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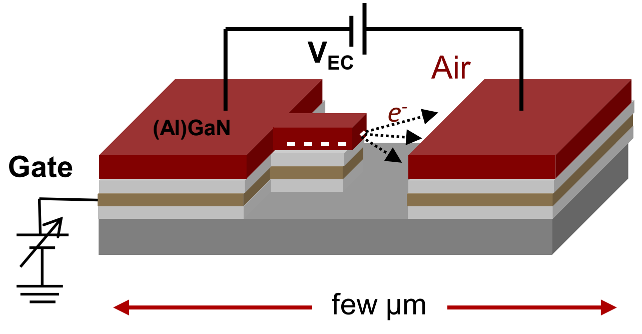

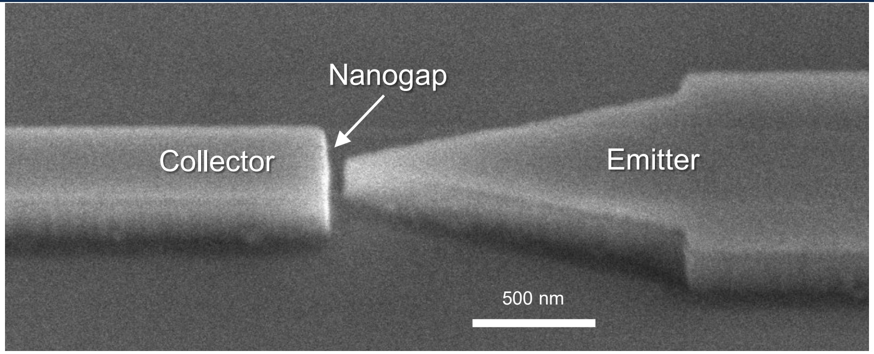

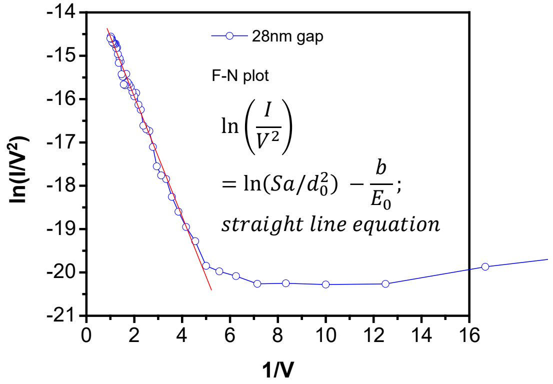

Ultra-low Voltage GaN Vacuum Nanoelectronics

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

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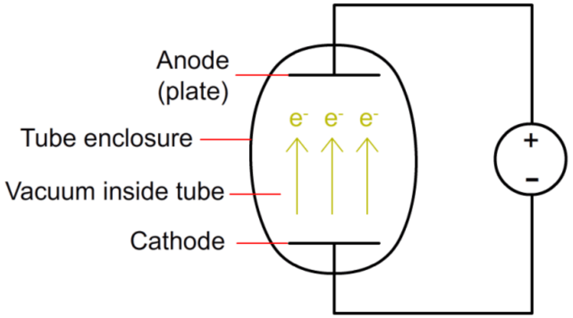
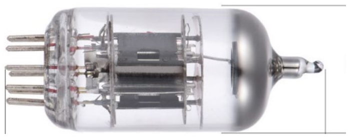
Vacuum Electron Devices – Still Around!

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

Vacuum electron device diagram



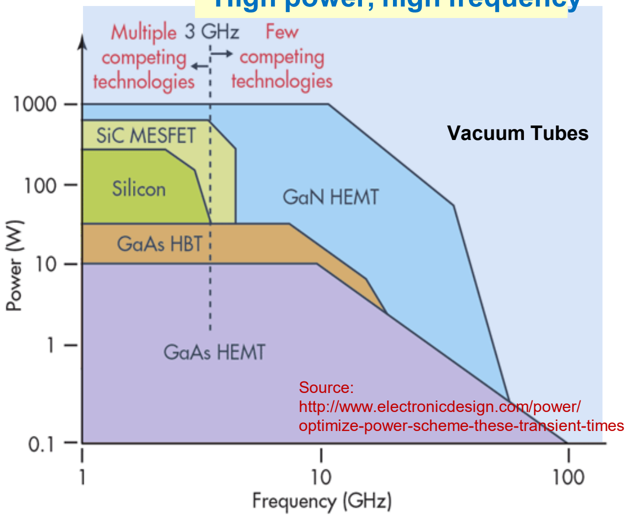


https://www.engineering.com/ElectronicsDesign/ElectronicsDesignArticles/ArticleID/16337/Vacuum-Tubes-The-World-Before-Transistors.aspx

Advantages: operation at higher frequencies, power, temperature, radiation than solid-state semiconductor devices

- **Ballistic transport in vacuum channel** (vs. scattering in solid channel)
- **No heat generation** during electron transport in vacuum
- **High dielectric breakdown** (Dielectric strength of perfect vacuum = 10^{12} MV/m)
- Operation in **harsh environments** (**radiation**, **temperature**): no junction, vacuum channel unaffected

High power, high frequency



Drawbacks of vacuum tubes: Size, cost, reliability, energy efficiency (thermionic emission), integration, vacuum requirement

“Integrated” vacuum electron devices: previous & current status

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~1980s-1990s: Microfabricated Si vacuum microelectronics

- Microfabricated Si or W/Mo tip arrays, **cold field emission**
- Drawbacks: high vacuum requirement, high turn-on voltages & low currents (high work function materials), emitter degradation

~2012-present: *Nanogap* vacuum nanoelectronics

- **Nano-scaling** of cathode-anode gap/channel
- Enhancement of local electric field: reduction of operating voltage and emitter sharpness requirement
- **Relaxation of vacuum requirement:** vacuum channel < mean free path of electron in air (~500 nm)
- Proof of concept demonstration in Si by NASA: vacuum-free “vacuum” transistor with 150 nm nanochannel & estimated cutoff frequencies to 460 GHz!

New class of solid-state “nanogap” vacuum electronics have strong potential for high-speed, resilient electronics, but outstanding challenges remain & further R&D needed!

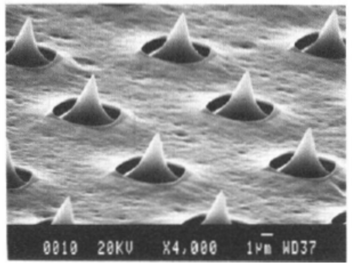
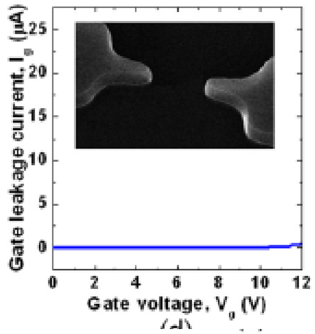
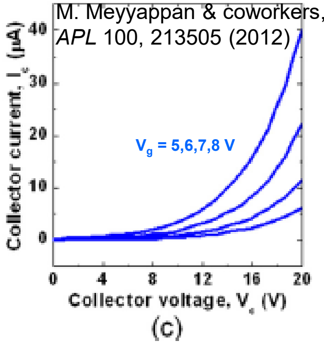


Figure 31. SEM micrograph of silicon tip emitters with maximum recess of the gates using the process of figure 29.

Betsui K 1991 Fabrication and characteristics of *Si* field emitter arrays *Technical Digest 4th Int. Vacuum Microelectronics Conf. (Nagohoma Japan)* p 26





M. Meyyappan & coworkers, *APL* 100, 213505 (2012)

GaN: A Superior Platform for Solid-State Vacuum Nanoelectronics?

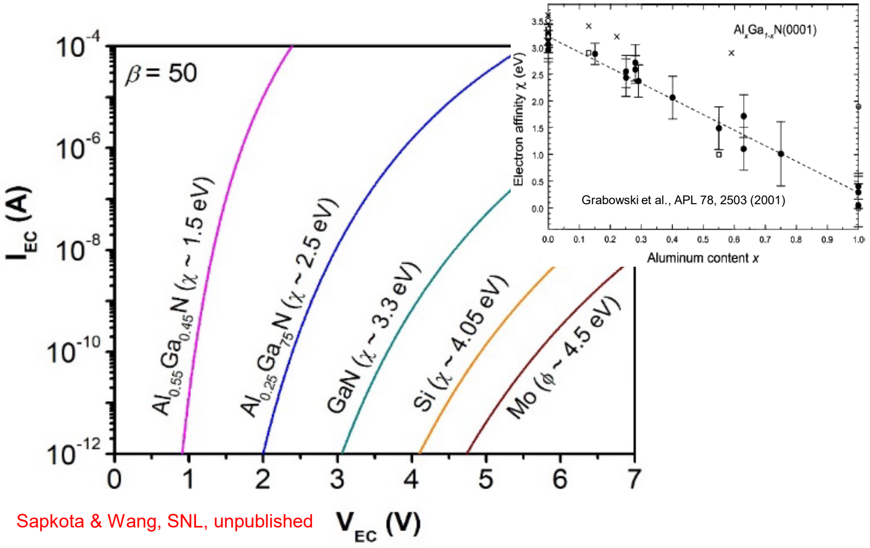
1. Low voltage field emission

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-type semiconductor

GaN: low χ ➔ Low voltage field emission

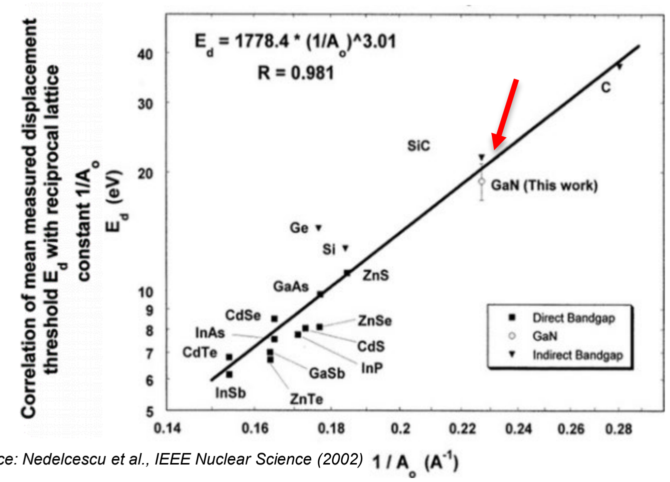


Sapkota & Wang, SNL, unpublished

2. Stability and reliability

GaN has significantly higher bond strength than Si

- ✓ Resistance to degradation
- ✓ Chemical stability
- ✓ Operable at high temperature
- ✓ Radiation hardness

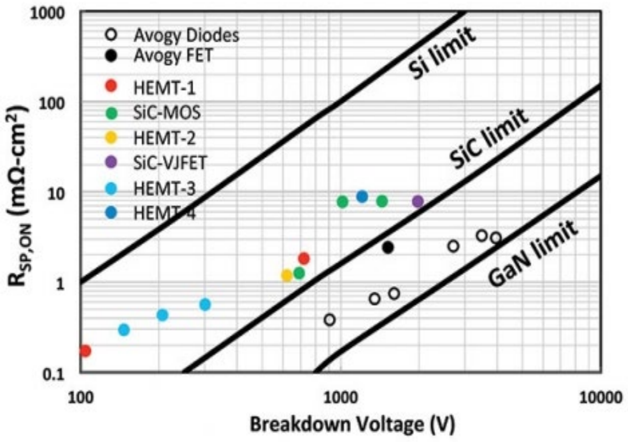


Source: Nedelcescu et al., IEEE Nuclear Science (2002)

3. High Power Operation

GaN has High Breakdown Field

- ✓ 3.3 MV/cm vs 0.3 MV/cm for Si
- ✓ High power operation
- ✓ High frequency operation



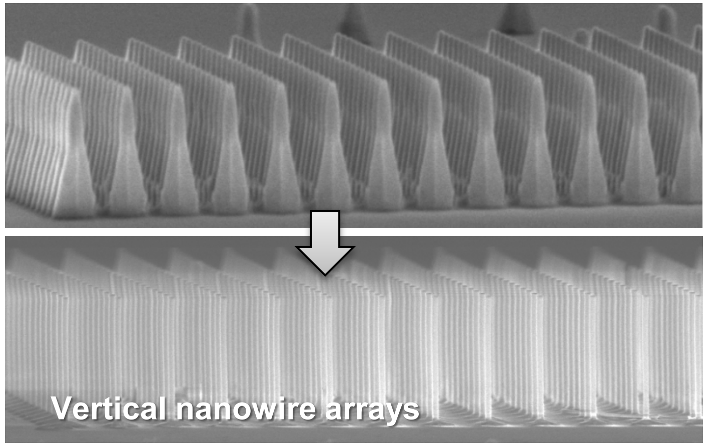
Source: https://compoundsemiconductor.net/article/98990

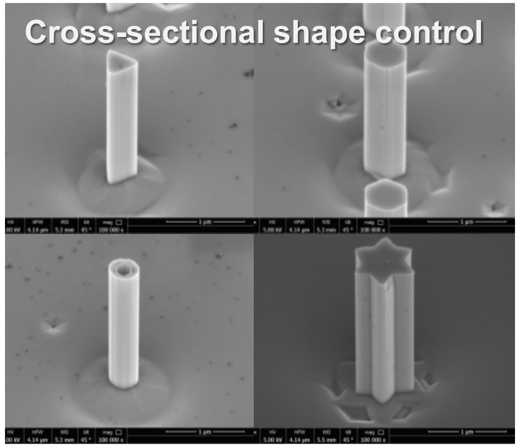
4. Mature & scalable materials & device platform (commercial UV-visible, LEDs, lasers)

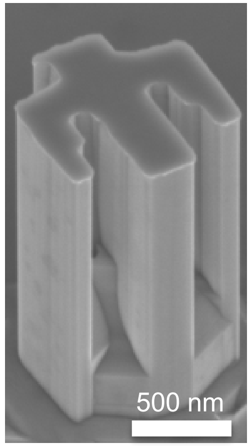
Enabling Capability: Top-Down 3D GaN Nanofabrication

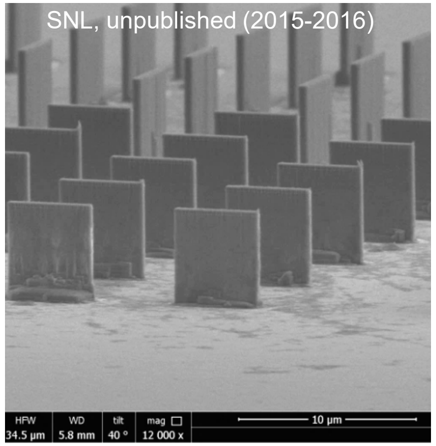
High quality, smooth & damage-free GaN-based nanostructures

Two-step dry + wet (KOH-based) GaN vertical etch

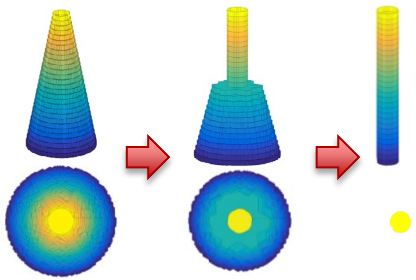






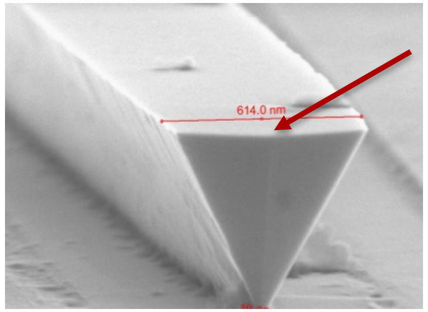


Simulation of facet etch evolution



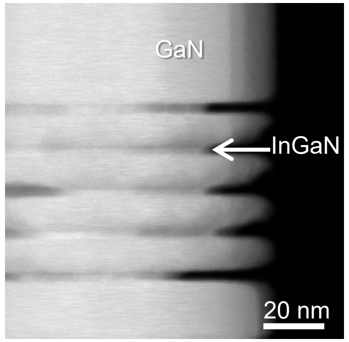
Q. Li et al., *Optics Express* **19**, 25528 (2011)
Q. Li et al., Opt. Exp., **20**, 17873 (2012)
Li, Changyi, et al., *Nanoscale* ***8***, 5682 (2016). …etc.

GaN undercut etch



Sharp emitter geometry for enhanced field emission

(In)GaN lateral etch



Selective removal of quantum wells allows for **ultrathin** vertical nanogap vacuum channel

Xiao et al, Elec. Acta 162, 163 (2015)

Fabrication: Integrated, lateral GaN nanoscale vacuum electron diodes

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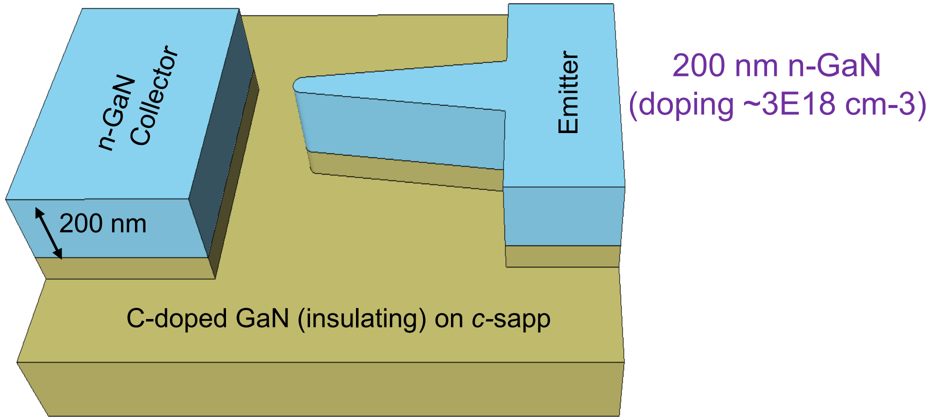
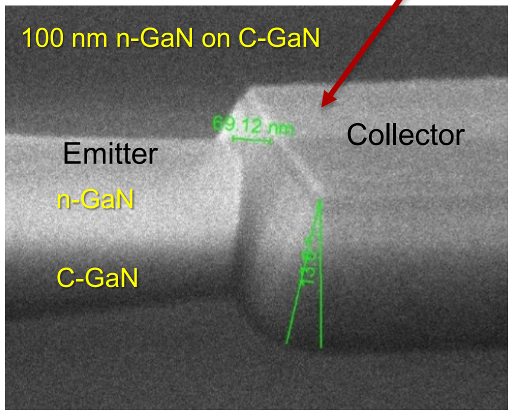
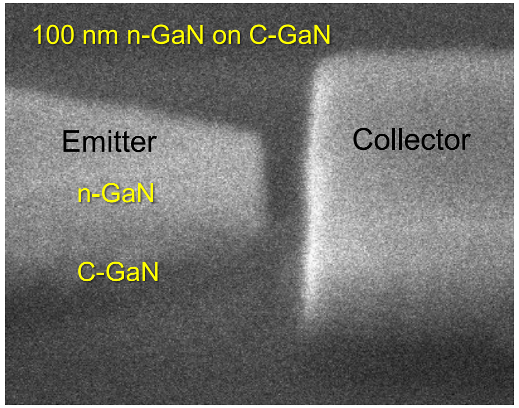
Lateral GaN vacuum nanodiode structure



Ti/Au/Ni/Au ohmic contact layer on emitter & collector



AZ400K wet etch



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

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

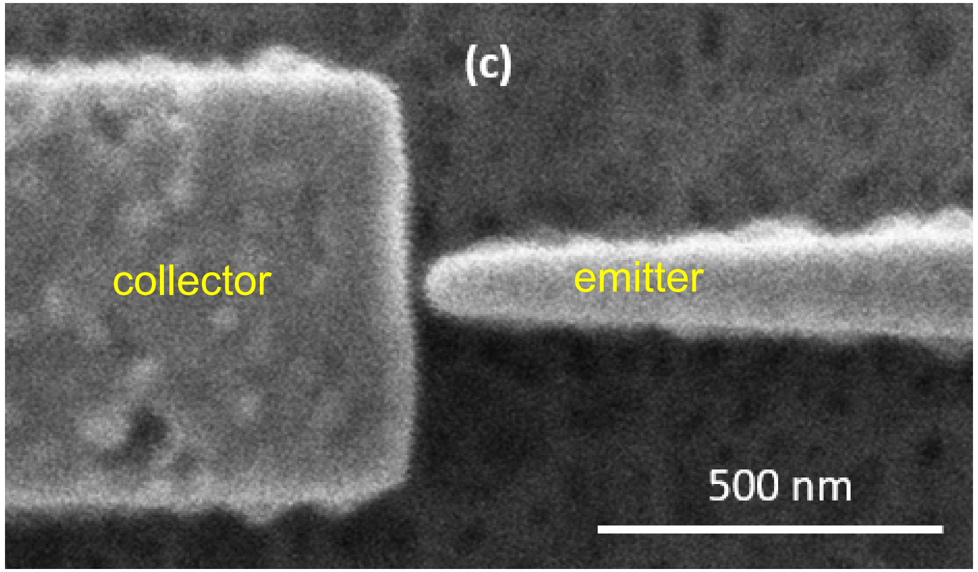
III-N top-down fabrication process

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

~30 nm gaps and ~20 nm radius emitters routinely achievable!

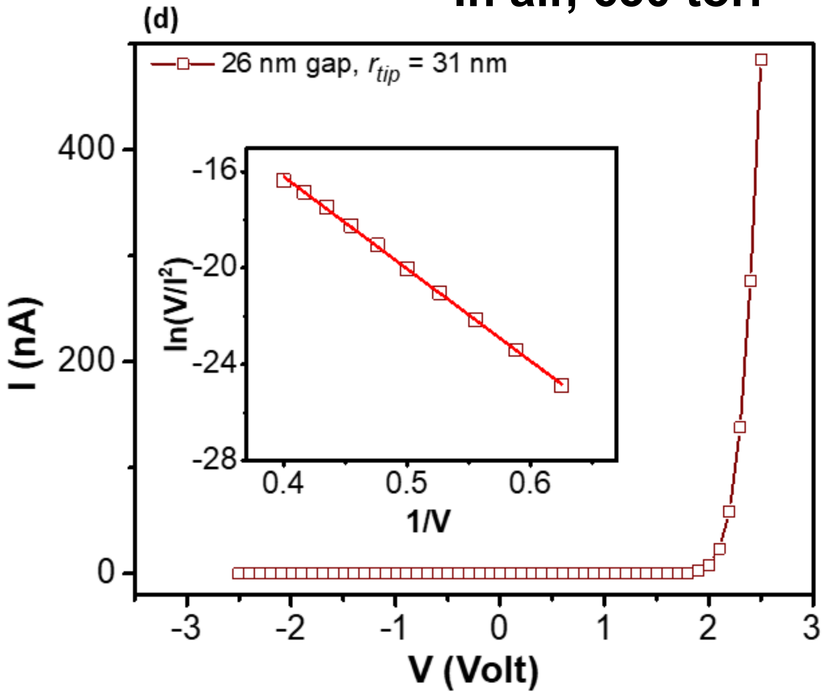
Working monolithic, on-chip GaN nanoscale vacuum electron diodes!

- Emitter tip radius ~ 31 nm; Nanogap size (emitter-collector separation) ~ 26 ± 5 nm
- **Low turn-on voltage (V_{on}) of ~1.8 V, high emission current (I_e) of ~485 nA at 2.5V!**
- **Field emission observed in air at atmospheric pressure (630 torr)!**
- I-V data good linear fit with the Fowler-Nordheim plot (confirms cold field emission)



31 nm tip radius, **~26 nm** gap

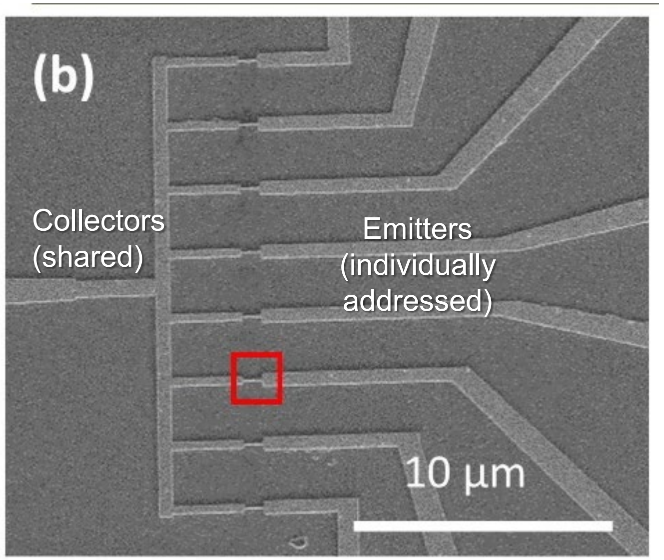
In air, 630 torr

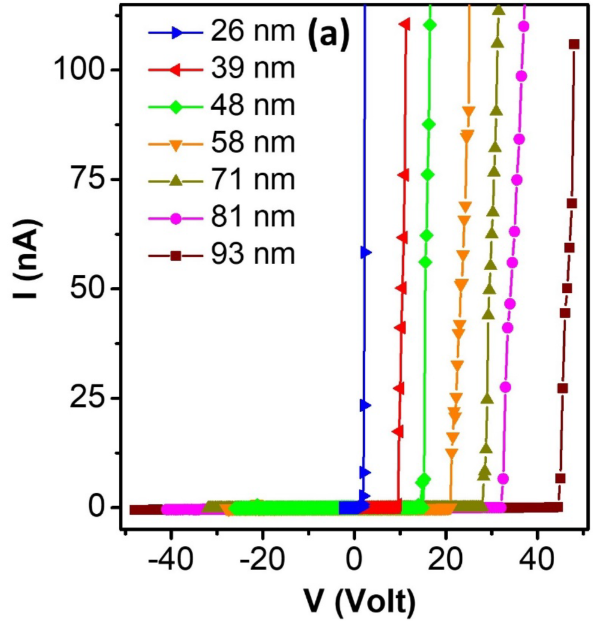


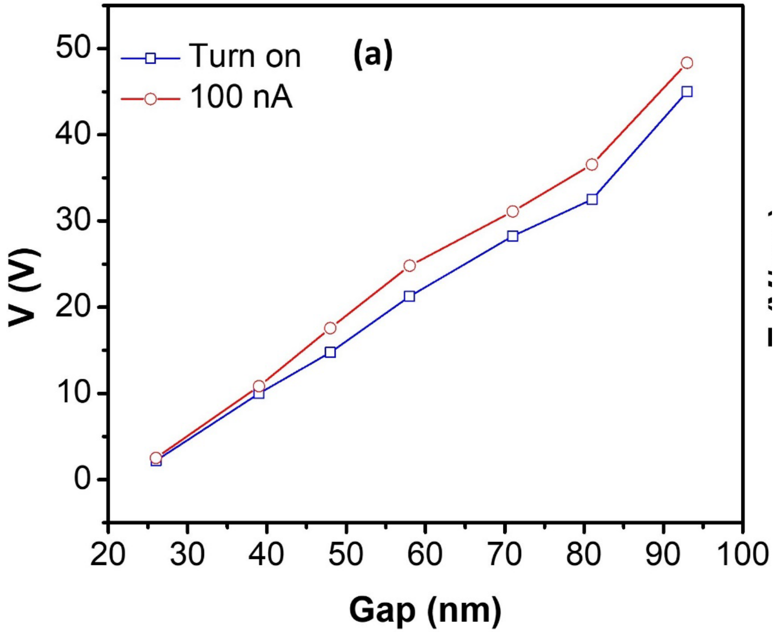
Nanogap Size Dependency of the Field Emission

Devices with seven nanogap sizes from ~26-93 nm were fabricated

- Emitter tip radius ~ 32 ±2 nm
- Field emission observed **from all seven devices (100% yield)** **<u>in air</u>** (atmospheric pressure), with very sharp current increase after turn on (turn-on V_{on}= V≥100 pA)
- I-V data: linear fit to the Fowler-Nordheim field emission equation (not shown)
- **Turn-on voltage increases *linearly* with increasing gap size**





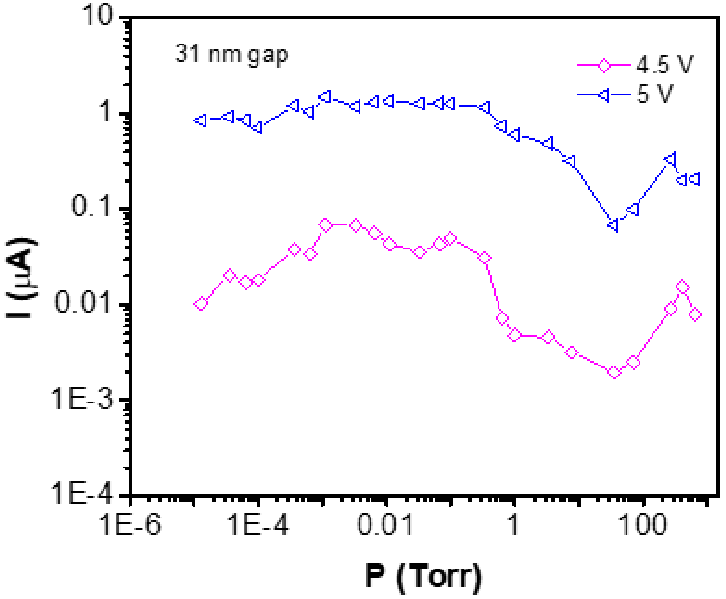


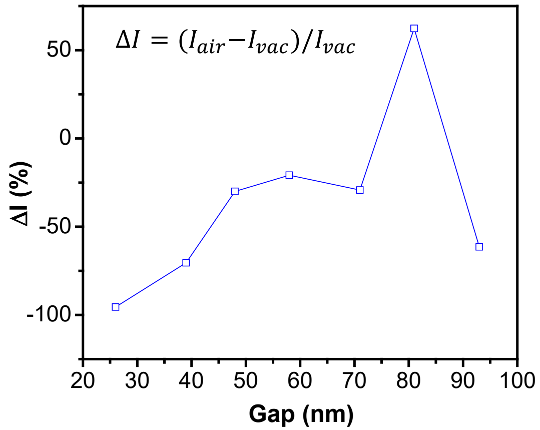
Effect of Pressure on Nanogap Field Emission

- **Assumption:** nanogap is vacuum-like if nanogap size << electron mean free path in air
- ***Does pressure actually affect field emission of nanogap device in this regime?***

Lateral GaN nanogap diodes measured from 5e-6 to 630 Torr (8 orders of magnitude)

- Performance at atmospheric pressure near to that at high vacuum (within factor of 10), can be compensated by slight boost in operating voltage
- *However, field emission is affected by pressure, but behavior complex (non-monotonic relationship)*

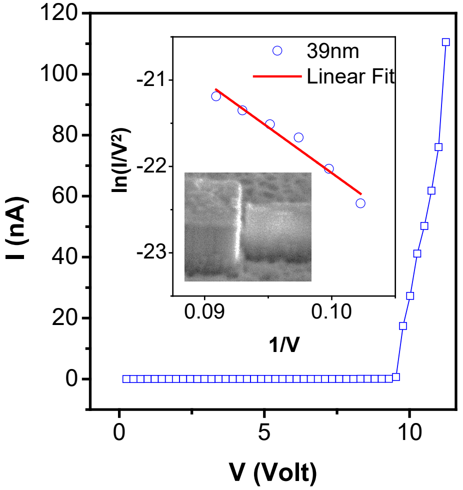




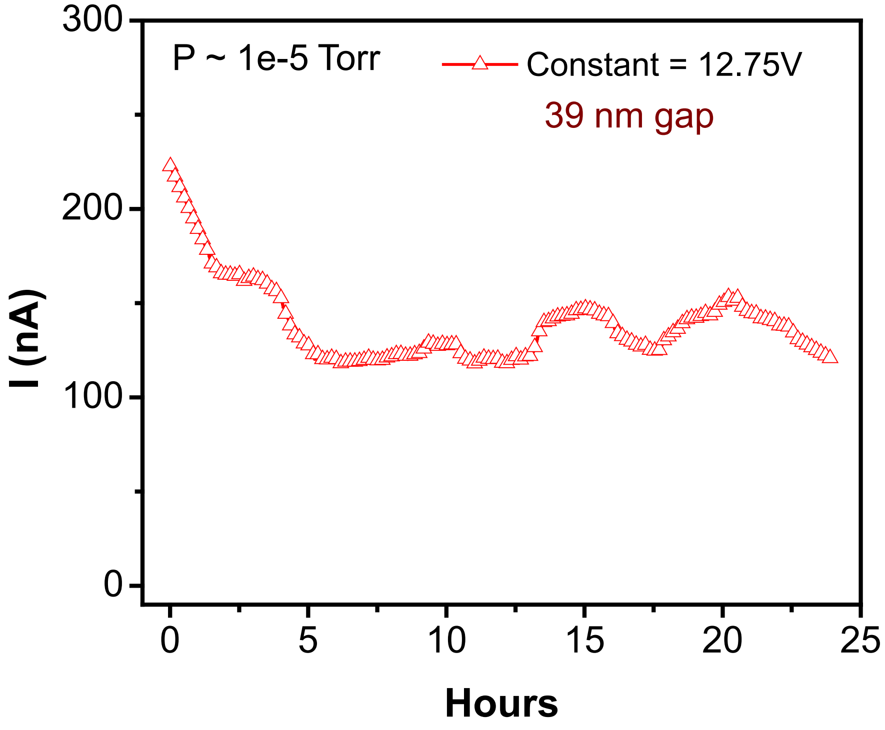
Reliability Measurements of GaN Nanogap Device (39 nm gap)

- **Continuously on** measurement: drop in current over first few hours, then stabilizes. Device performs for at least ~24 hours during continuous measurement (other device measured to 55 hours)
- **Pulsed** measurement: No degradation after 1.8×10^5 pulses at high currents (few µAs) (# pulses limited by measurement equipment)

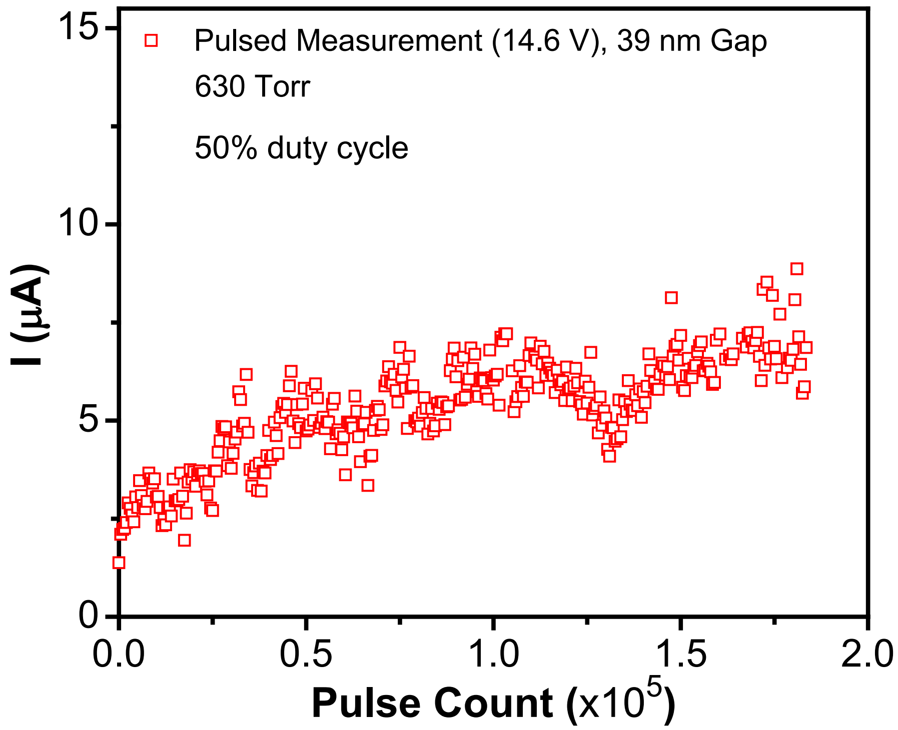
39 nm gap device I-V



Continuously On



Pulsed



Effect of Emitter Tip Size on Field Emission

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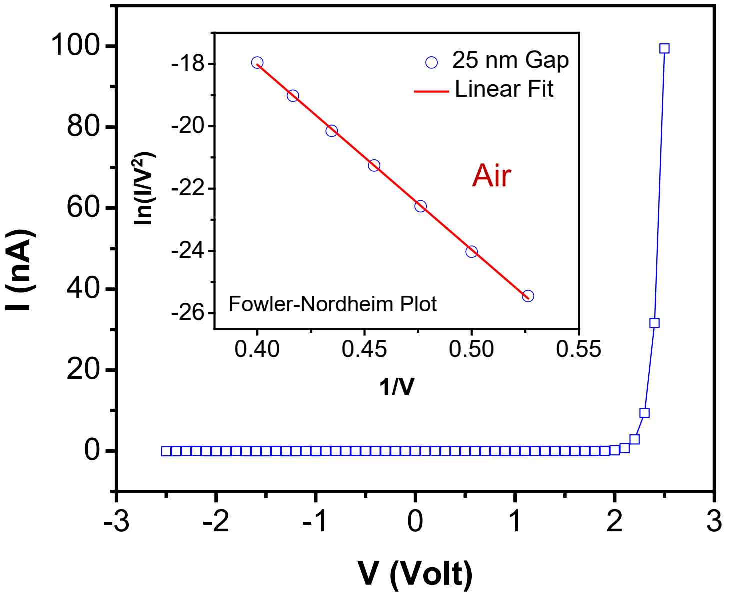
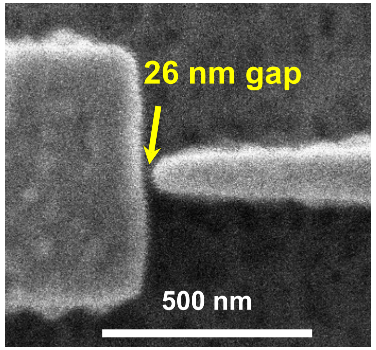
Sharper emitter is desired for lower voltage field emission

- Increases field enhancement β (depends on geometry)

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

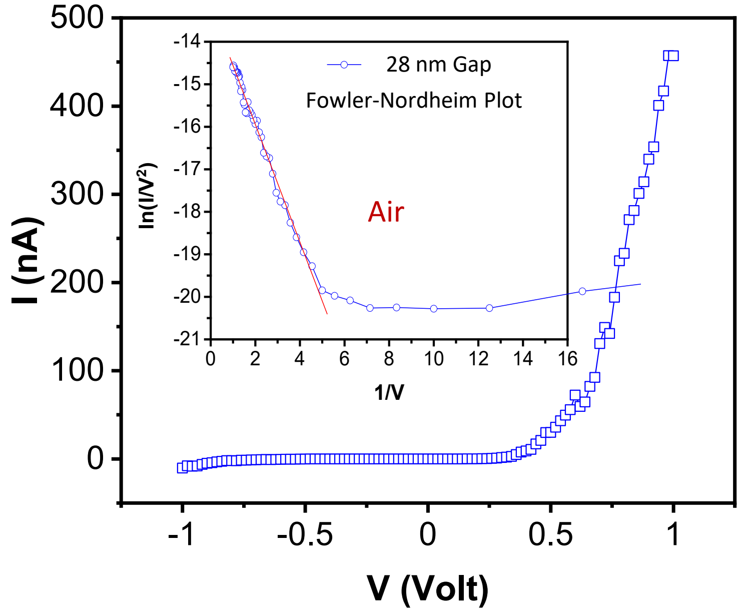
Emitter r_{tip} = 31 nm

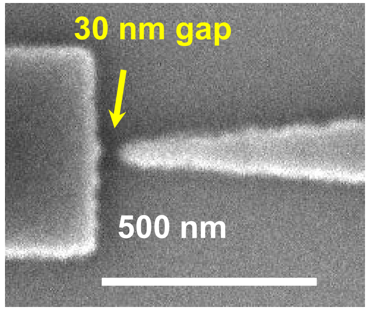




- Field enhancement factor (β) = 32
- Turn on voltage = **1.9 V** @ 50pA

Emitter r_{tip} = 17 nm





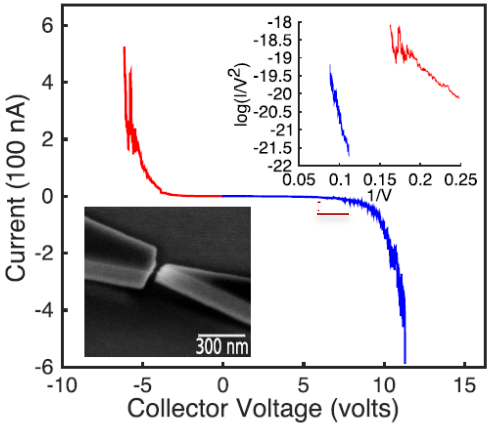
- Field enhancement factor (β) = 920
- Turn on voltage = **0.24 V** @ 50pA

Ultra-low turn-on voltage < 1 V achieved with 17 nm radius emitter!

Comparison of GaN to previous Si and SiC nanogap vacuum diodes

n-Silicon (200 nm) on 2000 nm SiO_2

W.M. Jones et al., APPLIED PHYSICS LETTERS 110, 263101 (2017)



Gap/channel size: 22 nm

Tip radius: ~15 nm (est.)

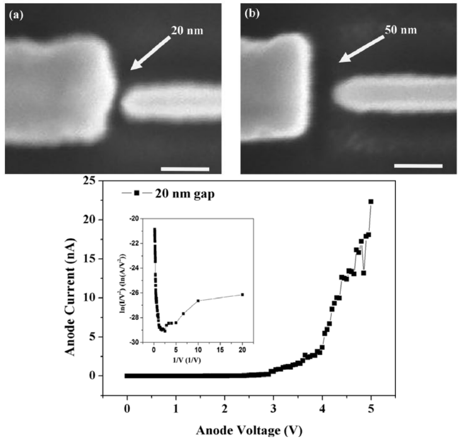
V_{on}: **~3.5 V**

I_e: 100 nA at ~4.8 V

In air? **No**

SiC nanowire (CVD grown & cut by FIB)

M. Liu et al., Journal of Vacuum Science & Technology B **35**, 031801 (2017); (R_{wire} = 0.015 Ohm-m.)



Gap/channel size: 20 nm

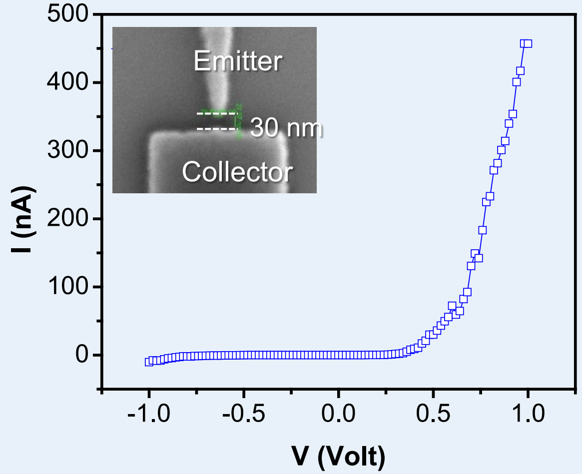
Tip radius: ~20 nm

V_{on}: **~2.6 V (est.)**

I_e: 22 nA at ~5.0 V

In air? **No**

This Work: n-GaN (200 nm) on C-GaN



Gap/channel size: 30 nm

Tip radius: ~17 nm

V_{on}: **~0.24 V**

I_e: **~457 nA at ~1.0 V**

In air? **Yes**

Note: V_{on}= V≥100 pA for all cases

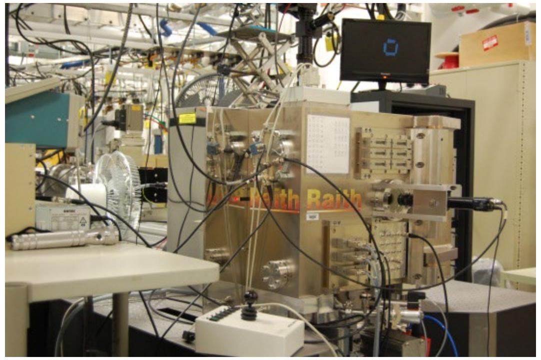
*K. Sapkota et al., *Nano Lett*. 21, 1928 (2021)

GaN nanoscale vacuum electron diode shows far superior performance vs previous Si and SiC devices!

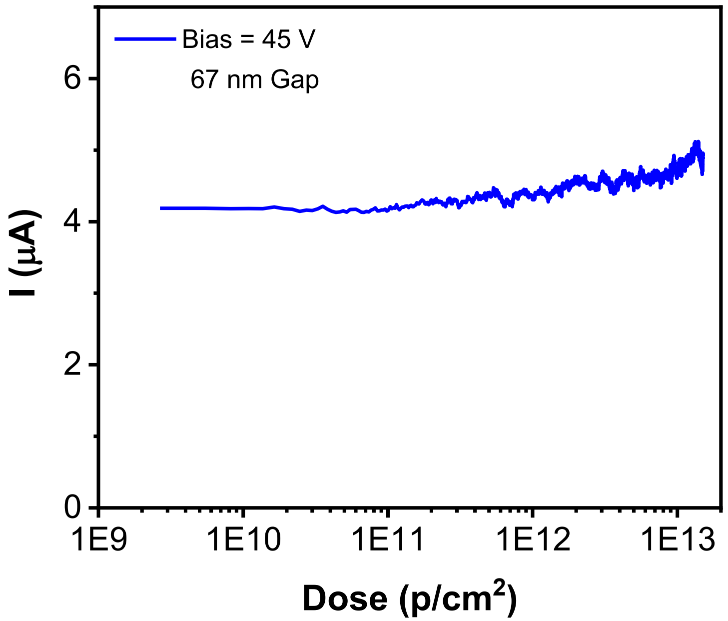
2.5 MeV Proton Irradiation Studies

- **No significant degradation** up to ~ 5e14 H^+/cm^2 2.5 MeV dose (600,000 krad)
  - In contrast, Sandia GaN P-i-N diodes see damage as low as 1e12 H^+/cm^2 dose*
- Measurements show very high damage threshold, likely due to vacuum channel and small interaction volume
- Other radiation testing underway (e.g. electron, neutron)

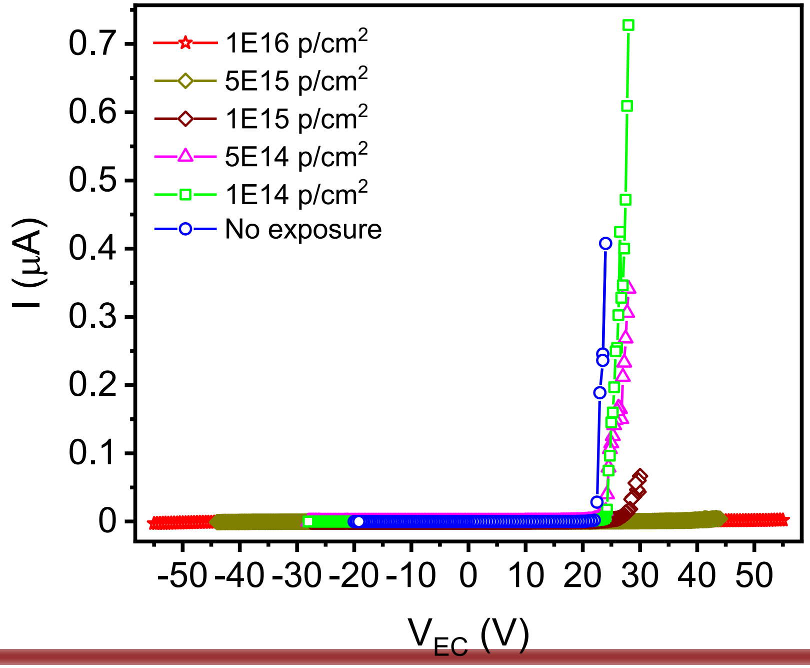
Light Ion Microbeam (Pelletron) at IBL



Continuous *in-situ* measurement



I-V vs total H^+ dose

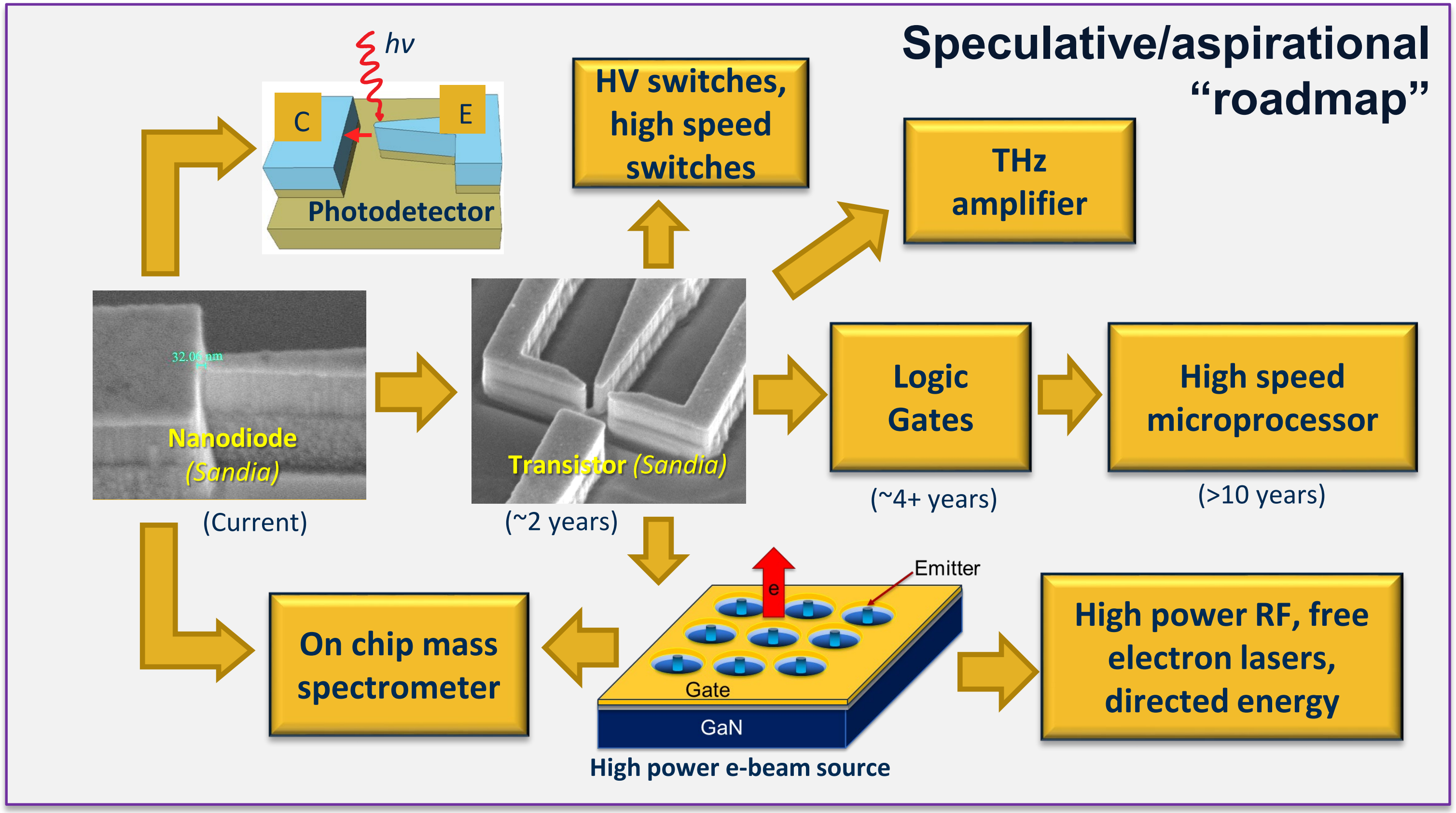


Acknowledgement: George Burns, Michael King, George Vizkalethy, Ed Bielejec

*M. P. King et al., "Performance and breakdown characteristics of irradiated vertical power GaN PiN diodes", IEEE Transactions on Nuclear Science, 62, 2912 (2015).

Conclusions

- High performance, on-chip lateral **GaN** nanogap field emission diodes were demonstrated using a **scalable,** high-yield, top-down fabrication approach
- Ultra-low turn-on voltage **down to ~0.24 V is achieved in air** with high field emission current & good diode behavior, superior to previous Si and SiC vacuum nanodiodes
- Promising stability & extreme radiation hardness to 2.5 MeV proton exposure (>600,000 krad) shown



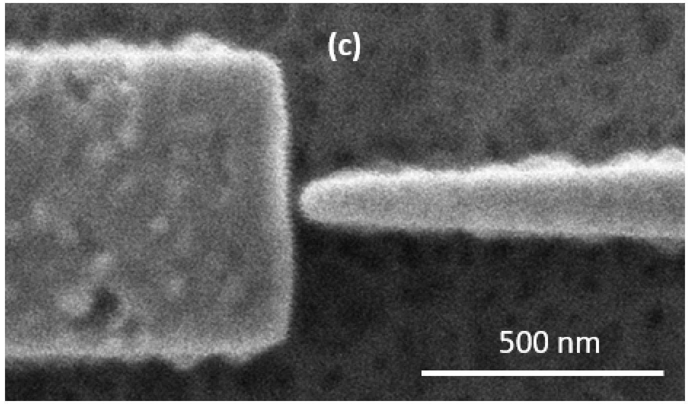
*K. Sapkota et al., *Nano Lett*. 21, 1928 (2021)

Questions? gtwang@sandia.gov

Backup Slides

Conclusions

- High performance, on-chip **GaN-based** nanogap field emission diodes were demonstrated using a **scalable, high-yield**, top-down fabrication approach
- Ultra-low turn-on voltage **down to ~0.24 V is achieved in air** with high field emission current (tested up to 10 μA) & good diode behavior, superior to previous Si and SiC vacuum nanodiodes of similar size & geometry
- Nanogap size dependent field emission characteristics show that **turn-on voltage increases linearly with nanogap size**
- **Stable field emission in air** with performance similar to that in vacuum; however, field emission exhibits complex pressure dependence
- GaN nanogap devices are found to be stable, surviving for multiple days of continuous operation and $>10^5$ pulses at high current (several μA)
- Extreme radiation hardness to 2.5 MeV proton exposure (>600,000 krad)



*K. Sapkota et al., *Nano Lett*. 21, 1928 (2021)

Questions?

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