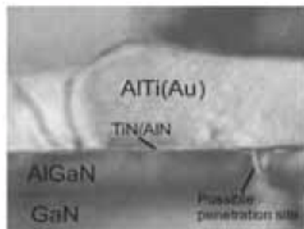
III-nitride device processing

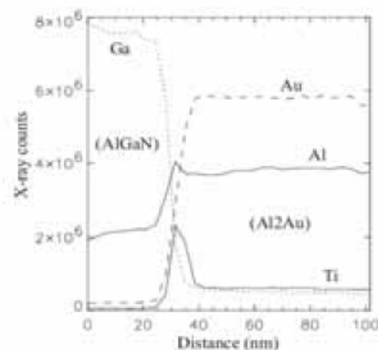
Basic device processing steps

- Metalization (Ohmic and Schottky contacts, interconnect)
- Etching (mesa, etch-down and vias; wet vs dry)
- Patterning (contact aligner and stepper, etching vs liftoff)
- Passivation

Metal contacts to GaN

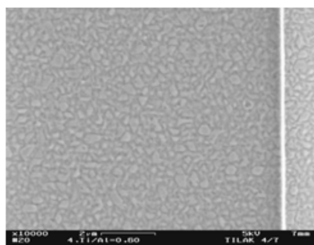
• The most commonly used N ohmic metal stacks to GaN is Ti/Al/Ti/Au followed by RTA. UIUC developed the Ti/Al/Mo/Au and related processes to get better edge acuity.

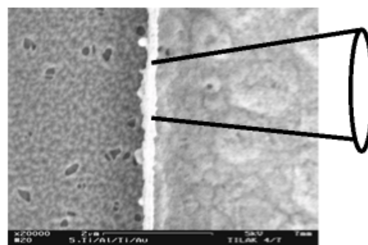


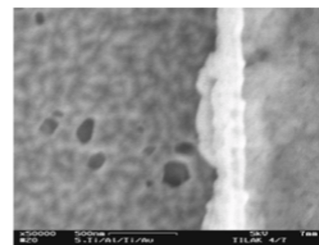


• The most commonly used p ohmic contact to GaN is Ni-based or Pt-based.
• The strategy is to use a metal with a large work function on GaN to form Schottky barrier, while a metal with a low work function should be selected for ohmic contact.
• Many tricks are played to improve contact resistance, like various cleaning techniques, dry etching, annealing… but ion-implantation does not work very well since the damages can be healed by thermal annealing for GaN.

Low contact resistance is not everything — edge acuity of ohmic contacts







Ti(600Å)/Al(1000Å)/Au(500Å) after 800^0C 90s and 900^0C 60s

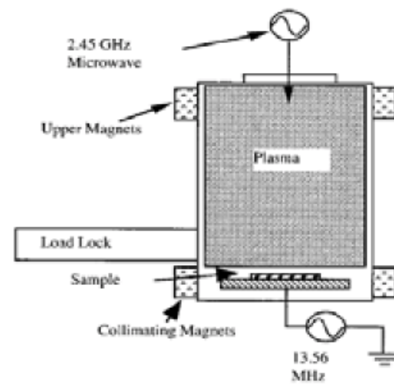
Ti(200Å)/Al(1000Å)/Ti(400Å)/Au(500Å) after 800^0C 90s and 900^0C 60s

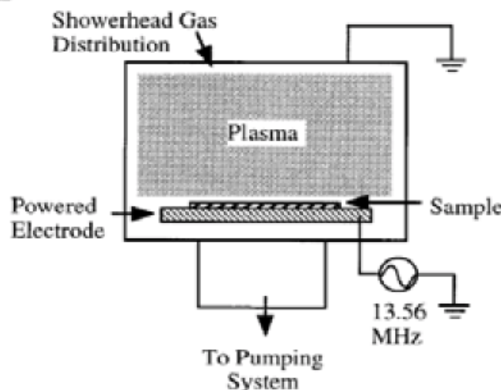
• Edge acuity is correlated with morphology, all bi-layers with Ti/Al ratio > 0.3 had good edge acuity
• Worst edge acuity in Ti(200 Å)/Al(1000Å)/Ti(400Å)/Au(500Å) sample
• "Creeping" of metal reduced 2 μm spacing to 1.6 μm

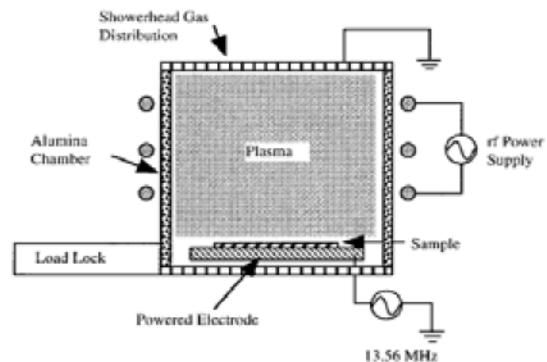
Edge acuity is especially important for HEMT applications.

Dry etching of GaN

• Cl-based plasma is commonly used for GaN dry etching.
• The plasma density of ECR or ICP is 2 to 4 orders of magnitude higher than that of RIE thus improving the III–N bond breaking efficiency and the sputter desorption of etch products formed on the surface. Additionally, since ion energy and ion density can be more effectively decoupled as compared to RIE, plasma-induced damage is more readily controlled.



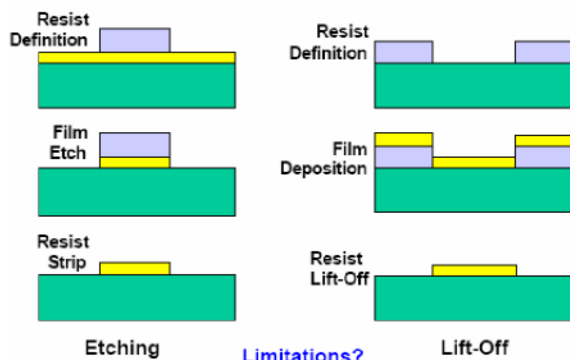




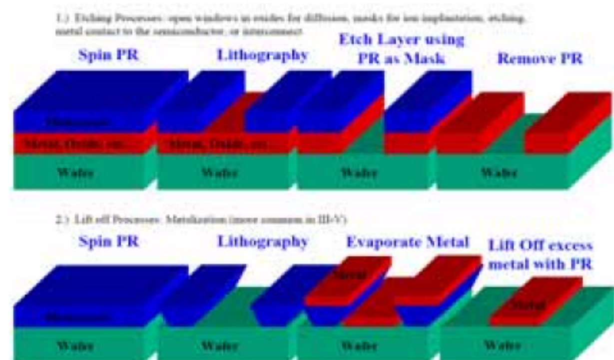
Three commonly used ways to do lift-off

- **Negative PR**
- **Image reversal process**
- **Double-layer PR technique**

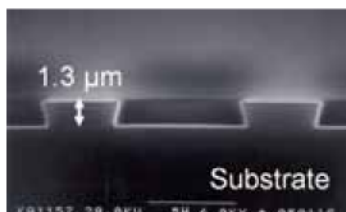
Whatever technique is used, the key point is to form a good undercut.



This schematic is too simplified.



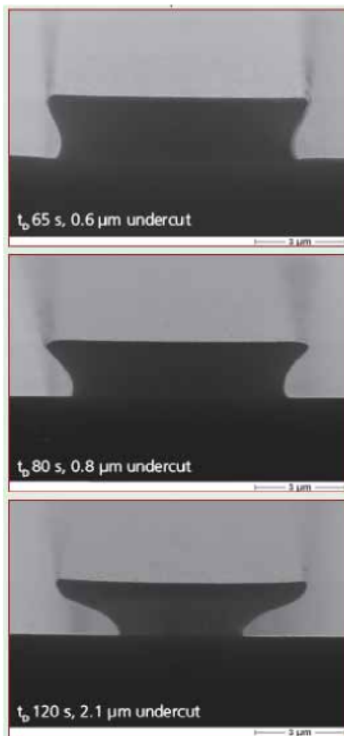
What is actually used.



Evaporation vs. Sputtering

Evaporation is usually used for liftoff.

Negative photoresist for liftoff



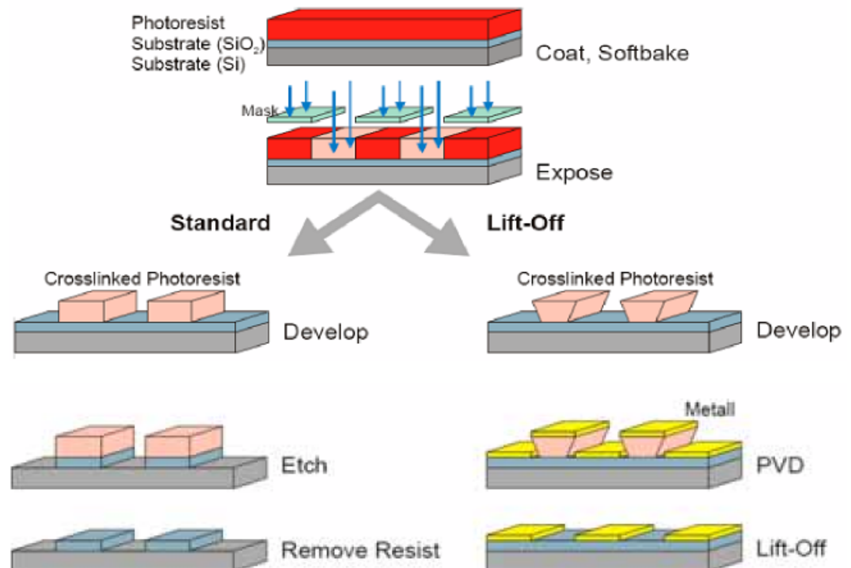
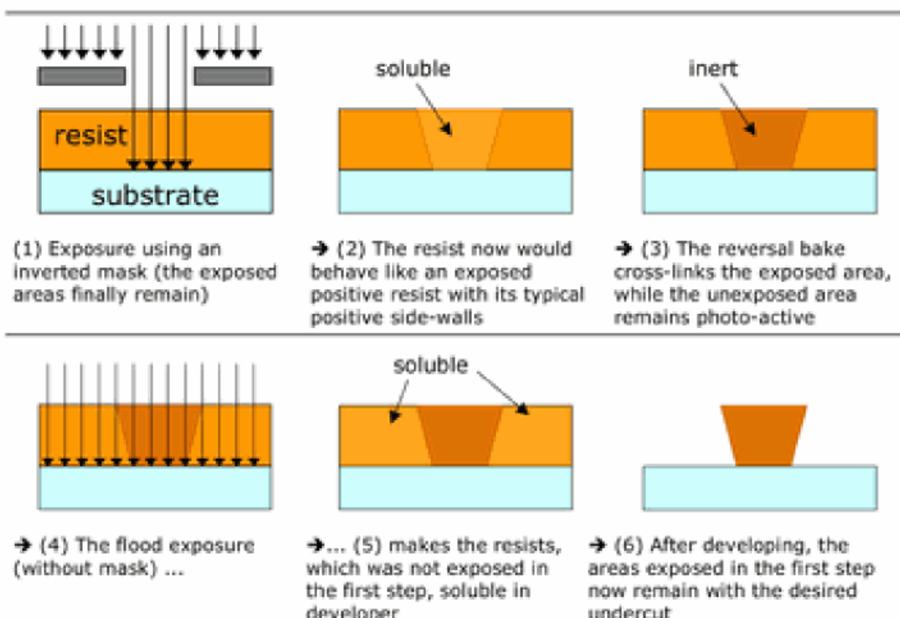
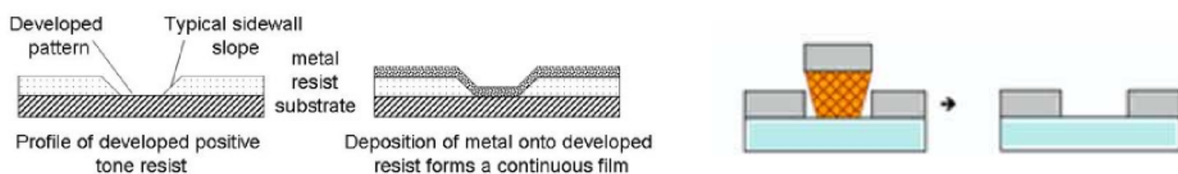


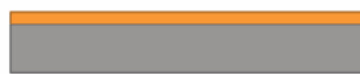
Image reversal process for liftoff





Double-layer PR technique for liftoff

LOR Lift-Off Resists



1. Coat and prebake LOR

4. Develop resist and LOR. LOR develops isotropically, creating a bi-layer reentrant sidewall profile

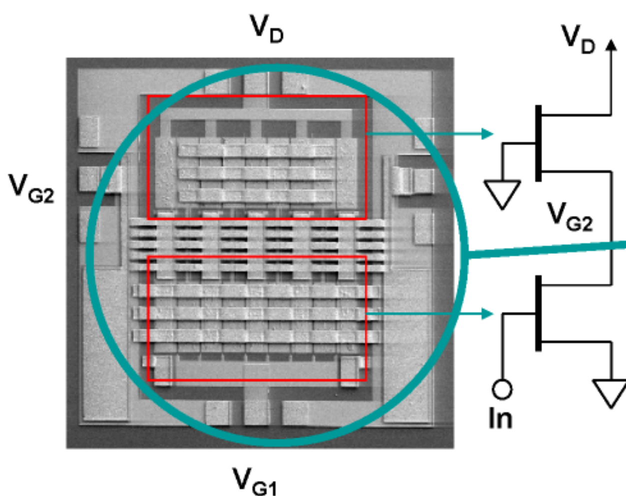
2. Coat and prebake imaging resist

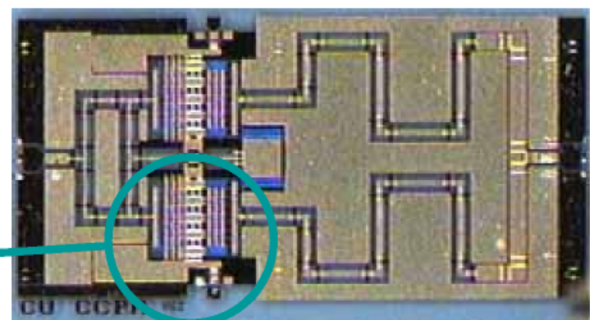
5. Deposit film. The re-entrant profile ensures discontinuous film deposition.

3. Expose imaging resist

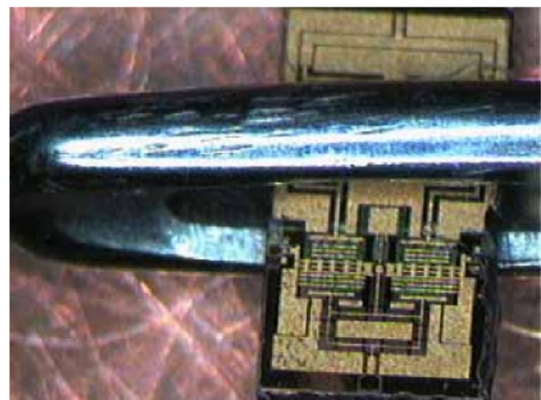
6. Lift-off bi-layer resist stack, leaving only desired film.

Fabricated Cascode Lossy Match Amplifier





Die Size: 3.2 X 1.6 mm^2

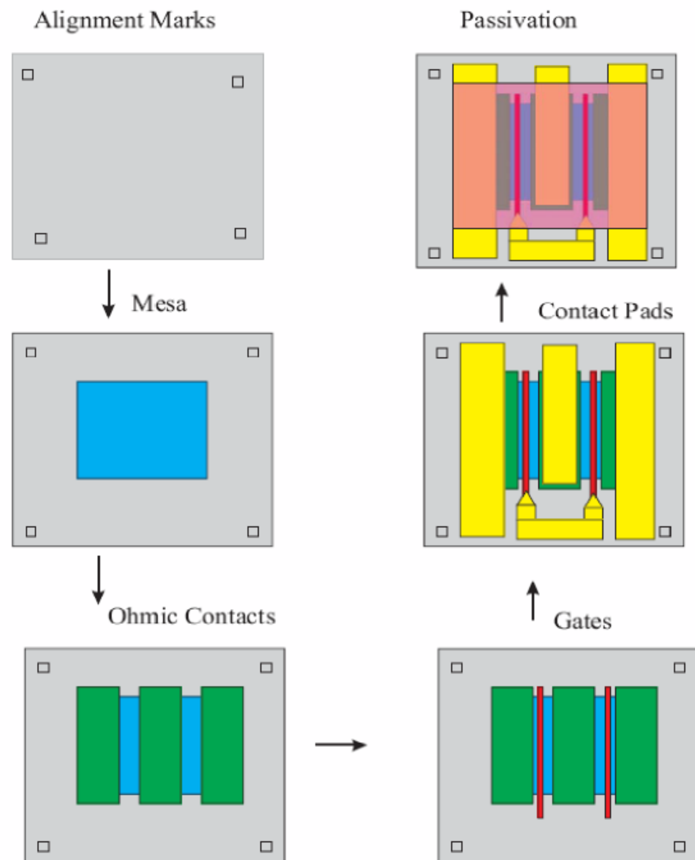


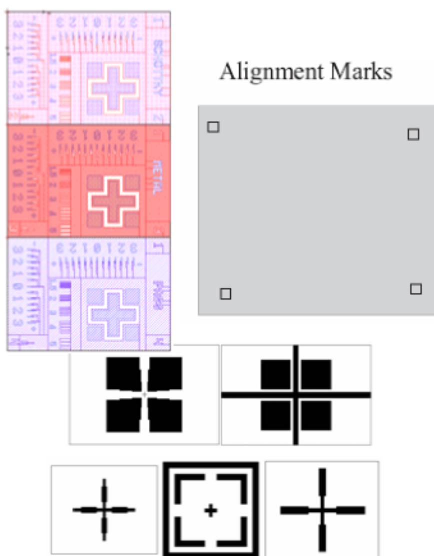
- 1 mm cascode cells with distributed common gate RF grounding.
- Small Die Size (~5 mm2) as seen by comparison with eye of 2” needle.

Process integration – how to make an AlGaN/GaN HEMT?

(The Cornell Process)

This is the basic process for a small periphery U device.





Alignment marks can be designed in various shapes and put at preferred locations as long as you can remember where it is and keep the consistency.

Bilayer PR + thin Au

Ready for evaporation

Ti is used as Adhesion layer.

Table B.1: Alignment level process steps **(The Cornell process)**

Step	Parameters	Remarks
Wafer Cleaning	Acetone, Methanol, IPA	Spin clean
De-Hydration Bake	170 C Hotplate, 5 Min.	
Resist Spinning	Copolymer 3.75k rpm, 60 S.	500nm thick
Bake	170 C 15 min.	Atleast 10 minutes
Resist Spinning	PMMA 2.5k rpm, 60s	200nm thick
Gold Evaporation	100Å Thermal Evaporation	Pressure in mid 5's
Exposure	10nA current, 1.6mm field size	Local Al marks should be in one exposure
Gold Etch	Transene Gold etch, 30s	can over etch as very high selectivity
Develop	MIBK:IPA(1:1),75s	Ensure all marks are in the chip
De-scum	Branson, process 2, 2 min	
Oxide Etch	30:1 BOE, 30 S	optional
Evaporation	CVC 4500, 200A Ti 2000A Platinum	Pressure in low 6
Lift-off	Immerse in Methylene Chloride	takes 1 minute

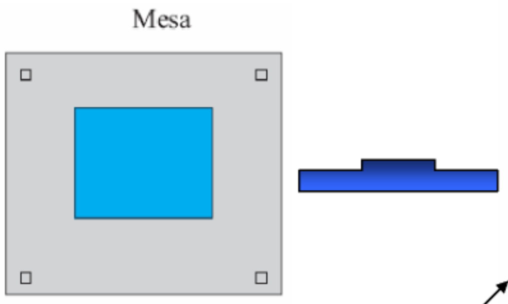


Table B.2: Mesa Level process steps **(The Cornell process)**

Step	Parameters	Remarks
Wafer Cleaning	Acetone, Methanol, IPA, DI, 1 min each.	
De-Hydration Bake	115 C Hotplate, 5 Min.	
Liquid Prime	P-20 primer,let sit for 10 S, 5000 RPM Spin dry 60 S.	
Resist Spinning	S-1813 5000 rpm, 60 S.	1.3μm thickness
Pre-exposure Bake	115 C 2.5 min. hot plate bake (2 min SiC).	
Exposure	5 X stepper, f=275 t=0.38 (290, 0.25 for SiC)	Numbers require calibration
Develop	1 min MIF 300	
Hard Bake	115 C 15 min. hot plate bake.	Harden resist
ECR Etch	12 Sccm Cl_2,4 Sccm Ar, 3 Sccm CH_4, Temp = -5C, Bias = 170V, - 70s 2000A	Usually 1500Å
Resist Removal	Branson Strip - 3min + 3min Max. Temp. 180C	
Resist Removal	1165(NMP), Overnight and Branson strip if required	

Prime is for better PR adhesion.

The key point in lithography:
E-beam: your job file
Stepper: the location of alignment marks
Contact: too simple.

Cooled chuck during dry etch to prevent PR fry. 1500A should be enough for HEMT isolation

The effect of plasma ashing: burn residual PR, burn hard PR crust resulted from other processes.

(The Cornell process)

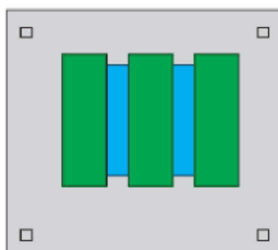


Table B.3: Ohmic Level process steps - I

Step	Parameters	Remarks
Wafer Cleaning	Acetone, Methanol, IPA 1 min each.	
De-Hydration Bake	170 C Hotplate, 15 Min.	
Resist Layer 1	3750 RPM 603 Copolymer MMA(8.5)MAA 11% 60 S.	(500nm thickness)
Resist Bake	170 C, 15 min. hot plate bake	
Resist Layer 2	2000 RPM 4 % PMMA 495 60S.	200 nm thickness
Resist Bake	170 C, 15 min. hot plate bake	
Gold Evaporation	Thermal Gold, 125 A	
E-beam writing	EBMF 10 nA beam current	focus= , Beam diam=
Gold Etch	30 S Transene TFA	
Develop	MIBK/IPA 1:1, IPA t=75 s	check 5μm TLM spacing to check development

E-beam lithography is used here for better accuracy but stepper is commonly used for production.

Thin gold layer is deposited as a conductive layer to prevent electron trapping.

There is special etchant for Au, but Pt is hard to be etched away.

Hex #: 307 Equipment Information Sheet CNF

CVC 4500 EVAPORATOR (EVEN HOUR)

	Work Phone	
Manager: Jim Clair	254-4831	Calls to staff phones will be automatically forwarded to their cell phones during accessible hours. At other times leave a message or send them an email.
Backup: Rob Ilic	254-4894	
Backup:		

Safety
- No unusual hazards during normal operation
- No buddy system restrictions

Process Restrictions

Material Restrictions
- SiO_2 and Al_2O_3 are the only oxides allowed
- No High vapor pressure materials (Pb, Sn, Zn, Cd, etc) (evaporants or substrates)

Parameter Restrictions

Scheduling / Sign-up Restrictions
- ONE FULL 2 hour block 8 AM - 6 PM / M-F on the EVEN hour
- You must indicate what you are evaporating (comments section)
- One 2 hour block 8 AM - 6 PM / M-F
- You must leave a minimum of 4 hours between your slots during off hours and weekends
- FAILURE TO COMPLY WILL RESULT IN CANCELLATION

Requirements (Do Every Time)
- Press "STOP" on 485 valve control first- Then wait to hear the gate valve close - Then push "VENT"
- Monitor the e-gun beam do not leave the area
- Vacuum the system thoroughly / bell jar, E-gun & thermal hearths
- Hang up the vacuum hose
- Leave the table neat and orderly

Prohibitions (Never Do)
- No Unauthorized materials
- Do NOT use e-gun gold (large pellets) for thermal evaporation
- Do NOT use thermal gold (small pellets) in the e-gun crucible
- Do NOT place material in a crucible that does not have one

• Clear rules make more efficient use of equipments.

After RTA, contact resistance is measured to determine whether additional steps should be added to save the ohmic contact.

Table B.4: Ohmic Level process steps - II

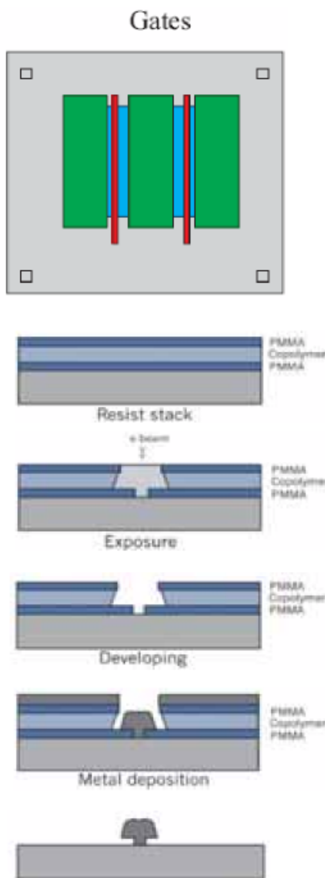
(The Cornell process)

Step	Parameters	Remarks
De-scum	Branson, process 2, 2 min	
Oxide Etch	30:1 BOE, 30 S	required
Evaporation	CVC 4500, 200A Ti, 1000A Al, 450 A Ti 550 A Au	Pressure $< 2\mu$ torr
Lift-off	Methylene Chloride	Overnight
Annealing	RTA 30S+30S 800C Nitrogen Ambient	Measure ohmics after each anneal cycle

• The oxide etch is done by short BOE dip just before loading into the evaporation chamber.

• The ohmic metal stack is usually TiAl-based, but details vary from group to group.

• 2-3 pre-runs are used to condition the RTA chamber.

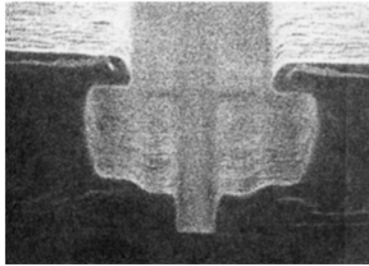


(The Cornell process)

Table B.5: Gate Level process steps - I

Step	Parameters	Remarks
Wafer Cleaning	Acetone, Methanol, IPA	1 min each
De-Hydration Bake	170 C Hotplate, 15 Min.	
Resist Layer 1	2500 RPM 496k 4% PMMA	190nm thickness
Resist Bake	170 C 15 min. hot plate bake	
Resist Layer 2	2500 RPM 11% Copolymer(3:1)	330 nm thickness
Resist Bake	170 C 15 min. hot plate bake	
Resist Layer 3	2500 RPM 496k 4% PMMA	190nm thickness
Resist Bake	170 C 15 min. hot plate bake	
Gold Evaporation	Thermal Gold, 100 A	Critical,Pressure $<50\mu$torr
E-beam writing	EBMF 0.7 nA beam current	focus= , Avg Scan=
Gold Etch	30 S Transene TFA	

(The Cornell process)



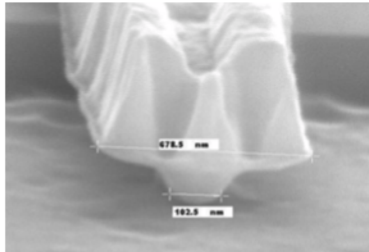


Table B.6: Gate Level process steps - II

Step	Parameters	Remarks
Develop	Tolune, Methanol/IPA (1:1), MIBK/IPA 1:1	Keep track of development monitors
De-scum	Branson, process 2 3.5 min	
Oxide Etch	30:1 BOE, 30 S	
Evaporation	CVC 4500, 200A Ni, 3800 A Au	Thermal gold used, pressure $<2\mu$torr
Lift-off	Methylene Chloride	Overnight

The development process is very tricky.

To do liftoff, the total PR thickness should be at least larger than that of deposited metal stack.

The resist is exposed with a three passes. One strong center line dose which helps in clearing the resist to define the foot of the gate first and two light side area doses, 50nm from the line dose to help develop a big head.

Thermal evaporation gives a better finish to the gate as spitting of the gold source can be controlled thereby depositing a smoother film.

Contact Pads

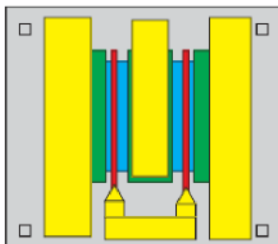


Table B.7: 1st level interconnect process steps

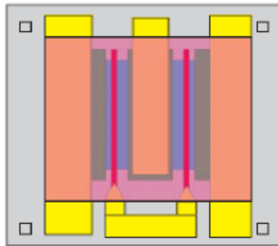
(The Cornell process)

Step	Parameters	Remarks
Wafer Cleaning	Acetone, Methanol, IPA, DI, 1 min each.	
De-Hydration Bake	115 C Hotplate, 3 Min.	
Liquid Prime	P-20 primer, let sit for 10 S, 4000 RPM Spin dry 30 S.	
Resist Spinning	S-1813 5000 rpm, 60 S.	1.3μu thickness
Pre-exposure Bake	115 C 2.5 min. hot plate bake (2 min SiC).	
Exposure	5 X stepper, f=242, t=0.34 S	numbers require calibration
Image Reversal	YES oven 80 min NH_3	
Flood Exposure	30 Sec. Flood Exposure Htg	Check lamp intensity, might require 60S sometimes
Develop	1 min MF-321	
De-scum	Branson, process 2 1 min	
Oxide Etch	30:1 BOE, 30 S	
Evaporation	CVC 4500, 250 A Ti, 0.35 μm Au, 100 A Ti	Thermal Gold, Pressure $<2\mu$torr
Lift-off	1165	overnight,use syringe for liftoff for circuits

The alignment requirements for this level and the levels that follow this one is about 2um, which is much less demanding than 0.25m alignment required between the ohmic and gate.As the contact pads a wide area exposure, this is done with conventional photolithography using the 5X g-line stepper

Ti(25nm)/Au(370nm)/Ti(5nm) is evaporated as the contact pad metal. Titanium is evaporated on top of the gold as it promotes adhesion of the "# layer that follows this level. The thickness of Au evaporated is maximized without compromising the liftoff, as we would like to minimize the contact pad resistance parasitic in the device.

Passivation



A layer of passivation is essential to prevent surface effects that are seen in the material system.

SiNx works particularly well to reduce current slump for nitride HEMTs. It might be related to the additional strain induced by the passivation layer.

Before the actual deposition, a pre coat of the machine is done and a run is done on silicon to determine the etch rate in BOE (6:1)

Table B.8: MIM capacitor and Passivation level process steps

(The Cornell process)

Step	Parameters	Remarks
Wafer Cleaning	Acetone, Methanol, IPA, DI, 1 min each., N_2 blow dry	
Oxide Etch	BHF 30:1 30 sec.	Not critical?
PECVD Nitride Dep.	13 min CNF Si_3N_4 60 sccm NH_3, 24 sccm Silane, 300 C, 550 mTorr,52 W, 50 Khz RF Power	Thickness=200nm
Resist Spinning	S-1813 5000 rpm, 30 S (1.1-1.3 μm thickness)	
Pre-exposure Bake	115 C 2.5 min hot plate bake	
Exposure	5 X stepper, f=255, t=.55s	
Develop	60s CD 26 or 300 MIF	
RIE Etch	Standard PT-72, Si_3N_4etch process	Etch rate= 1000Å/m
Intial Res. Strip	Branson Resist strip	3 minutes
Final Resist Strip	20 min 1165 Resist Strip	
Resist Descum	Branson Strip process	3 minutes

Table B.9: via-level airbridge process steps

Step	Parameters	Remarks
Wafer Cleaning	Acetone, Methanol, IPA, DI, 1 min each.	
De-Hydration Bake	115 C Hotplate, 5 Min.	
Liquid Prime	p-20 Primer, let sit for 10 S, 4000 RPM Spin dry 30 S	
Resist Spinning	S-1827 4000 rpm, 30 S	Thickness 2.7-2.9 μm
Pre-exposure Bake	115 c 2.5 min. hot plate bake (2 min SiC).	
Exposure	5 X stepper, f=255, t=1.4S	
Develop	60s MIF-300, DI rinse	
Post-Exposure Bake	30 min. 130 C	Use oven in E-beam room
De-scum	O_2 Branson descum 2 min process 2	
Evaporation	CVC 4500, 250 A Ti, 750 A Au	

Plating is used to deposite air-bridge metal, which needs a seed layer.

Table B.10: Plated airbridge process steps

(The Cornell process)

Step	Parameters	Remarks
Vapor Prime	YES oven, HMDS 34 min	
Resist Spinning	S-1827 4000 rpm, 30 S.	
Pre-exposure Bake	90 C 5 min. hot plate bake (sapp and SiC).	
Corner Flood Exposure	Cover all but corner w/ foil. HTG contact aligner, 2 sec.	
Exposure	5 X stepper, f=260, t=1.0 S	
Develop	MIF-300 60 sec.	
De-scum	O_2 Branson descum 2 min process 2	
Plating Setup	BDT-510 plating sol'n (250 ml) in beaker, 55 C, stirring	
Plating	Set J=3mA/cm^2 rate= 1μm Au/ 5 min (total time 12.5 min.)	Too high temp causes resist cracking
Flood Exposure	HTG contact aligner, 30 S.	
Develop	CD-26 Full stength 1 min., DI rinse	
Au Etch	Transene TFA gold etch, 60 S	
Ti Etch	Dillute HF 1:20, 20 S	
Resist Strip	1165 stripper 20 min.	

How CNF works? What can we learn?

The CNF is supported by the National Science Foundation, New York State Office of Science, Technology and Academic Research, Cornell University, industry & our users.

The CNF is a member of the National Nanotechnology Infrastructure Network.

The laboratory is a multi-user facility with over 525 users having access around the clock. CNF staff usually have no teaching and research responsibilities. Their role is to keep the lab running properly and share their processing expertise to help CNF users develop their process. Every faculty and his students can use the facilities but they have to obey the rule. On one has privilege!

Academic user fees are for bona-fide academic research only by students, postdocs, and full time university staff members. Employees of companies may not use visiting scientist status at Cornell or elsewhere to receive academic rates. Assignment in questionable cases is at the sole discretion of the management.

Who can use the lab and how to get access?

3.1 Categories of People

Staff- Full or part time employees of CNF.

Users- People working on an approved research project at CNF (students, faculty, postdocs, engineers, etc., both Cornell and non-Cornell). Users are divided into two categories.

Resident Users are those users who are resident at Cornell for an extended time period, e.g. > 3 months. These are primarily , but not exclusively, Cornell employees or students.

Non-resident users are those people who use the facility for short duration, typically 1-2 weeks, on an infrequent basis (generally from outside the Cornell community).

Visitors- People visiting the laboratory for a brief time and having no affiliation with a User research project.

Service Personnel- People in the facility to service equipment and facilities. This includes both Cornell and non-Cornell employees.

3.2 Access

The facility is for the exclusive use of CNF staff and users affiliated with and working on specifically approved research projects. Other use requires approval of the Director of the facility. The criteria for approval of projects are documented in the **CNF User Manual**. Being a graduate student at Cornell does not guarantee access to the facility. Use of the facility by any individual is a privilege that can be revoked by the facility management at any time.

3.3 Key Application

All Cornell users must have a **key application** signed by the principal investigator for their CNF research project.

All non-Cornell users must complete the **Memorandum of Understanding**, an agreement between their institution and Cornell University. This legal agreement must be signed by an **officer** of their institution (**not the principal investigator or department head**). Normally, the **Memorandum of Understanding** will be sent to the outside user several weeks prior to the scheduled visit.

To become a formal user, you need get training, training, and training..,

3.4 New User Orientation

An orientation and training process is required before any new user can receive a key to work in the facility. Upon completion of the key application, the orientations sessions may be scheduled. In general, this is a three part process.

Part 1. Orientation

A small group (< 5) of prospective users are taken through the laboratory by a staff member, discussing general rules, safety procedures, emergency exits, etc. After this session, a user can be issued a key allowing basic access to the laboratory. This session takes approximately 2 hours.

Parts 2 and 3 are required in order to use any chemicals in the laboratory.

Part 2. Chemical Safety Lecture

This 2-hour lecture/video by a staff member covers basics of The Laboratory Standard, chemistry, chemical safety, and toxicology. This is done with a small group. There will be a quiz.

Part 3 Chemical Practical

This is the final section for full chemical authorization. It is done generally 1 on 1 with a staff member. Emphasis is on proper technique in using chemicals and chemical safety protective equipment. This session also takes approximately 1 hour.

For users who will not be using chemicals, parts 2 and 3 may be waived at the discretion of the management. This generally applies only to people requiring access only to analytical equipment.

Part 1 is usually done on Monday mornings. **Part 2** is usually done on Monday afternoons. **Part 3** is done only by appointment. They cannot all be done in the same day to avoid information overload.

There is a one time up front $300 fee for all on-site new users for training and orientation required before a key will be issued.

To participate in orientation, users must

- **Have completely read and understood this Lab Safety Manual**
- **Have a completed key application or original Memorandum of Understanding on file**
- **Have their own safety glasses (available from CNF)**
- **Be appropriately attired for clean room access**

In all three sessions, the staff member will be looking for evidence that the user understands the language, rules, procedures, and consequences of working in the facility. The staff must evaluate whether the user can and will work safely in the laboratory. Actual approval for a key is conditioned upon their recommendation in these areas. The laboratory management may deny a key, or restrict access to particular conditions, based upon this evaluation.

In addition to the initial orientation, there will be an annual retraining requirement for each user.

- access orientation
- chemical training
- training for each particular equipment

Your behavior will be monitored by CNF staff as well as video cameras, violation of safety and operation rules can result in warning or suspension of access.

However, do not be scared, people there are nice, helpful and knowledgeable.

The lab runs very efficiently but safety is always the top

Short and Simple Rules

No unauthorized access
No loaning of keys
No waste into the drain
No unauthorized chemicals
No unauthorized solutions
No unlabeled solutions
No food
No bare legs
No chemicals in waste baskets
No unwashed bottles in waste baskets
No unauthorized use of equipment

Be neat, Be clean, Be Safe
Be courteous and clean up
Wear protective gear
Read Safety Data Sheets
Know emergency procedures
Read the signs, instructions and notices
Ask if you don't understand
Think before you act

3.9 Hours of Operation

The laboratory is open to qualified users both day and night, weekdays and weekends. Certain instruments and procedures may, however, be restricted to the normal work day, or only allowed in the presence of a staff member. **(See sections 5.6. and 7.6.12 regarding the buddy system.)** In general, a "buddy" is another knowledgeable user within the facility who can and will watch out for you in case of trouble. Laboratory "buddies" must of necessity communicate with each other to be effective.

The use of chemicals in particular is restricted to the buddy system after normal hours, i.e. all time outside 8 a.m.-6 p.m. normal workdays. You may not wet etch, mix chemicals, or dispose of waste without another user in the area. (see section 7.6.12.)

Certain instruments, (MOS Furnaces, for example) have formal procedures for sign in by the designated "buddy", as well as rules regarding the proximity of the "buddy". These procedures will be enforced. Other procedures (e.g. doped poly) are totally forbidden off-hours, with or without a "buddy". Please consult with the appropriate system manager for details.

5.4 Buddy System

The laboratory is open for most use 24 hours a day, every day. Some processes and equipment may not be available outside hours of the normal work week (M-F, 8 a.m.-6 p.m.). Some processes cannot be run at all during off periods (e.g. certain MOS processes involving highly toxic gases). Other systems may be run during off hours only with the presence of another User. For the buddy system, some knowledgeable user must be in the lab to assist you in an emergency. **The Buddy system particularly applies to all wet chemical use (see section 7.6.12) during off hours.** Additional procedures may apply to specific instruments. You will be advised of these when you are trained on each instrument.

In an emergency call "911":

Use the Red Emergency Phones
or dial (9-911) from any CNF phone
or Push the Orange 911 button on the phones

Then Call:

Lynn Rathbun [illegible]
Mike Skvarla 254-4674

Other staff as necessary (Appendix 3)

Reserve, log on, use, and log off

4.5 Equipment Scheduling

CNF equipment is reserved through a web based system accessible off the main CNF web page at **http://www.cnf.cornell.edu**. You must have a CNF computer account to make reservations on the system.

Depending on the instrument and demand, CNF may limit the amount of time you may reserve in advance or block out on any given instrument.

Failure to cancel an unneeded reservation is inconsiderate to other lab users and causes inefficient utilization of resources. We realize that all projects require a certain process flow between instruments so that one problem can throw off your entire process schedule. Also, processes can take longer than anticipated. Thus while we encourage you to sign up ahead, we also encourage you to be flexible and cooperative with other users in stretching, sharing, and relinquishing time slots.

Non-resident users working under the direction of a staff member have priority for system access during the normal working day (8 a.m. to 6 p.m.). This priority does not extend into the evenings or weekends. This is not an excuse for indiscriminate bumping of scheduled users except in an **extreme emergency**. Both the staff member host and the non-resident user should make a reasonable attempt to schedule time on each system well in advance. Unresolvable conflicts will be handled by the

4.2 Equipment Operations

CNF uses a computer-based system, called CAC, to login to instruments to enable operation and simultaneous charge generation. You will need a CNF computer account to access the system. You will be shown how to use CAC during orientation. CAC does not actually turn on any instrument, but it does enable/disable the instruments. You may be logged onto several instruments at once and you may log off them individually.

You must remember to log off, or you will generate large erroneous charges. There is a system monitor located at the exit of the laboratory. **PLEASE** check it as you leave to assure that you are not still inadvertently logged onto an instrument.

Note: you may log off from anywhere by TELNET-ing into the CNF computer system and running CAC.

All users are issued a computer account as **individuals**. You must use your **OWN ACCOUNT** when logging into instruments. "Group" use is not acceptable.

There are still a few smaller instruments with paper log sheets. **Please be sure to write complete information legibly to avoid erroneous charges!**