n^{++}GaN Regrowth Technique Using Pico-Second Laser Ablation to Form Non-Alloy Ohmic Contacts

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***Abstract*—Non-alloy ohmic contacts were implemented based on the heavily germanium-doped GaN regrown layer by using the pico-second laser ablation technique for the first time. Owing to the enhanced surface diffusion of the ablated high-energy atoms, smoothly refilled epitaxial layers were achieved in the AlGaN/GaN recess regions. Selective growth was successfully carried out by using hydrogen silsesquioxane (HSQ) film. Contact resistance of ∼0.17 Ω·mm with a specific contact resistance in the order of ∼ 10^{-7} Ω·cm^2 was obtained by using non-alloy Hf/Al/Ti metal stacks.**

***Index Terms*—GaN regrowth, n-type GaN, non-alloy ohmic contacts, power devices.**

I. Introduction

GAN devices are capable of dealing with higher power density if compared with Si devices [1]. However, specific contact resistance in GaN power devices has not yet been reduced to the same level of Si power devices. Typical specific contact resistance for GaN power devices is usually in the order of ∼ 10^{-6} Ω·cm^2, while that for Si ones is in the order of ∼ 10^{-8} Ω·cm^2. This means that the higher current handling capability of the GaN power devices cannot be fully exploited because of the presence of large contact resistance loss. This issue becomes critical in low voltage and high current applications. Hence, reduction of the contact resistance is crucial to increase the conversion efficiency of the GaN-based switching systems.

n^{++}GaN regrowth to refill the AlGaN/GaN recessed areas is expected to lower the on-resistance of GaN power FETs by reducing the contact resistance. There are several reports on n-type GaN regrowth by using MOCVD [2], [3] and MBE [4], however, either technique has some drawbacks in the epitaxy. Typical GaN epitaxial growth usually exhibits growth preference dependent on the crystal orientation [5], [6], and which makes it difficult to adhere the regrown region to the sidewalls of the recess area. Furthermore, the surface morphology of regrown GaN becomes rougher when the deposited material is more heavily doped.

In this letter, we demonstrate a new selective epitaxial technology to provide non-alloy ohmic contact region using PLD (Pulsed Laser Deposition) with Pico-second Laser. Extremely heavily Germanium-doped GaN layers with smooth refilling was achieved owing to the enhanced surface diffusion of the ablated high-energy atoms [7]–[9]. A new selective growth technique was carried out using spin-coated hydrogen silsesquioxane (HSQ) film. Contact resistance of ∼0.17 Ω·mm with a specific contact resistance in the order of ∼10^{-7} Ω·cm^2 was realized by using simple PLD technique for the first time.

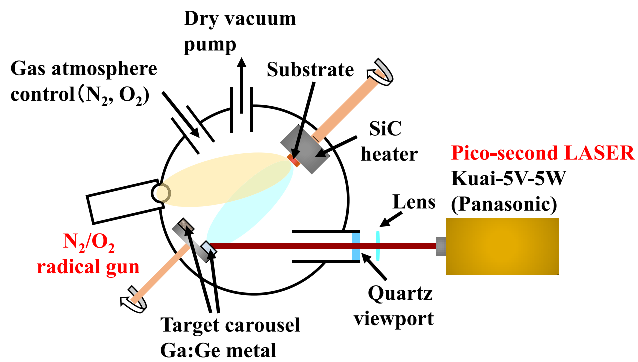

Fig. 1. Principal constituent parts of the PLD used in this work are presented. Among them, Pico-Second laser, Ga:Ge metal target, and nitrogen radical gun are the key elements in the growth of GaN.

II. GaN Epitaxy by PLD

Ge-doped GaN epitaxy was carried out by using Pico-Second Laser PLD system, as shown in Fig. 1, where a liquid alloy of Ga with Ge is used as a target, where Ge concentration was varied from 0.5 to 2 mol%. The target temperature was controlled to keep the melting condition during PLD. The PLD conditions for the n-type GaN regrowth were set to provide the laser pulse width of 24 ps with average power of 2 W at the repetition frequency of 50 kHz. It is noted that high pulse repetition frequency of the laser can reduce the

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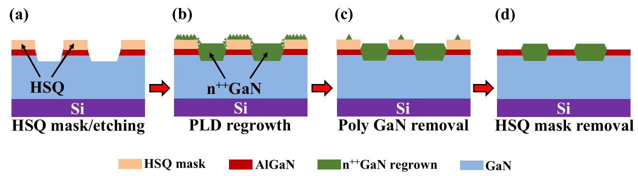

Fig. 2. n^{++}GaN regrowth by Pico-Second PLD. (a) HSQ mask after dry etching, (b) polycrystalline material is deposited on top HSQ mask, whereas on top GaN crystal n^{++}GaN is obtained, (c) after partial polycrystalline material removal from the top of the HSQ mask, (d) resulting n^{++}GaN regrowth after removal of the HSQ mask.

ablation threshold energy due to multi-pulse laser irradiation to the metal target [10]–[12], resulting in the increase of the deposition rate.

The nitrogen radical was generated by the ICP radical gun with the power of 300 W. The existence of nitrogen radical was confirmed by the plasma luminescence peaks at 742, 744, and 746 nm and 818, 821, and 824 nm [13] at the chamber pressure $\sim 8 \times 10^{-3}$ Pa.

The growth rate of 250 nm$\cdot$h^{-1} was obtained at the substrate temperature ~750 °C. Typical GaN epitaxial layers grown by PLD at 750 °C showed FWHM of ~650 arcsec for the layers grown on AlN/sapphire templates. SIMS analysis revealed that Ge concentration obtained by the target with highest Ga-Ge (2 mol%) achieved 6×10^{20} atom$\cdot$cm^{-3}. Electron density of $\sim 1 \times 10^{20}$ cm^{-3} and mobility of ~42 cm$^2\cdot$V$^{-1}\cdot$s^{-1} were obtained by Hall measurements.

III. Selective Regrowth

The starting material has heteroepitaxial layers of $Al_{0.3}Ga_{0.7}N$/GaN (10 nm/1.5 μm) on Si (111) substrate, which was designed to make normally-off HFET. The measured mobility and the sheet carrier density of 2DEG were 1300 cm$^2\cdot$V$^{-1}\cdot$s^{-1} and 7.6×10^{12} cm^{-2}, respectively. The process steps of the selective regrowth are shown in Fig. 2, where simple HSQ masking process are demonstrated [14].

Liquid HSQ was spin-coated followed by the annealing at 400 °C in the atmosphere. The resultant HSQ film had the thickness of 400 nm. After patterning by the photolithography, HSQ film was etched by using weak BHF (HF:NH_4F = 1:200). The wafer was dry-etched using Cl_2 gas to the depth approximately of ~150 nm as shown in Fig. 2 (a). It is noted that HSQ film is free from metal contamination with almost no outgas once it is annealed at 400 °C. HSQ film could be also used as a negative photoresist [15] to shorten the process steps if necessary.

N^{++}-GaN regrowth was carried out under the conditions of the laser energy of ~2 J$\cdot$cm^{-2} with the repetition frequency of 50 kHz, irradiating the nitrogen radical. It is noted that the selective growth was carried out under the previous conditions (Fig. 2 (b)).

It is reported that any planes of GaN except for the (0001) plane can be etched by TMAH [16]. Polycrystalline GaN layer deposited over HSQ mask was partially etched toward *a*-plane and *m*-plane directions by using TMAH (2.38%) solution at 80 °C exposing the underlying HSQ film (Fig. 2(c)). Polycrystalline GaN layer was completely lifted-off by the removal of HSQ using BHF (1:5) (Fig. 2 (d)). Extremely high etching rate of HSQ in BHF solution enables us to make quick lift-off of the polycrystalline GaN layer.

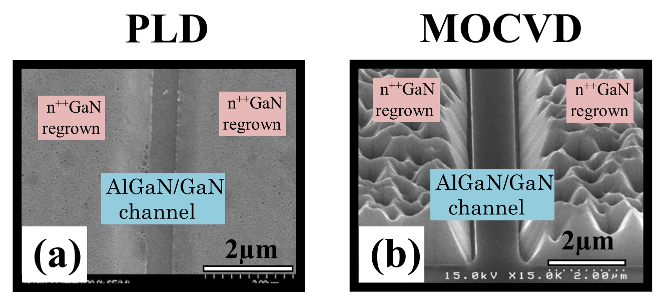

Fig. 3. Selective n^{++}GaN regrowth by PLD (~150 nm thick) (a). And (b) by MOCVD (~500 nm thick) from samples of the Ref. [2].

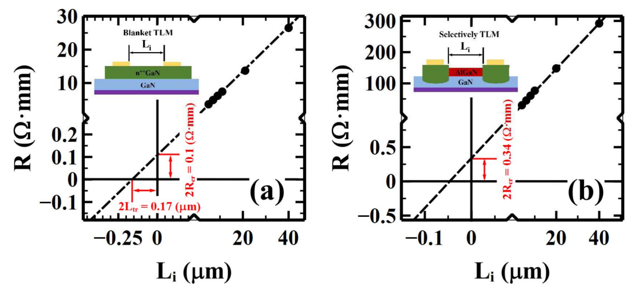

Fig. 4. Contact resistance from TLM on blanket-regrown layer (a) and n^{++}GaN selectively regrown epi structures (b). Resistance, R, versus distance between contact pads, L_i, data is plotted. The extrapolated linear regression line around contact resistance, R = 0 is emphasized. Inset in (a) and in (b) displays TLM patterns used in this work.

SEM image of the ~150 nm thick Ge-doped GaN region selectively grown by PLD over the recess of the AlGaN/GaN heterostructure is shown in Fig. 3 (a). The reference SEM picture of our previous report of Ge-doped GaN MOCVD regrowth technique [2] is shown in Fig. 3 (b). As is observed in the figure, PLD regrown layers show smooth surface with good refilling shape, which is free from facet formation even at the condition of high Ge incorporation. Finally, Hf/Al/Ti (20 nm/200 nm/20 nm) metal stacks were patterned by the lift-off process using e-beam deposition. It is noted that the work function of Hf (3.5 eV) is lower than Ti (4.1 eV) or TiN (4.7 eV), which have been widely used as ohmic electrode to n-type GaN materials [17].

IV. Results and Discussion

Two types of TLM pattern were used to extract the contact resistance for both n^{++}GaN selectively regrown epi structures and n^{++}GaN blanket-regrown layer on etch down regions. It is noted that separation for the selectively grown TLM is defined as the separation between the recesses, whereas that of blanket one is defined as the separation between metals (see inset in Fig. 4 (a) and (b)). Contact resistance can be extracted by Least Squares Method. Measured resistance of two TLM patterns are shown in Fig. 4 (a) and (b) as a function of the precisely measured separation of L_i.

The resultant contact resistance of blanket TLM pattern, as shown in Fig. 4 (a), was extremely low ~0.05 Ω$\cdot$mm with transfer length of ~0.08 μm, where specific contact resistance of metal-to-semiconductor was evaluated as $\sim 1.9\times 10^{-7}$ Ω·cm^2.

Owing to the low work function of Hf (3.5 eV) and very high carrier concentration ($\sim 1\times 10^{20}$ cm^{-3}), extremely low contact resistance was achieved by non-alloy process. By using the TLM pattern for the selective growth, the resultant contact resistance was ~0.17 Ω·mm, where three resistance factors, namely metal-to-semiconductor resistance (R_{cr}), n^{++}GaN access-resistance, and quantum resistance from regrown region to 2DEG [18], are included.

V. Conclusion

It is demonstrated that the heavily Ge-doped GaN regrowth technique using Pico-Second Laser ablation enables us to obtain the very high carrier concentration of $\sim 1\times 10^{20}$ cm^{-3} with smooth surface. Based on the technique, we achieved the non-alloy ohmic contact using Hf/Al/Ti, resulting in contact resistance of ~0.17 Ω·mm.

We believe that proposed Pico-Second PLD technique will contribute to lower the on-resistance for GaN power devices. The on-resistance reduction by the present technique become more important in low voltage applications. Our proposed pulsed Pico-Second laser epitaxy is free from hazardous material or Hydrogen, thereby no abatement or safety system is necessary, resulting in green and low-cost solution in future.

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