Zn-Doped GaN Comprising the Gate Structure of Normally Off AlGaN/GaN-HFETs

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***Abstract*— A mesa gate structure consisting of Zn-doped GaN (GaN:Zn) enables the normally off operation of AlGaN/GaN heterostructure field-effect transistors (HFETs) grown on an Si substrate. A back-gate structured transistor was prepared to estimate the energy level of Zn (E_T) within the energy band of GaN. The test device comprises AlGaN, GaN, GaN:Zn, and buffer layers on an Si wafer working as the back-side gate; the current transient was measured after a negative bias was applied to the gate. This experiment reveals $E_T - E_V = 0.32$ eV, where E_V is the valence band maximum of GaN, meaning that the Fermi level lies near E_V, as in p-type materials. Thus, a transistor equipped with a mesa-shaped gate structure with a Zn concentration of 1.2×10^{19} cm^{-3} achieves a gate-source voltage (V_{gs}) of +0.5 V at a drain current (i_d) of 10 μAmm^{-1}, and $V_{gs} > 0$ V even at $i_d = 10$ nAmm^{-1}.**

***Index Terms*— Gallium nitride (GaN), Zn-doped GaN(GaN:Zn), normally Off AlGaN/GaN HFET.**

I. INTRODUCTION

THE stacked structure of aluminum gallium nitride (AlGaN) and gallium nitride (GaN) generates two-dimensional electron gas (2DEG) with high electron mobility at its hetero-interface, thus forming a heterostructure field-effect transistor (HFET) using 2DEG as its channel. Although this characteristic is one of the most significant features of the GaN-based material class, the normally present 2DEG hampers normal off-transistor operation.

In addition to this, to suppress leakage current during an off-state, practical AlGaN/GaN-HFETs require a semi-insulation layer in their structure beneath the 2DEG. Therefore, because intentionally undoped GaN and its family materials naturally show n-type acceptor doping in the nitride layers is needed to satisfy this requirement. Carbon (C) [1], [2], magnesium (Mg) [3], and iron (Fe) [4] are impurities that are used for this purpose. However, these impurity elements are not satisfactory from the viewpoint of the production process. Mg and Fe have strong so-called memory effects such as unanticipated doping profiles caused by elements unintentionally remaining in a metal-organic chemical vapor deposition (MOCVD) chamber commonly used for GaN and its related nitride epitaxial growth [5]. C forms deep states in GaN, causing current collapse [6], [7].

Zinc (Zn) is another candidate for fabricating insulated GaN because Zn in GaN has been reported to form an efficient radiative center that emits blue light and acts as a deep acceptor, thereby showing the possibility of insulating GaN electrically [8], [9]. In fact, it has been reported that Zn-doped GaN (GaN:Zn) grown using an ammonothermal method shows p-type conductivity with a hole concentration of 4×10^{15} cm^{-3} [10]. This is an important step promoting Zn doping as a useful tool for the design of device structures; however, no studies have reported the utilization of GaN:Zn grown by MOCVD as a part of an HFET.

In this study, the authors demonstrate that Zn can operate as a dopant, thereby mitigating the negative impacts of Mg, Fe, and C on AlGaN/GaN HFETs. The next section describes how our team grew GaN-related materials and prepared test samples to investigate how Zn operates in GaN transistors. In section III, secondary ion mass spectroscopy (SIMS) reveals that Zn doping provides abrupt doping profiles, indicating that the doping technique is suitable for production. The fourth section deals with the energy levels of Zn (E_T) in the GaN energy band. For this purpose, we prepared back-gate structured transistors including the GaN:Zn layer; these devices have the source and drain electrodes on their surface, as well as on the gate formed on the back side of the substrate used. After the gate is negatively biased to the source, the charged state of Zn changes; thus, the drain current (i_d) of the transistor decays in a time-dependent manner, reflecting the energy level of Zn within the GaN band structure [11]. Section IV describes the main body, including the transistor characteristics of AlGaN/GaN HFETs with a top-mesa structure made of GaN:Zn. These experiments demonstrate that Zn doping successfully facilitates the normally off operation of GaN transistors. Finally, concluding remarks are provided in Section V.

II. EPITAXIAL GROWTH AND DEVICE STRUCTURES

A horizontal-chamber type MOCVD (Taiyo Nippon Sanso SR-6000) was used to grow GaN and AlGaN crystalline films on p-type, 6-inch, and 0.001 ohm-cm resistive (111) Si substrates. The precursors for Ga, Al, N, Mg, and Zn were trimethylgallium (TMGa), trimethylaluminum (TMAl), ammonia (NH_3), ethylcyclopentadienyl magnesium ($EtCp_2Mg$), and dimethylzinc (DMZn), respectively. The growth temperature and pressure ranged from 1090 to 1120 °C, and 60–85 kPa,

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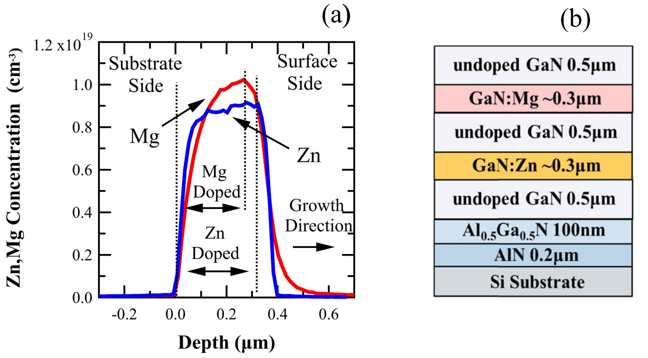

Fig. 1. (a) Comparison of the rise and fall behavior of Zn and Mg impurity profiles. (b) Sample structure for SIMS to compare the doping characteristics of Mg and Zn in GaN.

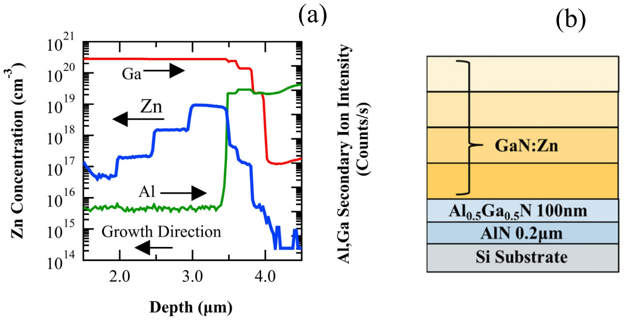

Fig. 2. (a) Impurity profile of the epi-grown samples with the flow rate of Zn source varied in a stepwise manner. (b) Structure of SIMS sample to check the controllability of Zn concentration in GaN.

TABLE I

PURPOSE-SPECIFIC GROWTH CONDITIONS FOR GaN:Zn AND GaN:Mg

	TMG Flow Rate (mol/min.)	DMZn Flow Rate (mol/min.)	$EtCp_2Mg$ Flow Rate (mol/min.)	Sample Structure
A	1.5×10^{-4}	5.2×10^{-4}	4.5×10^{-8}	Fig.1(b)
B	1.0×10^{-3}	8.5×10^{-6} - 8.5×10^{-4}	-	Fig.2(b)
C	3.5×10^{-4}	1.4×10^{-3}	-	Fig.3(c)
D	1.5×10^{-4}	4.2×10^{-5} - 1.1×10^{-3}	-	Fig.4(c)

respectively. Hydrogen (H_2) and nitrogen (N_2) are the carrier gases. The nitrogen source was ammonia, and its flow rate was constant at 8.0×10^{-1} mol/min.

We prepared four different types of samples: A, B, C, and D. These were used to study (A) how Zn and Mg doping profiles differ, (B) the doping controllability of Zn, (C) E_T analysis, and (D) transistor characteristics. The purpose-specific growth conditions for GaN: Zn- and Mg-doped GaN (GaN:Mg) are summarized in Table I.

A schematic of sample A is shown in Fig. 1(b). A 300-nm GaN:Zn or GaN:Mg layer was sandwiched between the undoped GaN layers. Fig. 2(b) shows the layer structure of sample B. Zn was supplied in a stepwise manner. In both cases, SIMS was used to measure the depth profile of the concentration of Mg ([Mg]) and Zn ([Zn]) in GaN films. Sample C has a back-gate structure, as shown in Fig. 3(c), to estimate E_T. The device structure and process used here are the same as those previously reported in [1] and [11]. Here, [Zn] is 1×10^{19} cm^{-3} in size in the 900-nm GaN:Zn layer. The source and drain electrode widths (W_g) and source–drain distances (L_{gd}) of the device were 200 and 10 μm, respectively.

Sample D is a lateral-type transistor equipped with a mesa-gate structure, as shown in Fig. 4(c). GaN:Zn is the gate layer material, whereas GaN:Mg is a material for the gate-part layer in similarly structured GaN transistors [12]. The value of [Zn] varies from 4.8×10^{17} to 2.4×10^{18} and 1.2×10^{19} cm^{-3}, respectively. This convex structure was fabricated using inductively coupled plasma dry etching with a $Cl_2/Ar/O_2$ mixed gas. The gate length (L_g), gate width (W_g), and gate–drain distance (L_{gd}) of the device were 0.9, 150, and 3.0 μm, respectively. The gate metal was 80 nm TiN, with a Schottky gate structure.

III. BENEFITS OF ZN DOPING IN GAN EPITAXIAL GROWTH

Fig. 1(a) shows the SIMS depth profiles of [Zn] and [Mg] in sample A. Each profile curve is superposed such that the zero position on the horizontal axis corresponds to the interface between the doped and undoped regions. The target impurity concentration was approximately 1×10^{19} cm^{-3}, and the doping abruptly started and ended by the mass-flow control turning on and off. The film thicknesses where the concentration rises and falls by one order of magnitude for Mg are 0.15 and 0.21 μm, respectively. In contrast, for Zn, they are 0.08 and 0.08 μm, respectively. As can be clearly seen, the curve of [Zn] rises and falls more sharply than that of [Mg]. This means that Zn doping is more easily controlled than Mg doping by mass-flow control, indicating that Zn is more preferable for production than Mg. This view is further reinforced by the SIMS depth profile of Zn in sample B, as shown in Fig. 2(a). In this experiment, as mentioned above, Zn was supplied in a stepwise manner, and the resulting [Zn] profile followed this stepwise doping design over a doping concentration range of 5×10^{16} to 1×10^{19} cm^{-3}. It has been reported that Zn easily diffuses in GaAs [13]; however, despite a total growth time of approximately 6 h for preparing sample B, [Zn] sharply changes, indicating that Zn diffusion is not that serious. This is another excellent feature of Zn as a dopant for GaN and its related nitrides.

IV. ESTIMATION OF $E_T - E_V$ OF ZN

To form a built-in potential between n-type GaN and GaN:Zn, the Fermi level (E_F) of GaN:Zn must lie near E_V, where E_V denotes the energy level of the valence band maximum (VBM). Therefore, we must estimate the $E_T - E_V$ value.

To this end, the team used the same method as reported by Tanaka *et al.* [11]; Fig. 3(c) includes the electrical bias configuration for this measurement. As discussed in [11], a negative gate-source voltage (V_{gs}) negatively charges Zn, assuming Zn as a deep acceptor (DA) in GaN, and consequently, the electrons in the 2DEG exponentially dissipate during the E_T dependent decay time of τ to decrease i_d. The temperature

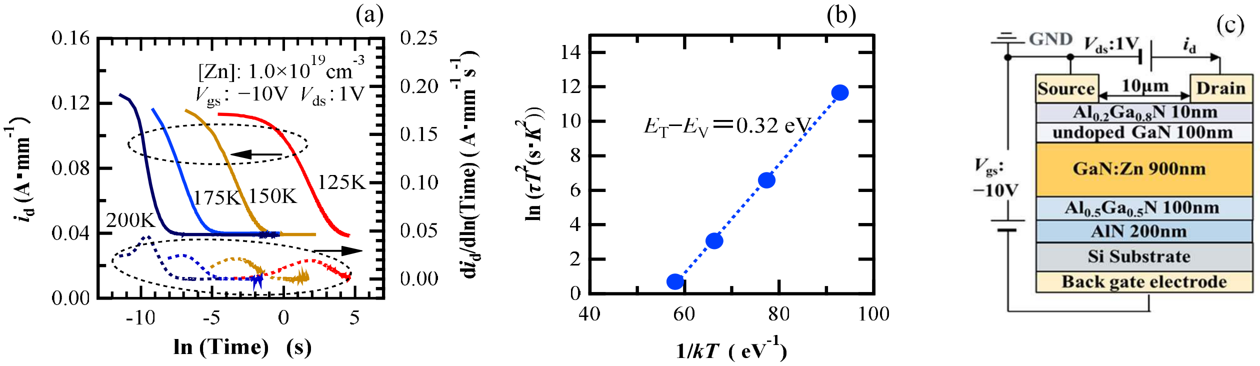

Fig. 3. (a) Temperature dependence of current transient for GaN:Zn. (b) Arrhenius plot of the decay time obtained from these curves. (c) Structure of the back-gate structure samples used to characterize the transient current flowing in GaN:Zn.

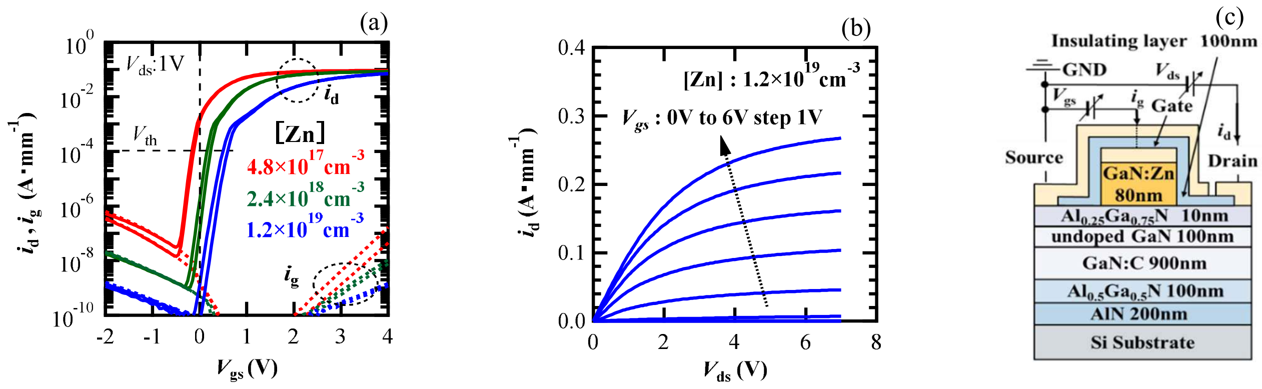

Fig. 4. (a) Measurement results of the i_d- V_{gs} and the i_g- V_{gs} characteristics of the mesa-structured GaN:Zn gated devices. V_{gs} sweeping rate is 3.5 V/s. (b) i_d-V_{ds} characteristics of the device with [Zn] of 1.2×10^{19} cm^{-3}. (c) Device structure.

dependence of the current transient measurements for GaN:Zn is shown in Fig. 3(a). To stabilize the current flowing between the drain and source electrodes, $V_{ds} = 1$ V and $V_{gs} = 0$ V were held for 0.3 s, then $V_{ds} = 1$ V and $V_{gs} = -10$ V were applied at t = 0 s, and finally, the current transition characteristics were measured. The horizontal axis represents the natural logarithm of the time elapsed since a negative V_{gs} is applied, and the vertical axis represents i_d. The moment when V_{gs} is given defines a time of zero along the horizontal axis. As can be seen, the measured descending trend in i_d indicates that negative charges are generated, validating the assumption that Zn forms a DA. The measured descending trend in i_d shifted to the longer side as the sample temperature decreased. The differential curves of the transient characteristics at each temperature are shown in the lower area of Fig. 3(a). Fig. 3(b) shows an Arrhenius plot of the decay times obtained from these curves. The $E_T - E_V$ value of GaN:Zn (0.32 eV) was obtained from the slope of this line. This value was comparable to previously reported values [9], [14], [15]. This means that the E_F of GaN:Zn is located near the VBM, and it is therefore worth adopting GaN:Zn as a material comprising the gate of AlGaN/GaN HFETs.

V. DEVICE CHARACTERISTICS

The p-type GaN mesa-gate structure is commonly used to achieve normally off GaN HFETs, for which p-type is always obtained through Mg doping. The mesa is composed of GaN:Zn with [Zn] = 4.8×10^{17}, 2.4×10^{18}, and 1.2×10^{19} cm^{-3} to estimate how [Zn] affects the HFET characteristic. Fig. 4(a) shows the i_d–V_{gs} and i_g–V_{gs} curves measured in the up and down sweeps. No hysteresis characteristic was observed in each case. It can be seen that the gate current is also suppressed to a low value. The i_d–V_{gs} results show that a larger [Zn] decreases i_d at $V_{gs} = 0$ V, and that [Zn] of 1.2×10^{19} cm^{-3} provides $V_{gs} > 0$ V even at 1.0×10^{-10} Amm^{-1}. If V_{gs} at $i_d = 1.0 \times 10^{-4}$ Amm^{-1} defines the threshold voltage (V_{th}), V_{th} positively shifts along with a larger [Zn] and reaches 0.5 V at a [Zn] of 1.2×10^{19} cm^{-3}. Fig. 4(b) shows the i_d–V_{ds} characteristics of a sample with [Zn] of 1.2×10^{19} cm^{-3}. Here, a normally off operation can be clearly observed. This V_{th} value is comparable to that of existing products on the market [12]. This experimental result demonstrates that Zn doping is practically useful for achieving a normally off operation of GaN HFETs.

VI. CONCLUSION

The research team studied Zn as a dopant to control the E_F of GaN. The estimated $E_T - E_V$ value of GaN:Zn shows that Zn works as a relatively deep acceptor. The authors also fabricated mesa-gate transistors by utilizing GaN:Zn as a material for the mesa structure and confirmed the normally off characteristics. Zn enables an abrupt doping profile control more easily than Mg, and thus, the team concludes that Zn is preferable for mass production.

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