A Novel GaN Device with Thin AlGaN/GaN Heterostructure for High-power Applications

*by Nariaki Ikeda *, Jiang Li *, Sadahiro Kato *, Mitsuru Masuda * and Seikoh Yoshida **

ABSTRACT GaN electron devices are expected to contribute significantly toward efficiency improvement and downsizing of power supplies since the devices have the potential of realizing higher breakdown voltages and lower on-state resistances in comparison to Si electron devices conventionally used. The authors have investigated, by thinning the AlGaN layer and simultaneously inserting an AlN layer, GaN/AlGaN heterojunction Field Effect Transistor (HFET) structures aimed at realization of normally-off type devices that are high in breakdown voltage yet comparatively low in on-state resistance characteristics. And, using AlGaN/GaN heterostructure epitaxial layers on a Si substrate-- one of the prerequisites for cost reduction, normally-off operation with a threshold voltage of 0 V has been achieved. A proprietary diode structure has also been proposed to enable loss reduction, and operation with a low on-state voltage has been confirmed where a current begins to flow at approximately 0 V. Moreover, an epitaxial AlGaN structure with a reduced thickness has been applied to this structure, and a diode featuring low leakage current as well as low on-state voltage operation has been obtained.

1. INTRODUCTION

GaN-based semiconductor devices have long been under development with the expectation that they would have superior characteristics in comparison to conventional Si-based devices since they, like SiC devices, belong to the family of wide band-gap semiconductors. In particular, GaN-based field effect transistors (FETs) are capable of operating in high output power, high frequency and high temperature conditions exhibiting many outstanding figures of merits 1)~5). Figure 1 shows the correlation between power capacity and frequency of various power devices together with the so-called “Si limit.” The wide band-gap semiconductor devices such as SiC and GaN can be expected, unlike conventional Si devices, to exceed the performance limit, so that expectations are growing that they would realize high-performance power supplies in the high-frequency range. In particular, the on-state resistance of wide band-gap FETs can be by two orders of magnitude lower than that of Si FETs. It is thus possible for GaN devices to reduce significantly, in comparison to Si devices, the power loss in switching devices such as inverters and converters thereby downsizing or eliminating the cooling devices included. In addition, high-speed switching and high-frequency operation using GaN FETs makes it possible to improve the efficiency of switching circuits, resulting in downsizing and high-density mounting of the circuits.

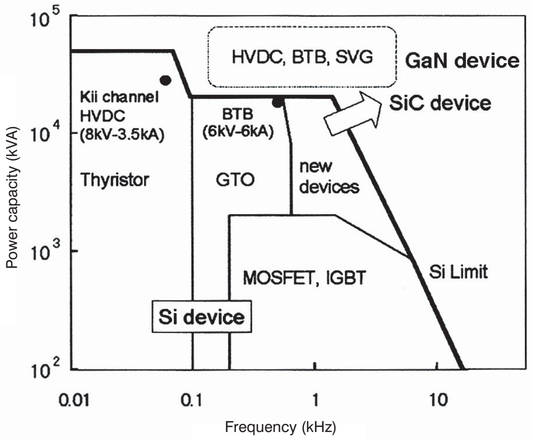


Figure 1 **Power capacity versus frequency for several types of power devices.**

We have reported the results of prototyping an inverter as one of the GaN-based power supplies. The inverter comprised a DC converter circuit and AC inverter circuit, and the operating output power was 50 W, reaching a maximum power of 200 W 6) . However, the devices used in these inverters were of the normally-on type. In this work, normally-off type devices were fabricated making full use of GaN HFET structures, developing into novel devices such as normally-off FETs and low-loss diodes. The developmental results will be presented in this report.

---

* Yokohama Research Lab., R&D Div.

2. DEVELOPMENT OF NORMALLY-OFF FET

This section presents the achievements of normally-off FET using GaN FET.

2.1 Past Reports on Normally-off GaN FET

In order to develop a general-purpose device for power supplies, it is essential to use a normally-off type element from the standpoint of making the equipment fail-safe. Normally-on elements, if they were used in the circuits, can lead to a complicated circuit structure. Despite this, traditionally, very few have reported on normally-off type GaN power devices. And most of the traditional studies made a positive use of the two-dimensional electron gas (2DEG) of high density that can be formed at the AlGaN/GaN interface in the common GaN devices.

Several candidate structures are conceivable for achieving normally-off operation. The first one is to dispose, like Si devices, an insulating layer such as SiO_2 between the gate electrode and the semiconductor. According to past reports, however, this structure was unable to achieve normally-off operation since gate bias could not be applied due to the interface state. It is considered that reducing the interface state is necessary for this technique to be successful. Another technique which makes full use of HFET structure is to reduce the thickness of the AlGaN layer near the gate to obtain the so-called recess structure as shown in Figure 2, thereby shifting the pinch-off voltage to achieve normally-off operation. Whereas a number of studies have reported the experimental results of this technique, it is true that none of them have sufficiently achieved normally-off operation [7]. Also, the problem with this technique is that there remains an issue of damage removal after etching in the recess etching process and that fluctuations in the threshold voltage might occur due to etching depth variations thus leading to low yields.

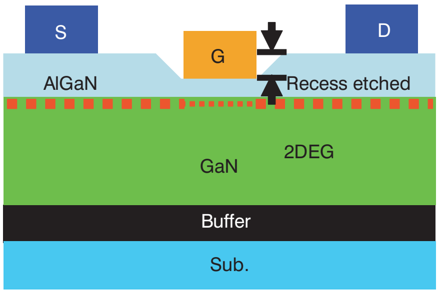


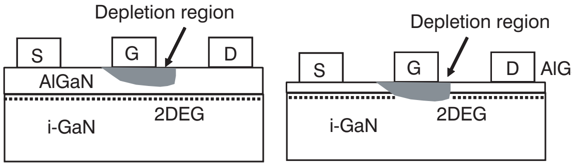
Figure 2 Recess-gate structure for HFET device proposed by others.

2.2 Control of Normally-off Threshold Voltage

The threshold voltage of HFETs is expressed by Equation 1, where the threshold voltage is determined mainly by three parameters; Φ_B: height of Schottky barrier, d: thickness of AlGaN layer and N_d: carrier concentration of 2DEG.

$$V_{th} = \Phi_B - \frac{\Delta E_c}{q} - \iint_d \frac{qN_D(x)}{\varepsilon} dx^2 \qquad (1)$$

Heretofore, we have achieved normally-off operation by doping the GaN layer of the HFET structure with carbon in order to obtain high resistivity [8]. The mechanism is that carriers in the 2DEG are compensated by carbon resulting in a decrease of N_d value, which generates a shift in the pinch-off voltage. However, carbon doping has limitations in terms of large-current operation. Accordingly, this time, we embarked on decreasing the d value by reducing the thickness of the AlGaN layer as a whole. Figure 3 shows schematics of the HFET structures of conventional normally-on type and normally-off type. It is thought that, due to the depletion region that extends to beneath the gate electrode, whereas in the case of normally-on type shown in (a) the gate potential has to be turned into negative in order to pinch off the channel by 2DEG, in the case of normally-off type shown in (b) the channel can be pinched off without applying a voltage on the gate because the AlGaN layer has originally a reduced thickness.



(a) Conventional HFET
(Thick AlGaN layer)

(b) Normally-off HFET
(Thin AlGaN layer)

Figure 3 Different HFET structures of: (a) conventional HFET with thick AlGaN layer and (b) normally-off HFET with thin AlGaN layer.

2.3 Fabrication Process of HFET Device

This time, the reduced-thickness AlGaN structure was used to carry out prototype fabrication of HFETs. The epitaxial layer was grown on an Si(111) substrate by metal organic chemical vapor deposition (MOCVD) method using ammonia, trimethyl gallium (TMGa) and trimethyl aluminum (TMA) as raw materials. The epitaxial layer structure was formed by layer deposition of AlN/GaN buffer layer, thick GaN layer (0.8 μm), AlN (0.5~1 nm) and AlGaN (5~40 nm) in this order. Devices having the above mentioned structure were fabricated followed by characteristics evaluation. A layered structure of Ti/Al was used for ohmic electrode and Pt/Au for Schottky electrode. Device dimensions were 2 μm in the gate length and 10 μm in the gate-drain distance, and devices with different gate widths were evaluated. The maximum gate length was 200 mm. After the fabrication processes, the devices were evaluated for their characteristics using a curve tracer by Sony Tectronics and a semiconductor parameter analyzer by Agilent.

2.4 Results of Device Evaluation

Figure 4 plots the dependence of the threshold voltage on the thickness of the AlGaN layer. As can be seen, the threshold voltage increases as the AlGaN layer decreases in thickness, reaching 0 V at a thickness of 5 nm. Schottky characteristics were evaluated between the gate-drain terminals, and Figure 5 shows the reverse characteristics of

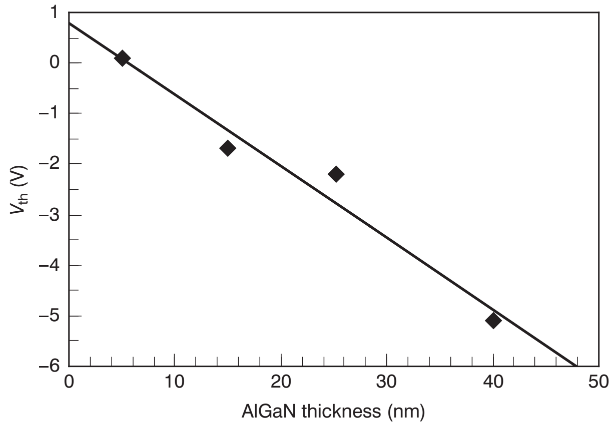


Figure 4 **Dependence of threshold voltage V_{th} on AlGaN thickness.**

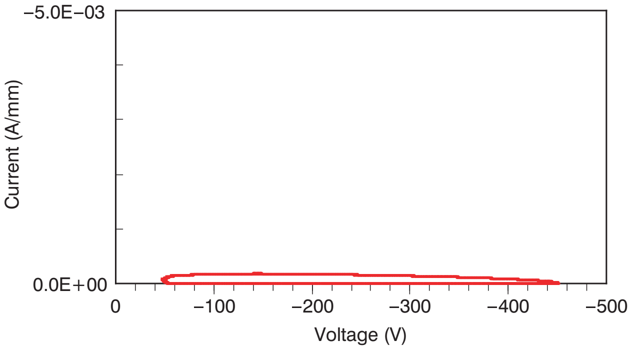


Figure 5 **Reverse characteristics of Schottky diode with a thin AlGaN structure.**

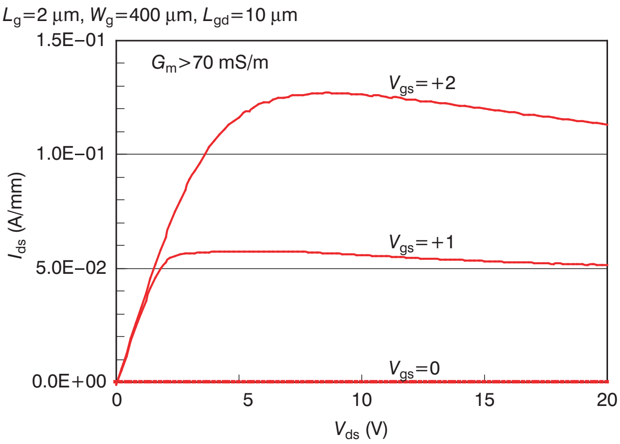


Figure 6 **I_{ds} versus V_{ds} of selected HFET of normally-off operation.**

Schottky diodes with an AlGaN thickness of 5 nm. From the Figure, it can be seen that a breakdown voltage of 450 V or higher is obtained. The leakage current here is approximately 0.1 μA/mm, which indicates that the HFET structure with an AlGaN layer thickness of 5 nm has improved the pinch-off performance, and as a result, the reverse leakage current has been sufficiently suppressed.

Figure 6 shows the drain current versus voltage characteristics of selected devices having a gate length of 2 μm, gate width of 400 μm and gate-drain distance of 10 μm. The drain currents are plotted while the V_{gs} was changed starting from 2 V with a 1-V step, exhibiting a good normally-off characteristic. A maximum current gain of 70 mS/mm has been obtained. Figure 7 shows the gate voltage versus drain current characteristics of similar devices using a logarithmic scale. An excellent pinch-off characteristic has been obtained, i.e. pinch-off voltage is virtually near 0 V and the leakage current then is not more than 10 nA/mm.

The multilayer interconnection method was used to combine 500 elements of the device with a gate width of 400 μm to form a 200-mm device, and the drain current versus voltage characteristics of the device are shown in Figure 8. From the Figure where the cases of V_{gs}=1 V and 0 V are plotted, it can be seen that a good normally-off characteristic has be obtained. Figure 9 shows the off-state characteristic of the same device, demonstrating a breakdown voltage of 300 V or higher. Since the area of the active region is 0.15 cm^2, the specific on-resistance is estimated as 30 mΩ·cm^2. Figure 10 shows, summarizing the results described above, the relationship between the breakdown voltage and on-state resistance, where the results with the normally-on type are represented by red circle, while those with the normally-off type by black square. The results obtained this time are seen to have significantly outperformed the Si limit, demonstrating that a GaN-based normally-off type HFET has been realized that is higher in breakdown voltage and lower in loss in comparison to conventional Si devices.

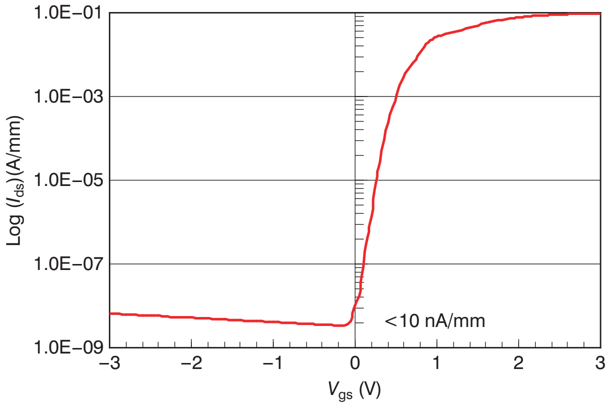


Figure 7 **Vgs versus I_{ds} of selected HFET of normally-off operation.**

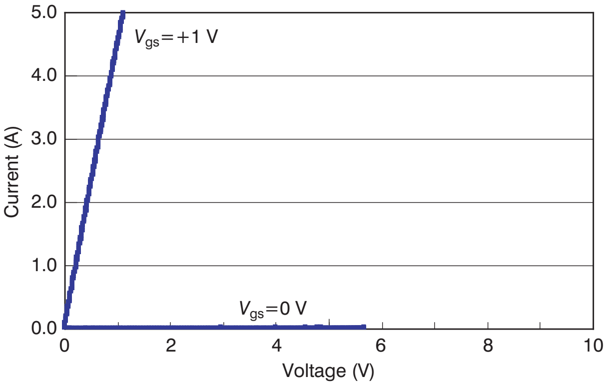


Figure 8 **Large current characteristics of normally-off HFET device.**

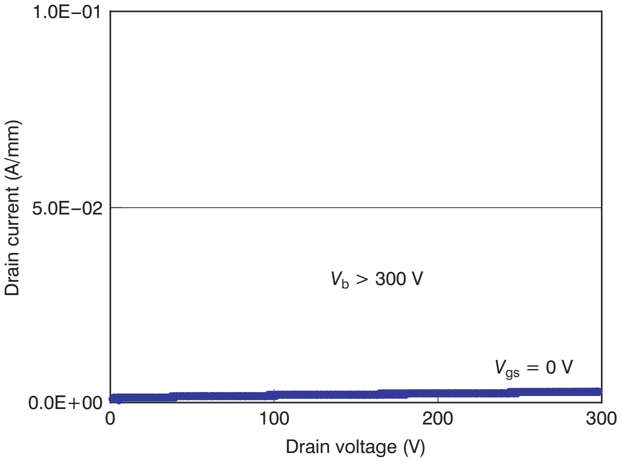


Figure 9 Gate-drain breakdown characteristics of normally-off HFET device.

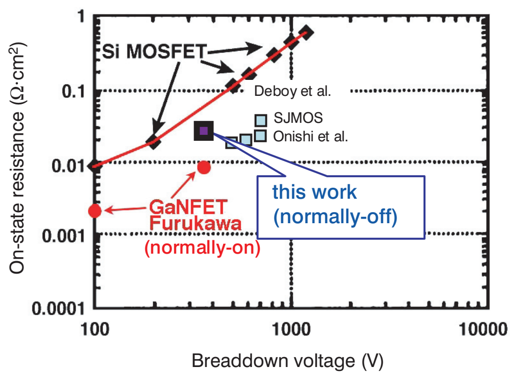


Figure 10 Correlation between on-state resistance and breakdown voltage.

3. DEVELOPMENT INTO FESBD WITH THIN AlGaN STRUCTURE

In order to realize a high-efficiency power supply, a high-speed diode is needed as well as an FET, and GaN-based diodes are expected to offer such a high switching speed due to their solid state properties. To this end, we have developed a diode capable of operation that is low in on-state voltage. The diode, which is commonly called field effect Schottky barrier diode (FESBD) [9], has been developed by application of reduced-thickness AlGaN structure based on our proprietary technology. The results will be presented below.

3.1 Mechanism for High Breakdown Voltage and Low On-state Voltage Operation of FESBD

In FESBDs, low on-state voltage is achieved by using a new electrode structure to replace the Schottky electrode of ordinary Schottky barrier diodes (SBDs), where a metal having a low Schottky barrier is embedded in a metal having a high Schottky barrier. Figure 11 shows a schematic of FESBD together with a schematic description of the working principle in the forward direction. The electrode structure comprises a metal SM1 having a low Schottky barrier enfolded in another metal SM2 having a high Schottky barrier, and the structure is formed on the AlGaN/GaN HFET structure. With regard to the forward characteristics, the current flows through the 2DEG channel formed on an AlGaN/GaN structure, so that due to the metal SM1 having a low barrier, an operation with lower on-state voltage compared to the case of conventional SBDs can be expected.

Meanwhile, the reverse characteristics of the FESBD are shown in Figure 12. Since the channel is pinched off due to the SM2 having a high barrier, the reverse characteristics are thought to be comparable with those of conventional SBDs. Thus, it is anticipated that the new structure results in an SBD of low on-state voltage while maintaining a high breakdown voltage.

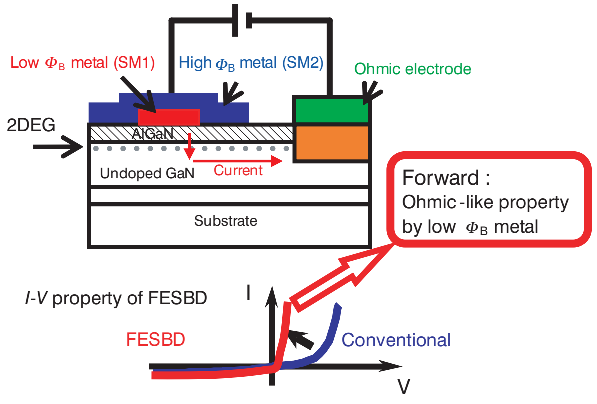


Figure 11 Mechanism for forward characteristics of FESBD.

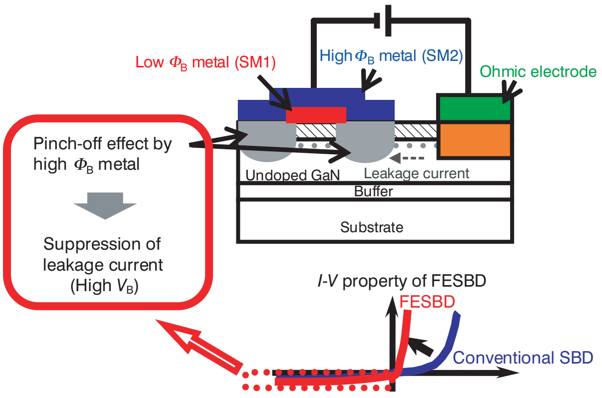


Figure 12 Mechanism for reverse characteristics of FESBD.

3.2 Fabrication Method of Device

The FESBD device is fabricated using a similar method as for HFETs described earlier except for the formation of Schottky electrode. In this development, Ti-based electrode having a low Schottky barrier and Pt-based electrode having a high barrier were used for SM1 and SM2, respectively. Since the rest of the fabrication process is compatible with both FESBD and HFET, it would be possible to integrate both of them in the future.

3.3 Results of Characterization of FESBD Device

Figure 13 shows the dependence of the device breakdown voltage on the SM1/SM2 electrode width ratio. The SBD structure using SM2 only (excluding SM1) is seen to have a breakdown voltage of 400 V, which shows, as the

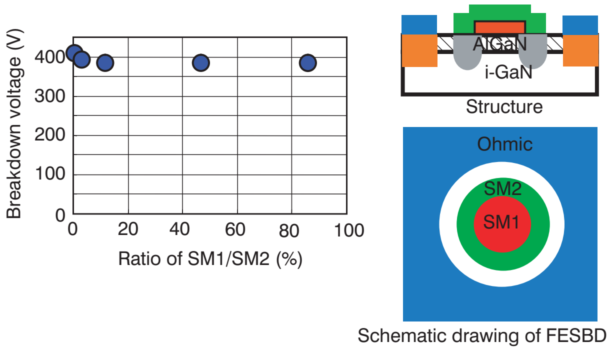


Figure 13 **Breakdown voltage versus SM1/SM2 ratio.**

ratio gradually increases until about 90 %, little change maintaining the nearly equal value as for the case of SM2 only. This behavior indicates that even a small fraction of SM1 is sufficient to maintain breakdown voltages by means of pinch-off effects. At the ratio of 95 % and higher, however, the breakdown voltage tended to decrease. The forward current dependence was also investigated indicating a linear relationship increasing with the area of SM1, so that it is desirable for the SM1/SM2 ratio to be as large as possible. Considering the trade-off relationship between the breakdown voltage and forward current, the optimum value for the ratio would be approximately 90 %.

Figure 14 compares the forward currents of conventional SBD and FESBD. It is seen that in the conventional structure the current begins to rise at around 1 V due to the offset caused by the height of barrier, while in the case of FESBD the current rises at approximately 0 V. On the other hand, Figure 15 shows the reverse characteristics of three different structures: conventional normally-on type SBD using an HFET epitaxial substrate with a 20-nm AlGaN layer; SBD using SM2 only with an AlGaN layer reduced to 5 nm in thickness; and FESBD with a 5-nm AlGaN layer. It can be seen that a reduction in the leakage current of about one to two orders of magnitude has been achieved in comparison to the case of 20-nm AlGaN layer. This is considered to result from the difference in the voltage required to pinch off the 2DEG channel. Thus, the validity of FESBD principles and the usefulness of the reduced-thickness AlGaN structures have been confirmed.

Figure 16 shows the forward characteristics of the large device with a Schottky electrode width, i.e. corresponding to gate width, of 200 mm. The current begins to rise at approximately 0 V and reaches a maximum of around 7 A, demonstrating that a large-current operation is also possible with the FESBD structure.

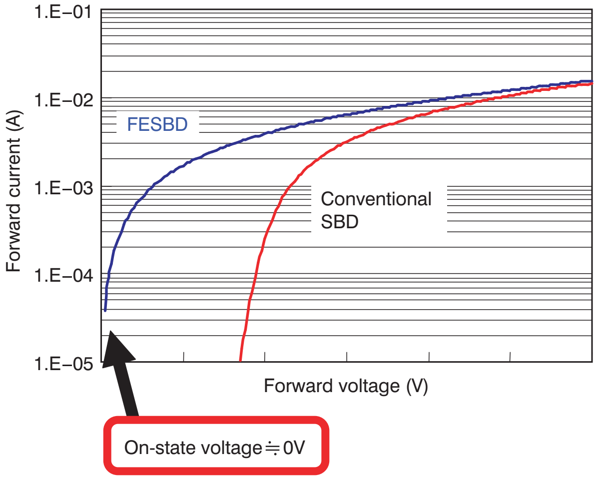


Figure 14 **Comparison of FESBD and SBD for forward characteristics.**

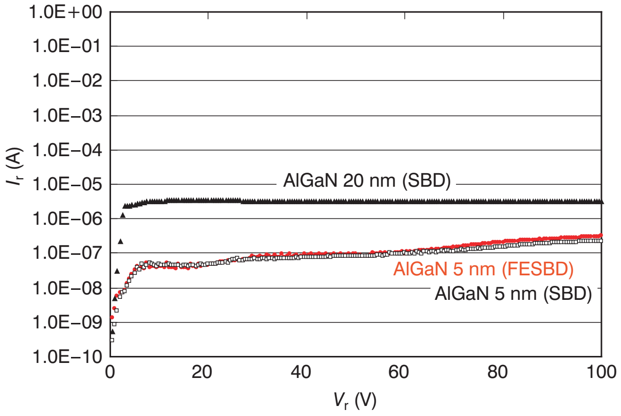


Figure 15 **Difference in reverse characteristics of several structures.**

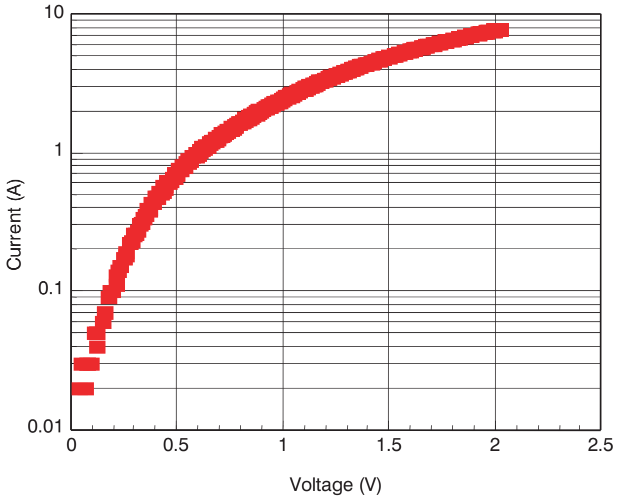


Figure 16 **Forward characteristics of large current FESBD.**

4. CONCLUSION

The normally-off FET and the low on-state voltage diode have been developed using a GaN-based HFET structure on a Si substrate. The reduced-thickness AlGaN structure has been employed to obtain the normally-off FET with a threshold voltage of 0 V. Its pinch-off characteristics are superior and the breakdown voltage is over 300 V. Moreover, the reduced-thickness AlGaN structure has been applied to the FESBD of Furukawa's proprietary structure, thereby realizing a high breakdown-voltage and high-current operation. Hereafter, we intend to apply these devices to various circuits in order to promote developments aimed at realization of high-efficiency power supplies.

REFERENCES

1) T.P. Chow, R. Tyagi, "Wide bandgap compound semiconductors for superior high-voltage unipolar power devices." IEEE Trans Electron Devices, Vol.41, pp.1481-1483, 1994.
2) O. Akutas, Z.F. Fan, S.N. Mohammad, A.E. Botchkarev, H. Morkoç, "High temperature characteristics of AlGaN/GaN modulation doped field effect transistors." Appl Phys Lett, Vol.69, pp.3872-3874, 1996.
3) W. Yang, J. Lu, M. Asifkhan, I. Adesida, "AlGaN/GaN HEMTs on SiC with over 100 GHz fT and low microwave noise." IEEE Trans Electron Devices, Vol.48, pp.581-585, 2001.
4) Seikoh Yoshida, Hirotatsu Ishii, "A high power GaN-based field effect transistor for large current operation." Phys Status Solidi (a), Vol.188, pp.243-246, 2001.
5) Nariaki Ikeda, Kazuo Kato, Jang Le, Kohji Hataya, Seikoh Yoshida," Normally-off operation GaN HFET using a thin AlGaN layer for low loss switching devices." Mater. Res. Soc. Symp. Proc. Vol.831, pp.355-360, 2005.
6) Seikoh Yoshida, Jiang Li, Takahiro Wada, and Hironari Takehara "High-Power AlGaN/GaN HFET with a Lower On-state Resistance and a Higher Switching Time for an Inverter Circuit", in Proc.15th ISPSD, pp.58-61, 2003.
7) V. Kumar, A. Kuliev, T. Tanaka, Y. Otoki, and I. Adesida, Electronics Letters , 39, 24, 1758 (2003).
8) Nariaki Ikeda, Jiang Li, and Seikoh Yoshida, "Normally-off operation power AlGaN/GaN HFET" Proceeding of ISPSD'2004, p.369-372, 2004.
9) Seikoh Yoshida, Nariaki Ikeda, Jiang Li, Takahiro Wada, and Hironari Takehara "A new GaN based field effect schottky barrier diode with a very low on-voltage operation", Proceeding of ISPSD'2004, p.323-326, 2004.