NANOMETER-THIN PURE B LAYERS GROWN BY MBE AS METAL DIFFUSION BARRIER ON GaN DIODES

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ABSTRACT

Pure boron layers, deposited by molecular beam epitaxy (MBE) on AlGaN/GaN/p-Si substrates to a thickness of ~ 7 nm, were applied as barriers to aluminum metallization. For low-temperature deposition from 250°C - 400°C, low-saturation-current diodes to the n-type GaN were fabricated that all tolerated alloying at 400°C. After alloying, the relatively high current level of the 250°C diode was reduced to that of the other low temperature diodes, whereas 700°C B deposition resulted in high-current diode characteristics. The results suggest a favorable B-to-GaN chemistry at 350°C - 400°C.

Keywords — pure boron; gallium nitride; molecular beam epitaxy; chemical vapor deposition; aluminum; diffusion barrier; diodes;

INTRODUCTION

Over the last 10 years PureB Si technology, where pure boron is grown on Si by chemical vapor deposition (CVD) at temperatures for 400°C to 700°C, has won terrain for photodiode applications that demand extremely shallow diodes with robust light/particle-entrance windows [1, 2]. The very robust nature of the PureB layers, even when as thin as 2 nm, has also been demonstrated for masking wet Si etching [3], as well as for forming efficient diffusion barriers to metallization with Al, Au and Cu [4, 5]. At the standard alloying temperature of 400°C, all these metals have reactions with the Si (spiking or metal-Si interdiffusion) that are detrimental to shallow junction formation [6, 7]. At present the most commonly used barrier layer between Al and Si is TiN, either sputtered for tens of nm thick layers or deposited by atomic layer deposition for thinner conformal layers [8]. TiN is also an important barrier layer in the processing of the most popular contacting layers to GaN, that employ stacks of TiN/Al/Ti. For Schottky diode formation on GaN, Ni-Au is the preferred metal stack. Nevertheless, both metallization schemes have reliability issues and Au is not CMOS compatible so new metallization methods are still very actively being sought after [9].

In this paper, a first study showing that pure B could also be useful as a diffusion barrier between Al and GaN is presented. Deposition of B layers on GaN by CVD was not readily successful, hence molecular beam epitaxy (MBE) was employed. Diodes were fabricated where the standard Ni-Au stack was replaced by B-Al stack. The substrates were diced from production-grade high-quality GaN-on-Si wafers. The buffer layer was covered with a stack of 1.5 µm intrinsic GaN, 20 nm $Al_{0.2}Ga_{0.8}N$, and a capping layer of only 3 nm GaN. With this stack, diode fabrication is very susceptible to any metal reactions with the GaN, making the resulting diode *I-V* characteristics a sensitive monitor of the stability of the metal stack.

EXPERIMENTAL PROCEDURE

A schematic of the fabricated diodes is shown in Fig.1. Before being transferred to the MBE chamber for B deposition, the GaN-on-Si substrates were ultrasonically cleaned in acetone and isopropyl alcohol for 5 min to remove any organic contaminants, and then given sequential dip in HNO_3:HCl (1:3) followed by rinsing in DI water and blow dried with N_2. The B deposition temperature was varied from 250°C to 700°C, as specified in Table I. A 150 nm Al contact layer was deposited by e-beam evaporation at room temperature and 1.5 x 10^{-7} mbar process base pressure. Al contacts are patterned by optical lithography, and wet etching in Al metal etchant. Diode *I-V* characteristics were measured with a Keithley 4200 SCS parameter analyzer. On-wafer measurements were performed by contacting the back of the substrates to the chuck of a probe station and directly connecting the diode metal with a probe needle on the front of the wafer.

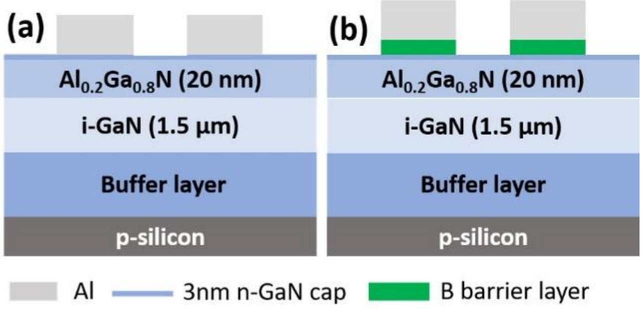

Fig.1. Schematic of the fabricated GaN diodes; (a) Al-on-GaN

Schottky diodes, and (b) Al-B-on-GaN diodes.

There was sufficiently good electrical contact between the Si substrate and the GaN layers to make this possible. The samples were then annealed at 400°C for 30 min in N_2 atmosphere and measured again.

RESULTS & DISCUSSION

The *I-V* characteristics of the fabricated GaN diodes are shown in Fig. 2. The curves are typical for diodes fabricated on HEMT layer stacks with a saturation of the reverse current at the voltage where the AlGaN layer and i-GaN layer are fully depleted [10]. In our devices this occurs at -2 V.

As expected, the sample without a B barrier displays high-current Schottky behavior before annealing (Fig.2a) and becomes short-circuited after annealing (Fig 2b). The B[700,0] sample has lower current levels but these are decades higher current levels than those of the samples with 250°C - 400°C B depositions.

TABLE I: BORON DEPOSITION TEMPERATURE AND THICKNESS; THE DIODE CURRENT AT -3 V REVERSE BIAS

Sample	**B dep. temp. (°C)**	**B thickness (nm)**	**Anneal temp. (°C)**	**Diode current at -3 V (A)**
Al[50,0]	no B	0	-	2.79×10^{-5}
B[250,0]	250	7.2	-	1.02×10^{-8}
B[350,0]	350	7,3	-	2.42×10^{-10}
B[400,0]	450	7.1	-	1.61×10^{-10}
B[700,0]	700	8.4	-	2.17×10^{-7}
Al[50,400]	no B	0	400	1.05×10^{-3}
B[250,400]	250	7.2	400	1.90×10^{-10}
B[350,400]	350	7.3	400	1.47×10^{-10}
B[400,400]	400	7.1	400	5.94×10^{-10}
B[700,400]	700	8.4	400	8.34×10^{-7}

Moreover, upon annealing, the 700°C sample displays 5 times increase in the reverse current while the forward current decreases by a decade. Therefore, it would appear that at 700°C the B deposition has a less favorable interaction with the GaN. The samples B[350,0] and B[400,0] display the lowest currents and stable behavior. After annealing the slightly higher current of the B[250,0] sample reduces to the same level as the other samples with B deposition temperatures below 400°C.

An overview of the electrical results is given in Table I and Fig. 3 where the diode currents at -3 V reverse bias and 0.5 V forward bias are plotted as a function of B layer deposition temperature. With B-deposition, it appears that the non-ideal leakage currents evident around -1 V to 1 V are decreased upon annealing. For both forward and reverse operation, the 350°C B deposition results in the lowest current levels. The 250°C sample is improved by the anneal and the 400°C sample displays a slight improvement in forward and 4 times increase in current in reverse. Overall, the differences between these samples with low-temperature B deposition are small and suggest that from 350°C – 400°C, the interaction of the B with the GaN surface is beneficial for obtaining low saturation current devices and at the same time the B layer prevents detrimental interaction with the Al.

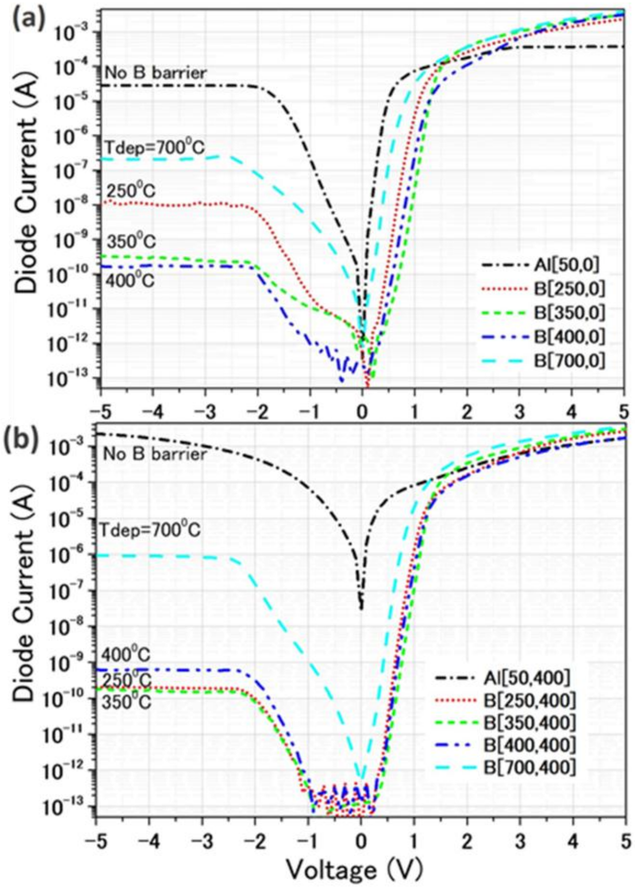

Fig.2. I-V characteristics of the fabricated diodes (a) before, and (b) after annealing at 400°C; circular diodes with a diameter of 200 µm.

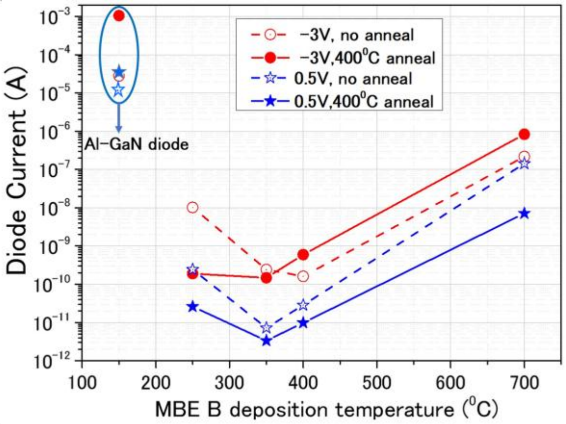

Fig.3. Diode current at -3V reverse and 0.5V forward bias for samples as a function of B layers deposition temperature with and without a 400°C anneal.

The fabricated diodes were inspected by optical and SEM imaging. Optical images of diodes before and after annealing of the 350°C sample are shown in Fig. 4. The as-deposited Al has a smooth appearance that becomes coarse upon annealing. It is well-known from Si technology that such thin layers of Al, will, upon annealing, coalesce into larger grains where hillocks and holes between the grains can give high surface roughness. For the present samples such behavior was confirmed by scanning electron microscopy (SEM) imaging of cleaved samples, and example of which is shown in Fig. 4c. The interface with the GaN does, however, not appear to be deranged by the anneal step.

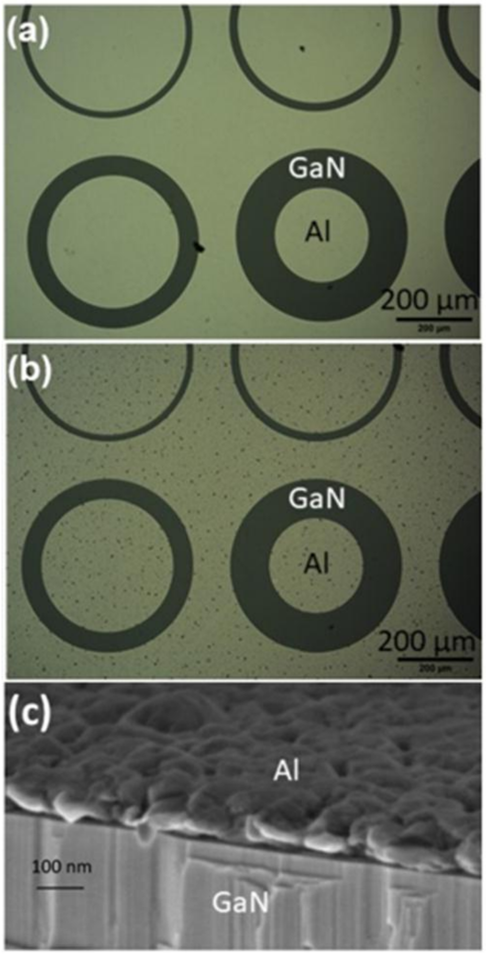

Fig.4. Optical images of the fabricated circular diodes of sample (a) B[350,0] before, and (b) B[350,400] after annealing at 400°C. (c) SEM image of the B[350,400] sample cleaved through one of the diodes.

CONCLUSIONS

With low-temperature MBE boron deposition it was possible to fabricate Al-contacted diodes to n-type GaN with low saturation currents and stable behavior upon annealing at 400°C. The best results were achieved for 350°C – 400°C is B deposition. For an even lower deposition temperature of 250°C the post-deposition anneal was beneficial in reducing the current level to that of the 350°C - 400°C diodes. This suggests that there may be a favorable B-to-GaN chemistry at 350°C - 400°C in addition to the nm-thin B-layers being a barrier to Al metallization.

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