Demonstration of 1.27 kV Etch-Then-Regrow GaN *p-n* Junctions With Low Leakage for GaN Power Electronics

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***Abstract*— This letter reports high performance GaN *p-n* junctions with regrown *p*-GaN by metalorganic chemical vapor deposition (MOCVD) on dry-etched surfaces. The breakdown voltage reaches 1.27 kV and the differential on-resistance is 0.8 m $\cdot$ cm^2. The effects of etching powers and surface treatments on the reverse leakage characteristics of the regrown *p-n* junctions have been investigated. It's found that lowering the etching power and damage is very effective to reduce the leakage currents and increase the breakdown voltages. Further analysis reveals that the charge concentration at the regrowth interface plays a critical role in the performance of the regrown samples. To avoid sacrificing the etching rate by using only low power etching, a multiple-RF-power etching recipe was developed with gradually decreased etching power. This work has demonstrated a practical and viable method to realize high performance regrown *p-n* junctions for various advanced GaN power electronics.**

***Index Terms*— Gallium nitride, regrowth, *p-n* diodes, breakdown, interface charge, leakage current.**

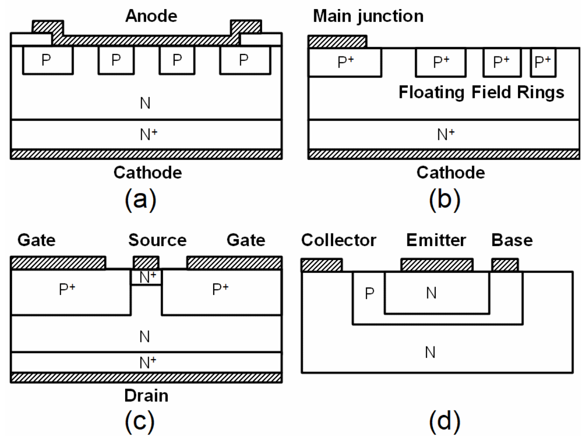

Fig. 1. Schematics of possible applications of regrown *p*-GaN for (a) junction barrier Schottky diode, (b) floating field rings, (c) field effect transistor, and (d) bipolar junction transistor.

I. Introduction

CAPABLE of offering remarkable improvements in energy conversion efficiency, switching frequency, and system volume, gallium nitride (GaN) has become one of the most promising materials for power electronics [1]–[3]. To achieve high-performance GaN power devices and integrated-circuits, selective-area doping is indispensable, especially for *p*-type doping [4]–[8]. Compared with diffusion and implantation methods, epitaxial regrowth is still regarded as the most feasible method for the selective-area doping [9]–[12]. Some possible applications where selective *p*-doping by regrowth can be used are shown in Fig. 1. In each case, dry etching is essential for forming selectively regrown areas prior to regrowth. However, this etch-then-regrow process is very challenging and remains a huge hurdle to realize the full potential of GaN power electronics. First, after regrowth, an interface containing a high concentration of contaminants such as silicon (Si), carbon (C), and oxygen (O) is formed even without any etching [13]–[15]. Secondly, the dry etching process can introduce surface damage. As a result, very high reverse leakage current has become one of the most serious challenges for regrown *p-n* junctions.

In this work, we investigated the influence of different dry etching processes and surface treatments on the reverse leakage characteristics of GaN *p-n* junctions with *p*-GaN regrown on the etched surface. A combination of low-damage etching and wet etching treatments has shown a great potential for producing high performance regrown *p-n* junctions.

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II. Growth and Device Fabrication

All samples were grown homoepitaxially by metalorganic chemical vapor deposition (MOCVD) on *c*-plane n^+-GaN free-standing substrates. Before regrowth, 9-μm-thick unintentionally doped (UID) GaN drift layers with a electron concentration of $\sim 10^{16}$ cm^{-3} were first grown on the substrates. Then different etching processes were applied to the drift layer, followed by the regrowth process including a thin UID-GaN layer as an insertion layer and a 500 nm *p*-GaN layer. The schematic structures and the regrowth process are shown in Fig. 2. Metal stacks of Pd/Ni/Au (20 nm/30 nm/50 nm) were deposited

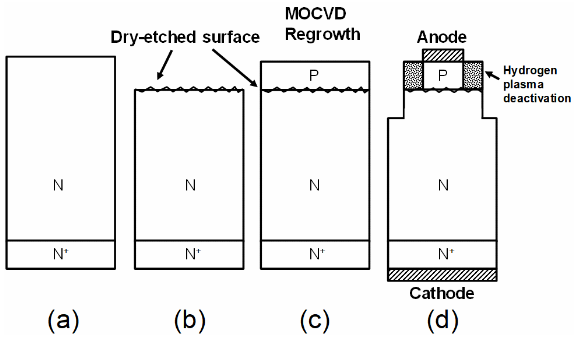

Fig. 2. Schematics of processes from (a) to (d) for investigating the regrown *p-n* diodes.

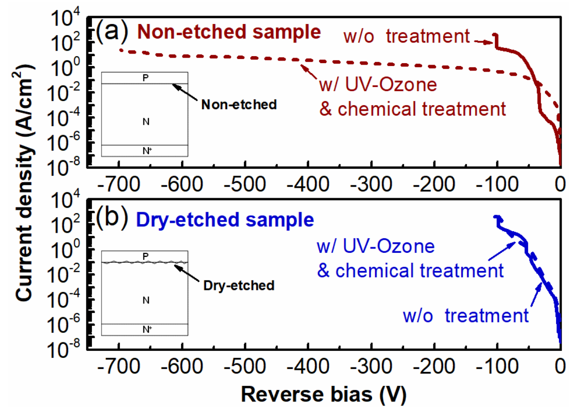

Fig. 3. Reverse leakage current w/ and w/o UV-Ozone combined chemical treatment for (a) non-etched sample and (b) dry-etched sample.

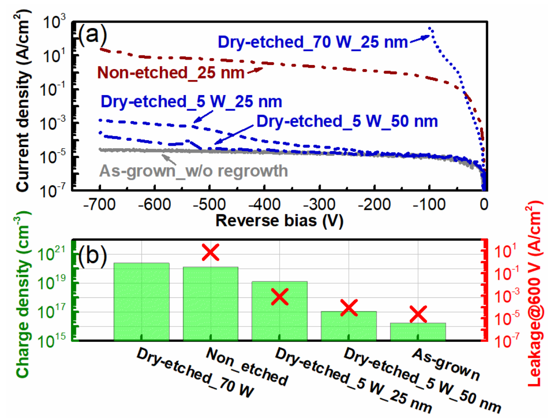

Fig. 4. (a) Reverse *I-V* curves for the non-etched sample, dry-etched samples with different etching powers and insertion thicknesses, and the as-grown sample without regrowth. (b) Charge densities at the regrowth interfaces (histogram) and leakage currents at 600 V (cross mark) for the samples in (a).

by electron-beam evaporation to form the p-contacts with a diameter of 80 μm. Mesa isolation and hydrogen-plasma passivation were used for the edge termination [16], [17]. Metal stacks of Ti/Al/Ni/Au (20 nm/130 nm/50 nm/150 nm) were deposited to form backside n-contacts. A Keithley 4200-SCS was used for the capacitance-voltage (C-V) measurement. A Keithley 2410 sourcemeter was used for current-voltage (I-V) measurement. A Tektronix 370A was used for reverse breakdown measurement where the samples were immersed in FC-70.

III. Results and Discussions

A chlorine-based inductively coupled plasma (ICP) dry etching recipe (ICP power = 400 W, RF power = 70 W, pressure = 5 mTorr, Cl_2 = 32 sccm, BCl_3 = 8 sccm, Ar = 5 sccm) was first used to etch the sample. To investigate the etching effects, another sample without dry etching was also co-loaded into the MOCVD reactor. No additional surface treatments were applied to the two samples except organic cleaning using acetone, isopropanol alcohol and deionized water. As shown by the solid lines in Fig. 3, the reverse leakage currents for both samples are very large and the breakdown voltages are only about 100 V. These results indicate that surfaces either with or without dry etching is not ideal for the regrowth process, which is the very issue that this work is trying to solve. Surface contaminants, dry etching damages, and/or native oxidations are possible causes for the large leakage currents.

Wet etching is a commonly used method to address these issues. Before the regrowth, etched and non-etched samples were first treated by UV-ozone for 45 minutes to oxidize the surface. Then the samples were immersed in hydrofluoric (HF) acid for 5 minutes and hydrochloric (HCl) acid for 5 minutes to remove contaminants. As shown by the dashed lines in Fig. 3, after these chemical treatments, the non-etched sample showed a significantly decreased leakage current and an increased breakdown voltage. However, no big difference was observed for the etched sample. These results indicate that the non-etched surface can be improved by the UV-chemical treatment while the dry-etched surface is too severely damaged by the plasma etching process to be repaired. Therefore, reducing the etching damage may be the key to improving the reverse leakage characteristics of regrown GaN devices.

One way to reduce the ICP etching damage is to lower the RF power and reduce the physical plasma damages. A low-damage ICP etching recipe with a very low RF power was used for the etching process (ICP power = 400 W, RF power = 5 W, pressure = 5 mTorr, Cl_2 = 32 sccm, BCl_3 = 8 sccm). The same UV-chemical treatment was also utilized to treat the samples before the regrowth process. As shown in Fig. 4(a), with the low-damage ICP etching, the reverse leakage of the etched sample was dramatically decreased to a level that is even lower than the non-etched sample. Thicker insertion layer could move the regrowth interface (insertion-UID-GaN/drift layer) far away from the peak electric field in the p-n junction depletion region, thus decreasing the trap-assisted reverse leakage by reducing the electric field at the regrowth interface where there are a lot of interface states. However, it is not practical in many applications if the insertion thickness is too thick. With a 50-nm-thick insertion layer, the reverse leakage current for the regrown sample is about 71.6 $\mu A/cm^2$ at -600 V, which is very close to the as-grown sample. Therefore, low-damage etching is very effective in reducing reverse leakage for the regrown GaN devices.

Figure 4(b) shows the leakage currents at -600 V and charge concentrations at the regrowth interface extracted from capacitance-voltage (C-V) measurements [15] for the regrown

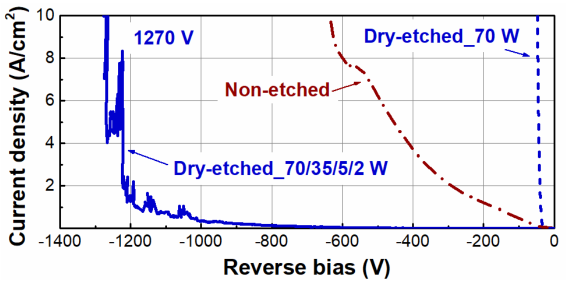

Fig. 5. Reverse leakage curves for regrown *p-n* diodes on the dry-etched samples and non-etched sample.

samples in Fig. 4(a). The as-grown sample showed a low and constant charge concentration on the order of $\sim 10^{16}$ cm^{-3}. However, the regrown samples had remarkably high charge concentrations on the order of 10^{17}-10^{20} cm^{-3} at the regrowth interface. Higher charge concentration at the regrowth interface can lead to larger electric field and a thinner effective barrier for trap assisted tunneling. Therefore, there are two factors causing the reverse leakage: (a) dry etching damages that usually cause deep interface states, and (b) interface charges that may come from donor-like Si or O contaminants although the the reason for the contaminants is still not well understood so far. Besides, the dry etching damages could also cause interface charges traped by interface states. The low-damage ICP etching recipe could be helpful for both aspects. The regrowth interface charges were reduced by the low-RF-power etching method with very minor damage, which means that some contaminants may already be there before the regrowth process and the chemicals only treatment in this work can not remove these contaminants completely. That is why the dry-etched sample with a low RF power showed even lower leakage than the non-etched sample.

Although the low-damage etching could reduce the reverse leakage current, the etching rate is very slow ($\sim$20 nm/min). However, some practical applications require high etching rate for deep trench structures. A multiple-RF-power etching recipe was developed using multiple etching steps with gradually decreased RF power from 70 W ($\sim$280 nm/min) to 35 W to 5 W to 2W. The multiple-RF-power etching recipe can not only give reasonable etching rates, but also effectively reduce the reverse leakage. Figure 5 shows that the regrown sample with the four-step-etching recipe and 50 nm insertion layer exhibited a very high breakdown voltage of 1270 V.

Ideality factor is another factor used to evaluate the performance of a *p-n* junction. The regrowth interfacial layer can be regarded as a n^+ layer due to the contaminants. This introduces an equivalent diode (n^+-n) which is in reverse series with the regrown *p-n* diode. This therefore decreases the forward current and increase the ideality factor of the regrown diode which is usually much larger than 1. The low-damage etching could be helpful to solve the problem. Figure 6 shows the forward performance for the regrown *p-n* junction by multiple-RF-power etching recipe. The differential on-resistance is less than 0.8 m$\Omega \cdot$ cm^2 and the ideality factor is 2 which is considerably lower than the previous reports [11], [15]. To benchmark the device performance, breakdown voltages and on-resistances of reported

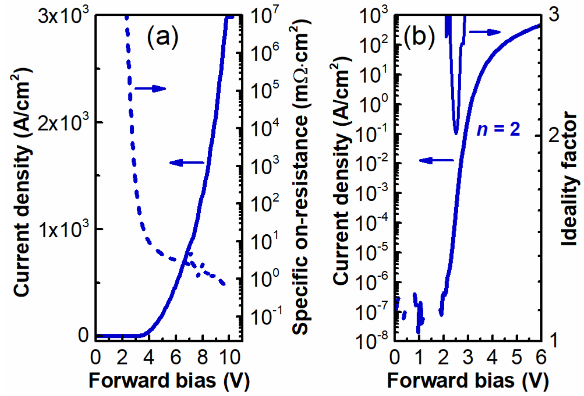

Fig. 6. (a) Forward *I-V* curve in linear scale and differential on-resistance in logarithmic scale for the multiple-RF-power etched sample in linear scale. (b) Forward *I-V* curve and ideality factor in logarithmic scale.

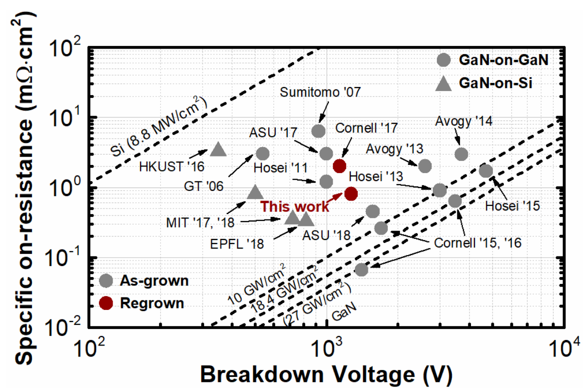

Fig. 7. Specific on-resistance vs. breakdown voltage benchmark plot for as-grown and regrown GaN-on-GaN vertical *p-n* diodes. All the data points for the specific on-resistance, as reported, are calculated by the area of *p*-contact.

GaN-on-GaN *p-n* diodes [11], [17]–[32] are plotted in Fig. 7. The Baliga's FOM (V^2/R_{on}) for the regrown *p-n* diodes in this work is 2.0 GW/cm^2 which is even comparable to some of as-grown *p-n* diodes.

IV. Conclusion

The influence of dry etching processes on reverse leakage current of regrown GaN-on-GaN vertical *p-n* diodes has been investigated. Using low-RF-power dry etching and UV-chemical treatment could effectively reduce the reverse leakage of the regrown *p-n* junction. The regrown sample with a multiple-RF-power etching shows a high breakdown voltage of 1270 V, a low on-resistance of 0.8 mΩ·cm^2, and a record-low ideality factor of 2. The high charge concentration at the regrowth interface could be one of important reasons resulting in large leakages for regrown GaN *p-n* junctions. This work could also be helpful for *a*-plane and *m*-plane devices since they have quite similar problems.

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