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Zn-doped GaN Mesa Structure as a Gate for Normally-off AlGaN/GaN-HFET

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Abstract

The impurity level of Zn in GaN (GaN:Zn) is estimated to be about 0.3 eV above the valence band maximum of GaN by measuring the transient time of the conductivity of GaN:Zn. The resulting semi-insulating attribute of GaN:Zn is used to form a 0.1-μm high mesa gate structure of the GaN heterostructure field-effect transistors (HFETs) comprising the AlGaN/GaN epilayer stacks grown on Si. The research team confirmed the normally-off operation of the GaN-HFETs.

1. Introduction

The gallium nitride (GaN) hetero-structure field-effect-transistor (HFET) has already been commercialized, and many of them use Mg as a dopant to structure its semi-insulating gate for a normally-off operation [1]. However, this dopant always shows a so-called memory effect, exemplifying a doping delay, or its unintentional stay in a metal-organic chemical vapor deposition (MOCVD) chamber [2].

However, zinc (Zn), which was previously studied as a *p*-type dopant candidate for GaN light-emitting diodes (LEDs), was completely abandoned owing to its insufficient hole generation [3]. The LED is a current-driven device, thus mobile holes are indispensable; however, this is not necessarily a crucial prerequisite for power devices. If a dopant changes the Fermi level (E_F) of electrons in a semiconductor, the dopant satisfies the requirement to form a potential barrier, which is the key factor for all practical semiconductor devices.

In this study, Zn was re-investigated as an acceptor dopant to control the E_F of GaN, and the team shows that it works. The authors prepared di-methyl Zn (DMZn) as a precursor of Zn and grew AlGaN and GaN in a MOCVD to fabricate test elements to measure the energy level (E_t) of Zn gauging from the valence band maximum of GaN (E_v). The previously reported method [4] to estimate $E_t - E_v$ of Zn ($(E_t - E_v)^{Zn}$) reveals that $(E_t - E_v)^{Zn}$ is approximately 0.3 eV. Secondary-ion mass spectroscopy (SIMS) determined that the doping profile of Zn in GaN showed no memory effect, unlike Mg. In addition, GaN HFETs were fabricated in which a Zn-doped GaN (GaN:Zn) mesa structure bears their gate function; the transistors exhibit a normally-off operation.

2. Experiments

All GaN and AlGaN crystalline films used in this study were grown by MOCVD (SR-6000, Taiyo Nippon Sanso). The source materials of Ga, Al, N, Mg, and Zn are tri-methyl Ga, tri-methyl Al, NH_3, bis-ethylcyclopentadienyl Mg ($EtCp_2Mg$), and DMZn, respectively. 6-inch (111)-face Si wafers were used as substrates. The wafers are boron-doped *p*-type and have a conductivity of ~0.001 Ω·cm.

Fig. 1(a) shows the structure of the back-gate structured test element used to investigate the electrical behavior of GaN:Zn. We chose Zn concentration to be 1×10^{19} cm^{-3} for the test. The two Ohmic electrodes comprising 20-nm Ti and 200-nm Al were deposited onto the top-AlGaN layer, and the substrate functioned as the gate. As shown in Fig. 1(a), a gate-source voltage (V_{gs}) and drain-source voltage (V_{ds}) are applied, and the drain current (I_{ds}) is detected. The time-transient behavior of I_{ds} was used to determine $E_t - E_v$, as previously reported in Ref. [4]. In addition, SIMS was used to determine the depth profiles of the Zn ([Zn]) and Mg ([Mg]) concentrations and compare the differences.

Fig. 1(b) shows the structure of the HFET studied here. The gate width was 150 μm. [Zn] in the mesa GaN:Zn was separately set to 2×10^{18}, 1×10^{19}, and 5×10^{19} cm^{-3} to investigate its impact on the threshold voltage (V_{th}) in the I_{ds}-V_{gs} characteristics.

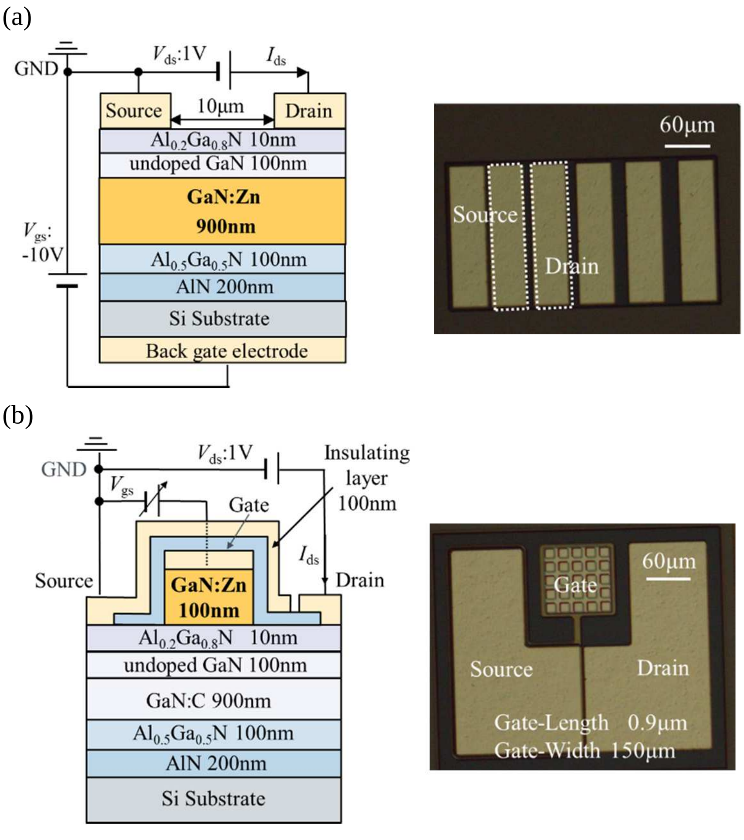


Fig. 1 The cross-section structure and the appearance of the samples used in the study. (a) Back-gate structured test element. (b) GaN-HFET.

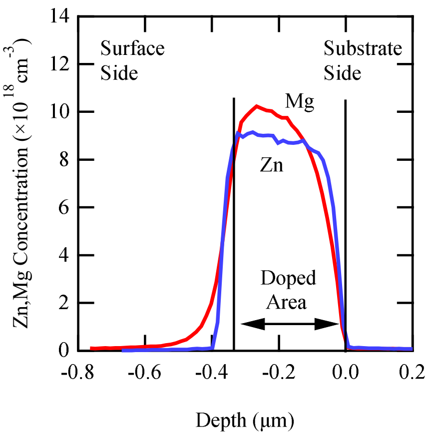
3. Results and Discussion

Figs. 2(a) and (b) show the SIMS depth profiles of Zn and Mg in GaN:Zn and Mg-doped GaN (GaN:Mg), respectively.

The samples used in Fig. 2(a) were prepared such that the precursors of Zn and Mg were abruptly supplied and halted under the same growth conditions as the dopants. In Fig. 2(a), the 0 μm and −0.3 μm points on the horizontal axis show where the doping starts and halts, respectively. As can clearly be seen, the doping profile of Zn was superior to that of Mg in its abruptness. Thus, Zn was better than Mg from the viewpoint of the memory effect.

In Fig. 2(b), the sample is used with the same structure as the one shown in Fig. 1(a) but with a thicker GaN:Zn layer and no top two layers. The flow rate of DMZn varied in a stepwise manner to grow GaN:Zn, and the [Zn] only in GaN was accurately quantified, but not in AlGaN. As shown in the figure, [Zn] varies according to the stepwise doping design. These two experimental results indicate that Zn was more effective than Mg in doping controllability.

(a)



(b)

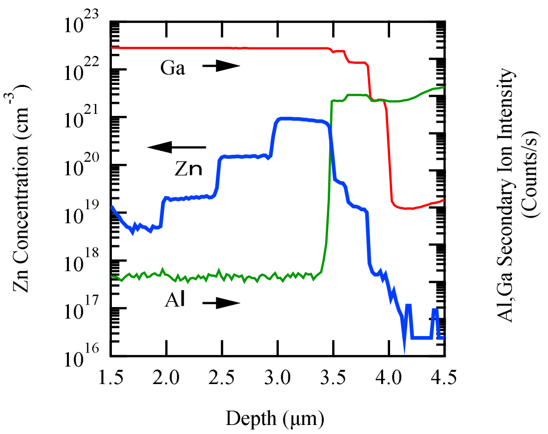


Fig. 2 SIMS profile of Zn and Mg in GaN. (a) The difference in the doping profile for single-step doping. (b) How [Zn] varies for stepwise doping. The secondary ion intensity is shown for Al and Ga.

Next, the team estimated $E_t - E_v^{Zn}$ in GaN. The methodology is the same as that reported in Ref. [4]. Fig. 3 shows the time-transient curve of I_{ds} of the test element shown in Fig. 1(a) measured at V_{ds} = 1 V and V_{gs} = −10 V. This I_{ds} decay provided a time constant of 0.25 ms for GaN:Zn, and thus the $(E_t - E_v)^{Zn}$ of Zn in GaN was estimated to be 0.3 eV.

Finally, the I_{ds}-V_{gs} characteristics were measured for the HFET, the structure shown in Fig. 1(b). As shown in Fig. 4, a higher [Zn] increases V_{th}. [Zn] = 5×10^{19} realizes a normally-off operation.

4. Conclusions

The authors investigated the function of Zn in GaN HFETs. SIMS analysis revealed that Zn had a negligible memory-effect compared to Mg. The I_{ds} time transient measured using a back-gate test element showed that the $(E_t - E_v)^{Zn}$ was approximately 0.3 eV. The I_{ds}-V_{gs} characteristics of the HFET with a GaN:Zn mesa-gate structure realized a normally-off operation for [Zn] = 5×10^{19}.

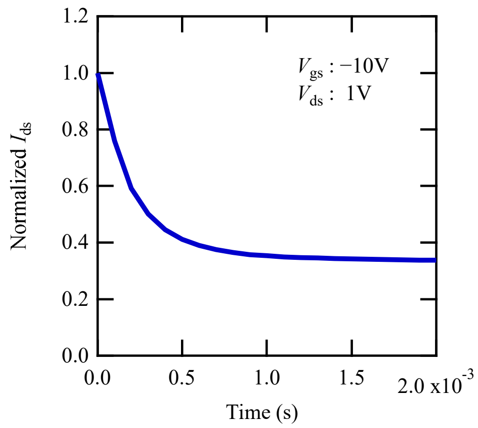


Fig. 3 I_{ds} transient characteristic of a Zn-doped back-gate structured test element

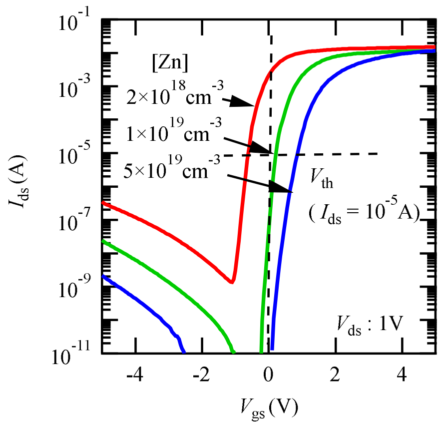


Fig. 4 How Zn doping changes the I_{ds}-V_{gs} characteristic. V_{th} is defined as the V_{gs} at I_{ds}=1×10^{-5}A

References

[1] Y. Umemoto *et al*., IEEE Trans. Electron. Devices, Vol. 54, No. 12, December 2007

[2] Huili Xing *et al*., Jpn. J. Appl. Phys. Vol. 42 No. 50, 2013

[3] H. Amano *et al.*, J. Cryst. Growth, Vol. 93, 79-82, 1988

[4] T. Tanaka *et al.*, IEICE Trans. Electron., Vol. E103-C, No. 4, April 2020