Characteristics of GaAs/AlGaAs-Doped Channel MISFET's at Cryogenic Temperatures

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Abstract—**We present high-frequency measurements at cryogenic temperatures to 125 K of 0.3-μm gate length GaAs/$Al_{0.3}Ga_{0.7}As$ metal-insulator semiconductor field-effect transistors (MISFET's) with a doped channel. Experimental results demonstrate significant improvement in performance including an increase in the maximum frequency of oscillation f_{max} from 70 to 81 GHz and an increase in the unity current gain cutoff frequency f_T from 46 to 57 GHz. Independently determined decreases in electron mobility and increases in electron velocity under similar conditions lead to the conclusion that carrier velocity and not mobility controls transport in these devices. These results show the high-speed potential of doped channel MISFET's at both room temperature and cryogenic temperatures.**

I. Introduction

The doped channel metal-insulator field-effect transistor (MISFET) has emerged as an attractive device for high-speed applications. The structure is straightforward to grow and is distinguished by a doped narrow-gap active channel and undoped wide-gap insulator, which is opposite to the doping scheme of modulation-doped field-effect transistors (MODFET's). Doped channel MISFET's offer several advantages over conventional MODFET's including better threshold uniformity [1], [2], higher current drivability [3], and high values of cutoff frequency over wide ranges of bias [4]. To date, the highest reported maximum frequency of oscillation f_{max} is 41 GHz for a GaAs channel MISFET with a gate length $L_g = 0.5$ μm [3] and a current gain cutoff frequency f_T of 45 GHz for a GaAs channel MISFET with $L_g = 0.4$ μm [5]. It is well known that a decrease in gate length and operation at cryogenic temperatures are avenues to enhance device performance. In this paper, we present a comparative study of device performance at room and cryogenic temperatures for AlGaAs/GaAs-doped channel MISFET's with 0.3-μm T-gates.

II. Device Structure and Fabrication

The device layers for this study were grown by molecular beam epitaxy in a custom-built chamber [6]. The substrate temperature was 580°C. A 1-μm undoped GaAs buffer layer was grown on semi-insulating (100) GaAs. This was followed by 300 Å of Si-doped GaAs ($n = 2 \times 10^{18}$ cm^{-3}) which serves as the active channel, 200 Å of undoped $Al_{0.3}Ga_{0.7}As$ which serves as a gate insulator, and 100 Å of Si-doped GaAs ($n = 2 \times 10^{18}$ cm^{-3}) for good ohmic contact. The layers were processed into devices using electron beam lithography and a mesa-isolated recessed gate process. The ohmic contacts are alloyed Au/Ge/Ni/Au and the gate is Ti/Au. The gate width is 100 μm, the source-to-drain spacing is 2 μm, and $L_g = 0.30$ μm with a T cross section.

III. RF and DC Results

S-parameter measurements were made from 0.5 to 26.5 GHz using a Hewlett-Packard 8510 B network analyzer. Measurements have been made at a temperature of 300 K using a Cascade model 42 D high-frequency probe station and at 150 and 125 K using a custom-built cryogenic high-frequency probe station [7]. In Fig. 1, results of f_T determined from extrapolation of the measured *S* parameters are plotted versus gate bias. Calibrations have been made off wafer using an impedance substrate from Cascade Microtech. The f_T values reported here are "extrinsic" and have not been corrected for pad parasitics. The measured f_T at 125 K is 20–30% larger than at 300 K with gate bias varied from −0.4 to +0.4 V. By cooling to 125 K a 16% increase in f_{max} is measured (70 to 81 GHz) compared to 300 K. We find close agreement between the measured f_T from *S* parameters, f_T calculated from *y* parameters ($f_T = g_{m|ext}/2\pi C_{gs}$), and f_T modeled using an equivalent circuit and Touchstone® software [8]. The agreement between these values is a good check on the validity of the extrapolation of the measured *S* parameters and the model topology, which is shown in Fig. 2. Table I shows the modeled small-signal circuit element values at 300 and 125 K at a bias point of $V_{ds} = 1.5$ V, $V_{gs} = +0.1$ V, and $I_{ds} \sim 15$ mA at both temperatures.

Typical 300 and 125 K drain current and drain–source voltage characteristics (I_{ds} versus V_{ds}) of 0.3-μm × 100-μm doped channel MISFET's are shown in Fig. 3. The peak extrinsic dc transconductance g_m (dc) was measured to be 305 mS/mm at 300 K and 295 mS/mm at 125 K. The threshold voltage increased from −0.35 V at 300 K to −0.27 V at 125 K. In Fig. 4 g_m (dc) and g_m (RF), from y_{21}, versus gate bias at 300 and 125 K are plotted. The g_m (RF) at a frequency of 5 GHz is consistently larger than g_m (dc) with V_{gs} varied from −0.4 to +0.4 V.

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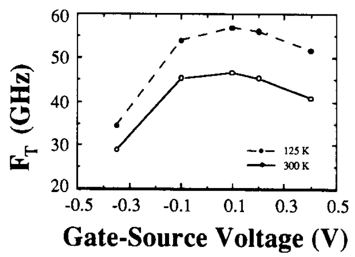

Fig. 1. Plot of the measured f_T versus gate bias for V_{ds} = 1.5 V at 300 K and 125 K. The gain roll-off is smooth, follows a 6-dB/octave roll-off, and is extrapolated to unity current gain resulting in maximum f_T values of 46 GHz at 300 K and 57 GHz at 125 K, an increase of 24%.

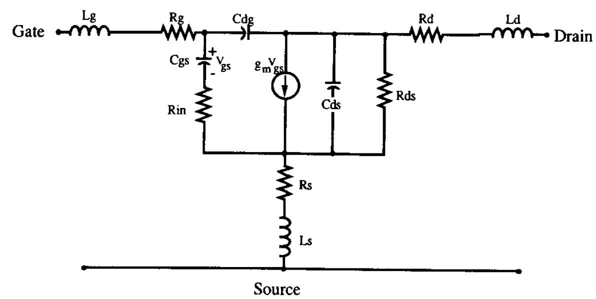

Fig. 2. Equivalent circuit used to model the measured *S* parameters. Circuit element values at temperatures of 300 and 125 K are given in Table I.

TABLE I
MODELED SMALL-SIGNAL ELEMENT VALUES

Model Element	300 K	125 K
G_{mlint} (ms/mm)	530	630
τ (ps)	0.75	0.69
C_{gs} (fF)	135	125
C_{dg} (fF)	19	22
C_{ds} (fF)	40	37
R_{in} (Ω)	1.73	1.47
R_{ds} (Ω)	376	325
R_g (Ω)	5.6	5.0
R_d (Ω)	13.4	10.9
R_s (Ω)	3.8	3.2
L_g (pH)	35.7	40.2
L_d (pH)	79.6	67.6
L_s (pH)	4.5	4.8

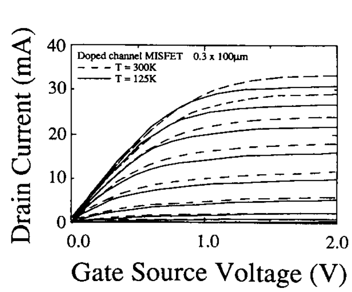

Fig. 3. (——) I_{ds} versus V_{DS} characteristics at 300 K of 0.3-μm × 100-μm doped channel MISFET. The gate voltage is swept from −1.0 to +0.8 V with a step voltage of +0.2 V for both temperatures. The dc $g_{m|max}$ = 305 mS/mm. (---) I_{ds} versus V_{ds} characteristics at 125 K of same device. The dc $g_{m|max}$ = 295 mS/mm.

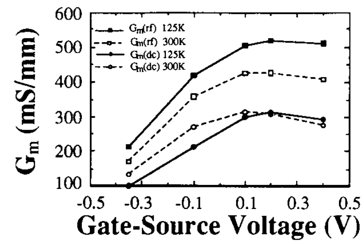

Fig. 4. Plot of g_m (RF), as calculated from Y_{21}, and g_m (dc) from I_{ds}–V_{gs} characteristics, versus V_{gs} for V_{ds} = 1.5 V at 300 and 125 K. The increase in g_m at RF frequencies is attributed to traps as explained in the text. The increase in g_m versus V_{gs} is due to a reduction in scattering with higher electron concentrations in the channel and an increase in the velocity of the electrons traveling in the lateral direction from source to drain.

IV. Discussion

From these results the following trends are observed: 1) the extrinsic g_m (RF) and effective saturation velocity v_{eff} (as calculated from the measured f_T) increase with decreasing temperature; 2) drain current I_{ds} slightly decreases and V_T becomes more positive with decreasing temperature; 3) C_{dg} and C_{gs} change by less than 16% with decreasing temperature; and 4) there is a large difference between extrinsic g_m (dc) and extrinsic g_m (RF) (43% at 300 K and 75% at 125 K). In AlGaAs/GaAs MODFET's similar discrepancies between g_m (RF) and g_m (dc) [9] and positive shifts in V_T at low temperature [10] have been attributed to deep-level traps which affect dc operation but cannot respond at high frequencies above 1 GHz [11]. In GaAs MESFET's, a positive shift in V_T at low temperature has been related to interface traps at the metal–semiconductor interface [12]. The similar behavior and similar materials structure of our MISFET's also imply a trap-related cause and underscore the importance of AlGaAs layer quality for dc device performance. To minimize the influence of trapping effects we have cooled the samples under strong illumination and the dc and high-frequency measurements were made under illumination.

Apart from the higher values at 125 K, the general functional behavior of f_T versus gate bias remains the same at 300 and 125 K in Fig. 1. At low gate bias, the device is operated in the depletion regime as indicated by the linear dependence of f_T on gate bias [4]. As V_{gs} is increased to approximately 0.1 V the f_T begins to saturate due to saturation of v_{eff}. Beyond this bias point f_T decreases with increasing V_{gs} due to increased gate leakage. The gate leakage could be reduced by increasing the Al mole fraction of the barrier layer with a penalty of increased trapping problems. Reducing the gate leakage should allow us to increase the bias range over which large values of f_T are maintained due to enhanced screening of ionized impurity scattering because of larger channel densities [13].

Based on independent calculations and measurements the electron mobility is found to decrease slightly in bulk GaAs from 300 to 77 K for an impurity concentration of 1×10^{18} cm^{-3} [14], [15]. In our lab, we have measured a 2% decrease of electron mobility in bulk n-type GaAs (n = 1.4×10^{18} cm^{-3}) from 300 to 77 K. Electron mobility enhancement has been reported in heavily doped GaAs quantum wells compared to bulk material [13], but even in quantum wells the electron mobility remains approximately the same at 300 and 77 K. Direct measurements of velocity-field characteristics of electrons in doped GaAs with $n = 2 \times 10^{18}\ cm^{-3}$, however, show a 33% increase in velocity from 300 to 77 K with an applied field of 10 kV/cm [16]. Ensemble Monte Carlo calculations [17] show that a doped channel MISFET with $1 \times 10^{18}\ cm^{-3}$ electrons in the channel has a 38% increase in drift velocity for $L_g = 0.3\ \mu m$ at an applied field of 20 kV/cm. Based on the evidence of very little temperature changes in mobility and of increases in cutoff frequencies which are consistent with drift velocity increases, we conclude that the carrier velocity controls transport in these devices leading to a significant improvement of doped channel MISFET frequency performance at cryogenic temperatures.

V. Summary

We observed a 20 to 30% increase of f_T in the first reported cryogenic high-frequency measurements of doped channel MISFET's. Independently measured and calculated decreases in electron mobility (~2%) and increases in electron velocity (33-38%) from 300 to 77 K led to the conclusion that carrier velocity controls transport in these devices. We also report an f_{max} of 70 GHz at 300 K and 81 GHz at 125 K with $L_g = 0.3\ \mu m$. These results show the high-speed potential of doped channel MISFET's at cryogenic temperatures.

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