Experimental and Theoretical Investigation of the DC and High-Frequency Characteristics of the Negative Differential Resistance in Pseudomorphic AlGaAs/InGaAs/GaAs MODFET's

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Abstract—We report a detailed investigation of the negative differential resistance (NDR) in the I-V characteristics of pseudomorphic AlGaAs/InGaAs/GaAs MODFET's with gate lengths of 0.3 μm. We experimentally verify the existence of abrupt multiple NDR in both the input circuit (I_d versus V_g) and the output circuit (I_d versus V_d). The NDR occurs over a short range of drain voltage (less than 200 mV) and gate voltage (less than 5 mV) in contrast to a smooth and broader bias range (greater then 1 V) for NDR induced by thermionic emission. We provide a general interpretation of the measured dc results based on tunneling real-space transfer (TRST) which occurs because of the formation of hybrid excited states across the InGaAs channel and AlGaAs donor layer. We verify the existence of stable reflection gain in both the input and output circuits with stable broad-band frequency response in the output circuit to at least 49 GHz. These results show that NDR via TRST in pseudomorphic MODFET's can provide wide-band frequency response not limited by the electron transit time from source to drain.

I. INTRODUCTION

The recent evidence of negative differential resistance (NDR) in the drain circuit of pseudomorphic InGaAs modulation doped field-effect transistors (MODFET's) [1], [2] and GaAs/AlGaAs metal-insulator semiconductor FET's (MISFET's) [3] has shown the existence of real-space transfer (RST) [4], [5] in conventional III-V transistors. The decrease of drain current I_d with increasing drain field resulting in NDR in the drain circuit of III-V FET's is accompanied by an increase in the gate current I_g [1]-[3]. The increase in I_g is due to a real-space transfer of electrons from the low-bandgap channel layer (either InGaAs or GaAs) to the wide-bandgap AlGaAs donor layer. It has also been established that the NDR which appears in the drain circuit can provide a high-frequency instability to 24 GHz [1], and oscillation frequency of 19.6 GHz [1], and stable wide-band reflection gain to 26.5 GHz [2]. More recently, Bigelow and Leburton [6], [7] have proposed the existence of tunneling real-space transfer (TRST) in MODFET-like structures with NDR features similar to the experimental observations of Laskar et al. [2]. In addition, the negative transconductance g_m provides a mechanism by which special analog and digital functions can be implemented with reduced device count [8] including the possible implementation of complementary logic functions [9].

In this paper we present the results of further investigations of the dc and high-frequency characteristics of NDR in MODFET's. We experimentally verify the existence of abrupt multiple NDR in both the input circuit (I_d versus V_g) and the output circuit (I_d versus V_d). Theoretically, we show that the intermixing of sublevels across the InGaAs channel and AlGaAs donor layer leads to the formation of hybrid excited states causing NDR via TRST. Finally, we investigate several different modes of high-frequency operation for these MODFET's. These devices can be operated in a conventional FET manner providing cut-off frequencies greater than 100 GHz. We observe that at certain bias points near the transitions in I_d, no oscillations are produced over a wide frequency range, verifying the existence of stable broad-band reflection gain. In addition, the NDR produced at the gate circuit is shown to provide a narrow-band frequency gain around 28 GHz. These results show the real-space transfer via tunneling between hybrid sublevels in the channel and donor layer leads to NDR in both the input and output reflection coefficients with a frequency response of at least 49 GHz.

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**II. DC RESULTS**

A. Experimental Investigation

The pseudomorphic MODFET's were grown by molecular beam epitaxy or semi-insulating (100) GaAs substrates. A diagram of the device structure is shown in Fig. 1. Several growth and processing runs have been performed with different indium channel compositions (15%, 17%, and 20%) and threshold voltages from $-1$ to $0$ V. A Cambridge 6.5 EBMF electron-beam lithography system was used to fabricate devices with gate lengths of 0.3 $\mu$m having a T cross section. Device fabrication techniques are described elsewhere [10].

The dc results were obtained with an HP 4142 source/monitor unit and a Cascade coplanar waveguide probe system [11]. The devices have a ground-signal-ground layout for high-frequency measurements. The devices exhibit 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 $V_{ds}$ [12]. We have observed pronounced NDR in the input (gate) and output (drain) circuits. The $I_d$ versus $V_g$ characteristics for a typical 0.3-$\mu$m x 50-$\mu$m pseudomorphic MODFET are shown in Fig. 2. The $I$-$V$ characteristic of Fig. 2 was reproducible over many measurements and was observed with both digital and analog curve tracers.

There are several salient features associated with the $I$-$V$ characteristics shown in Fig. 2. First, we confirm the existence of multiple NDR in the output circuit (drain-source characteristics). The sharp decreases in the drain current are experimentally correlated to sharp increases in the gate current. The $I_d$ transitions occur over a $V_{ds}$ range of less than 200 mV in contrast to the relatively large transition voltages observed in [1], [3]. In general, as $V_{ds}$ is lowered a corresponding higher $V_{cs}$ value is required for the onset of NDR and at high enough $V_{cs}$ we observe no NDR.

Second, we show for the first time the existence of multiple NDR in the input circuit ($I_{ds}$-$V_{gs}$ characteristics) of these MODFET's. Typical $I_d$ versus $V_{gs}$ and $I_{ds}$ versus $V_{gs}$ curves are shown in Fig. 3. The $V_{gs}$ transition voltages occur over a range of less than 5 mV and are much smaller than transition voltages reported in previous work [1], [3]. We observe that the sudden decreases in $I_{ds}$ versus $V_{gs}$ for a given $V_{ds}$ correspond to simultaneous increases in $I_{ds}$.

Third, the existence of negative $g_{ms}$ is confirmed [2], although for practical applications the bias range for negative $g_{ms}$ should be increased. Finally, the existence of multiple NDR in the $I_{ds}$-$V_{gs}$ characteristics—corresponding to multiple transition points in the $I_{ds}$-$V_{ds}$ characteristics—and the relatively small-voltage bias range over which all
current transitions occur conclusively distinguishes our observations from the thermionic emission as observed in previous work.

B. Model

Tunneling real-space transfer of charge occurs when two-dimensional hot-electron states in the high-mobility MODFET channel mix with cold two-dimensional quantized states in the high-gap low-mobility AlGaAs barrier. The mixing or hybridization between barrier and channel states establishes the tunneling process producing charge transfer and inducing NDR in the device characteristics [6]. In the recessed-gate MODFET of Fig. 1, an application of \( V_{ds} \) heats up the carriers in the InGaAs channel and increases the occupation of higher energy levels. AlGaAs and InGaAs states that remain sufficiently far apart have wave functions which are localized in their respective channels. However, increasing \( V_{gs} \) has the effect of lowering sublevels and creating additional localized states in the AlGaAs layer. At certain values of \( V_{gs} \), the AlGaAs levels cross higher InGaAs levels where they form a hybrid pair as shown in Fig. 4. Real-space transfer of charge from the high-mobility InGaAs channel to the low-mobility AlGaAs can take place and NDR is induced if enough hot electrons have been excited to the hybrid levels. In addition, the charge redistribution caused by carrier heating modifies the potential in the channel, which shifts the quantum levels and results in wave function mixing that is more sudden than in cold carrier systems [13]. The hybridization is therefore a sensitive function of voltage so that the states in the channel delocalize over a small voltage range and produce abrupt NDR. This is especially important in pseudomorphic MODFET's where there is always some conservation of the in-plane momentum due to the electron effective mass difference between AlGaAs and InGaAs. But if the wavefunctions in the transverse direction are hybridized for only a small voltage range, energy conservation permits fast elastic tunneling for these bias configurations only.

Only the source end of the channel presents conditions favorable for TRST-induced NDR to occur since the carrier loss from the InGaAs channel will determine the current, regardless of what occurs further along the channel. In addition, since the longitudinal electric field does not exceed 3 kV/cm at the source end of the channel, moderate carrier heating takes place which repopulates the InGaAs upper energy levels without inducing thermionic carrier transfer. The latter mechanism would result in a smoother NDR [1], [3] and offset TRST. Given the low value of the longitudinal field near the source end of the channel, we can apply the gradual channel approximation and look at a slice of the device in this region.

By using a charge-control model in the InGaAs channel and a velocity–field relationship given by [14]

\[
\nu(x) = \frac{\mu_x E(x)}{1 + \frac{E(x)}{E_c}}
\]

the longitudinal field at the source end of the gate edge can be derived as [15]

\[
E_s = \frac{E_F}{1 + \frac{2E_L \text{eff}(V_{ds})}{V_{gs} - V_T}}
\]

for a device in saturation. Here \( \mu_x \) and \( E_F \) are the zero field electron mobility and the saturation field in the InGaAs, respectively. \( L_{\text{eff}} \) is the effective channel length and \( V_T \) is the threshold voltage. This simple expression for the source field shows that both \( V_{gs} \) and \( V_{ds} \) determine the longitudinal field at the source, the latter through the effective channel length \( L_{\text{eff}} \) which shrinks as \( V_{ds} \) increases when the device is in saturation.

In our model the electrons are characterized by a Fermi–Dirac energy distribution with an electron temperature \( T_e \). The relationship between the longitudinal field and \( T_e \) is calculated with the Stratton model [16] which mainly considers polar-optic phonon scattering. We assume no more electrons are added in their respective channels as they are heated which results in a nonequilibrium situation. We calculate the quasi-Fermi level self-consistently with a Schrödinger/Poisson equation solver and find the band-edge profile and the wavefunctions in both InGaAs and AlGaAs layers. Fig. 4 shows the conduction band edge and bottom three sublevels for the bias configuration at which tunneling is predicted to occur. The wavefunctions are superimposed on the energies of the corresponding sublevels and show the mixing between the two closest levels.

In this elementary analysis of the NDR characteristics we only focus on the interaction between the lowest AlGaAs level and the first excited InGaAs level, as this crossing of levels yields the greatest occupation of elec-
trons. The device is then assumed to operate in one of two modes. In the decoupled mode there is no hybridization nor tunneling between the two levels so the carriers are characterized by two different quasi-Fermi levels on each side of the heterobarrier. In the coupled mode, electrons tunnel through the heterobarrier into the AlGaAs and relax the separation of quasi-Fermi levels. The abruptness in the current drop is due to the transition between the two modes of operation and depends upon the quasi-Fermi level separation before tunneling occurs.

The overall current is calculated from

\[ I_{dd} = eW(n_1\mu_1 + n_2\mu_2)E_z \]  

(3)

where \( e \) is the electron charge, \( n_1 \) is the electron density in the low-mobility (\( \mu_1 \)) AlGaAs layer, \( n_2 \) is the electron density in the high-mobility (\( \mu_2 \)) InGaAs layer, and \( W \) is the device width. For the simulation, we used [17], [18] \( W = 50 \mu m \), \( V_F = -0.48 \) V, \( V_{sat} = 1.35 \times 10^7 \) cm/s, \( \mu_1 = 300 \) cm\(^2\)/V \cdot s, and \( \mu_2 = 9160 \) cm\(^2\)/V \cdot s. From (1), \( V_{sat} = \mu z E_z / 2 \), giving \( E_z = 2.9 \) kV/cm. \( I_{th} \) was estimated from measured \( I_{dd} \) and \( V_{dd} \) values. From (3) it is seen that if appreciable carrier transfer between \( n_2 \) and \( n_1 \) occurs more rapidly than the increase in electric field significant NDR will occur.

C. Discussion of dc Results

The experimental and theoretical \( I_{dd}-V_{dd} \) relationships at \( V_{dd} = 4.0 \) V are shown in Fig. 3(a). The model predicts NDR to occur at \( V_{g1} = 0.67 \) V, in excellent agreement with the experimental results and supports our approach of considering only the source end of the channel. The condition for NDR is illustrated in Fig. 4 when the lowest AlGaAs level forms a hybrid pair with the first excited InGaAs level. The model also agrees with other trends seen in the \( I_{dd}-V_{dd} \) curves shown in Fig. 2. First, we see that the onset of NDR occurs at lower \( V_{dd} \) for higher \( V_{g1} \) values, since increasing \( V_{g1} \) lowers the AlGaAs level with respect to the InGaAs level and thus requires a smaller \( V_{dd} \) value to heat up and redistribute the carriers in the channel to align the sublevels. In addition, as seen in (2), increasing the gate bias increases the field near the source. Secondly, a threshold gate bias is necessary for the lowest AlGaAs level to cross the highest InGaAs level to induce TRST. Finally, the drop in the drain current occurs over a much smaller voltage range in the \( I_{dd}-V_{dd} \) than in the \( I_{dd}-E_z \) curves because the wavefunction coupling is more sensitive to changes with the perpendicular field \( (V_{g2}) \) rather than with the longitudinal field \( (V_{g1}) \).

In our one-dimensional approximation, we have calculated the fields and gate biases necessary to create the conditions for TRST. The longitudinal field in the channel is not constant along the channel and this variation of the field needs to be taken into account in order to explain all the features of the experimental curves. In Fig. 5 we show a qualitative profile of the field along the channel for two values of gate bias \( V_{g1} \) and \( V_{g2} \) where \( V_{g1} < V_{g2} \). As mentioned before, increasing the gate bias increases the field near the source. For \( V_{g1} \), there is a range of longitudinal electric field values for which a pair of levels are coupled together, bounded by \( E_1 \) and \( E_2 \). Likewise, a range of fields bounded by \( E_1 \) and \( E_2 \) will couple the same two levels for \( V_{g2} \). Since the effect of the gate is to lower the AlGaAs level with respect to the InGaAs level, the values for the longitudinal field needed for coupling are smaller for larger gate biases. This means the position in the channel where TRST occurs for a given level crossing will move toward the source for larger gate biases, as shown in Fig. 5. Eventually, for large enough values of gate bias, the conditions for coupling cannot be met along the channel and the carriers will remain in the InGaAs channel, resulting in a switch back to the higher drain current value as seen in Fig. 3(a). These arguments also apply for constant \( V_{g2} \) and increasing \( V_{dd} \). However, since the hybridization is more sensitive to changes in gate bias, the effects are not as evident. In Fig. 2, the increase in drain current can be seen for gate biases between 0.2 and 0.8 V for \( V_{g1} \sim 3.0 \) V.

With these considerations, the distinction between the NDR observed in the short-gate-length device [2], [4] and in devices with longer gates [1], [3] becomes more understandable. In order to maintain the same field distribution for TRST to occur in the longer gate devices, the drain-source bias would have to be increased substantially. Therefore, at the position where the field conditions for TRST are present, the potential drop in the channel is high enough for the electrons to achieve thermionic emission over the barrier and mask out the TRST.

The coupling between the first AlGaAs and second InGaAs levels is not the only occurrence of TRST. Other AlGaAs and InGaAs levels couple at different gate biases, although the effect on the current is expected to be weaker because of smaller occupation of electrons at these levels. The other couplings that create the multiple drops in current are identified in Fig. 3(b). These other couplings also create the multiple NDR observed in the \( I_{dd}-V_{dd} \) curves as
seen in Fig. 2. However, in this case, the level couplings are controlled by the heating of carriers in the channel due to the applied drain bias and have a similar behavior with field along the channel as discussed for the first AlGaAs and second InGaAs level coupling.

III. HIGH-FREQUENCY RESULTS

The high-frequency results were obtained using an HP 8510B automatic vector network analyzer and a Cascade Microtech 42D probe station. The scattering (S) parameters of the MODFET were measured from 0.5 to 30.0 GHz in a coaxial 50-Ω measurement system. One-port reflection measurements were made on the drain-source circuit of these devices using an external millimeter-wave U-band one-path, two-port test set. Waveguide to coaxial transitions were used to couple the high-frequency signal into wide-bandwidth millimeter-wave coplanar probe heads, providing a measurement bandwidth of 40 to 49 GHz. The electrical reference plane was established by an off-wafer short-open-load-thru calibration on an impedance standard substrate supplied with the high-frequency probe system.

In our investigation of the high-frequency performance of these MODFET's that exhibit NDR we have operated the devices in three distinct modes: 1) "conventional" III-V FET operation for peak gm resulting in high f2 and fmax values, 2) stable reflection gain in the output or drain reflection coefficient (S21), and 3) stable reflection gain in the input or gate reflection coefficient (S11) of the device. The measured S-parameters are used to calculate both the unilateral gain (G U) and current gain (H 21). Both the G U and the H 21 show a −6-dB/octave roll-off and the optimum value for fmax is ~120 GHz and for f2 is ~63 GHz, as shown in Fig. 6. There is no evidence of instability in either the input or output reflection coefficients allowing the device to be operated as a high-speed switch or microwave amplifier.

In the second mode of operation the device is biased near the first NDR point in the Vgs-Vds characteristic for given Vgs values. The first issue we address is whether we can obtain stable reflection gain in the output circuit. To this end we have measured the frequencies of oscillation with a Tektronix 2755 spectrum analyzer. From the spectrum analyzer trace in Fig. 7 we see that there is a bias point at which almost no energy is detected over a wide frequency range on the spectrum analyzer resulting in stable reflection gain over a similar frequency range on the network analyzer in Fig. 8. This broad-band reflection gain has been measured to at least 49 GHz (the limit of our network analyzer), see Fig. 9, and there is no evidence of roll-off in the gain at these frequencies.

The final mode of operation is the input reflection coefficient S11 versus frequency when NDR is observed in the Vgs-Vds characteristic. The condition for NDR in the gate arises from a sharp increase in Ids and a corresponding decrease in Vgs for Vds = 1.0 V in Fig. 3(a). One possible mechanism for this switching effect is the termination of tunneling between hybrid states between the donor and channel layers as discussed above. As we begin to apply a positive gate bias to the device with the particular Vgs-Vds characteristics shown in Fig. 3 we see a stable narrow-band region of gain exists for S11 centered around 28 GHz as shown in Fig. 8.
There are several mechanisms which also might be expected to produce dc NDR in the drain \( I-V \) characteristic of the MODFET including: thermal heating [19], kink effect [12], and the transferred electron effect. 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 [19]. 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 [20]. The abrupt decrease in \( I_{ds} \) and corresponding increase in \( L_{ds} \) indicates a sudden rise in electron flow across the hetero-interface. The high-frequency microwave signal generated by this mechanism, up to 49 GHz, proves that a high-speed mechanism is involved. The wide bandwidth of the reflection gain in the output circuit precludes impact ionization operation which produces narrow-frequency bands related to the transit time, such as in the IMPATT [19]. The narrow-band response observed in the input circuit maybe due to a combination of transit time limited operation and a different loading impedance caused by a larger gate-source impedance.

The investigation of the frequency response of this reflection gain is important since the ultimate cut-off frequency is not limited by the \( f_{max} \) value measured in a conventional FET mode which is governed by the conventional transit time \( \tau = W/V \) where \( W \) is the electron transit distance and \( V \) is the electron velocity. In the NDR mode of operation the transit frequency is limited by the real-space transfer of the electrons via tunneling from the channel to the donor layer. We can estimate the characteristic tunneling time from the uncertainty principle giving \( \tau_{tun} = h/2 \Delta E \) [21] where \( \Delta E \) is the sublevel separation. For \( \Delta E \approx 3 \text{ meV} \), \( \tau_{tun} \) has been estimated to be less than 1 ps [6]. We have also attempted to obtain stable reflection gain at the second NDR point in the \( I_{ds}-V_{ds} \) characteristic but we have generally found that there is energy across a broad frequency range on the spectrum analyzer. We have not achieved stable gain at the higher \( V_{ds} \) values and this may partially be due to the increase of thermionic emission over the heterostructure and/or the influence of Gunn domain formation at the high fields.

Previous results with three-terminal RST, via thermionic emission, heterostructure devices have been operated in two distinct types of devices. The first type of device is the charge injection transistor (CHINT) [22] which is based on the control of charge injection of hot electrons from a channel into another conducting layer via a heating field. The CHINT has exhibited extrapolated cut-off frequencies as high as 29 GHz in the GaAs/AlGaAs material system [23] and as high as 60 GHz in the InGaAs/AlGaAs/GaAs material system [24]. The second type of device is the negative resistance transistor (NERFET) [25] which exhibits NDR in the source–drain circuit controlled by a third terminal voltage. The NERFET has exhibited a peak-to-valley ratio as large as 160 [26] and high-frequency signal to 2 GHz [27]. The high-frequency results due to TRST reported here are significant for they show that even with a basic MODFET design the possibility exists for good high-frequency performance. Further work is necessary to provide a wider transition bias range over which TRST occurs before practical applications can be realized.

IV. Summary

In summary, we have experimentally confirmed the existence of multiple abrupt NDR in both the input and output circuits of pseudomorphic InGaAs MODFET's. The NDR occurs over a small-voltage range in contrast to the NDR induced by thermionic emission. A first-order theoretical model based on TRST gives both qualitative and quantitative agreement with the measured dc results. In addition to the conventional high-frequency operation of the device we have experimentally shown that the device can provide reflection gain in both the input and output circuits. This mode of operation provides a stable broadband frequency response in the output circuit to at least 49 GHz where the cut-off frequency is controlled by TRST and not by the electron transit time from source to drain.

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