Yale University

Final Scientific/Technical Report

Regrowth and Selective Area Growth of GaN for Vertical Power Electronics

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Contract Administrator:	Kenechia Clarke, Yale University
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Public Executive Summary

Gallium Nitride (GaN) has a great potential in high-power and high-frequency applications due to its wide energy gap and good transport property. So far all commercial GaN optoelectronic and electronic devices have planar junctions and heterostructures prepared by epitaxial growth. To take the advantage of the merits of GaN material properties, more sophisticated device configurations such as current-aperture vertical electron transistors (CAVETs), junction field-effect transistors (JFETs), and super-junction (SJ) devices require the ability to form in-plane, lateral junctions by selective area doping (SAD). In this project, we explored a novel approach of realizing SAD through selective-area etching (SAE) followed by selective-area growth (SAG).

In this process, selective area etching of GaN is considered to be the most challenging and critical step. The commonly used inductively-coupled plasma (ICP) etching is known to produce damages and introduce impurities to the as-etched surface or interface. Once placed near the active region of the power devices, these imperfections are detrimental to the device performance. In this project we explored the use of tertiarybutyl-chloride (TBCl) as an etching precursor for the first time to demonstrate in-situ, damage-free, and clean etching of GaN. We also discovered, that TBCl etching of GaN is chemically selective and can be impeded by other species such as silicon or aluminum. By minimizing impurities originated extrinsically, we demonstrated that TBCl etching is a promising etching method for high-power electronic applications.

Non-planar selective area growth of GaN was also investigated towards the formation of lateral p-n junction devices. The growth evolution in this process was studied and explained by the kinetic Wulff diagram. With the help of atom probe tomography (APT), non-uniform Mg doping was observed in the selectively grown p-GaN region, and the local Mg doping concentration was found to vary inversely with the local growth rate. In addition, scanning spreading resistance microscope (SSRM) revealed a high concentration of silicon and oxygen in regrown regions, mainly originated from the SiO2 mask. To find an intrinsically-clean masking material for the selective-area growth of GaN, low-temperature AlN mask was employed and demonstrated to provide great selectivity.

Acknowledgements

This work represents a fruitful collaboration among five universities including Yale University (Jung Han), Northwestern University (Lincoln Lauhon), University of Michigan (Rachel Goldman), Rensselaer Polytechnic Institute (Christian Wetzel), and Michigan State University (Rebecca Anthony). We acknowledge valuable contributions from the PIs listed above and numerous postdocs and graduate students involved. This work is supported by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000871 as part of the PNDIODES program managed by Dr. Isik Kizilyalli.

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Accomplishments and Objectives

This award allowed Yale University and the team to demonstrate a number of key objectives. The focus of the project was on building a vertical GaN power transistor using lateral pn junctions enabled by selective area doping.

A number of tasks and milestones were laid out in Attachment 3, the Technical Milestones and Deliverables, at the beginning of the project. The actual performance against the stated milestones is summarized here:

Table 1. Key Milestones and Deliverables.

Tasks	Milestones and Deliverables
Task 1: Development of work plan	Q1: Work plan finalized **Actual Performance:** (12/17/2017) Complete work plan approved by the Program Director and submitted to the ARPA-E Deputy Director of Technology.
Task 2: Achieving atomic smoothness in regrowth:	Q1: Atomic smoothness after 10 nm regrowth, detected by AFM; RMS roughness < 1 nm (area:10x10 um^2). **Actual Performance:** After 10 nm regrowth on air-exposed GaN surface, the surface roughness is less than 1nm. (This task was completed on 12/18/2017.)
Task 3: Discovering the origins of electronic defects; nanoscale characterization.	Q3: Systemic understanding of electronic defects. Acceptance of a report about characterization using SIMS, SSRM, APT, and CL by ARPA-E. **Actual Performance:** We found that the air-exposed regrowth interface has detectable amount of Si by SIMS and SSRM. More Si was introduced to the surface if exposed to dry etching plasma. (This task was complete on 6/18/18)

Task 4: In-situ controlled layer removal	Q3: in-situ atomic layer removal. Report a controllable in-situ removal rate >100nm/hr; maintain atomic smoothness after 10 nm removal with RMS roughness < 1 nm (area:10x10 um^2). **Actual Performance:** (3/18/18) Calibrated the H_2 etching of GaN at 11/23/2017 using in-situ reflectometry. The etching was found to strongly depend on the temperature and H_2/NH_3 flow rate. And a etch rate of >11nm/min was achieved at 1030°C, 2 slm of NH_3, and 6 slm of H_2. Using a condition with etch rate of 5nm/min, we removed 15 nm of GaN. The surface RMS after etching was <1nm.
Task 5: Achieving low-defect interface through recess and back-fill process.	Q4: Low defects and atomic smoothness in the regrowth interface. No detectible impurity rise across regrowth interfaces by SIMS ([C]<$1x10^{16}cm^{-3}$; [O]<$2x10^{16}cm^{-3}$; [Si]<$1x10^{16}cm^{-3}$); $1x10^{16}cm^{-3}$<n<$1x10^{18}cm^{-3}$ by SSRM, RMS roughness < 1 nm (area:10x10 um^2); and report of doping/impurity profile measured by APT. **Actual Performance:** (9/18/18) At the regrowth interface, the C and O were unobservable. The ubiquitous presence of Si was investigated in details using SIMS. Si was not measured if the interface was not exposed to the surrounding environment prior to regrowth. But once the interface was exposed to environments, Si started to accumulate at a rate of $5x10^{11}$ cm^{-2} per day. This study completed at 06/15/2018. APT is not able to evaluate Si, the signal of Si overlaps with N.
Task 6: p-GaN regrowth and characterizing its defects **Subtask 6.1:** Establishing baseline doping/impurity profiles **Subtask 6.2:** Low defects and atomic smoothness in the regrowth interface.	Q4: Establishing baseline doping/impurity profiles. Report of doping/impurity profile measured by SIMS and APT for a regular continuously grown p-n junction as a baseline ([C], [O], [Si], [Mg]). Q5: $1x10^{16}cm^{-3}$<p<$5x10^{17}cm^{-3}$ by SSRM, RMS roughness < 3 nm (10x10 um^2). No detectible impurity rise across regrowth p-n interfaces compared with M6.1 ([C]<$1x10^{16}cm^{-3}$; [O]<$2x10^{16}cm^{-3}$; [Si]<$1x10^{16}cm^{-3}$). **Actual Performance:** We established p-type Mg doping of GaN with a concentration of $3x10^{19}$ cm^{-3}. C and O were at the detection limit in the p-layer. It was completed at 06/20/2018. p-GaN was also regrown on the air-exposed GaN surface. Surface roughness is the same as continuously-grown p-layer (RMS ~1nm). Unfortunately, there was detectable Si at the regrowth interface, as mentioned in the task 5. C and O were undetectable.

Task 7: In-situ controlled etching using TBCl. **Subtask 7.1:** Understanding the etching chemistry **Subtask 7.2:** Pyramid-free selective area etched surface/ trenches **Subtask 7.3:** Atomic understanding of the TBCl etching process	Q6: Calibrate the etch rate under different conditions. Understand the rate limiting factor, gas phase chemistry and surface kinetics. Q7: Pyramid-free selective area etched surface/ trenches. Smooth surface under SEM with considerable etch rate (>600nm/hr). Q8: Atomic understanding of the TBCl etching process. Smooth surface under AFM with considerable etch rate (>600nm/hr), RMS <1nm (10x10 um^2) **Actual Performance:** In-situ etching of GaN by TBCl was calibrated using in-situ reflectometry again. The etch rate depended strongly on temperature, NH_3 flow rate, and TBCl flow rate. Also the etching was more efficient in H_2 ambient than N_2. The process started with H_2 etching of GaN. Ga adatoms are the etching products. TBCl, once decomposed to form HCl, would remove Ga from the surface by forming GaCl. We have also demonstrated selective-are etching of GaN using SiO_2 masks. By reducing ammonia flow rate and pressure or increasing reactor temperature, pyramidal surface morphology was suppressed, and a smooth surface was achieved. Our typical etching condition gave rise to an etch rate of 600nm/hr, with a smooth surface. This task was completed on 08/15/2019.
Task 8: Demonstration of high performance regrowth p-n diodes	Q9: Breakdown voltage >= 150V; Leakage current <= 1×10^{-9}A (@150V); Turn-on Voltage: 2.6-3.4V; Specific R_{DSON} < 3mΩ·cm^2 (without passivation and field plate or any edge temination). **Actual Performance:** We have demonstrated a TBCl etched-and-regrown p-n diode with a leakage current and forward-bias behavior close to the continuously grown diode. The leakage current (for devices with diameter of 400um) at 150V is <$1x10^{-5}$A/cm^2. On-resistance is 0.3mΩ·cm^2. This task was completed on 10/30/2020.

Task 9: Achieving low-defect SAG on TBCl / dry-etched GaN and characterizing the electronic defects.	Q12: Atomic smoothness by AFM, RMS roughness < 1 nm (10x10 um^2) after etching or regrowth surface treatment. SEM will be used to check the uniformity during the nucleation stage. Low impurity level across regrowth interfaces by SIMS ([C]<$1x10^{16}cm^{-3}$; [O]<$5x10^{16}cm^{-3}$). **Actual Performance:** Atomic smoothness after TBCl etching was confirmed using AFM (08/15/2019). We found that the non-uniform GaN growth within the SAE trenches created by TBCl is likely caused by the SiN nano-masks. Si was introduced during the patterning process of the SiO_2 mask and also the TBCl etching. So, we were looking for other masking materials and patterning process introduces less impurities.
Task 10: Controlling SAG dynamics and profile using Wulff principle.	Q11: Acceptance of a report (topography during SAG measured by SEM, APT, electrical property measured by SSRM, SCM and CL) by ARPA-E. **Actual Performance:** The non-planar growth of GaN was dominated by the concave growth front developed at the bottom corner of trenches. We successfully used kinetic Wulff diagram and Wulff construction to explain the shape evolution observed using SEM and APT. Also APT was used to study the origin of non-uniform Mg doping. (This task was completed at 03/20/2021)
Task 11: Study and suppression of SAG mask contamination	Q12: Acceptance of a report (of SAG with masks such as SiO2, SiNx, refractory metal, ALD AlOx, other ALD dielectrics, AlN) by ARPA-E. **Actual Performance:** LT-AlN was grown by MOCVD at 500°C. It was patterned using photolithography and wet etching using TMAH-based developer. We have successfully demonstrated selective area growth of UID-GaN and p-GaN using LT-AlN mask. (This task was completed at 11/20/2020.)

Task 12: Demonstration of high-performance regrowth lateral junction devices	Q13: Vertical diode with lateral PN-junction will be fabricated and measured via I-V and C-V measurements. Simulation and experiment will be combined to optimize the structure. Breakdown voltage >= 600V; Leakage current <= 1×10^{-9}A (@400V); Turn-on Voltage: 2.6-3.4V; Specific R_{DSON} < 3mΩ·cm^2; I_{on}/I_{off} Ratio > 10^{10} **Actual Performance:** We fabricated a vertical diode with lateral PN junction on 12/30/2021. Under reverse bias, the device had low leakage current below 10V, <1×10^{-7} A/cm^2. It started to rise up quickly above 10V, and reached 1×10^{-2} A/cm^2 at 45V. The forward leakage current (before turn-on) was low, ~1×10^{-8} A/cm^2. The on-off ratio was >10^{10}.
Task 13: Technology To Market	Q1: Background IP assessment. Acceptance of a background assessment and IP strategy report by ARPA-E Q4: IP Update. Acceptance of an invention disclosure and patent application update report by ARPA-E Q4: Presentation and publication. Present results at appropriate Conference or submit manuscript for publication in peer reviewed journal Q8: IP Update. Acceptance of an invention disclosure and patent application update report by ARPA-E Q8: Presentation and publication. Present results at appropriate Conference or submit manuscript for publication in peer reviewed journal Q13: IP Update. Acceptance of an invention disclosure and patent application update report by ARPA-E Q13: Presentation and publication. Present results at appropriate Conference or submit manuscript for publication in peer reviewed journal **Actual Performance:** Please see Project Output Section.

Project Activities

This project tackled the challenges in realizing selective-area doping of GaN through selective-area etching followed by selective-area growth. The major assumption was that defect-free and impurity-free selective area etching can be achieved in-situ prior to the selective area doping in order to form GaN lateral junction devices. To provide a technical summary of the overall effort and accomplishment, we use Figure 1 to denote the intellectual building blocks for this project and to present our accomplishments in these four respective categories:

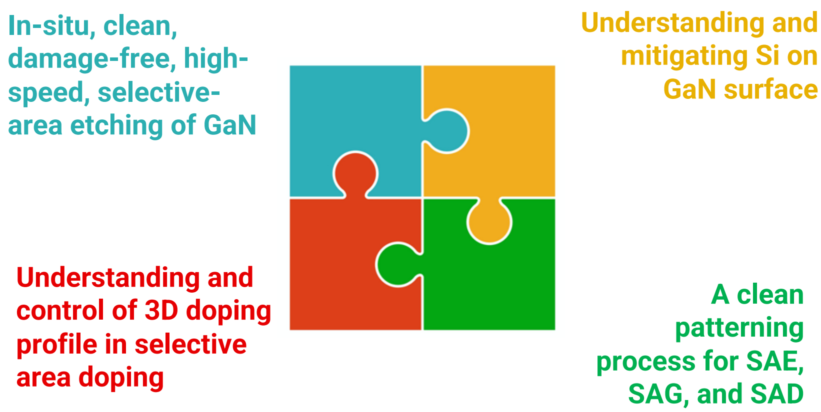

Fig 1. The four building blocks needed to realize GaN selective area doping through selective etching and regrowth for GaN lateral pn junction electronics.

(1) Development of in-situ, low-defect, damage-free GaN etching by employing a novel MOCVD-precursor (TBCl)

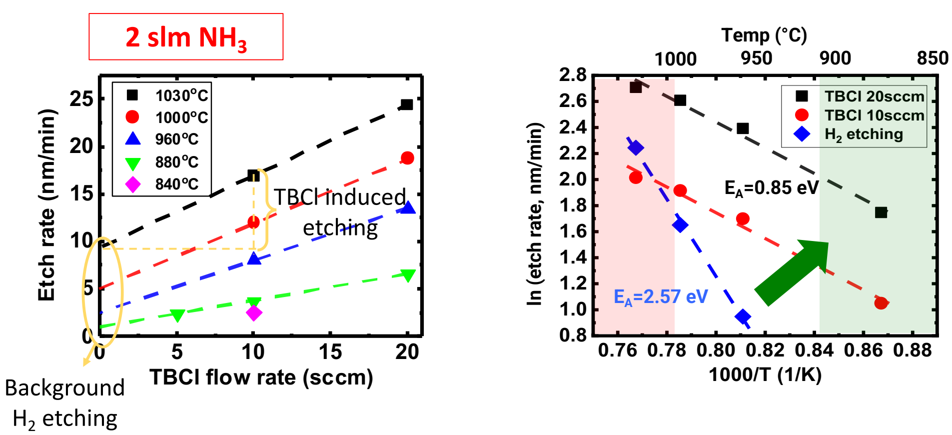

Fig 2. (Left panel) Measured etch rates of GaN at different TBCl flow rates and at different temperatures. (Right panel) Arrhenius plot of etch rates of GaN with TBCl (black and red lines), and with H2 only (blue line), indicating different etching mechanisms.

Having confirmed the limitation of using hydrogen as an in-situ etchant in 2018, we identified a novel MOCVD precursor, TBCl, in 2019 and demonstrated very promising results in GaN etching. Fig 2 shows the observed in-situ etching rate of GaN using TBCl, which can support high-speed selective area etching. The quality of the TBCl etching was verified by atomic force microscopy (AFM) showing atomically smooth surface (Fig 3a). Photoluminescence (PL) shows that TBCl etching is damage free (green curve in Fig 3b) as evidenced by a healthy near-band edge emission. Furthermore, we concluded that TBCl etching is capable of repairing dry-etching caused damages (blue curve in Fig 3b).

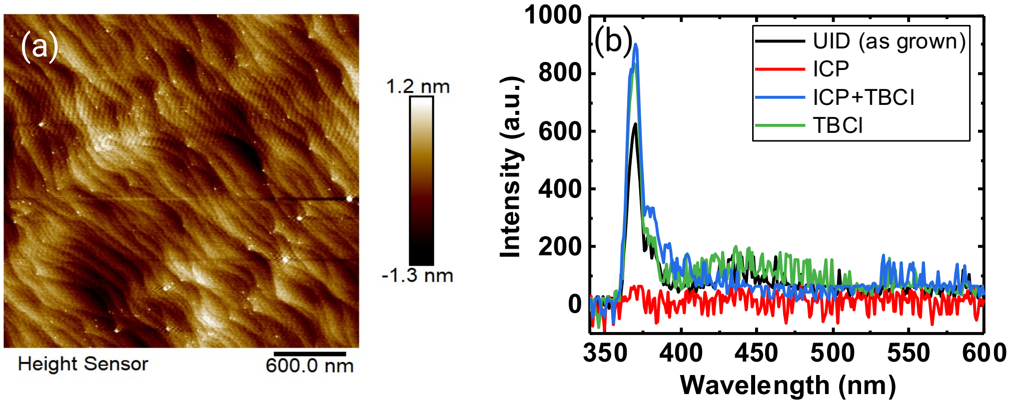

Fig 3. The quality of the TBCl etching was verified by atomic force microscopy (AFM) showing atomically smooth surface (a). (b) Photoluminescence (PL) shows that TBCl etching is damage free (green curve) and is capable of repairing dry-etching caused damages (blue curve).

The promise of this in-situ TBCl etching was also confirmed electrically with both etched Schottky diodes (Fig 4a) and etched and regrowth GaN PIN diodes (Fig 4b). In both cases the devices based on TBCl-etched surface (green curves) approach the ideal GaN surface (black curves) in terms of leakage and breakdown behaviors.

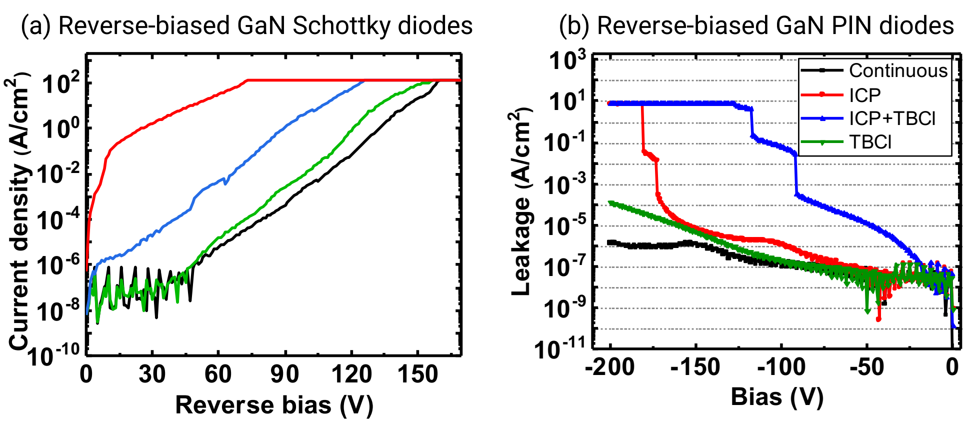

Fig 4. Reverse-biased I-V characteristics of (a) four GaN Schottky diodes, and (b) four GaN PIN diodes. In each case the black curves represent the ideal references of, respectively, as-grown GaN for Schottky diodes and continuously-grown PIN diodes. The green curves represent diodes made from TBCl etched surfaces that closely approach the ideal curves.

In terms of using TBCl for selective area etching, we demonstrated (Fig 5) that reactor pressure and NH_3 flow are two sensitive knobs which can be used to achieve smooth, featureless GaN selective area etching for subsequent selective area regrowth and doping. However, we also discovered that TBCl etching, being purely chemistry-based, is elemental-specific and cannot effectively remove certain impurities such as silicon that are ubiquitous in many processes. In the next section we summarize our study of the roles and sources of Si impurities.

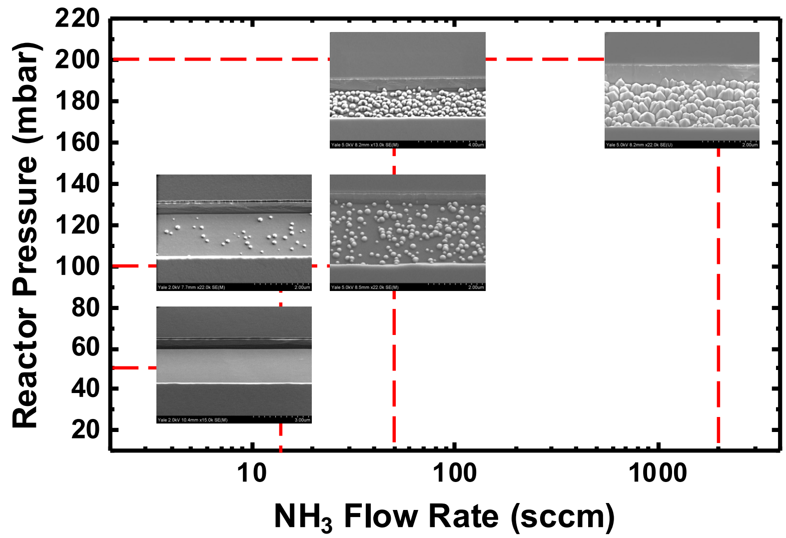

Fig 5. Surface morphology of selectively etched GaN (GaN etched regions appear in between the SiO_2 masked regions in dark contrast). As the NH_3 flow rate and reactor pressure decrease, islands and etching residues gradually disappear into a featureless region (lower left corner).

(2) Systematic investigation of the sources and influences of silicon impurities

To understand the roles of silicon, we prepared a series of GaN samples and subject the surfaces to a range of conditions, and the samples were capped by a subsequent regrowth of GaN. The exposed surfaces then became buried interfaces and characterized by SIMS. Figure 6 summarizes the dosage of silicon (in 2D unit, cm^{-2}) incurred in in-situ (green panel), ex-situ ambient (yellow panel), and ICP etching (red panel). Our study helped to identify minimally-acceptable process conditions toward the ultimate completion of a clean regrowth interface.

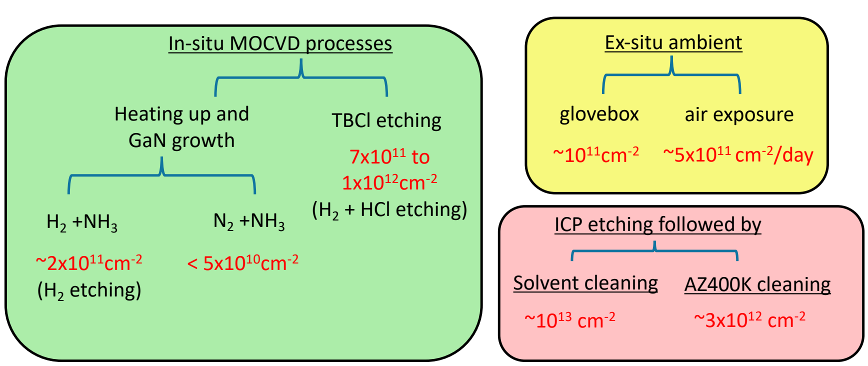

Fig 6. Summary of the amount of silicon impurities (in 2D concentration, in red) introduced by different processes, as

determined by secondary ion mass spectroscopy (SIMS) after regrowth of GaN on the exposed GaN surfaces.

(3) Understanding and control of 3D doping profile in selective area doping

An important goal of this project is to develop and apply novel nanoscale probes to study 3D-distribution of electronic impurities and defects. We made significant progress toward this goal by applying atom probe tomography (APT), scanning spreading resistivity microscope (SSRM), scanning capacitance microscope (SCM), and cathodoluminescence (CL) to provide a holistic understanding of the defect and impurity incorporation during selective regrowth and doping. Fig 7 depicts how APT can be used to provide 3-dimensional, nanometer-scale information of impurities distributions, local growth rates, and evolution of surface orientations. Our studies lead to three important findings for selective-area doping (SAD) and selective area etching (SAE):

(i) Mg doping is inversely proportional to the local growth rates, regions with a high local growth rate in selective growth have a low Mg concentration (Fig 7c),

(ii) (ii) growth rates are determined by the concave growth that can be described by the kinetic Wulff plot, and

(iii) (iii) in the selective area doping of GaN, Mg precursors tend to diffuse readily in the gas-phase together with the Ga precursors, but Mg adatoms on the surface do not diffuse much compared with the surface diffusion of Ga adatoms. These findings will enable us to design, interpret, and control doping profiles in selective area doping.

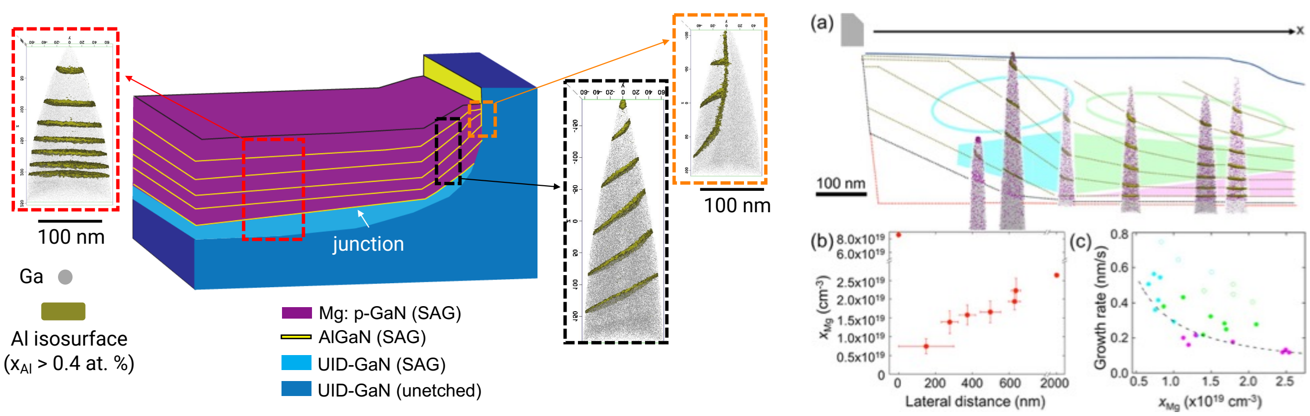

Fig 7. (Left panel) APT reconstructions of regrown p-GaN. Ga atoms are shown as gray dots, and Mg atoms are shown as purple spheres. Regions in which xAl > 0.4 atom % are encapsulated in dark-yellow isosurfaces. (Right panel) (a) APT reconstructions from transitional region (ii) in Figure 1d superposed on the schematic of initial and final growth interfaces. Ga and Mg atoms are shown as gray and purple dots, respectively, and dark-yellow isosurfaces encapsulate regions with xAl > 0.4 atom %. The initial trench profile is taken from Figure 1d. Colored overlays act as a key for the data shown in (c). (b) Mg concentration as a function of distance from the trench edge measured 49 nm from the regrowth interface. The point at zero was taken at the trench edge. (c) Correlation of Mg concentration with the growth rate. The dashed line indicates an inverse proportionality. The colors of the points indicate the region where the data were acquired as indicated in (a). Solid and open circles represent data points collected near and away from the regrowth interface, respectively.

(4) A clean patterning method for selective area etching, growth, and doping

The ultimate demonstration of lateral junction by selective-area doping with selective-area etching, however, was hampered by the presence of extrinsic impurities either from ambient or introduced in the processing. While we have demonstrated unambiguously the effectiveness of TBCl in performing damage-free in-situ etching, it is noted that additional processing techniques need to be developed to address the sensitivity of TBCl etching to Si-containing layers and masks. We proposed two new processing approaches:

(i) The use of a silicon-free AlN mask layers (Fig 8, region in green) for selective area etching and growth, as shown in Fig 8. In Fig 8 we have demonstrated SAG with AlN mask and SAE by ICP with AlN mask.

(ii) The other one is using a novel maskless in-situ etching process (a provisional application has been filed as described in E.2).

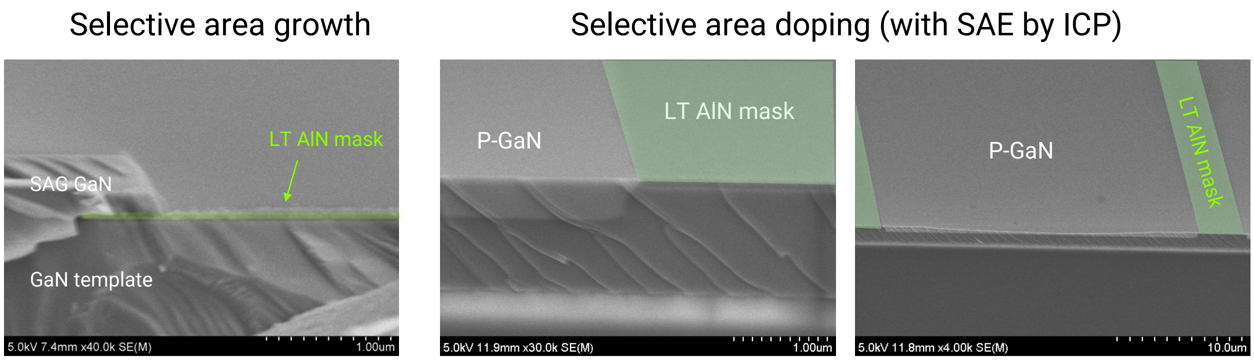

Fig 8. (Left) A cross-sectional SEM image confirming selective area growth using AlN as a mask, (Center and right) p-type selective area doping of GaN after selective area etching (using ICP).

Project Outputs

A. *Journal Articles*

1. Alexander S Chang, Bingjun Li, Sizhen Wang, Sam Frisone, Rachel S Goldman, Jung Han, Lincoln J Lauhon, Unveiling the influence of selective-area-regrowth interfaces on local electronic properties of gan pn junctions for efficient power devices, Nano Energy, 107689 (2022).
2. Bingjun Li, Sizhen Wang, Mohsen Nami, Andrew M. Armstrong, and Jung Han, Etched-and-regrown GaN P-N diodes with low-defect interfaces prepared by in-situ TBCl etching, ACS applied materials & interfaces, 13 (44), 53220-53226 (2021).
3. Bingjun Li, Sizhen Wang, Alexander S. Chang, Lincoln J. Lauhon, Yafei Liu, Balaji Raghothamachar, Michael Dudley, and Jung Han, Selective area etching and doping of GaN for high-power applications, ECS transactions, 104 (2021).
4. Houqiang Fu, Kai Fu, Chen Yang, Hanxiao Liu, Kevin A Hatch, Prudhvi Peri, Dinusha Herath Mudiyanselage, Bingjun Li, Tae-Hyeon Kim, Shanthan R Alugubelli, Po-Yi Su, Daniel C Messina, Xuguang Deng, Chi-Yin Cheng, Reza Vatan Meidanshahi, Xuanqi Huang, Hong Chen, Tsung-Han Yang, Jingan Zhou, Andrew M Armstrong, Andrew A Allerman, T Yu Edward, Jung Han, Stephen M Goodnick, David J Smith, Robert J Nemanich, Fernando A Ponce, and Yuji Zhao, Selective area regrowth and doping for vertical gallium nitride power devices: Materials challenges and recent progress, Materials Today (2021).

5. Alexander S Chang, Bingjun Li, Sizhen Wang, Mohsen Nami, Paul JM Smeets, Jung Han, and Lincoln J Lauhon, Selective Area Regrowth Produces Nonuniform Mg Doping Profiles in Nonplanar GaN p–n Junctions, ACS Appl. Electron. Mater., 3, 2, 704–710 (2021).
6. Bingjun Li, Sizhen Wang, Mohsen Nami, and Jung Han, A study of *in-situ* etching of GaN in metalorganic chemical vapor deposition (MOCVD) by tertiarybutylchloride (TBCl), J. Cryst. Growth, 534, 125492 (2020).
7. Bingjun Li, Mohsen Nami, Sizhen Wang, and Jung Han, *In-situ* and selective area etching of GaN by Tertiarybutylchloride (TBCl), Appl. Phys. Lett. 115, 162101 (2019).

B. Papers and conference presentations

1. *Bingjun Li, Sizhen Wang, Jung Han, High-Speed MOCVD Growth of GaN Assisted by TBCl, 64th Electronic Materials Conference (2022).*
2. *Bingjun Li, Sizhen Wang, Jung Han, Growth evolution in non-planar GaN selective-area epitaxy, 64th Electronic Materials Conference (2022).*
3. *Bingjun Li, Sizhen Wang, Sam Frisone, Joshua Cooper, Erdem Ozdemir, Jiaheng He, Guanjie Cheng, Zhirong Zhang, Rachel Goldman, Jung Han, Low-damage, in-situ chemical etching of GaN by tertiarybutyl-chloride (TBCl), Compound Semiconductor Week (2022).*
4. *Sam Frisone, Alexander Chang, Sizhen Wang, Bingjun Li, Rachel Goldman, Lincoln Lauhon, Jung Han, Understanding radiative emissions in the vicinity of selected-area regrown GaN diodes, APS March Meeting (2022).*
5. *Bingjun Li, Sizhen Wang, Alexander S. Chang, Lincoln J. Lauhon, Yafei Liu, Balaji Raghothamachar, Michael Dudley, and Jung Han, Selective area etching and doping of GaN for high-power applications, 240th ECS meeting (2021).*
6. *Bingjun Li, Sizhen Wang, and Jung Han, Low-defect etched-and-regrown PN diodes by in-situ tertiarybutylchloride (TBCl) etching, 2021 Virtual MRS Spring Meeting & Exhibit (2021).*
7. *Jiaheng He, Guanjie Cheng, Zhirong Zhang, Maggie Chen, Sam Frisone, Alexandra Zimmerman, Fabian Naab, Sizhen Wang, Bingjun Li, Jung Han, Rachel Goldman, Influence of Surface Treatments on the Structure of GaN Layers, APS March Meeting (2021).*
8. *GuanJie Cheng, Jiaheng He, Alexandra Zimmerman, Davide Del Gaudio, Fabian Naab, Mohsen Nami, Bingjun Li, Jung Han, Rachel Goldman, Influence of interfacial defects on the electronic states at GaN pin diode interfaces, APS March Meeting (2020).*
9. *Alexander Chang, Mohsen Nami, Bingjun Li, Jung Han, and Lincoln Lauhon, Atom Probe Tomography Study of Dopant and Impurity Distributions Near Planar and Non-Planar GaN Homojunctions, 61st Electronic Materials Conference (2019).*
10. *Jiaheng He, Guanjie Cheng, Davide Del Gaudio, Jordan Occena, Fabian Naab, Rachel S. Goldman, Mohsen Nami, Bingjun Li, and Jung Han, Identifying Defects and Their Electronic Signatures in Regrown GaN Heterostructures, 61st Electronic Materials Conference (2019).*
11. *Bingjun Li, Mohsen Nami, Jiaheng He, Guanjie Cheng, Davide Del Gaudio, Jordan Occena, Fabian Naab, Rachel S. Goldman and Jung Han, Investigation of Contaminations and Damages on C-Plane GaN Induced by Dry Etching, 61st Electronic Materials Conference (2019).*
12. *Bingjun Li, Mohsen Nami, and Jung Han, Selective area growth and doping of GaN, 19th International Conference on Crystal Growth and Epitaxy (2019).*
13. *Jiaheng He, Guanjie Cheng, Davide Del Gaudio, Jordan Occena, Fabian Naab, Rachel Goldman, Mohsen Nami, Bingjun Li, and Jung Han, Identifying Defects and their Electronic Signatures in Regrown GaN Heterostructures, APS March Meeting (2019).*

C. Status Reports

NA

D. Media Reports

NA

E. Invention Disclosures

1. Jung Han, and Bingjun Li, Organometallic vapor phase epitaxy (OMVPE) of GaN at high growth rates (2019).
2. Jung Han and Bingjun Li, Maskless in-situ differential etching of GaN (2022)

F. Patent Applications/Issued Patents

A. Jung Han, and Bingjun Li, IN-SITU AND SELECTIVE AREA ETCHING OF SURFACES OR LAYERS BY ORGANOMETALLIC CHLORINE PRECURSORS, PCT/US2020/037921 (pending)

G. Licensed Technologies

NA

H. Networks/Collaborations Fostered

NA

I. Websites Featuring Project Work Results

NA

J. Other Products (e.g. Databases, Physical Collections, Audio/Video, Software, Models, Educational Aids or Curricula, Equipment or Instruments)

NA

K. Awards, Prizes, and Recognition

NA

Follow-On Funding

NA