Low Resistance Ohmic Contact on Epitaxial MOVPE Grown $\beta$-$\text{Ga}_2\text{O}_3$ and $\beta$-$(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3$ Films

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Abstract—We report on the realization of record low resistance Ohmic contacts to MOVPE-grown heavily Si-doped $\beta$-$\text{Ga}_2\text{O}_3$ and $\beta$-$(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3$ epitaxial films. Transfer length measurement (TLM) patterns were fabricated on the heavily Si-doped homoepitaxial $\beta$-$\text{Ga}_2\text{O}_3$ films with electron concentration $n$ ranging from 1.77 to $3.23 \times 10^{20} \text{ cm}^{-3}$. Record low specific contact resistance ($\rho_c$) and total contact resistance ($R_C$) of 1.62 $\times 10^{-7}$ $\Omega \text{ cm}^2$ and 0.023 $\Omega \text{ cm}$ were realized for $\beta$-$\text{Ga}_2\text{O}_3$. Si films with $n > 3 \times 10^{20} \text{ cm}^{-3}$, TLM structures were also fabricated on heavily Si doped coherently strained $\beta$-$(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3$/$\beta$-$\text{Ga}_2\text{O}_3$ ($x = 12\%$, 17% and 22%) films. The film with 12% Al composition ($n = 1.23 \times 10^{20} \text{ cm}^{-3}$) showed $\rho_c$ of 5.86 $\times 10^{-5} \Omega \text{ cm}^2$, but it increased to 2.19 $\times 10^{-4} \Omega \text{ cm}^2$ for a layer with a 22% Al composition. Annealing the samples post metal deposition has generally led to a decrease in contact resistance, but for high Al content $\beta$-$(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3$, the contact resistance did not change significantly after the annealing process. The low contact resistance values measured in this work are the lowest for ultrawide bandgap semiconductors and are very promising for the fabrication of high frequency power devices.

Index Terms—$\text{Ga}_2\text{O}_3$, $(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3$, MOVPE, specific contact resistance, heavy doping, TLM, Hall.

I. INTRODUCTION

B eta gallium oxide ($\beta$-$\text{Ga}_2\text{O}_3$) has received significant attention in semiconductor research for applications in power electronic devices due to its fundamental properties, including a high breakdown field of $\sim 8 \text{ MV/cm}$ [1], availability of high quality melt grown native substrates [2], and controllable donor doping [3], [4]. The availability of high quality $\text{Ga}_2\text{O}_3$ substrates has resulted in the rapid development of high quality $\beta$-$\text{Ga}_2\text{O}_3$ epilayers and devices [5], [6], [7], [8]. Excellent device results, such as breakdown voltages and critical fields exceeding 2.5 kV and 3 MV/cm, have been reported on numerous lateral and vertical $\beta$-$\text{Ga}_2\text{O}_3$ power devices [6], [9], [10], [11], [12]. However, as a gateway to the external world, reliable low resistance Ohmic contacts are critical for the efficient performance of any device. High contact resistance at the metal/$\beta$-$\text{Ga}_2\text{O}_3$ junction leads to slower device switching speeds and device failure due to local contact heating from a significant voltage drop at the junction during device operation [13], [14].

A common method for decreasing the ohmic contact resistance is to greatly increase the dopant concentration in the semiconductor, promoting tunneling across the metal-semiconductor junction. Various techniques, including ion implantation [15], spin-on-glass [16], and regrowth methods [5], [17], have been employed to achieve this high semiconductor doping and reduce the contact resistance at the source/drain (S/D) ohmic contacts in $\text{Ga}_2\text{O}_3$ MOSFETs and MESFETs. Both ion implantation and spin-on-glass methods expose the material to a high annealing temperature ($\sim 900\text{-}1200 \degree\text{C}$) and potentially deteriorate the quality of the device’s active region [15], [16]. However, regrowth process is typically performed at a much lower substrate temperature ($\sim 600 \degree\text{C}$) and a low contact resistance can be achieved without affecting the material quality. Recently, MOVPE based regrowth process has been applied to fabrication of various FETs, realizing a metal/n$^+$-$\text{Ga}_2\text{O}_3$ contact resistance as low as 0.08 $\Omega \text{ mm}$ and $\rho_c$ of $\sim 8 \times 10^{-7} \Omega \text{ cm}^2$ [5]. However, a systematic study to heavily dope $\beta$-$\text{Ga}_2\text{O}_3$ epitaxial layers using MOVPE and achieve low contact resistance is still lacking. In this work, we report on the demonstration of record low resistance Ohmic contacts on heavily Si doped epitaxial $\beta$-$\text{Ga}_2\text{O}_3$ and pseudomorphic Si doped $\beta$-$(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3$ epitaxial layers with varying Al composition.

II. MATERIALS GROWTH AND DEVICE FABRICATION

Three heavily Si doped homoepitaxial $\beta$-$\text{Ga}_2\text{O}_3$ films (samples A, B, and C, see Table I) and three fully strained heavily Si doped $\beta$-$(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3$/$\beta$-$\text{Ga}_2\text{O}_3$ heterostructures with Al composition ($x$) of 12% (Sample D), 17% (sample E), and 22% (sample F) were grown using Agnitron Technology’s Agilis 100 MOVPE reactor on (010) $\beta$-$\text{Ga}_2\text{O}_3$:Fe substrates. The doped $\beta$-$\text{Ga}_2\text{O}_3$ and $\beta$-$(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3$ layers were grown...
at ~600 °C on an ~250 nm and ~150 nm thick unintentionally doped (UID) Ga2O3 buffer layers (Fig. 1), respectively, with TEGa, TEAl, O2, and silane (SiH4) as precursors, and Ar as carrier gas. The layer thickness and electron concentration for the heavily Si doped β-Ga2O3 and β-(AlxGa1-x)2O3 films are shown in Table I. The purity of the phase, Al composition (x), and layer thickness for the β-(AlxGa1-x)2O3 layers were determined using HRXRD [18]. Hall effect measurements were performed on each of the samples to determine their electron concentration (n), mobility (μ), and sheet resistance (Rₛ). The films were then processed into linear transmission line model (TLM) test structures to characterize their contact resistance. TLM structures were mesa isolated to the β-Ga2O3 substrate using BCl3 chemistry-based reactive ion etching (RIE) process. A 20 nm/150 nm/50 nm Ti/Au/Ni metal stack was deposited via e-beam evaporation and was annealed at 470 °C in N2 for 1min. Four probe current – voltage (I-V) measurements were performed on each of the samples to determine their total contact resistance (Rc) and transfer length (Lt) respectively, were obtained.

The sheet resistance (Rₛ) extracted from the TLM after contact annealing is compared with the values measured from Hall effect measurements (Table I). The Rₛ values obtained from the two methods are very comparable, showing the consistency of the results obtained for each film. Fig. 3 shows the specific contact resistance (ρc) and total contact resistance (Rc) measured post contact annealing as a function of electron concentration for Ga2O3/Si. Both ρc and Rc decreased with the increase in electron concentration. All the Ga2O3 epitaxial layers studied in this work (n > 1.7 × 1020 cm⁻³) demonstrated ρc of < 1.66 × 10⁻⁶ Ω.cm² (the lowest being 1.62 × 10⁻⁷ Ω.cm²), much lower than all the specific contact resistance values reported in the literature so far [5], [15], [19], [20], [21]. The lowest specific contact resistance (ρc) of 1.62 × 10⁻⁷ Ω.cm² obtained in this work is lower than the best specific constant resistance reported by the MOVPE regrowth method by ~4 × ref. [5] and ion implantation method by 23 × ref. [15]. The Rc values were also lower than 0.05 Ω.mm for Ga2O3 samples with n > 2.5 × 10²⁰ cm⁻³. Both ρc and Rc values obtained in this work are the lowest among UWBG
materials, suggesting that MOVPE-regrown contacts could play a significant role in the future development of efficient and fast switching RF devices.

Fig. 4(a) and 4(b) presents the specific contact resistance ($\rho_c$) and total contact resistance ($R_c$) measured post contact annealing as a function of Al composition for $\beta$-(Al$_x$Ga$_{1-x}$)$_2$O$_3$/$\beta$-Ga$_2$O$_3$ heterostructures. The left panel ($y$-axis) for both figures show the measured electron concentration ($n$) dependence on Al composition. The values at $x = 0$ is for pure Ga$_2$O$_3$.

![Fig. 4. (a) $\rho_c$ and (b) $R_c$ as a function of Al composition measured after metallization contact anneal. The left panel on both figures shows electron concentration ($n$) dependence on Al composition. The values at $x = 0$ is for pure Ga$_2$O$_3$.](image)

Table II compares $\rho_c$ values measured before and after contact annealing. $R_c$ measured after the contact annealing is shown.

| Samples | $\rho_c$ ($\Omega \cdot cm^2$) | $R_c$ ($\Omega \cdot mm$) |
|---------|-------------------------------|---------------------------|
| A       | $4.23 \times 10^6$            | 0.110                     |
| B       | $1.68 \times 10^6$            | 0.047                     |
| C       | $1.12 \times 10^6$            | 0.023                     |
| D       | $1.30 \times 10^5$            | 0.340                     |
| E       | $3.56 \times 10^5$            | 1.270                     |
| F       | $3.96 \times 10^4$            | 3.350                     |

![Fig. 5. $\rho_c$ (a) and $R_c$ (b) from this work as compared to the best reported results from various methods [5, 15-17, 20, 21, 24, 25]. Results measured for $\beta$-(Al$_x$Ga$_{1-x}$)$_2$O$_3$ films with Al composition of 12% and 22% are also included.](image)

It is a common practice to perform rapid thermal annealing following metallization at a temperature ranging from 400 to 500 °C to improve the contact resistance at the metal/n$^-$-Ga$_2$O$_3$ junction [15], [19], [22]. In this work, as indicated above, we measured the contact resistance of each of the samples before and after annealing the Ti/Au/Ni metal stack contacts in N$_2$ at 470 °C to study the effect of annealing on the $\beta$-(Al$_x$Ga$_{1-x}$)$_2$O$_3$ layers. Table II compares the $\rho_c$ for the Ga$_2$O$_3$ and $\beta$-(Al$_x$Ga$_{1-x}$)$_2$O$_3$ samples. For the Ga$_2$O$_3$ films, the $\rho_c$ decreased following the annealing process, showing the expected improvement in contact resistance. But, for $\beta$-(Al$_x$Ga$_{1-x}$)$_2$O$_3$ layers, a significant decrease in $\rho_c$ after annealing was observed only for a film with lower Al composition (12%). For higher Al composition $\beta$-(Al$_x$Ga$_{1-x}$)$_2$O$_3$, the $\rho_c$ stayed relatively the same or increased following the annealing process (See Table II). This is likely due to the differences in interfacial reaction and interface chemical composition of Ti/AlGaO as compared to Ti/Ga$_2$O$_3$ annealed interfaces [14].

A heavily Ge doped MOVPE grown $\beta$-Ga$_2$O$_3$ film (GeH$_4$/N$_2$ as Ge source) with $n = 2.6 \times 10^{20}$ cm$^{-3}$ and $\mu_e \sim 38$ cm$^2$/Vs [18], [23] was also fabricated into TLM and $\rho_c$ and $R_c$ values of $2.1 \times 10^{-6}$ (\Omega \cdot cm$^2$) and 0.06 (\Omega \cdot mm) were obtained. Although less desirable as a dopant for Ga$_2$O$_3$ due to its strong process dependence and severe memory effect, Ge can still be used to obtain low resistance Ohmic contacts for FETs [6], [10], [23].

Fig. 5(a) and 5(b) benchmarks our specific contact resistance ($\rho_c$) and total contact resistance ($R_c$) values with the existing literature reports. The comparison shows that the obtained $\rho_c$ and $R_c$ values for the Ga$_2$O$_3$ is the lowest of all the values reported. Even for $\beta$-(Al$_{0.12}$Ga$_{0.88}$)$_2$O$_3$, the obtained $\rho_c$ and $R_c$ values are comparable to those reported for pure Ga$_2$O$_3$ using ion implantation method [20]. Thus, utilizing low temperature MOVPE epitaxy, heavily doped Ga$_2$O$_3$ and $\beta$-(Al$_x$Ga$_{1-x}$)$_2$O$_3$ epitaxial films can be grown to realize a low metal/semiconductor contact resistance. Such a result is very encouraging for high frequency devices where low parasitic resistance is critical.

**IV. Conclusion**

We successfully demonstrated record low resistance Ohmic contacts to MOVPE-grown heavily Si doped $\beta$-Ga$_2$O$_3$ and $\beta$-(Al$_x$Ga$_{1-x}$)$_2$O$_3$ epitaxial films. For $\beta$-Ga$_2$O$_3$: Si with an electron concentration of $3.23 \times 10^{20}$ cm$^{-3}$, $\rho_c$ and $R_c$ values of $1.62 \times 10^{-7}$ (\Omega \cdot cm$^2$) and 0.023 (\Omega \cdot mm) were obtained. For $\beta$-(Al$_x$Ga$_{1-x}$)$_2$O$_3$, the electron concentration was found to decrease with the increase in Al composition, and thus led to an increase in $\rho_c$ and $R_c$. The record low metal/semiconductor contact resistance measured both for $\beta$-Ga$_2$O$_3$ and $\beta$-(Al$_x$Ga$_{1-x}$)$_2$O$_3$ in this work will have significant impact in advancing the performance of RF devices, where low parasitic resistance is paramount.

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