X-band GaN HEMT and Free-standing GaN Substrate for Marine Radar

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Abstract

We have developed GaN solid-state marine radars that have a number of advantages such as low-power consumption, long-life, non-preheat, and object-tracking in comparison with conventional magnetron radars. A fine-tuned GaN HEMT achieving a power added efficiency of 77.8 % at 9.6 GHz, a 200-W internally-matched FET power amplifier, a solid-state radar module and an X-band marine radar are demonstrated. We also report high-quality GaN-on-GaN HEMTs that can give more low-power consumption and low-cost to marine radars.

INTRODUCTION

AlGaN/GaN HEMTs are currently the first choice among various semiconductors transistors such as GaAs, Si and SiC for high power microwave systems. The reasons are its capability of higher power density (Pd), higher power added efficiency (PAE), and wider bandwidth thanks to a wide bandgap of GaN and two-dimensional electron gas generated by an AlGaN/GaN heterostructure. The largest application is in wireless communications, that is, 5G base stations and satellite communications systems.

GaN HEMTs have also been applied to radar systems where vacuum electron devices (VED) have been used. GaN solid-state power amplifiers (SSPA) can realize a compactness, lightweight, long-life and hot-start RF source, furthermore, can give new radar functions such as a vector detection of a moving object. In marine radars, a magnetron which is one kind of VEDs has been used widely. Although a magnetron has to be exchanged in 5,000 hours, GaN HEMTs having MTTF over 1,000,000 hours are in semipermanent use and can realize a safe navigation due to a tracking of vessels and floating wreckages.

In this paper, we report a high-PAE X-to-Ka band GaN HEMT, a 200-W internally-matched FET (IMFET) power amplifier (PA), a solid-state radar module, and a 96-nautical mile X-band marine radar. Furthermore, in order to achieve great low-power consumption and low-cost, we have also developed GaN HEMTs by replacing the common SiC substrate with a free-standing GaN substrate. High-quality GaN-on-GaN HEMTs showing better current collapse and lower distortion are also reported.

ALGAN/GAN HEMT

We developed a high PAE AlGaN/GaN on SiC HEMT with a gate length (Lg) of 0.2 µm for X-to-Ka band applications. The HEMT is fabricated by well-known conventional and reliable structures and techniques, which are an iron doped buffer layer, an ion-implanted isolation, a Si-implanted ohmic contact region, and a T-shaped gate with a source-connected field plate (SFP). Although those are ordinary in GaN HEMTs, we optimized fabrication processes, epitaxial layers, and electrode layout and design to achieve a high PAE with high reliability. Fig. 1 shows PAE dependency on a length of SFP (Lsfp). A longer SFP can improve the current collapse, but drain-source capacitance (Cds) increases. As a result, PAE has a peak in Lsfp as shown in Fig. 1. The best PAE is 77.8 % at 9.6 GHz at a Lsfp of 0.6 µm.

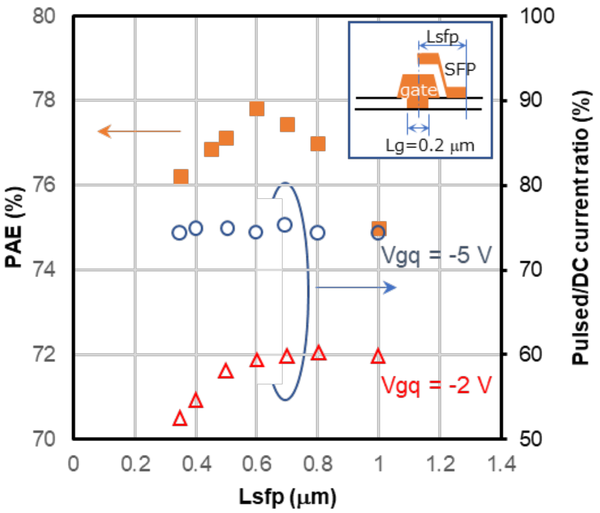

Fig. 1. Effect of Lsfp on PAE and pulsed/DC current ratio. PAE is measured at Vdq = 30 V and 9.6 GHz. Power gain (Gp) is 15.9 dB and power density (Pd) is 3.9 W/mm at the maximun PAE of 77.8 % where Lsfp is 0.6 µm. A gate width (Wgt) is 0.416 mm. Pulsed DC currents are measured at Vd = 5 V and Vg = 2 V.

Current collapse that is indicated by pulsed/DC current ratio is also shown. It is clear that current collapse by semi-on bias (Vgq of -2 V) is improved by a longer SFP, but is saturated at a Lsfp of 0.6 µm where the best PAE is achieved. Current collapse by off bias (Vgq of -5 V) is almost constant 75 % against Lsfp. The results mean that traps working at semi-on bias dominates efficiency.

GaN High Power Amplifier

Several MMIC PAs based on the developed GaN HEMT have been demonstrated from X-band to Ka-band [1]-[4]. We designed and fabricated an X-band 200-W GaN HEMT with a total gate width (Wgt) of 29.6 mm for marine radars. A GF-38 package IMFET PA containing the GaN die and input/output networks having non-uniform comb lines were also designed and fabricated. The networks enable to suppress parasitic oscillations [4]. Fig. 2 shows a measured input-output characteristics at 9.6 GHz. The PA showed an RF output of 240 W and a PAE of 51 %. X-band performance was also measured at marine radar frequencies between 9.36 GHz and 9.46 GHz. A PAE can be hold 47 % over the frequencies at an output power of 270 W. We also developed a 400-W PA containing two GaN dies. The PA showed an RF power of 467 W and the same PAE of 46 % as a 200-W PA between 9.2 and 9.6 GHz. Table I is a comparison of recently reported X-band GaN IMFET PAs.

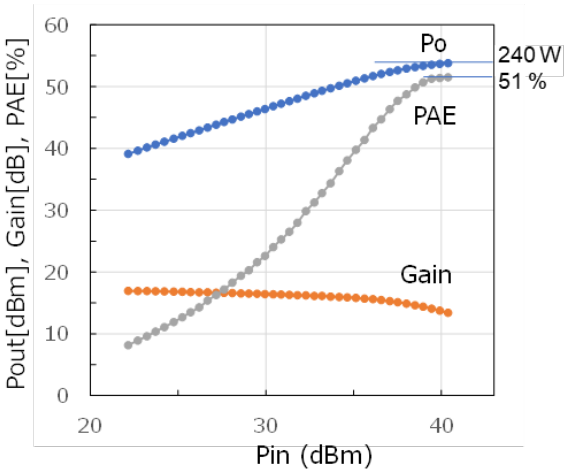

Fig. 2. Measured input-output characteristics of X-band IMFET PA. An output power is 240 W and a PAE is 51 % at 9.6 GHz. Total gate width (Wgt) is 29.6 mm and Vdq is 40 V.

TABLE I Comparison of X-band IMFET PAs.

Ref.	Pout (W)	PAE (%)	Freq. (GHz)
2017 SEI [5]	230	38	8.5-9.8
2020 SEI [6]	340	38	9.3-9.5
2020 Nanjin EDI [7]	550	44	8.2-8.8
This Work	270	47	9.36-9.6
	467	46	9.2-9.6

Solid-State Power Amplifier and Marine Radar

GaN SSPAs can give a number of advantages such as low-power consumption, long-life, non-preheat, and object tracking in comparison with conventional magnetron radars. The tracking realizes safe navigation by Doppler analysis of reflected radar signals identifying vessels at a risk of collision. Doppler analysis is enabled by RF signal with low-phase noise and high stability of frequency from a GaN SSPA.

A SSPA using a 200-W GaN HPA is equivalent with a 25-kW magnetron. A developed GaN SSPA had a power efficiency of 26 % at an output power of 200 W between 9.39 GHz and 9.43 GHz. A power consumption of a 25-kW magnetron and a drive circuit is totally 71 W. The GaN SSPA can decrease a power consumption to 27 W drastically. The size is also reduced. The footprint of a GaN SSPA is a quarter of a magnetron and a circuit. Fig. 3 draws frequency stability of radar pulses from the GaN SSPA and a magnetron. Frequency deviation of the GaN SSPA is 0.15 MHz that is 40 times smaller than a magnetron having 6 MHz. Phase deviation of the GaN SSPA and a magnetron were 4 degree and 450 degree in the center 80 % range of a pulse duration respectively. This high-frequency stability and low-phase noise enables Doppler analysis.

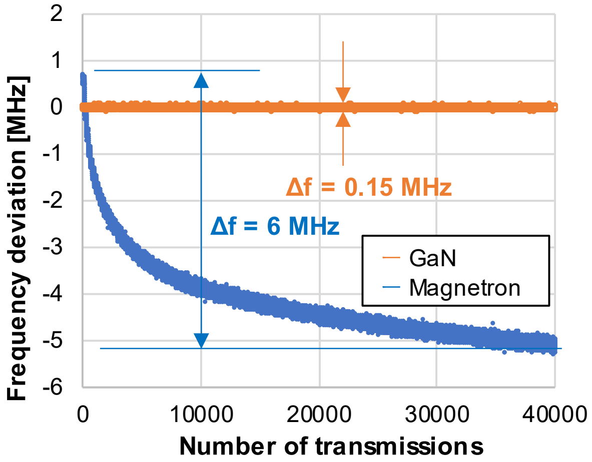

Fig. 3. Frequency deviation of GaN SSPA and magnetron at pulse width of 1.2 µs.

Furthermore, in microwave applications, a narrower bandwidth is expected and unwanted emissions have to be reduced to use limited frequency resource effectively. Fig. 4 is a comparison of frequency spectrum of the GaN SSPA and a magnetron. Occupied bandwidth (OBW) of the GaN SSPA was nearly 60 % narrower than a magnetron at the same pulse width of 1.2 µs.

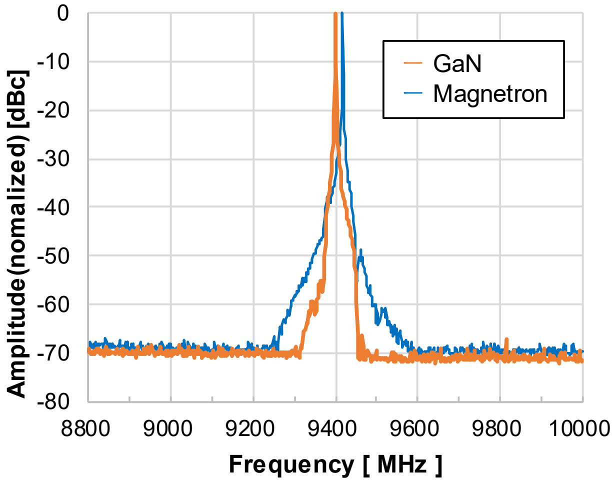

Fig. 4. Radar pulse spectrum. Pulse width is 1.2 μs at the center frequency of 9.4 GHz.

GAN-ON-GAN HEMT

High-power RF GaN HEMTs using a semi-insulated SiC substrate have been commercialized, but a GaN substrate is ideal from a viewpoint of crystalline quality. We counted the number of etch pits originated by threading dislocation on GaN-on-SiC (GoSiC) and GaN-on-GaN (GoG) surfaces. The density of GoG was 3.0 x 10^6 counts/cm^2 that was 1/230 of GoSiC. A part of those dislocations traps electrons and causes performance deterioration, that is current collapse, memory effect, and lags, leading to PAE decreasing and RF signal distortion.

Firstly, we fabricated two-fingers HEMTs with a Lg of 1.0 μm on 15 x 15-mm SiC and GaN substrates to check their performance as a primary test. Fig. 5 shows a pulsed/DC current ratio describing current collapse of GoSiC and GoG. The ratio of GoSiC is steeply degraded at semi-on stress Vgq = -1 V and Vdq = 40 V. On the other hand, there is no significant degradation in GoG. The result indicates that there are less critical traps in high-quality GoG and GoG could achieve higher efficiency. This prediction is supported by Lsfp dependency as described in the former section. Furthermore, less traps suggest that Lsfp could be shortened and achieve higher PAE in GoG.

Nextly, the third-order intermodulation distortion (IM3) and RF power characteristics were evaluated [8]. Fig. 6 shows IM3 at the center frequency (fc) of 2.4 GHz and a spacing frequency (Δf) of 2 MHz. GaN HEMTs were biased shallow-class AB in a linear region. Smaller distortion of GoG than GoSiC was confirmed. RF power characteristics are compared in Fig. 7. The results clearly demonstrate that GoG has better performance than GoSiC, e,g. PAE was 6 points better.

We are currently fabricating a 200-W class AlGaN/GaN on GaN.

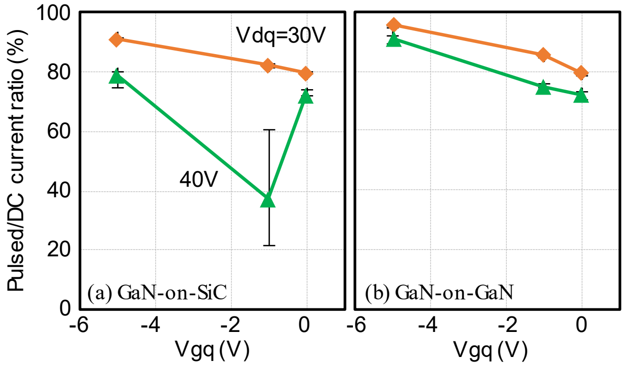

Fig. 5. Pulsed/DC current ratio of (a) GaN-on-SiC and (b) GaN-on-GaN. Pulsed current is measured at Vd = 5 V by 1 μs pulse and duty is 1000.

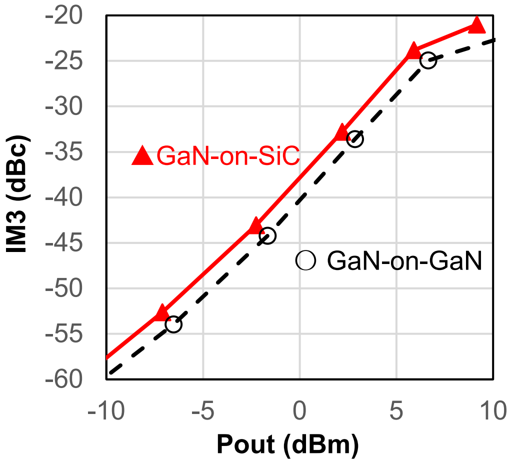

Fig. 6. Third-order intermodulation distortion (IM3) of GaN-on-SiC and GaN-on-GaN. The center frequency is 2.4 GHz and a spacing frequency is 2 MHz. A bias condition is Vdq = 20V and Idq = 75 mA/mm.

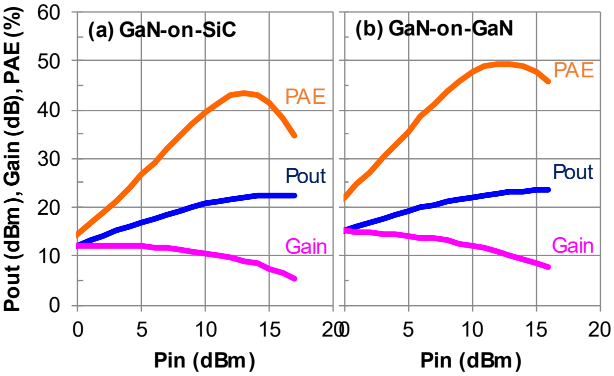

Fig. 7. RF power characteristics of (a) GaN-on-SiC HEMT and (b) GaN-on-GaN HEMT at 2.4 GHz. A total gate width (Wgt) is 0.2 mm. The bias condition is Vdq = 20 V and Idq = 15 mA/mm.

CONCLUSIONS

We have developed GaN solid-state marine radars. An AlGaN/GaN HEMT having the maximum PAE of 77.8 %, a 200-W IMFET PA having the maximum PAE of 51 % and a PAE of 46 % between 9.36 GHz and 9.6 GHz, and a 200-W SSPA having the PAE of 26 % at X-band were demonstrated. Radar pulse spectrum was very clear, which could decrease power-consumption and cost further. We also showed that high-quality GaN-on-GaN HEMTs could achieve higher performance than conventional GaN-on-SiC HEMTs.

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ACRONYMS

HEMT: High Electron Mobility Transistor
FET: Field Effect Transistor
MTTF: Mean Time to Failure
MMIC: Monolithic Microwave Integrated Circuit