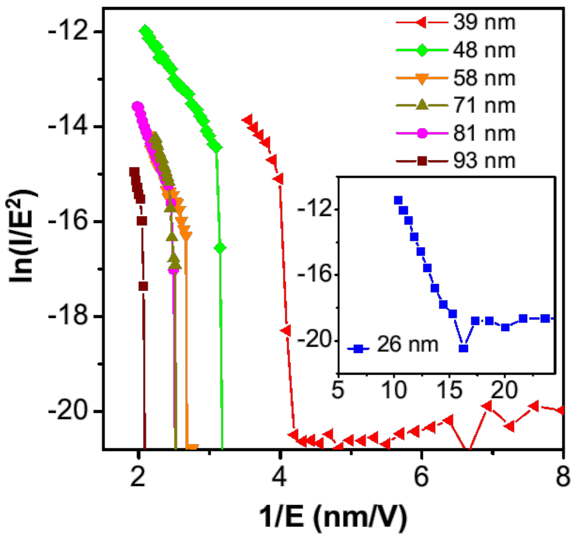
Nanogap Size Dependency of the Field Emission

Devices with various nanogap sizes were fabricated

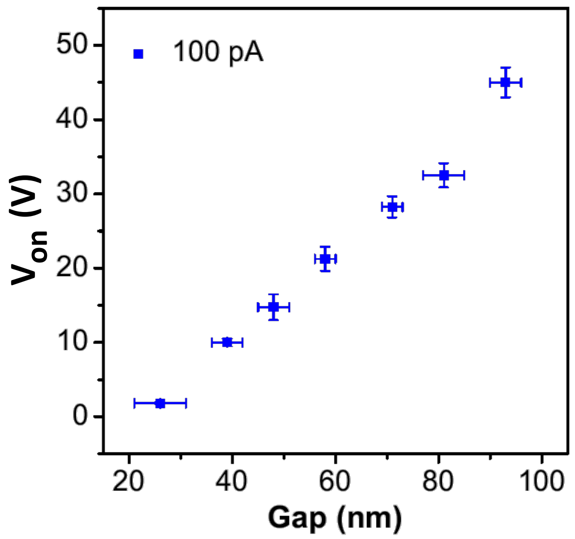
- Emitter tip radius ~ 30 ± 2nm
- Field emission observed **<u>in air</u>** (atmospheric pressure) with gap size as large as 93 nm
- IV data for different nanogap sizes can be explained by Fowler-Nordheim field emission
- Turn-on voltage depends linearly with nanogap size
- Field enhancement factor decreases with increase in gap size



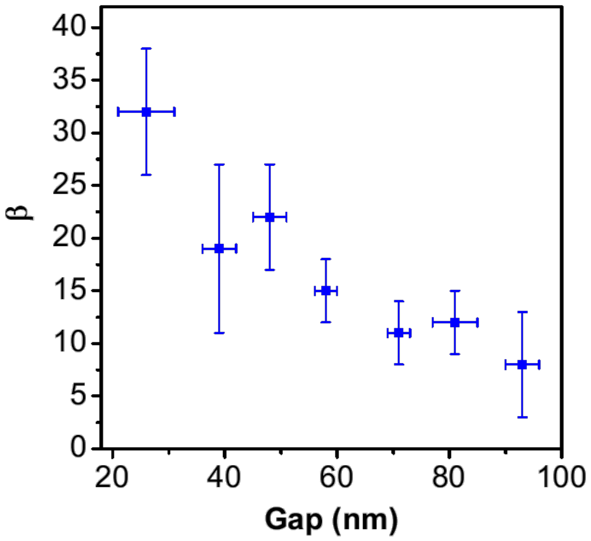
Field emission for various nanogaps



Fowler Nordheim Plots



Nanogap size dependent turn on voltage

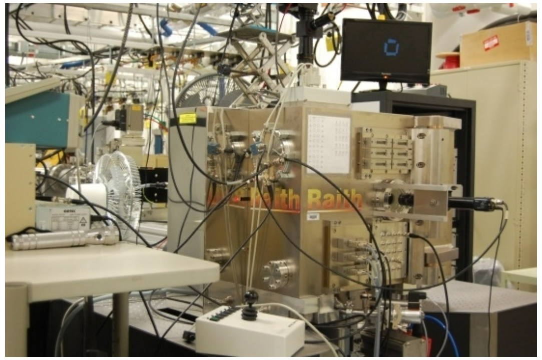


Nanogap size dependent field enhancement factor

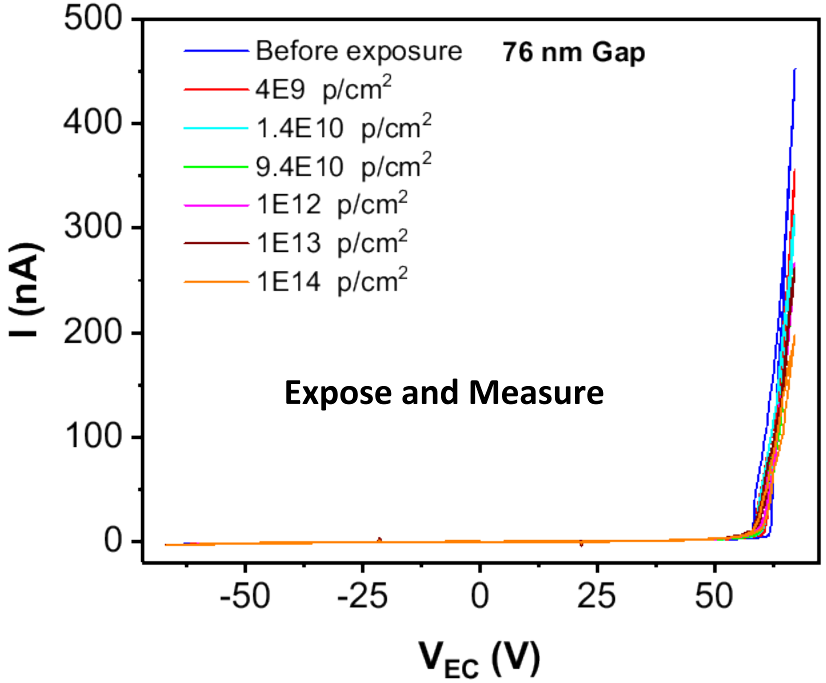
Sapkota et al., "Ultralow Voltage GaN Vacuum Nanodiodes in Air", *Nano Letters (2021)*

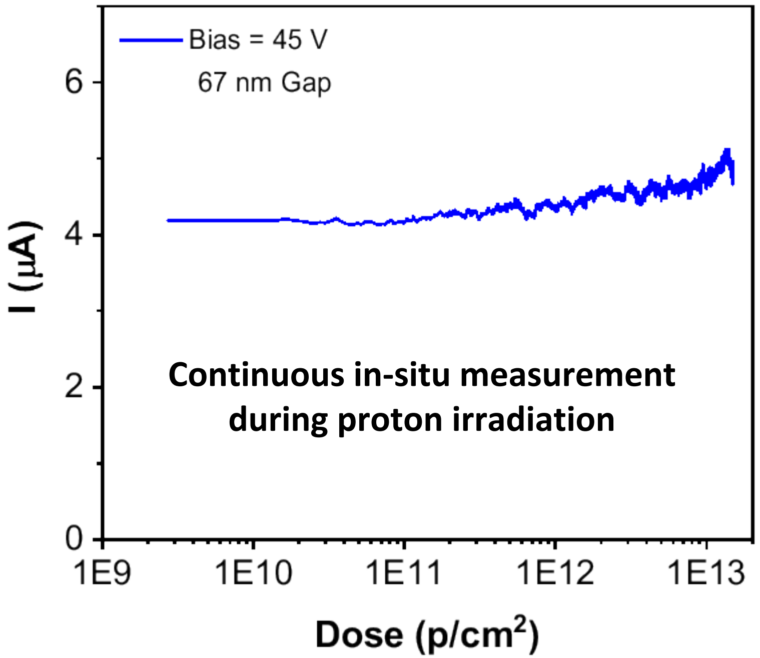
2.5 MeV Proton Irradiation on GaN Vacuum Nanodiodes

- 2.5 MeV proton accelerator (Pelletron) at Ion Beam Lab
- Exposed GaN vacuum nanodiode to total ionization dose (TID) 1e9-1e14 H^+/cm^2 doses
- **No significant degradation** in performance after 1e14 H^+/cm^2 dose (within error)
- In contrast, GaN P-i-N diodes see damage as low as 1e12 H^+/cm^2 dose



IV vs TID

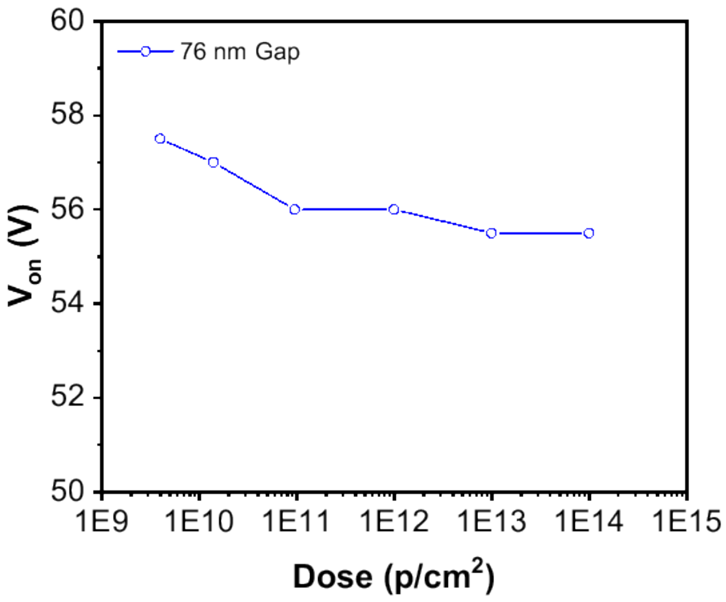


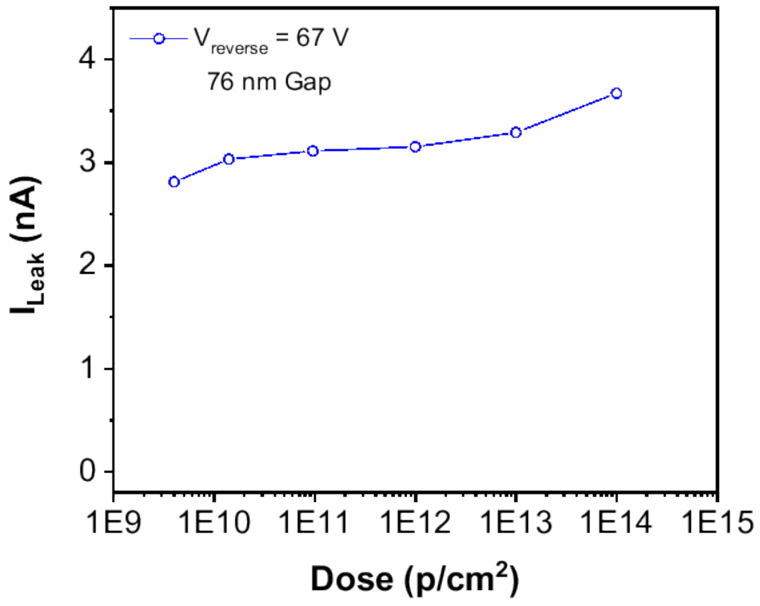


Radiation hardness of GaN Vacuum Nanodiodes

Impressive radiation hardness performance with minimal effect on V_{on} and reverse I_{leak}

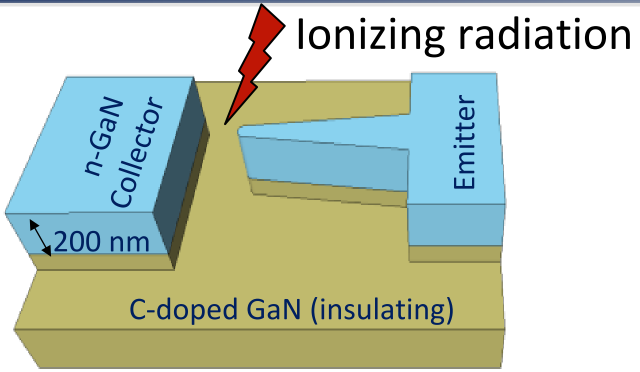
- Less than 4% change in V_{on} at 1e14 H^+/cm^2 dose
- Change in reverse leakage current within error range

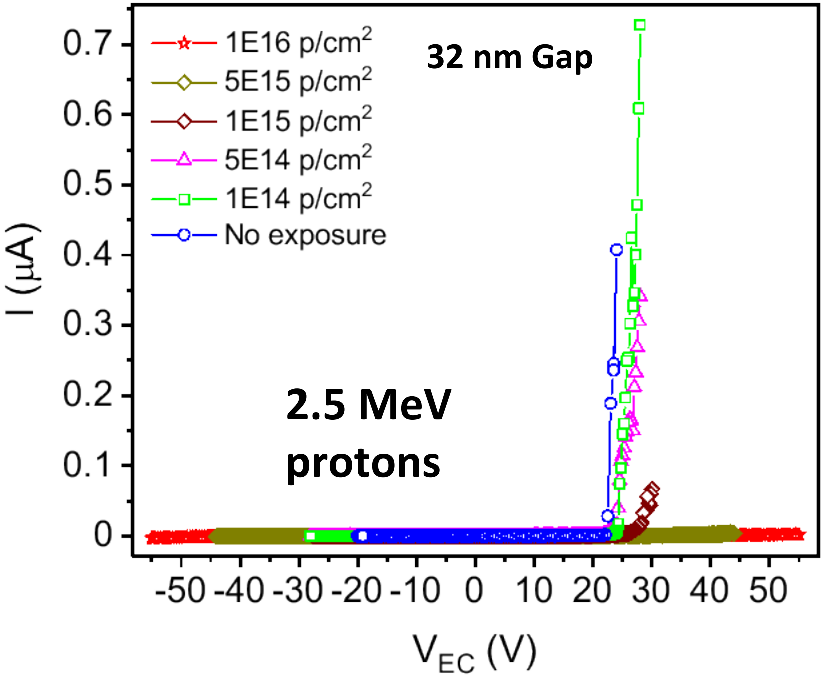




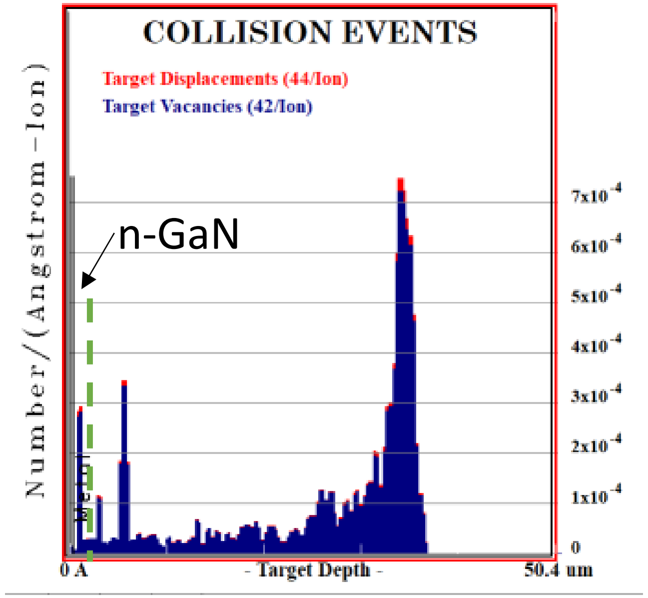
High TID exposure and device degradation

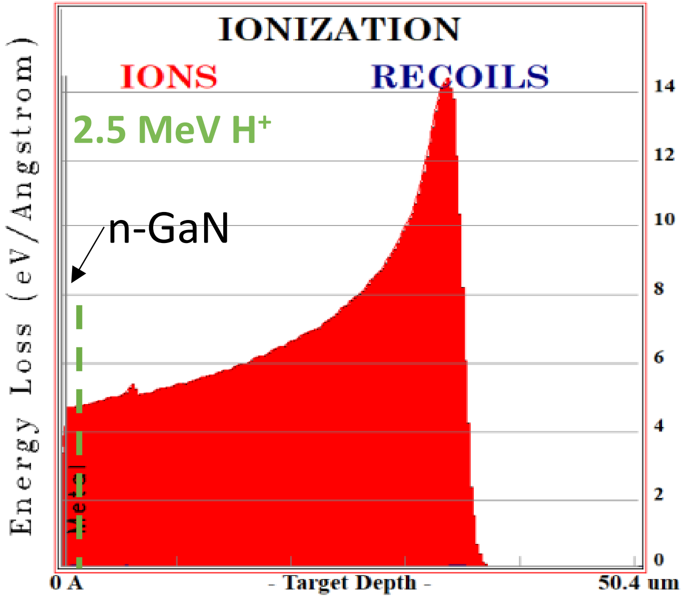
- GaN vacuum nanodiodes operable up to dose **1200 Mrad** (2.5 MeV, 1e15 H^+/cm^2) which is two order of magnitude higher dose than for state of art GaN PiN diodes
- Performance degradation at high TID is primarily contributed by generation of defects and dopant compensation in n-GaN layer
- **Intrinsic Radiation hardness due to vacuum channel and small interaction volume**





IV vs Total Ionizing Dose





SRIM (The Stopping and Range of Ions in Matter) calculations for collision events and energy loss during 2.5 MeV H^+ irradiation

Conclusions

- All GaN-based nanogap field emission vacuum nanodiode devices were successfully demonstrated
- If nanogap size << electron mean free path, field emission in nanogap device can be achieved in air
- Low turn-on voltage down to 0.24 V is achieved with high field emission current for 28nm gap, ~20 nm radius sharp emitter tip device
- Nanogap size dependent field emission characteristics are studied: turn-on voltage and constant current bias potential increase linearly with nanogap size
- GaN vacuum nanodiodes show significant radiation hardness with total ionizing dose as high as 600 Mrad (2.5 MeV, 1e15H^+/cm^2) which is 100x higher TID than the operable TID of state of the art diode
- For TID > 600 Mrad, significant degradation observed due to radiation generated defects and dopant compensation in n-GaN
- **Intrinsic Radiation hardness of GaN vacuum nanodiode is due to vacuum as a transport channel and small interaction volume of n-GaN**