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BCl_3 Plasma Treatment for Enhanced Ohmic Contact Performance to p-Type 4H-SiC

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Abstract: Heavily p-type doped (P^+) implants are commonly used to achieve low specific contact resistance (SCR) for p-body diodes through a costly ion implantation process. Alternatively, our study proposes a single-step plasma treatment method using BCl_3 plasma. This method incorporated a high concentration of self-activated p-type boron dopants in the SiC lattice with minimal damage.

Experimental I-V data from Schottky Barrier Diodes (SBDs), combined with TCAD simulation, demonstrated that approximately 40 % of boron atoms were activated in the SiC lattice (at a depth of 30-40 nm) without the need for high temperature ion implant activation. Our approach using plasma treatment realizes an SCR value ρ_c of ~ 5.6×10^{-5} $\Omega\cdot cm^2$, which is approximately 1 order of magnitude lower than that of untreated samples.

Introduction

Variations caused by a rapid change in drain-source voltage (dV_{ds}/dt) can influence the electrical potential within the p-body region during transistor switching [1]. Several factors contribute to such influence: (i) Increased output capacitance charge due to higher doping concentrations in the drift layers, leading to a high displacement current during switching; (ii) Low hole mobility of SiC from the high sheet resistance of the p-body region [2]; and (iii) High SCR in the p-body ohmic contact [3-4].

P^+ implantation plays a critical role in enhancing carrier injection and hole tunneling at the metal-SiC (MS) interface, despite its high cost and unwanted defects [5]. Plasma doping offers a promising method for incorporating dopants into the SiC lattice with minimal crystal damage at lower temperatures [6]. This study investigates the effectiveness of a single-step BCl_3 plasma treatment for self-activated p-type boron dopant incorporation into SiC. This method to form ohmic contacts at the p-body could facilitate higher switching speeds and minimize switching losses in SiC MOSFETs.

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Results and Discussion

First, a 1 µm-thick p-type epitaxial (p-epi) SiC layer with an aluminum doping of 10^{17} cm^{-3} on an n-type SiC substrate was used. This substrate was chosen to emulate the p-body region of the SiC MOSFET. The samples were wet cleaned and treated with different BCl_3 plasma conditions for further analysis as per previous work [7].

1 (a) 1(b)

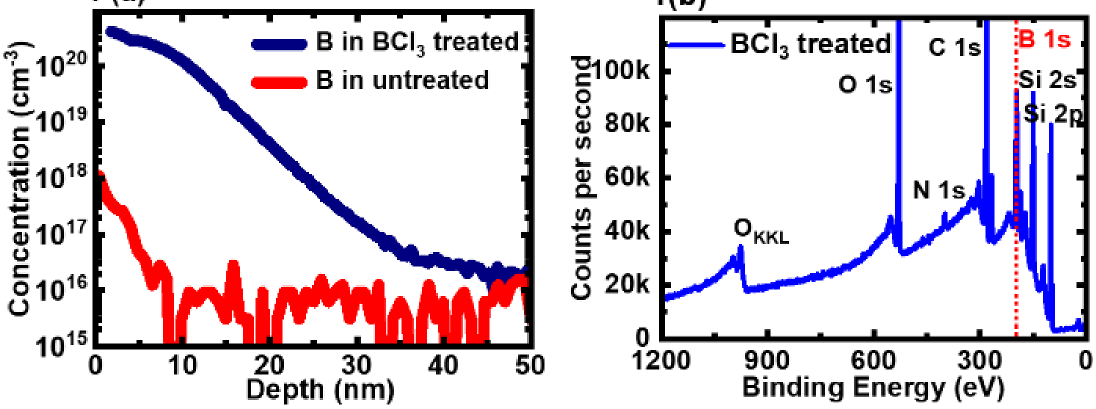

Fig. 1. (a) SIMS analysis of boron concentration in SiC lattice before and after BCl_3 treatment (b) XPS spectra of SiC surface after BCl_3 plasma treatment.

Boron concentration of more than 10^{20} cm^{-3} was observed near the surface with an enhanced concentration up to a depth of 30-40 nm over the untreated sample, as shown in the secondary ion mass spectrometry (SIMS) profile in Fig. 1 (a). In Fig. 1 (b), X-ray Photoelectric Spectroscopy (XPS) spectra revealed a notable presence of boron atoms on the surface of the treated samples, with the boron 1s peak detected at 180-189 eV. These results indicate the presence of Boron atoms at the surface and in the SiC lattice up to 30 nm after BCl_3 plasma treatment.

2 (a) **2 (b)**

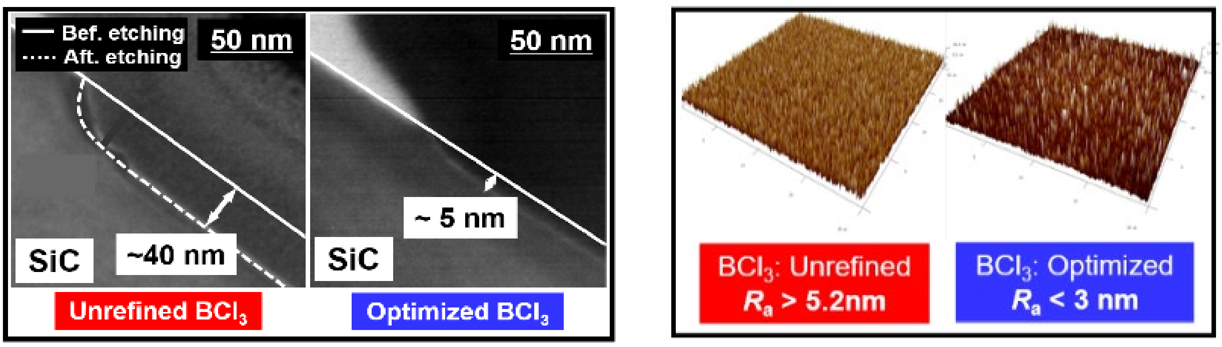

Fig. 2. (a) TEM cross-section of samples with unrefined and optimized BCl_3 recipe (b) AFM of samples after BCl_3 treatment $R_a < 3$ nm after optimization.

Previous studies have established that BCl_3 plasma has the capability to etch SiC [8-9]. Therefore, it was critical that the treatment process had to be optimized to minimize surface etching with a minimal etching depth less than 5 nm, as evidenced in transmission electron microscopy (TEM) images in Fig. 2 (a). With the unrefined recipe, a large etching depth of ~ 40 nm was observed which is undesirable for good ohmic contacts. After optimizing the plasma conditions in the recipe, a minimal surface etching of 5 nm was obtained. We further conducted atomic force microscopy (AFM) to examine the surface roughness after plasma treatment, showing low roughness values R_a of < 3 nm, as depicted in Fig. 2 (b). It is noteworthy that prior research has addressed how minor surface etching and low R_a values are unlikely to substantially affect the quality of the ohmic contact [8].

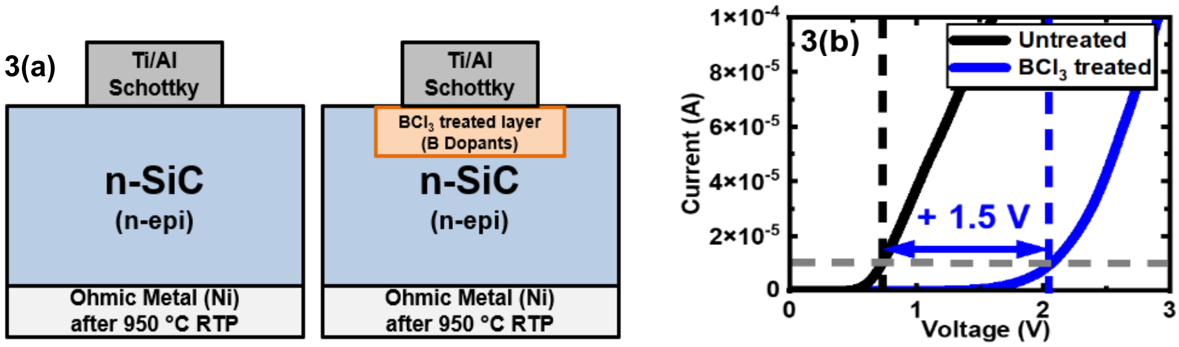

Fig. 3. (a) Cross-section of samples with unrefined and optimized BCl_3 recipe (b) AFM of samples after BCl_3 treatment $R_a < 3$ nm after optimization.

The self-activation of boron atoms after BCl_3 plasma treatment was investigated using Schottky barrier diodes (SBDs). The diodes were fabricated on commercial n-epi wafers with a nitrogen doping of (~ 10^{16} cm^{-3}) as shown in Fig. 3 (a). A Ti/Al Schottky metal on the frontside and a Ni-based ohmic metal contact on the backside was employed in this study. Electrical measurements (I-V tests) conducted on the SBDs revealed a substantial increase in the knee voltage (V_{knee}) by +1.5 V for treated samples, as depicted in Fig. 3 (b). This could have indicated self-activation of the boron atoms during the plasma treatment process.

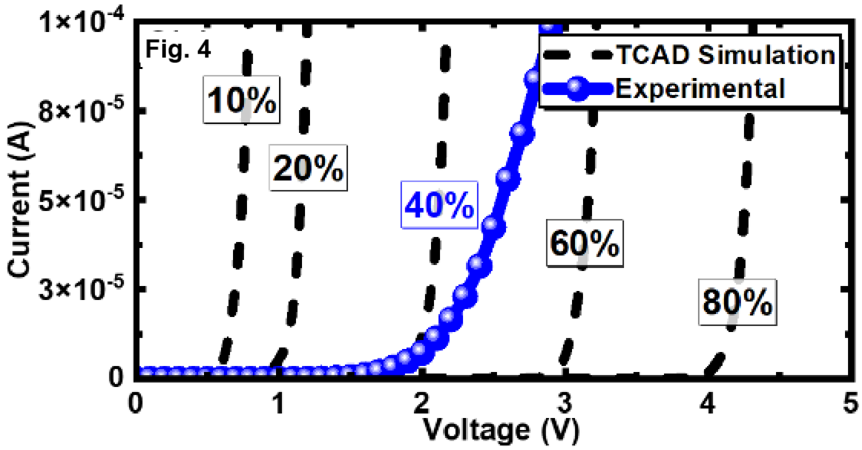

Fig. 4. TCAD simulation of Schottky barrier diodes (SBDs) with different percentage of boron activation with correlation to experimentally obtained I-V data.

Simulations in Sentaurus TCAD estimated that approximately ~ 40 % of the boron dopants were activated, consistent with experimental observation of the increased V_{knee} after plasma treatment, as demonstrated in Fig. 4. This partial activation could have been made possible due to the high energy plasma source. However, high temperature annealing would still be required to achieve fully activated dopants in the SiC lattice.

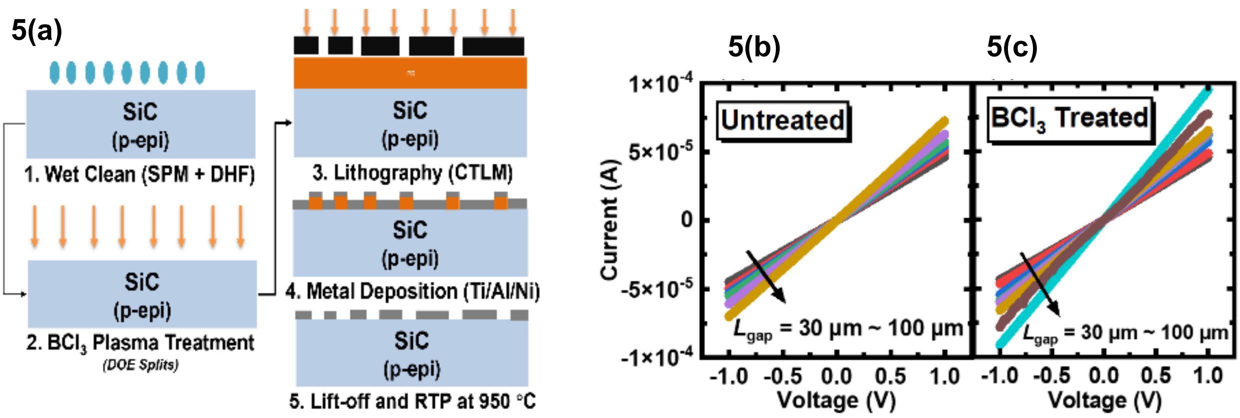

Fig. 5. (a) CTLM process flow with gap spacings of 30 – 100 μm. I-V after PMDA at 950 °C (b) untreated and (c) BCl_3 treated.

Circular transmission line method (CTLM) structures were fabricated with a Ti-based metal stack (Ti/Al/Ni) on the p-SiC as shown in Fig. 5 (a) for SCR extraction as per previous work [7]. The BCl_3 treatment was carried out across the sample prior to lithography and metal deposition. Ohmic I-V behaviour was observed on CTLM structures from different gap spacings of 30-100 µm after post metal deposition annealing (PMDA) at 950 °C as shown in Fig. 5 (b-c). The SCR of treated samples extracted, exhibited a one order of magnitude reduction from 10^{-4} Ω·cm^2 (untreated) to 5.6×10^{-5} Ω·cm^2 (treated) as shown in Fig. 6 (a-b). The SCR values were obtained from three sets of CTLM structures.

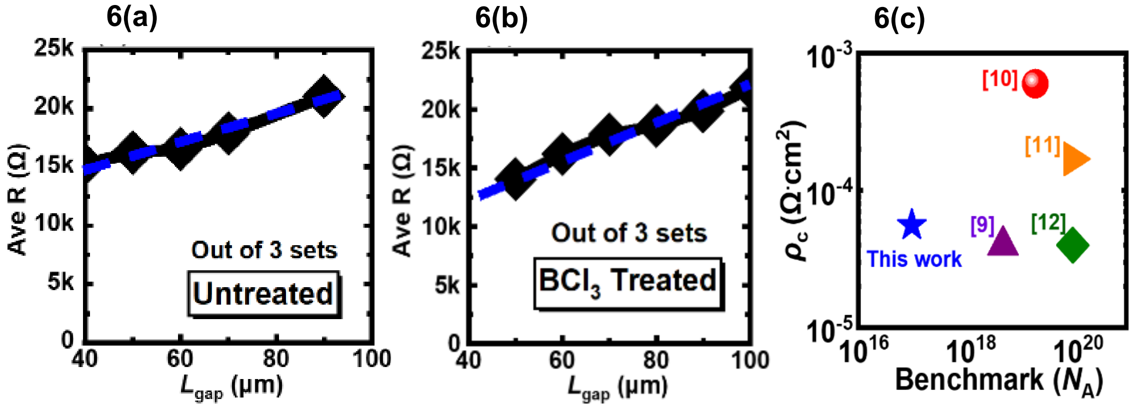

Fig. 6. Ave R vs. Gap of CTLM structures (a) untreated and (b) BCl_3 treated (c) Benchmarking of SCR value with other work on highly doped substrates.

This reported SCR value is relatively low for moderately doped p-SiC (10^{17} cm^{-3}) as benchmarked with other studies on highly doped substrates (> 10^{19} cm^{-3}) as illustrated in Fig. 6 (c) [9-12]. A higher N_D should yield a lower SCR value with this BCl_3 plasma treatment which will be studied in future work.

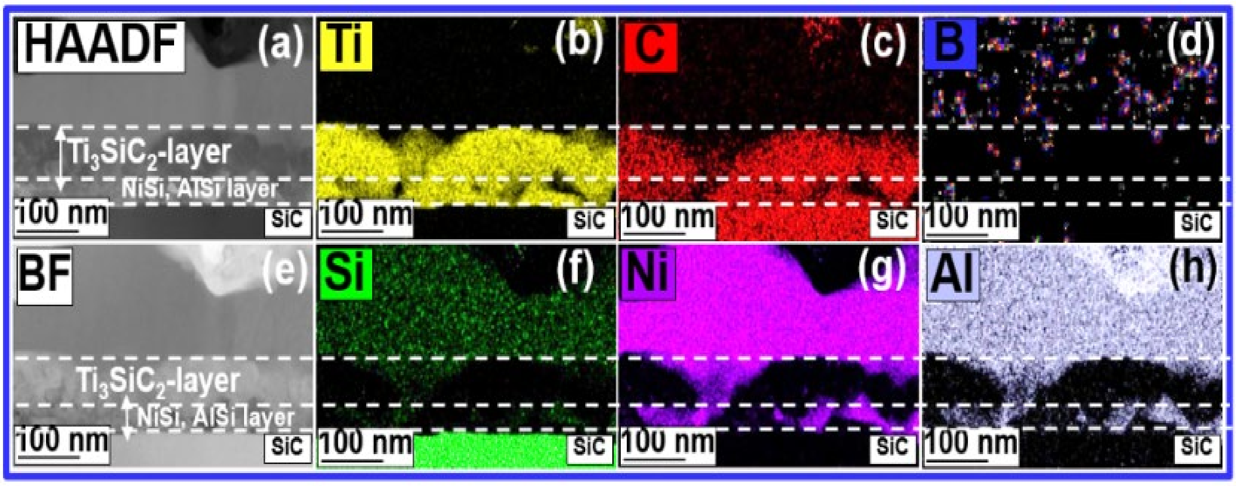

Fig. 7. (a-j) TEM-EDX and elemental colour map of metal silicide at the Metal-SiC junction after 950 °C PMDA.

TEM-EDX colour mappings in Fig. 7 (a-j), revealed intermetallic diffusion of both Ni and Al into the SiC and the formation of Ti_3SiC_2 layers after PMDA. This formation of the stable and favourable Ti-silicide phase was the main mechanism of the ohmic contact formation. Carbon out diffusion was also observed after PMDA, and the formation of Ti-based carbide complexes could also be seen. Boron atoms were observed in the SiC lattice and out diffusion to the surface after PMDA.

Conclusion

In this study, we have experimentally demonstrated a BCl_3 plasma treatment method that incorporated activated boron dopant atoms (~ 40 %) in a single step at low temperatures (< 200 °C). This high concentration of boron atoms at the MS interface could have facilitated high carrier injection which formed favourable ohmic contacts reducing the SCR by almost 1 order of magnitude to $\rho_c \sim 5.6\times10^{-5}\ \Omega\cdot cm^2$. The SCR value obtained was relatively low for mildly doped p-SiC when benchmarked with highly doped p-type substrates. This novel single step plasma treatment allows for the reduction of SCR at the source region in p-SiC.

Acknowledgement

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