Extended Abstracts of the 2008 International Conference on Solid State Devices and Materials, Tsukuba, 2008, pp. 770-771

G-5-1 (Invited)

# GaN HEMTs "Present Status and Future Prospect"

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## 1. Introduction

The GaN HEMTs have a high breakdown voltage with high cutoff frequency, compared to the other material based devices, leading to high power systems with high efficiency. Figure 1 shows the commonly-used commercialization roadmap of GaN electronic devices. Currently GaN HEMTs for transmitter amplifiers of wireless base stations have been commercialized since 2005. GaN HEMTs for higher frequency application up to X-band have been developed close to commercialization phase. Millimeter-wave amplifiers have also been developed for new markets.

Recently, power electronics using GaN are attracting much attention. In these applications, enhanced-mode operation has been required with high reliability. This commercialization will start after 2010.

In this paper, current device performance all over the world will be addressed. Power and efficiency status will be discussed, which was followed by power electronics status. Then, manufacturing status in Eudyna will be introduced. Finally, future prospect was shown with some recent device developments in Fujitsu.

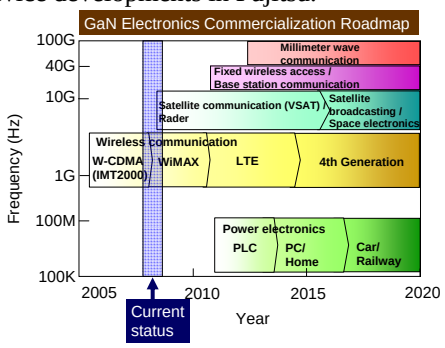


Fig. 1. Commercialization roadmap of GaN HEMT for several applications divided by the frequency.

## 2. Experimental procedures

A specific device structure to achieve high efficiency operation for wireless communication application at 2 GHz was developed. This GaN HEMT consists of MOVPE-grown n-GaN / n-AlGaN / i-GaN structure, which was called surface-charge-controlled structure [1]. Recessed ohmic technique was used to reduce the ohmic contact resistance. SiC substrates were used to obtain good thermal managements.

## 3. Results and discussions

### *Present status of device performance*

Figure 2 (a) shows the trends of output power of GaN HEMTs. An over 1 kW output power could be obtained on SiC substrates [2]. Figure 2 (b) shows power densities with total output power. At the lower output power level, power densities up to 40 W/mm could be available. At the higher output power level over 10 W, power density of 10 W/mm has been the highest power density due to the thermal management issues.

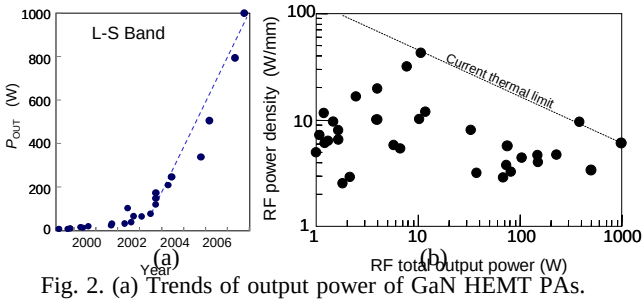


Fig. 2. (a) Trends of output power of GaN HEMT PAs.
(b) Power density vs. total output power.

Next generation networks including mobile WiMAX and LTE will necessitate much higher power efficiency. Table 1 shows the PA efficiency comparison using GaN HEMTs. High maximum efficiency at CW mode could be obtained. Figure 3 shows the drain efficiency using moderation signals as a function of output power. Compared with Si-LDMOS, GaN HEMT showed a higher efficiency, indicating the advantage of GaN HEMT for future PAs.

In the power electronics, the benchmark of the on-resistance as a function of the breakdown voltage is commonly used for comparing materials as shown in Fig. 4. Low on-resistance of less than 10 m$\Omega$cm$^2$ with breakdown voltages of 400-1000 V was obtained using GaN.

Substrates are key technologies to decrease the cost. GaN on Si is a good candidate for realizing low cost. Figure 5 shows the thermal resistance of commercially available GaN HEMTs on Si, compared with those on SiC. GaN HEMTs on SiC showed superior thermal results.

Table 1 Efficiency of PA technologies using GaN HEMT for base station applications around 2 GHz.

| PA type | Maximum efficiency (%) @CW mode | Efficiency (%) @modulation signal |
|---|---|---|
| Class AB | 65-75 [1] | 40 [1] |
| Class D | 78 [3] | — |
| Class E/J | 82 [4] | 45 [4] |
| Class F | 90 [5] | — |
| Class S | — | 90 (without driver) [6]<br>80 (with driver) [6] |
| Doherty | 65-75 [7] | 45-50 [7] |
| Envelop tracking | — | 75 (without ET amp.) [8]<br>55 (with ET amp.) [8] |

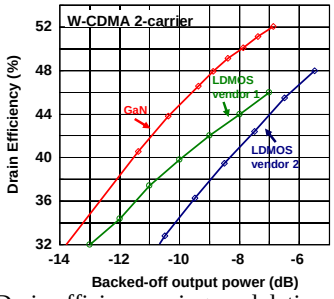


Fig. 3. Drain efficiency using modulation signals.

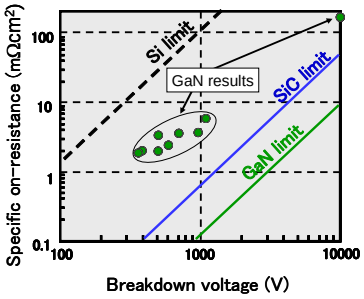


Fig. 4. Benchmark of materials for power electronics.

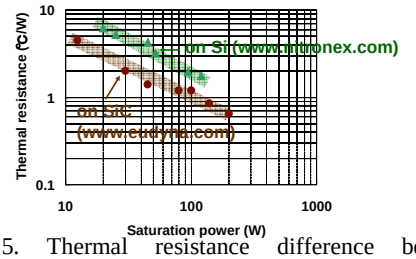


Fig. 5. Thermal resistance difference between substrates.

### *Manufacturing status*

Reliability is the most significant issue to be discussed for manufacturing. First, initial degradation should be improved. Surface defects are related to three terminal pinched-off leakage current as shown in Fig. 6 [9].

Figure 7 shows long term reliability results which were operated at 300°C . Saturation current at Vg of 0 V, $I_{DSS}$, was stable for 3000 h.

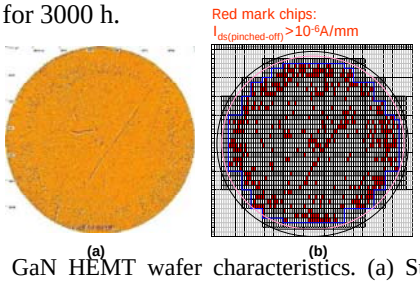


Fig. 6. GaN HEMT wafer characteristics. (a) Surface defect mapping. (b) Three terminal pinched-off leakage current mapping.

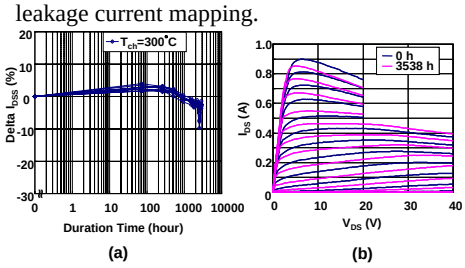


Fig. 7. (a) Long term reliability of $I_{DSS}$ for 3000 h at 300°C. (b) I-V characteristics of degraded device after 3538 h.

### *Future prospect*

Table 2 shows the key features of future GaN technologies for wireless communication and power electronics.

Table 2 Required parameters for future GaN devices.

| Parameters | Current proven technology @2 GHz | Future technology | |
|---|---|---|---|
| | | Wireless > 1 GHz | Power electronics <100 MHz |
| Pinched-off voltage | D-mode | D/E-mode | E-mode |
| Breakdown voltage without collapse (V) | >300 | >100@Lg=0.1μm | >1000 |
| Operation voltage (V) | 50 | > 50@ 2 GHz > 30@>10 GHz | 100～600 |
| $L_g$ (μm) | 0.5～1.0 | 0.1～0.5 | >1.0 |
| Gate | Schottky | MIS | MIS |
| Device type | Lateral | Lateral | Vertical |
| Cost | —— | Too lower | Extremely lower |
| Substrate size (inch) | 3 | 4～6 | 6～8 |

For example, developments of MIS HEMTs and millimeter wave HEMTs were shown in Figs. 8 and 9. The Ta2O5 MIS-HEMTs show the small current collapse, the large gm of 200 mS/mm (Fig. 8) and very low gate-leakage current with a high breakdown voltage BVgd of 400 V. Both a high output power over 100 W and high gain of 16 dB were successfully achieved at 2.5 GHz [10]. For millimeter wave HEMTs, high fmax of 200 GHz was confirmed with a high BVgd of up to 200 V (Fig. 9) [11].

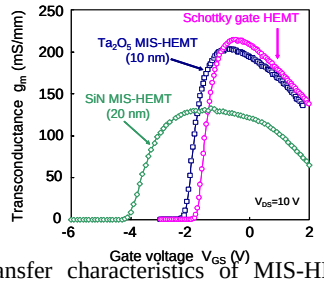


Fig. 8. Transfer characteristics of MIS-HEMTs and Schottky gate HEMT.

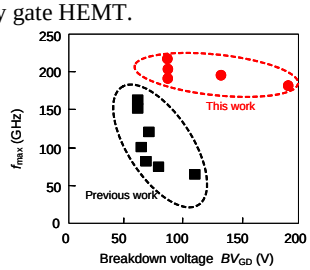


Fig. 9 Benchmark of millimeter-wave GaN HEMTs.

## 3. Conclusions

Commercial products of GaN HEMTs have been available with high reliability. Next generation technologies are currently developed to extend the application area.

**Acknowledgements**

The work in the section of "future prospect" was partially supported by the Ministry of Internal Affairs and Communications, Japan.

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