A Pseudomorphic AlGaAs/n$^+$-InGaAs Metal-Insulator-Doped Channel FET for Broad-Band, Large-Signal Applications

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***Abstract*—We demonstrate MBE-grown L_g = 1.7-μm pseudomorphic $Al_{0.38}Ga_{0.62}As/n^+$-$In_{0.15}Ga_{0.85}As/GaAs$ metal-insulator-doped channel FET's (MIDFET's) displaying extremely broad plateaus in both f_T and $f_{\max}$ versus V_{GS}, with f_T sustaining 90% of its peak over a gate swing of 2.6 V. Drain current is highly linear with V_{GS} over this swing, reaching 514 mA/mm. We find no frequency dispersion in g_m up to 3 GHz, indicating the absence of electrically active traps in the undoped AlGaAs pseudoinsulator layer. These properties combine to make the pseudomorphic MIDFET highly suited to linear, large-signal, broad-band applications.**

RECENT experiments on GaAs-based heterostructures have demonstrated that the metal-insulator-doped channel FET (MIDFET) can match many key figures of merit of the modulation-doped FET (MODFET) while avoiding several of its inherent drawbacks [1]. In particular, by removing all donors from the gate pseudoinsulator and placing them in the heavily doped channel layer, the MIDFET achieves a very large breakdown voltage V_B and a high transconductance g_m over an extremely broad gate-source voltage V_{GS} swing [2], [3], free from collapse due to pseudoinsulator donor-state filling [4]. As a result of the g_m plateau and extended forward gate bias, the MIDFET realizes high linearity in drain current I_D versus V_{GS} and very large values of both I_D and channel electron sheet density n_s [2], [3]. These features are further enhanced by using a pseudomorphic InGaAs channel to improve channel electron confinement [5], [6], and combine to make pseudomorphic MIDFET's well suited for a very important class of linear and high-power telecommunications applications including efficient microwave power amplifiers [7] and laser-diode drivers.

In this study, we experimentally demonstrate the pseudomorphic AlGaAs/n$^+$-InGaAs MIDFET's unique suitability for large-signal, broad-band operation, an area in which the MODFET exhibits severe limitations. We have fabricated devices with extremely broad plateaus in the V_{GS} dependence of g_m, f_T, and $f_{\max}$, directly attributable to electron velocity saturation in the channel maintained over most of the useful gate swing. These plateaus are in contrast with the highly peaked characteristics of the MODFET [8], [9] and permit both accurate reproduction of large-signal, high-frequency transients as well as flexible circuit biasing. In addition, our devices show an almost complete lack of frequency dispersion in g_m, permitting extremely broad-band operation and indicating the absence of electrically active, deep-level traps in the undoped AlGaAs pseudoinsulator layer. Such dispersion is intrinsic to MODFET's [10] and has also been observed in MIDFET's reported to date [11].

The MBE-grown heterostructure, shown in Fig. 1, consists, from top to bottom, of a 50-Å GaAs cap, a 300-Å $Al_{0.38}Ga_{0.62}As$ gate pseudoinsulator, a 150-Å n^+-$In_{0.15}Ga_{0.85}As$ channel ($N_d = 4 \times 10^{18}$ cm^{-3}), a 100-Å GaAs electron confinement layer, a 1000-Å $Al_{0.38}Ga_{0.62}As$ buffer/confinement layer, and a 1000-Å GaAs buffer, grown on a semi-insulating (100) GaAs substrate. Growth takes place under typical As-stabilized overpressure conditions using an As cracker, with an initial substrate temperature of 580°C maintained through the completion of the AlGaAs buffer. The substrate temperature is then ramped down during growth of the GaAs back confinement layer, reaching 530°C by the start of the InGaAs channel. A reduced temperature is necessary in order to avoid In reevaporation during channel growth and thus to obtain accurate temperature-insensitive InAs mole fraction control in that layer. This relatively low temperature is maintained for the remainder of the growth. Although previous studies have indicated that high-quality AlGaAs growth requires temperatures above 600°C [12], [13], we are able to obtain excellent AlGaAs crystal quality here at 530°C, possibly due to our use of a pre-cracked As source or to a low concentration of chamber impurities. High-purity growth in our Varian GEN II MBE growth system has been previously demonstrated. We have achieved two-dimensional electron gas mobilities of over 1×10^6 cm^2/V · s at 4.2 K in structures with a relatively

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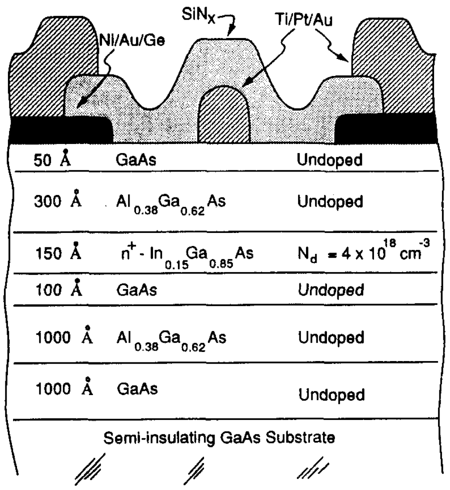

Fig. 1. Schematic cross section of the pseudomorphic $Al_{0.38}Ga_{0.62}As/n^+$-$In_{0.15}Ga_{0.85}As/GaAs$ MIDFET.

small 200-Å spacer as well as record low threshold currents of 0.35 mA in patterned quantum-well lasers [14].

Low-frequency and T-gate microwave MIDFET's as well as diodes and a variety of test structures are fabricated using a non-self-aligned five-mask process with double-level metal and dielectric passivation. After a mesa etch for device isolation, we evaporate and pattern Ni/Au/Ge ohmic contacts and alloy them by RTA at 420°C for 10 s. We then form a Ti/Pt/Au gate-interconnect layer, followed by LPCVD deposition of 1750 Å of SiN_x at 190°C for passivation and intermetal isolation. Next, we etch via holes and pad openings in the dielectric using HF, and conclude fabrication with a final Ti/Pt/Au pad/interconnect layer. Our process provides high yields, permitting fabrication of working circuits as complex as a 13-stage ring oscillator. As a result, we report all data as statistical averages over many devices, unless otherwise stated.

Fig. 2 shows g_m and I_D versus V_{GS} for $L_g = 1.7$-μm and $W_g = 30$-μm MIDFET's at $V_{DS} = 3.5$ V, obtained through a pointwise computer averaging of 20 randomly selected devices. We observe a peak g_m of 165 ± 5 mS/mm, with g_m maintaining over 90% of this value over a broad gate swing of 1.65 ± 0.11 V (tolerances are one standard deviation). By injecting current from gate to source with floating drain and measuring V_{DS}, we extract $R_s = 1.53 \pm 0.10\ \Omega \cdot$ mm, yielding an intrinsic $g_{m0} = 222 \pm 11$ mS/mm. Drain current is highly linear with V_{GS} over the g_m plateau, reaching a maximum of 514 ± 17 mA/mm, the velocity saturation current limit of the extrinsic channel [3]. This linearity is highly desirable for power applications. The breakdown voltage is 19.4 V, defined as the value of V_{DS} at which $I_D = 1$ mA/mm with V_{GS} at threshold (−2.4 V). The reverse gate breakdown voltage is −17 V at $I_G = -10$ μA.

Fig. 3 presents both f_T and $f_{\max}$ versus V_{GS} for typical $L_g = 1.7$-μm and $W_g = 200$-μm T-gate MIDFET's at $V_{DS} = 5$ V. Both curves show distinct and extremely broad and flat plateaus, with peak $f_T = 8$ GHz and peak $f_{\max} = 21$ GHz and with the f_T plateau exceeding 90% of peak over a gate swing of 2.6 V. Because our parasitic C_{gs} and C_{gd} are less than 7% of intrinsic C_{gs}, f_T accurately reflects the effective channel electron velocity v_e, yielding an almost constant $v_e = 9 \times 10^6$ cm/s. Thus, the f_T and $f_{\max}$ plateaus provide direct evidence that the pseudomorphic MIDFET operates in velocity saturation over most of the useful V_{GS} swing, as has been observed in InAlAs/InGaAs MIDFET's [15], and make the device uniquely suitable for high-frequency large-signal operation.

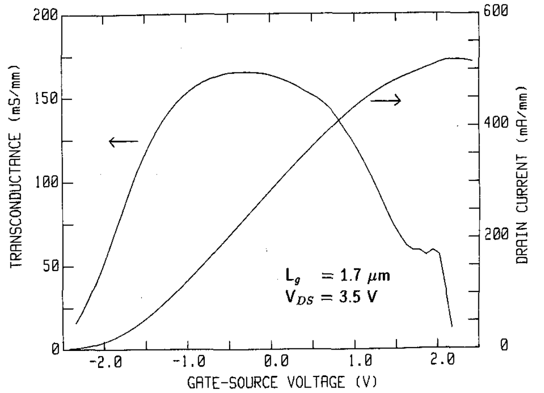

Fig. 2. Statistically averaged g_m and I_D versus V_{GS} for 20 randomly selected 1.7-μm × 30-μm MIDFET's ($V_{DS} = 3.5$ V).

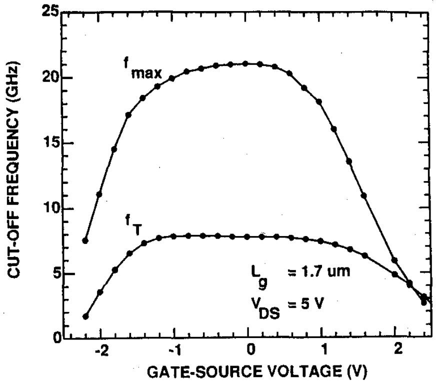

Fig. 3. f_T and $f_{\max}$ versus V_{GS} for a typical 1.7-μm × 200-μm T-gate MIDFET ($V_{DS} = 5$ V).

We also extract the RF transconductance from Re $[y_{21}]$, obtained through the measured S parameters. Fig. 4 shows g_m versus V_{GS} both at dc and 3 GHz. We find almost no difference between the two curves to within the accuracy of the parameter extraction. This lack of frequency dispersion is also evident in capacitance-voltage characterization of 200-μm × 200-μm gate diodes, measured at 10 kHz, 100 kHz, and 1 MHz for V_{GS} above threshold. Taken together, both g_m and CV data encompass an extremely broad-band frequency range, and should reveal dispersion if electrically active traps exist in the AlGaAs pseudoinsulator. The lack of any such dispersion indicates high-quality trap-free AlGaAs, and is an important merit of the undoped pseudoinsulator MIDFET design. In addition, by computing the area beneath C_{gs} versus V_{GS} from $V_{GS} = -1.8$ V (threshold voltage in the diode structures) through $V_{GS} = 0.5$ V (beginning of gate

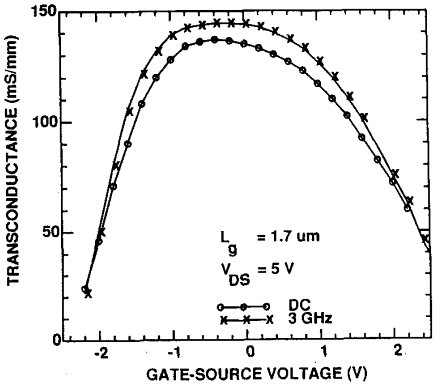

Fig. 4. g_m versus V_{GS} for a typical 1.7-μm × 200-μm T-gate MIDFET, measured at dc and 3 GHz ($V_{DS} = 5$ V).

leakage influence), we find a maximum channel electron sheet density of over 6×10^{12} cm^{-2}, a value unattainable in a single heterojunction MODFET.

In summary, we demonstrate $L_g = 1.7$-μm pseudomorphic AlGaAs/n$^+$-InGaAs/GaAs MIDFET's that display a broad g_m versus V_{GS} characteristic and thus achieve high drain current linearity and exceptional $I_{D,\max}$. We observe extremely broad plateaus in f_T and $f_{\max}$ versus V_{GS}, direct evidence for MIDFET operation in velocity saturation over most of the gate swing, and find a lack of frequency dispersion in both g_m and in C_{gs} versus V_{GS} from dc through microwave frequencies. These features combine to make the MIDFET well suited to many large-signal, broad-band telecommunications applications.

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