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Lawrence Livermore National Laboratory

Gallium Nitride Superjunction Fin Field Effect Transistor
21-ERD-036

Noah Allen

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Disclaimer

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Project Overview

The goal of this project is to develop the gallium vacancy assisted diffusion (GAID) method in GaN and apply it to demonstrate 2-terminal, 3-terminal, and large area Superjunction-enhanced modules. These devices will find use in high efficiency power conversion applications with the capability of operating at higher voltages, higher frequency, and less loss than comparable stat-of-the-art devices.

Driven by first principles simulations of atomic defect formation in GaN, we have selectively diffused Mg into GaN resulting in the first demonstration of selective area doping by diffusion at low temperatures. Confirmation was provided with the analysis of atomic composition along with laterally mapped electrical characterization of prepared layers. Although great progress has been made to simulate and fabricate enhanced GaN-based power devices, development of a contactable p-type layer by diffusion has proven difficult thus impeding demonstration of a PN diode or GaN Superjunction-enhanced device. Recently, it was discovered that the GaN growth conditions play a larger role in Mg incorporation than previously thought but can be partially overcome with an in-situ bias during diffusion. Finally, the Raith EPBG5200 e-beam writer was delivered and qualified in early June 2021 permitting the development of GaN devices with geometries needed (according to TCAD simulations) to exhibit Superjunction enhancement.

Mission Impact

This project directly supports LLNL's Energy and Resource Security mission area. Because power electronic switches touch nearly aspect of electricity generation and consumption, even small gains in efficiency can drive outsized effects in energy consumption and improve United States energy security and reduce greenhouse gas emissions. It also falls with the Advanced Materials and Manufacturing core competency, as GaN is a next generation semiconductor material, and the project will be developing new manufacturing techniques for GaN devices.

Publications, Presentations and Patents

- Varley, Joel Basile, Noah Patrick Allen, Clint Frye, Kyoung Eun Kweon, Vincenzo Lordi, and Lars Voss. "Field assisted interfacial diffusion doping through heterostructure design." U.S. Patent Application 17/166,962, filed August 19, 2021.

- Voss, Lars F., Clint D. Frye, Noah A. Allen, Sarah E. Harrison, Kyoung Kweon, Joel Basile Varley, Vincenzo Lordi, Rebecca Nikolic, Travis J. Anderson, and Jennifer K. Hite. "Moderate Temperature Mg Diffusion Doping of GaN." In *ECS Meeting Abstracts*, no. 26, p. 1810. IOP Publishing, 2020.

- [Invited Abstract] Voss, Lars F., Clint D. Frye, Noah A. Allen, Sarah E. Harrison, Kyoung Kweon, Joel Basile Varley, Vincenzo Lordi, Rebecca Nikolic, Travis J. Anderson, Jennifer K. Hite., Jung Han, and Bingjun Li. "Prospects for Magnesium diffusion doping of GaN" *ECS Meeting Abstracts, 2021*

Abstract

The goal of this project is to develop the gallium vacancy assisted diffusion (GAID) method in GaN and apply it to demonstrate 2-terminal, 3-terminal, and large area Superjunction-enhanced modules. These devices will find use in high efficiency power conversion applications with the capability of operating at higher voltages, higher frequency, and less loss than comparable stat-of-the-art devices.

Driven by first principles simulations of atomic defect formation in GaN, we have selectively diffused Mg into GaN resulting in the first demonstration of selective area doping by diffusion at low temperatures. Confirmation was provided with the analysis of atomic composition along with laterally mapped electrical characterization of prepared layers. Although great progress has been made to simulate and fabricate enhanced GaN-based power devices, development of a contactable p-type layer by diffusion has proven difficult thus impeding demonstration of a PN diode or GaN Superjunction-enhanced device. Recently, it was discovered that the GaN growth conditions play a larger role in Mg incorporation than previously thought but can be partially overcome with an in-situ bias during diffusion. Finally, the Raith EPBG5200 e-beam writer was delivered and qualified in early June 2021 permitting the development of GaN devices with geometries needed (according to TCAD simulations) to exhibit Superjunction enhancement.

Background and Research Objectives

The power MOSFET switch is a necessary device in power conversion circuitry used to gate incoming electrical energy into passive elements (inductors and capacitors) such that the output voltage can be increased (boost converter) or decreased (buck converter) without power loss. For applications that require higher power conversion and lower loss, the fundamental material from which the switch is fabricated must be considered. Silicon as a power semiconductor has stayed relevant due to the ability to form a Superjunction structure, beating the breakdown vs. specific on-resistance 1-D unipolar material limit. This is accomplished by cleverly designing a charged balanced layer (CBL) into the voltage sustaining region so that the electric field is distributed throughout the volume and not concentrated at an interface. Power devices fabricated from so-called wide-bandgap semiconductors such as gallium nitride (GaN) have been shown to outperform state-of-the-art silicon-based power devices but because of the limited processing knowledge a GaN-based Superjunction has yet to be demonstrated. This project aims to develop the first GaN Superjunction FinFET by harnessing technology developed at Lawrence Livermore National Laboratory.

Currently, GaN lacks a method to selectively dope regions of the material without introducing significant damage into the bulk of the semiconductor. Without this capability, a Superjunction structure cannot be realized. Previous work performed at LLNL has revealed a mechanism to enhance solid-state diffusion of magnesium in GaN at low temperatures. By patterning a thin layer of a Mg-containing film (MgF_2, MgO, Mg_3N_2 etc.) on the surface of the GaN followed by a gallide forming metal, we have shown that Mg can be incorporated into the bulk with temperatures as low as 700°C. With this process, GaN-based power device capabilities can be further extended by patterning charged balanced layers (CBL) and realizing the world's first GaN Superjunction-enhanced devices.

The goal of this project is to harness first principles and TCAD simulation tools to drive diffusion and device design experiments, respectively, and demonstrate progressively more complicated CBL-enhanced device structures. Simultaneously, with the recent delivery of the Raith E-Beam direct write lithography system, GaN-based finFET process technology will be developed and merged with our CBL work to realize a SJ-enhanced finFET device. Ultimately, the aim of this project is to establish GaN Superjunction finFET processing technology and work with industrial partners to transfer into the market resulting in high efficiency power conversion modules for previously unreachable applications.

Throughout the first year of funding, we have focused most effort on improving the Mg incorporation into GaN such that a PN diode is realized. Here we used first principles simulations to understand the material and thermodynamic parameter-space and fabricated samples on GaN wafers purchased under this project. Material analysis shows high concentrations of Mg at the surface of prepared samples while electrical results reveal positive voltage shifts in the IV characteristics. However, additional work is needed before a PN diode is observed.

Scientific Approach and Accomplishments

Project main thrusts:

1. First principles simulation
2. TCAD simulation
3. Fabrication and diffusion of Mg-containing bilayer samples
4. SIMS analysis
5. Electrical measurement and data analysis

Summary of first principles simulation work:

With first principles simulations (VASP), models of atomic diffusivities, charge states, and activation energies can be used to understand the parameter-space of gallium vacancy enhanced diffusion experiments. Capitalizing on the success of previous work, simulations focused primarily on understanding MgF_2 as a diffusion source and possible compensation defects that may arise. However, recent work has targeted the prospect of other sources such as MgN and Mg/B. Summary of findings are detailed below:

Fluorine interstitial diffusion and complexes in GaN

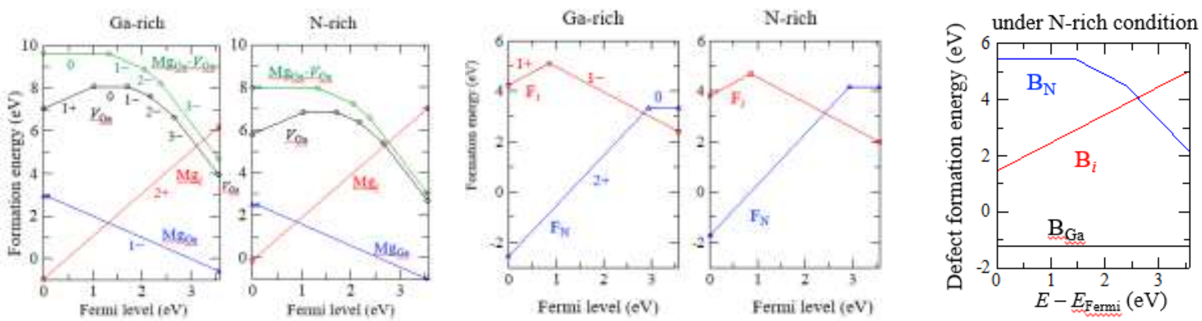
- Under both Ga- and N-rich conditions fluorine appears as an interstitial donor (F_i) when the fermi level is near the valence band and in the neutral nitrogen substitutional (F_N) when the fermi level is near the conduction band
- Fluorine interstitial diffusion is enhanced with presence of gallium vacancies

Formation and diffusion of H_i in GaN

- Hydrogen interstitials largely slowed down under n-type conditions (fermi level closer to conduction band)

Boron versus Mg Diffusion in GaN

- Boron diffuses more readily in the presence of gallium vacancies but with a higher activation energy than Mg
- Boron on gallium sites energetically favor a neutral configuration (no electrical compensation)



(A) (B) (C)

Figure 1. First principles simulations of the formation energy vs. fermi level position in GaN for (A) Mg/V_{Ga} (B) fluorine (C) and boron along with relevant complexes in GaN.

Summary of TCAD Work:

SILVACO is used to both understand non-ideal electrical behavior in fabricated devices and predict geometries required to observe enhancement in fabricated devices. A Summer intern, was successful in developing a testbed for evaluating the complex geometries needed to observe Superjunction behavior in simulation. TCAD Simulation work completed is summarized below:

Positive Voltage Shift in Diffused Devices

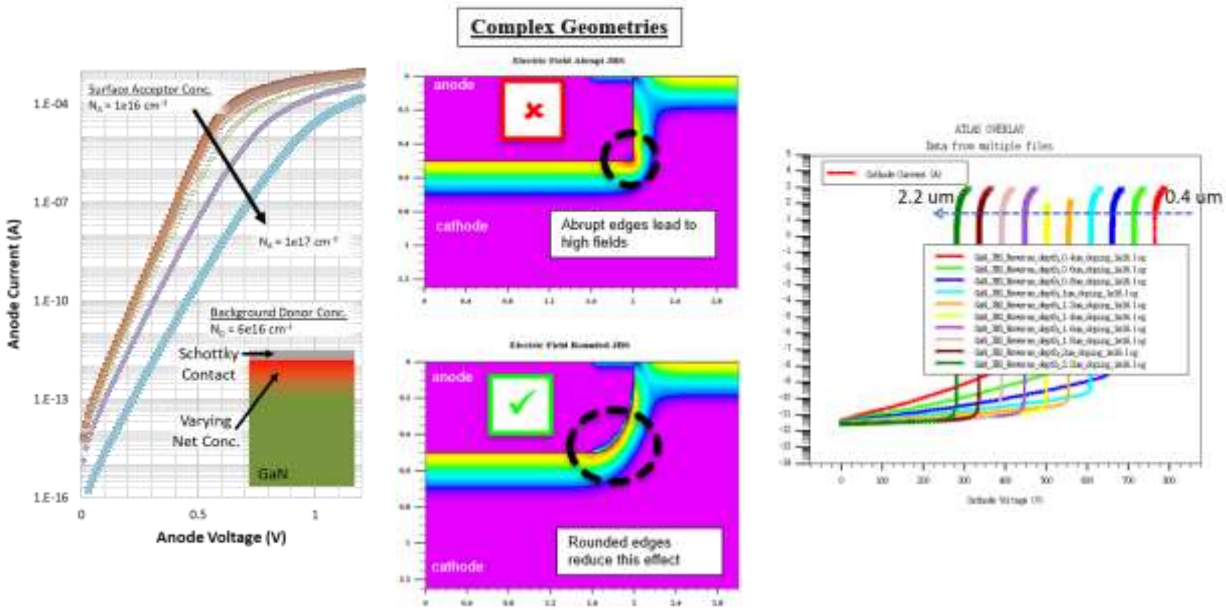
Two hypotheses were formed to explain the positive forward I-V voltage shifts (shown later) in the diffused region of processed samples. The first assumes that the surface of the semiconductor is doped p-type except for small patches which would allow parallel Schottky diode conduction. A second hypothesis was developed where the complete surface of the semiconductor was doped but the stringent requirements to make a p-type ohmic contact had not been met. From simulations it was concluded that the latter was the cause of the voltage shift indicating that the gallium assisted diffusion process is successful but will not yielded PN diode behavior until the acceptor concentration is increased.

Complex Geometry Testbed

Ideal functionality of a SJ-finFET relies on many parts working correctly. To help inform parameter selection for use in subsequent device fabrication procedures, a SILVACO simulation testbed was created where parts of the final devices could be tested in isolation. Work from a Summer intern realized the ability to simulate avalanche breakdown and forward operating points in complex structures.

Enhanced Device Geometry

Continuing where the Summer intern left off, device fabrication parameters in PN, JBS, SJ-JBS diodes were evaluated. Focus has been understanding the effects of device geometry and doping levels on avalanche breakdown. Results from these simulations will inform future device fabrication procedures.



(A) (B) (C)

Figure 2. SILVACO TCAD simulation results show the (A) effects of donor compensation at a Schottky contact, (B) dispersion of electric field at a rounded interface and (C) breakdown characteristics of a JBS diode with varying Schottky diode areas.

Summary of Sample Fabrication and Diffusion

Due to the limited supply of available GaN to this project, three 4" wafers were purchased from IQE, each with a 3um thick active layer grown on a bulk GaN substrate. Specific free carrier concentrations were defined for each wafer and grown with special consideration given to lowering the background carbon concentration. This was done to ensure carrier compensation was minimized due to the introduction of impurities during the MOCVD growth process.

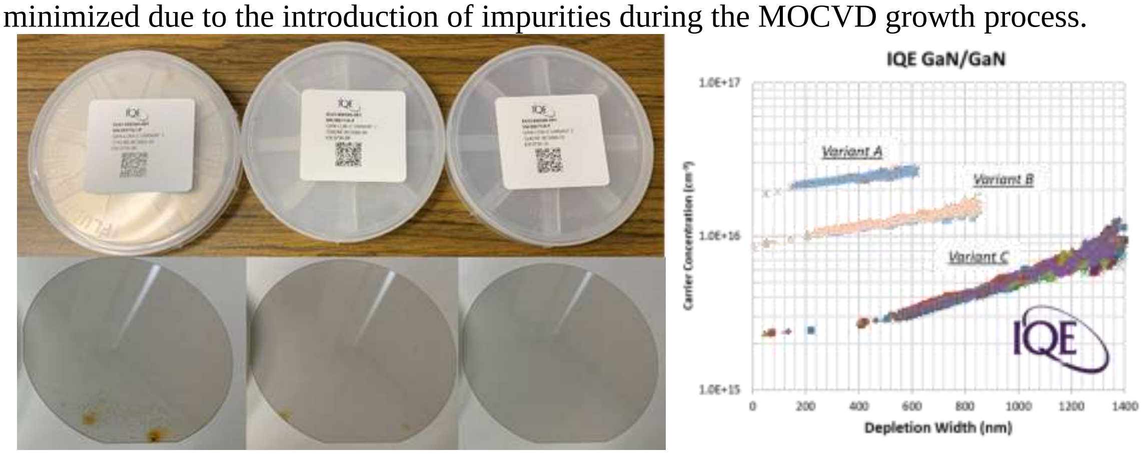


Figure 3. (Left) Image of three 4" MOCVD-grown GaN-on-GaN wafers purchased from IQE. Each wafer consists of a 3um thick low-doped layer targeted to have differing electron concentrations. (Right) Carrier concentrations extracted from C-V measurements on each

Test samples were fabricated by first dicing 5x5mm^2 coupons from the full wafers. Next, a Ti/Al/Ni/Au stack is evaporated on the backside of each sample as the ohmic contact followed by e-beam deposition of the test bilayer through a 2mm circular metal mask. Once completed, samples were annealed at temperatures between 600 and 1000 °C from 5 to 100 minutes in a controlled environment to understand the effect that temperature and time have on the diffusion of Mg into the GaN. Additionally, a two-probe vacuum feedthrough was developed to test the effect of in-situ bias. Here two stainless steel wires are fed through a two-hole ceramic isolator encased in a stainless-steel tube. Torr-seal was used to epoxy the atmosphere end of the assembly and the vacuum seal was made with an o-ring, like a quick connect coupling, between the tubing and the annealing chamber. Inside the chamber, the stainless-steel wires are cantilevered onto the sample and the conductive sample holder used to make backside contact. Sample fabrication and the bias-assisted probe setup are shown below in Figure 4. Once the diffusion process was complete, the bilayer and back ohmic contacts are removed in subsequent soaks of aquaregia, 44% KOH, and 49% HF revealing a clean GaN surface ready for SIMS or electrical measurements.

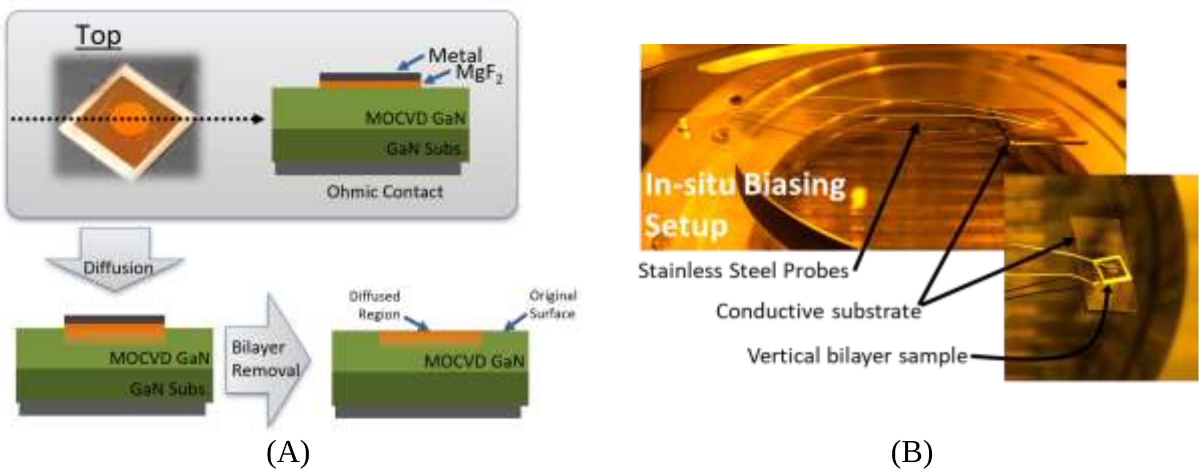


Figure 4. (A) Summary of basic fabrication process to test diffusion parameters and (B) two probe in-situ biasing setup created for this project.

Summary of SIMS Analysis

SIMS was performed on selected samples to investigate the diffusion of Mg in GaN under varying bilayer configuration, temperatures, times, and biasing conditions. Samples were sent to EAG Laboratories for tests. Each sample was scribed prior to bilayer removal to indicate the location of diffusion. A summary of SIMS data is below:

Yale GaN-on-GaN Bias Assisted Comparison

Two samples processed according to the images below on samples grown in collaboration with Yale University were sent to EAG Laboratories for magnesium and fluorine concentration profiling by SIMS. The results are shown below in Figure 5 reveal two distinct profiles. The magnesium concentration in the sample measured with no in-situ bias has a profile very similar to results from previous experiments (not shown) where the GaN layer was grown on sapphire. Applying a +4 V in-situ bias during the annealing process appears to increase the surface concentration while also extending the >1e18cm^{-3} crossing point from 10 to 35nm. Additionally, the +4 V in-situ bias suppresses the fluorine concentration when compared to the sample processed with no in-situ bias. These results are exciting and indicate that the core premise of surface fermi-level tailoring predicted by first principles simulations are correct.

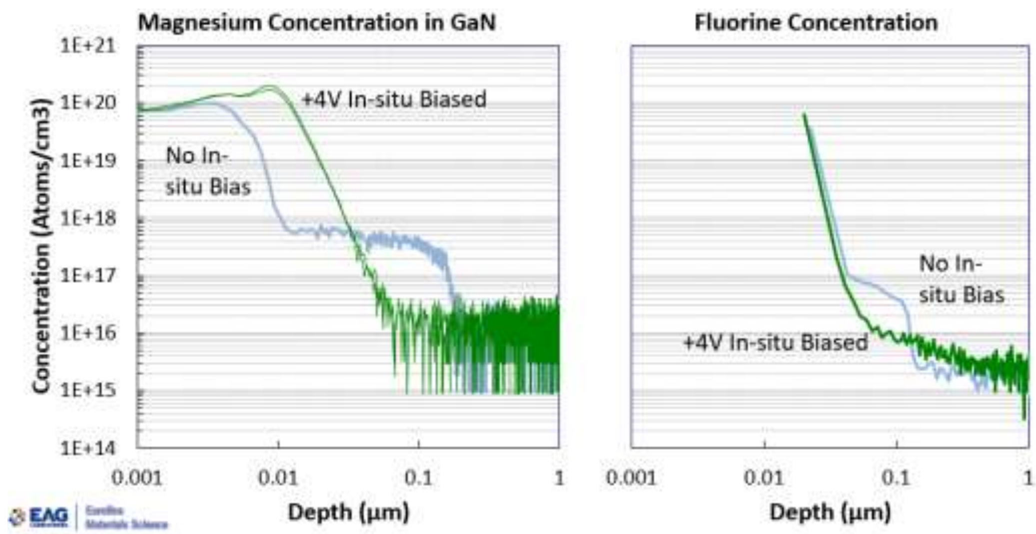


Figure 5. SIMS measurement results for the depth dependent (Left) Mg and (Right) F concentrations in

IQE GaN-on-GaN Diffusion Parameter Comparison

Recently, seven samples were prepared from the IQE wafers according to the legend below in Figure 6(A) where temperature, bulk concentration, and in-situ biasing conditions were compared. Here it can be observed that for most samples a high concentration of Mg is present at up to 10nm into the GaN surface, but samples annealed with a +4V in-situ bias show a larger tail down to 100nm. Interestingly, samples annealed either without or at negative bias reveal a shallower profile than those annealed under similar conditions but on material grown elsewhere. This implies that the MOCVD growth conditions play a large role in Mg diffusivity but can be mitigated by applying a bias while at temperature.

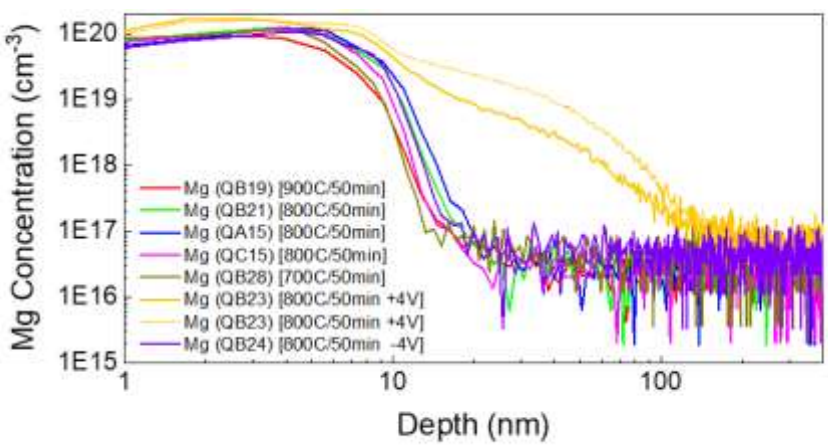


Figure 6. SIMS measurement results from IQE

Summary of Electrical Testing and Results

To ensure that electrical results were indicative of the bilayers role during diffusion, $5x5mm^2$ samples were patterned with 100µm circular contacts composed of a Pd/Ni/Au stack. Assuming the diffusion resulted in a high concentration of acceptors at the surface, a PN diode could be formed under the 2mm circular bilayer region, otherwise a Schottky diode would be formed.

Samples were then electrically measured and mapped with an automated probing setup. An example of a processed sample and generated data is shown below in Figure 7(A) and (B), respectively.

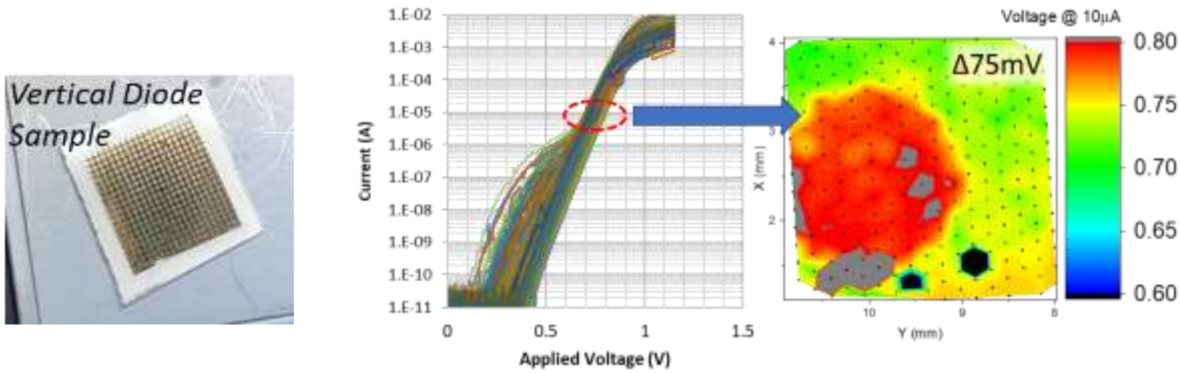


Figure 7. (A) Patterned sample ready for measurement and (B) a sample of electrical results generated from 2D mapping

By extracting the voltage at which the diode reaches 10 uA for each contact, contour maps were created making it clear that the patterned bilayer does indeed alter the surface of the semiconductor such that the I-V characteristics are shifted on the voltage-axis. Additionally, a shift in the voltage required to reach 10uA while still maintaining the thermionic emission limited region (linear region on semi-log plot) suggest that the energy barrier at the M-S interface is varying. As discussed previously, TCAD simulations indicate that an increasing barrier can be described by varying the carrier concentration at this interface while still maintaining a Schottky contact.

From this analysis, the voltage shift change, extracted from forward I-V measurements both within and outside of the bilayer region, were used as a method for comparing the effects of bilayer structure and diffusion conditions. Additionally, a similar process was followed to compare the effects on reverse leakage current. Below is a summary of the data extracted from fabricated devices. Thus far, results show that under certain conditions the forward IV curves can be shifted to higher voltages while lowering the reverse leakage current, implying near surface acceptor doping. Additionally, an in-situ bias has shown to improve these results further however, the results are inconsistent. This could be due to the incorporation of additional defects during the diffusion process that prevent incorporated Mg from presenting as a shallow acceptor at room temperature. Although PN diode behavior has not been observed under the tested conditions, these results indicate that progress is being made.

Table 1. Results from IV testing on Yale3 material

Material	Sample Name	Bilayer	Annealing Conditions			FWD IV ΔV @10uA	REV IV $\Delta log(I)$ @-50V
			Temp. (°C)	Time (min)	In-situ Bias		
Yale3 (n = 5e16cm^{-3})	T198	Au/MgF_2 100/100nm	700	5	No Bias	-	-
	T208				+4V	-	-
	T218	Au/MgF_2 100/100nm		50	No Bias	+75mV	-
	T228	Y/MgF_2 100/100nm			No Bias	-30mV	1.58
	T238				+4V	+20mV	-
	T248	Au/MgF_2 100/100nm	800	50	No Bias	+150mV	-1.03
	T258		900	50	No Bias	+60mV	1.38

Table 2. Results from IV testing on first round of IQE material

Material	Sample Name	Bilayer	Annealing Conditions			FWD IV ΔV @10uA	REV IV $\Delta log(I)$ @-50V
			Temp. (°C)	Time (min)	In-situ Bias		
IQE - Variant 1 N_{Si} = 5e16cm^{-3}	QA2	Au/MgF_2 100/100nm	700	50	No Bias	+60mV	-
	QA3		800	50	No Bias	+150mV	-1.55
	QA4		900	50	No Bias	-60mV	3.05
	QA5		800	50	+4V	+70mV	-2.12
IQE - Variant 2 N_{Si} = 2e16cm^{-3}	QB2		700	50	No Bias	+90mV	3.13
	QB3		800	50	No Bias	+100mV	-
	QB4		900	50	No Bias	-50mV	4.29
	QB5		800	50	+4V	+80mV	-
IQE - Variant 3 N_{Si} = 1e16cm^{-3}	QC2		700	50	No Bias	+80mV	-
	QC3		800	50	No Bias	+120mV	2.84
	QC4		900	50	No Bias	-	-
	QC5		800	50	+4V	+40mV	-

Table 3. Results from IV testing on second round IQE material

Material	Sample Name	Bilayer	Annealing Conditions			FWD IV ΔV @10uA	REV IV $\Delta log(I)$ @-50V
			Temp. (°C)	Time (min)	In-situ Bias		
IQE - Variant 1 N_{Si} = 5e16cm^{-3}	QA7	Au/MgF2 100/100 Full MgF2 Cover	900	50	No Bias	+100mV	-
	QA8		800	50	+4	-100mV	+3
	QA9		800	100	No Bias	Fabricating	
IQE - Variant 2 N_{Si} = 2e16cm^{-3}	QB7		900	50	No Bias		
	QB8		800	50	+4	-	-
	QB9		800	100	No Bias	-	-
IQE - Variant 3 N_{Si} = 1e16cm^{-3}	QC7		900	50	No Bias	-	-
	QC8		800	50	+4	+150mV	+3
	QC9		800	100	No Bias	-	-

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Conclusion

Although SIMS analysis shows high concentrations of Mg at the surface of prepared samples, additional work is needs to improve the concentration of ionized acceptors at room temperature such that a PN diode can be formed. In the near-term, concentration improvement efforts will focus on exploiting the in-situ bias method with the aim to develop a feedback mechanism. First principles simulations will continue to be used to identify new Mg sources and possible compensation mechanisms while TCAD simulations are used to define geometries and dopant concentration needed to observe Superjunction enhancement.

Publications, Presentations and Patents

- Varley, Joel Basile, Noah Patrick Allen, Clint Frye, Kyoung Eun Kweon, Vincenzo Lordi, and Lars Voss. "Field assisted interfacial diffusion doping through heterostructure design." U.S. Patent Application 17/166,962, filed August 19, 2021.

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