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Current-collapse-free Operations up to 850 V by GaN-GIT utilizing Hole Injection from Drain

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Abstract — **Current collapse at high drain voltage in a GaN-based transistor is successfully suppressed by the introduction of p-GaN region which is placed beside the drain of a Gate Injection Transistor (GIT). The additional p-GaN region enables hole injection which effectively releases trapped electrons at around drain region after the application of high drain voltages. The p-GaN region is electrically connected to the drain electrode so that this is named as Hybrid Drain-embedded GIT (HD-GIT). The fabricated HD-GITs are free from current collapse at 850 V of the drain voltage or over, which significantly helps to achieve stable system operations and is very promising for future switching power supply applications.**

Ⅰ. Introduction

AlGaN/GaN field-effect transistors (HFETs) have emerged as a promising alternative for highly-efficient power switching systems, since those on Si substrates have shown better performances than conventional Si devices together with expectation of low fabrication cost [1]. Overcoming the inherent high sheet carrier concentration at AlGaN/GaN caused by the polarization, a Gate Injection Transistor (GIT) has demonstrated a normally-off operation with low on-state resistance and high drain current [2]. While the p-type gate of the GIT lifts up the potential at the heterojunction leading to the normally-off operation, hole injection from the gate produces a large number of electrons and increases the drain current. The GITs with the breakdown voltages of 600 V or more have been applied to power switching systems so far, of which the performances are far more superior than those by existing Si-based power devices [3-5].

In addition to the normally-off operation, increase of the dynamic on-state resistances after applying high drain voltage has been a serious technical issue on GaN-based power devices. This phenomenon is called as current collapse for which various solutions have been proposed so far. Improvement of the surface properties and reduction of the electric field by field plates have been demonstrated as viable solutions for it [6-7]. However, complete elimination of the phenomena in normally-off GaN power transistors with the operating voltage at 600 V or over has never been reported.

In this paper, current-collapse-free operations of normally-off GaN GITs on Si are demonstrated. The device introduces an additional p-GaN region beside the drain electrode. Since the p-GaN region is electrically connected to the drain, the device can be called as Hybrid Drain-embedded GIT (HD-GIT). Injected holes from the p-GaN at the off-state effectively release the trapped electrons so that the current collapse is fully eliminated. Switching tests using multi-pulses and inductive load which are the most severe testing conditions for GaN devices reveal that the dynamic on-state resistances are not increased up to 850 V with satisfactory long life time. The new structure greatly helps to ensure the long reliability for the practical applications.

Ⅱ. Device Structure and Fabrication

Fig. 1 illustrates schematic cross sections of (a) a conventional GIT and (b) a proposed HD-GIT free from

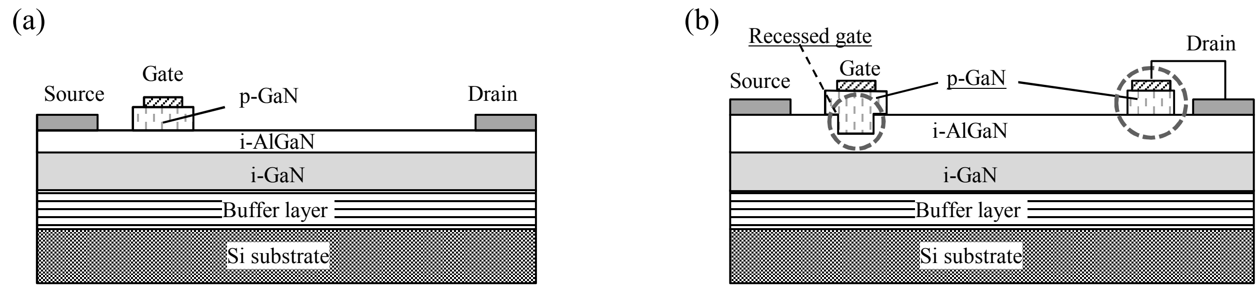

Fig. 1. Schematic cross sections of (a) a conventional Gate Injection Transistor (GIT) and (b) a proposed Hybrid-Drain-embedded GIT (HD-GIT). A p-GaN at the drain and a recessed-gate structure are introduced in the HD-GIT.

current collapse. A notable feature of the HD-GIT is the p-GaN region formed in the vicinity of the drain. This p-GaN region is electrically connected to the drain electrode by the interconnection metal layers. In order to avoid the depletion of the 2DEG (2 dimensional electron gas) under the p-GaN region, thicker i-AlGaN layer is employed. The normally-off operation is achieved by selectively thinning the i-AlGaN layer underneath the p-GaN controlling gate as shown in Fig. 1(b).

The detailed processing flow of the HD-GIT is as follows. An AlGaN/GaN heteroepitaxial structure is grown by metal organic chemical vapor deposition (MOCVD) on a 6-inch Si substrate with buffer layers. After the formation of a recess around the controlling gate, p-GaN is grown again by MOCVD to form the two p-GaN regions of the HD-GIT. The depth of the recess determines the threshold voltage so that this structure serves high threshold voltage as well as low on-state resistance. The formation of the device isolation, electrodes and interconnections are followed by the epitaxial growths to fabricate the device structure as shown in Fig. 1(b).

Fig. 2 shows the operating principle of the proposed HD-GIT. Holes are injected from the p-GaN at the off-state by applying high drain voltage, which effectively release the trapped electrons [8] during the process of switching. Thus, the current collapse is successfully eliminated in the HD-GITs.

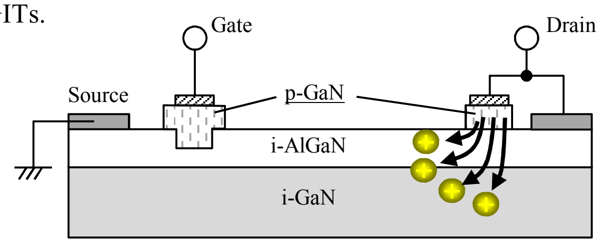

Fig. 2. Illustration of the operation of the HD-GIT. Holes are injected from the p-GaN at the high-voltage off-state.

Ⅲ. RESULTS AND DISCUSSIONS

Fig. 3 shows I_{ds}-V_{ds} characteristics of the fabricated HD-GIT. Extending the gate width W_g to 210 mm enables low Ron of 76 mΩ with the V_{th} of 1.2 V. Identical characteristics with those in the conventional GIT are confirmed. It is noted that the addition of the p-GaN at the drain does not affect the reverse conduction characteristics. Addition of an extra p-GaN region beside the drain does not increase the voltage off-set in the reverse I_{ds}-V_{ds} characteristics as seen in the figure, since the thick AlGaN maintains high enough sheet carrier concentration in this area. The HD-GIT can work as a flywheel diode without any external diodes, as the conventional GIT functions.

Fig. 4 shows the off-state I_{ds}-V_{ds} characteristics of both the conventional GIT and the proposed HD-GIT. The backside of the substrate is grounded for the measurement. The slight increase of the off-state leakage current from the conventional GIT at and over the V_{ds} of 300 V is caused by the hole-injection from the p-GaN at the drain.

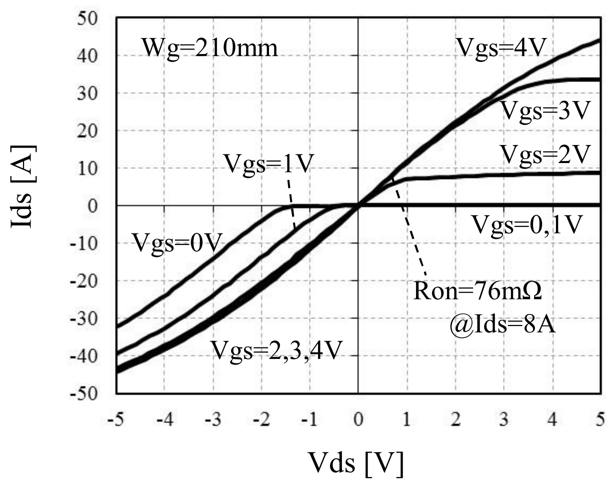

Fig. 3. I_{ds}-V_{ds} characteristics of fabricated HD-GIT.

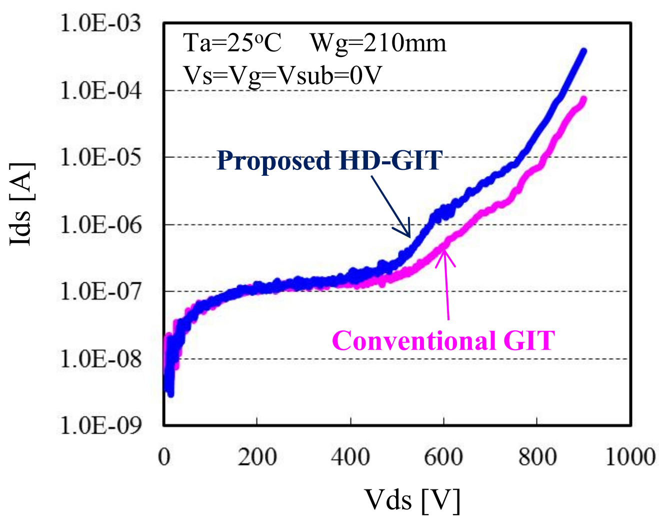

Fig. 4. Off-state breakdown characteristics of a conventional GIT and a proposed HD-GIT.

As for the evaluation of current-collapse, the most severe switching test should be chosen for considering the stable operations in practical switching systems. Here, multi-pulse and inductive load tests are employed for which the circuit diagram is shown in Fig. 5. Dynamic Ron (R) which is an indicator if the current collapse happens is measured at 4.5 μs after the switching from OFF state to the ON state for the fabricated HD-GITs. Since the values of dynamic Ron saturate after certain numbers of the applied pulses during the measurement, the saturated values are defined as the dynamic Ron in this study. The R normalized by the DC value R_0 is plotted as a function of the applied drain voltages as shown in Fig. 6. The HD-GIT is free from current collapse even at 850 V while the sharp increase of the R/R_0 is observed at 620 V for the conventional GIT. It is noted that the slight increase of R/R0 in the HD-GIT is presumably due to the increase of the junction temperature after the application of the number of switching pulses.

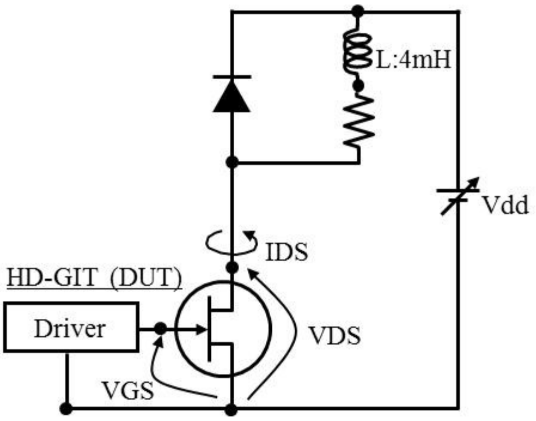

Fig. 5. A test-circuit diagram for inductive-load switching tests.

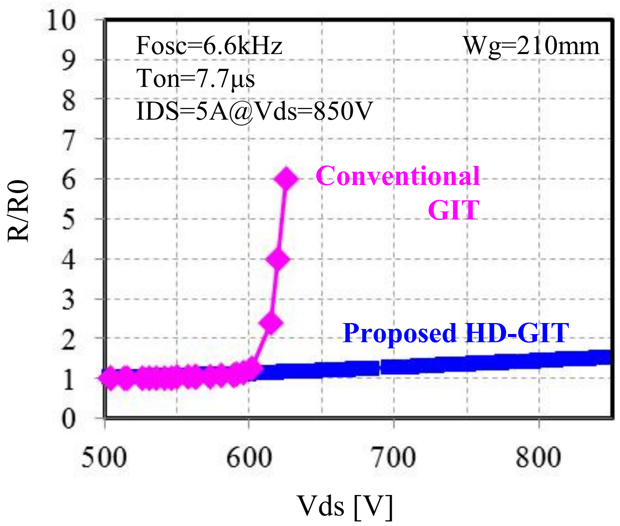

Fig. 6. Values of dynamic Ron normalized by the DC values (R/R0) measured by the circuit shown in Fig. 5. The values are plotted as a function of the off-state drain voltages.

The test circuit in Fig. 5 is also used for the reliability test by the dynamic operations of which the switching waveform is shown in Fig. 7. Locus curves of the waveform are shown in Fig. 8, in which both high voltage and high current are simultaneously applied. That implies the test covers very large area of the device operations and the condition is very severe for the device. Note that the HD-GIT samples for the switching measurements are packaged into TO-220. Even after switching operations of 300 hours, the DC characteristics such as threshold voltage, on-state resistance and off-state leakage current are stable in the HD-GIT as shown in Fig. 9 and 10.

In addition to the life time during the switching tests, high

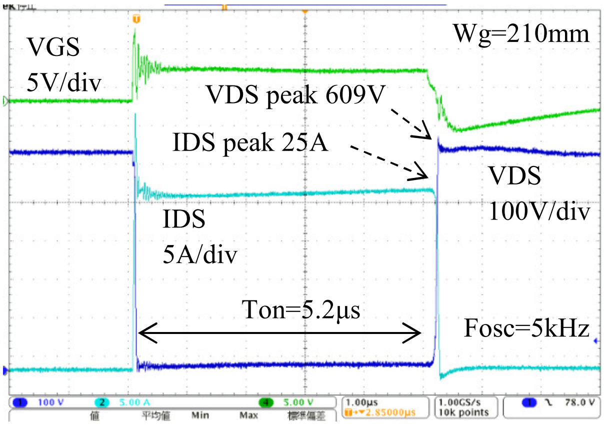

Fig. 7. Measured switching waveform during the reliability test for the HD-GIT.

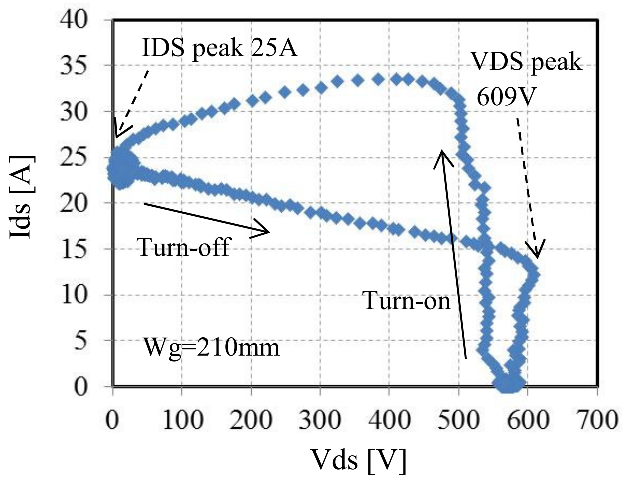

Fig. 8. Locus curves of the switching waveform in Fig. 7. The curves include very high current at high voltage so that the test conditions are very severe.

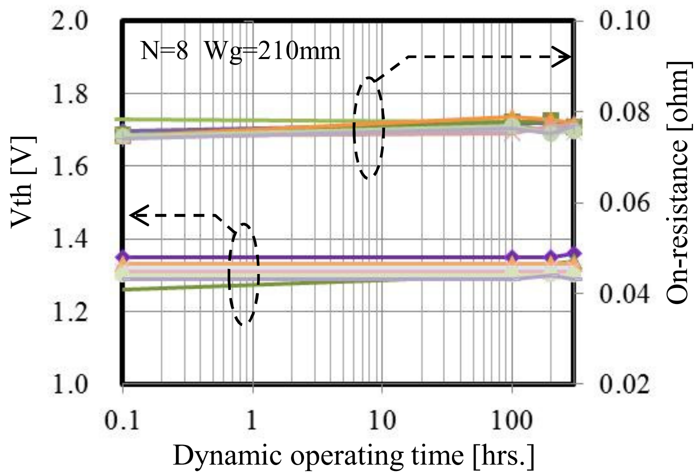

Fig. 9. Measured Vth and on-resistance for HD-GITs after the reliability test employing the dynamic switching. The values are very stable even after 300 hours of the test.

temperature reverse bias (HTRB) reliability test is performed at 150 °C for the fabricated HD-GITs in TO220 package. The devices are sufficiently reliable over 1000 hours after the reliability tests for the drain voltage of 600 V as shown in Fig. 11.

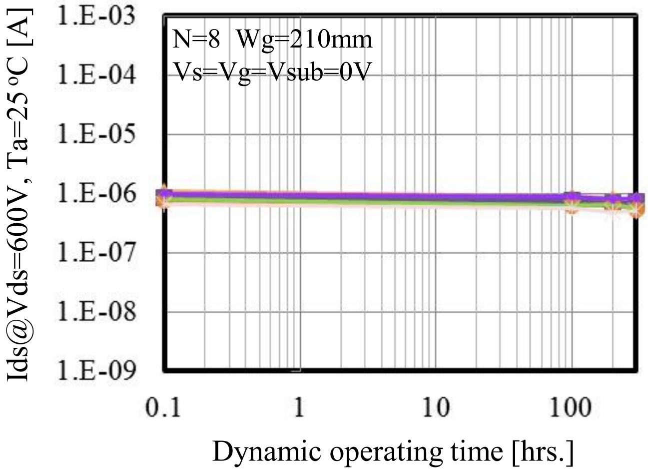

Fig. 10. Measured off-state drain current Ids for HD-GITs after the reliability test up to 300 hours.

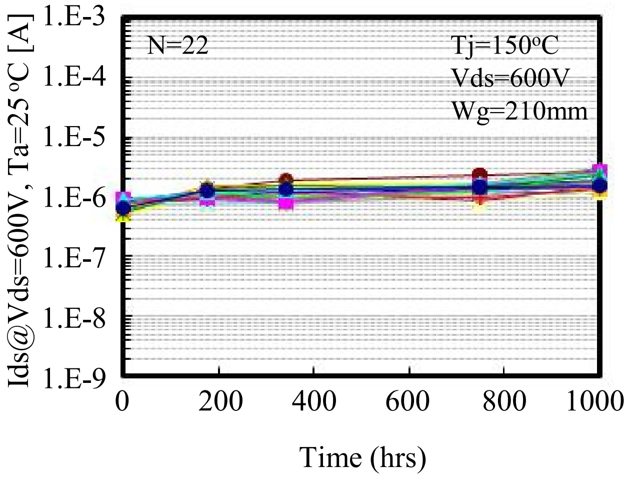

Fig. 11. Bias-temperature reliability test results for HD-GITs. Stable off-state leakage currents up to 1000 hours are confirmed.

IV. CONCLUSION

In conclusion, a new structure of normally-off AlGaN/GaN transistor named as hybrid drain-embedded GIT (HD-GIT) free from the current collapse up to 850 V is demonstrated. Injection of holes from the p-GaN region which is placed in the vicinity of the drain effectively releases the trapped electrons at the off-state. The device maintains low dynamic Ron even at the switching tests with inductive load of which the locus curve covers the wide area of the current-voltage characteristics. The fabricated HD-GITs exhibit sufficiently good reliability over 1000 hours at the drain voltage of 600 V, indicating that these devices are very promising for practical switching power supply applications.

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REFFERENCES

[1] T. Ueda, M. Ishida, T. Tanaka and D. Ueda, "GaN transistors on Si for switching and high-frequency applications", Jpn. J. Appl. Phys. **53**, 100214 (2014).

[2] Y. Uemoto, M. Hikita, H. Ueno, H. Matsuo, H. Ishida, M. Yanagihara, T. Ueda, T. Tanaka and D. Ueda, "Gate Injection Transistor (GIT)-A normally-Off AlGaN/GaN Power Transistor Using Conductivity Modulation", IEEE Trans. Electron Devices **54**, 3393 (2007).

[3] T. Morita, S. Tamura, Y. Anda, M. Ishida, Y. Uemoto, T. Ueda, T. Tanaka and D. Ueda, "99.3 % Efficiency of Three-Phase Inverter for Motor Drive Using GaN-based Gate Injection Transistors", APEC2011, proceeding, 481 (2011).

[4] T. Morita, H. Handa, S. Ujita, M. Ishida and T. Ueda, "99.3 % Efficiency of Boost-up Converter for Totem-pole Bridgeless PFC Using GaN Gate Injection Transistors", PCIM Europe 2014, Conference Digest, 325 (2014).

[5] H. Umeda, Y. Kinoshita, S. Ujita, T. Morita, S. Tamura, M. Ishida, and T. Ueda, "Highly Efficient Low-Voltage DC-DC Converter at 2-5 MHz with High Operating Current Using GaN Gate Injection Transistors", PCIM Europe 2014, Conference Digest, 45 (2014).

[6] P. Moens, C. Liu, A. Banerjee, P. Vanmeerbeek, P. Coppens, H. Ziad, A. Constant, Z. Li, H. De Vleeschouwer, J. Roig Guitart, P. Gassot, F. Bauwens, E. De Backer, B. Padmanabhan, A. Salih, J. Parsey and M. Tack, "An Industrial Process for 650V rated GaN-on-Si Power Devices using in-situ SiN as a Gate Dielectric", Proceedings of ISPSD'14, 374 (2014).

[7] W. Saito, T. Nitta, Y. Kakiuchi, Y. Saito, T. Noda, H. Fujimoto, A. Yoshioka and T. Ohno, "Influence of Electric Field upon Current Collapse Phenomena and Reliability in High Voltage GaN-HEMTs", Proceedings of ISPSD'10, 339 (2010).

[8] K. Tanaka, M. Ishida, T. Ueda and T. Tanaka, "Effects of Deep Trapping States at High Temperatures on Transient Performance of AlGaN/GaN Heterostructure Field-Effect Transistors", Jpn. J. Appl. Phys. **52**, 04CF07 (2013).