2-V-Operation δ-Doped Power HEMT's for Personal Handy-Phone Systems

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***Abstract*— A high-efficiency and high-power-density δ-doped AlGaAs/InGaAs HEMT with low adjacent channel leakage has been developed for the digital wireless personal handy-phone system (PHS). When qualified by 1.9-GHz π/4-shifted quadrature phase shift keying (QPSK) modulated PHS standard signals, the 2.0-V-operation HEMT with a 1-mm gate width demonstrated a power-added efficiency of 45.3% and an output power density of 105 mW/mm. This is the highest power density ever reported by the power transistors for the PHS. The state-of-the-art results for the PHS operating at 2.0 V were achieved by the δ-doped power HEMT for the first time.**

I. INTRODUCTION

THE advanced digital wireless personal handy-phone system (PHS) [1] requires high-performance power transistors with high efficiency and low adjacent channel leakage under π/4-shifted quadrature phase shift keying (QPSK) modulation conditions. Recently, high-performance GaAs MESFET's were used for PHS handsets with a high supplied voltage of 4.8 V [2]. A high operating voltage increases the needs of battery cells and therefore increases the size and the weight of a handset. In order to reduce the operating voltage of PHS handsets, different power field-effect transistors (FET's), such as 3.5-V-operation 2-mm-wide conventional AlGaAs/InGaAs HEMT's [3], 3.0-V-operation 3.6-mm-wide GaAs/InGaAs HEMT's [4], and 3.0-V-operation 4-mm-wide ion-implanted MESFET's [5], [6] were reported. It is noted that either a high operating voltage or a large gate width strongly enhances power performance of FET's. Although a large gate width can compensate the output power and the efficiency greatly reduced by a low operating voltage, it does increase chip area and reduce the number of chips available and device yields. In recent years, a 2.7-V-operation 1-mm-wide ion-implanted MESFET [7] was presented for PHS applications. The output power of 18.4 dBm, however, was not high enough to meet the requirements for the PHS. In this work, a 2.0-V-operation 1-mm-wide δ-doped AlGaAs/InGaAs HEMT was developed for the PHS for the first time. The HEMT, which had the minimum operating voltage and gate width ever reported for the PHS, exhibited high power-added efficiency and high output power density as well as low adjacent channel leakage. This is the first report on the power performance of power HEMT's with a δ-doped structure, qualified by π/4-shifted QPSK modulated signals, for digital wireless communication applications. The developed δ-doped AlGaAs/InGaAs power HEMT not only demonstrated the high performance for the new-generation 2-V-operation PHS cordless phones, but also showed great potential for various advanced low-voltage-operation digital wireless communication applications in the future.

II. HEMT STRUCTURE AND FABRICATION

Fig. 1 shows the δ-doped AlGaAs/InGaAs power HEMT structure used in this work, which was grown by molecular beam epitaxy (MBE) on a 3-in (100)-oriented semi-insulating GaAs substrate. The HEMT had a 10-nm-thick undoped $In_{0.2}Ga_{0.8}As$ channel. A two-dimensional electron gas was formed in the InGaAs quantum well by the electrons transferred from the upper and lower silicon δ-doping layers through the undoped spacers. The δ-doped scheme gave a 30-nm undoped $Al_{0.2}Ga_{0.8}As$ Schottky barrier layer to suppress gate leakage and increase device breakdown voltage. An undoped AlGaAs/GaAs superlattice buffer was employed to improve substrate leakage and reduce output conductance. The Au/Ge/Ni/Au ohmic metals with a total thickness of 400 nm were deposited on the n^+ GaAs cap layer and alloyed by rapid thermal annealing at 310°C for 12 s to obtain a low specific contact resistance below $1 \times 10^{-6}\ \Omega \cdot cm^2$. The eight Ti/Pt/Au gate fingers with a unit finger width of 250 μm were evaporated by an electron gun system. The Au-plating airbridges with a thickness of 2 μm were used to connect the multiple source fingers. A Si_3N_4 passivation film was formed by plasma-enhanced chemical vapor deposition (PECVD) to protect the HEMT and enhance reliability. The backside of the wafer was thinned to a thickness of 50 μm and plated by Au metal to reduce thermal resistance. Fig. 2 shows the fabricated 1-mm-wide HEMT with a 1-μm gate length. The fabricated device was bonded in a ceramic package to assist the thermal dissipation during power measurements.

III. PERFORMANCE

Fig. 3 shows the output power ($P_{\rm out}$) and the power-added efficiency (PAE) as a function of the input power at a drain

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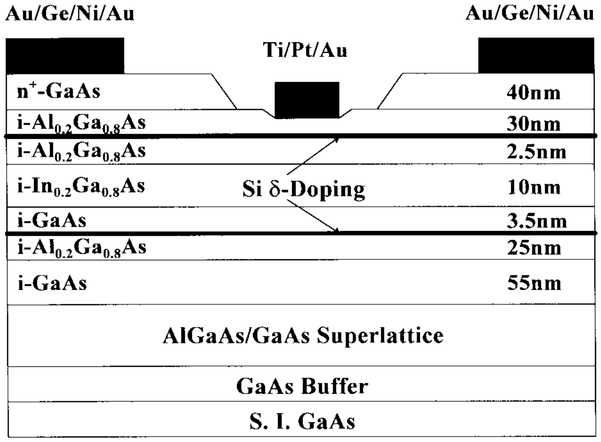

Fig. 1. Structure of the δ-doped AlGaAs/InGaAs power HEMT.

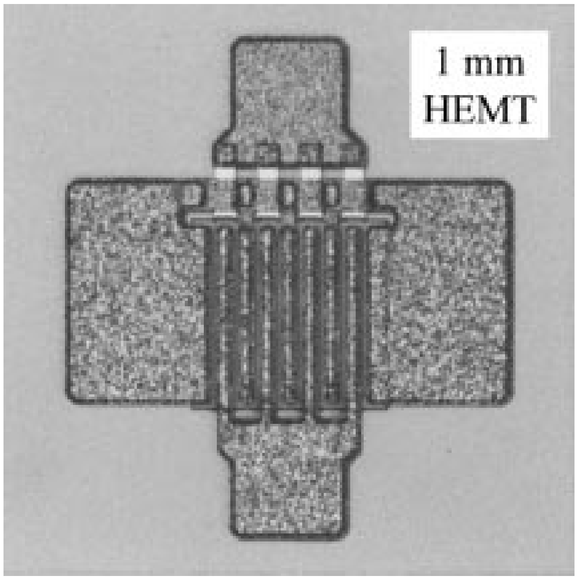

Fig. 2. Photograph of the fabricated 1-mm-wide δ-doped AlGaAs/InGaAs power HEMT.

voltage (V_{ds}) of 2.0 V. The dependence of the drain current (I_{ds}) on the input power is also depicted. The radio frequency (RF) input signals for the power measurements were the π/4-shifted QPSK modulated PHS standard signals with a center frequency of 1.9 GHz. The data rate of the input signals was 384 kb/s. The HEMT was operated at the class AB condition with a quiescent drain current of 97 mA [20% of a maximum drain current ($I_{\max}$)]. The I_{ds} remained stable and almost constant in a range from 97 to 100 mA during RF input power swing. The 1-mm HEMT exhibited a PAE of 40% at $P_{\text{out}} = 19$ dBm. The PAE reached to 45.3% when the P_{out} increased to 20.2 dBm (105 mW/mm). The power performance of the HEMT is better than that of 2.7-V-operation 1-mm MESFET's (PAE $=$ 26.4% at $P_{\text{out}} = 18.4$ dBm (69.2 mW/mm) [7]). The power characteristics of the δ-doped HEMT are even comparable to those of power FET's with a high operating voltage and a large gate width, such as 3.5-V-operation 2-mm HEMT's (PAE $=$ 34.2% at $P_{\text{out}} = 21.5$ dBm (70.6 mW/mm) [3]), 3.0-V-operation 3.6-mm HEMT's (PAE $=$ 53.5% at $P_{\text{out}} = 20.4$ dBm (30.5 mW/mm) [4]), and 3.0-V-operation 4-mm MESFET's (PAE $=$ 37% at $P_{\text{out}} = 23.6$ dBm (57.3 mW/mm) [5] and PAE $=$ 47% at $P_{\text{out}} = 22$ dBm (39.6 mW/mm) [6]). The δ-doped HEMT had the higher PAE and output power density than the most high-voltage-operation FET's [3], [5]. Although the PAE of the developed 1-mm HEMT biased at $V_{ds} = 2.0$ V is lower than those of the 3.6-mm HEMT's [4] and the 4-mm MESFET's [6] biased at $V_{ds} = 3.0$ V, the output power density of the fabricated 2.0-V-biased HEMT is much higher than those of the 3.0-V-biased FET's. The δ-doped HEMT has demonstrated the highest output power density ever reported for the PHS. Both the high output power density and the high PAE were attributed to the δ-doped AlGaAs/InGaAs HEMT structure which provided an $I_{\max}$ of 485 mA/mm (at a gate voltage of $+0.5$ V) and a transconductance (g_m) of 310 mS/mm. The gate-to-drain breakdown voltage (BV_{gd}) of the HEMT was 18 V. The δ-doped carrier supply scheme, the high-mobility-carrier transport property in the InGaAs quantum well, and the large conduction-band discontinuity at the AlGaAs/InGaAs/GaAs heterointerfaces led to the high $I_{\max}$ and the high g_m of the HEMT and enhanced the power performance at the low operating voltage.

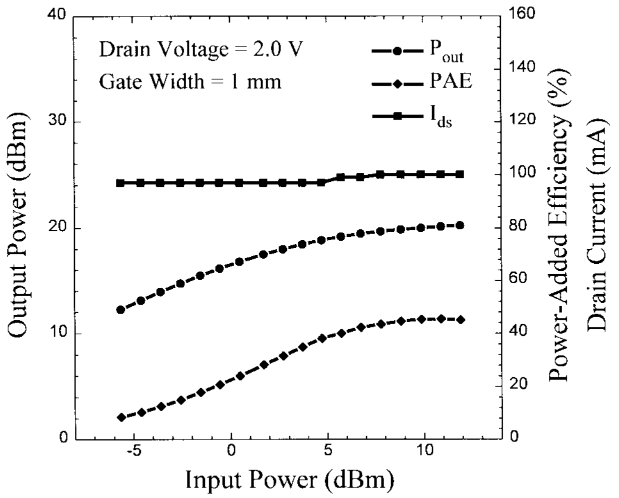

Fig. 3. Output power (P_{out}), PAE, and drain current (I_{ds}) as a function of input power for the 1-mm-wide δ-doped power HEMT at a drain voltage of 2.0 V. The RF input signals are the 1.9-GHz π/4-shifted QPSK modulated PHS standard signals.

Fig. 4 depicts the dependence of the adjacent channel leakage power (P_{adj}) on the P_{out} of the HEMT to reflect the actual channel interference and spectrum regrowth for the PHS. Under the conditions of $V_{ds} = 2.0$ V and $P_{\text{out}} = 19$ dBm, the P_{adj} measured at 600 and 900 kHz apart from the 1.9-GHz center frequency were -55.2 and -61 dBc, respectively. The low adjacent channel interference at the 2.0-V drain voltage for the PHS was achieved by the δ-doped AlGaAs/InGaAs power HEMT for the first time. The low-interference property associated with the high PAE and the high output power density was measured by the source-pull and load-pull methods. The source impedance and load impedance for the optimum power performance of P_{adj}, PAE, and P_{out} at $V_{ds} = 2.0$ V were $Z_S = 8.21 + j15.86\ \Omega$ and $Z_L = 25.78 + j1.43\ \Omega$, respectively.

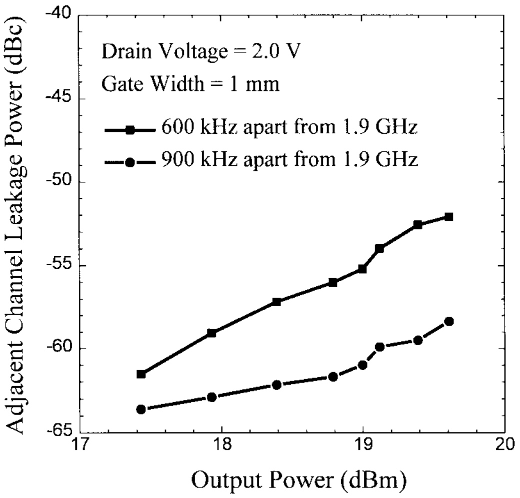

Fig. 4. Adjacent channel leakage power as a function of output power for the 1-mm-wide δ-doped power HEMT at a drain voltage of 2.0 V. The RF input signals are the 1.9-GHz π/4-shifted QPSK modulated PHS standard signals.

The most significant result in this work is that the excellent power performance for the PHS including the low $P_{\rm adj}$ and the high PAE as well as the high output power density is accomplished by the low-voltage-operation HEMT with the small gate width. Therefore, the problems of a high operating voltage and a large gate width are eliminated. The 2-V-operation HEMT developed is a potential candidate for the portable wireless handsets with dual NiMH or NiCd rechargeable battery cells.

IV. CONCLUSIONS

A δ-doped AlGaAs/InGaAs power HEMT was first developed for PHS applications. The HEMT exhibited an $I_{\max}$ of 485 mA/mm and a g_m of 310 mS/mm. The BV_{gd} was 18 V. When measured by π/4-shifted QPSK modulated signals, the HEMT demonstrated a PAE of 45.3% and an output power density of 105 mW/mm at a 2.0-V drain bias. The $P_{\rm adj}$ at 600 kHz apart from 1.9 GHz was -55.2 dBc at $P_{\rm out} = 19$ dBm. The outstanding performance of the HEMT at the low operating voltage was attributed to the optimum δ-doped AlGaAs/InGaAs power HEMT structure which demonstrated great potential for future-generation digital wireless communication applications.

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