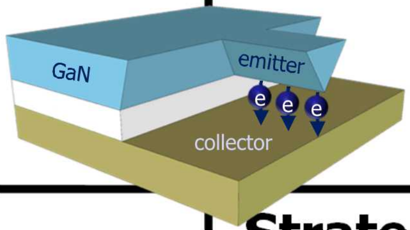
GaN Vacuum Nanoelectronics: A New Platform for Radiation-Hard Electronics

SAND2018-8900PE

George T. Wang (PI), Ronald Manginell (PM), FY19-21, $1.71 M Total

Project Purpose & Overview:

- Vacuum electron devices (i.e. vacuum tubes) have distinct advantages over solid-state devices, such as superior radiation hardness, and high-temperature, high power, and high frequency operation, but are bulky and power-hungry
- We will lay the foundation for a **novel class of chip-based GaN vacuum nanoelectronics** that combine the benefits of vacuum & semiconductor devices & can **operate in air**



Proposed R&D:

- Leverage and build on world-leading 3D etch technologies for GaN
- Build scientific understanding of GaN-based nanogap vacuum electron devices
- Develop efficient (Al)GaN based field emitters and demonstrate prototypical GaN-based vacuum nanoelectronic devices
- Study radiation hardness of devices

Goals and Milestones:

- Push state-of-the-art 3D etch processes for GaN and AlGaN needed for device designs
- Model, fabricate and study field emission characteristics of GaN and AlGaN nanoemitter designs
- Demonstrate and study prototypical GaN vacuum electron devices: diode and field effect transistor
- Irradiate prototype devices to select radiation sources and measure change in properties

Strategic Alignment and Benefit:

- New **game-changing** capability for **efficient and robust solid-state vacuum nanoelectronics** for mission and commercially relevant devices requiring high radiation hardness, high-temperature and high-frequency operation
- **Establish leadership position** in a new, critically important field with vast follow-on potential

Sandia National Laboratories

LDRD

Laboratory Directed Research and Development

GaN Vacuum Nanoelectronics: A New Platform for Radiation-Hard Electronics

Proposal #19-0730

George T. Wang (PI), Ronald Manginell (PM)

Team members: François Leonard (8342), A. Alec Talin (8342), Keshab Sapkota (1876), Brendan Gunning (1876), Michael King (5268)

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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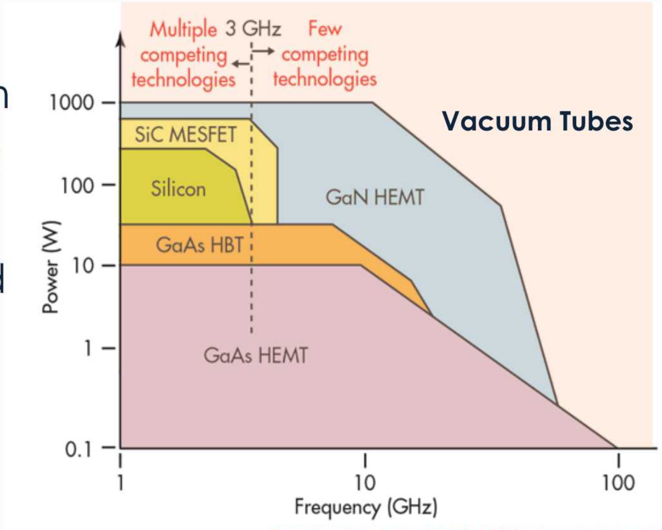
Vacuum Devices – Still Around!

- 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!

Advantages of vacuum electron devices

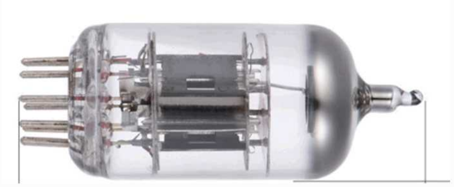
- **Ballistic transport in vacuum channel:** no scattering to degrade signal, power, speed, etc.
- **No heat generation** during electron transport in vacuum
- **No dielectric breakdown** (Dielectric strength = 10^{18}V/m)
- Operation in **harsh environments (radiation, temperature)**: no junction, vacuum channel unaffected
    - Example: tubes are 10,000 to 50,000 times more resistant than solid-state to destruction by an EMP.
      http://www.nutsvolts.com/magazine/article/vacuum_tube_in_its_100th_yearc
- As a result, vacuum devices can operate at **higher frequencies & power** than solid-state semiconductor devices

High power, high frequency



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

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



Vacuum devices: previous & current status

- **~1980s-1990s: Microfabricated Si vacuum microelectronics**
  - Microfabricated Si or W/Mo tip arrays, cold field emission
  - Drawbacks: vacuum requirement, low currents (high workfunction materials), emitter degradation & oxidation

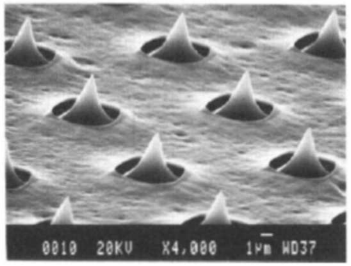
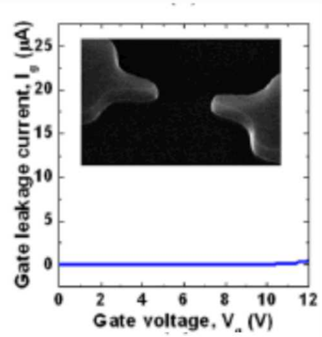


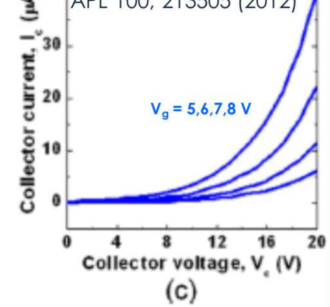
Figure 31. SEM micrograph of silicon tip emitters with maximum recess of the gates using the process of figure 29.

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

- **~2012-present: "Back to the Future": *Nanogap* vacuum nanoelectronics**
  - Recent advances in nanofabrication enables **nano-scaling** of vacuum electron devices
    - Enhancement of local electric field, reduction of operating voltage
    - **Relaxation of vacuum requirement** as vacuum channel becomes smaller than 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 & **operation to 460 GHz!**



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



Challenges for Si-based nanogap vacuum electronics

- **High turn-on/operating voltage**
- **Low emission current**
- **Potential oxidation and degradation**

Solution: (Al)GaN instead of Si as a Superior Platform for Vacuum Nanoelectronics?

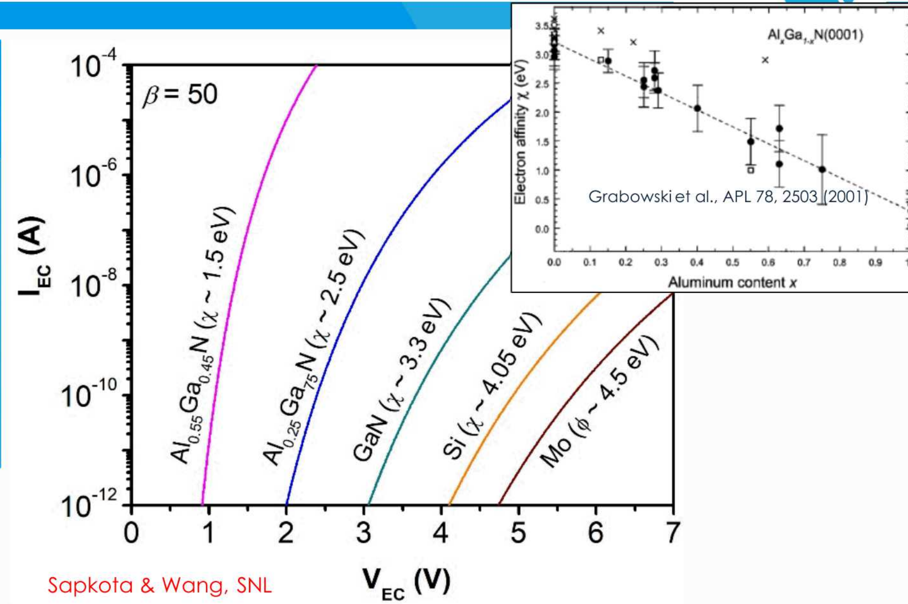
<u>Lower Work Function (Electron Affinity):</u>
Much lower turn-on V/ higher field emission I

Field emission current *J* given by Fowler-Nordheim (FN) eqn:

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

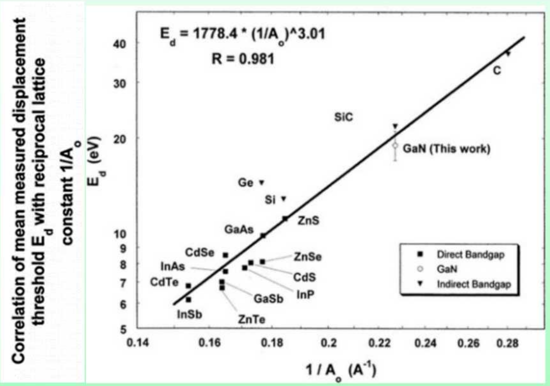
φ ➔ work function. $\chi \sim \varphi$ for heavily n-doped semiconductor

Field emission heavily dependent on χ (lower is better)



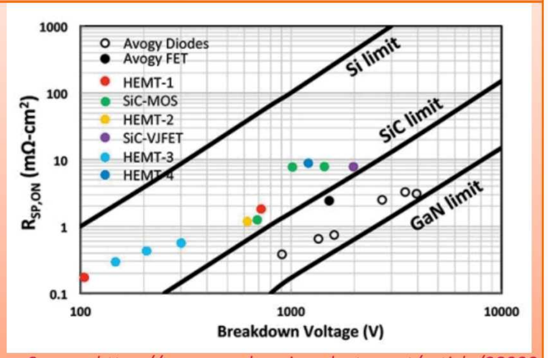
Sapkota & Wang, SNL

<u>Higher Bond Strength</u>: *Chemical stability, sputtering resistance, higher temperature, radiation hardness*



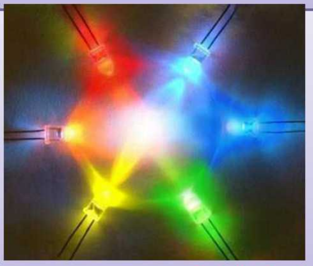
Source: Nedelcescu et al., IEEE Nuclear Science (2002)

<u>Higher Breakdown Field:</u>
Higher power



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

<u>Direct Bandgap</u>
New integrated logic & optoelectronic devices?

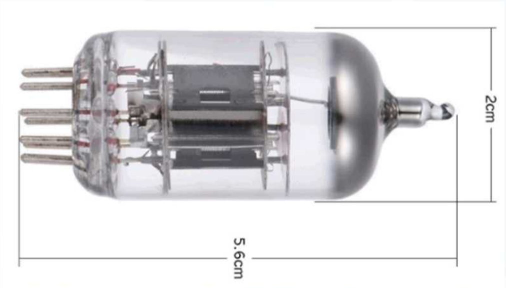


F. Schubert

Solution: Solid-state, III-nitride based nanogap "vacuum" nanoelectronics!

Combines advantages of vacuum & semiconductor devices: high frequency/power, radiation hardness, high temperature, size, integration, energy efficiency, cost, reliability

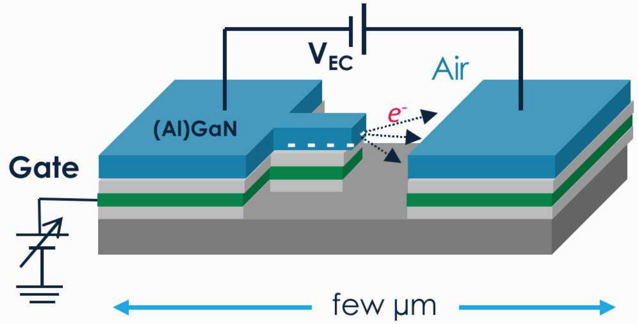
Vacuum tube



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

?

GaN-based "vacuum" electron device



Overcome key barriers by **nanoscaling**: *vacuum-free operation, lower operating voltages, reduced emitter sharpness requirements*

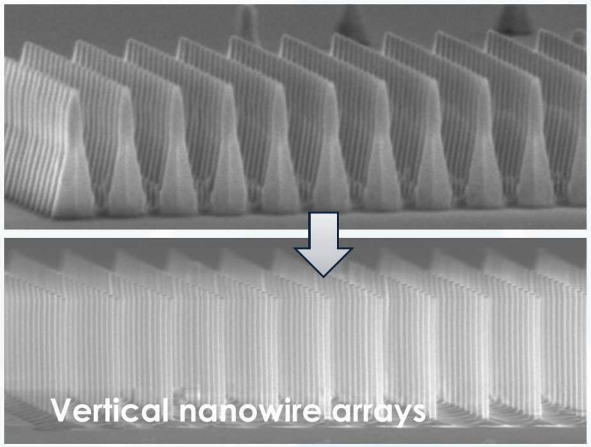
Overcome key barriers by **(Al)GaN**: *high emission currents at lower V, emitter stability and durability, higher breakdown/power, novel optoelectronics*

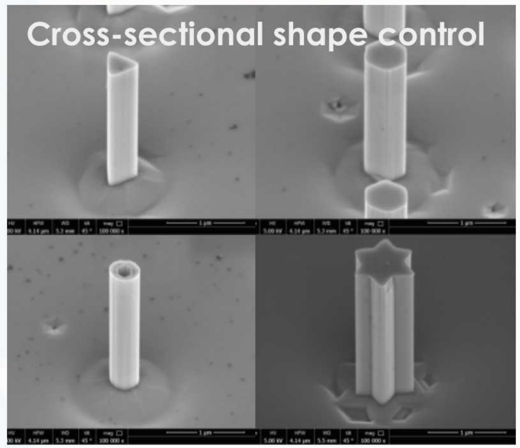
Overall LDRD goal: Establish the scientific and technological foundation to enable a unique, new class/field of III-nitride based vacuum nanoelectronics

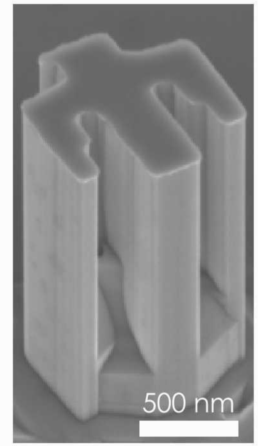
Enabling Sandia Capability: 3D GaN Nanofabrication

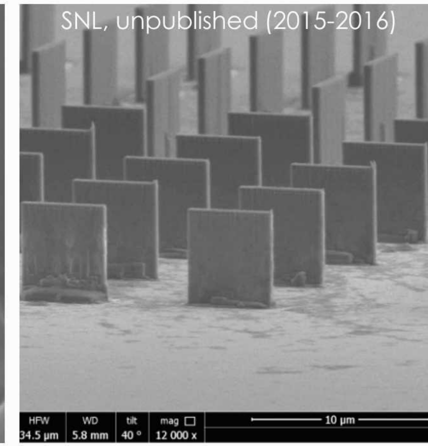
Enabling Sandia Capability: World-leading capabilities for the top-down fabrication of 3D, high quality, GaN-based nanostructures

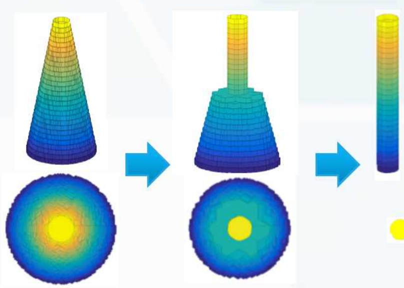
GaN vertical etch



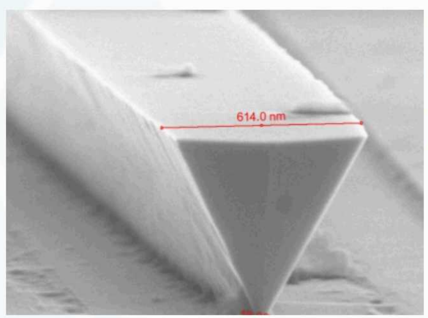






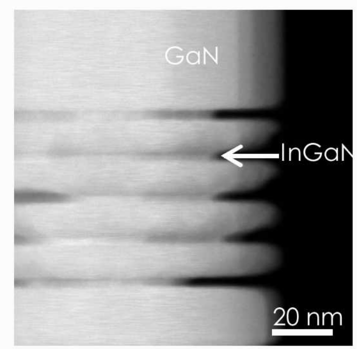


Simulation of facet etch evolution



Sharp emitter geometry for enhanced field emission

GaN undercut etch

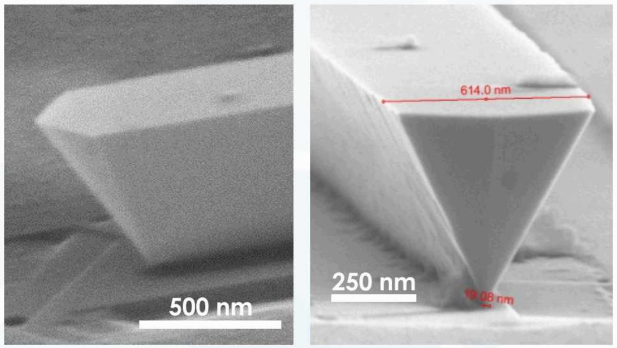


Selective removal of quantum wells allows for ultrathin vertical nanogap vacuum channel

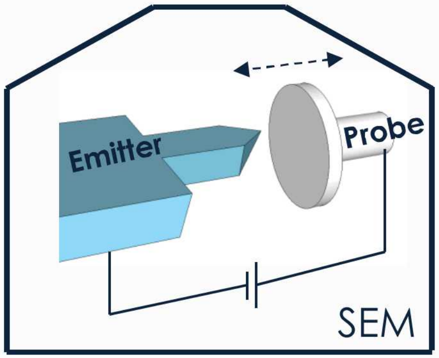
(In)GaN lateral etch

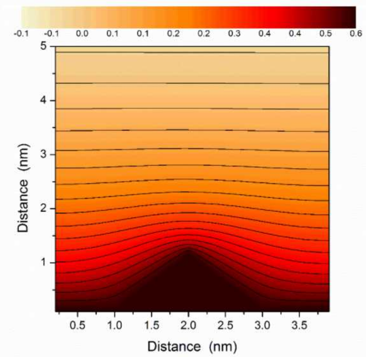
Approach

Task 1 - Three-dimensional etching of III-N (Al)GaN nanostructures

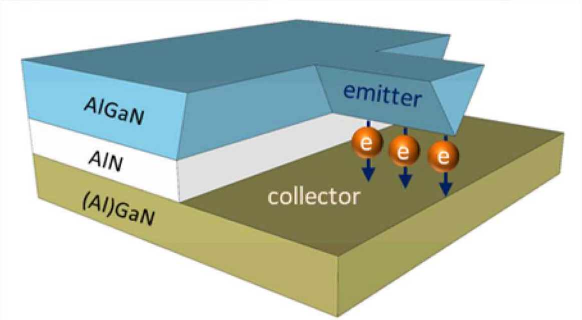


Task 2 - Field emission studies of GaN and AlGaN nanoemitters

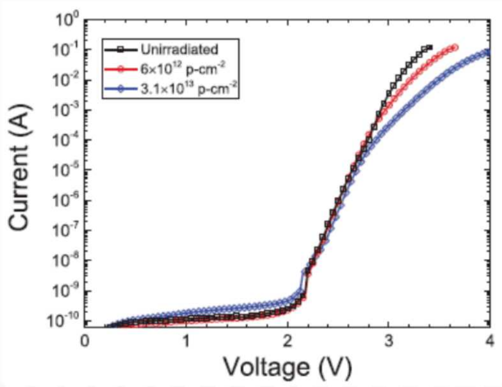




Task 3 - Design and demonstration of (Al)GaN vacuum nanogap prototype devices

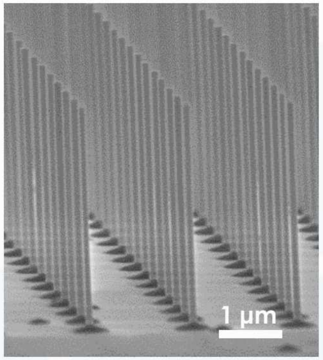


Task 4 - Radiation effects studies



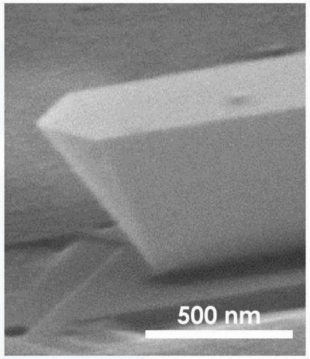
Task 1 – Three-dimensional etching of III-N (Al)GaN Nanostructures

GaN vertical etch



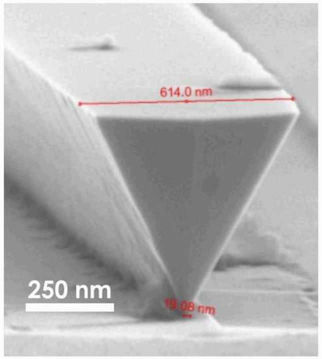
Vertical nanowire arrays

GaN tapered etch



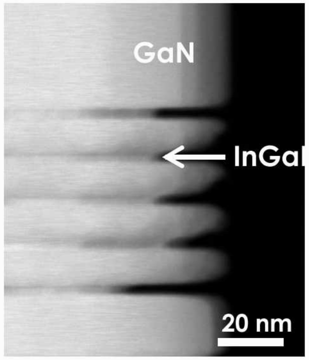
Pointed lateral wire

GaN undercut etch



Wedged shaped wire

(In)GaN lateral etch

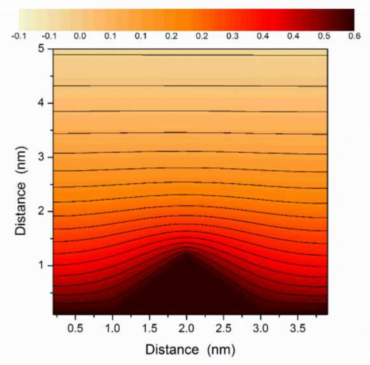


Nanowire with nanogaps

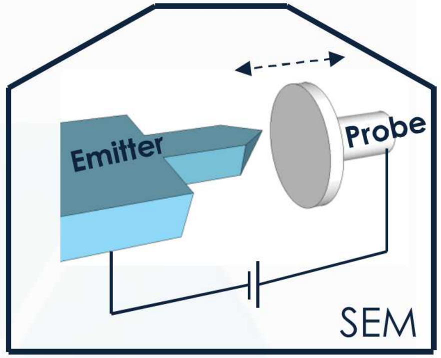
- Push limits of state-of-the art 3D GaN etch processes needed for vacuum electronic emitter and device designs
- Extend to **AlGaN**, which may be superior to GaN as an emitter, but where 3D etches are *virtually unexplored*

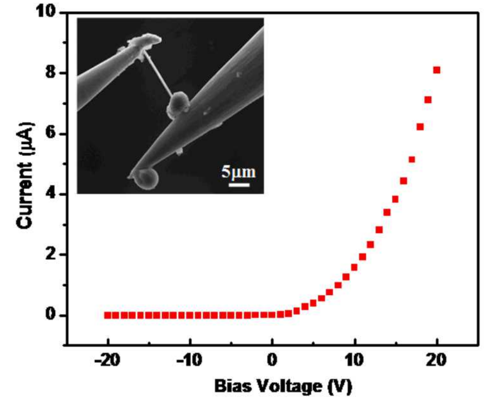
Challenge: Explore and understand how various etch chemistries for different materials (GaN, AlGaN, AlN) can be combined to realize complex 3D (Al)GaN nanochannel vacuum electronic designs

Task 2 – Field emission studies of GaN and AlGaN nanoemitters



Finite element simulations of tip





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In-situ environmental SEM: electrical nanoprobes, hot stage, variable pressure

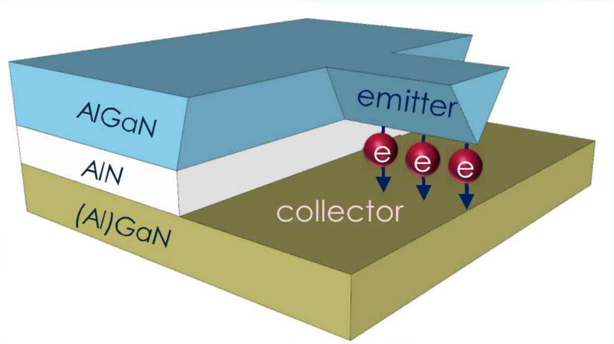
- 3D finite element modeling to guide emitter design
- Fabricate, study & compare field emission properties: GaN vs AlGaN nanostructures
  - Use nanoprobe in SEM as collector with variable gap size/position
  - Change environment from vacuum to variable pressure in H_2O vapor
  - Heat samples in SEM to study hydrocarbon contamination
- Degradation studies:
  - Study emitter breakdown at high voltages
  - Study field emission behavior over time

Challenge: Understanding and overcoming barriers for efficient and stable field emission from (Al)GaN nanostructures

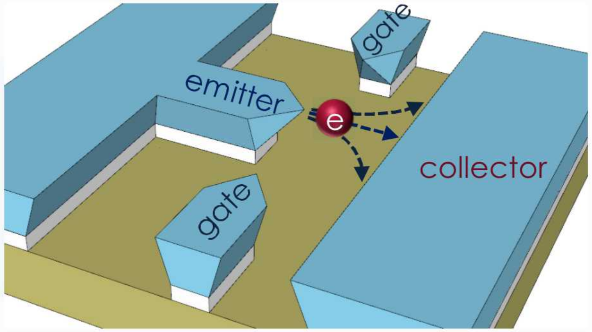
Task 3 – Design and demonstration of (Al)GaN vacuum nanogap prototype devices

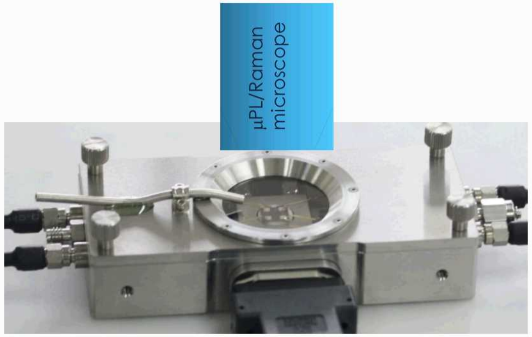
Goal: Fabricate & test 3D (Al)GaN vacuum nanoelectronic protoype devices

Vacuum diode (vertical gap)



Vacuum FET (lateral gap)





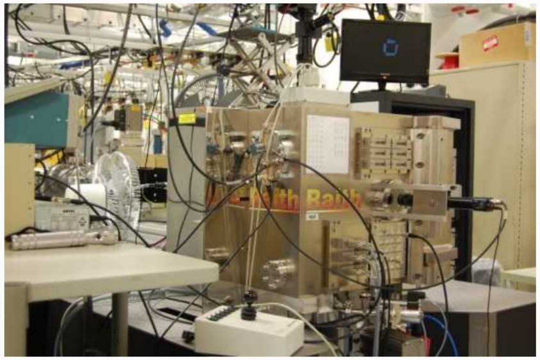
Controlled-ambient electrical test cell with optical window, heater/cooler

- Downselect emitter design based on emission characteristics, fabrication ease, etc.
- 3D finite element simulations to refine device designs
- **First**: demonstrate **vacuum diode** (consider vertical vs lateral gap designs)
- **If successful:** demonstrate **vacuum FET** (prioritize lateral gap design)
- <u>Measure</u>: turn-on voltage, I-V, breakdown voltage, frequency response in controlled ambient (vacuum vs air)
- Theoretical modeling together with measurements to **elucidate device physics**, deviations from standard F-N behavior/physics (cathodoluminesce, space-charge effects, nanogap dimensions, etc.)

Task 4 – Radiation effects studies of (Al)GaN-based nanoemitters and vacuum nanoelectronic devices

- Proposed vacuum nanoelectronic devices **expected to exhibit high radiation hardness** compared to standard solid-state devices
- Here, study device characteristics of fabricated (Al)GaN vacuum nanoelectronic devices following irradiation to particles of interest (similar studies carried out for GaN power devices under Ultra-Wide Bandgap GC LDRD)

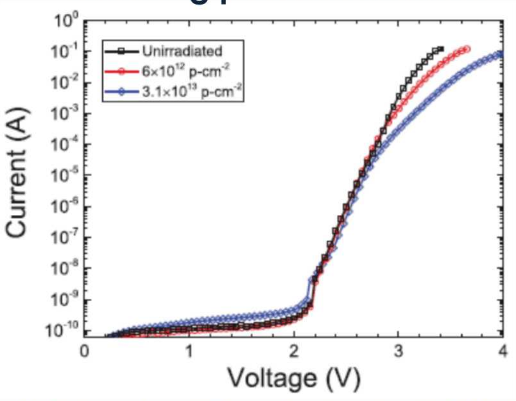
Light Ion Microbeam (Pelletron) at IBL



- Light Ions – H, He3, He4, N (lower resolution spots)
- Energy range from ~300 keV to 3 MeV
- Spot size as small as ~150 nm

  - 2.5 MeV proton accelerator (Pelletron) at IBL
  - 10 keV X-ray exposure (Aracor 4100)
  - Prompt gamma irradiation at Little Mountain Test Facility (Ogden, Utah) – if time/availability

GaN P-i-N diode characteristics following proton irradiation



M. P. King et al., IEE Trans. Nuclear Sci. 62, 2912 (2015)

Metrics for Success

Project Plan: Tasks (T) & Milestones (M)		Done by:	Status by first review
T1	**Three-dimensional etching of III-N nanostructures**		
M1	Develop vertical crystallographic wet etch for AlGaN and AlN	FY19 Q3	completed
M2	Develop tapered crystallographic wet etch for GaN and AlGaN	FY20 Q1	In progress
M3	Develop selective lateral etch for Al(Ga)N/GaN heterostructures	FY20 Q4	
M4	Determine achievable emitter tip geometries and vertical gap dimensions	FY20 Q4	
T2	**Field emission studies of GaN and AlGaN nanoemitters**		
M1	Model electric field profiles for candidate field emitter geometries	FY19 Q3	completed
M2	Compare emission of GaN vs AlGaN nanoemitters as function of Al composition	FY20 Q2	Complete first field emission studies of GaN nanowires
M3	Study dependence of emission behavior on nanogap size and ambient (vacuum vs air)	FY20 Q3	
M4	**Demonstrate emission current > 1 µA (> 100 nA at 5V) and downselect to optimal emitter design(s)**	**FY20 Q3**	**Go-no-go for devices: emission current too low or unstable**
M5	Study time-dependent degradation effects in vacuum and atmospheric ambients	FY21 Q2	
T3	**Design and demonstration of (Al)GaN vacuum nanogap prototype devices**		
M1	Propose preliminary 3D lateral and vertical nanogap diode and FET device designs	FY20 Q1	In progress
M2	Grow required heteroepitaxial III-N epilayer structures by MOCVD	FY20 Q2	
M3	Demonstrate III-N vacuum diode with turn on V < 5 V	FY21 Q1	
M4	Develop theoretical model of nanogap vacuum device physics	FY21 Q3	
M5	Demonstrate III-N vacuum FET with turn on V < 5 V and frequency > 100 GHz	FY21 Q4	
T4	**Radiation effects studies**		
M1	Evaluate x-ray radiation response of (Al)GaN emitters and device structures	FY20 Q4	
M2	Study impact of proton damage on emitter and device operating characteristics	FY21 Q2	
M3	In-situ measurement of device response in transient radiation environment	FY21 Q4	
Final SAND Report		FY21 Q4	

Metrics for success: Milestones, publications, presentations, IP

Right Team and Resources

*"The team is **extremely knowledgeable in GaN fabrication**, where the bulk of the effort lies, and Alec Talin has extensive experience characterizing & understanding field emission devices. The team also has an SEM that will facilitate the characterization of why the device are functioning (or not functioning)… and that capability **puts them ahead of most groups in this field**." "Also, **there are two managers at Sandia with extensive experience in field emission device physics**. Both could advise with interpreting the data, sleuthing problems, etc. without draining the budget.*

Name	Org	FTE	Role
George T. Wang	1876	0.27	Principal Investigator
Keshab Kapkota	1864	0.60	Tip/device nanofabrication, characterization, field-emission studies
François Leonard	8342	0.17	Theoretical Modeling
Brendan Gunning	1876	0.18	III-nitride MOCVD growth
A. Alec Talin	8342	0.15	Device/field-emission characterization
Michael King	5268	0.15	Radiation effects studies

- Key Enabling Resources: MESA (Nipon Sanso MOCVD Tool, MESA ANT Tool), CINT (Nanofabrication, device fabrication, etc.), Ion-Beam Laboratory
- Access/ownership to all needed growth, fabrication, characterization and modeling tools

Year	Labor	Purchases	Travel	Total
FY19	$545K	$10K	$5K	**$560K**
FY20	$555K	$10K	$5K	**$570K**
FY21	$565K	$10K	$5K	**$580K**

Why Sandia? Why Now?

- **World leading enabling capabilities for 3D fabrication of GaN nanostructures**
  - Thousands of man-hours invested ,18 publications, 3 patents, in top-down nanowire photonics since 2011 (>350 citations)
- **Vast investments/expertise** in III-nitride growth, fabrication, characterization, modeling, and devices: solid-state lighting, lasers, HEMTs, power-electronics
- **Expertise in field-emission devices**
- **Strong mission-relevance/impact:** rad-hard, high-T electronics, high-speed (GHz-THz) devices, novel optoelectronics, sensors, etc.
  - Nuclear weapons, radar/communications, deep UV optoelectronics
- **No current known competition in this area**

Opportunity to open and lead a new field for III-nitride based vacuum nanoelectronics!

Vision of a Successful Project

Vision: Establish the scientific & technological foundation for a new, world-leading and differentiating capability for III-N Vacuum Nanoelectronics

- Provide *fundamental scientific understanding* of:
  - Behavior and physics of III-N nanogap vacuum emitters & devices at atmosphere
  - Operational characteristics
  - Barriers & mitigation: e.g., stability, degradation issues, etc.
  - Outlook and viability of (Al)GaN for vacuum electron devices
- Advance state-of-the-art in 3D etch processes for GaN and AlGaN
- Demonstrate first-ever prototype (Al)GaN vacuum nanoelectronic devices
- *Broad impact* across multiple application spaces: rad-hard, high temperature, high-speed devices, integrated optoelectronic-logic, etc.
- Break open a new field and establish clear leadership position to pursue numerous follow-on opportunities
  - *On-chip electron-beam pumped deep UV optoelectronics?*
  - *Mission-related applications*

Reviewer Feedback

- *"The proposed project has **very high programmatic strength**…This may facilitate radiation-hard high-voltage and/or high-frequency electronics, thus addressing two of the IA's thrusts (trusted radiation-hardened microsystems, nanoscale and microscale enabled performance). Further, application to sensors and optoelectronics, two more IA thrusts, is also possible. Beyond potential application to the mission, the **basic science knowledge** generated in this project is likely to be **new, novel, and publishable**."*
- *"**The convenience of not requiring a vacuum are appealing to reduce traditional barriers to producing and fielding vacuum electronics**. The low electron affinity, and chemical and radiation robustness of (Al)GaN over Si makes the material platform highly advantageous"*
- *This work **leverages Sandia's capability in GaN and AlGaN fabrication** to explore an opportunity in nano-gap field emission devices… Given our mission space, **we should be taking a critical look at this technology**. ... GaN and AlGaN materials are [vs. Si] more refractory, potentially have more stable surface states, and its higher band gap could produce effective ballast behavior with higher voltage breakdown. **These properties should lead to more stable, better performing devices** (on paper, at least). **This work could open up a new field in high speed, rad-hard electronics.***
- *The work in this proposal **gets high marks for game-changing potential**, but at the same time, it is **also high risk** because the physics simply may not cooperate... They will be challenged to hit the performance metrics they seek - yet this is appropriate for an NMRF LDRD.*

Response to Reviewer Feedback

NMRF Committee Feedback: "Some concern was raised about operation in air ambient and potential for GaN surface modification or contamination, leading to device failure"

Response: These effects will be studied as proposed. (Al)GaN is expected to be **more chemically stable** (surface states, oxidation) compared to Si or metal. If an issue, we note hermetic packaging in inert gas or even vacuum chip packaging are mitigation options. For inert gas packaging, sputtering can still present an potential issue, but should be mitigated by the high bond strength of GaN. Additionally, the lower required operating voltages enabled by nano-scaling the vacuum channel should also mitigate sputtering effects.

Response to Technical Reviewer 1 Feedback

"how small must the separation between the anode and cathode be, and how well controlled can the etch be to achieve this? "

Response: Recent demonstration for Si vacuum nanoelectronic FET using 150 nm gap. With e-beam lithography, < 100 nm gap size can be achieved for a lateral gap, and with bandgap selective etching, < 5 nm gap size is possible.

"there is no good etch-stop for AlGaN, and PEC etches lower band gaps, yet the highest band gap AlN layer is what needs to be etched to create the right gap, based on Fig. 4."

Response: Chemically selective (vs. bandgap selective) etch for AlN over (Al)GaN can be explored

"What is the required tip geometry? Figure 3 implies ~ 1 nm. What makes the proposers confident that this can be [achieved]"

Response: This is just a simulation. Due to the nanoscale gap and local field enhancement, very sharp tips are not expected to be required. Less sharp tip designs have the potential benefits of more uniform fabrication, stable operation, lifetime, and higher breakdown.

Is there relevance of a vertical geometry if it cannot produce a FET device?"

Response: Vertical gaps can be made smaller (down to few nm), enhancing scaling benefits for diodes and other concepts like resonant tunneling diodes, even if FETs are difficult to realize

Response to Technical Reviewer 1 Feedback

"100 GHz is listed as the target frequency. What performance metrics lead to achieving such a high frequency? Is it a case of "it works or it doesn't? "

Response: An electron travels through 100 nm vacuum channel at 5 eV of energy (5 V bias = 500kV/cm) takes $\tau = 0.15$ ps; cutoff frequency $f_c = 1/2\pi\tau$ = **1.07 THz theoretical**. Recent demonstration for Si vacuum FET with 460 GHz cut-off frequency. 100 GHz was thus chosen as an impressive yet potentially realistic target given stray capacitance and other effects.

What is the projected current level of such devices, and what mission need is met by such devices? A specific mission pull is not identified to match the technology push."

Response: The projected current level could range from tens to thousands of nanoamps. Higher currents could be achieved with arrays of nanoemitters and higher powers could be enabled by larger emitters with lower β. As the project proceeds, more specific mission related applications will become more easily identified. Mission-relevant needs may include rad-hard nuclear weapons electronics, radar, satellite and other high frequency electronics (e.g. K and K_a bands), logic and sensors for harsh environments, integrated optoelectronics/sensors, and others.

Response to Technical Reviewer 2 Feedback

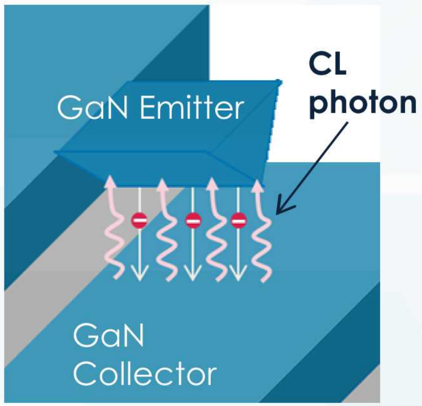
“The key technical risk… is in the team's ability to understand the electron emission physics enough within the budgetary confines of an LDRD ... The GaN/AlGaN system is particularly challenging in that there are multiple areas of physics acting on field emission, including low work function surfaces, band structure, semiconductor carrier limitation, surface states(absorbed molecules, oxides, carbides, etc), and vacuum space charge. With operation in air … I expect field emission will come from a tricky surface state (as is the case in Si, metals, nanotubes, etc.) that will not have the low work function of GaN/AlGaN (because low work function surfaces are reactive), but might be more stable than for Si. The team is well aware of this, but the budget does not support both building devices and performing detailed surface science studies (although the in -situ SEM will be very helpful)… The risk is in understanding what knobs to turn on iteration#2 to achieve operation at 5V and reasonably stable currents in individual devices above 100 nA. ”

Response: Agreed, there are many complex and challenging issues regarding field emission. We hope to identify the most significant of these and consider performing limited surface science studies, perhaps through collaboration or with the help of a student. We also have the benefit of drawing on the expertise in field emission here at Sandia (including the reviewer!). We note that operation at higher currents, emission from single contaminants becomes less important. Nanogap scaling may also provide novel ways of mitigating these challenges.

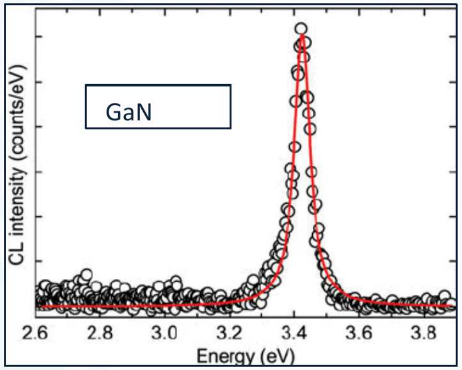
Backup Slides

Cathodoluminescence: A novel mechanism to enhance emission in direct bandgap vacuum electronic devices

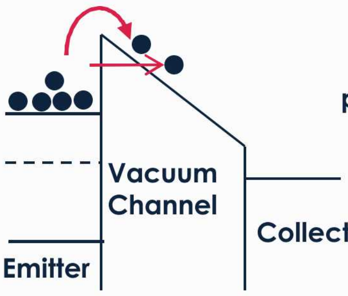
Cathodoluminescence (CL) and Feedback Mechanism



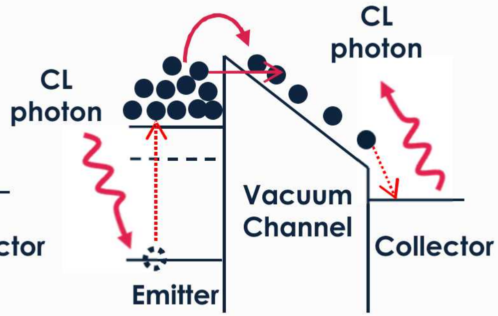
CL feedback arrangement



Gunasekhar eal., Microscopy and Microanalysis (2013)



No CL feedback

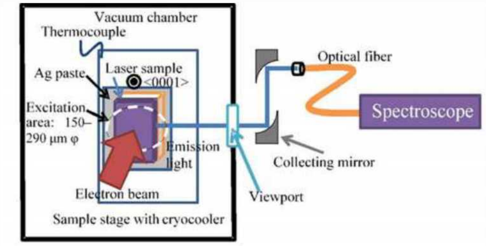


CL feedback

- Never explored before! (relevant for direct-bandgap materials e.g. GaN)
- Potential Effects/Benefits:
  1. Reduction of turn-on voltage?
  2. Novel heat-removal mechanism via photon emission
  3. On-chip electron-beam pumped deep-UV optoelectronics?

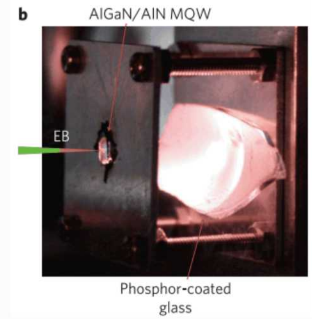
GaN nanogap electronics: A route to fully integrated electron beam pumped Deep UV Optoelectronics

- Deep UV light sources important for water purification, lithography, chem/bio detection, etc.
- AlGaN: most promising solution for solid-state-based deep UV emitters. However, difficulties in p-type doping of AlGaN leads to low device efficiencies.
- Recently, electron beam pumped UV emission/lasing from AlGaN-based structures has been demonstrated and removes the p-doped layer requirement. However, this requires external e-beam gun and vacuum chamber, without an obvious on-chip integrated implementation.



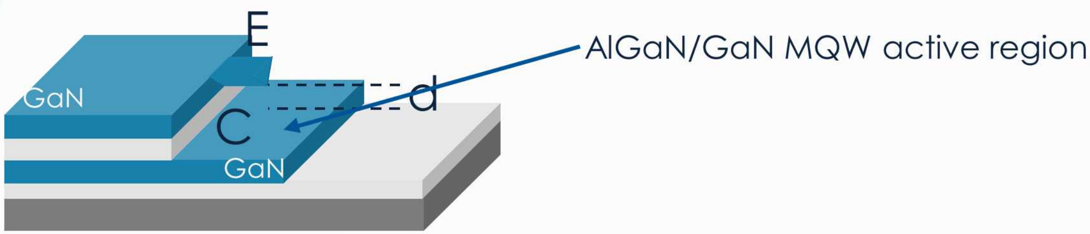
ucture. (b) Exterior photograph of the electron beam excitation

T. Hayashi et al., *Sci. Rep*. 2017



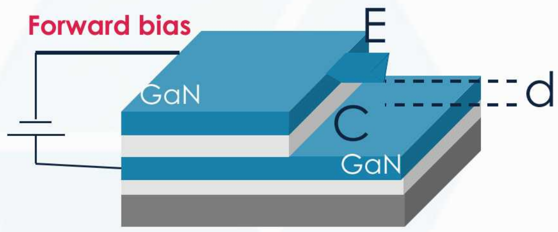
T. Oto et al. *Nat. Phot.* 2010

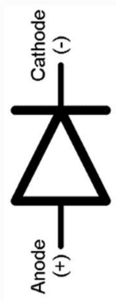
We propose that 3D GaN nanogap electronics can enable integrated deep UV LEDs and lasers by adding an optical active region (e.g. AlGaN/AlGaN MQWs) to the collector, and without the need for vacuum or an external electron gun.

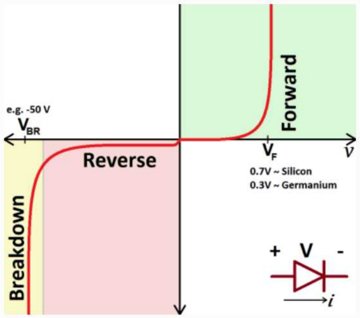


Demonstrate GaN nanogap vacuum diodes

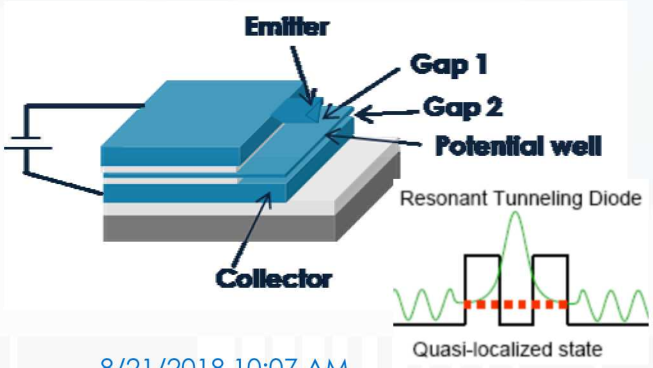
1. **Vacuum Diodes (VD):** Optimize field enhancement factor β via sharp 3D emitter designs

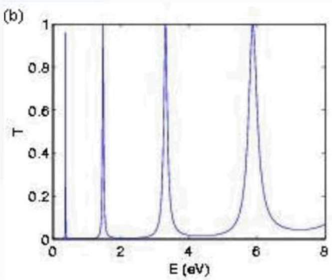




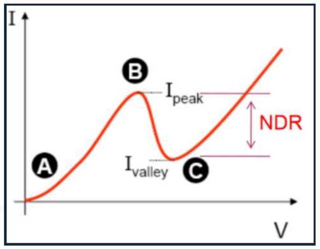


2. **Resonant Tunneling Vacuum Diodes (RTVD):** Creating two vacuum channels separated by a potential well (N^+ doped GaN) between emitter and collector act as a resonant tunneling diode. **Application: IV characteristics often exhibits Negative Differential Resistance (NDR) which can be utilized for signal amplification**

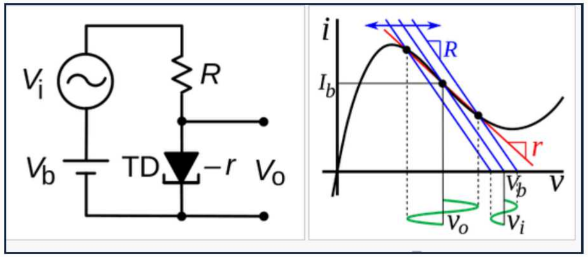




Transmission probability



Typical I-V characteristics

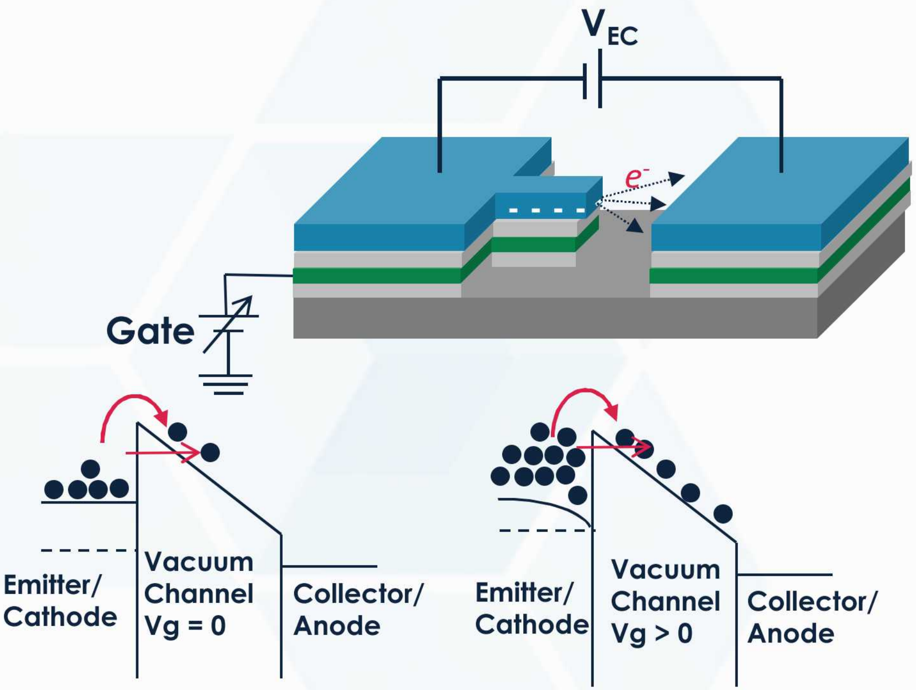


RTVD as an amplifier

Demonstrate GaN nanogap vacuum transistors

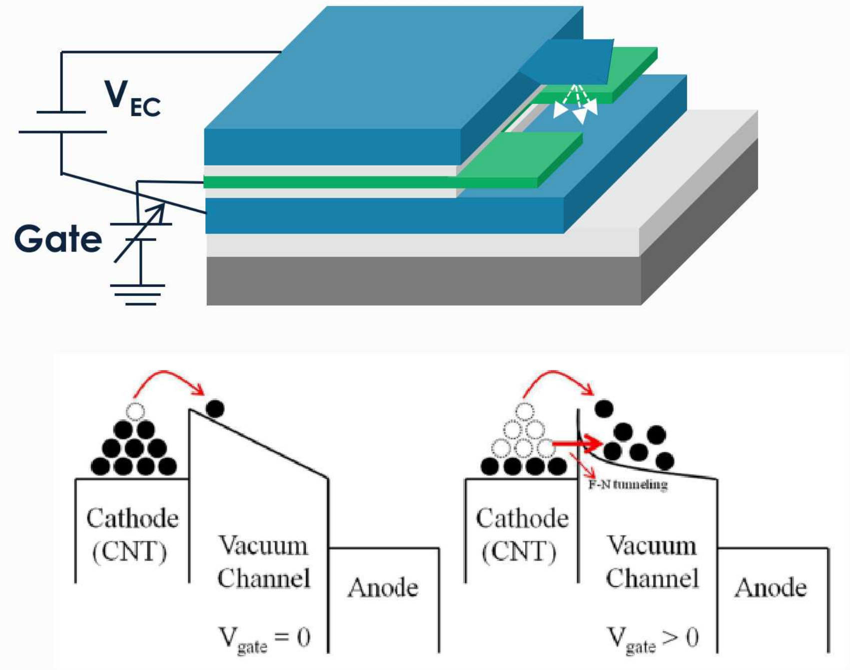
Vacuum Field Effect Transistors (VFET):

Lateral Nanogap VFET



Easier to fabricate but gap size limited by lithography resolution

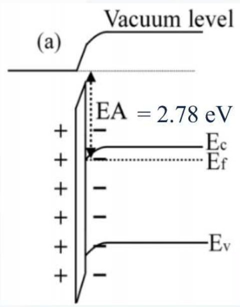
Vertical Nanogap VFET



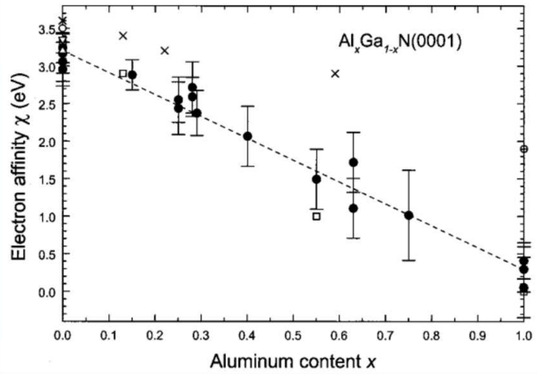
Smaller nanogap possible by selective etching of thin epitaxial sacrificial layer

Study Field Emission in 3D GaN Designs

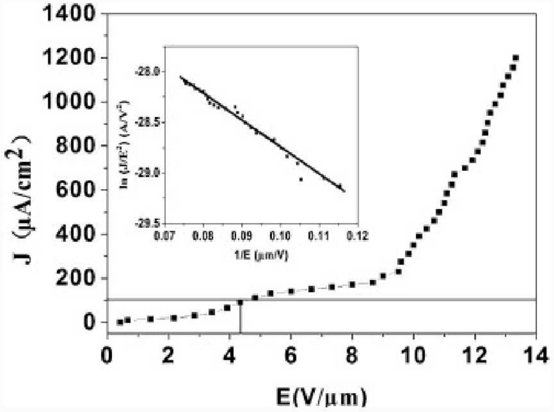
- **Study of GaN based field electron emission property, optimize for low voltage emission**
  One of the Major challenge in fabricating useful VNE is to realize low voltage field emitter. GaN is an ideal choice due to its low electron affinity. Doping of Al on GaN further reduces its electron affinity



N-Polar GaN surface
Reddy et al., JAP (2014)



Grobowski et al., APL (2001)



Nagaosa et al., Materials Research Bulletin (2014)

- **Theoretical background**

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

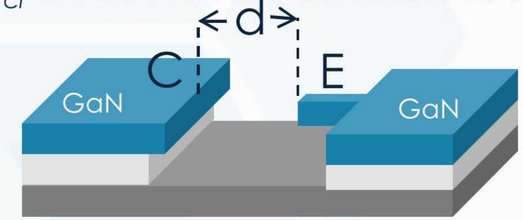
J ➔ Emission current density
φ ➔ Work function. For heavily doped n-GaN, $\varphi \sim \chi$
V ➔ Potential difference between emitter and collector separated by distance d
β ➔ Field emission enhancement; A and B are constants

- **How to improve J while keeping V low?**
  1. **Improving β:** Reported β for GaN nanowires ~ *555* (Kim et al., J. Crystal growth (2003)). β can be further improved by defining sharp emission geometry
  2. **Reducing φ** by doping suitable amount of Al and using nitrogen polar surface as emitter
  3. **Reducing d** by specific device designs. Horizontal devices will have lithographically defined gap between emitter and collector, vertical devices will have interlayer-etch defined gap which will have higher resolution
  4. **Cathodoluminescence Feedback**

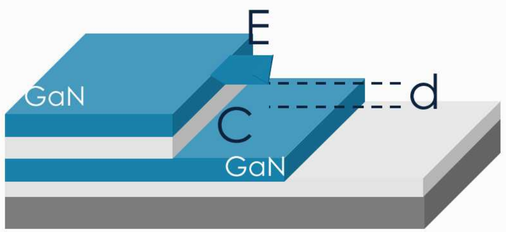
Study Field Emission in 3D GaN Designs

- **Experiments: (1) Device fabrication (2) I-V measurements at various conditions**
- **Target Turn-on Field < 5 V/µm?. For a device with d = 20nm, target turn on voltage < 100mV. This achievement will be comparable to or better than common low voltage solid-state FET but with ~∞ breakdown voltage!**

1. **Air as a vacuum channel:** Find **critical distance/gap (d_{cr})** between emitter and collector in air so that $d \le d_{cr}$ is vacuum like emission at STP



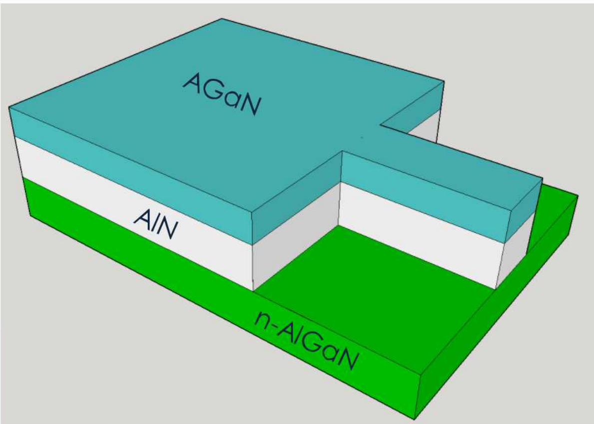
Horizontal device layout



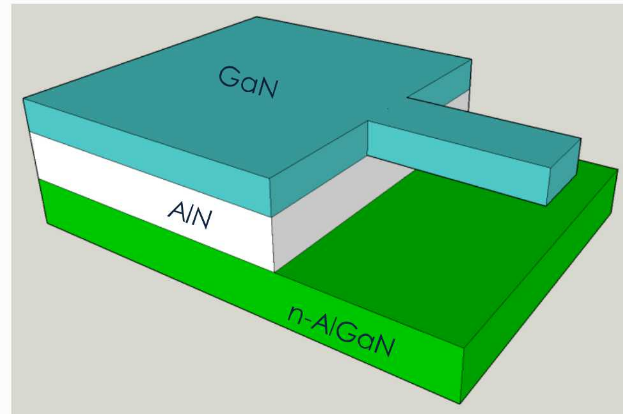
Vertical device layout with wedge shape emitter

2. **Emitter geometry optimization (enhancing β):** Fabricate by e-beam lithography and selective etches GaN emitter both in horizontal and vertical layouts with various sharp geometries to test the **effect of geometry (radius of curvature) on the field emission.**
3. **Test fabrication limits to minimize d:** E-beam lithography and etching (ICP, PEC, Wet) experiments on horizontal and vertical device layouts to **minimize d** while retaining field emission properties.
4. **Reducing work function (*φ*):** n-doping of GaN can reduce the *φ* up to the point of electron affinity **(*χ*)**. Alloying of Al on GaN reduces electron affinity thus provides more room to tune work function.

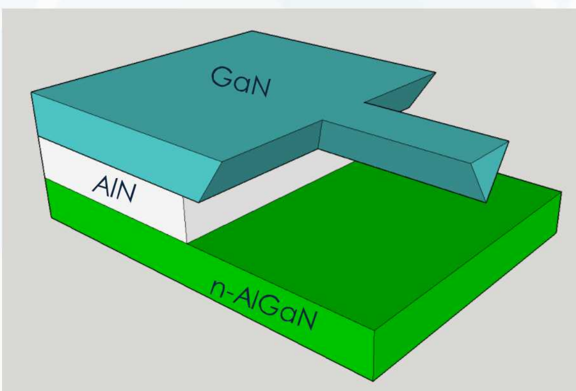
Vertical VFET Fabrication Steps



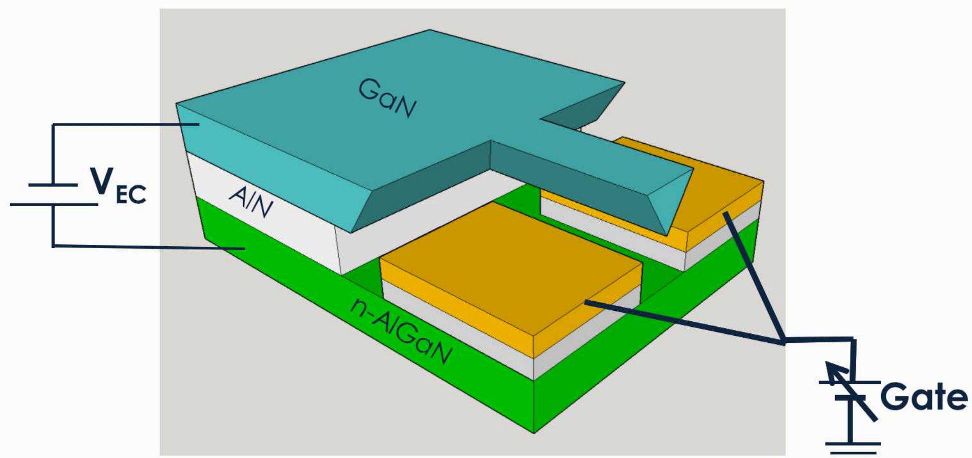
Step1: EBL and ICP etch



Step2: AlN selective wet etching



Step3: KOH etching to produce wedge shape on the N-polar surfce



Step4: Dielectric and metal deposit for gate

How much field can a nanogap in air hold?

- Possible mechanism of electric breakdown of nanogap in air
  1. **Paschen's law is insignificant.** According to this law, electrons emitted from cathode (emitter in our case)acquire enough energy to dislodge electrons from oxygen (1st ionization energy ~12 eV)or nitrogen (1st ionization energy ~15.6 eV)molecules, causing avalanches of electrons which repeat the process and produce electric discharge/breakdown through air. This mechanism is significant only if an electron can travel more than its mean free path (~ 500 nm) in air. Thus, nanogap < 100 nm cannot produce electric breakdown by this mechanism. Although there may be negligible collision probability of electron with air molecules, almost all of such collisions will be elastic if the bias across nanogap is <12V.
  2. **Breakdown by molecular orbital distortion:** One possible mechanism of breakdown is to rip off electrons from oxygen or nitrogen molecules. For an oxygen molecule of size ~ 152 pm and the 1st ionization energy ~12 eV, the electric field required to remove electron is 80KV/µm. The actual operating voltage of VFET transistors/diodes will be 10V/ µm. Thus VFET devices are highly unlikely to suffer from breakdown in wide range of operating conditions.

Science Questions

- **Time Dependent Field Emission:** During high frequency operation of vacuum device, emitter will be subjected to time dependent electric field and the electrons emission may undergo through non-equilibrium cold field emission process, a not-well-studied area! For GaN, $m^* = 0.2\ m_e$, $n = 1E25\ m^{-3}$, $\varepsilon = 5.8$ (high Hz), plasma frequency: $f_p = 11.8$ THz. Does operation of VFET at THz frequency interact with plasma frequency? Other unknown phenomenon during high frequency operations!

- **Non-Linear Field Emission:** Irregular surface morphology in nm scale causes strong variation of electric field on the surface and affects field emission of electrons. This situation cannot be well represented Fowler-Nordheim Field Emission equation and demands new empirical and theoretical investigations to a **field emission.**

- **Vacuum like field emission on air environment**

- **How CL affects the electron collection efficiency at collector?**

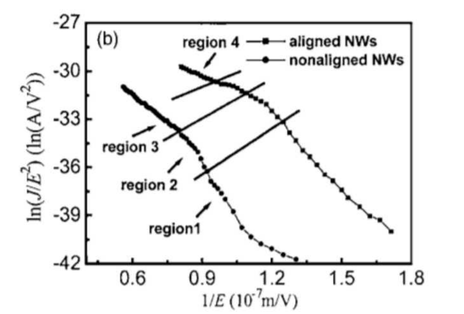


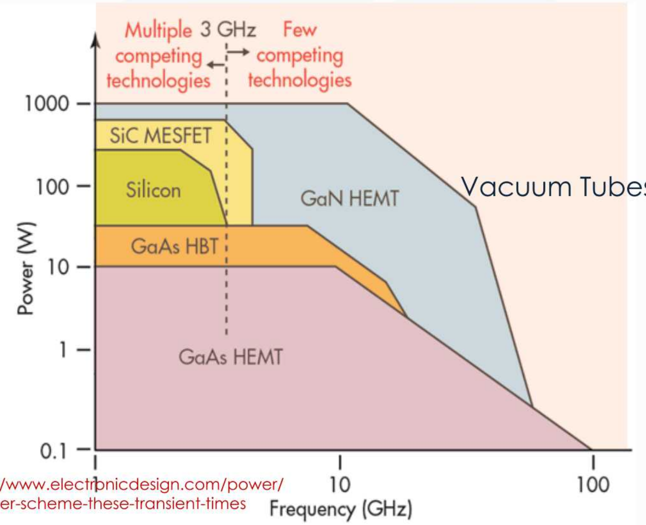
FIG. 3. (a) *J-V* curves of the aligned and nonaligned In_2O_3 NWs, and (b corresponding F–N plots, which were divided into several regions.

Non-linear field emission

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 use!

High power high frequency



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

Resistant to radiation and EMP

Example: tubes are 10,000 to 50,000 times more resistant than solid-state to destruction by an EMP. http://www.nutsvolts.com/magazine/article/vacuum_tube_in_its_100th_yearc

- **US Military/NNSA:** Radar, Communication Systems, MMW explosive detection spectroscopy, Nuclear systems monitoring, nuclear weapons, microwave electronic warfare applications
- **NASA:** Satellite communications, Electronics for space missions
- **US Electricity and Nuclear Power Stations:** Grid voltage surge monitor/control units, Monitor/control electronics in radiation harsh environments
- **Industry:** Industrial RF heating, RF broadcasting, THz technologies
- **Laboratories**: Particle accelerators

Why GaN for Vacuum Nanoelectronics?

Efficient Field Emission

Cold field emission current J is given by:

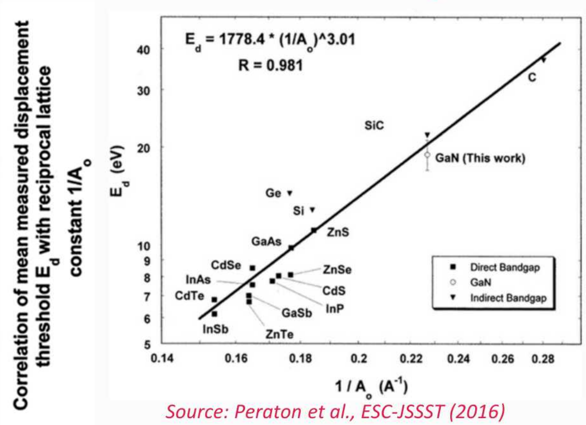
$$J = A\left(\frac{\beta^2 V^2}{\phi d^2}\right)\exp\left(-\frac{B\phi^{3/2}d}{\beta V}\right)$$

φ ➔ work function. $\chi \sim \varphi$ for heavily n-doped semiconductor

Lower χ is better for field emission

Rad & Electromagnetic Hard, High T

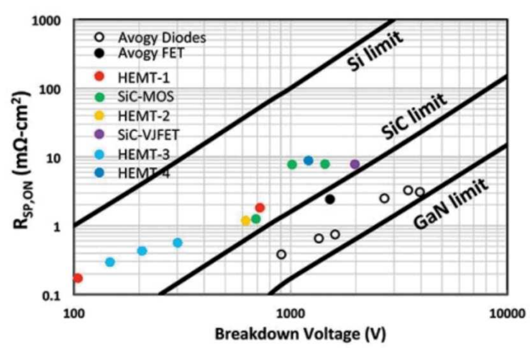
Stronger at. bonding, larger k, E_g are better



Source: Peraton et al., ESC-JSSST (2016)

High Power, High Frequency

Larger E_K, E_g are better



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

χ ➔ Electron affinity, E_K ➔ Critical field
K ➔ Thermal conductivity, μ ➔ Mobility

Best | 2nd best

Materials	Eg (eV)	Gap type	χ (eV)	k (W/cm ⁰C)	E_K (MV/cm)	μ (cm²/Vs)	Atomic Bond (eV/atom)
GaN (*polar surface)	3.4	Direct	Bulk - 4.1 Ga*- 3.4 N*- 2.78	1.3	5	1500	8.92
GaAs	1.4	Direct	4.07	0.5	0.4	5000	6.52
GaP	2.26	Indirect	3.8	1.1	1	250	
Si	1.14	Indirect	4.05	1.3	0.3	1300	2.34
Ge	0.67	Indirect	4.0	0.58	0.1	3900	
SiC (3C)	2.36	Indirect	4.0	3.6	~1.3	260	7.40

Sources:
http://www.ioffe.ru/SVA/NSM/Semicond

Hudgins et al., IEEE Power Electronics (2003)

Cathodoluminescence feedback | **Electron emission** | **High T applicable** | **High power & high Freq. applicable** | **Electrical transport** | **Rad. Hard Chemically stable**