Cryogenic Microwave Performance of 0.5-μm InGaAs MESFET's

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***Abstract*—Microwave and dc properties of 0.5-μm InGaAs MESFET's were measured at 300 and 125 K. We have measured approximately 30% increases in RF $g_{m|\text{ext}}$ and f_T when cooling from 300 to 125 K. We also observe a 0.06-V increase in gate built-in voltage at 125 K that results in smaller gate leakage currents. The improved gate characteristic at 125 K leads to better RF properties at higher gate bias.**

I. Introduction

Recently, metal-semiconductor field-effect transistors (MESFET's) have become more important for practical applications in VLSI circuits and communications. The reported high-frequency performance of MESFET's now rivals the best results achieved with modulation-doped field-effect transistors (MODFET's) [1]. It is well known that the velocity-field characteristic of the channel material is an important factor which determines the high-speed performance of field-effect transistors.

The velocity-field characteristic of InGaAs has a higher peak electron velocity than GaAs, which improves high-speed device performance [2]. The InGaAs MESFET has demonstrated impressive 60-GHz power performance, as reported previously [3].

In this paper, the first study of the high-speed performance of InGaAs MESFET's at cryogenic temperatures is presented. We have studied the temperature dependence of dc and microwave device parameters from 300 to 125 K. Our data indicate that improved performance at cryogenic temperatures is due to an increase in the effective saturation velocity in the channel.

II. Device Structure and Fabrication

The devices are fabricated on (100) GaAs substrates. An $In_xGa_{1-x}As$ layer is grown using an EMCORE GS3300 MOCVD reactor, and the InAs concentration is graded from 18% at the substrate to 0% at the surface. These graded devices show superior Schottky gate characteristics compared to nongraded structures. Total channel thickness is 1600 Å. The graded $In_xGa_{1-x}As$ layers are doped by silicon ion implantation, at 80 keV with dose of 6.5×10^{12} cm^{-2}.

Recessed gate devices (0.5 μm $\times$ 100 μm) were patterned using standard MESFET processing techniques. Details of fabrication have been reported previously [4].

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III. Variable Temperature DC Performance

The I-V characteristics of the InGaAs MESFET demonstrate stable low-temperature behavior, as shown in Fig. 1. Device threshold voltage V_T increased from -1.62 V at 300 K to -1.35 V at 125 K, and showed an approximately linear dependence with temperature. The threshold voltage in MESFET devices has several temperature-dependent terms, including the Schottky barrier built-in voltage, the channel-to-substrate built-in voltage, and the charge density variation in the channel due to piezoelectric and deep-level transient effects [5]. For $V_{gs} > -0.25$ V, there is more drain current at 125 K due to a higher effective electron velocity in the channel. The positive shift in V_T results in smaller channel currents at 125 K for $V_{gs} < -0.25$ V.

The gate turn-on voltage, defined as the gate voltage resulting in 1 mA of gate current, increases from 0.54 V at 300 K to 0.63 V at 125 K. In Fig. 2, the gate current is plotted as a function of gate voltage at 300 and 125 K. The onset of gate conduction is clearly shifted to higher gate voltages at lower temperature. The gate built-in voltage V_{bi} was measured from CV data, and increased from 0.70 to 0.76 V when cooling from 300 to 125 K. The increase in built-in voltage is consistent with the change in the gate diode characteristic.

Extrinsic values of dc g_m were also computed by sweeping the gate voltage with a drain bias of 2.0 V. The maximum dc g_m was 435 mS/mm at 300 K and 517 mS/mm at 125 K.

IV. Variable Temperature Microwave Performance

S-parameter data were collected from 0.5 to 26.5 GHz using a Hewlett-Packard 8510B network analyzer. Measurements at 300 K were performed using a Cascade model 42 D high-frequency probe station, and 125-K measurements were made using a custom-built cryogenic high-frequency probe station [6]. Calibration with an impedance standard substrate from Cascade Microtech was performed and verified at 300 and 125 K by measuring the response of an open-circuited coplanar stub.

The measured S parameters were converted to Y parame-

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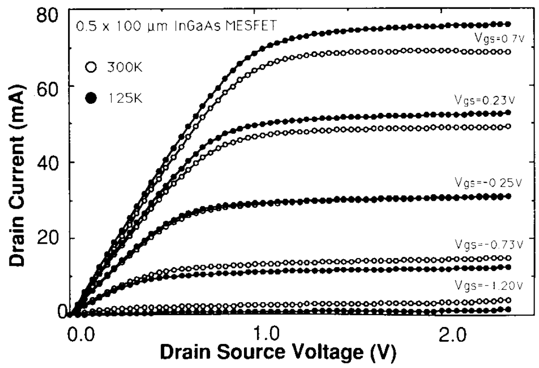

Fig. 1. Drain current I_d versus drain-source voltage V_{ds} and gate-source voltage V_{gs}. At 125 K characteristics spread apart, indicating higher g_m. Threshold voltage V_T is less negative at 125 K.

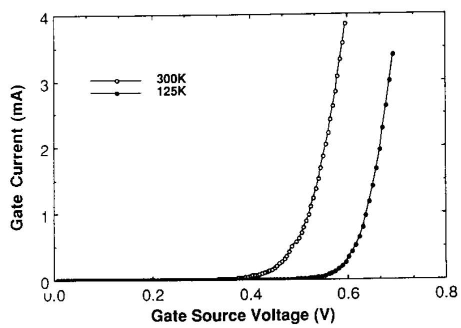

Fig. 2. Gate leakage current I_g versus gate-source voltage V_{gs}, showing larger gate built-in voltage at 125 K.

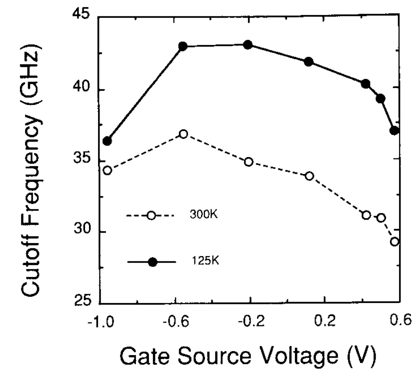

Fig. 3. Current gain cutoff frequency f_T versus gate-source voltage V_{gs}, showing higher frequency operation at 125 K.

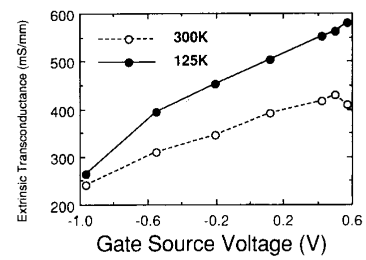

Fig. 4. Extrinsic transconductance $g_{m|\mathrm{ext}}$ versus gate-source voltage V_{gs} showing higher modulation efficiency at 125 K. At 125 K, the peak $g_{m|\mathrm{ext}}$ occurs at a higher V_{gs} value. Improvement in $g_{m|\mathrm{ext}}$ is larger at higher V_{gs} values.

ters, and Y parameters were used to compute f_T ($f_T = g_{m|\mathrm{ext}}/2\pi C_{gs}$), where $g_{m|\mathrm{ext}}$ is the extrinsic transconductance and C_{gs} is the gate-to-source capacitance [7]. In Fig. 3 the calculated f_T values for InGaAs 0.5-μm MESFET's are plotted versus V_{gs} at 300 and 125 K. The calculated f_T values agree well with those determined by extrapolating the measured $|h_{21}|$ curve to unity current gain, based on a 6-dB/octave rolloff. It is important to note that when the temperature is reduced from 300 to 125 K, the f_T improves over the entire bias range ($V_{gs} = -1.0$ to 0.6 V), although the dc channel current at 125 K is greater only for $V_{gs} > -0.25$ V. Peak f_T improves from 37 GHz at 300 K to 43 GHz at 125 K. However, the largest percentage change in f_T occurs at $V_{gs} = 0.42$ V, where f_T increases from 31 to 40 GHz, a 29% improvement.

The small-signal parameters that mainly determine f_T are $g_{m|\mathrm{ext}}$ and C_{gs}. Fig. 4 shows $g_{m|\mathrm{ext}}$ versus V_{gs} as computed from the Y parameters at 300 and 125 K. At $V_{gs} = 0.42$ V, $g_{m|\mathrm{ext}}$ improves by 32%, which corresponds to the change in f_T. The maximum RF $g_{m|\mathrm{ext}}$ at 300 K was 430 mS/mm at $V_{gs} = 0.50$ V, and improved to 580 mS/mm at 125 K, with $V_{gs} = 0.57$ V. At 300 K, the $g_{m|\mathrm{ext}}$ decreases due to gate conduction at $V_{gs} = 0.57$ V, while the $g_{m|\mathrm{ext}}$ at 125 K increases out to $V_{gs} = 0.57$ V due to smaller gate leakage.

The small-signal element that reflects the improved high-speed device operation at cryogenic temperature is $g_{m|\mathrm{ext}}$. Parasitic elements were not found to change significantly with temperature. Source resistance, related to the on resistance in the linear region of the I-V characteristic, does not change significantly with temperature as is clear in Fig. 1.

The improvement in $g_{m|\mathrm{ext}}$ at 125 K is larger at higher gate bias. As the gate bias increases, the degradation of $g_{m|\mathrm{ext}}$ due to gate leakage is more severe. The smaller gate leakage at 125 K causes the $g_{m|\mathrm{ext}}$ to improve more at higher gate bias. This in turn leads to a higher f_T over a wider bias range.

The average electron drift velocity is directly related to f_T, since $v_{\mathrm{ave}} = 2\pi f_T L_g$. At $V_{gs} = 0.42$ V, the v_{ave} computed from f_T increases from 9.74×10^6 cm/s to 1.26×10^7 cm/s. A similar percentage increase in velocity is observed in the doped-channel metal-insulator-semiconductor field effect transistor (MISFET) [8]. This implies that the high-speed transport mechanisms are similar in the MESFET and the MISFET.

V. Conclusions

From the above data we can draw several conclusions. First, the 32% improvement in RF $g_{m|\mathrm{ext}}$ (and similar improvement in f_T) indicates a higher average saturation velocity (V_{ave}) as the temperature is reduced. Low-temperature operation reduces scattering due to lattice vibrations, leading to a higher average electron velocity in the channel.

The built-in voltage of the Schottky gate increases at low temperature, causing a higher gate turn-on voltage and smaller gate leakage currents. This causes a shifting behavior in the bias dependence of f_T and $g_{m|\text{ext}}$ and leads to a higher f_T over a wider bias range.

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