

# High PAE and Low Intermodulation Distortion Performance of Newly Developed GaAs FETs Using Ion Implantation Process

Kazutaka Takagi, Hideki Kimura, Tomohito Ohmori, Takuji Yamamura

Microwave Solid-state Engineering Dept, Komukai Operations, Toshiba Corporation  
1, Komukai-Toshiba-cho, Saiwai-ku, Kawasaki, 212-8581, Japan

Kazu.taka@toshiba.co.jp

**Abstract** — Ion-implantation GaAs MESFETs were improved for Ku-band applications. Over 20% of the power added efficiency (PAE) was achieved at -25dBc of third order of intermodulation distortion ratio (IM3) at 14.5GHz. In order to achieve high PAE and low IM3, the carrier profile was designed by using ion-implantations and the transconductance (gm) along the load-line was measured. This PAE was 5% higher than conventional MESFET, HFET and pHEMT.

**Index Terms** — Ion-implantation, GaAs, MESFET, IM3, PAE.

## I. INTRODUCTION

Many kinds of compound semiconductor device structures have been developed for solid-state power amplifiers (SSPAs). They are MESFET, Heterojunction Field-Effect Transistor (HFET) and High Electron Mobility Transistor (HEMT).

MESFET is mostly based on ion-implantation into semi insulating substrates to make the active layers. This is the least expensive process concerning raw material cost, since no epitaxial layers are required.

HFET has a hetero junction that is based on an epitaxial wafer. HEMT also has a hetero junction. That means, HEMT is in the broader category of HFET. HEMT features single- or double-heterojunction transitions that deliver the high electron mobility in the two-dimensional electron gas (2DEG) [1]. In this paper, we used HFET as Heterojunction MESFET, not HEMT. HEMT has an advantage for the gain because of the high electron mobility. HEMT is a suitable device for high frequency applications.

HFETs and HEMTs with over 10W of saturated output power and over 40% of power added efficiency (PAE) have been reported at Ku-band [2]-[4]. The PAE with the intermodulation distortion was not reported.

In L-band, a PAE of 39.5% at -35dBc of the intermodulation of the third order (IM3) was reported [5]. In small output power devices such as those with less than 0.1W, InP HBT with 48% of PAE at -30dBc of IM3 was reported at 10GHz [6].

In this paper, we compare PAEs at -25dBc of IM3 for our MESFETs, HFETs and HEMTs at practical IM3 in Ku-band. The newly developed ion-implantation GaAs MESFET showed the highest PAE.

## II. DEVICE STRUCTURES

Fig.1 shows structures of the devices that we compared. Fig.1-a is a structure of MESFET fabricated by Si-implantation with a buried p-layer formed by Carbon-implantation with n+GaAs regions formed by high Si-implantation for the ohmic contacts. A combination of multi Si-implantations and Carbon-implantation can make various carrier profiles.

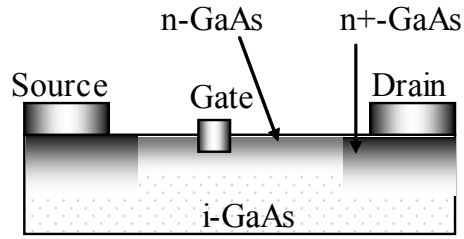
Fig.1-b is a HFET structure fabricated by Si-doped epitaxial GaAs layer and AlGaAs layer, and highly Si-doped epitaxial layer for the ohmic contacts.

Fig.1-c is a HEMT structure which has double-heterojunctions and 2DEGs in InGaAs layer. The InGaAs layer is pseudomorphic, i.e. it is thin enough that the lattice mismatch between InGaAs and GaAs is absorbed by the strain in the InGaAs layer. This type of transistor is called pHEMT. The double-heterojunction structure makes a larger drain current than a single-heterojunction one. For good performance of IM3, it is important to design the concentrations of both AlGaAs layers, above and below the InGaAs layer.

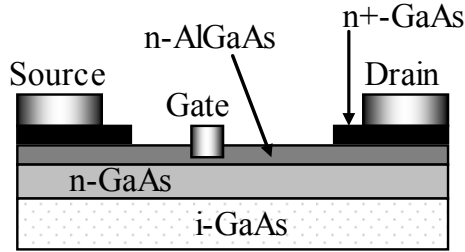
We made three types of device structures to compare the PAE and IM3. One of the MESFET types was a newly developed MESFET, called type-A. MESFET type-B, HFET and pHEMT were our conventional products.

## III. DEVICE DESIGN

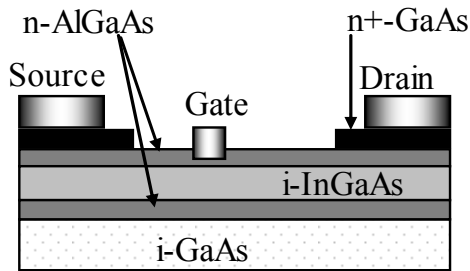
Fig.2 shows the drain current and voltage characteristics of 200 $\mu$ m periphery MESFET type-A and -B when the gate voltage was swept from +1V to -3.5V, 0.5V step. MESFET type-A kept the drain current constant with the drain voltage increased, that was that drain-conductance (gd) was small. The drain current of MESFET type-B increased while the drain voltage increased. The drain current and voltage characteristics of MESFET type-A were able to achieve smaller drain current and higher drain efficiency than that of MESFET type-B. The characteristics of MESFET type-A



(a) GaAs MESFET



(b) AlGaAs/GaAs HFET



(c) InGaAs pHEMT

Fig.1 Device structures of the devices for which we compared the PAE.

were achieved from the tuning co-implantation conditions for Si and C.

To achieve low IM3, the linearity of the gm and the gd are important. Because they depend on the drain voltage and the gate voltage, we should know them along the load-line. To simplify, the load-line in fig.2 was drawn as pure resistance of 250 ohms for the bias point that is 10 V of the drain voltage and 16 mA of the drain current for 200  $\mu\text{m}$  periphery MESFET type-A and -B.

We measured the gm along the load-line. Fig.3 shows the gm with the drain voltage kept at 3 V constant and the gm along the load-line of MESFET type-A and -B. The gm with the drain voltage kept at 3 V constant of MESFET type-B had a wider flat range than that of MESFET type-A. The gm along

the load-line of MESFET type-A is much more linear than that of MESFET type-B. The gm along the load-line of MESFET type-B changed the slope of the decrease around  $-1.2$  V of the gate voltage. It came from an increase of the drain current. On the other hand, MESFET type-A made a linear decrease of the gm from 0 V to  $-2$  V of the gate voltage. This is a result of the tuning of the co-implantation conditions for Si and C.

#### IV. PACKAGED DEVICE DESIGN

The finger lengths of MESFET type-A, type-B and HFET were 100 $\mu\text{m}$ . The total gate widths for each were designed at 20 mm. The finger length of pHEMT was 135  $\mu\text{m}$ . The total gate width of pHEMT was designed at 27 mm. The finger length of the pHEMT was designed longer than others because pHEMT has a high enough gain at 14.5 GHz.

Two dies from each device were assembled with an input internal matching circuit and an output internal matching circuit in each package. The package size was 21 mm by 12.9 mm.

The input and the output impedances were matched at 50 ohm.

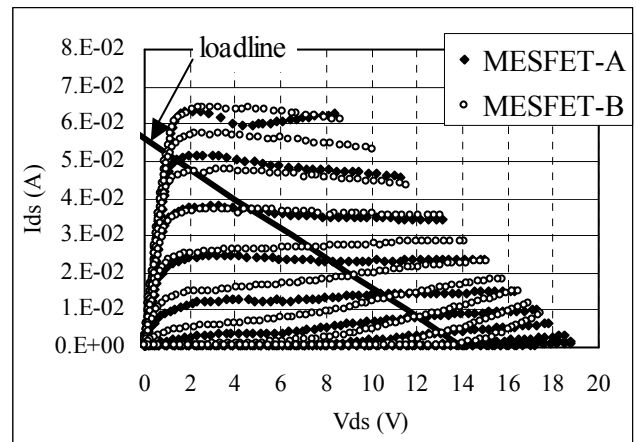
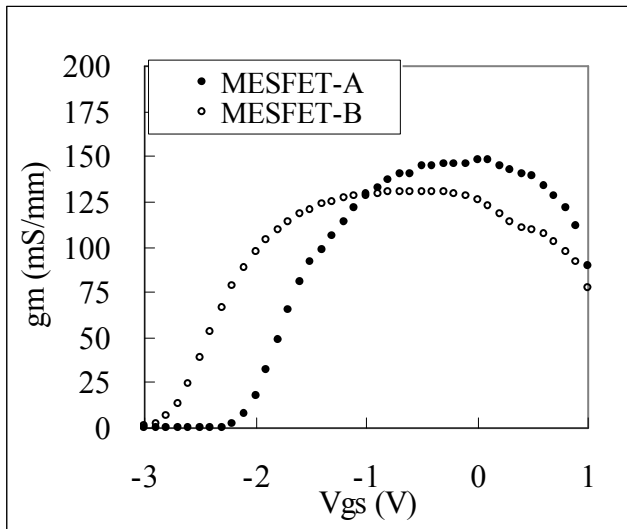
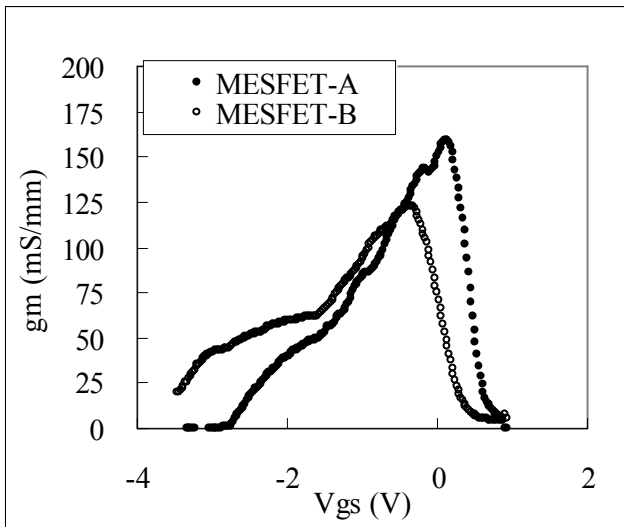


Fig.2 The drain current and voltage characteristics of 100 $\mu\text{m}$  periphery MESFET type-A and type-B with a load-line of 250 ohms.



(a) The gm curves at  $V_{ds}=3$  V constant.



(b) The gm curves along the load-line.

Fig.3 The gm curves of MESFET type-A and -B.

## V. INPUT AND OUTPUT POWER CHARACTERISTICS

Fig.4 shows the input power and output power characteristics and PAE of the packaged devices for single tone. MESFET type-A showed the highest peak of the PAE, 34.2%. But, MESFET type-A showed the second smallest 1dB compression output power (P1dB), 14.5W(41.6dBm) and saturation output power (Psat), 14.8W(41.7dBm). The pHEMT showed the second highest peak of the PAE, 28.9%, and the highest 22.4W(43.5dBm) of P1dB and

23.4W(43.7dBm) of Psat. The HFET showed 27.8% of PAE at the peak, 20.0W(43.0dBm) of P1dB and 20.0W(43.0dBm) of Psat. And The MESFET type-B showed 17.2% of PAE at the peak, 12.3W(40.9dBm) of P1dB and 14.1W(41.5dBm) of Psat.

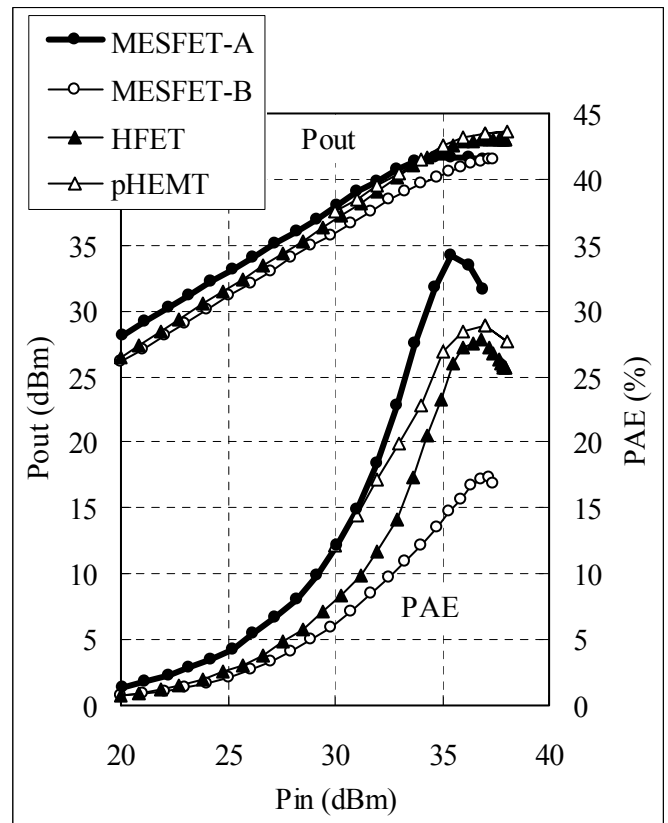


Fig.4 Input and output power characteristics of the packaged devices.

Fig.5 shows IM3 and output power for a single carrier of two tone characteristics of four kinds of devices. MESFET type-A showed 4.5W (36.6dBm) of output power at -25dBc of IM3. The saturation output power of MESFET type-A was the smallest, but the output powers at -25dBc of IM3 were almost the same for all devices. MESFET type-A showed the largest output power, 2.6W (34.1dBm) at -42dBc of IM3 of the four devices. The output power was 6.5dB back-off from P1dB for MESFET type-A. MESFET type-B showed 1.5W (31.7dBm) of the output power at -42dBc of IM3. The output power was 9.7dB back-off for MESFET type-B. MESFET type-A achieved -42 dBc of IM3 with a lower back-off than the others.

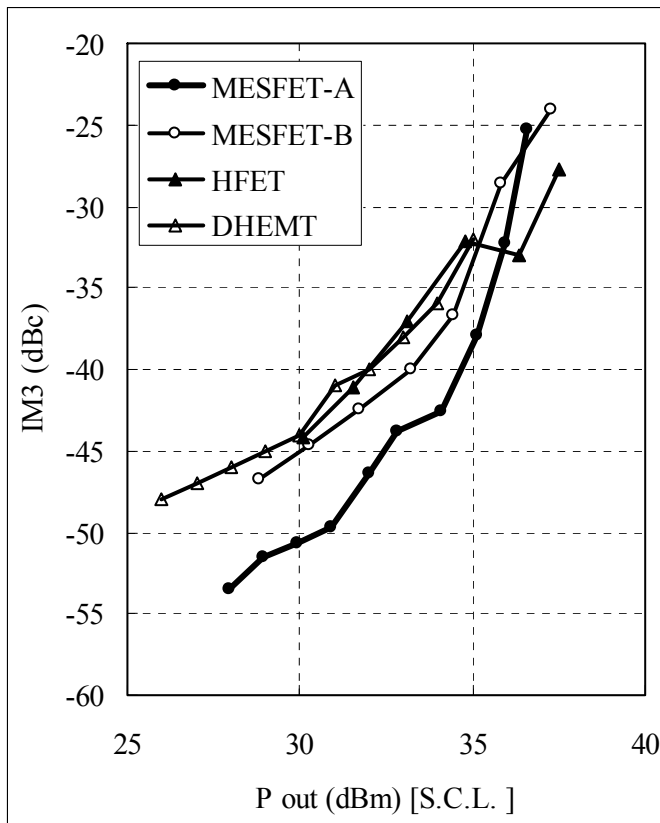


Fig.5 IM3 and output power characteristics of the packaged devices.

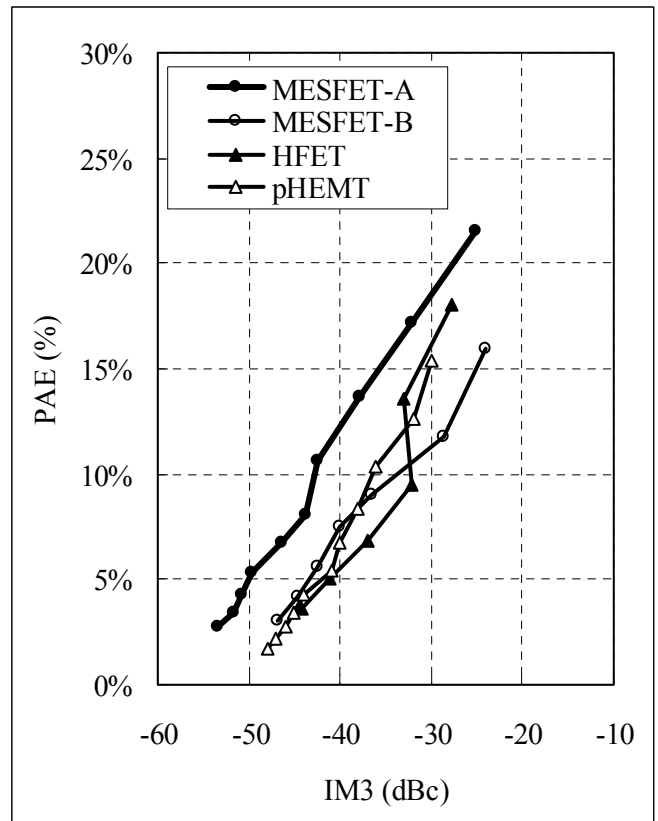


Fig.6 PAE and IM3 characteristics of the packaged devices.

## VI. PAE AND IM3

Fig.6 shows the PAE and IM3 characteristics for four devices. PAE at  $-25\text{dBc}$  of IM3 was 22% for MESFET type-A and 15% for MESFET type-B. The PAE of MESFET type-A was at least 5% higher than the PAE of the others.

## VII. CONCLUSION

A newly developed ion-implantation GaAs MESFET was compared with other structures and showed a higher PAE than the others. The device was designed with the gm along the load-line. As the result, the PAE at  $-25\text{dBc}$  of IM3 was 22%. The output power at  $-25\text{dBc}$  of IM3 was 4.5W (36.6dBm).

## REFERENCES

- [1] William Liu, "Fundamentals of III-V Devices"
- [2] Kohji Matsunaga, Yasuhiro Okamoto and Masaaki Kuzuhara, "Ku-Band 10W High Efficiency HJFET Power Amplifier", 1995 IEEE MTT-S International Microwave Symposium Digest, pp.335-338, 1995.
- [3] Y. Tarui, A. Tsuchiko, M. Kasahara, H. Utsumi, T. Ohshima, and Y. Itoh, "Ku-Band 20W GaAs PHEMT High Power Amplifiers using Power Splitting and Combining Circuits with Asymmetric Structure", 1998 Asia-Pacific Microwave Conference Digest, pp.107-110, 1998.
- [4] K. Mori, J. Nishihara, H. Utsumi, A. Inoue, M. Miyazaki, "X-Band 14W High Efficiency Internally-Matched HFET", 2008 IEEE MTT-S International Microwave Symposium Digest, pp.315-318, 2008.
- [5] K. Otobe, K. Nakata, and S. Nakajima, "Super low-distortion and high power hetero GaAs MESFETs with asymmetrical LDD structure", 2000 Gallium Arsenide Integrated Circuit (GaAs IC) Symposium Digest, pp67-70, 2000.
- [6] L. Kehias, T. Jenkins, T. Quach, P. Watson, R. Welch, R. Worley, A. K. Oki, H. C. Yen, A. Gutierrez-Aitken, W. Okamura, and E. Kaneshiro, "Highest Efficiency, Linear X-Band Performance Using InP DHBTs-48% PAE at 30 dB C/IM3", IEEE Microwave And Wireless Components Letters, vol.11, no.9, September 2001, pp361-363.