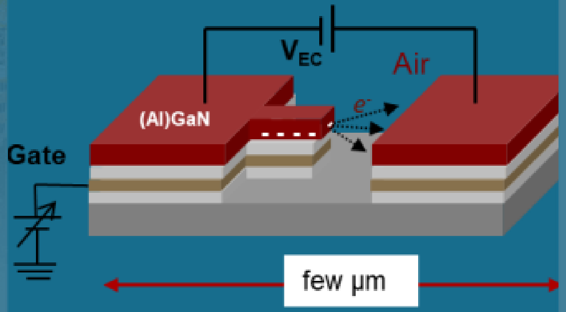
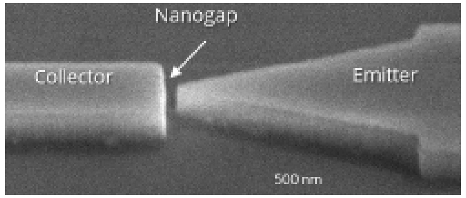
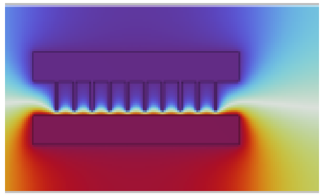
SAND2023-00358C

Sandia National Laboratories

Achieving very-high current density with GaN nanoscale field emitters array







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APS March Meeting 2023 (Las Vegas, NV)

This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. DOE, Office of Basic Energy Sciences, user facility.

Vacuum Devices – Still Around!

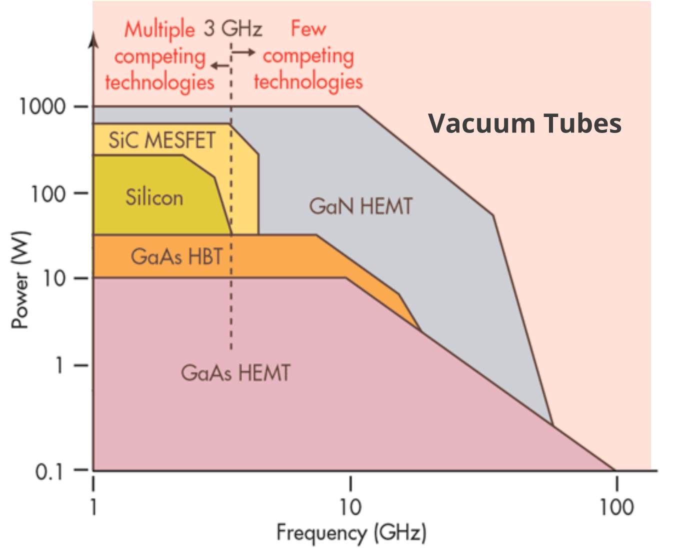
- Solid state devices began to replace vacuum tubes more than 60 years ago
- But vacuum electron devices have distinct advantages and are still in limited use!
  - **Communication:** Radar, RF broadcasting
  - **NASA:** Satellite communications, Electronics for space missions
  - **Industry:** Industrial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

Advantages of vacuum electron devices

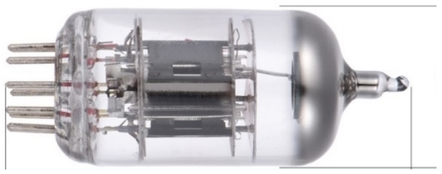
- **Ballistic transport in vacuum channel**
- **No heat generation** during electron transport in vacuum
- **No dielectric breakdown** (Dielectric strength = 10^{18}V/m)
- Operation in **harsh environments (radiation, temperature)**: no junction, vacuum channel unaffected
- As a result, vacuum devices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

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

High power, high frequency



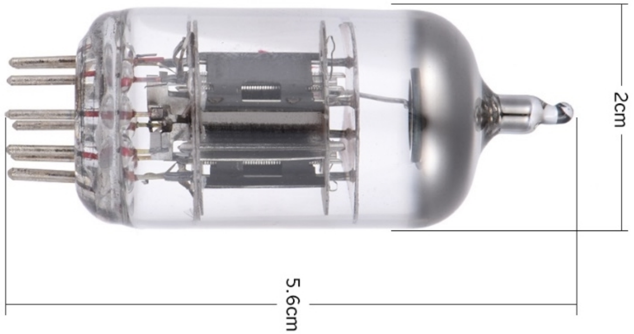
Source: http://www.electronicdesign.com/power/optimize-power-scheme-these-transient-times



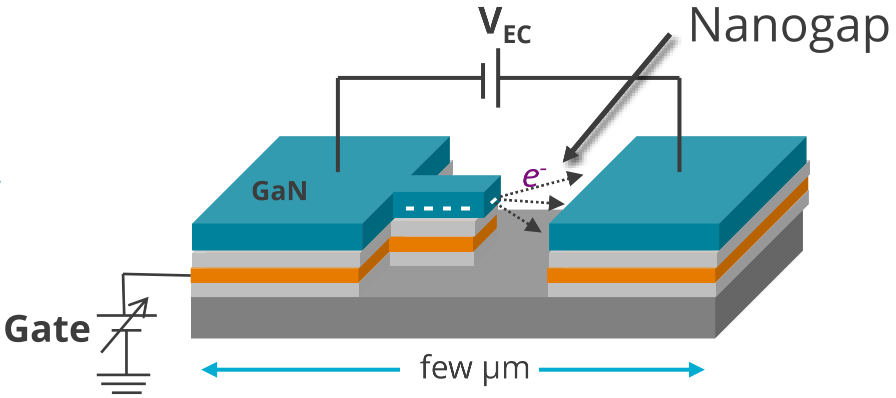
Solid-State, Vacuum-Free “Vacuum” Electronics

- ✓ 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 tubes and semiconductor nanofabrication

GaN: Superior Platform for Vacuum Nanoelectronics

Major Challenges for Vacuum Nanoelectronics

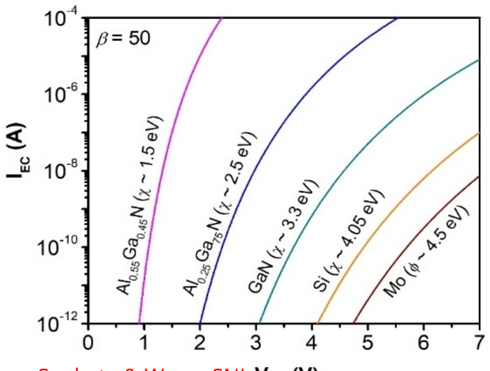
1. Difficult to get low voltage field emission

Fowler-Nordheim (FN) equation

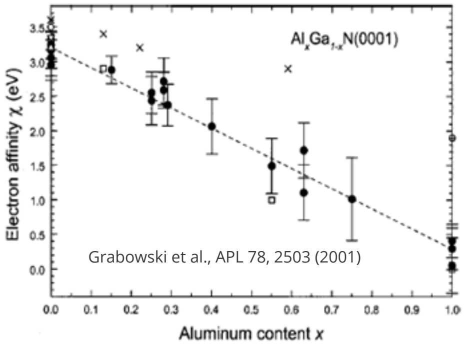
$$J = A\left(\frac{\beta^2 V^2}{\phi d^2}\right)\exp\left(-\frac{B\phi^{3/2}d}{\beta V}\right)$$

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

GaN: low χ ➔ Low voltage field emission



Sapkota & Wang, SNL

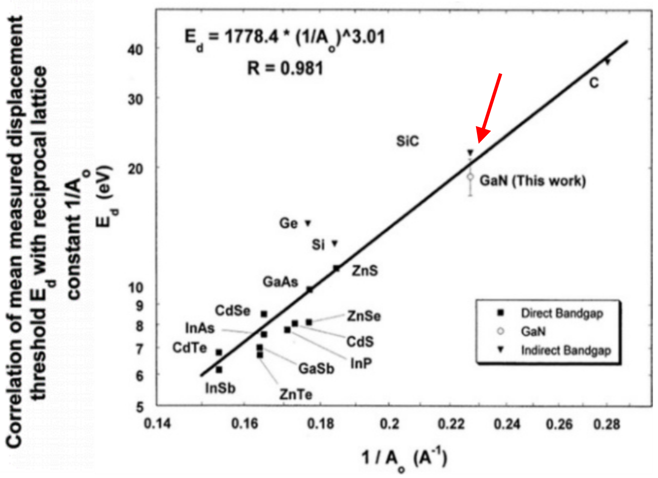


Grabowski et al., APL 78, 2503 (2001)

2. Device degradation/chemical instability

GaN has significantly higher bond strength

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

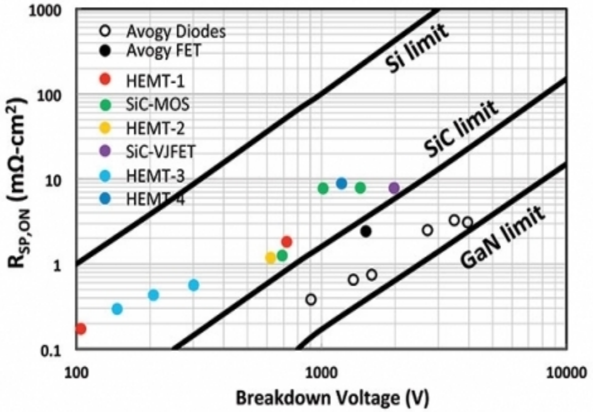


Source: Nedelcescu et al., IEEE Nuclear Science (2002)

3. High Power Operation

GaN has High Breakdown Field

- ✓ High power operation
- ✓ High frequency operation



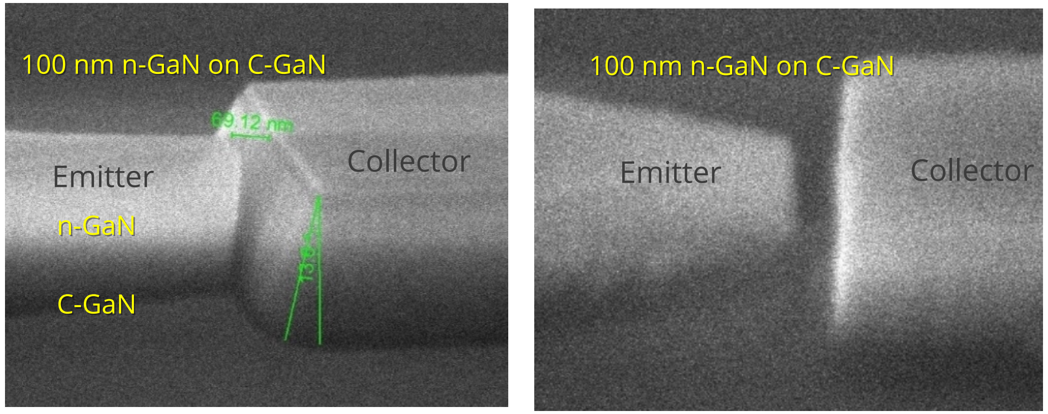
Source: https://compoundsemiconductor.net/article/98990

Nanofabrication of GaN Lateral Field Emission (FE) Structures

III-N top-down fabrication process

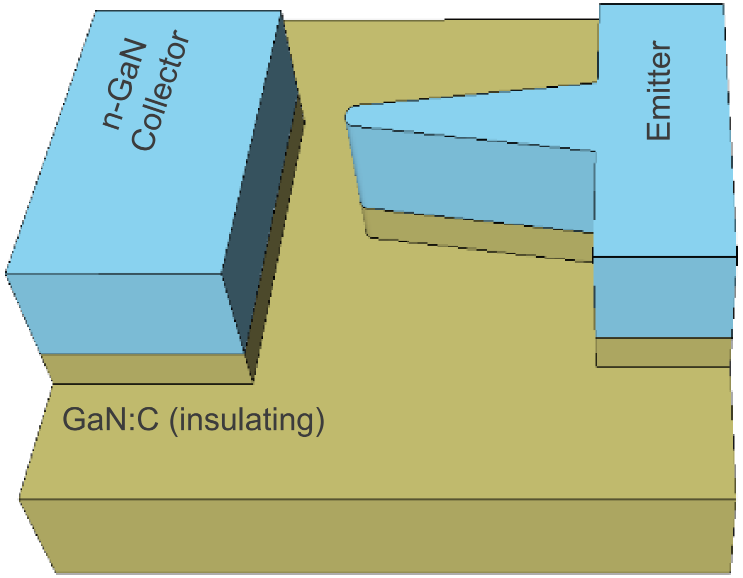
Electron Beam Lithography → Dry Etching (ICP/RIE) → Wet Etching (KOH based)

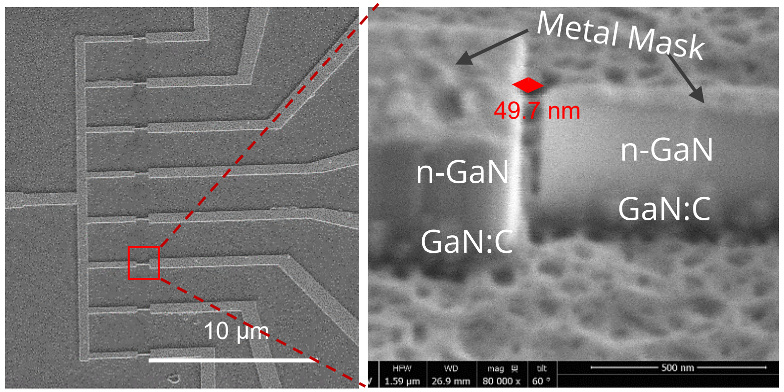
From knowledge of KOH wet etching of GaN:
- Orient collector // to m-plane to avoid microfacet protrusions
- Limit wet etch time to reduce wedge retraction effect
- consider dependence of wet etch on doping and composition

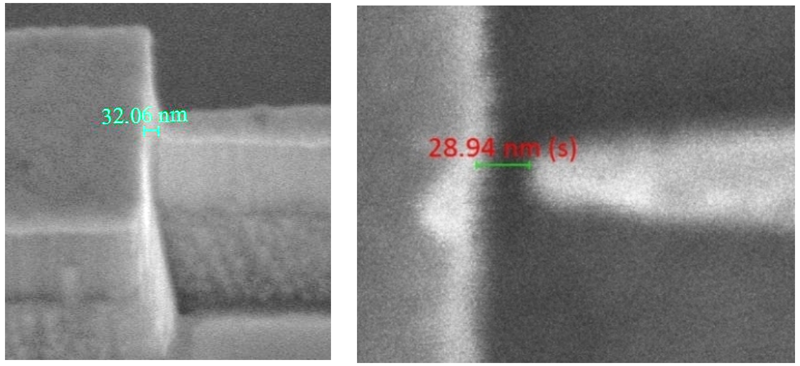


<u>ICP dry etch</u>: Angled side walls – variable gap size, possible shorting at bottom, sidewall damage

<u>+ AZ400K wet etch</u>: Vertical side walls, cleared gap, remove sidewall damage, smoother m-face collector







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

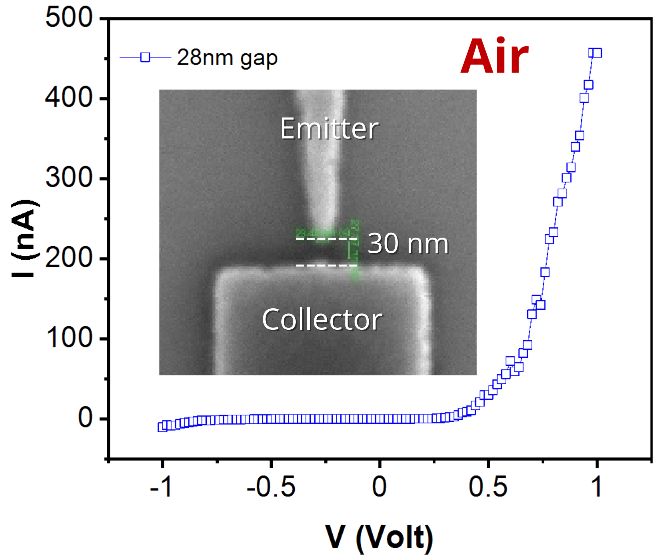
Epilayer designs: 200 nm n-GaN (doping ~5E18) on 2 µm GaN:C

Working GaN Field Emission Devices

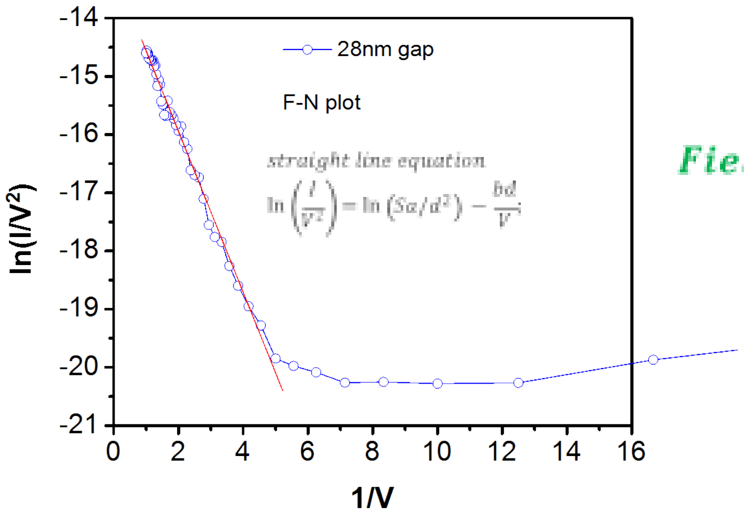
Successful field emission (FE) in air with low turn on voltage and high emission current!

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

Field enhancement factor
$\beta = 920$ for $= 4\ eV$

Sapkota, Keshab R., et al. "Ultralow voltage GaN vacuum nanodiodes in air." *Nano Letters* 21.5 (2021): 1928-1934.

Very low turn on and very high FE current!

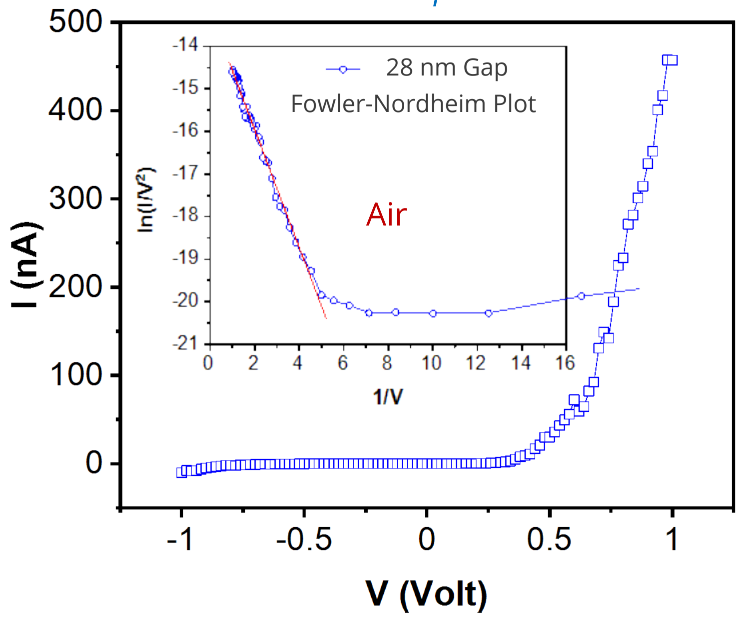
Effect of Emitter Size on Field Emission

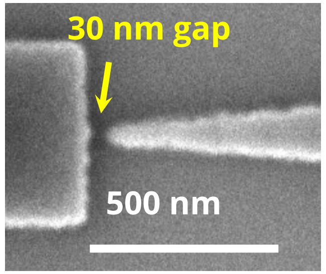
Sharper emitter is desired for low voltage field emission
- Increases field enhancement
- Reduces the device turn on voltage

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

β ➔ Field enhancement factor, depends on geometry

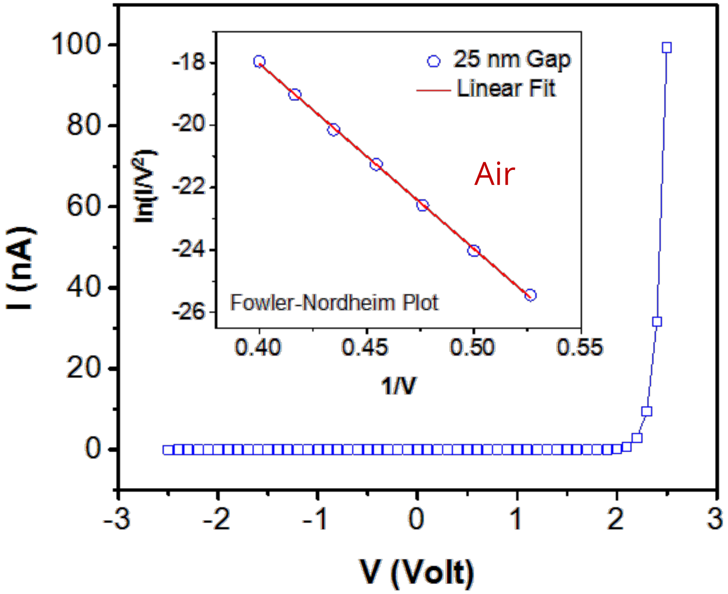
Emitter r_{tip} = 17 nm

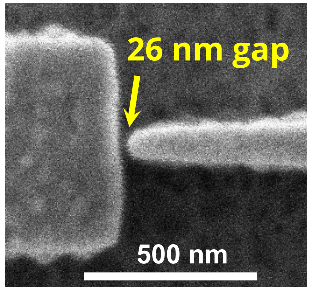




- Field enhancement factor (β) = 920
- Turn on voltage = 0.24 V @ 50pA

Emitter r_{tip} = 31 nm



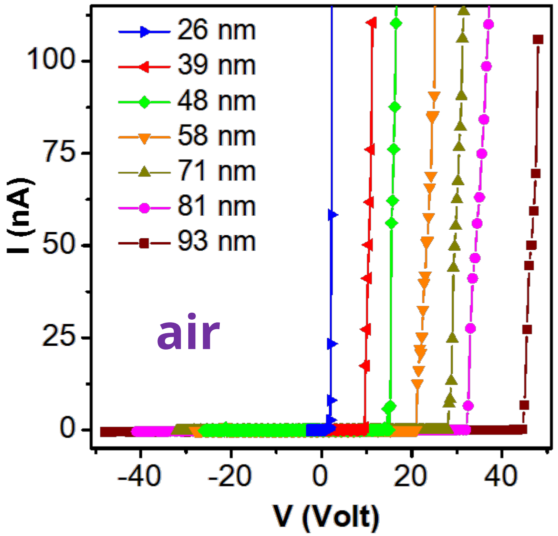


- Field enhancement factor (β) = 32
- Turn on voltage = 1.9 V @ 50pA

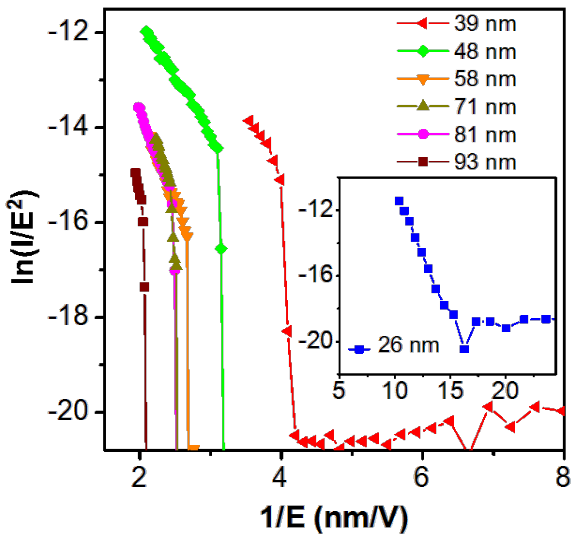
Nanogap Size Dependency of the Field Emission

Devices with various nanogap sizes were fabricated

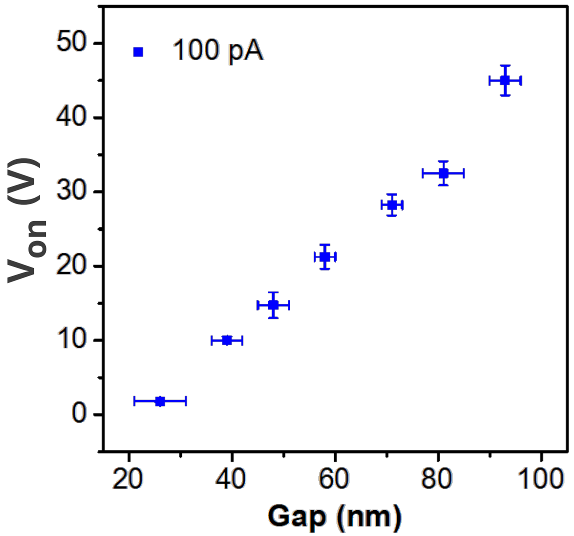
- Emitter tip radius ~ 30 ± 2nm
- Field emission observed **<u>in air</u>** (atmospheric pressure) with gap size as large as 93 nm
- IV data for different nanogap sizes can be explained by Fowler-Nordheim field emission
- Turn-on voltage depends linearly with nanogap size
- Field enhancement factor decreases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



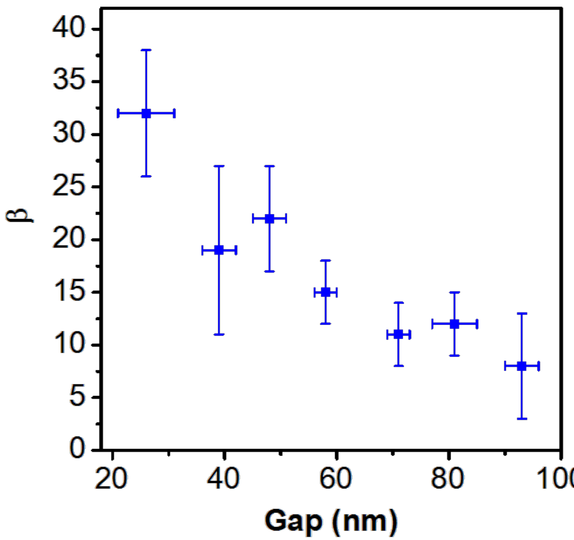
Field emission for various nanogaps



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)*

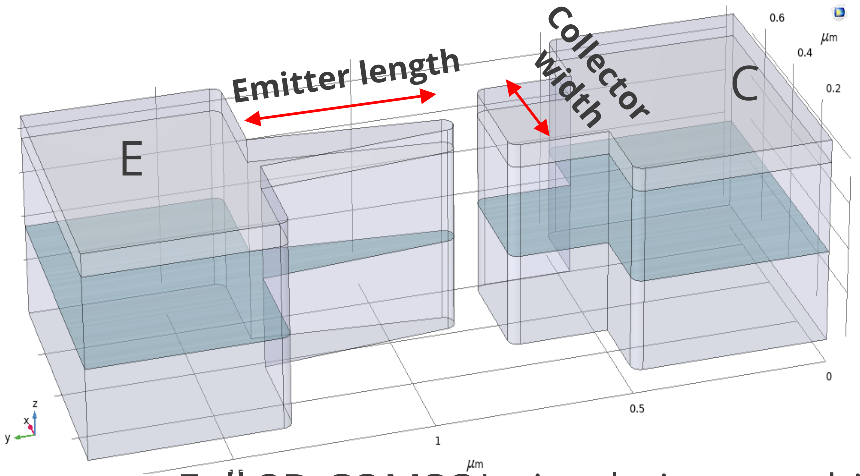
Optimization of GaN VED: 3D Simulation

- Developed 3D COMSOL model to simulate field emission current as a function of various device parameters

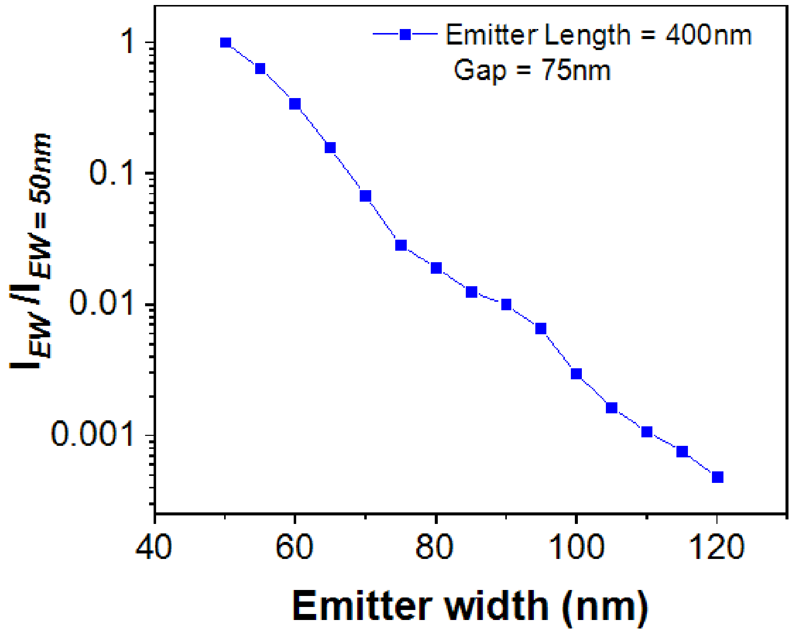
Electric field: $\boldsymbol{E} = \nabla V$

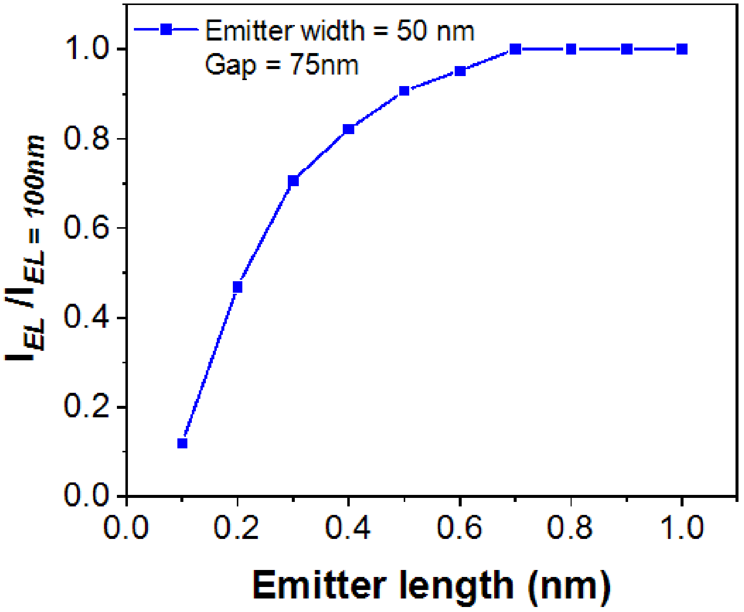
Poisson's Equation: $\nabla.(\epsilon_o \epsilon_r \boldsymbol{E}) = \rho_v$

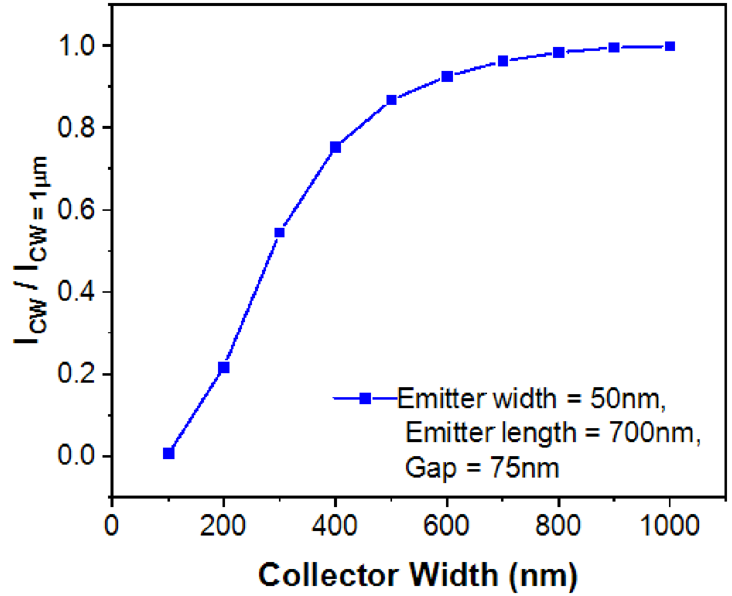
Fowler Nordheim equation: $I = A\left(\frac{\beta^2 V^2}{\phi d^2}\right)\exp\left(-\frac{B\phi^{3/2} d}{\beta V}\right)$



Full 3D COMSOL simulation capability

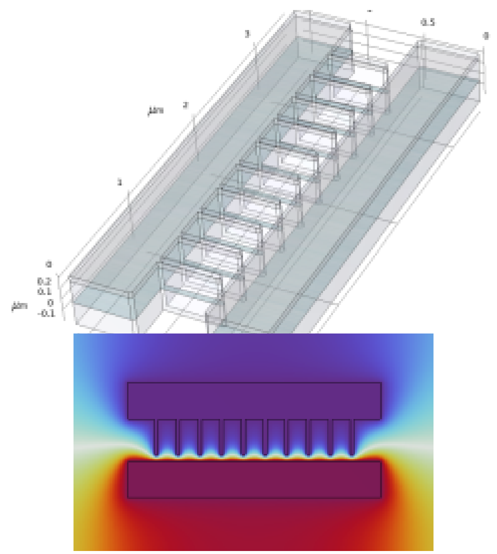




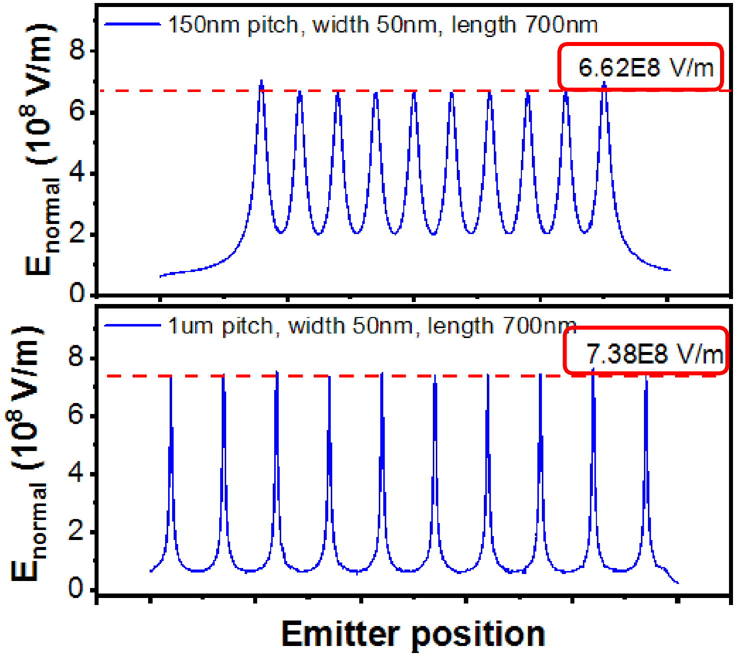


Designing array of diodes: Electric field screening effect

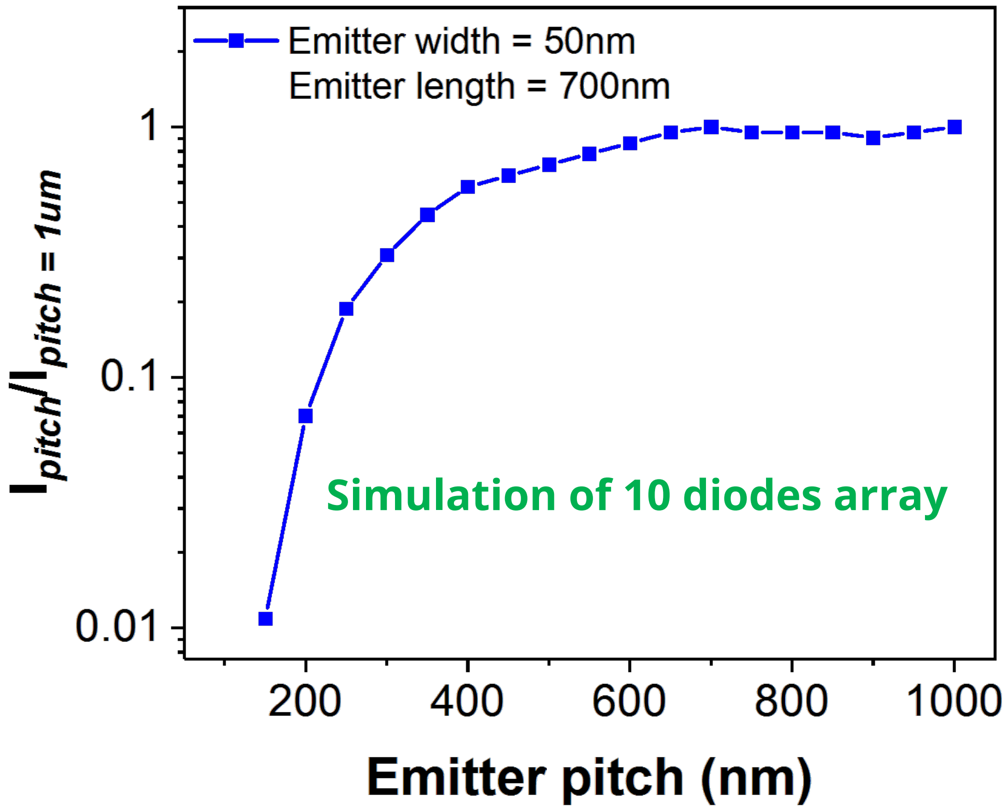
- Array of diodes suffer from the electric field screening due to presence of neighboring emitters
- Field emission current is significant impacted for short emitter periodicity (emitter pitch).
- Optimal design: emitter pitch ≥ 500nm for current emitter geometry



3D model of 10 diodes array



Electric field screening: field at the tips for 150nm and 1um pitch



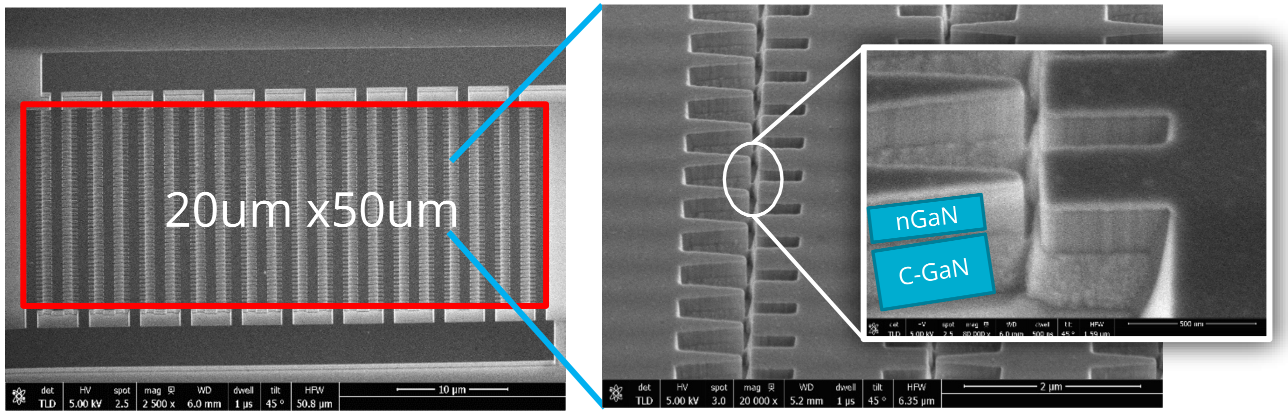
Field emission current at various emitter pitch

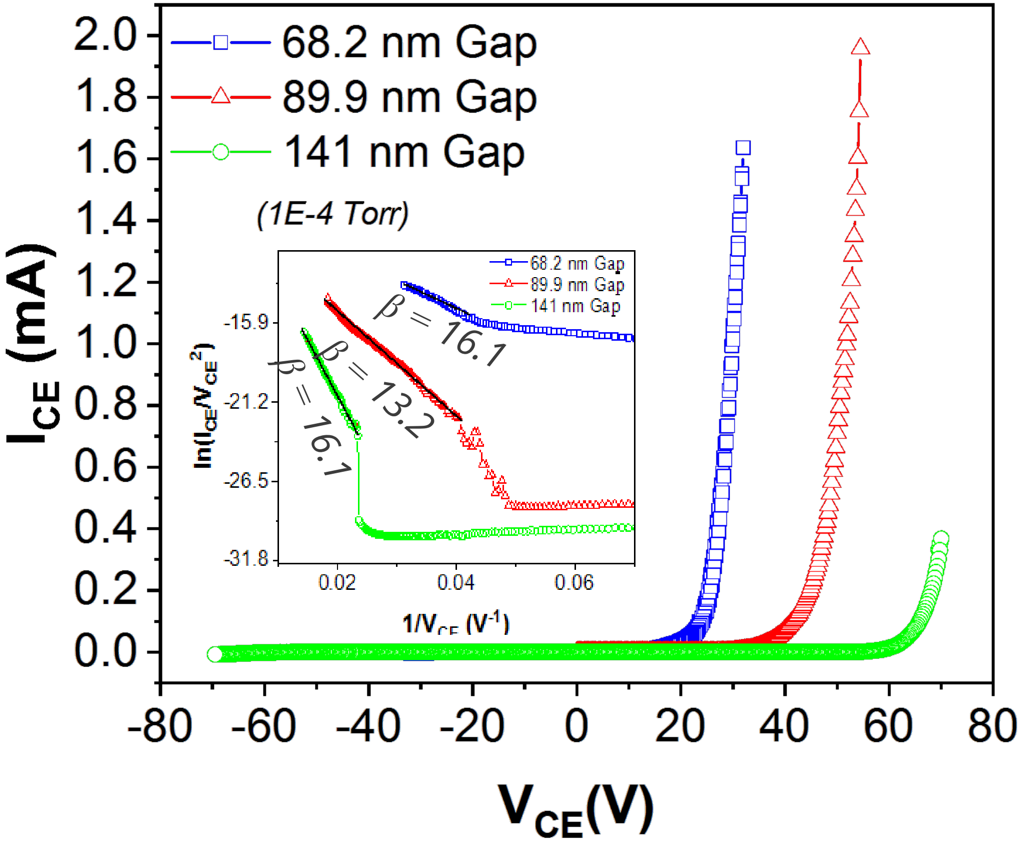
Diode arrays for achieving milliamps of field emission current

- Typical rating of GaN emitter: 1uA/emitter
- Fabricated 1000 FE diodes in 20um x 50um area
- Diodes are operated in parallel

Record high current density = 171 A/cm^2

Previous record[1] of 100A/cm^2 for semiconductor field emitters





Field emission current from 1000 diodes array

Further optimization of arrays can significantly improve the field emission current density

[1] Guerrera, *IEEE ELECTRON DEVICE LETTERS, VOL. 37, NO. 1 (2016)*

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
- Developed 3D COMSOL model and optimized the GaN nanoscale vacuum electron diode (NVED) device by simulated field emission current as a function of various device parameters
- For optimal field emission: a wide collector and a long and narrow emitter are desired
- 3D simulation of array of GaN NVED revealed that dense array of field emitters suffer from electric field effect
- We experimentally demonstrated field emission current up to 2mA from 1000 diodes and record high current density of 171 A/cm^2