Process Development Challenges Associated with Gallium Nitride Materials

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Introduction

- New faculty in RIT's Microelectronic Engineering program have helped expand its materials and processing portfolio.

- For decades silicon has been the semiconductor of choice used in the manufacturing of power transistors.

- The physical limitations of Si scaling are forcing the investigation and adoption of new materials.

- There has recently been an increased effort in the development of production-ready III-V compound semiconductors.

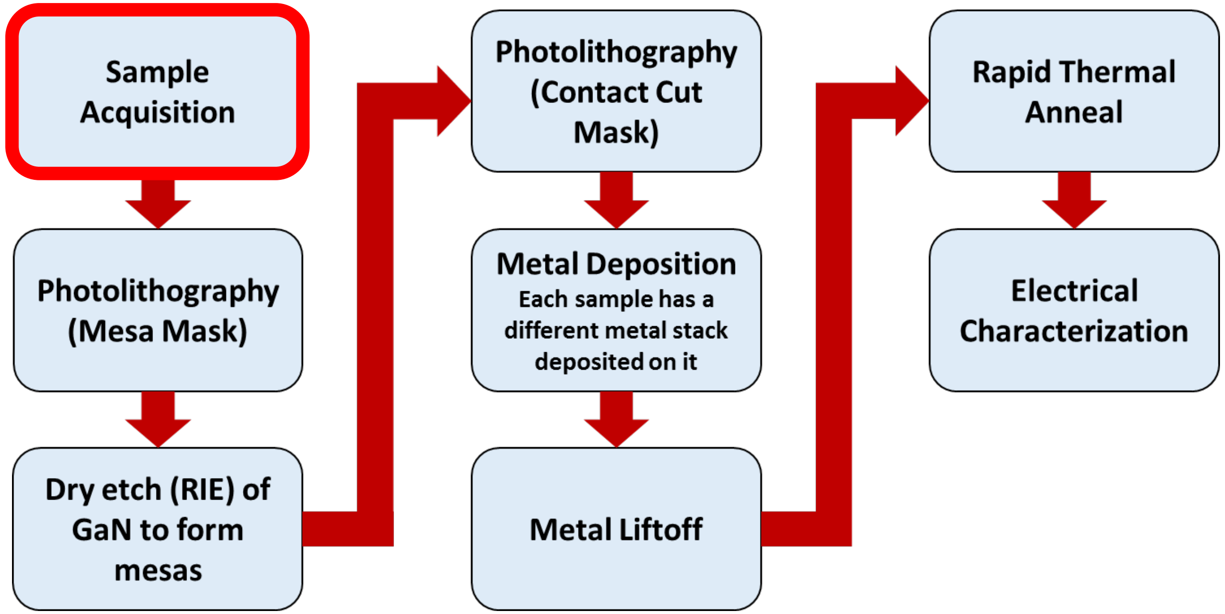
- **Gallium Nitride (GaN)** is an appealing alternative to Si.
  - ***Advantages***: Higher bulk mobility than Si, higher on-currents and lower off-currents, better thermal stability.[6,7]
  - ***Disadvantages***: Epitaxial growth of GaN films is still in development, further work needed for integration into a CMOS manufacturing environment.[6,7]

Project Goal

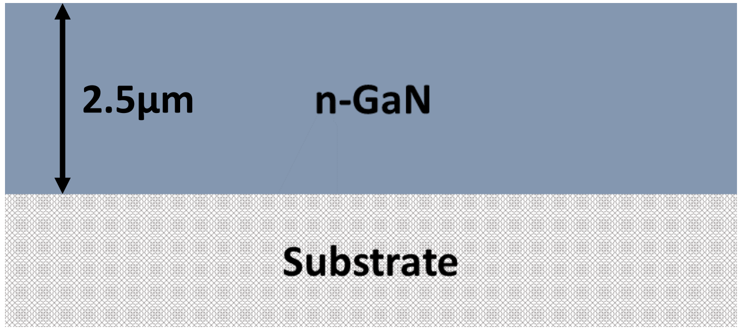
To develop a low resistance Ohmic contact metallization scheme to n-GaN and n-AlGaN substrates.

To develop reliable, *in-house* solutions to the processing challenges associated with GaN materials.

Project Process Flow

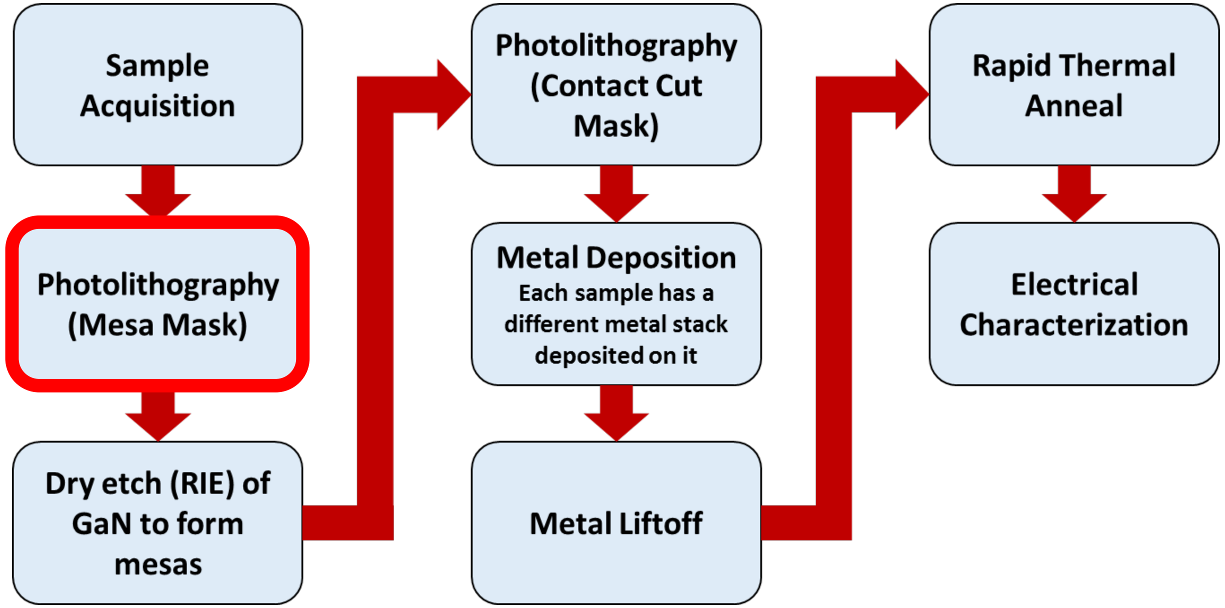


The process flow for the fabrication of Transfer Length Method (TLM) structures.



A starting GaN Sample.

Project Process Flow



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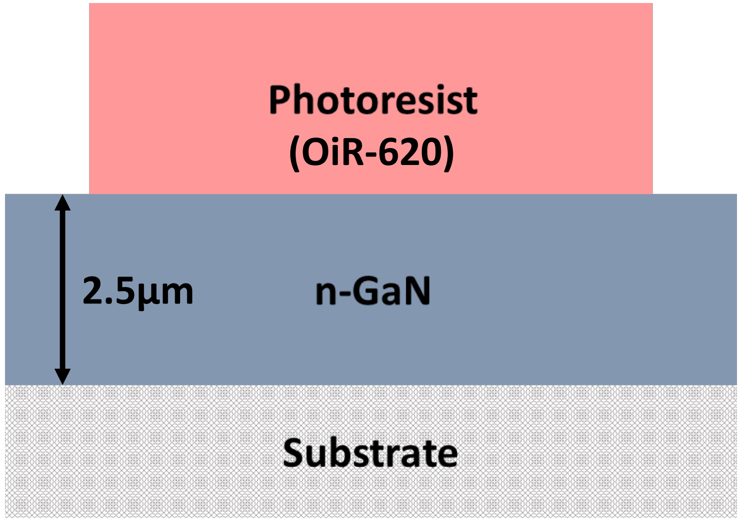
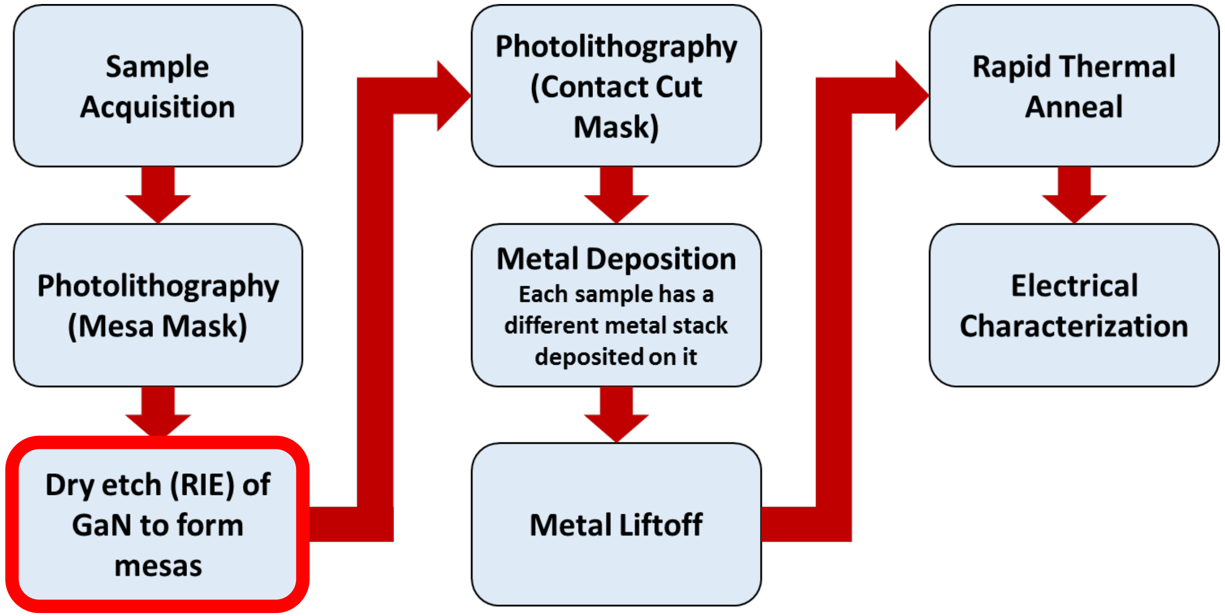


Mesa level photoresist patterning.

Project Process Flow



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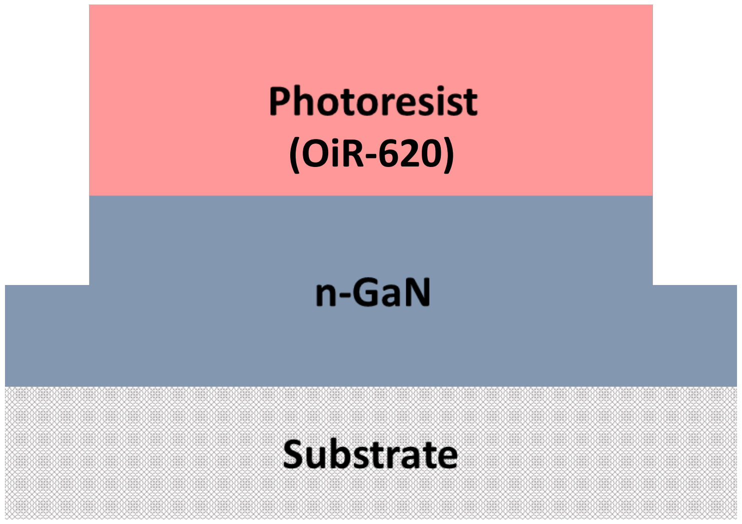
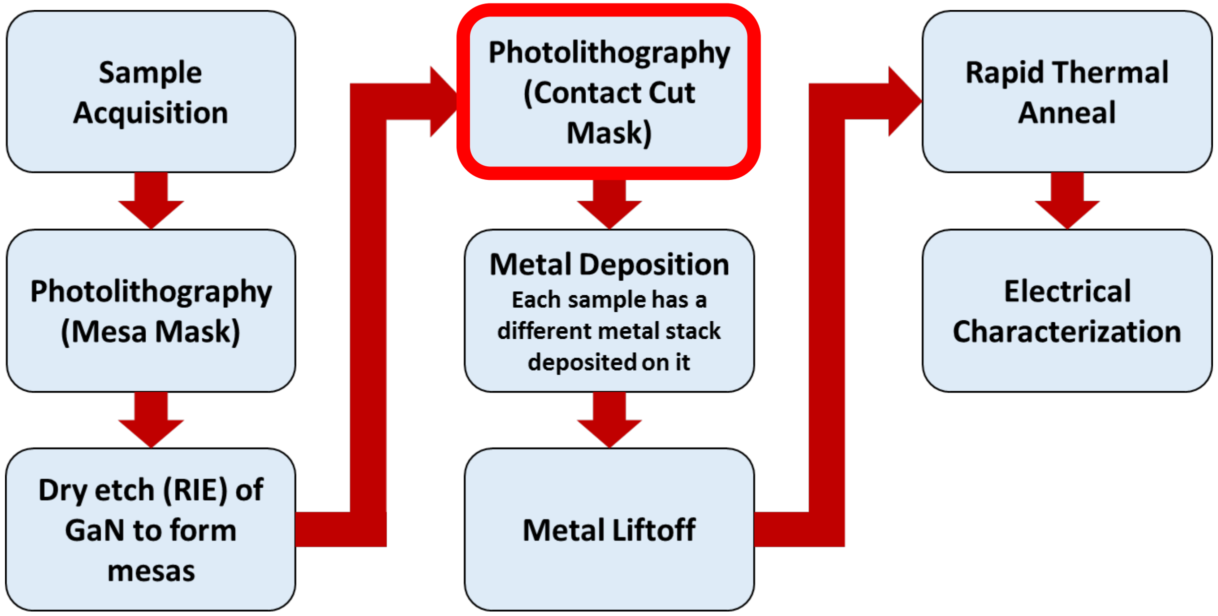


Dry etch of GaN to form mesas.

Project Process Flow



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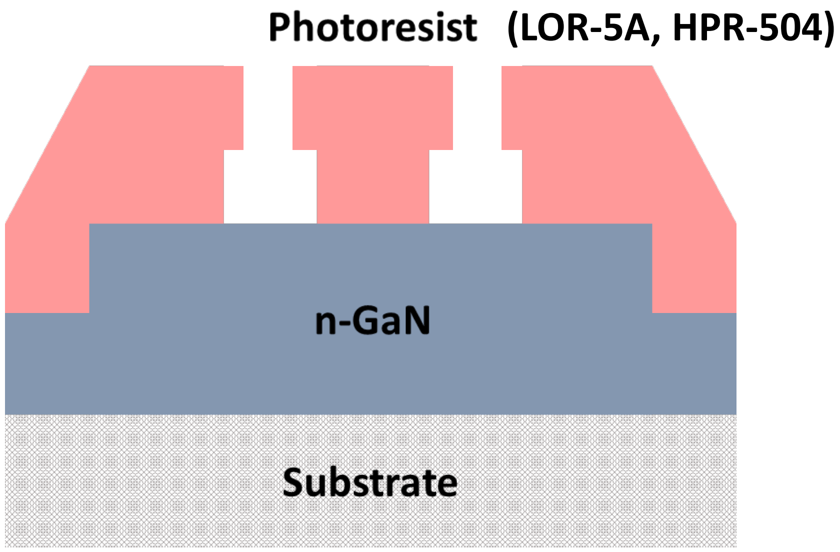
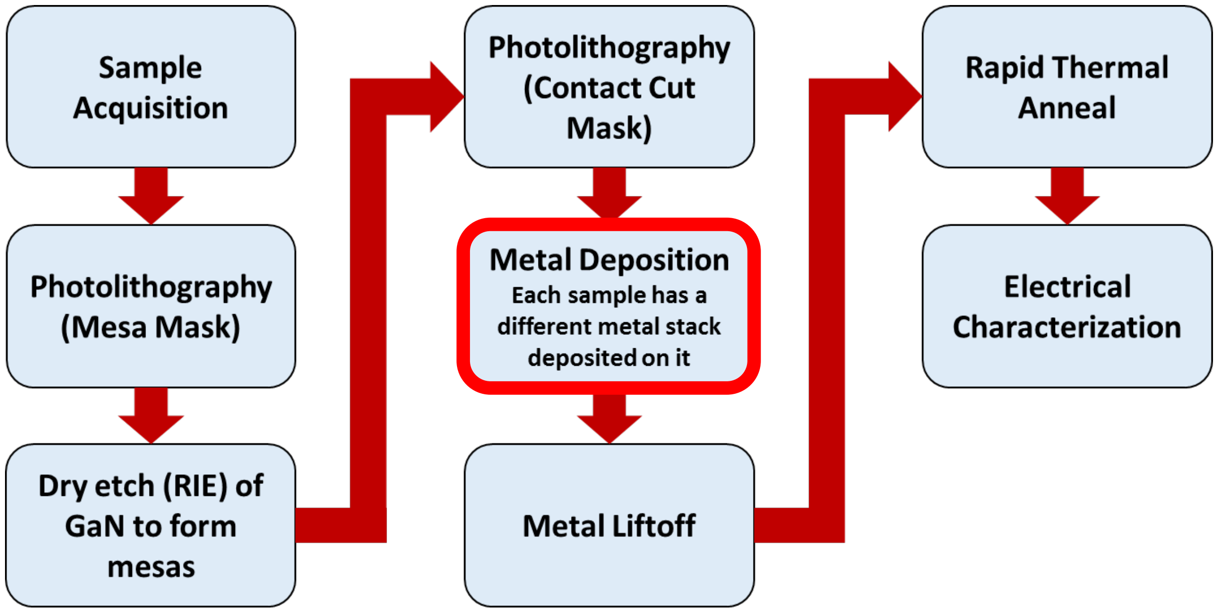
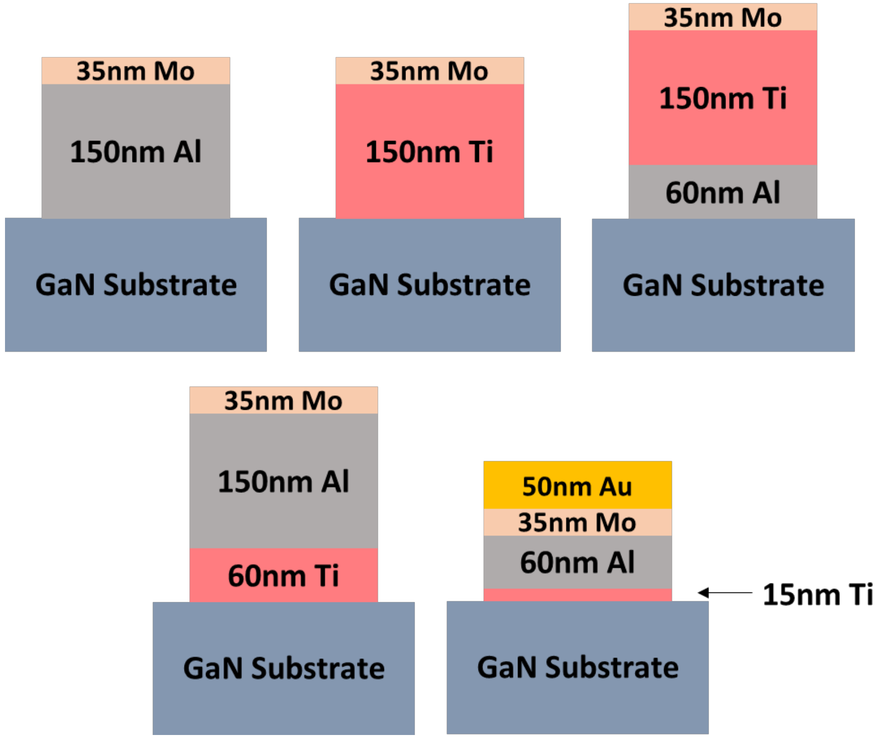


Contact cut level photoresist patterning.

Project Process Flow

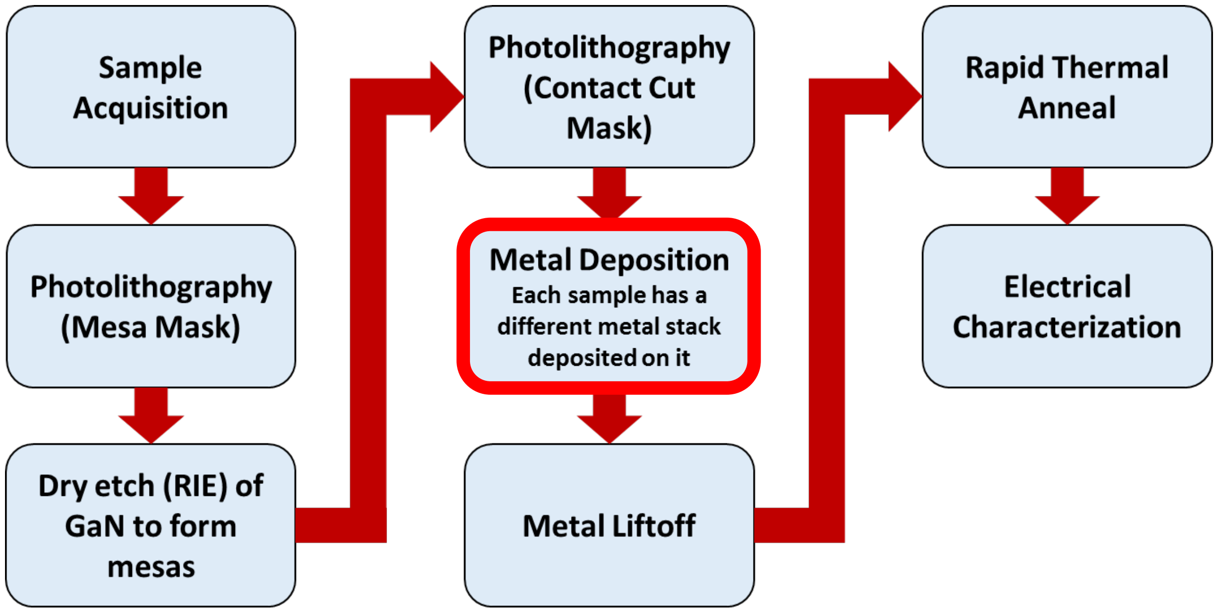


The process flow for the fabrication of Transfer Length Method (TLM) structures.



The principle metal stacks to be fabricated.[9]

Project Process Flow



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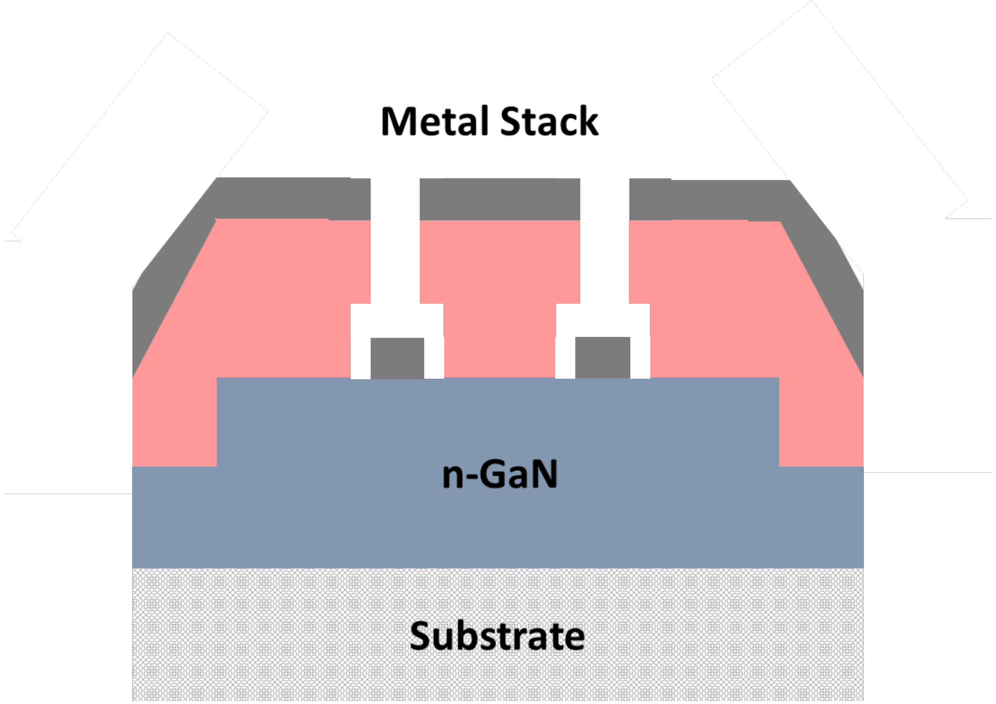
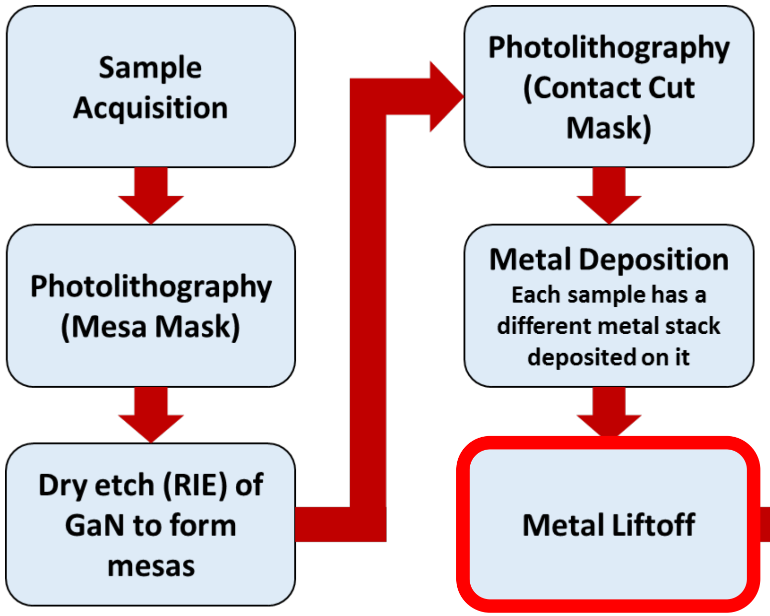


Metal deposition.

Project Process Flow



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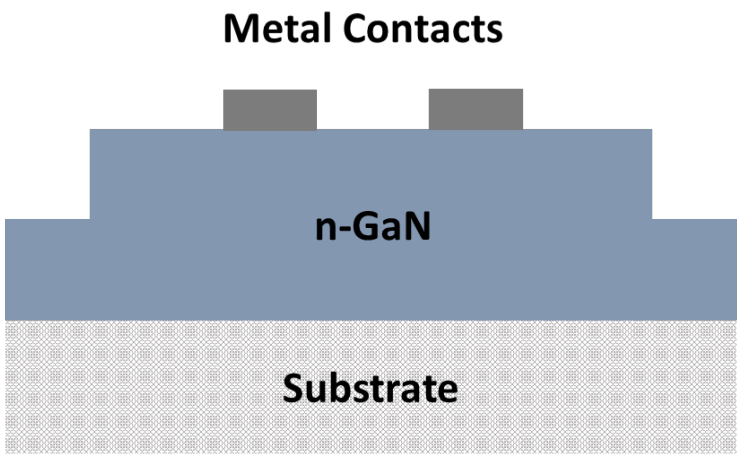
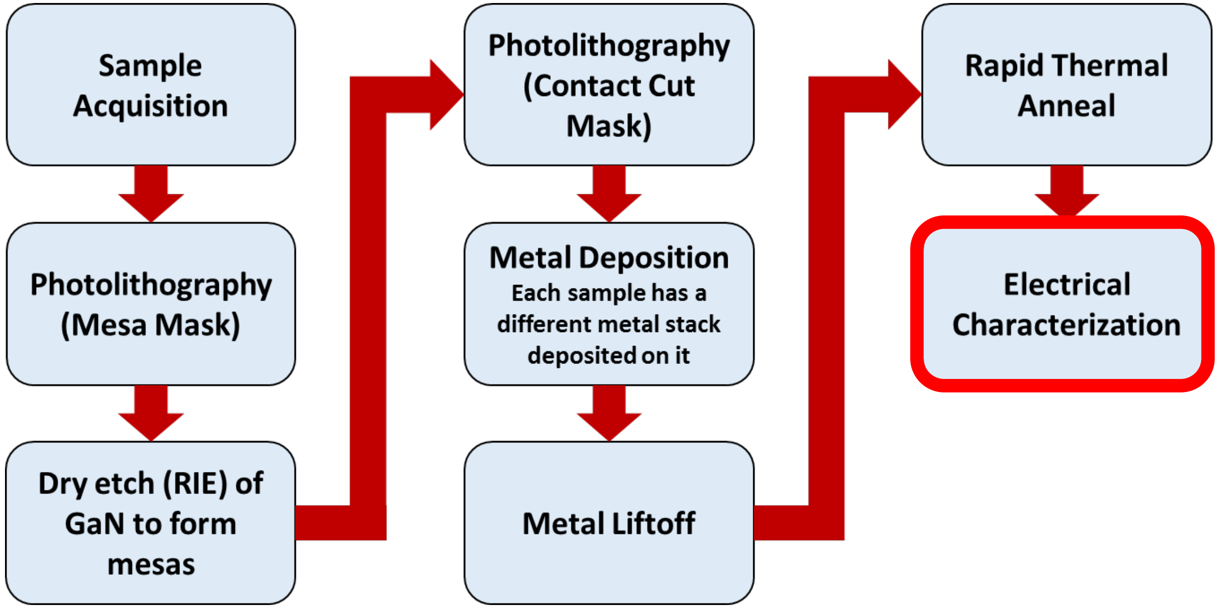


Metal liftoff via bi-layer resist liftoff process.

Project Process Flow



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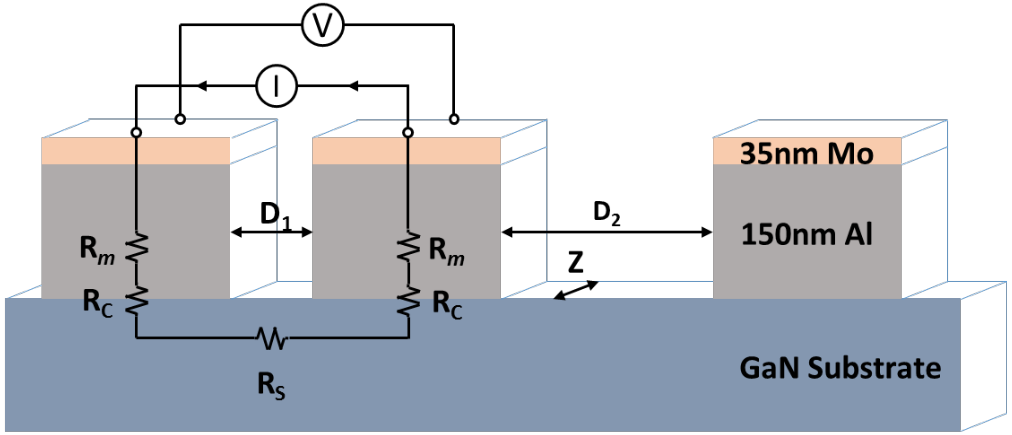


R_T = Total measured resistance (Ω)
R_m = Resistance of metal contacts (Ω)
R_C = Contact resistance (Ω)
R_S = Semiconductor resistance (Ω)
ρ_S = Semiconductor sheet resistance (Ω/sq)

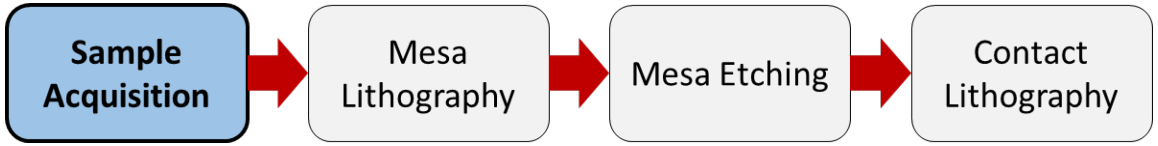
Electrical testing of a TLM structure.[5]

Major Process Challenges

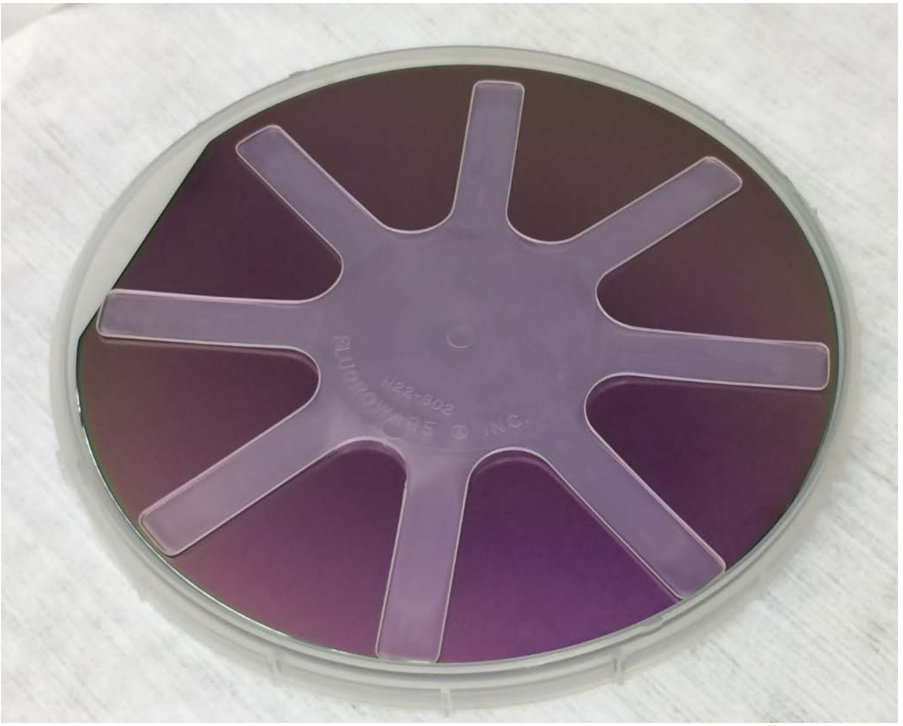
Four major processing challenges were encountered during this project:

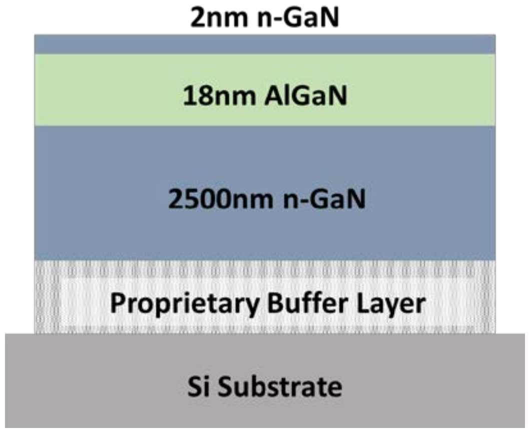
- Sample Acquisition
- Mesa Lithography
- Mesa Etching
- Contact Cut Lithography

Sample Acquisition



- GaN is epitaxially grown through metal-organic chemical vapor deposition (MOCVD) or molecular beam epitaxy (MBE). RIT's SMFL does not currently have the toolset necessary for either growth method.
- GaN growth is expensive, and outside vendors typically ask high prices.
- Free samples were provided by RIT alumnus Brian Romanczyk (UCSB), Texas Instruments, and Veeco.

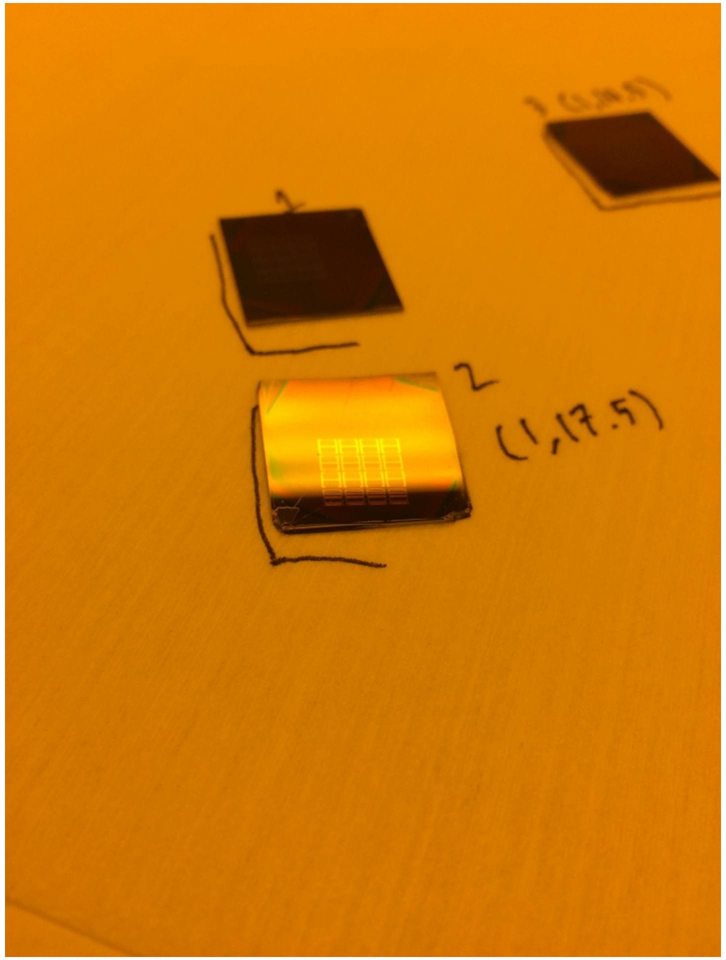




A 6" GaN-on-Si wafer provided by Texas Instruments.

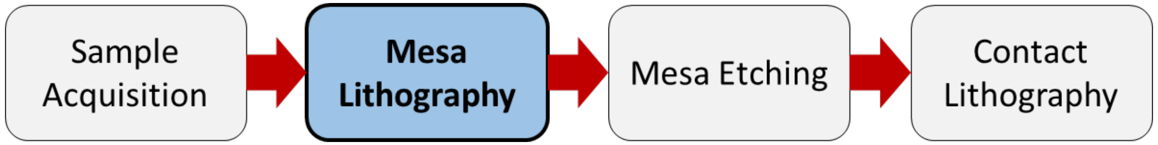
Mesa Lithography:
Issue

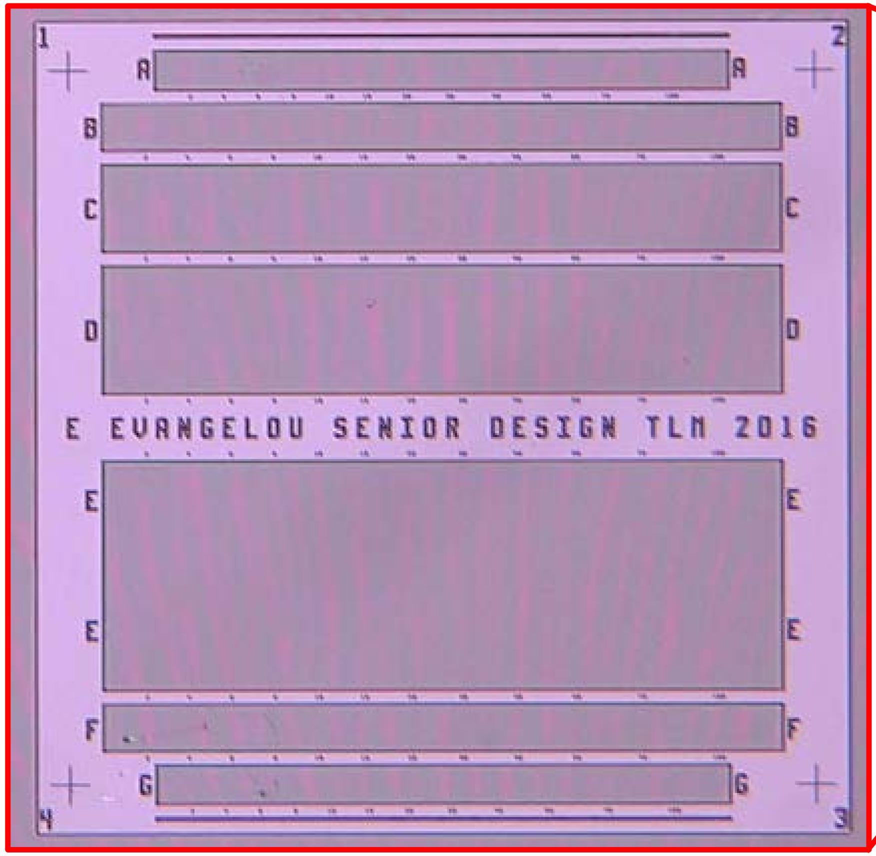
Sample Acquisition → **Mesa Lithography** → Mesa Etching → Contact Lithography



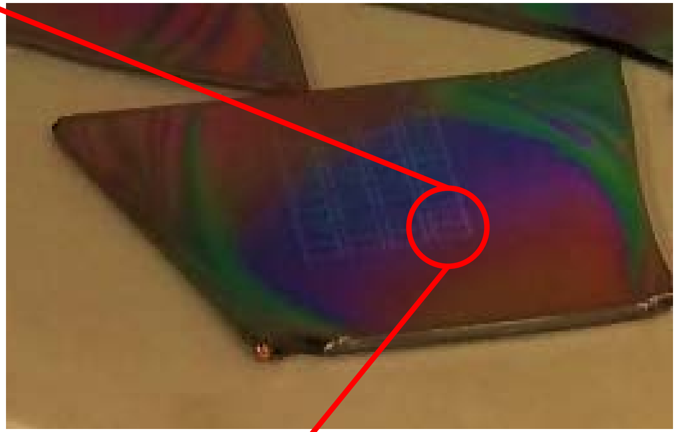
- Piece processing is a major “requirement” of working with III-V’s and is not standard in the SMFL.
- Spin coating OiR-620 photoresist on 4cm^2 GaN pieces required a new coating recipe to achieve the 1µm resist coating necessary as a hardmask during mesa etch. Traditional 2” Si wafer coating recipes did not produce uniform resist coatings.

Mesa Lithography:
Solution





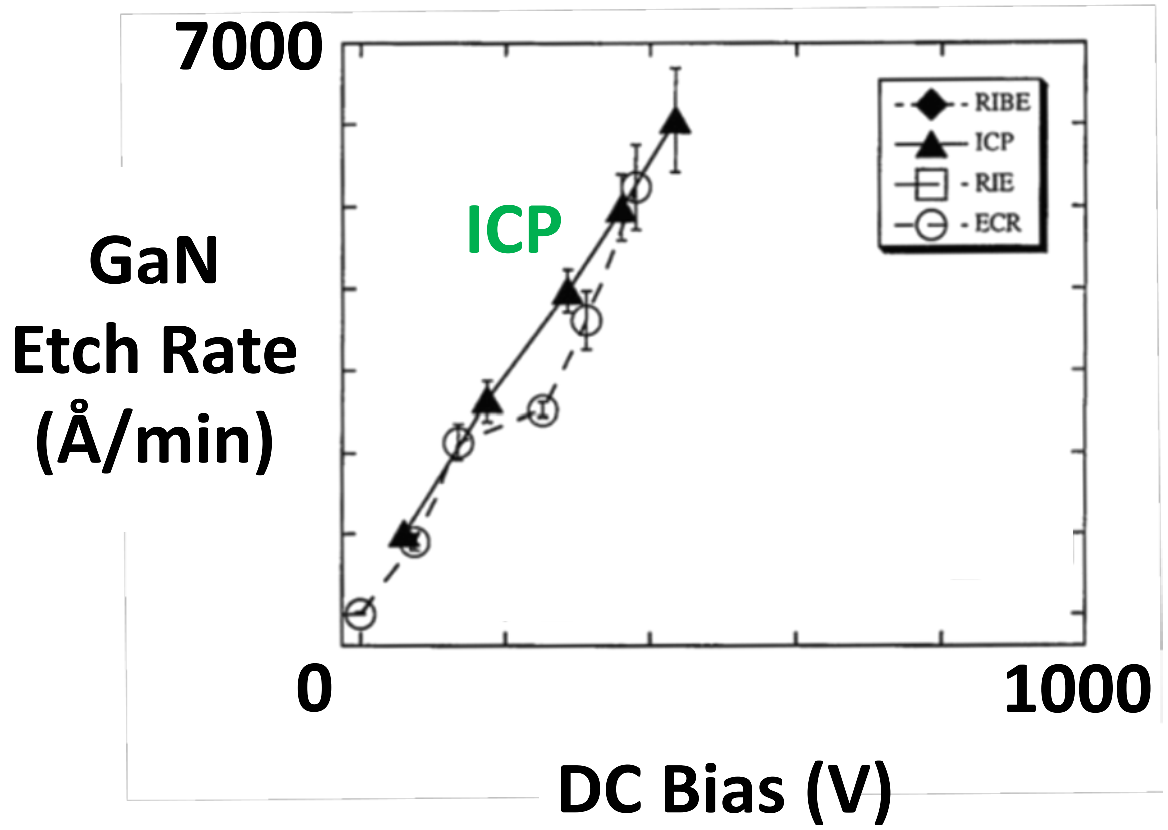
Mesa pattern imaged in OiR-620 resist on a GaN sample.



- The optimal coating procedure was determined iteratively, and was found to be:

  Puddle Coat,
  Step 1: 1500 RPM, 1s
  Step 2: 3500 RPM, 40s
  Step 3: Ramp down, 10s
- The resist had an average thickness of 1.103µm.
- **99% of die produced were usable.**
- Resist thickness needed to be measured using profilometry, as traditional interferometry was not producing accurate thickness measurements.

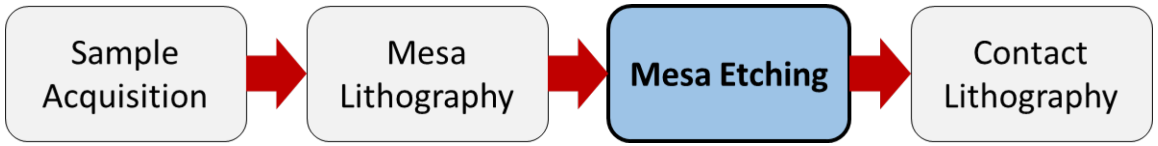
GaN Etch Theory



Etch rate of GaN in ICP etchers as a function of bias.[8]

- GaN is a tough material to etch. The Ga and N atoms are ionically bonded to one another, and as such it has a higher bonding energy than traditional Si or most other III-Vs materials.[8]
- GaN is typically etched through a combination of chemical and physical mechanisms. Chlorine is used to chemically react with the Ga to form $GaCl_3$, which is volatile in low pressure environments.[3]
- Argon is used to physically sputter the material away, increasing the overall etch rate.

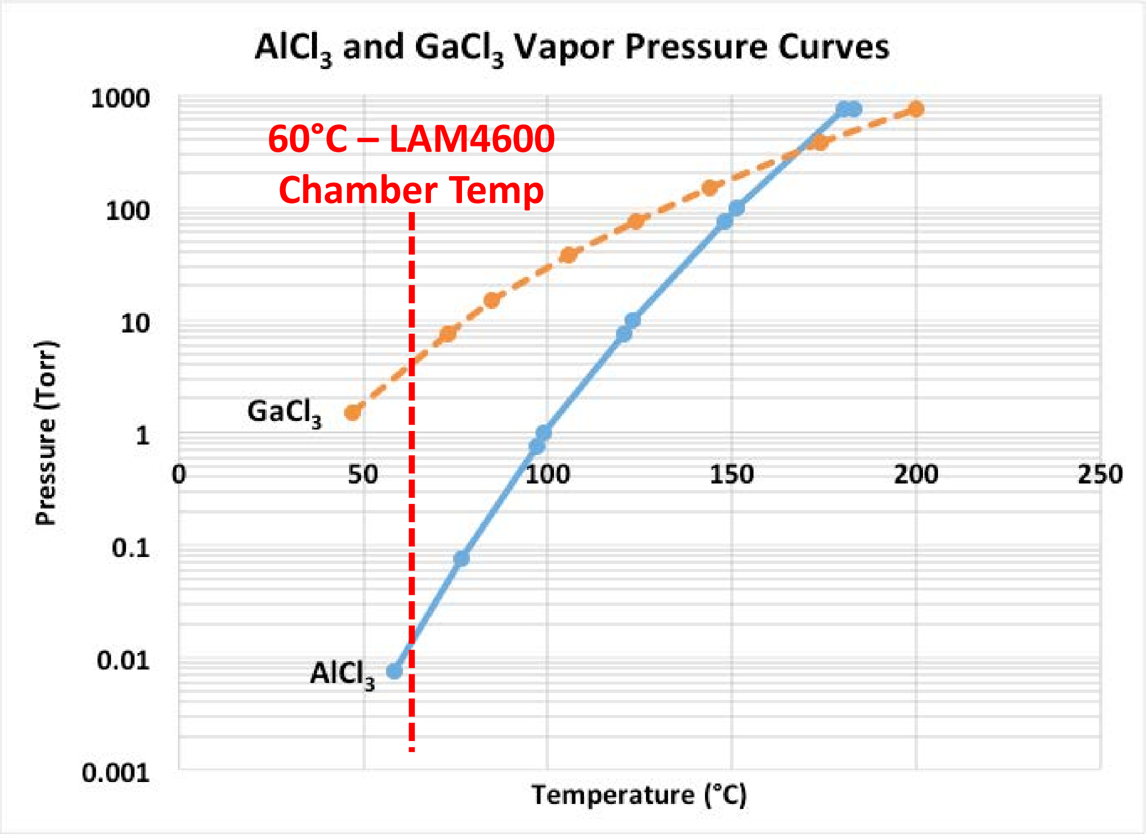
Mesa Etch: Problem …Compounded



- The SMFL does not have an inductively coupled plasma (ICP) etcher, and wet etching of GaN involves hazardous chemicals. There was no pre-existing way to etch GaN at RIT.
- Cornell's Center for Nanoscale Fabrication (CNF) has an ICP etcher dedicated to etching III-Nitride materials.
- The etch at CNF was not successful. Two thirds of all of the samples were severely over-etched to the point that there was no longer any GaN left on them.

Mesa Etch:
Solution at RIT

Sample Acquisition → Mesa Lithography → **Mesa Etching** → Contact Lithography



Volatility of $AlCl_3$ and $GaCl_3$ compared.[2,4]

- An attempt was made to perform a reactive ion etch (RIE) of GaN for the first time at RIT.
- The LAM4600 RIE tool in the SMFL is traditionally used to etch Al films, but has the necessary gas hookups to etch GaN (Cl_2, BCl_3, $CHCl_3$, and Ar).
- In order to qualify this etch, the tool owner needed verification that the etch byproducts would be volatile and not contaminate the processing chamber.
- A vapor pressure curve for GaCl3 (the most common byproduct in GaN etching) was produced from various vapor pressure measurements reported in literature[2,4].
- The LAM4600 chamber is kept at 60°C, and as such the vapor pressure curve proved that the etch would not be hazardous.

Mesa Etch:
LAM4600 Recipe

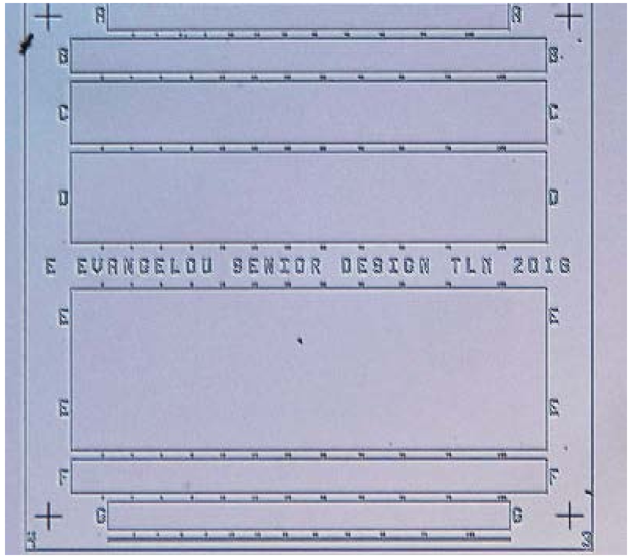
Sample Acquisition → Mesa Lithography → **Mesa Etching** → Contact Lithography

Etch Recipe

Pressure (mTorr)	100
RF Top (W)	0
RF Bottom (W)	125
Gap (cm)	3
O_2 flow (sccm)	0
N_2 flow (sccm)	0
BCl_3 flow (sccm)	25
Cl_2 flow (sccm)	30
Ar flow (sccm)	20
$CHCl_3$ flow (sccm)	8

Etch Results

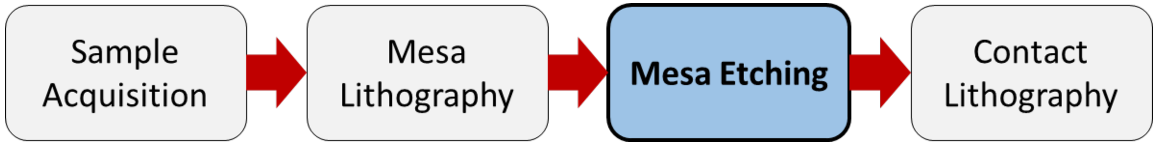
GaN Etch Rate (Å/s)	3.12
Photoresist Etch Rate (Å/s)	7.65
GaN / PR Selectivity	1 / 2.45

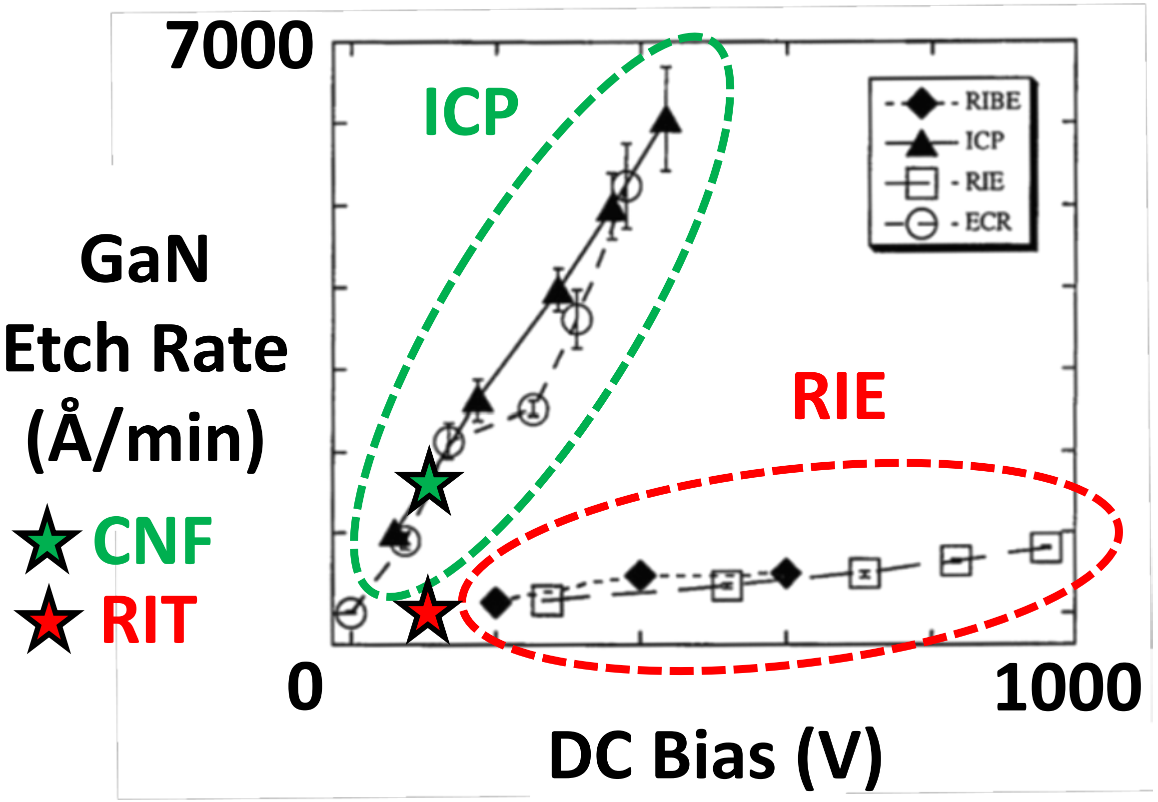


GaN Etch recipe and results on the LAM4600

- The etch was first performed for 120 seconds, trenches and remaining resist height were measured, and then continued for another 300 seconds.
- The etch was successful. 100nm deep mesas were etched on all of the remaining pieces.

Mesa Etch:
Results

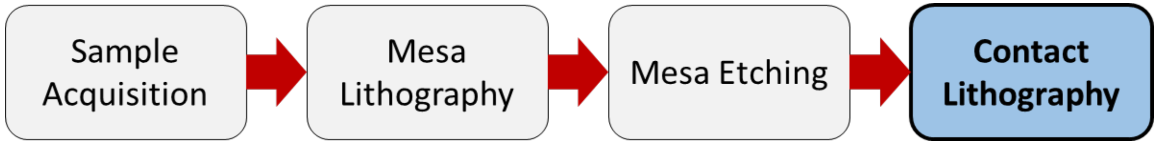




Etch rates of GaN in ICP vs. RIE etchers.[8]

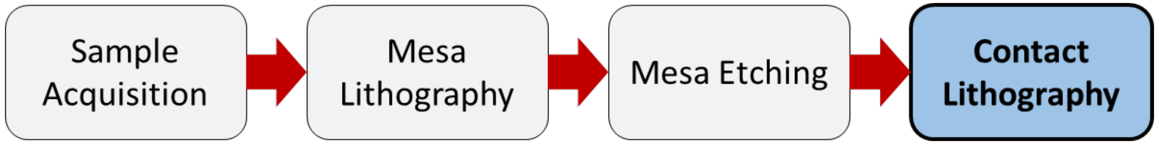
The RIE etch rate was significantly lower than the ICP's etch rate, but the selectivity was almost exactly the same as what was recorded at CNF.

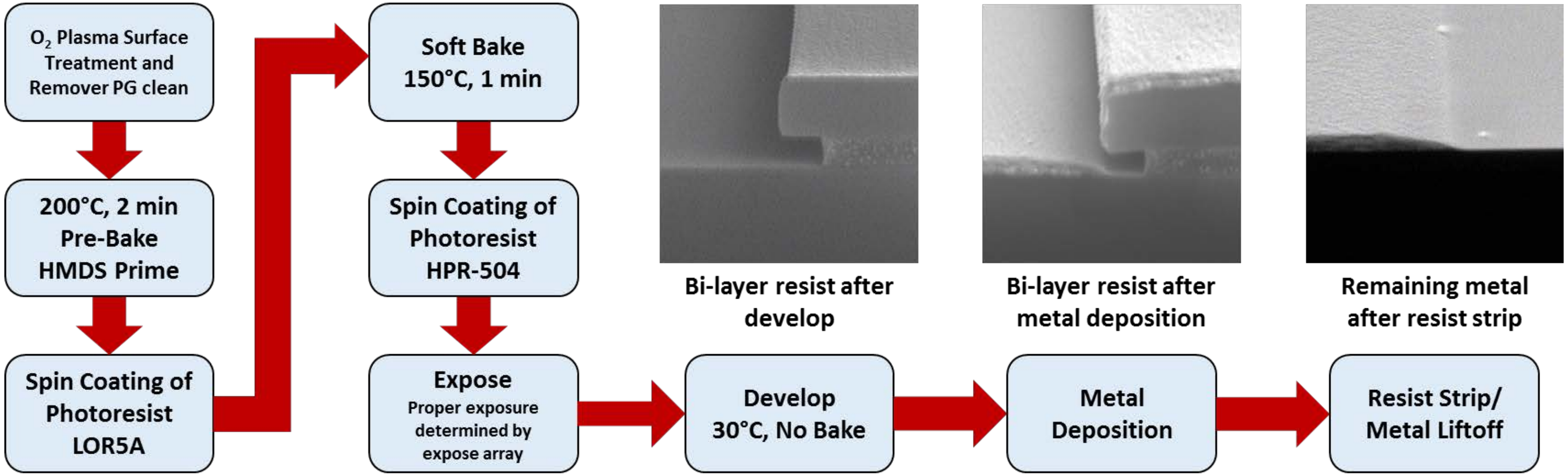
Contact Cut Lithography: Issue



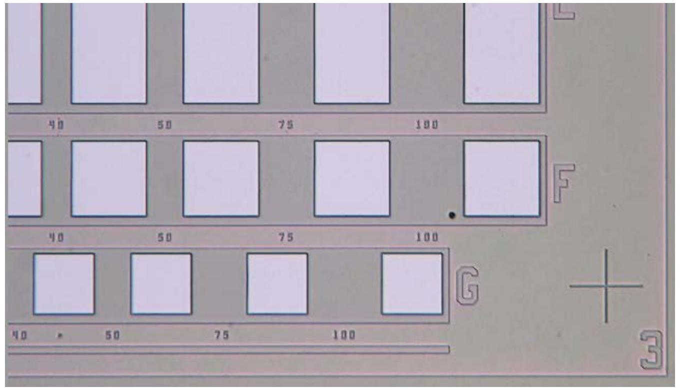
- After the mesa etch the surface of the GaN was rougher than it had been before. Increased surface roughness meant that the photoresist was not adhering.

Contact Cut Lithography: Solution





Bi-layer liftoff resist process overview.[1]



Close-up of the contact windows.

- The addition of an HMDS prime and an extended pre-bake significantly improved the adhesion of the LOR-5A to the GaN substrate.
- An O_2 plasma surface treatment was also performed to help clean the surface.
- Contact windows were defined. An alignment offset of +/-10µm in both the x and y directions was allowable to make processing on pieces easier.

Conclusions

- GaN samples were acquired from TI, Veeco, and an RIT alumnus.
- A successful etch recipe was developed for the etching of GaN on RIT's LAM4600 RIE tool.
- Coating procedures were developed for the application of LOR-5A liftoff resist and OiR-620 positive photoresist on GaN substrates.
- The procedures developed during this project will assist future GaN-focused projects in the SMFL, which will allow for the development of new and exciting opto-electronic and power-electronic devices.
- **The original project objective was partially met: a contact to n-GaN was fabricated, it was just never optimized for low resistance.**

Acknowledgements

- **My sincerest thanks to the entire staff of the SMFL. Patricia Meller, Sean O'Brien, and John Nash in particular have been tremendously supportive of my work, and without them none of this would have been possible.**
- Dr. Zhang, for being a supportive and knowledgeable advisor, and for organizing CNF access.
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- Dr. Rommel, for constantly reminding me how many days there were left until today. Comfort like that is hard to come by.

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