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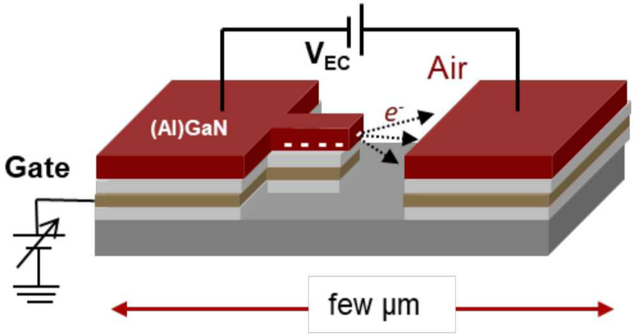

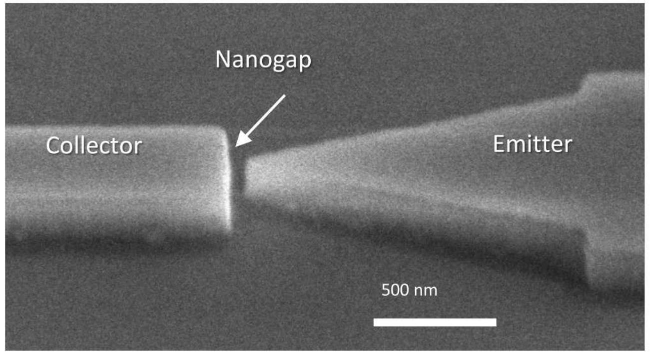

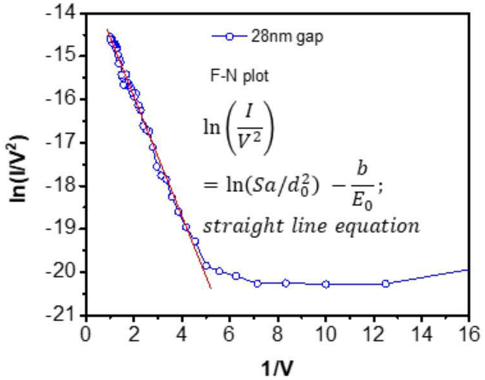

Field Emission Characteristics of Solid-State, GaN-Based Vacuum Nanoelectronic Devices

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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!

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- 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

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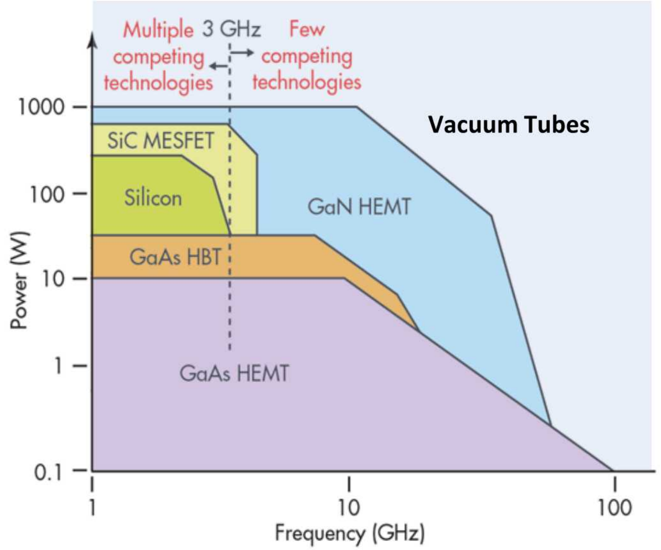
Advantages of vacuum electron devices

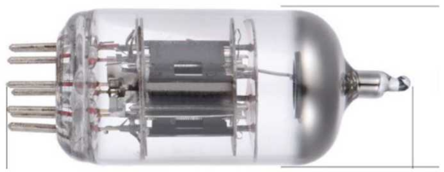
- **Ballistic transport in vacuum channel:**
- **No heat generation** during electron transport in vacuum
- **No dielectric breakdown** (Dielectric strength = 10^{18}V/m)
- Operation in **harsh environments (radiation, temperature)**: no junction, vacuum channel unaffected
- As a result, vacuum devices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

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

High power, high frequency



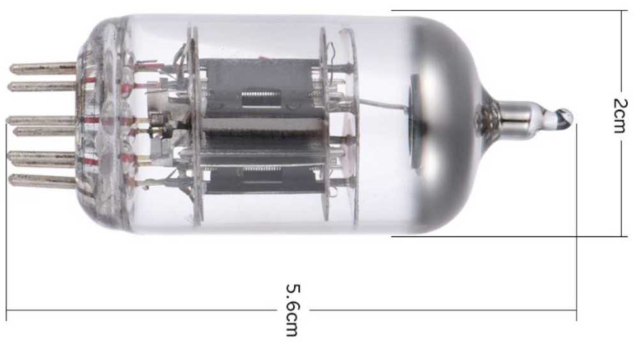
Source: http://www.electronicdesign.com/power/optimize-power-scheme-these-transient-times



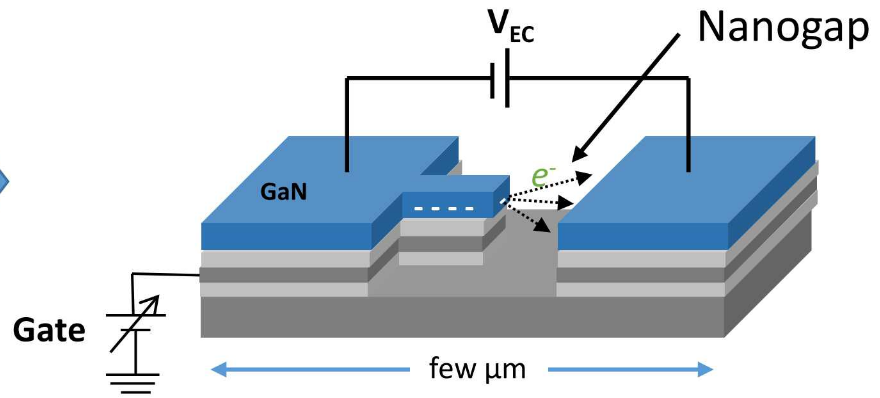
Solid-State, Vacuum-Free "Vacuum" Electronics

- ✓ 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 devices and semiconductor nanofabrication

GaN: Superior Platform for Vacuum Nanoelectronics

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Major Challenges for Vacuum Nanoelectronics

1. Difficult to get low voltage field emission

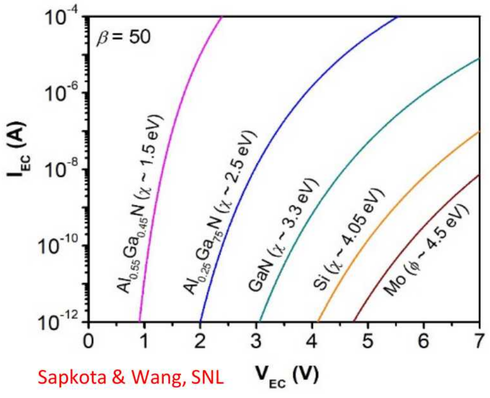
Fowler-Nordheim (FN) equation

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

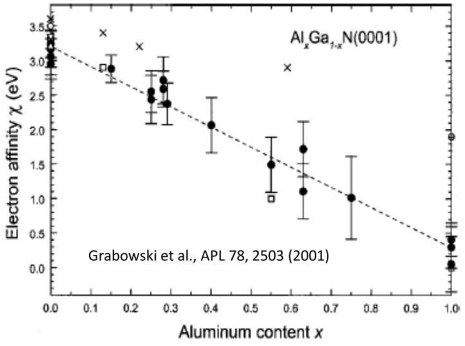
φ ➔ work function;

$\varphi \sim \chi$ (electron affinity) for n-doped semiconductor

GaN: low χ ➔ Low voltage field emission



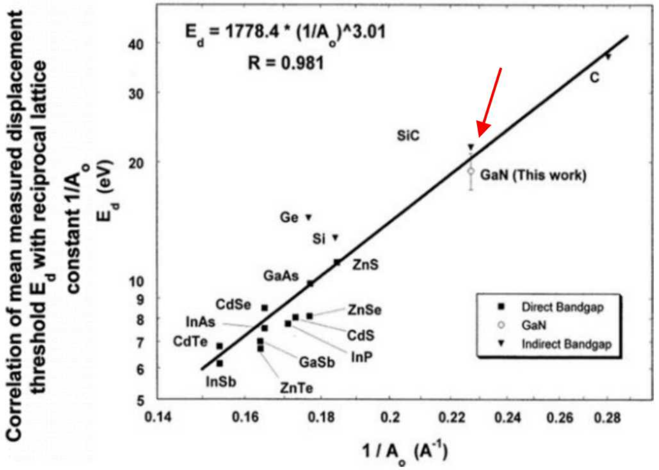
Sapkota & Wang, SNL



2. Device degradation/chemical instability

GaN has significantly higher bond strength

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

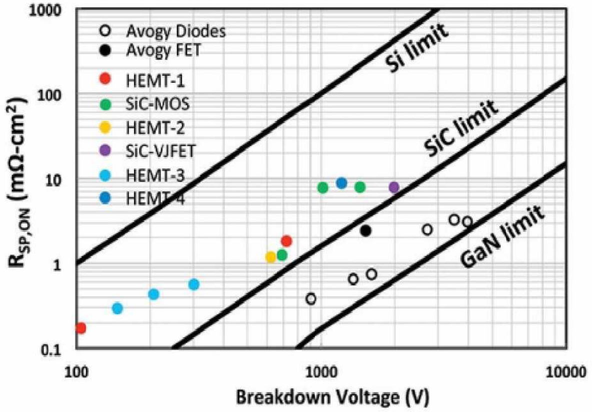


Source: Nedelcescu et al., IEEE Nuclear Science (2002)

3. High Power Operation

GaN has High Breakdown Field

- ✓ High power operation
- ✓ High frequency operation

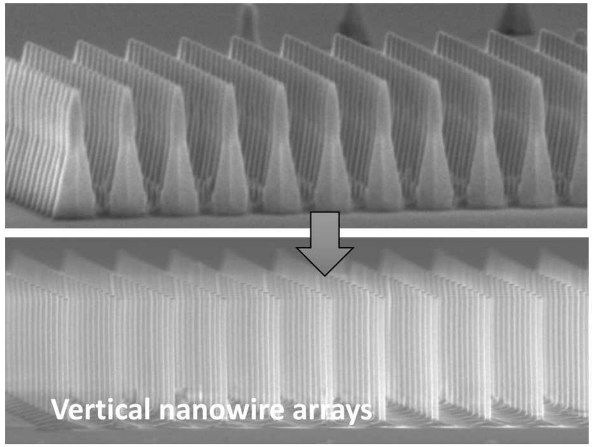


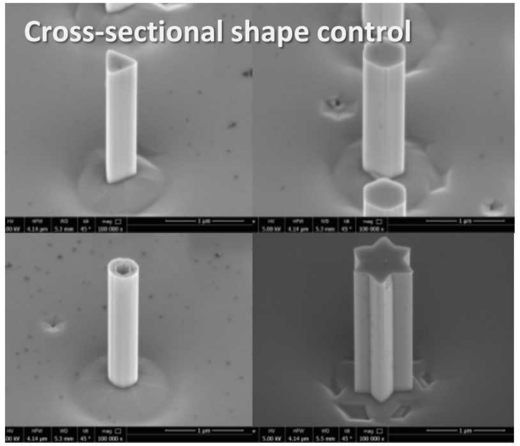
Source: https://compoundsemiconductor.net/article/98990

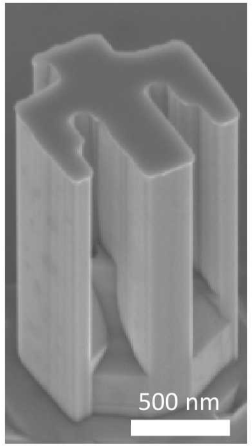
Enabling Sandia Capability: 3D GaN Nanofabrication

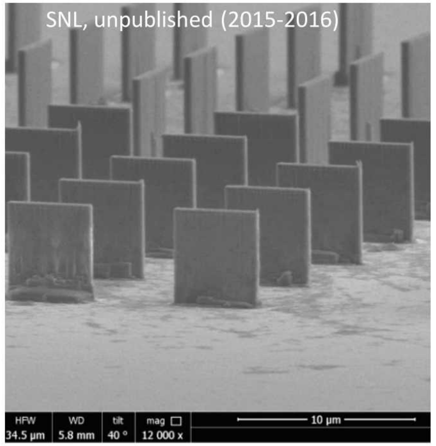
World-leading capabilities for the top-down fabrication of 3D, high quality, GaN-based nanostructures

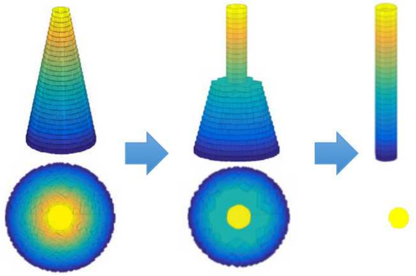
GaN vertical etch



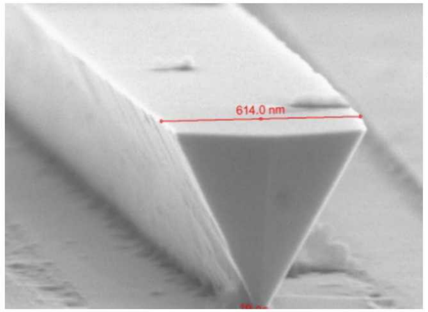






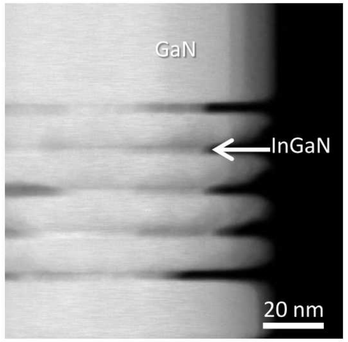


Simulation of facet etch evolution



Sharp emitter geometry for enhanced field emission

GaN undercut etch



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

(In)GaN lateral etch

Nanofabrication of GaN Lateral Field Emission (FE) Structures

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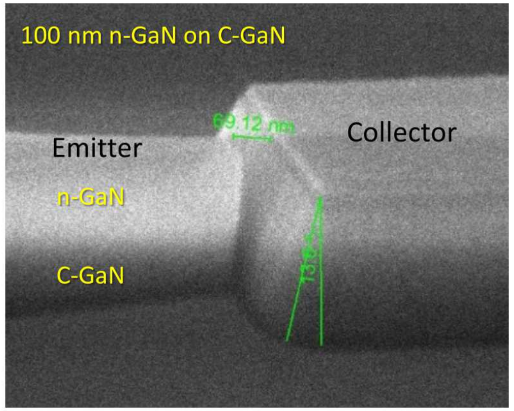
III-N top-down fabrication process

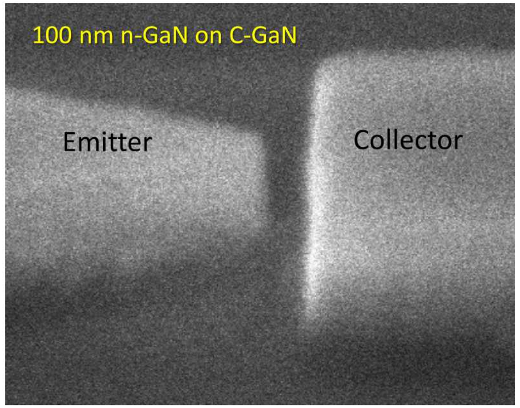
Electron Beam Lithography → Dry Etching (ICP/RIE) → Wet Etching (KOH

From knowledge of KOH wet etching of GaN:

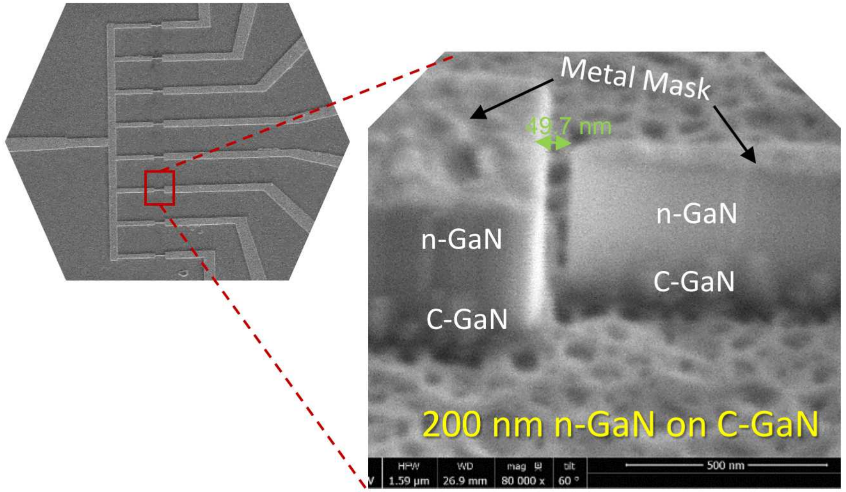
- Orient collector // to m-plane to avoid m-plane microfacet protrusions
- Limit wet etch time to reduce wedge retraction effect
- consider dependence of wet etch on doping and composition (GaN v. AlN)



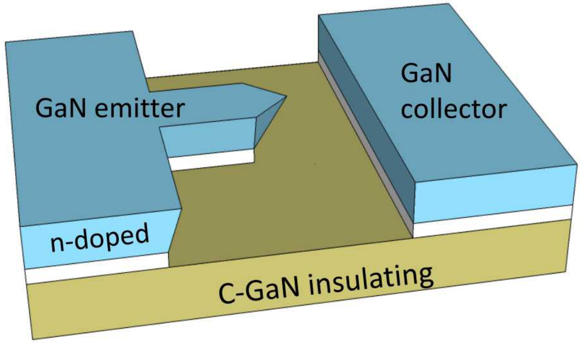
<u>ICP dry etch</u>: Angled side walls – variable gap size, possible shorting at bottom, sidewall damage

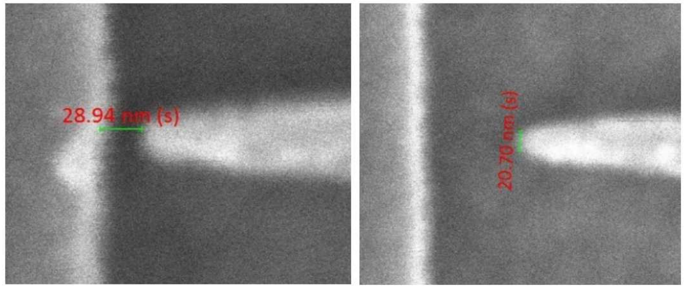


<u>+ AZ400K wet etch</u>: Vertical side walls, cleared gap, remove sidewall damage, smoother m-face collector



Epilayer designs: 100nm and 200 nm n-GaN on C-GaN, doping ~5E18





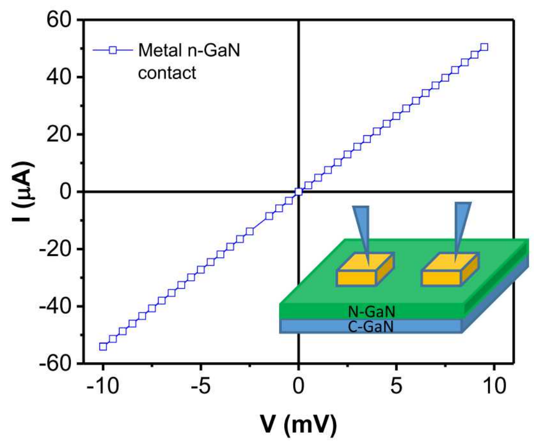
GaN structures down to ~30 nm gaps and ~20 nm wide emitters

Working GaN Field Emission Devices

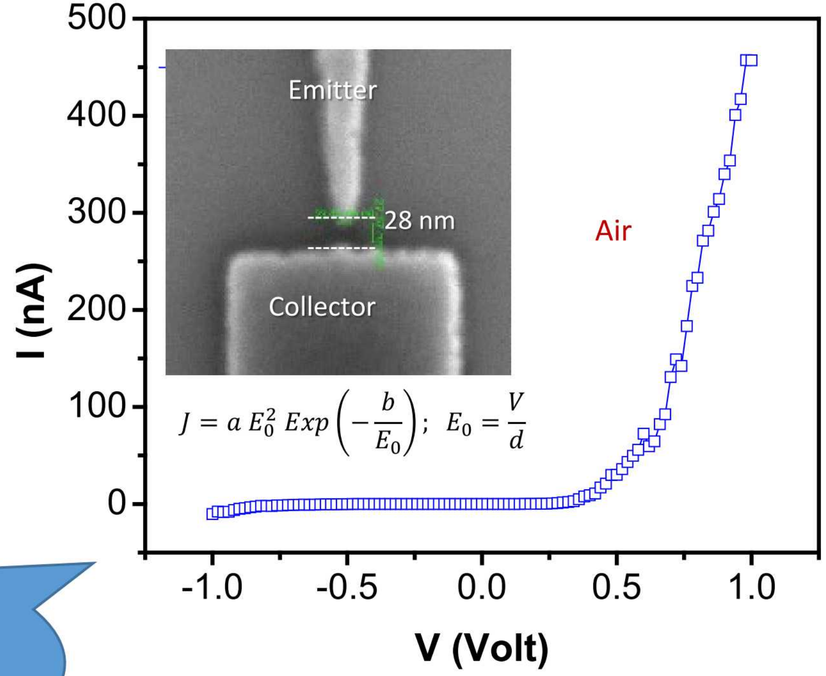
Proof-of-concept: Successful field emission (FE) in air with low turn on voltage and high emission current!

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

Ohmic contacts to n-GaN (Ti/Ni/Au)

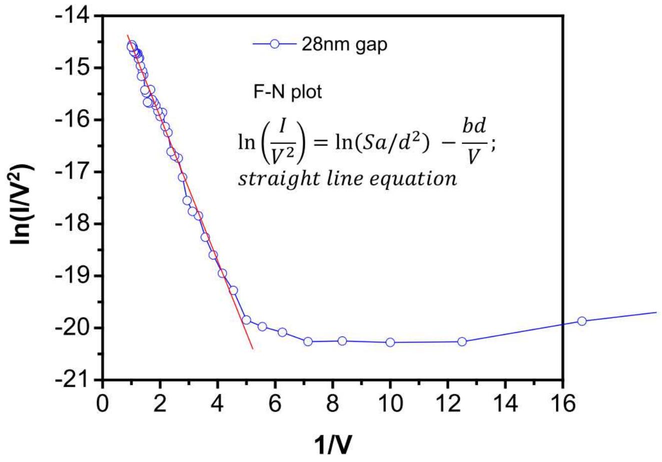


Device Geometry:
Gap = 28nm
Emitter tip width ~ 20nm



IV measurement: **Diode** characteristics

"Hero" device shows very low turn on and very high FE current!



Fowler-Nordheim (FN) test for field emission

Straight line fitting of data
Slope = -1.40; Y-intercept = -13.16

$$\boldsymbol{Field\ enhancement\ factor\ \beta = 920\ using\ \phi = 4\ eV}$$

Effect of Emitter Size on Field Emission

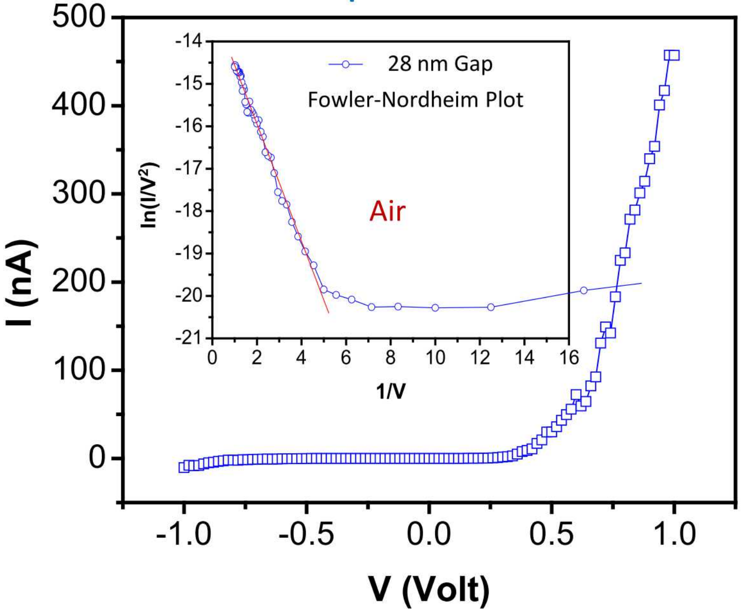
Sharper emitter is desired to low voltage field emission

- Increases field enhancement
- Reduces the device turn on voltage

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

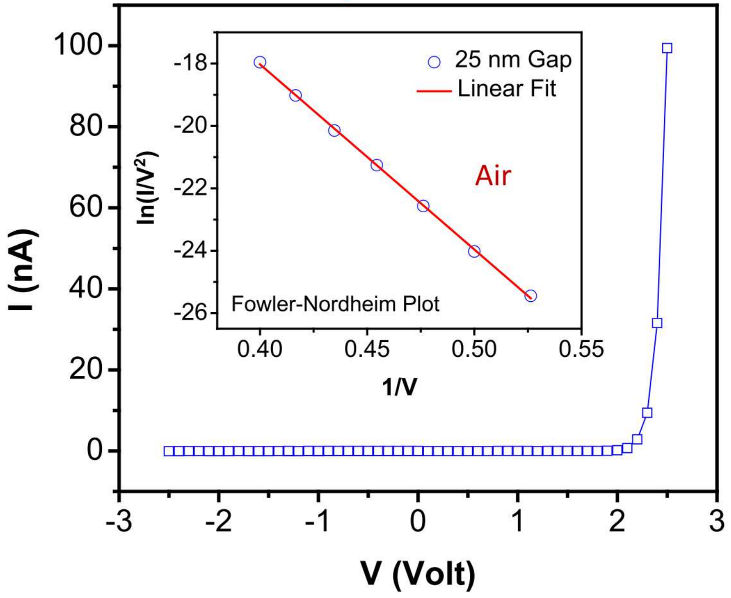
β ➔ Field enhancement factor, depends on geometry

Emitter tip width ~ 20 nm



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

Emitter tip width ~ 50 nm



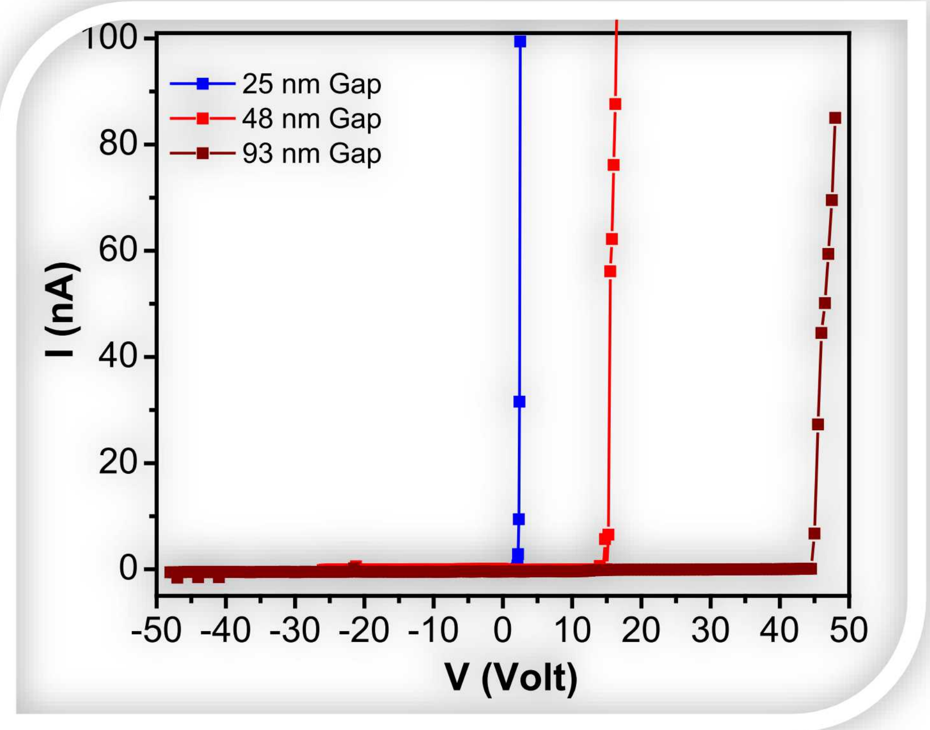
- Field enhancement factor (β) = 32
- Turn on voltage = 1.9 V @ 50pA

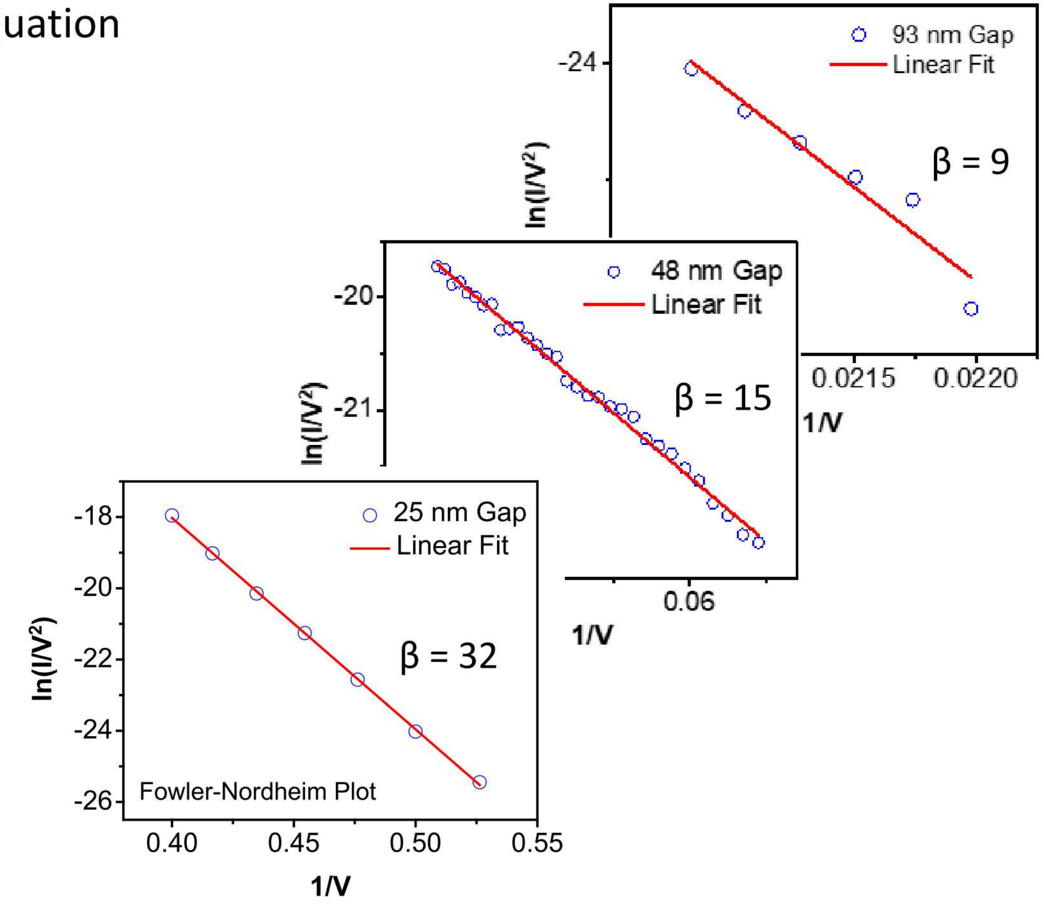
Nanogap Size Dependency of the Field Emission

Devices with various nanogap sizes were fabricated

- Emitter tip width ~ 50nm
- Field emission observed **in air** (atmospheric pressure) with gap size as large as 93 nm
- IV data can be fitted with the Fowler-Nordheim field emission equation
- Turn-on voltage increases with increasing gap size

Diode characteristics of nanogap devices





Effect of Pressure on Nanogap Field Emission

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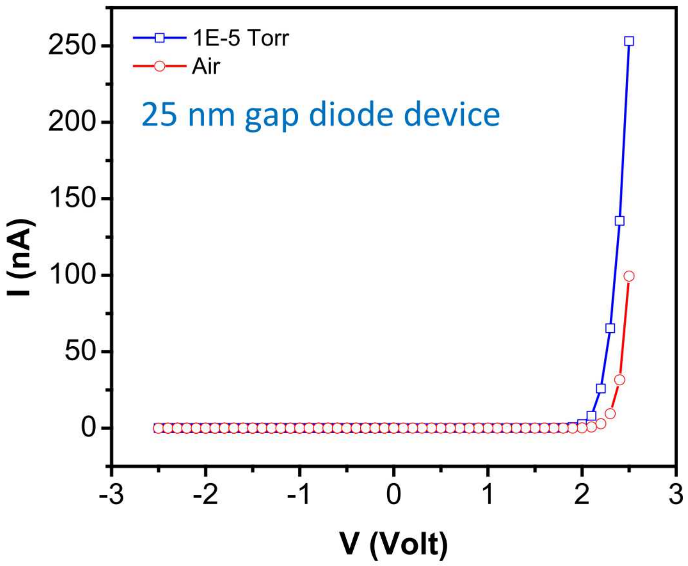
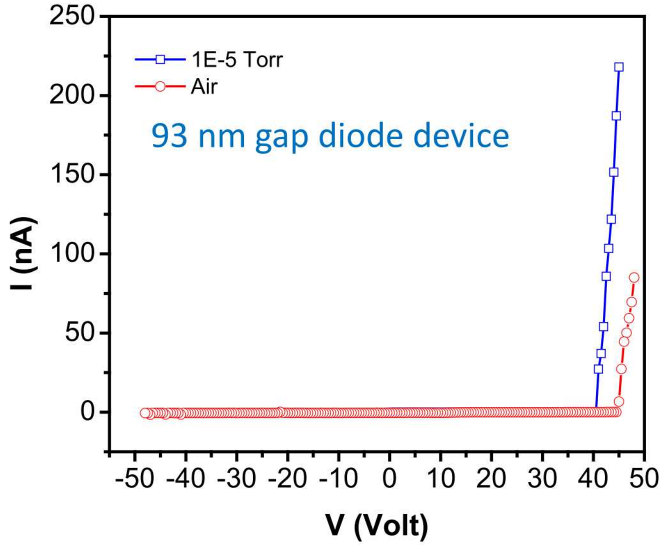
Established convention: nanogap is vacuum-like if nanogap size << electron mean free path
Does pressure affect field emission of nanogap device?

This experiment establishes

- Vacuum is not required to achieve field emission in nanogap device
- *However, field emission is affected by pressure*
- Pressure generally decreases field emission current and increase turn on voltage
- Overall pressure dependent behavior depends on gap size, gas species, and bias voltage (> gas ionization energy?)





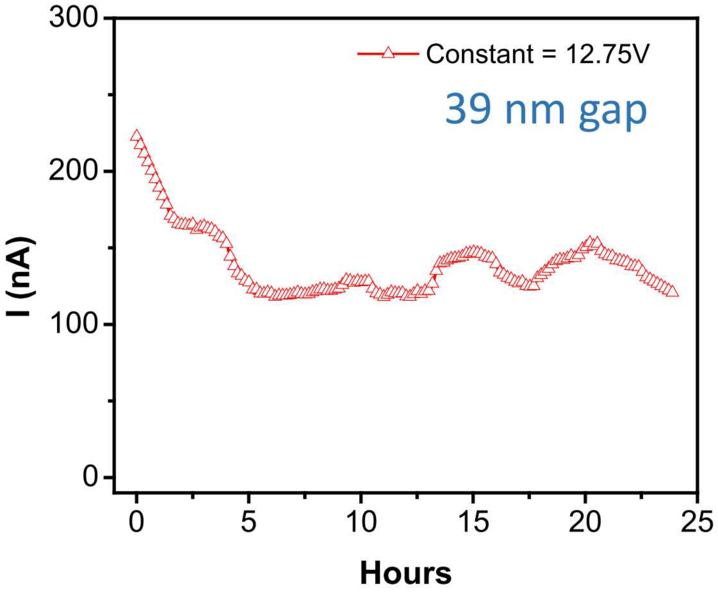
GaN Nanogap Devices Stability Check

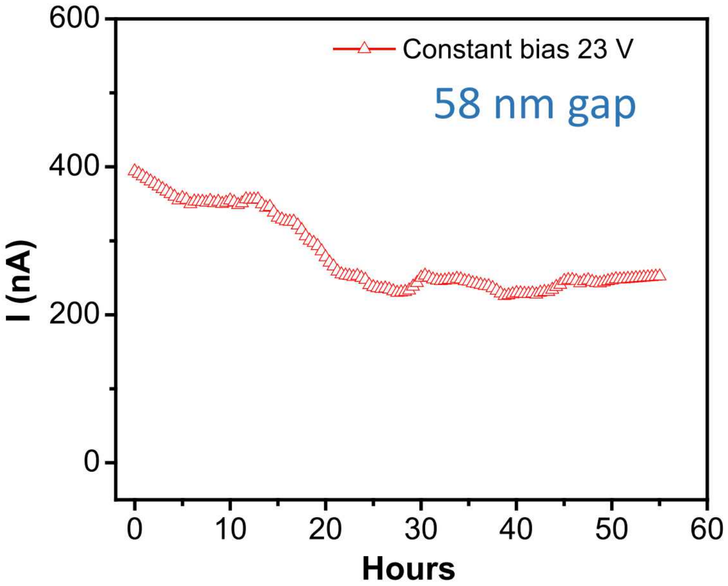
Stability measurement:

- Time dependent measurements were carried out by applying constant bias for several hours
- Devices sitting in ambient environment for several days prior to measurements

Results

- Devices performed well for more than 55 hours during continuous measurement
- Devices exhibit excellent field emission behavior after long continuous measurements





P ~ 1e-5 Torr

GaN nanogap field emission devices are highly stable and resilient against environment

Conclusions

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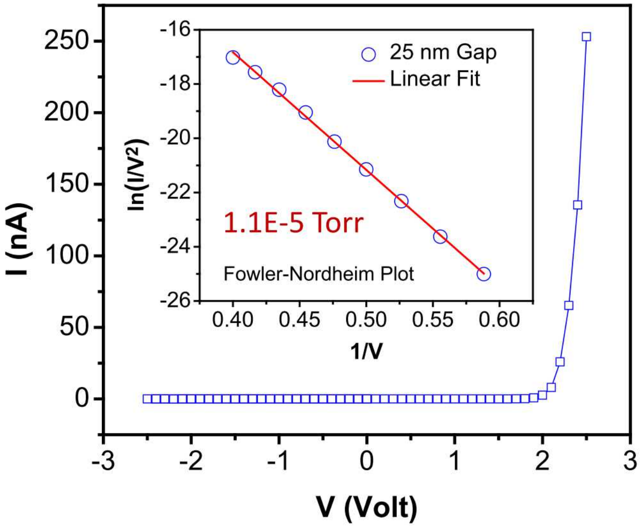
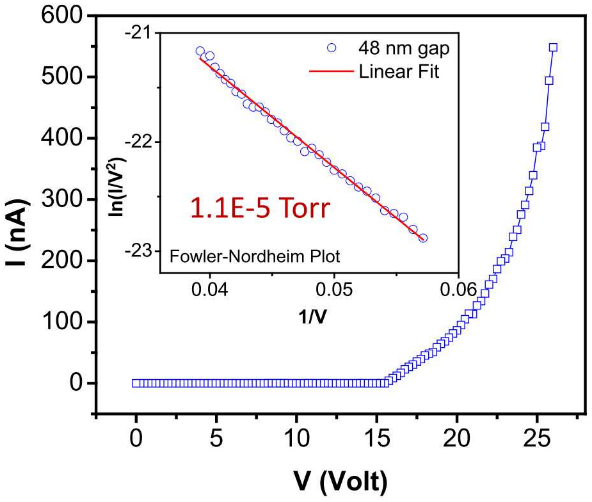
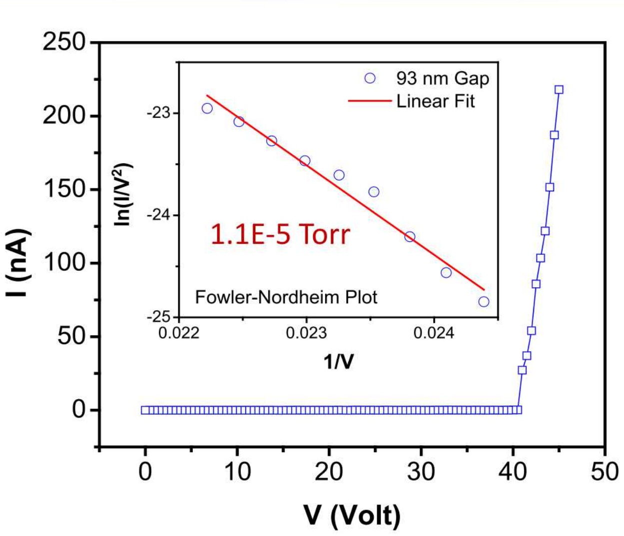
- All GaN-based nanogap field emission diode devices were successfully demonstrated for the first time
- Low turn-on voltage down to 0.24 V is achieved with high field emission current for 28nm gap, ~20 nm radius sharp emitter tip device
- The field emission characteristics can be well explained by Fowler-Nordheim equation
- Nanogap size dependent field emission characteristics are studied: turn-on voltage and constant current bias potential increase linearly with nanogap size
- If nanogap size << electron mean free path, field emission in nanogap device can be achieved in air, however, field emission is affected by gas environment and pressure
- GaN nanogap devices are found to be highly stable, surviving for several days of continuous operation

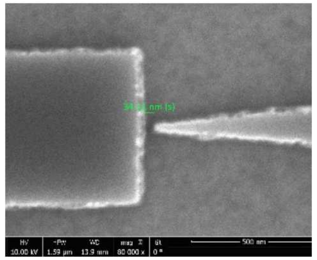
Back up slides

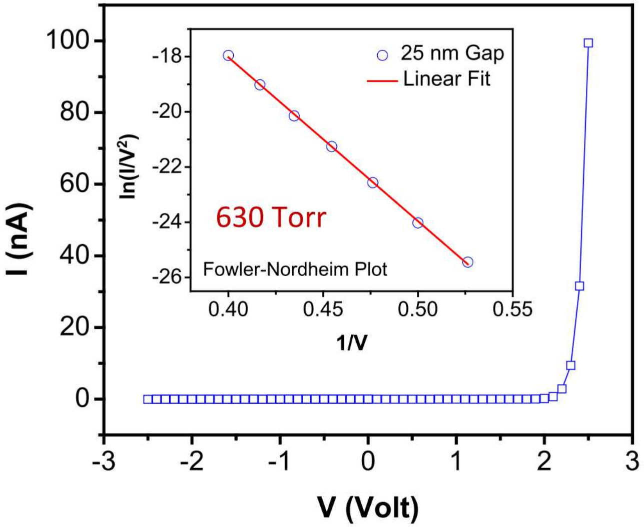
Working GaN Field Emission Devices

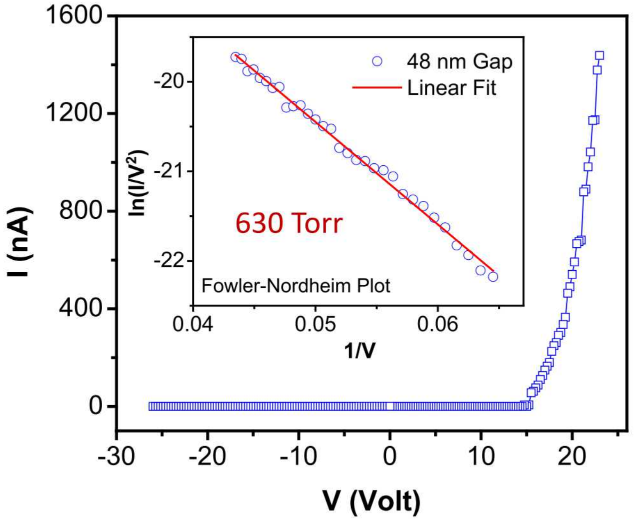


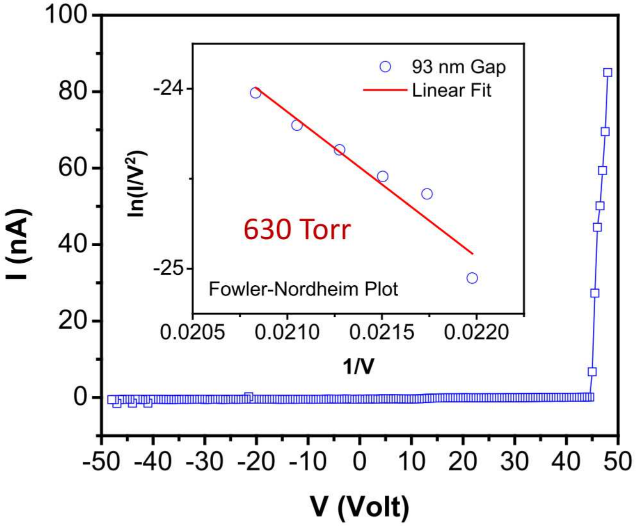


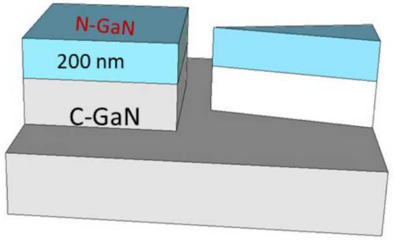












Nanogap Size Dependency of the Field Emission

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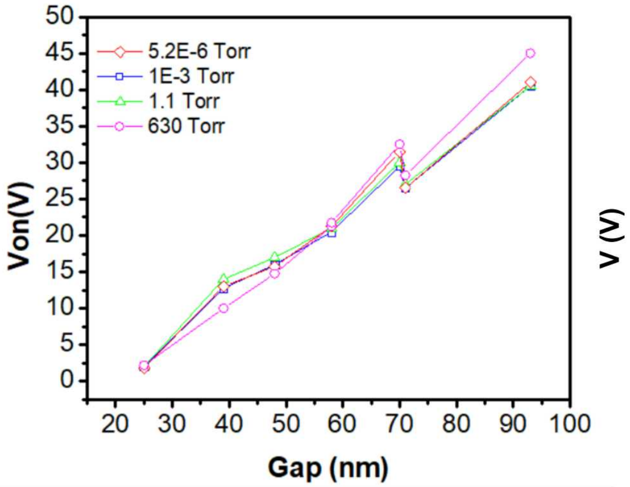
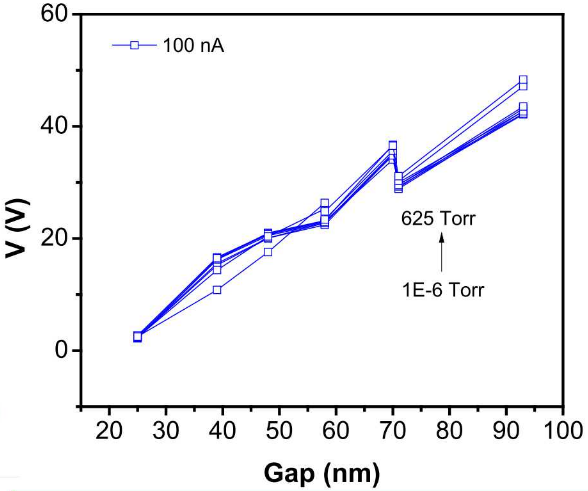
Experimental Results

- Device turn on voltage increases linearly with nanogap size
- Bias voltage needed to produce a fixed field emission current increases linearly with nanogap size



Nanogap size dependent turn on voltage (Von)



Nanogap size dependent bias (V) for fixed field emission current

Simulation Results

Fowler-Nordheim equation can be written in linear form

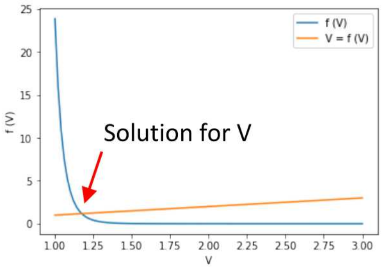
$$\ln\left(\frac{Id^2}{V^2}\right) = A + B\frac{d}{V}$$

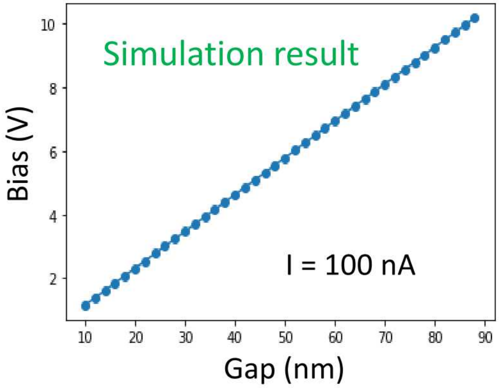
Here, A and B are constants which can be obtained by linear fitting of field emission data, d is nanogap size

- Solve V for I and d:

  $V = d\sqrt{I} * e^{\left(A+\frac{Bd}{V}\right)/2} \Rightarrow V = f(V)$

- V can be solved numerically





Bias voltage linearly depends on the gap size for fix field emission current

Experimental results satisfy nanogap size dependent Fowler-Nordheim type field emission