Gate-Controlled Negative Differential Resistance in Drain Current Characteristics of AlGaAs/InGaAs/GaAs Pseudomorphic MODFET's

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Abstract—**We report the observation of negative differential resistance (NDR) and negative transconductance at high drain and gate fields in depletion-mode AlGaAs/InGaAs/GaAs MODFET's with gate lengths $L_g \sim 0.25$ μm. It is shown that under high bias voltage conditions, $V_{ds} > 2.5$ V and $V_{gs} > 0$ V, the device drain current characteristic switches from a high current state to a low current state resulting in reflection gain in the drain circuit of the MODFET. The decrease in the drain current of the device corresponds to a sudden increase in the gate current. We show that the device can be operated in two regions: 1) standard MODFET operation for $V_{gs} < 0$ V resulting in $f_{\max}$ values > 120 GHz, and 2) NDR region which yields operation as a reflection gain amplifier for $V_{gs} > 0$ V and $V_{ds} > 2.5$ V resulting in 2 dB of reflection gain at 26.5 GHz. We attribute the NDR to the redistribution of charge and voltage in the channel caused by electrons crossing the heterobarrier under high-field conditions. The NDR gain regime which is controllable by gate and drain voltages is a new operating mode for MODFET's under high bias conditions.**

I. INTRODUCTION

THERE has been a great deal of interest in three-terminal negative differential resistance (NDR) transistors [1]. Recently, a high-frequency high-field instability was observed in the drain current of 1.2-μm gate-length AlGaAs/InGaAs/GaAs double heterojunction MODFET's [2] and was attributed to real space transfer [3]. Hot-electron effects have also been reported in the gate current of 0.25-μm gate-length InP/InGaAs/InAlAs MODFET's at microwave frequencies [4]. Trapping effects have resulted in NDR in the drain circuit of MODFET's but are not present at microwave frequencies [5], and do not give high-frequency gain.

In this paper, we report the observation of NDR and also negative transconductance g_m in the drain circuit of AlGaAs/InGaAs/GaAs pseudomorphic MODFET's with gate length $L_g \sim 0.25$ μm. The I_{ds}–V_{ds} characteristic clearly shows switching between high and low current states resulting in NDR. Our observation differs from the gradual drop in the I_{ds}–V_{ds} characteristic as previously observed in [2]. We also show a correlation between the decrease in the drain current and corresponding rise in gate current at the onset of the NDR similar to results reported for 1.2-μm gate-length HIGFET's [6]. The mechanism responsible for the NDR is shown to be a broad-band high-frequency phenomenon and it is unrelated to thermal heating effects [7], or to trapping effects which are limited to frequencies below 1 GHz [8].

II. DEVICE STRUCTURE AND FABRICATION

The pseudomorphic MODFET's were grown by molecular beam epitaxy on semi-insulating (100) GaAs substrates. The structure consists of a 1-μm undoped GaAs buffer layer, a 150-Å undoped $In_{0.15}Ga_{0.85}As$ channel layer, a 50-Å undoped $Al_{0.25}Ga_{0.75}As$ spacer layer, a 400-Å Si-doped $Al_{0.25}Ga_{0.75}As$ (2×10^{18} cm^{-3}) donor layer, and a 100-Å Si-doped GaAs (1×10^{18} cm^{-3}) cap layer. A Cambridge 6.5 EBMF electron-beam lithography system was used to fabricate devices with gate lengths of 0.25 μm having a T cross section. Device fabrication techniques are described elsewhere [9].

III. EXPERIMENTAL RESULTS

The dc results were obtained with an HP 4145A semiconductor parameter analyzer. Fig. 1 shows typical I_{ds} versus V_{ds} and I_g versus V_{ds} characteristics of a depletion-mode 0.25 × 50-μm T-gate pseudomorphic MODFET. The device shows good pinch-off, low output conductance, and no evidence of the so-called kink effect, which is characterized by a sharp increase in the output conductance with increasing V_{ds} [5]. Under high gate and drain bias, $V_{ds} > 0$ V and $V_{ds} > 2.5$ V, we see an abrupt decrease in the drain current from a high current state to a low current state resulting in NDR. These bias conditions correspond to a strong accumulation of electrons under the gate and high electron energies. The sharp decrease in the drain current is experimentally correlated to a sharp increase in the gate current. At higher gate biases, $V_{gs} > +0.8$ V, the NDR effect does not occur, and we believe this is due to the forward bias of the gate electrode along with charge accumulation in the AlGaAs barrier which prevents the gate field from affecting the charge in the channel. The I–V curve of Fig. 1 was reproducible over many measurement scans and was observed with both digital and analog

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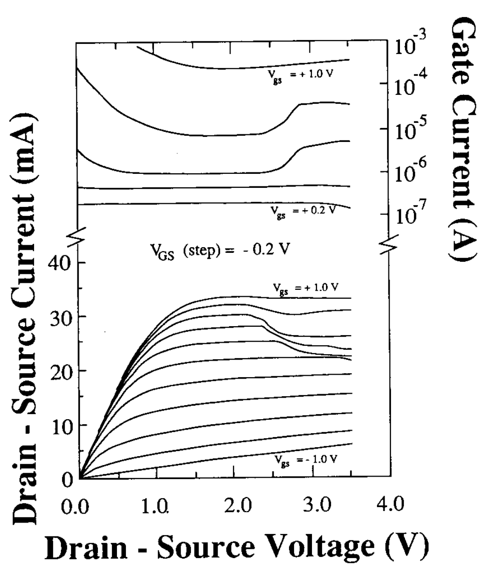

Fig. 1. Measured gate current (upper curves) and drain current (lower curves) versus V_{ds} at 300 K of MODFET having a T-gate structure with $L_g = 0.25$ μm, $W_g = 50$ μm, and $L_{sd} = 2$ μm. The maximum $V_{gs} = +1.0$ V with a step of -0.2 V for both upper and lower curves.

curve tracers. This NDR effect was also observed in several different devices having the same structure. NDR effects in the drain current characteristic of heterostructure FET's have been simulated [10] and are similar to the I_{ds} versus V_{ds} curves in Fig. 1. Fig. 2 shows the g_m versus V_{gs} for two different drain source values. At low bias, $V_{ds} \sim 1.0$ V, we observe a typical g_m response with a peak extrinsic g_m value of 450 mS/mm. When V_{ds} is increased to 3.0 V, a rapid drop in g_m to negative values is observed which corresponds to the switching point in the drain I-V characteristic. The existence of negative g_m in MODFET's is significant and may have applications for complementary circuits. Negative values of g_m have not been observed in previous reports of NDR in MODFET's [2].

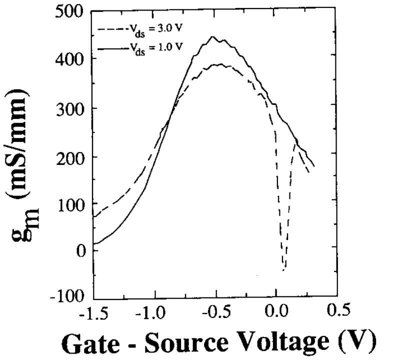

Fig. 2. Transconductance g_m versus gate voltage for high fields with $V_{ds} = 3.0$ V (dashed line) and low fields with $V_{ds} = 1.0$ V (solid line) at 300 K. The peak dc extrinsic $g_m = 450$ mS/mm at $V_{ds} = 1.5$ V and $V_{gs} = -0.5$ V. At $V_{ds} = 3.0$ V and $V_{gs} = +0.1$ V the transconductance is negative with $g_m = -50$ mS/mm.

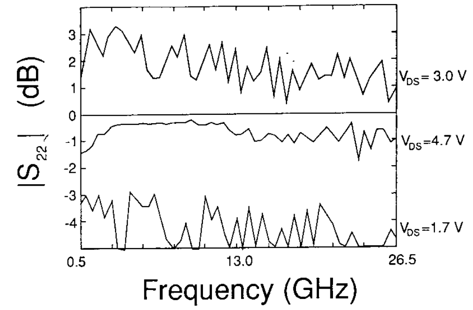

Fig. 3. Reflection coefficient $|S_{22}|$ versus frequency for $V_{ds} = 4.7$, 3.0, and 1.7 V with $V_{gs} = +0.6$ V. Gain ($|S_{22}| > 1$) is observed for $V_{ds} = 3.0$ V in the NDR regime. No gain ($|S_{22}| < 1$) is observed for $V_{ds} = 4.7$, 1.7 V outside of the NDR regime.

The microwave results were obtained using an HP 8510B network analyzer and a Cascade Microtech 42D microwave probe station. The scattering parameters of the MODFET were measured from 0.5 to 26.5 GHz. Both unilateral (G_u) and current (h_{21}) gains show a -6-dB/octave roll-off and the device was biased for an optimum $f_{\max}$ of 121 GHz and f_t of 63 GHz [11]. The microwave performance is excellent and shows no instability when the device is biased outside of the NDR region. When the device is biased in the NDR region, reflection gain is observed in the drain circuit of the MODFET, allowing the device to be operated as a broad-band reflection gain amplifier ($|S_{22}| > 1$) to at least 26.5 GHz. In the NDR region, the device was bias stabilized by varying the series resistance of the measurement apparatus. By using an external resonant circuit we expect that the device could also be used as a narrow-band microwave oscillator. Fig. 3 gives the output reflection coefficient S_{22} versus frequency and shows the effect of drain bias on $|S_{22}|$ for $V_{gs} = +0.6$ V. These results were measured on a device with similar I_{ds}-V_{ds} characteristics as shown in Fig. 1. The magnitude of S_{22} is larger than one only when the device is biased within the NDR region. The broad bandwidth of the response, from 0.5 to 26.5 GHz, is distinct from previous observations of narrow bandwidth of ~1 GHz for NDR in MODFET's [2].

IV. Discussion

We will now discuss mechanisms which might be expected to produce dc NDR in the drain I-V characteristic of the MODFET including thermal heating [7], kink effect [5], transferred electron effect, tunneling between subbands, and/or thermionic emission over the AlGaAs barrier. For our observations, thermal heating can be ruled out since the drain current characteristic flattens out under higher bias conditions and does not decrease under higher power dissipation. Thermal effects will not give reflection gain [7]. The kink effect caused by deep trapping centers in the AlGaAs cannot be responsible for the NDR here since the time constant associated with trapping is large, resulting in effects at relatively low frequencies below 1 GHz [8]. The abrupt decrease in I_{ds} and corresponding increase in I_g indicates a sudden rise in electron flow across the heterointerface. The high-frequency microwave signal generated by this mechanism, up to 26.5 GHz, proves that a high-speed mechanism is involved. The wide bandwidth of the reflection gain precludes impact ionization transit-time operation which produces narrow frequency bands related to the transit time, such as in the IMPATT [7]. We expect that the mechanism causing the NDR involves a redistribution of charge and voltage in the channel caused by electrons crossing the heterobarrier toward the gate by thermionic emission. This real space transfer effect has previously been observed in semiconductor heterolayers [12].

V. SUMMARY

We show a clear switching between current levels in the drain $I-V$ characteristic of pseudomorphic MODFET's. The sudden drop in I_{ds} corresponds to an increase of I_g resulting in negative g_m and significant NDR in a three-terminal device. The NDR yields broad-band reflection gain from dc to 26.5 GHz. We can also operate the device as a conventional MODFET with an $f_{\max}$ of 121 GHz. The dc and microwave results show that electrons transfer across the heterointerface via a very fast switching mechanism. These results indicate that MODFET's can be operated in a new mode under high bias conditions as gate- and drain-controlled NDR-type microwave amplifiers or oscillators. By adjusting bias conditions, the same device could also be used as a conventional MODFET.

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