Activation of Ion Implanted Si in Semi-Insulating C-Doped GaN by High Pressure Annealing for Photoconductive Semiconductor Switch (PCSS) Applications

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Keywords: GaN, Si, PCSS, Ion Activation, SMRTA

Abstract

There is a need for selective-area n-type and p-type doping for many GaN-based devices, including N+ doping using Si, for reduced contact resistance in RF HEMTs and p-type doping, using Mg, for the body and termination regions of vertical power switches. We report the successful demonstration of n-type doping using ion implanted Si activated by high pressure annealing. In this work, we used semi-insulating GaN photoconductive switches (PCSS) as a test vehicle to separate implanted Si dopant activation from leakage paths generated by N vacancy formation due to decomposition and damage during annealing. We observed n-type conductivity consistent with Si activation in implanted regions while preserving semi-insulating GaN with high breakdown voltage and high photoresponse in unimplanted regions. Optimization of the process has led to record low ohmic contact resistivity to GaN below 2x10^{-8} ohm-cm^{2}.

INTRODUCTION

Current GaN technology uses selective area regrowth method, such as confined N+ regions for reduced contact resistance in HEMTs and n-p-n stacks for vertical trench MOSFET or CAVET devices, because ion implantation and activation has not been well studied. Development of this technology would allow truly planar devices, tailoring of doping profile both laterally and vertically, and eliminate the impurities incorporated at regrowth interfaces. We have previously demonstrated activation of implanted Mg using the SMRTA process [1], [2]. However, lateral n-type devices such as HEMTs can also benefit from ion implanted n-type doping processes for reduced contact resistance. Here, we apply components of the SMRTA process, including a protective cap and nitrogen overpressure to study implanted Si activation in lateral GaN devices.

One challenge with activation of implanted dopants is that it requires temperatures which are high enough to destabilize and decompose GaN in the absence of significant nitrogen overpressure. As this damage is often n-type due to the presence of excessive nitrogen vacancies, it can be difficult to optimize a Si doping process and effectively resolve conduction from impurity doping from native defect generation. For this work we used semi-insulating GaN by carbon compensation as a test vehicle to ensure that the unimplanted film retained semi-insulating properties while the implanted regions became conductive. The structures used here are relevant to photoconductive semiconductor switch (PCSS) devices. As an optically controlled switch, no gate contact is needed allowing effective isolation and fast triggering to reduce switching losses.

EXPERIMENTAL

Semi-insulating GaN films were grown 4 µm thick on SiC doped with 5E17 cm^{-3} carbon. Regions were masked and implanted with Si following the implant profile in Figure. 1 with a total dose of 1.5E14 cm^{-2}. Assuming full carbon compensation, a maximum sheet carrier density of 1.25E14 cm^{-2} could occur from Si activation. A 200 nm AlN capping layer was deposited using ambient temperature reactive sputtering on an AJA international system. Samples were annealed in pure N_2 under various conditions using a conventional RTA system at atmospheric pressure or in a custom high-pressure RTA system at 30 atm. Raman spectroscopy was used to assess initial implant effects. Figure

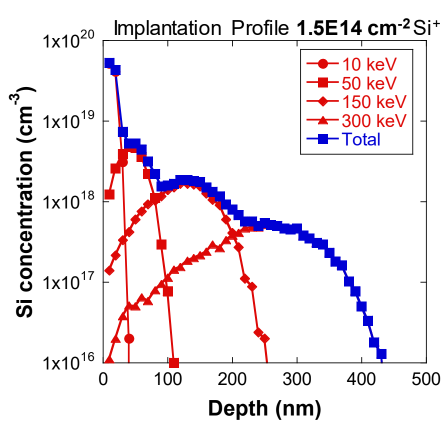

Fig. 1. Si implantation profile used for all samples. Subtracting the 5E17 C concentration give a theoretical max of sheet density of 1.25E14 cm^{-2} from Si activation.

2 shows the A_1 (LO) Raman peak broadens from ion implantation and is recovered by even atmospheric pressure anneals. Following anneals, the AlN cap removal was performed using a process described in previous work [3]. The samples were patterned with Ti/Al/Ni/Au and heated at 850°C for 30 s to create ohmic contacts. The process flow for fabrication of PCSS devices is highlighted in Figure 3.

Circular transmission line measurements (CTLM) were performed using a Keithley 4200 with preamplifiers using an outer circle diameter of 70 µm with spacings ranging from 4-20 µm. The resistivity and contact resistance were extracted (results in Figure 4).

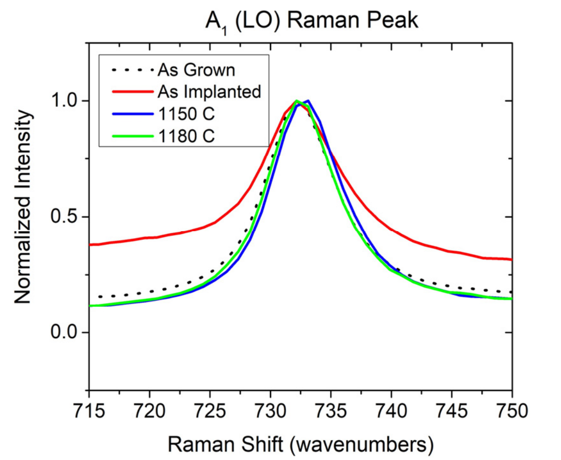

Fig. 2. Raman spectra of the samples before implantation, after implantation, and recovery with 1 atm RTA. Those recovered under different conditions yield similar results.

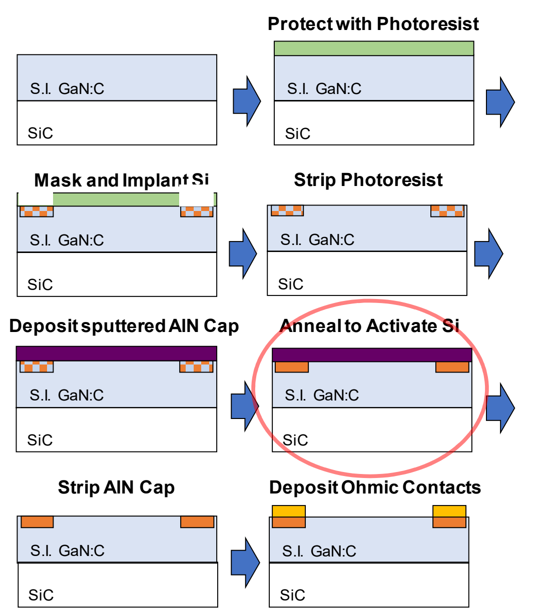

Fig. 3. Process for fabrication of PCSS devices used. The work studies the effects of varying the "Annealing to Activate Si" Step.

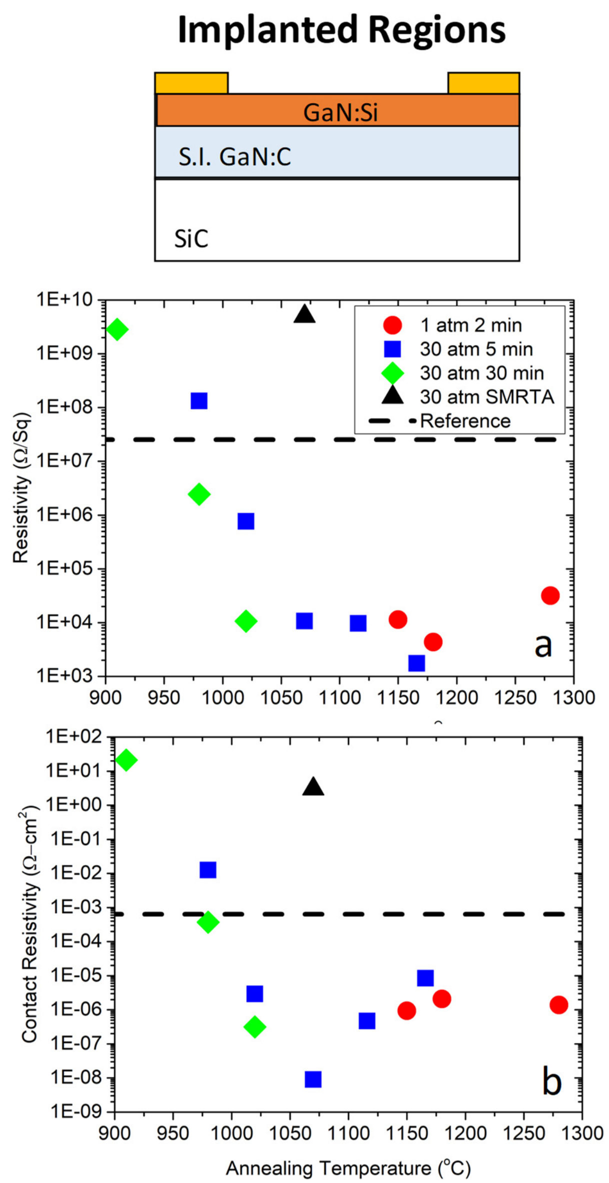

Fig. 4. The resistivity (a) and contact resistance (b) of the implanted regions at different annealing temperatures, determined using CTLM.

The unimplanted regions were tested for breakdown voltage (Fig 5a) and leakage current (at 5 V) (Fig. 5b) using CTLM structures with 125 µm outer circle diameters with 250 µm and 25 µm gaps respectively.

Hall Effect measurements were performed in the LakeShore CRX-VF Probe Station using currents ranging from 10–1000 µA and fields ranging from 0.5–2 T. Van der Pauw's calculations produced consistent sheet resistivities (R_S), electron mobilities (μ), and sheet densities (n_s) to at least 3 significant digits at all measured currents and fields for all samples with results shown in Figure 6.

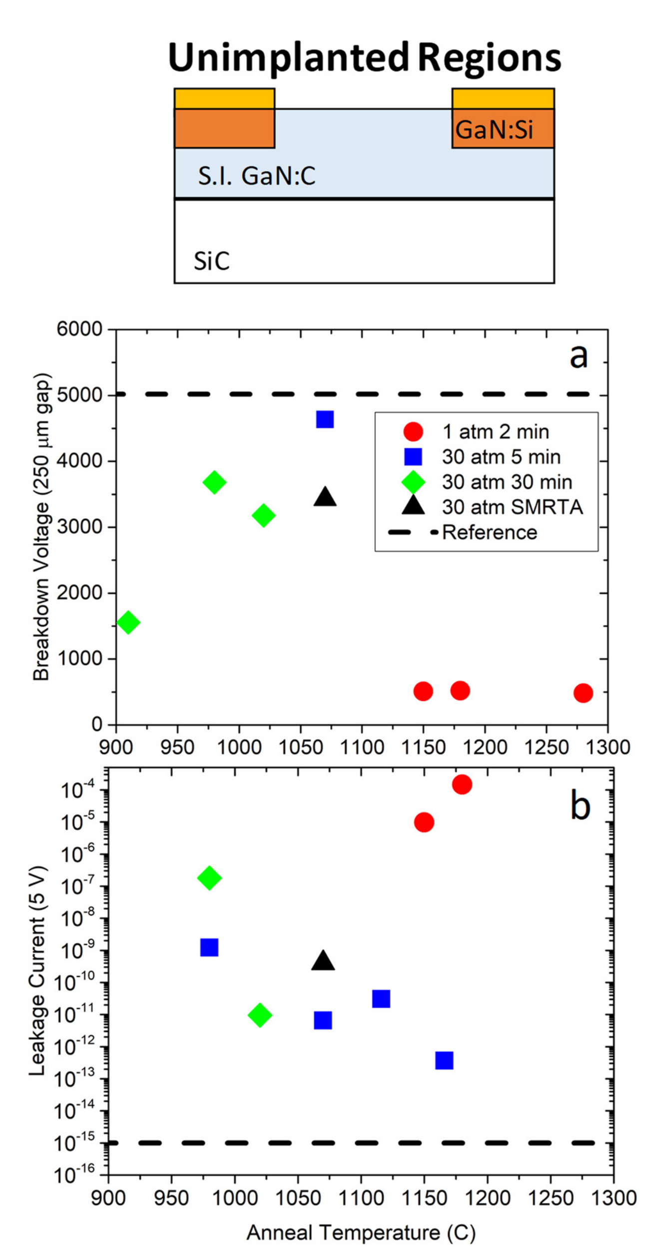

Fig. 5. (a) The breakdown voltage for a 250 μm CTLM structure and (b) Leakage current at 5 V of 25 μm CTLM structures.

Photoionization spectroscopy [4] was performed across the GaN devices using a Keithley 4200 semiconductor system with an external monochromatic light source. A 10 V bias was applied across devices that had a gap of 25 μm with an illumination time of 10 s. Results are shown in Figure 7.

Discussion

From the analysis of the implanted regions, it is clear that Si activation occurred in both the conventional and overpressure RTA samples. Raman spectroscopy in Figure 2 shows the implant-induced broadening of the A_1 (LO) peak. Since this peak is caused by phonon-plasmon coupling and changes with n-type carrier concentration [5]–[7], the induced broadening is from implant-induced defect carriers in addition to crystal damage. After annealing, the peak returned to its original width, suggesting that these defects are repaired. This occurred even when the less than ideal atmospheric pressure conditions were used.

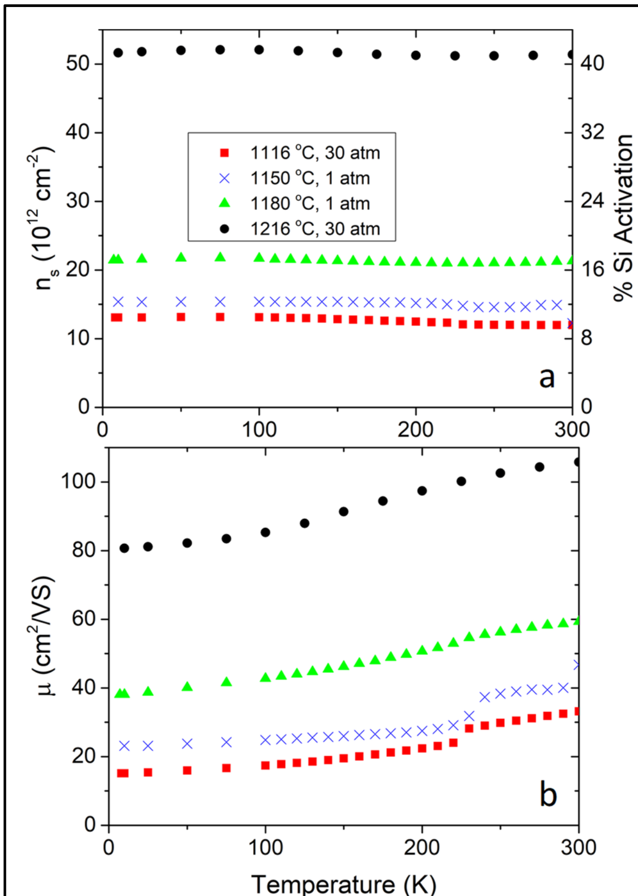

Fig. 6. The temperature dependent sheet density (a) and mobility (b) extracted using the Hall effect. The percentage of Si activated is plotted in (a) assuming the theoretical max is 1.25E14 from Fig. 1, and carriers are purely from Si.

Electrical measurements on the implanted regions showed an increase in the conductivity with annealing temperature up to about 1070°C (see Fig. 4a). A minimum in contact resistivity was also observed at the same temperature. Most of the carriers created by the annealing are likely from either Si doping or nitrogen vacancy formation. The higher leakage current and lower breakdown voltage from Figure 5, show that nitrogen vacancy formation was more prevalent for atmospheric pressure anneal.

From the temperature-dependent Hall effect measurements (Figure 6), the sheet density is constant with respect to temperature. This effect has been observed in samples with high Si concentration [8]. The results reveal that higher temperature annealing can lead to Si activation of over 40%, with a reduction in mobility. Since the mobility increased with temperature, the increase indicates a reduction in ionized impurities such as nitrogen vacancies.

The photoionization spectroscopy was able to detect a Carbon acceptor at Ec – 3.0 eV with a Frank-Condon shift of 0.28 eV [9]. Different GaN samples were subjected to various anneals and their photoresponse spectra are shown in Figure 7. Two anneals that were 30 minutes long seem to decrease the total photo response by 2-3 orders of magnitude. One anneal which was over 1000°C, corresponded to a decrease in the signal from the Carbon acceptor. A 5 min anneal at 1070°C appears to preserve the highest photoresponse, while removing the carbon acceptor.

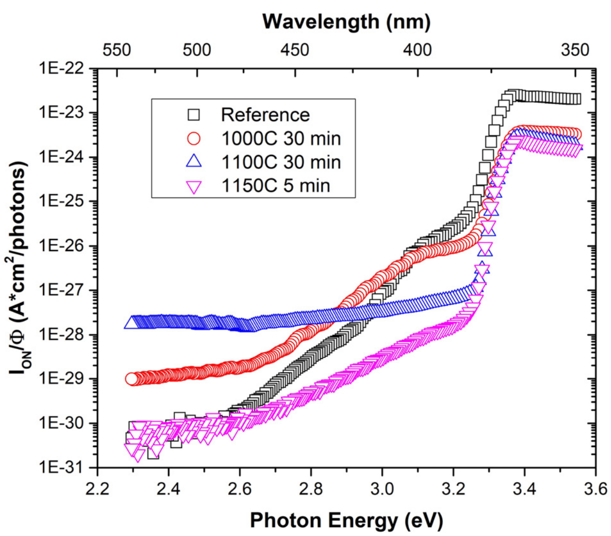

Fig. 7. The normalized current per photon of PCSS devices fabricated from GaN annealed under 30 atm overpressure Carbon acceptors can be seen at photon energy of 3.0 with a Frank-Condon shift of 0.28 eV. Long anneals decrease the total photoresponse while higher temperature anneals decrease the concentration of the carbon acceptors.

Conclusions

In summary, ion implanted Si is efficiently activated using AlN capping under both conventional atmospheric pressure RTA and under 30 atm N_2 overpressure. It was shown that activation of Si ions under the contact pad successfully reduced the contact resistivity to record low levels. Additionally, annealing with a 30 atm N_2 overpressure formation, demonstrated improved breakdown voltages compared to atmospheric pressure anneals.

Acknowledgements

Funding for this research was provided by the Office of Naval Research and the American Society for Engineering Education. JCG, GMF, and AGJ gratefully acknowledge the support of the American Society of Engineering Education and the U.S. Naval Research Laboratory Postdoctoral Fellowship Program

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Acronyms

PCSS: Photoconductive Semiconductor Switch
CTLM: Circular Transmission Line Measurement
RTA: Rapid Thermal Annealing
SMRTA: Symmetric Multicycle Rapid Thermal Annealing