# High-Efficiency and Low-Distortion Directly-Ion-Implanted GaAs Power MESFET's for Digital Personal Handy-Phone Applications

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***Abstract*—We report a high-efficiency and low-distortion GaAs power MESFET using direct ion implantation technology for the digital wireless personal handy-phone system (PHS). When qualified by 1.9-GHz $\pi$/4-shifted quadrature phase shift keying (QPSK) modulated PHS standard signals, the 2.2-V-operation device with a gate width $(W_g)$ of 2 mm exhibited a power-added efficiency (PAE) of 57.2% and an adjacent channel leakage power $(P_{\rm adj})$ of $-58$ dBc at an output power of 21.3 dBm. The MESFET with the optimized direct ion implantation conditions and fabrication process achieved the highest PAE for PHS applications. The low-cost MMIC-oriented direct ion implantation technology has demonstrated the state-of-the-art results for new-generation PHS handsets for the first time.**

## I. Introduction

HIGH-PERFORMANCE power transistors with high power-added efficiency (PAE) and low adjacent channel leakage power $(P_{\rm adj})$ under $\pi$/4-shifted quadrature phase shift keying (QPSK) modulation conditions are very important for the advanced digital wireless communication applications, such as the personal handy-phone system (PHS) [1]. Recently, epitaxy-grown power HEMT's, including 3.5-V-operation conventional AlGaAs/InGaAs HEMT's (PAE = 34.2%) [2] and 3-V-operation GaAs/InGaAs HEMT's (PAE = 53%) [3], exhibited good performance for PHS applications. However, the epitaxial devices have the disadvantages of complicated epitaxy structure, difficult uniformity control, and high wafer costs, which cause negative impact on manufacturing yields and production costs. Ion implantation is an efficient approach to increase the yields and reduce the costs for device fabrication. Ion-implanted GaAs MESFET's [4]–[6] were presented for 3-V-operation PHS applications. The PAE of these MESFET's was in the range from 26.4% to 47%. The reported HEMT's and MESFET's for the PHS are suitable for the handsets with a single cell of 3.6-V Li-ion battery. The operating voltage of PHS handsets needs to be further reduced to lower the power consumption of handsets and extend the lifetime of batteries.

In recent years, directly-ion-implanted (DII) GaAs MESFET's [7] were demonstrated for low-noise applications. The high drain current-voltage product of DII MESFET's [8] also showed potential for power applications. In this work, we developed a DII GaAs power MESFET operating at 2.2 V for the power amplifiers of next-generation PHS handsets [9] with double cells of 1.2-V NiMH rechargeable battery. When qualified by $\pi$/4-shifted QPSK modulated signals, the MESFET with the minimum operating voltage ever reported for the PHS exhibited a PAE of 57.2% and a $P_{\rm adj}$ of $-58$ dBc at an output power $(P_{\rm out})$ of 21.3 dBm. The best PAE performance associated with the low $P_{\rm adj}$ at a 2.2-V operating voltage for the PHS was, for the first time, achieved by the GaAs power MESFET using direct ion implantation technology. This high-yield and low-cost technology is promising for mass production of GaAs power MMIC's for advanced low-voltage-operation digital wireless communication applications.

## II. Device Fabrication

The GaAs power MESFET developed was fabricated by three direct ion implantations into a 3-in (100)-oriented semi-insulating GaAs substrate. The channel implantation was formed by the $^{29}Si^+$ ion implantation with an energy of 175 keV and a dosage of $6.2 \times 10^{12}$ cm$^{-2}$. The surface implantation was formed by the $^{29}Si^+$ ion implantation at 25 keV and $1.2 \times 10^{12}$ cm$^{-2}$. The $Be^+$ ion implantation with an energy of 160 keV and a dosage of $1.6 \times 10^{12}$ cm$^{-2}$ was carried out for formation of the p-buried layer. After ion implantation, the wafer with 0.2-$\mu$m-thick silicon nitride capping films was annealed using rapid thermal annealing (RTA) at 940 °C for activation of the implanted ions. The 0.4-$\mu$m thick Au/Ge/Ni/Au ohmic metal was deposited by an electron-beam evaporation system followed by 295 °C rapid thermal annealing. An optimized double gate recess process using citric acid solutions was used to accurately control the drain current and obtain a high breakdown voltage. The 0.5-$\mu$m-thick Ti/Pt/Au gate with a length of 1 $\mu$m and a width

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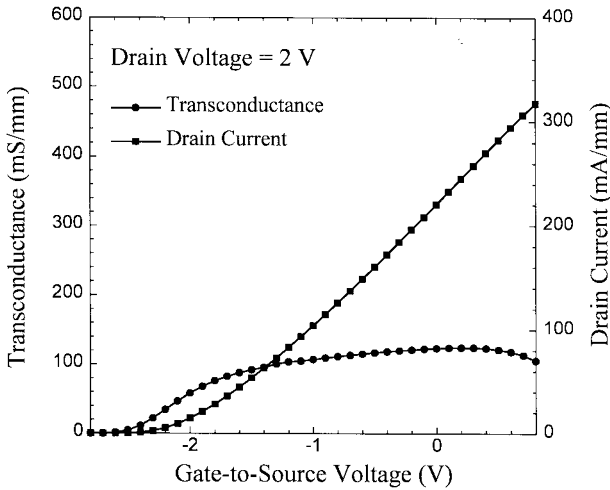


Fig. 1. Transconductance and drain current as a function of gate-to-source voltage for the directly-ion-implanted GaAs power MESFET.

of 2 mm was defined by the standard photolithography. The device was passivated by the $Si_3N_4$ films for device protection and reliability enhancement. The backside of the wafer was thinned to a thickness of 50 $\mu$m for via-hole process and then plated by Au metal to reduce thermal resistance.

## III. DC and Power Performance

Fig. 1 shows the transconductance ($g_m$) and the drain current ($I_{ds}$) as a function of gate-to-source voltage ($V_{gs}$) at a drain voltage ($V_{ds}$) of 2 V. The $g_m$ was near-constant around 120 mS/mm in a $V_{gs}$ range between $-1.8$ V and $+0.8$ V. The pinch-off voltage ($V_p$) was approximately $-2.4$ V. The $I_{ds}$ at a $V_{gs}$ of 0 V and a $V_{ds}$ of 2 V, was 440 mA. The effective knee voltage ($V_{knee}$) [10], defined as the $V_{ds}$ value when the $I_{ds}$ became 100 mA/mm with $V_{gs} = +0.5$ V, was 0.3 V. The gate-to-drain breakdown voltage ($BV_{gd}$), defined at a gate-to-drain current ($I_{gd}$) of $-1$ mA/mm, was 29 V. The constant $g_m$, low $V_{knee}$, and high $BV_{gd}$ directly resulted from the optimized ion implantation profile and the fabrication process. The $^{29}Si^+$ surface and channel ion implantation associated with appropriate ohmic metallization accomplished the low $V_{knee}$. The $Be^+$ implanted p-buried layer compensated the tail of n-channel implantation and enhanced the $g_m$ characteristics. The current-leakage and pinch-off problems of the DII MESFET's without buried-layer implantation [7], [8] were improved. This led to a high $BV_{gd}$. Furthermore, the double-recess gate structure spread the electric field between gate and drain and alleviated the breakdown effect [11]. The recess shape with an optimized depth and lateral expansion was used to achieve a high $BV_{gd}$ while keeping a sufficiently high $I_{ds}$ [12]. The excellent dc performance of $V_{knee}$, $I_{ds}$, $g_m$, and $BV_{gd}$ benefited the rf power performance of the MESFET.

The power characteristics of the DII GaAs MESFET were measured by a computer-controlled power tuning system, in which the $\pi$/4-shifted QPSK modulated PHS standard signals were generated through the inphase (I) and the quadrature phase (Q) signal channels. The device operated at a drain bias of 2.2 V and under the class AB condition with a quiescent drain current of 99 mA. The bit rate of the input signals was 384 kb/s. Fig. 2 shows the $P_{out}$, the PAE, and the $P_{adj}$ of the device as a function of the input power. The 2-mm MESFET exhibited a PAE of 57.2% at $P_{out} = 21.3$ dBm (67.4 mW/mm). The associated $P_{adj}$ measured at 600 kHz apart from the 1.9 GHz center frequency was $-58$ dBc. The PAE became 61.7% and the $P_{adj}$ was $-50.8$ dBc when the $P_{out}$ increased to 21.9 dBm (77.4 mW/mm). When the operating voltage of the MESFET dropped to 2.0 V, the PAE was 55.8% and the $P_{adj}$ was $-52$ dBc at a $P_{out}$ of 20 dBm. The specifications of PHS handsets require a $P_{out}$ of 19 dBm with a $P_{adj}$ less than $-50$ dBc for signal transmission [2]. The 2.2-V-operation DII GaAs power MESFET demonstrated excellent power performance for power amplifiers of PHS handsets and provided sufficient margin for loss and degradation of circuits. The power characteristics of the 2.2-V-operation ion-implanted GaAs MESFET, in terms of the PAE, $P_{adj}$ and output power density, are comparable to those of high-voltage-operation epitaxy-grown HEMT's, such as 3.5-V-operation 2-mm conventional AlGaAs/InGaAs HEMT's (PAE = 34.2% and $P_{adj} = -58.1$ dBc at $P_{out} = 21.5$ dBm (70.6 mW/mm)) [2] and 3.0-V-operation 3.6-mm GaAs/InGaAs HEMT's (PAE = 53.5% and $P_{adj} = -60$ dBc at $P_{out} = 20.4$ dBm (30.5 mW/mm)) [3]. The power characteristics of the developed ion-implanted GaAs MESFET are also comparable to those of ion-implanted MESFET's with different structures, such as 3.0-V-operation 4-mm BP-LD$^3$ GaAs MESFET's (PAE = 37% and $P_{adj} = -55$ dBc at $P_{out} = 23.6$ dBm (57.3 mW/mm)) [4], 3.0-V-operation 4-mm selectively-ion-implanted GaAs MESFET's (PAE = 47% and $P_{adj} = -61$ dBc at $P_{out} =$ 22 dBm (39.6 mW/mm)) [5], and 2.7-V-operation 1-mm self-aligned GaAs MESFET's (PAE = 26.4% at $P_{out} = 18.4$ dBm (69.2 mW/mm)) [6]. Table I shows the comparison of power performance of the DII GaAs MESFET with that of the power

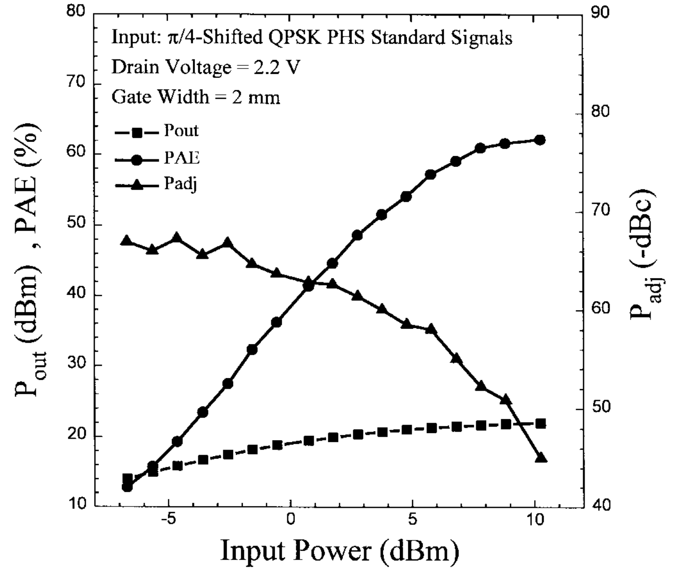


Fig. 2. Output power ($P_{out}$), power-added efficiency (PAE), and adjacent channel leakage power ($P_{adj}$) as a function of input power for the directly-ion-implanted GaAs power MESFET at a drain voltage of 2.2 V. The rf input signals are the 1.9-GHz $\pi$/4-shifted QPSK modulated PHS standard signals.

TABLE I
COMPARISON OF POWER PERFORMANCE OF THE DII GaAs MESFET WITH THAT OF THE POWER TRANSISTORS PREVIOUSLY REPORTED FOR THE PHS

| Device | $V_{ds}$ (V) | Wg (mm) | PAE (%) | $P_{adj}$ (dBc) | $P_{out}$ (dBm) | $P_{out}$ Density (mW/mm) | Reference |
|---|---|---|---|---|---|---|---|
| AlGaAs/InGaAs HEMT | 3.5 | 2 | 34.2 | -58.1 | 21.5 | 70.6 | [2] |
| GaAs/InGaAs HEMT | 3.0 | 3.6 | 53.5 | -60 | 20.4 | 30.5 | [3] |
| BP-LD[3] GaAs MESFET | 3.0 | 4 | 37 | -55 | 23.6 | 57.3 | [4] |
| Selectively-Ion-Implanted GaAs MESFET | 3.0 | 4 | 47 | -61 | 22 | 39.6 | [5] |
| Self-Aligned GaAs MESFET | 2.7 | 1 | 26.4 | - | 18.4 | 69.2 | [6] |
| Directly-Ion-Implanted GaAs MESFET | 2.2 | 2 | 57.2 | -58 | 21.3 | 67.4 | This Work |

transistors previously reported for the PHS. It should be noted that the developed MESFET with the minimum operating voltage ever reported for PHS applications has demonstrated the highest PAE. The most significant result in this work is the simultaneous achievements of high PAE, low $P_{\rm adj}$, and high output power density at a low operating voltage using the simple direct ion implantation technology. The p-buried layer with the $Be^{+}$ ions suppressed the deep-level trapping, improved the substrate leakage, and reduced the output conductance of the devices, which led to stable power matching and enhanced the $P_{\rm out}$ and the PAE.

The power characteristics of high PAE, low $P_{\rm adj}$, and high output power density were obtained by the rf power matching with the source-pull and load-pull methods. The input and output tuners with variable capacitors and inductors were adjusted for the optimum performance of PAE, $P_{\rm adj}$, and output power density with regard to the $\pi$/4-shifted QPSK input signals. The optimum source impedance $(Z_S)$ and load impedance $(Z_L)$ were 4.8 + j20.1 Ω and 22.5 + j7.5 Ω, respectively. These power matching data for circuit design combined with the DII power MESFET technology can be used to fabricate power MMIC's for new-generation PHS handsets.

Moreover, the ion-implantation conditions and the gate-recess target of the DII GaAs power MESFET can be further adjusted to obtain a low $I_{\rm ds}$ at a $V_{\rm gs}$ of 0 V while keeping a low $V_{\rm knee}$ and sufficient $BV_{\rm gd}$ to achieve a low power dissipation at the standby mode and high power efficiency at the active mode for a single-voltage-supply MMIC power amplifier.

The direct ion implantation technology has the advantages of simple process, high throughput, high uniformity, and low costs for manufacture. We have demonstrated that this technology has great potential for mass production of GaAs power MMIC's for advanced digital wireless communication applications.

## IV. CONCLUSIONS

A high-efficiency and low-distortion 2.2-V-operation GaAs power MESFET for PHS applications has been developed using direct ion implantation technology for the first time. The MESFET exhibited a flat $g_m$ around 120 mS/mm and a high $BV_{\rm gd}$ of 29 V. The $V_p$ was −2.4 V. When measured by $\pi$/4-shifted QPSK modulated signals, the device demonstrated a PAE of 57.2% and a $P_{\rm adj}$ of −58 dBc at $P_{\rm out} = 21.3$ dBm. The excellent power performance was attributed to the optimized direct ion implantation conditions and fabrication process. The low-cost DII power MESFET technology has not only demonstrated high performance for new-generation PHS handy phones but also showed great potential for various low-voltage-operation digital wireless communication applications.

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