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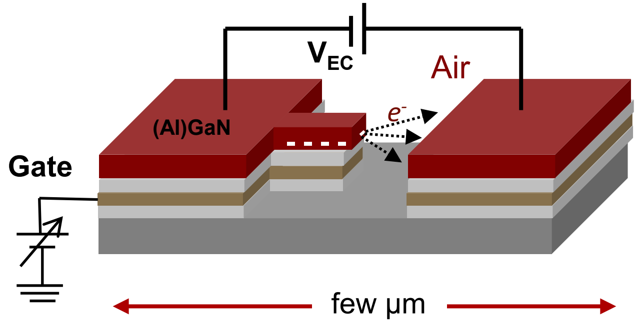

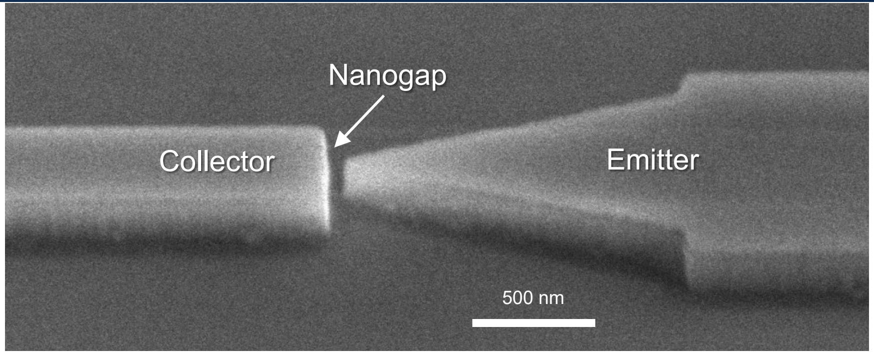

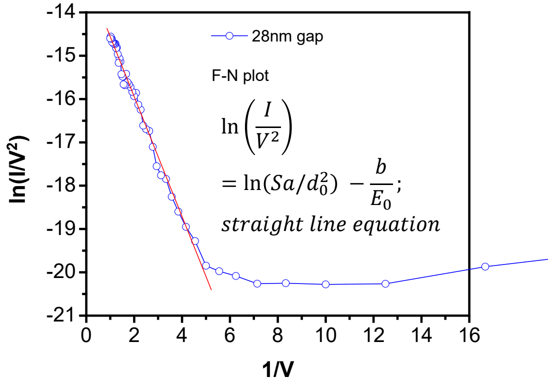

On-chip, Ultra-Low Voltage GaN Vacuum Nanoelectronics

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

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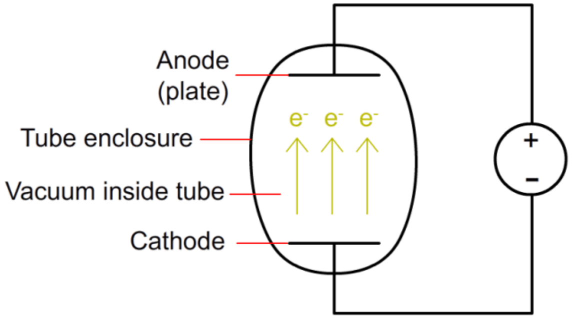
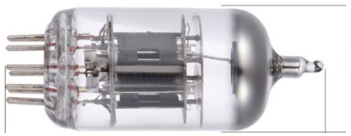
Vacuum Electron Devices (VEDs)

- Silicon solid state devices began to replace vacuum tubes > 60 years ago
- But vacuum electron devices (magnetrons, traveling wave tubes, klystrons, etc.) have distinct advantages and are still in use!
  - **Communication:** Radar, RF broadcasting
  - **NASA:** Satellite communications, electronics for space missions
  - **Commercial/Industrial:** Microwave ovens, CRTs, industrial RF heating, THz technologies, Microwave electronic applications

Vacuum electron device diagram



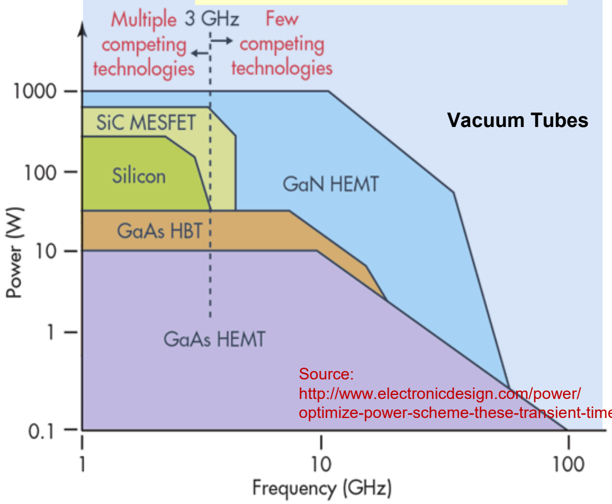


https://www.engineering.com/ElectronicsDesign/ElectronicsDesignArticles/ArticleID/16337/Vacuum-Tubes-The-World-Before-Transistors.aspx

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



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

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

"Integrated" on-chip vacuum electron devices

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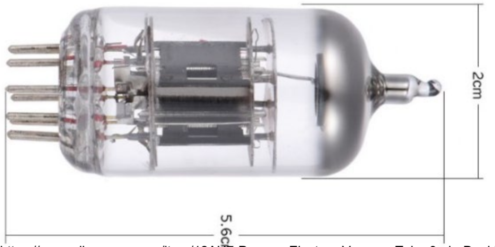
GOAL: Combine advantages of vacuum & semiconductor devices

Vacuum: high frequency/power, radiation hardness, high temperature

Vacuum tube

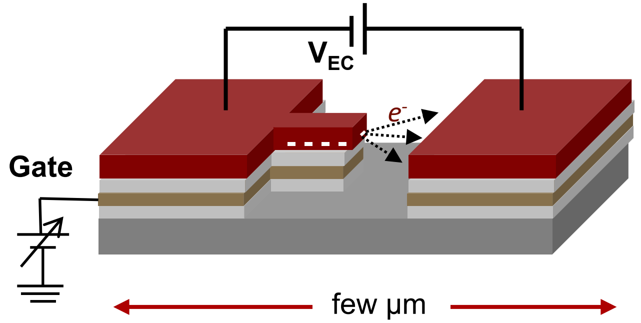


https://www.aliexpress.com/item/12AU7-Preamp-Electron-Vacuum-Tube-9-pin-Dual-Triode-for-ECC82-6189-5963-5814-Tube-Replacement/32796854172.html

?

Semiconductor: size, integration, energy efficiency, cost, reliability

Solid-state "vacuum" electron device



~1980s-1990s: Microfabricated Si vacuum microelectronics

- Microfabricated Si or W/Mo tip arrays ("Spindt tips") on a wafer, **cold field emission** for lower power consumption
- **Limitations: high vacuum requirement, high turn-on voltages (e.g. ~100 V) & low currents (high work function materials), emitter degradation**

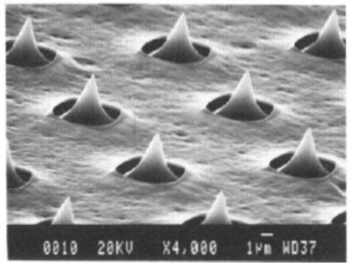
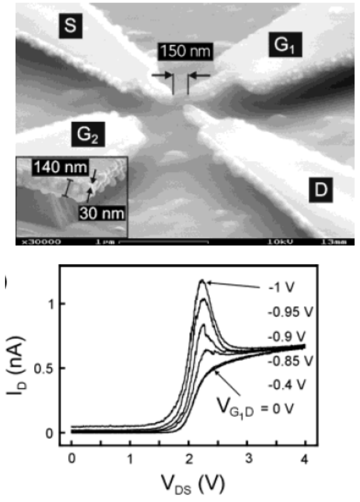


Figure 31. SEM micrograph of silicon tip emitters with maximum recess of the gates using the process of figure 29.

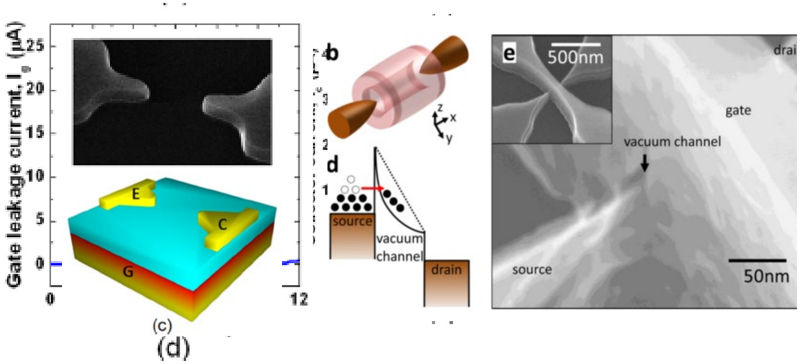
Betsui K 1991 Fabrication and characteristics of *Si* field emitter arrays *Technical Digest 4th Int. Vacuum Microelectronics Conf. (Nagohoma Japan)* p 26

Nanogap Vacuum Nanoelectronics (~2012-present)

- **Nano-scaling** of cathode-anode gap/channel (e.g. < 200 nm)
- Enhancement of local electric field: **reduction of operating voltage and emitter sharpness requirement**
- **Operable in air:** vacuum channel < mean free path of electron in air (~500 nm)

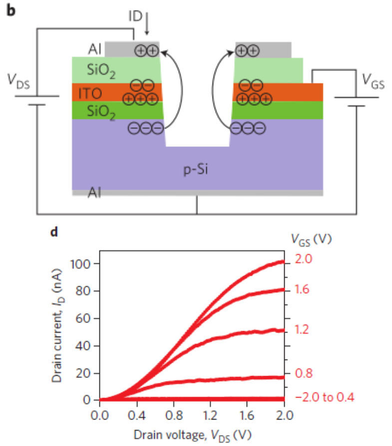


Lateral field-emission triode at atmospheric pressure on SOI
Pescini et al., Adv. Mat. (2001)

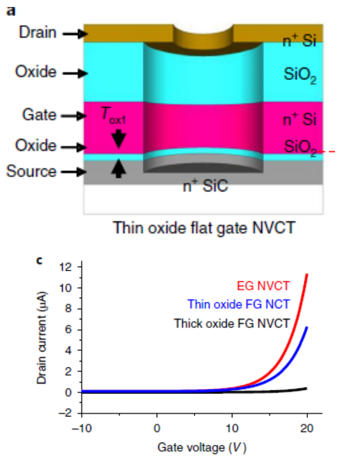


Lateral back-gate-insulated & surround gate nano vacuum channel transistor
Han et al., APL (2012), Han et al., NL (2017)

- NASA: vacuum-free "vacuum" Si transistor with estimated cutoff frequencies to **460 GHz** (2012)
- Operating V < 5, I > 3 uA (2017)



Vertical nano-void vacuum channel FET on Si
Srisonphan et al., Nat. Nanotech. (2012)



Vertical SiC vacuum channel transistors
Han et al., Nat. Elec. (2019)

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

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

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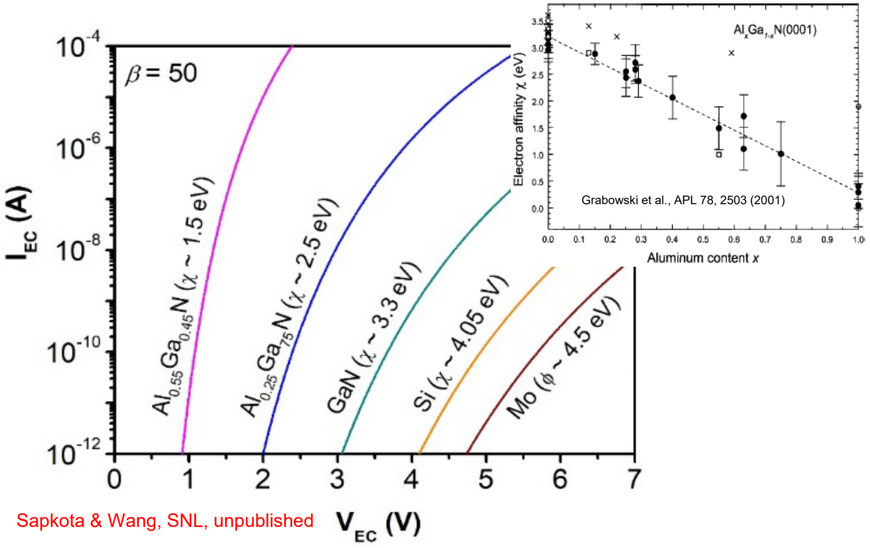
1. Low voltage field emission

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;
φ ~ χ (electron affinity) for n-type semiconductor

GaN: low χ ➔ Low voltage field emission

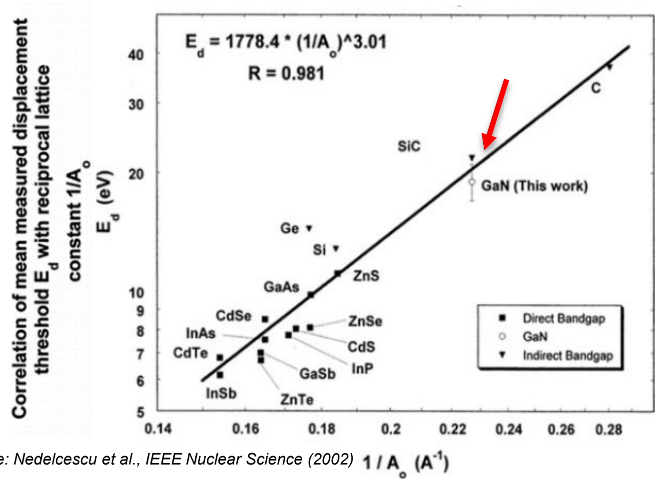


Sapkota & Wang, SNL, unpublished

2. Stability and reliability

GaN has significantly higher bond strength than Si

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

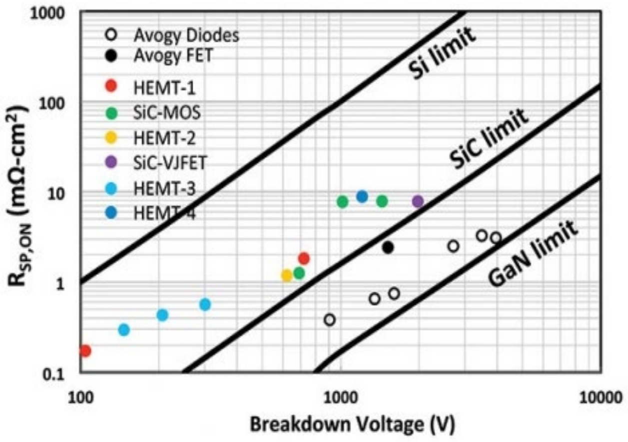


Source: Nedelcescu et al., IEEE Nuclear Science (2002)

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



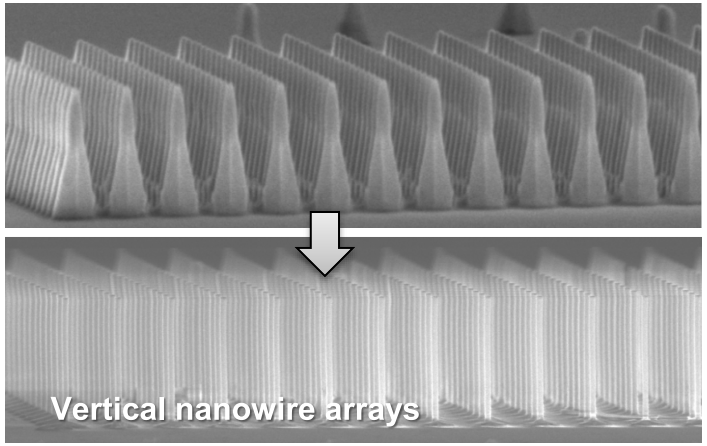
Source: https://compoundsemiconductor.net/article/98990

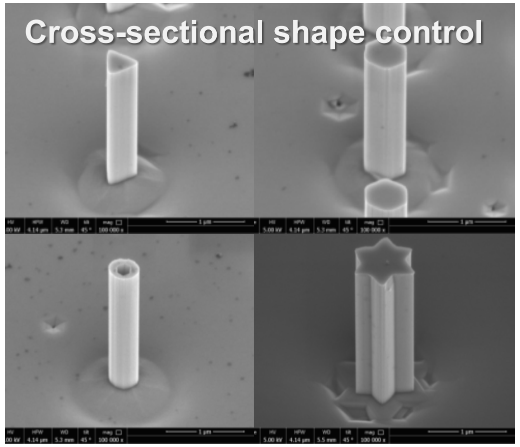
4. Mature & scalable materials & device platform (commercial UV-visible, LEDs, lasers)

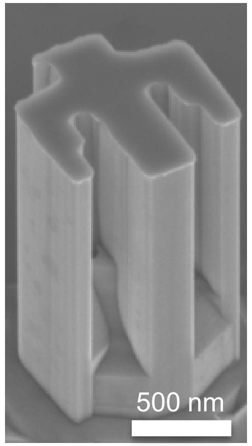
Enabling Capability: Top-Down 3D GaN Nanofabrication

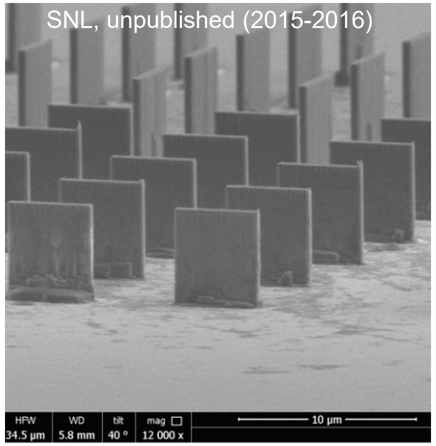
High quality, smooth & damage-free GaN-based nanostructures

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

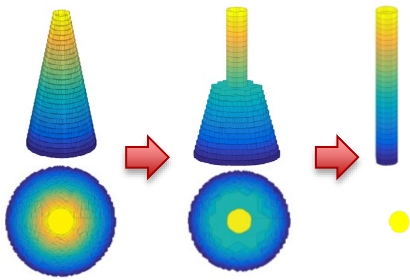






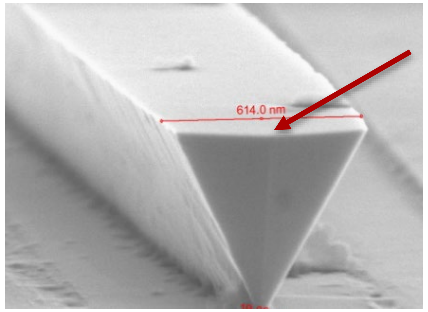


Simulation of facet etch evolution



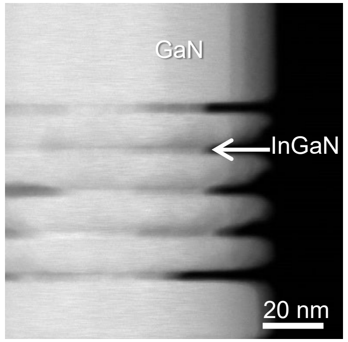
Q. Li et al., *Optics Express* **19**, 25528 (2011)
Q. Li et al., Opt. Exp., **20**, 17873 (2012)
Li, Changyi, et al., *Nanoscale* ***8***, 5682 (2016). …etc.

GaN undercut etch



Sharp emitter geometry for enhanced field emission

(In)GaN lateral etch

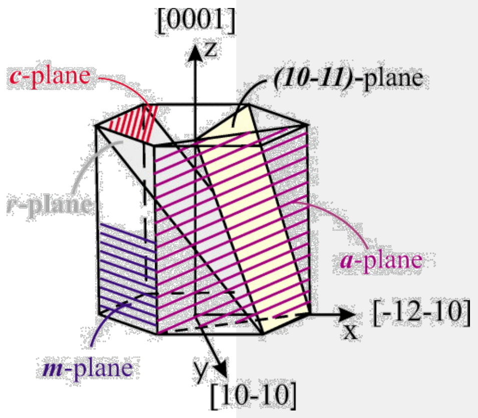


Selective removal of quantum wells allows for **ultrathin** vertical nanogap vacuum channel

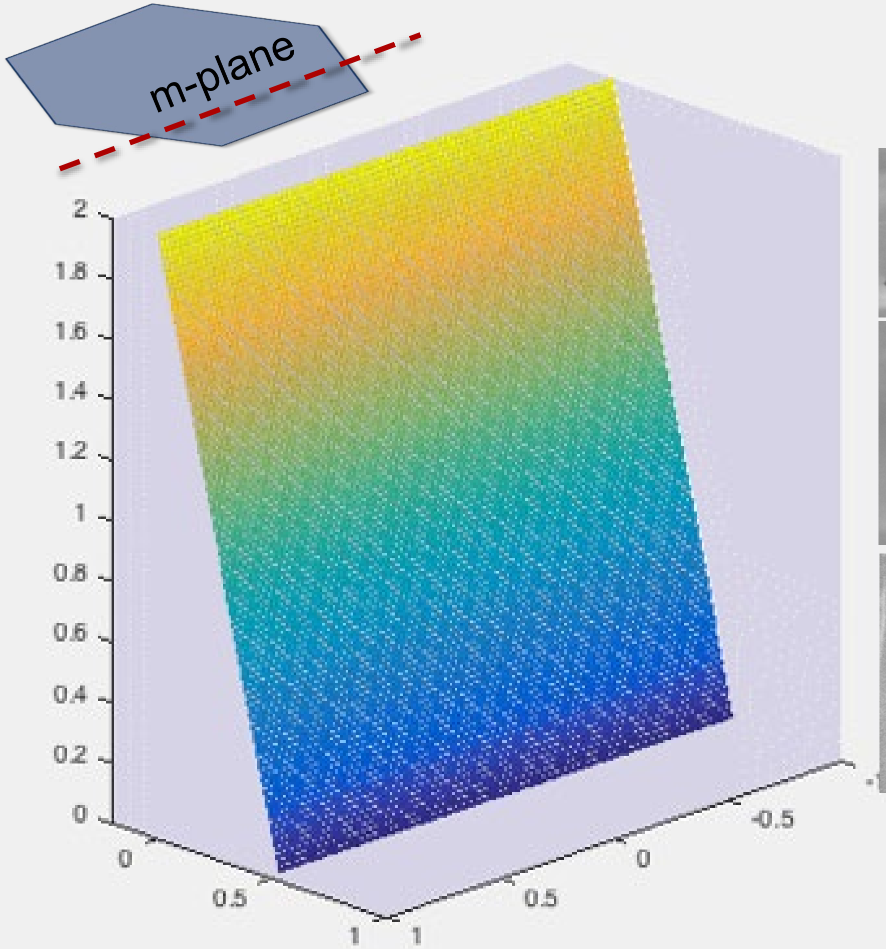
Xiao et al, Elec. Acta 162, 163 (2015)

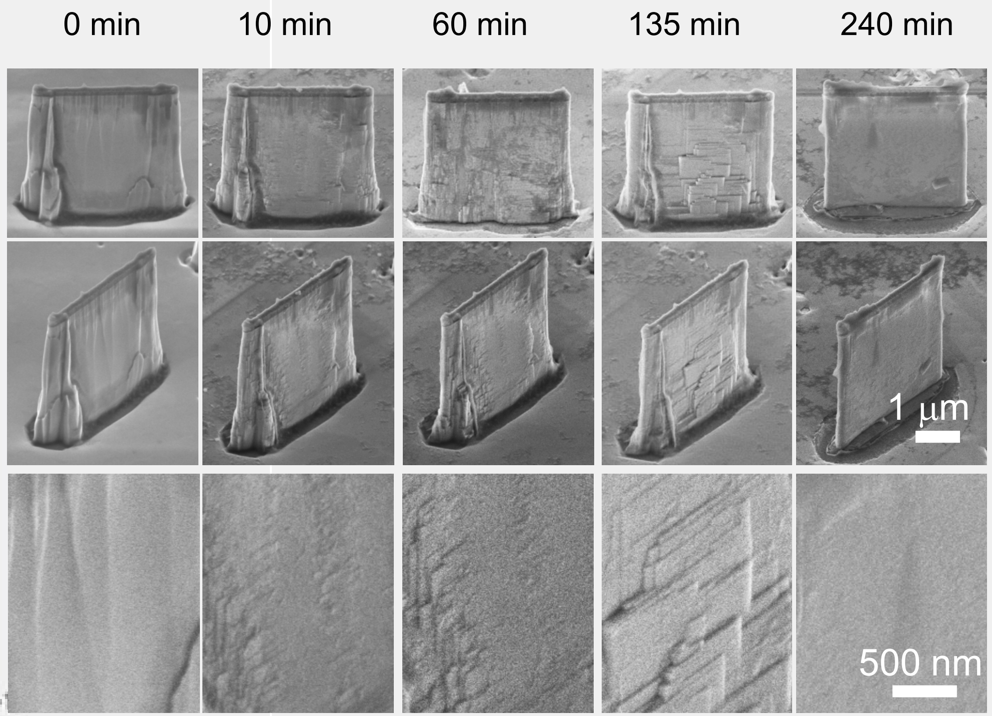
Etch evolution of m-plane wall

Etch mask defined parallel to *m*-plane



V. Darakchieva et al., JAP 108, 073529 (201)

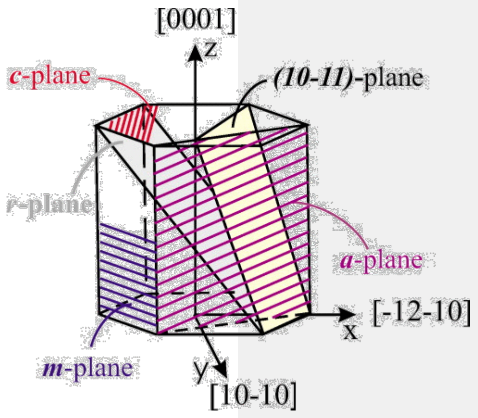




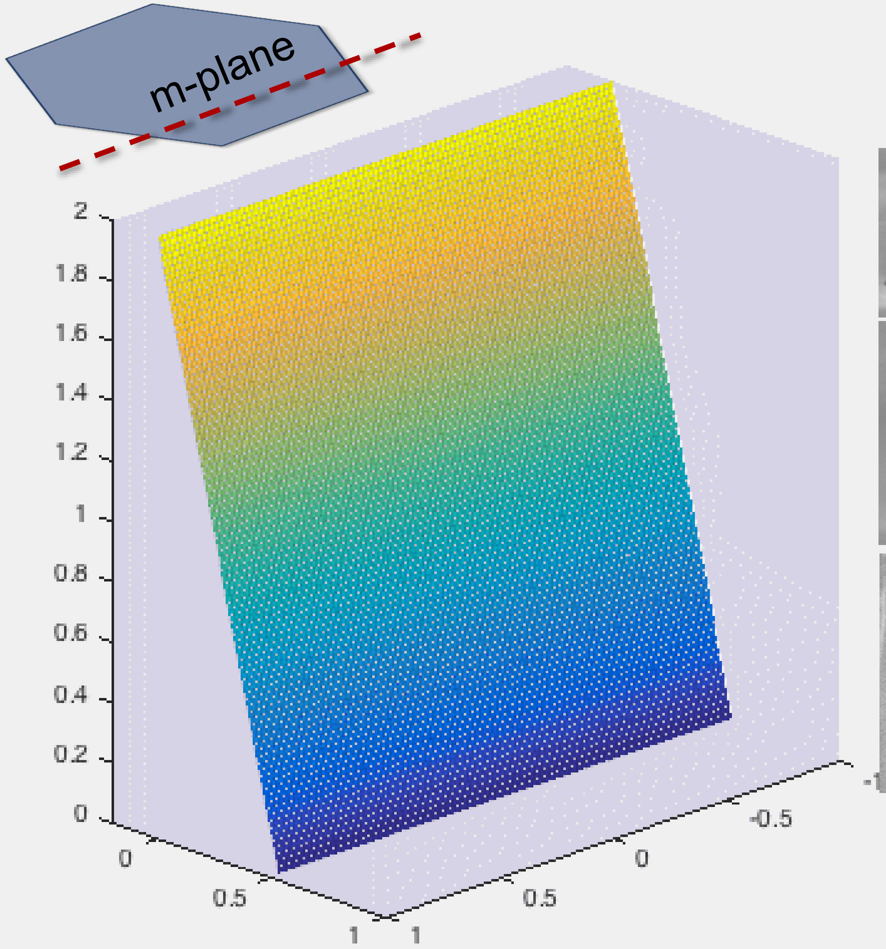
AZ400K, 65°C

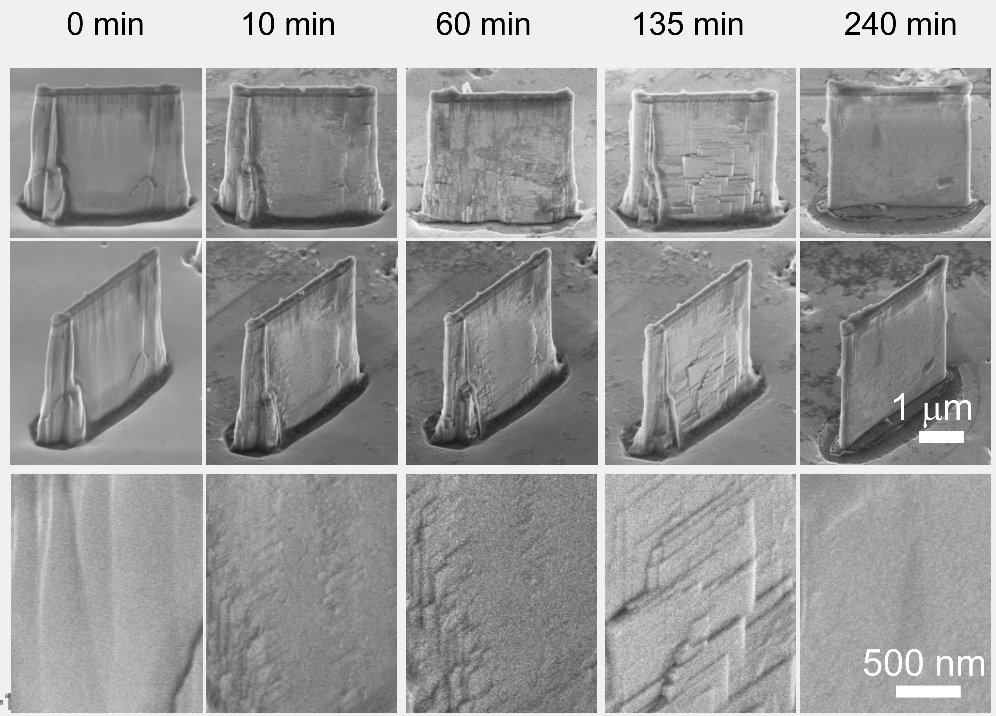
KOH-based Wet etch evolution of *m*-plane wall

Etch mask defined parallel to *m*-plane



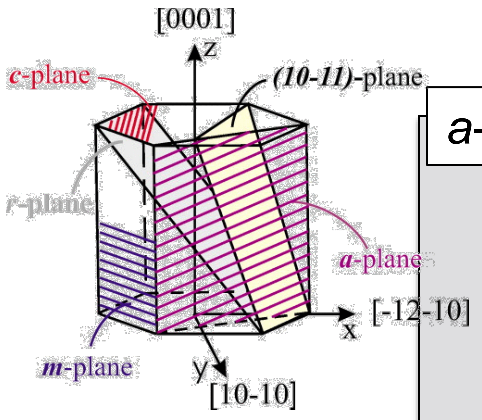
V. Darakchieva et al., JAP 108, 073529 (201)



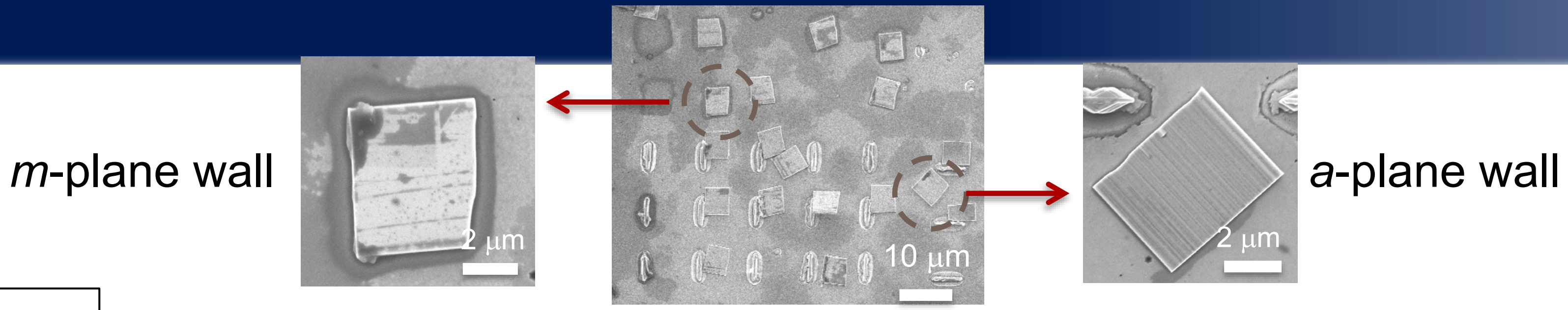


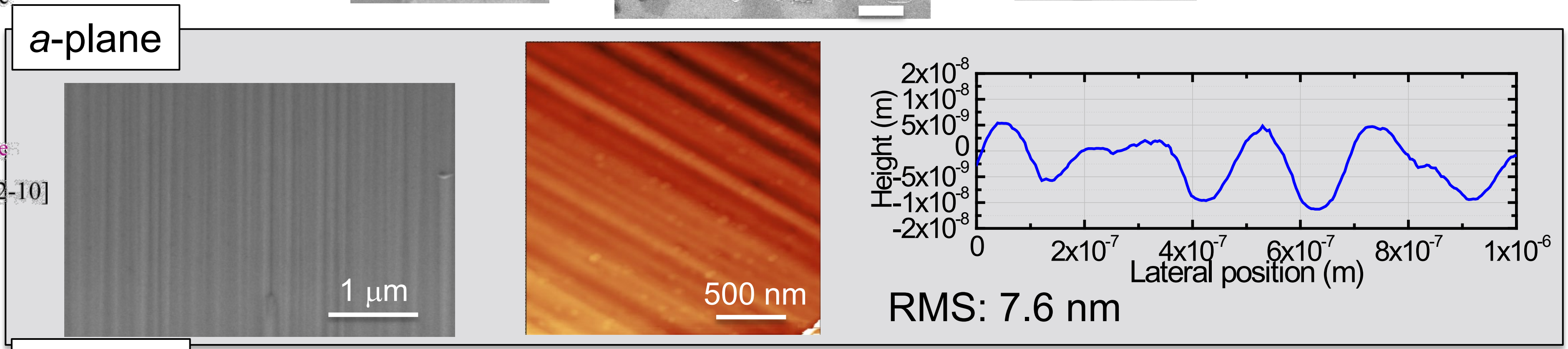
AZ400K, 65°C

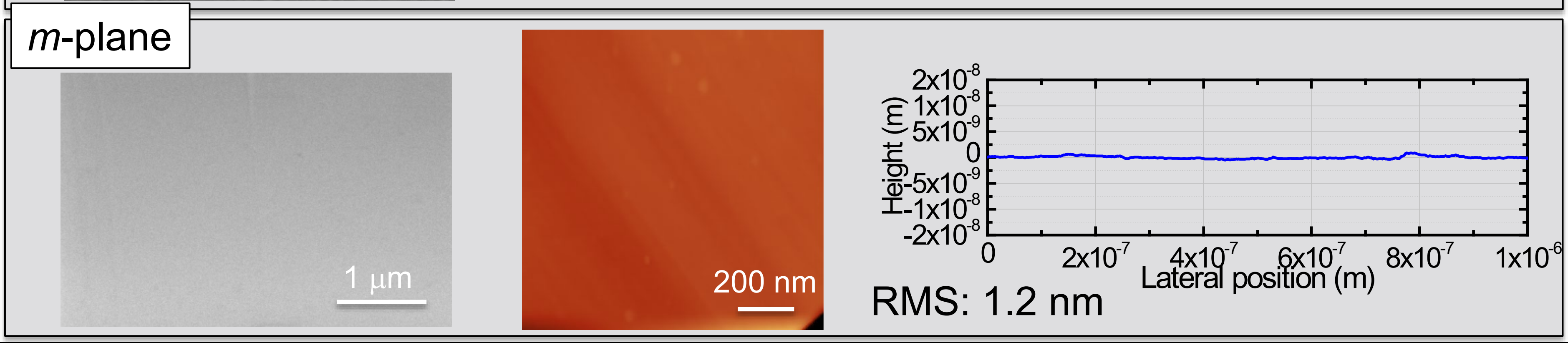
Measured wet etched nanowall morphology by AFM



V. Darakchieva et al., JAP 108, 073529 (201)







Achieved atomically smooth m-plane surfaces through a two-step top-down process!

Fabrication: Integrated, lateral GaN nanoscale vacuum electron diodes

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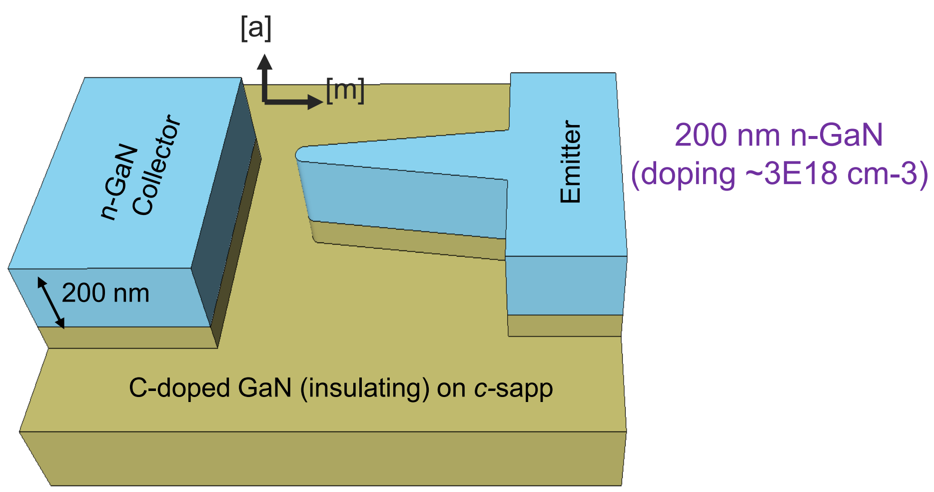
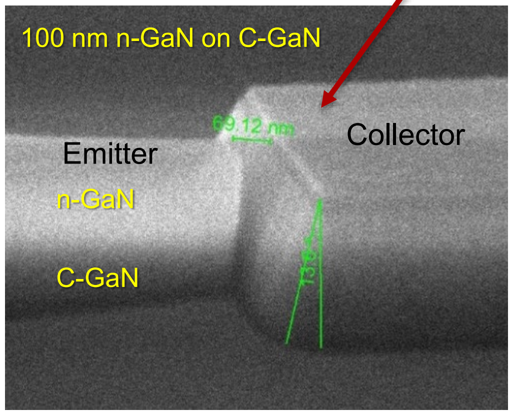
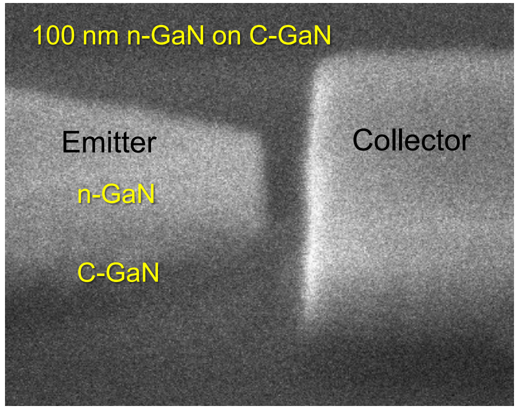
Lateral GaN vacuum nanodiode structure



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

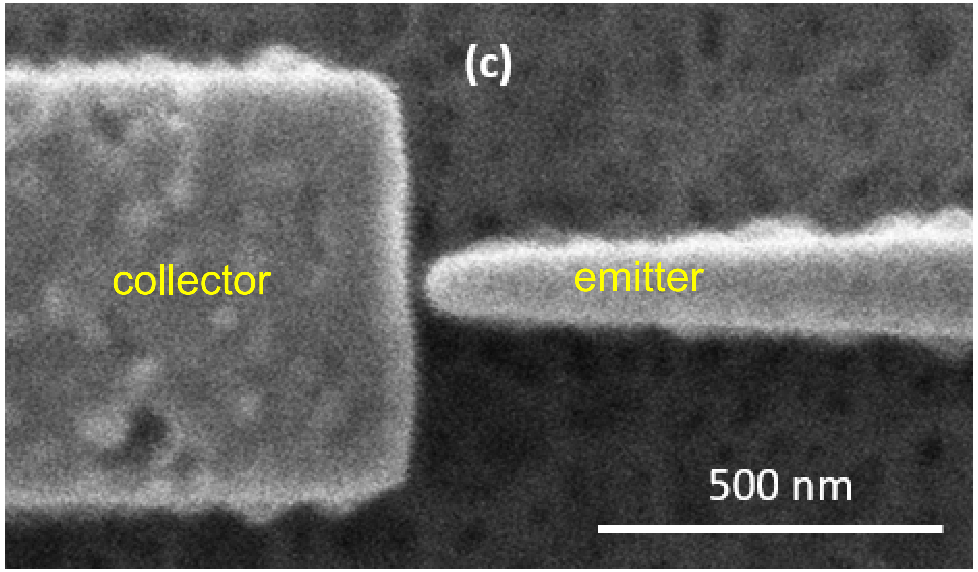
III-N top-down fabrication process

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

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

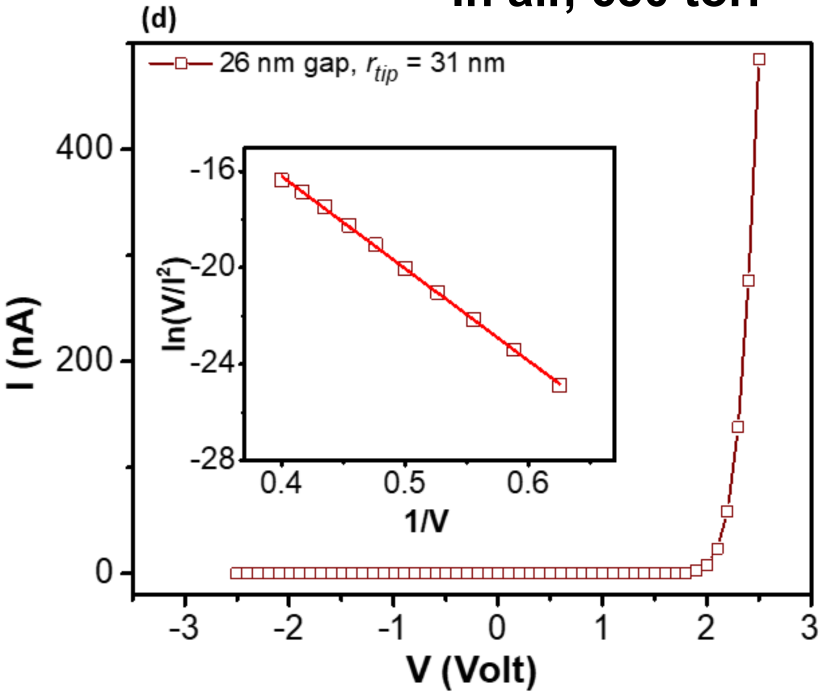
Working monolithic, on-chip GaN nanoscale vacuum electron diodes!

- 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

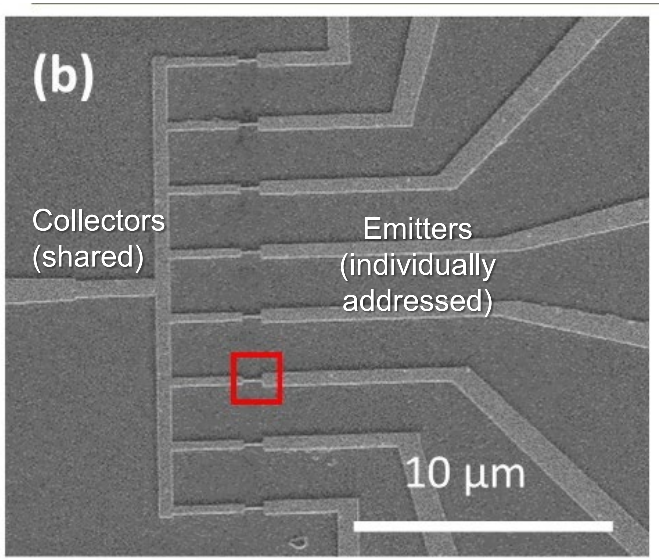
In air, 630 torr

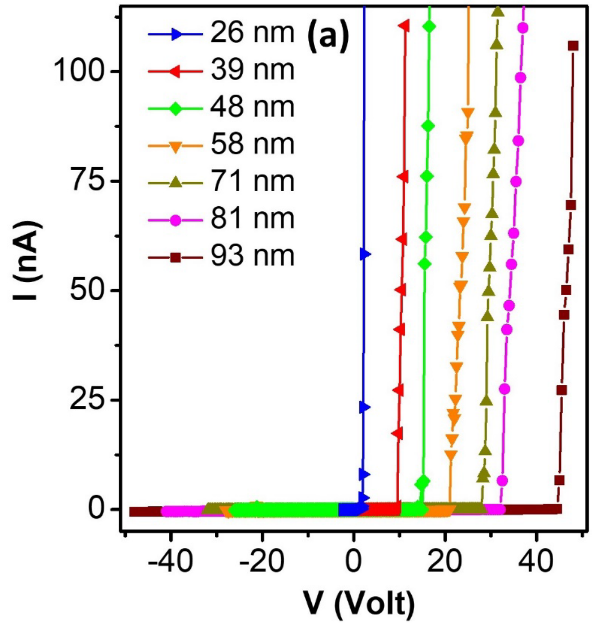


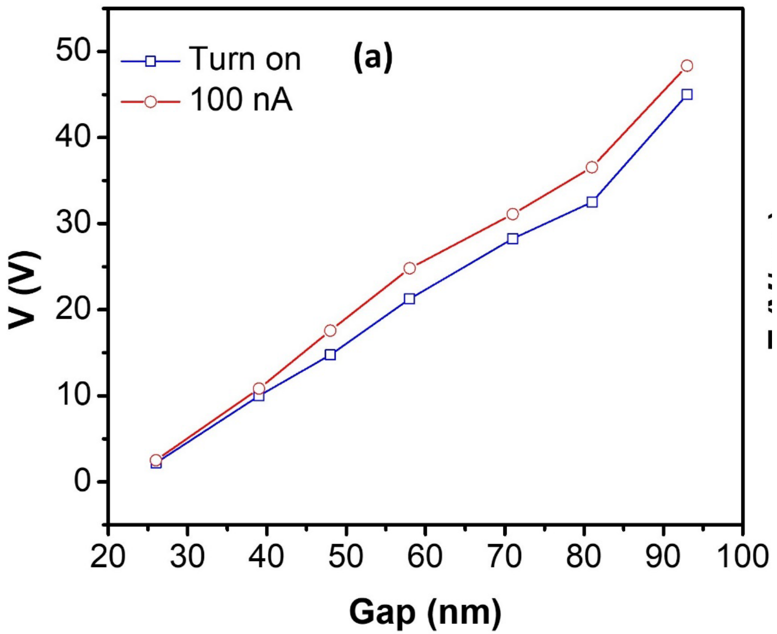
Nanogap Size Dependency of the Field Emission

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

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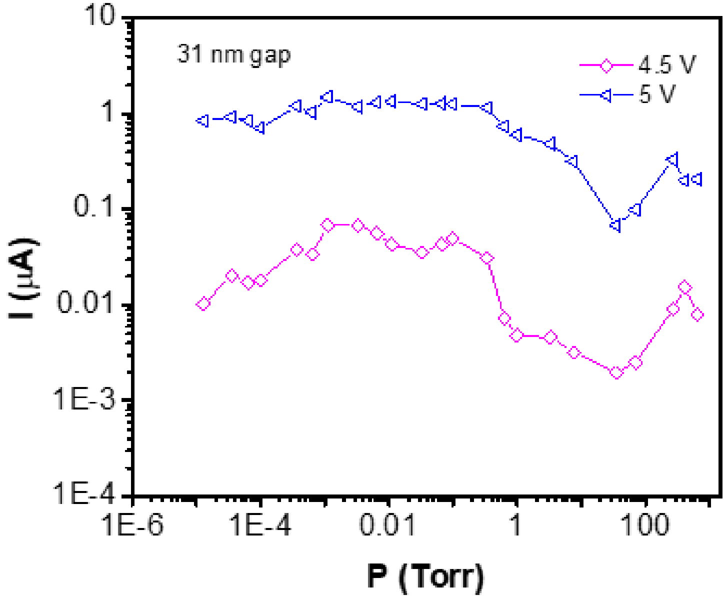
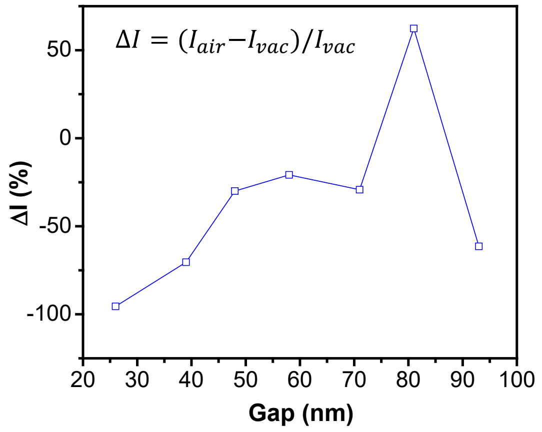
- **Assumption:** nanogap is vacuum-like if nanogap size << electron mean free path in air
- ***Does pressure actually affect field emission of nanogap device in this regime?***

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)*

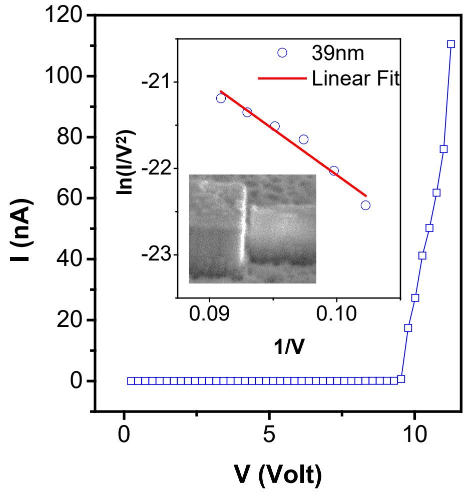




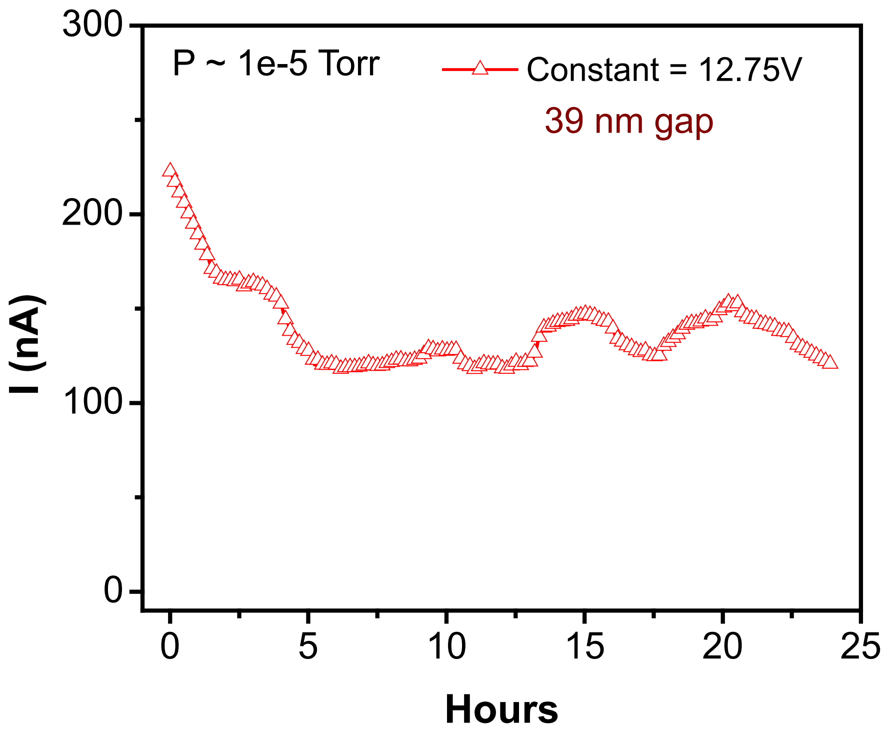
Reliability Measurements of GaN Nanogap Device (39 nm gap)

- **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)

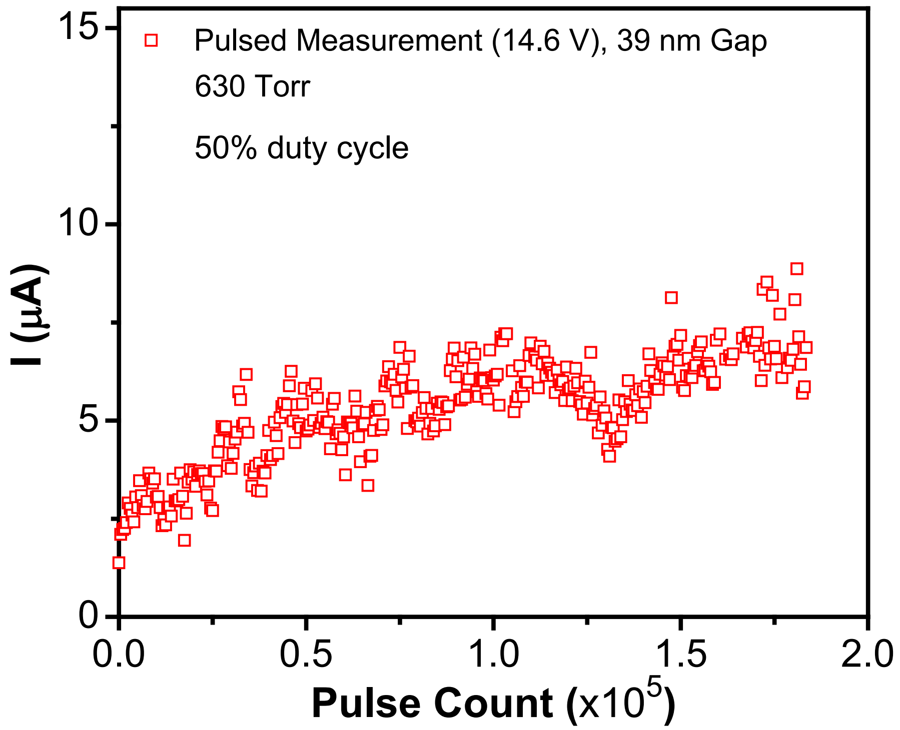
39 nm gap device I-V



Continuously On



Pulsed



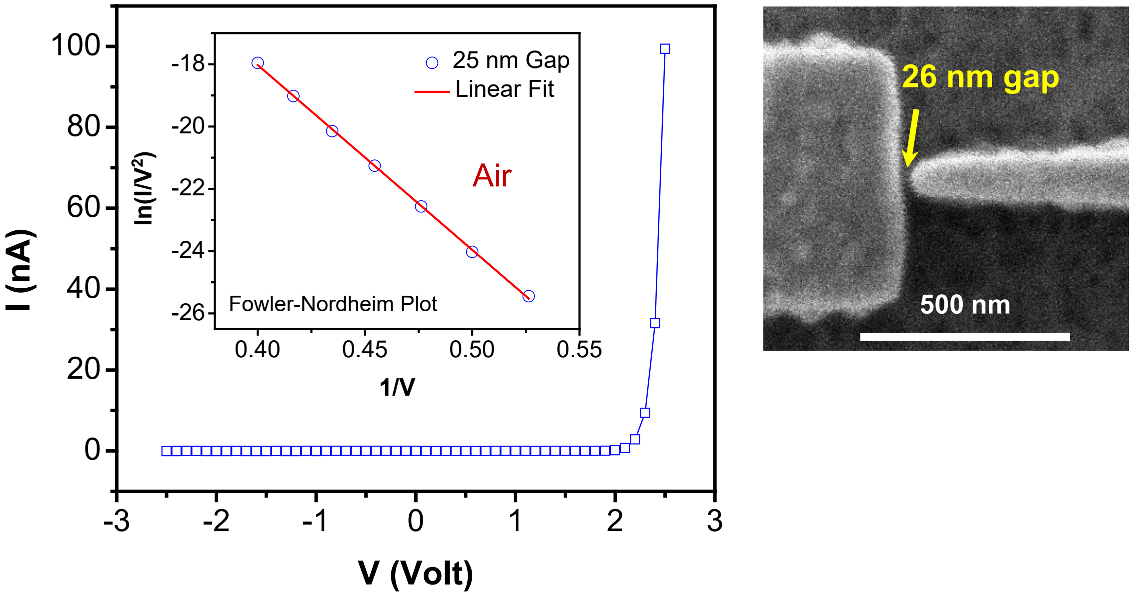
Effect of Emitter Tip Size on Field Emission

Sharper emitter is desired for lower voltage field emission

- Increases field enhancement β (depends on geometry)

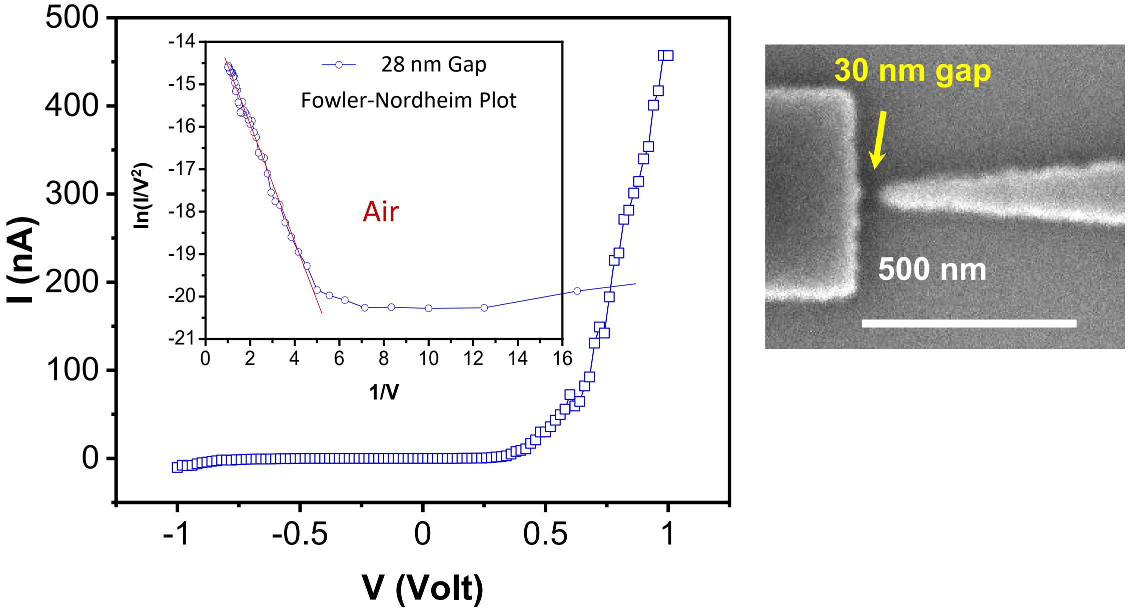
$$J = A\left(\frac{\beta^2 V^2}{\phi d^2}\right)\exp\left(-\frac{B\phi^{3/2} d}{\beta V}\right)$$

Emitter r_{tip} = 31 nm



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

Emitter r_{tip} = 17 nm



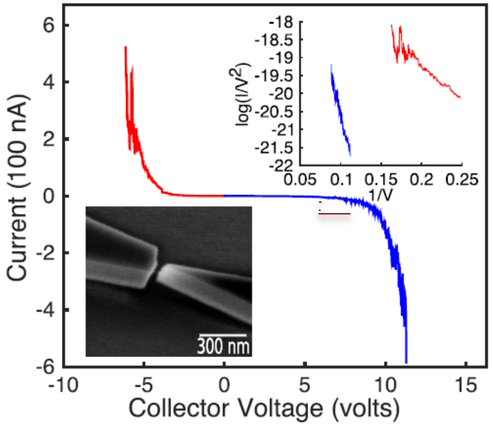
- Field enhancement factor (β) = 920
- Turn on voltage = **0.24 V** @ 50pA

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 SiO2

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



Gap/channel size: 22 nm

Tip radius: ~15 nm (est.)

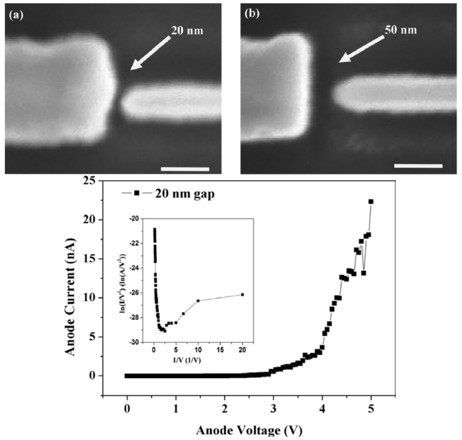
V_{on}: **~3.5 V**

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

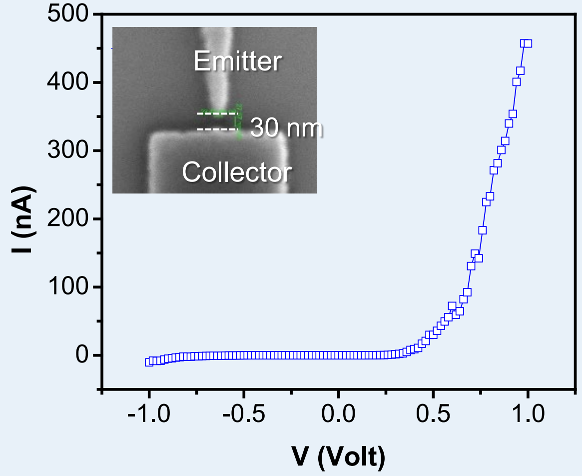
Tip radius: ~20 nm

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**

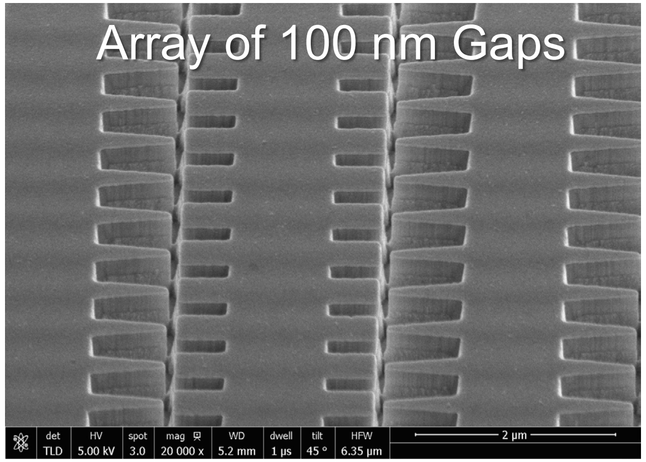
In air? **Yes**

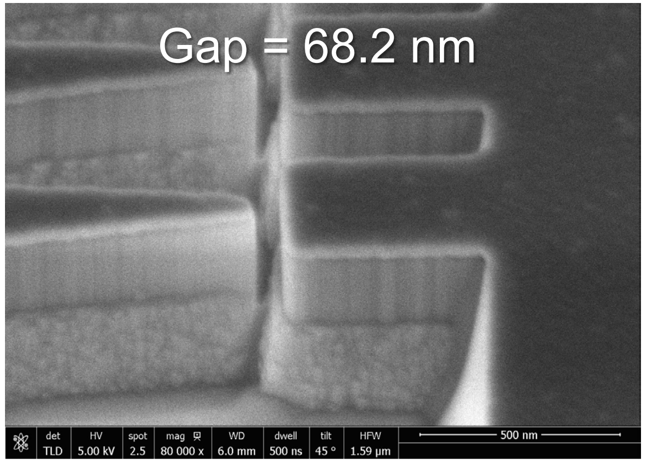
Note: V_{on}= V≥100 pA for all cases

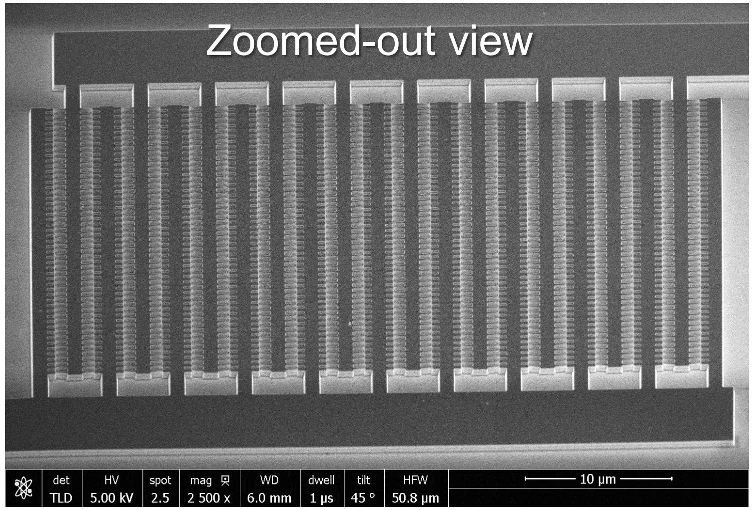
*K. Sapkota et al., *Nano Lett*. 21, 1928 (2021)

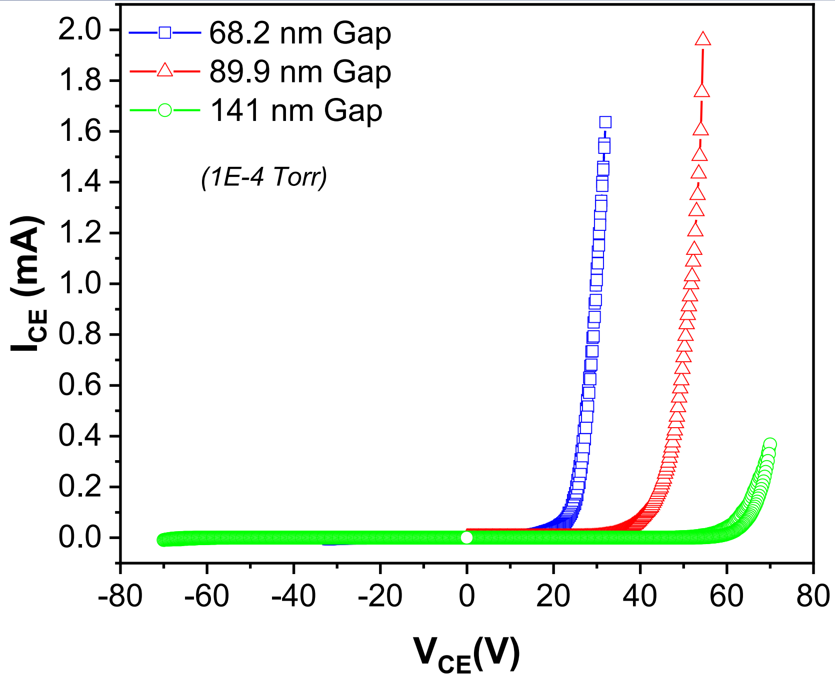
GaN nanoscale vacuum electron diode shows far superior performance vs previous Si and SiC devices!

High-current, 1000 vacuum nanodiode arrayed device!









- Proof-of-concept array of 1000 connected GaN vacuum nanodiodes with ~ 2mA field emission current
- Array design can provide higher current, improve reliability, and device predictability compared to single devices
- Achieved current density 171 A/cm^2 (semiconductor record?)!
- Scale-up potential to amps of current?!

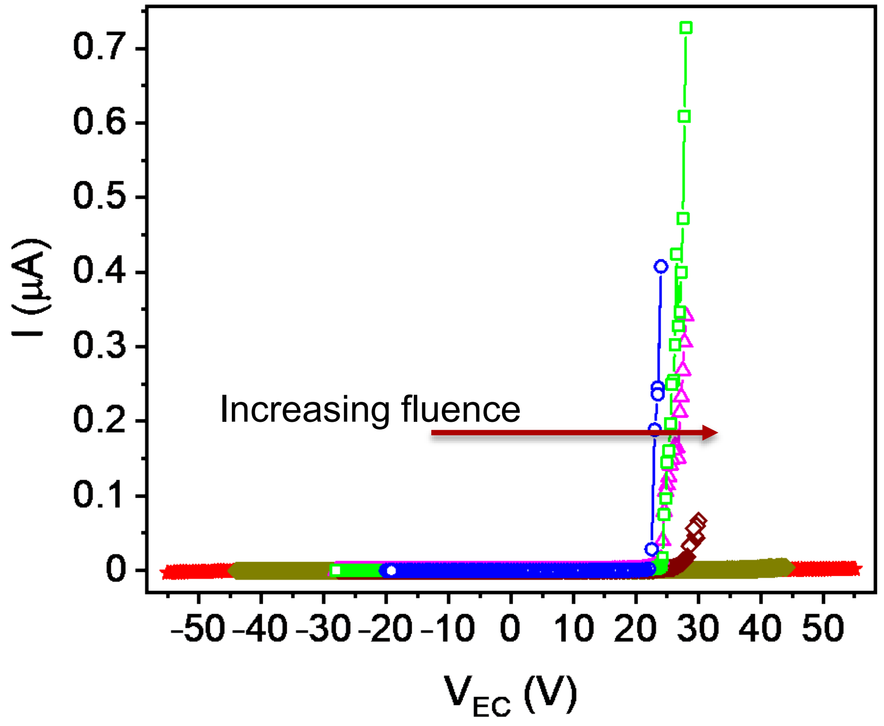
2.5 MeV Proton Irradiation Studies

Acknowledgement: George Burns, Michael King, Edward Bielejec

Done at Light Ion Microbeam (Pelletron) at IBL

- **Trend of slightly decreasing current up to certain fluence,** possibly due to carrier compensation in n-GaN due to defect formation (e.g. Ga vacancies), but **no substantial degradation**.
- At higher fluence, significant increase in V_{on} observed and eventually no field emission current observed at highest fluence

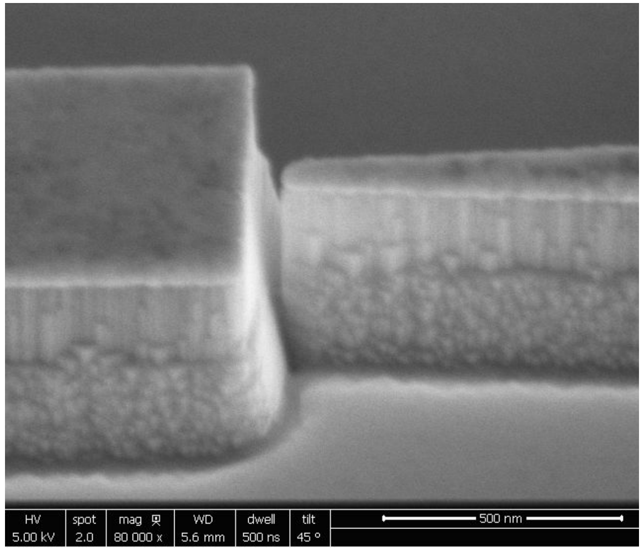
I-V vs total H^+ fluence



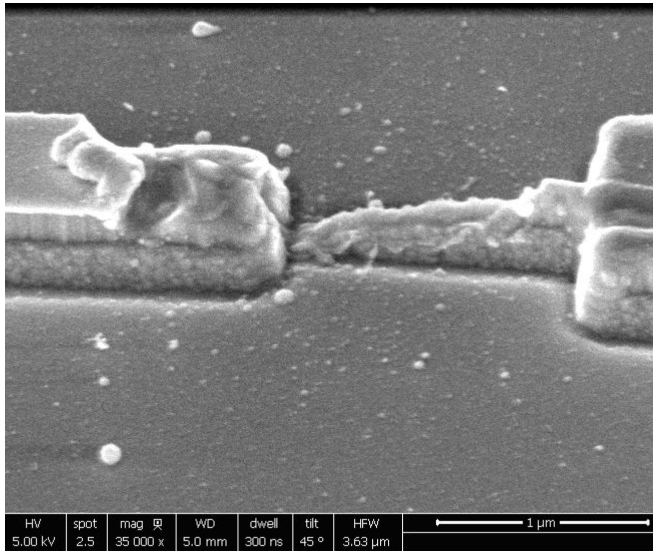
2.5 MeV Proton Irradiation Studies

- SEM shows **physical damage at highest fluence after** exposure & I-V measurement, likely due to Joule heating from increased resistivity based on damage occurring only at narrow emitter & collector regions.
- Very high damage threshold, likely due to GaN, vacuum channel, and small interaction volume
- Other radiation testing currently underway (e.g. electron, neutron)

Before proton exposure

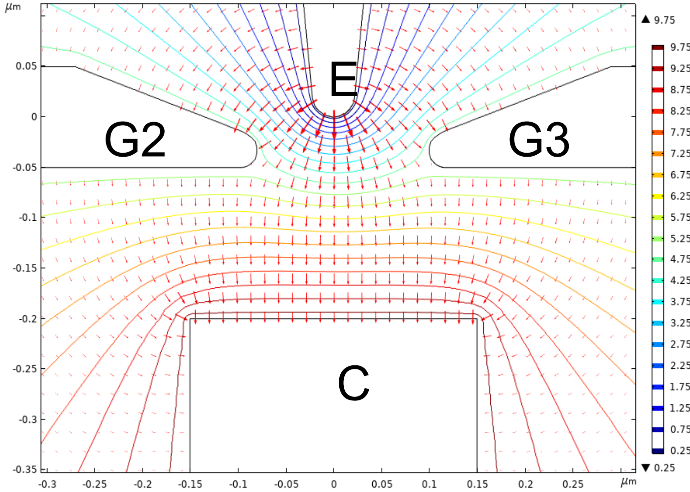


After exposure & I-V

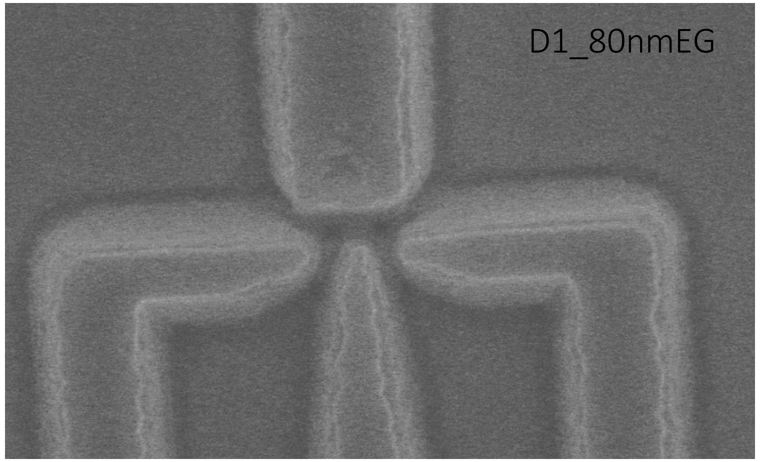


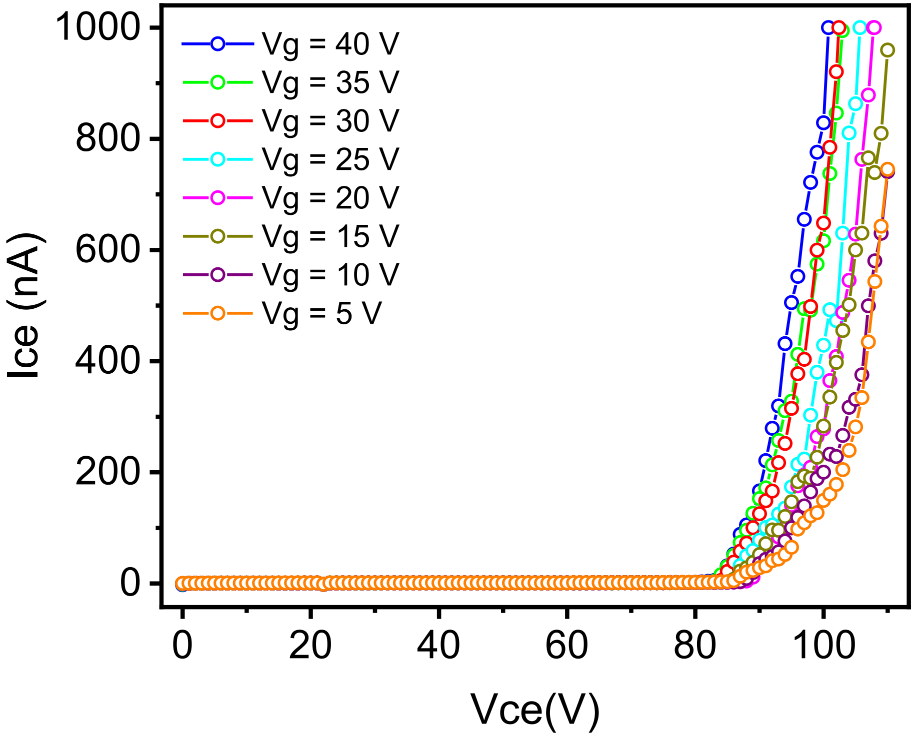
Lateral GaN nanogap field emission transistor

Electric field modulation simulation (COMSOL)



SEM – fabricated GaN lateral vacuum nanogap transistor

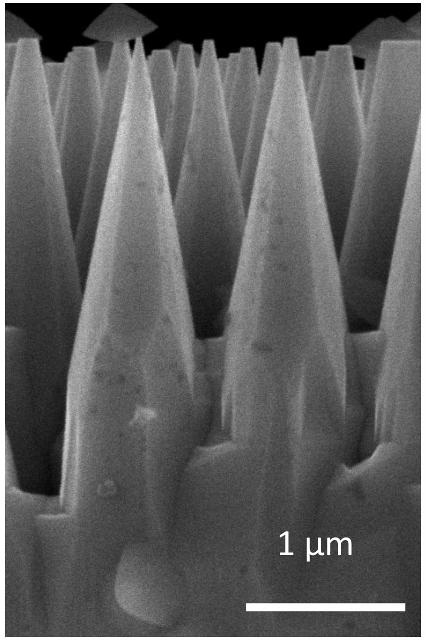




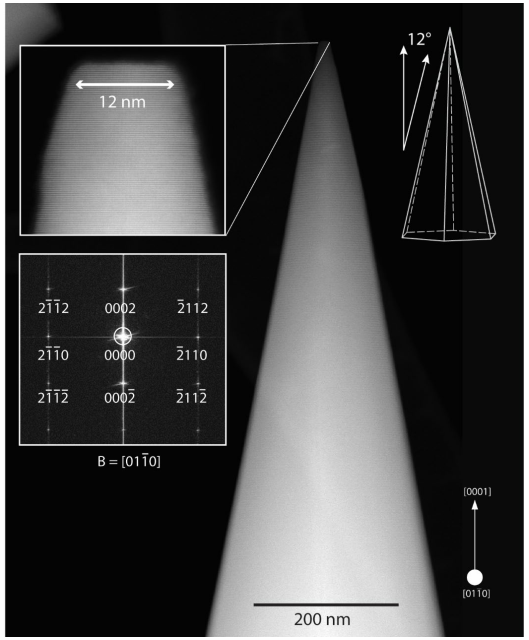
- Transistor – additional circuit element needed for various devices
- First lateral GaN vacuum nanotransistor demonstrated
- Gate voltage decreases the turn on, increases current (expected)
- Gate electrodes act as field emitter at V_g <= 5V
- Other designs (e.g. top gate, back gate) need exploring to increase response to V_g

Vertical GaN nanowire field emitter arrays

SEM

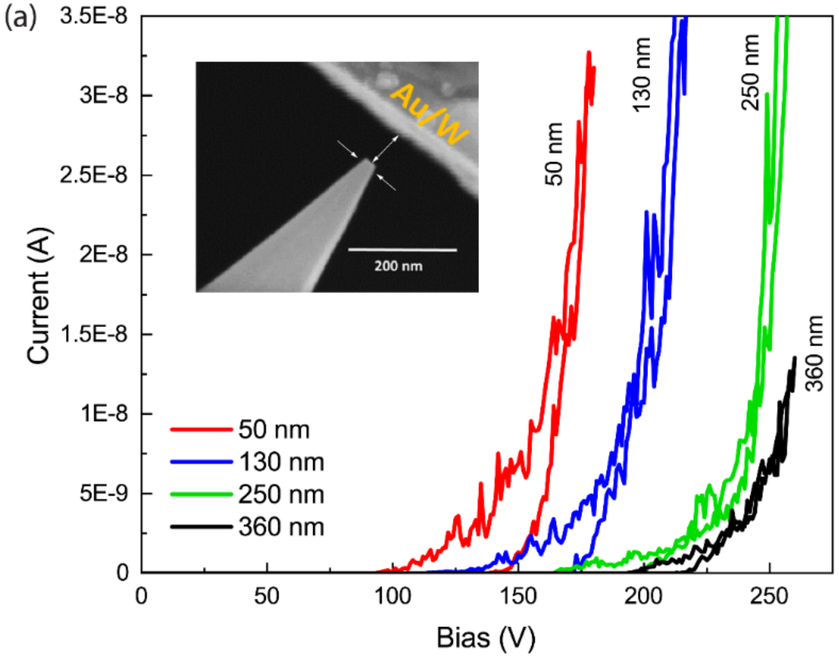


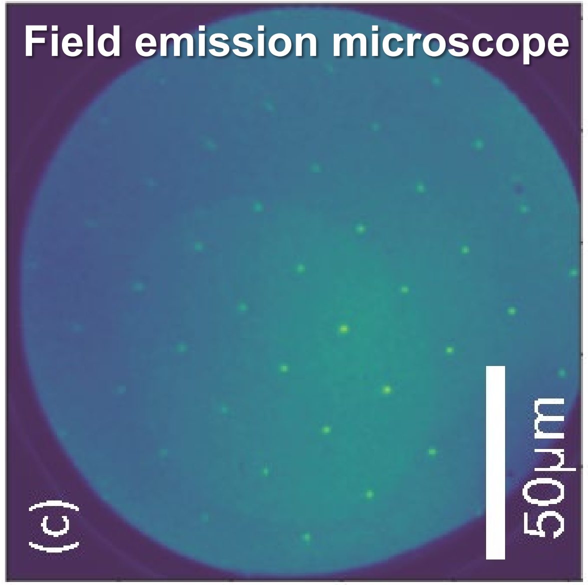
TEM



w/B. Kazanowska, K. Jones, UF

Field emission measurements (in-situ SEM)





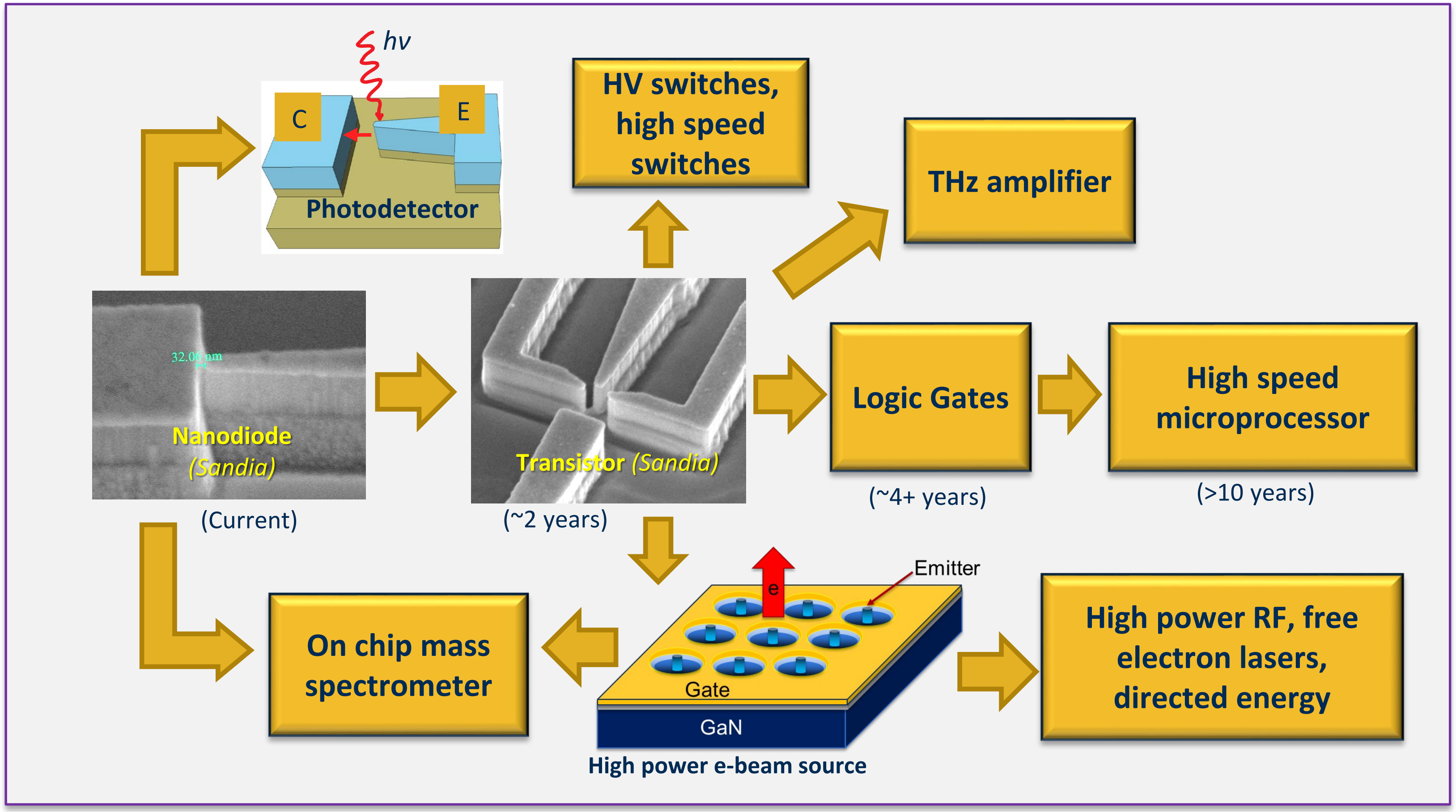
E. Bussmann, T. Ohta, *SNL*

- Developed **new H_3PO_4 etch** for tapered, vertical GaN nanowire fabrication*
- Field emission microscope: very uniform turn-on across nanowire array
- Can serve as field emitter arrays for **vertical** GaN vacuum nanoelectronic architectures.

*B. Kazanowska et al., *Nanotechnology* **33** 035301 (2022)

Future directions for nanogap vacuum nanoelectronics?

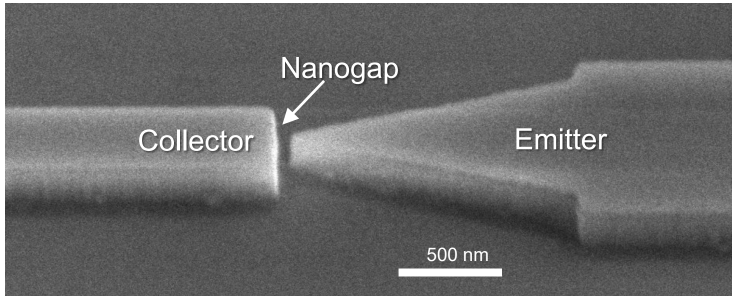
Speculative/aspirational "roadmap"



- What are the potential "killer" or niche apps for nanogap vacuum electronics?
- High speed microwave/RF devices
- High speed logic circuits
- On-chip electron sources
- Detectors
- Radiation hard & high temperature [opto]electronics

Conclusions

- Nanoscale vacuum nanoelectronics have the potential to combine the advantages of vacuum electron and solid-state devices: ideal medium for electron transport, no junction to damage, integratability/cost, efficiency
- High performance, on-chip lateral **GaN** nanogap field emission diodes were demonstrated using a **scalable** 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. **1000 diode array** with **record(?) current density** demonstrated.
- Operating voltages are compatible with modern electronic circuits
- Promising for a variety of future high T, rad-hard devices but **killer & niche applications need to be identified**
- Relatively small field, needs further investment to explore **different materials & architectures** & to understand fundamental physics, performance characteristics (strengths & weaknesses), reliability, etc.

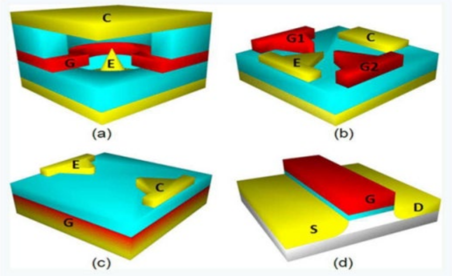


Contact: gtwang@sandia.gov

Backup Slides

Vacuum Nanoelectronics: Current Status

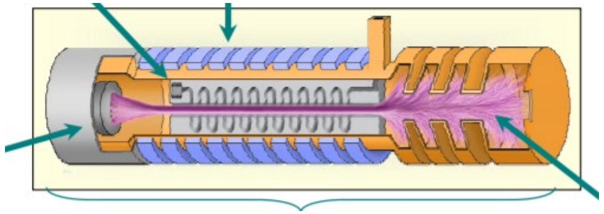
- **Relatively new field, significant new interests**



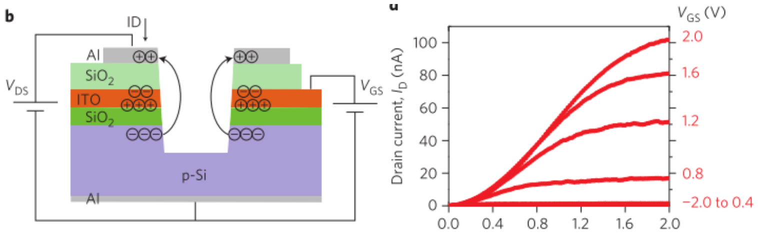
NASA's recent patented designs of Vacuum Channel FETs based on Si

PL.3: Vacuum Electronics and the World Above 100 GHz

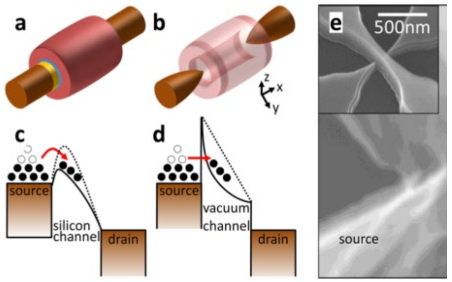
***Mark J. Rosker**[(1)] **and H. Bruce Wallace**[(2)]*
(1) MTO, DARPA, Arlington, VA, 22203
(2) MMW Concepts LLC, Havre de Grace, MD 21078

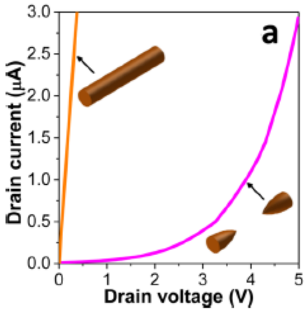


- **Most current works are on Si based Vacuum Nanoelectronics**



Nano-void vacuum channel on Si
Srisonphan et al., Nature Nanotechnology (2012)





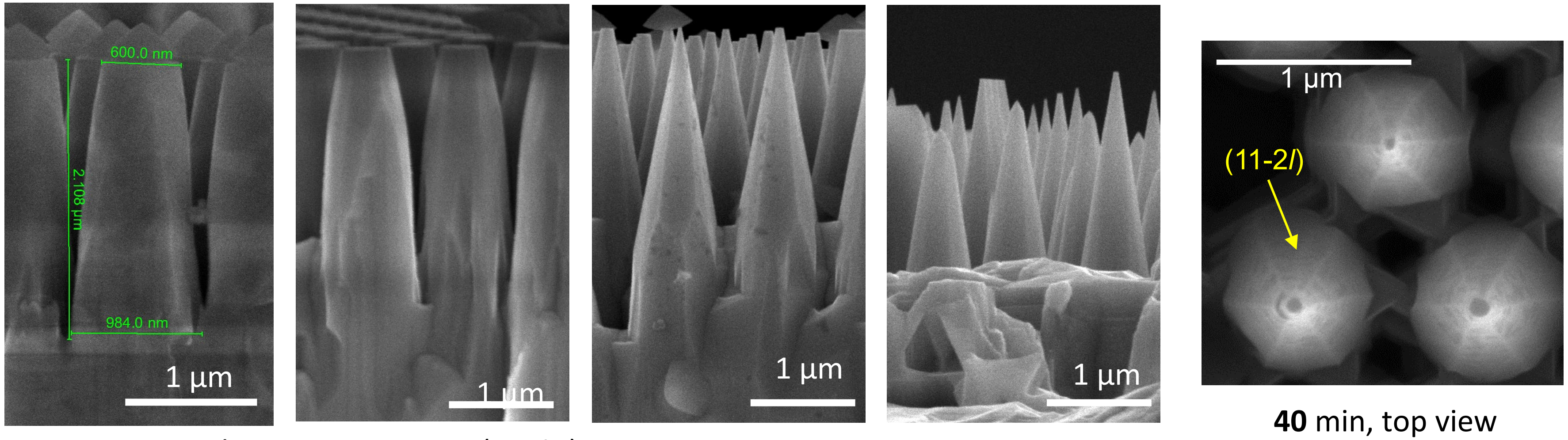
50 nm channel

Drum Gate VC-FET
Han et al., Nanoletters (2017)

- **Major Challenges**
  - **High operating voltage and low emission current**
  - **Weak gate control and significant gate leak**
  - **Long channel length generally defined by lithography**
- **No GaN based Vacuum Nanoelectronics reported in the literature**

H_3PO_4 wet etching of tapered GaN nanowires

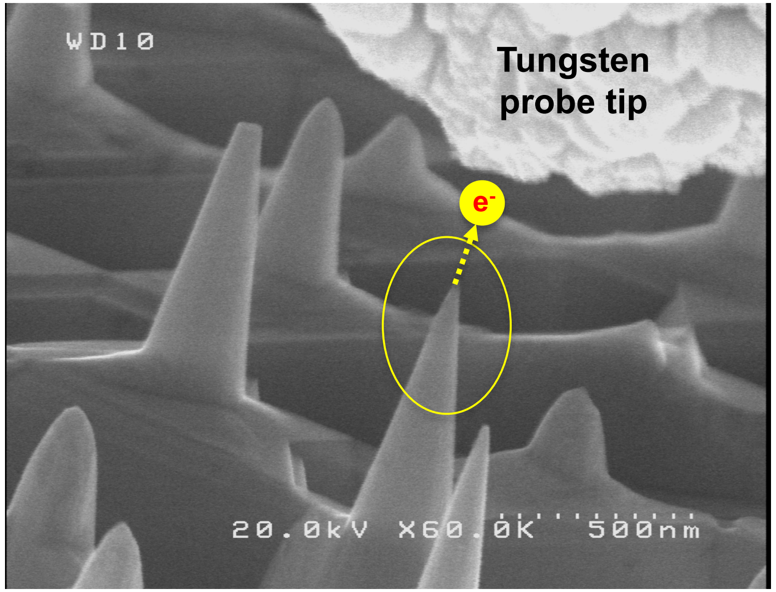
93-96 °C H_3PO_4

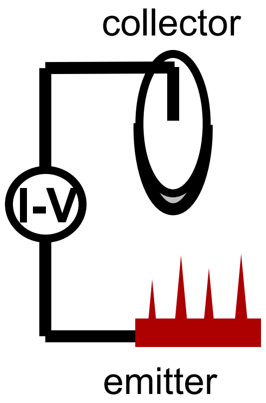


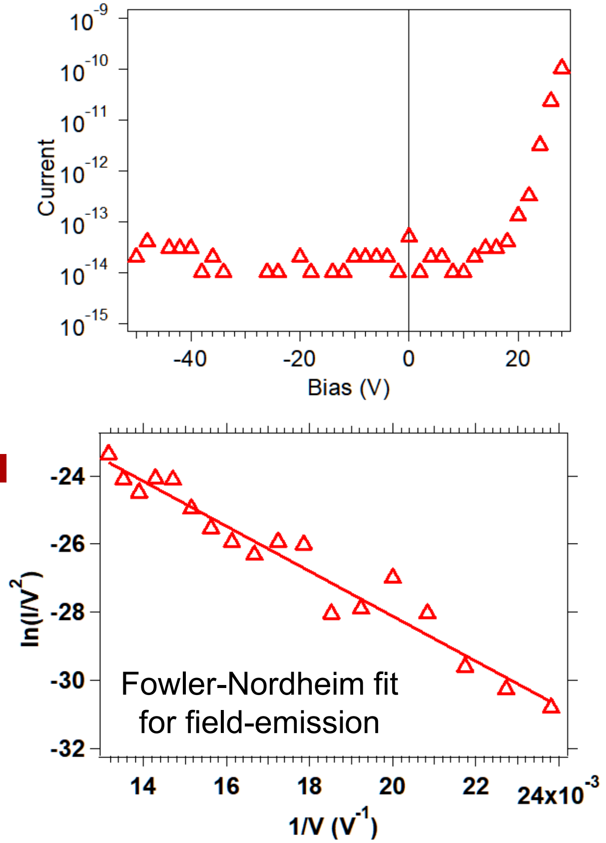
30 min ICP only | **10** min H_3PO_4 (~95°C) | **40** min | **55** min | **40** min, top view

- H_3PO_4 wet etching of ICP dry etched GaN nanowires leads to inclined {11-2*l*} facets not seen in KOH-based etch
- Micro-faceting not observed during etch in contrast to KOH-based etch. Also top corners not "protected" as in KOH-based etch.
- Leads to "pointy" tapered nanowires instead of straight vertical nanowires

Field emission from pointy vertical GaN nanowires







- Field emission shown from pointed GaN nanowires etched by H_3PO_4
- Need sparser nanowires to decrease gap between probe and nanowire to increase current/reduce turn-on V