DC CHARACTERISTICS (I-V) OF PSEUDOMORPHIC GaAs/InGaAs/AlGaAs QUANTUM-WIRE FETs

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ABSTRACT

We have measured the static I-V characteristics of pseudomorphic conventional HEMTs and FETs based on parallel array of quantum wires (UNIFETs) at ambient, 77, and 1.5K, respectively. These measurements show that at ambient temperature the saturation-regime extrinsic transconductance ($g_m$) of the UNIFETs is about 80% higher than that of the conventional HEMTs. The $g_m$ of both types of devices increases as the temperature is lowered. The rate of increase is higher for the UNIFETs due to the one-dimensional character of electron transport. FETs based on array of parallel quantum wires are well-suited for high-frequency applications because of their high transconductance resulting from size quantization and lateral confinement of the carriers.

INTRODUCTION

Due to lateral confinement, transverse moments in a quantum wire (QWI) are strongly quantized and electrons are free to move only along the length of the wire. The resulting band structure consists of a series of discrete one-dimensional (1D) subbands, called modes or channels (Fig.1). At finite temperatures such that $kT$ is larger than the intersubband

Fig.1. Band structure of a quantum wire. $E_1$, $E_2$, ... are the 1D subbands.
separation $\Delta E$ and when the number of subbands occupied is fairly high, transport is quasi-two-dimensional (2D). However, as the temperature is lowered and $kT$ approaches and then drops below $\Delta E$, the effect of 1D subband structure is felt. The mobility rises sharply due to significant decrease in the impurity and phonon scattering rates caused by reduction of phase space resulting from 1D nature of transport$^{1,2}$. This effect is enhanced further if the number of subbands occupied is small. Field-effect transistors (FET), based on arrays of parallel QWIs, hereafter called UNIFETs to emphasize the 1D transport character, are then expected to have a higher transconductance, especially at low temperatures, because of the enhanced mobility due to 1D nature of electron transport and due to the better charge control from lateral confinement$^3$.

In this work we report and compare the ambient and low-temperature DC characteristics of UNIFETs and conventional two-dimensional (2D) HEMTs and present evidence for mobility enhancement in UNIFETs due to 1D electron transport, especially at low temperature.

**DEVICE FABRICATION**

UNIFETs and conventional HEMTs were fabricated from the same GaAs/InGaAs/AlGaAs pseudomorphic heterostructures grown by MBE. The device fabrication was based on conventional mesa-isolated lift-off technology$^4$. Deep-mesa, wet etching was used to fabricate arrays of parallel quantum wires of different widths ($W_L$) and periods ($P$) (Fig.2). Both HEMTs and UNIFETs had Ti/Pt/Au, T-shaped gates of length $L_g = 0.3 \mu m$, with gate recess defined by reactive ion etching (RIE).

![Schematic cross section of deep mesa-etched quantum wires.](image)

**RESULTS AND DISCUSSION**

The static, $I_{ds} - V_{ds}$ and $I_{ds} - V_{gs}$ characteristics of HEMTs and UNIFETs were measured both in the saturation and linear regime of transport and at three different
temperatures, viz., 300, 77 and 1.5K. Since the transconductance in the linear regime is directly proportional to the low-field mobility, the objective of the transconductance measurements in the linear regime at different temperatures was to determine the temperature dependence of the electron mobility.

**Saturation Regime**

Figures 3 and 4 show the $I_{ds} - V_{ds}$ characteristics at ambient temperature of a UNIFET with a total channel width of 10.5 $\mu$m ($W_L = 0.15 \mu$m and $P = 0.7 \mu$m) and a $75 \times 0.3 \mu$m$^2$ HEMT. Since the total channel widths of the transistors are different, $I_{ds}$ is normalized with respect to unit channel width so that the characteristics of the different transistors could be directly compared. In Fig.5 is shown the gate-voltage ($V_g$) dependence of the transconductance in the saturation regime. The extrinsic maximum transconductance ($g_{m}^{\text{max}}$) of the UNIFET (400 mS/mm) is about 80% higher than that of the conventional HEMT (225 mS/mm). It should be noted that these values were obtained using the lithographic width, $W_L$, of the QWIs. In fact the effective width, $W_E$, of the wires is less than the geometrical width due to the depletion at the gated side walls of the deep-mesa etched wires ($W_E = W_L - 2W_D$, where $W_D$ is depletion width at each wall). The current-carrying capability of the UNIFET as shown in Fig.3 is thus underestimated, since $W_D$ is estimated$^5$ to be about 30 nm at $V_g = 0.45$ V. The UNIFET also shows better pinch-off characteristics. The $g_{m}^{\text{max}}$ of both types of devices increases as the temperature is lowered to 77K, reaching 528(mS/mm) for the UNIFET and 250(mS/mm) for the HEMT.

The results cited above clearly show that FETs based on parallel quantum-wire array are better suited for high-frequency applications than conventional HEMTs.

![Fig.3. I-V characteristics of UNIFET at ambient temperature.](image)

**Linear Regime**

In the linear, low-field regime of transport, the electric field $E$ under the gate can be
Fig. 4. I-V characteristics of conventional HEMT at ambient temperature.

Fig. 5. Extrinsic transconductance $g_m$ of UNIFET and conventional HEMT at ambient temperature in the saturation regime.

considered to be uniform. In such a case, the transconductance is proportional to $(\partial n/\partial V_g) \mu E$, where $n$ is the electron density and $\mu$ the mobility. One can write $E = V_{ds}/L_g$, where $V_{ds}$ is the drain-source voltage, if the access resistance of the transistor can be neglected in comparison to the channel resistance. In the linear part of the $I_{ds} - V_g$ curve where $g_m$ has the constant maximum value, all the electrons responsible for channel conduction reside in the InGaAs quantum well and $\mu$ is independent of $V_g$. The linear dependence is the result of $(\partial n/\partial V_g)$ being a constant, which is expected to be independent of temperature. Any variations of the low-field transconductance $g_m^{max}$ with temperature then results from the temperature dependence of the mobility. The above analysis is certainly true for HEMTs, which have negligible access resistance ($\approx 0.5\Omega/mm$). For UNIFETs, this value is not known, since the gate does not cover the entire length of the wires. If the access resistance can not be neglected and changes with temperature, so does the electric field $E$ since $V_{ds}$ remains the same. One can get around this problem
by assuming that the thermal dependence of access resistance is the same as that of the channel resistance. Since for UNIFETs the access resistance comes mainly from the resistance of the ungated lengths of the QWIs, this assumption is not unreasonable. \( E \) is then independent of temperature as for HEMTs.

In Figs.6 and 7 we show the low-field transconductance of the same UNIFET and HEMT, as used for the saturation-regime measurements, at 300, 77 and 1.5K as a function of the gate voltage. As explained above, the observed increase of \( g_{\text{max}}^{\text{mL}} \) as the temperature is lowered is an indication of mobility enhancement. Notice that \( g_{\text{max}}^{\text{mL}} \) of UNIFET increases much more rapidly than that of HEMT as temperature decreases. Table I summarizes the results, which can be interpreted as indicating a sharp increase of the mobility of the UNIFET channel compared to that of the conventional HEMT. We interpret this as a clear evidence of 1D transport in the UNIFET. However, the transconductance is found to increase very little between 77K and 1.5K, contrary to the dramatic increase expected in a 1D electron system due to rapid increase in mobility. Indeed temperature will cease to
have any effect when kT becomes equal to or smaller than the impurity induced lifetime broadening $\Gamma$ of the 1D sublevels. It should be noted that the mobility at low temperature of the 2D electron gas of a pseudomorphic heterostructure is fairly limited due to interface roughness scattering. The low mobility resulting from this reduces the electron lifetime in a given state and adds to level broadening.

TABLE I

Maximum low-field conductance $g_{mL}^{\text{max}}$ of UNIFET and HEMT at different temperatures.

<table>
<thead>
<tr>
<th>Transistor</th>
<th>$g_{mL}^{\text{max}}$ (mS/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEMT</td>
<td>10.6</td>
</tr>
<tr>
<td>UNIFET</td>
<td>20.5</td>
</tr>
<tr>
<td>300 K</td>
<td>77 K</td>
</tr>
<tr>
<td>77 K</td>
<td>14.9</td>
</tr>
<tr>
<td>1.5K</td>
<td>16.4</td>
</tr>
<tr>
<td>52</td>
<td>45.9</td>
</tr>
</tbody>
</table>

CONCLUSION

This work shows improved characteristics of FETs based on array of parallel quantum wires (UNIFETs) compared to conventional HEMTs. The superior performance of the former results from one-dimensional electron transport character because of size quantization and better charge control due to lateral confinement. UNIFETs are thus well-suited for high-frequency applications, especially at liquid-nitrogen temperature, because of their high transconductance. Due to the limited mobility at low temperatures, pseudomorphic structures in their present state of development are not the best heterostructures to be used for UNIFETs.

REFERENCES

5. S. Bollaert, P. Legry, E. Delos, and A. Cappy, Preprint.
**TABLE I**

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<table>
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<th>Transistor</th>
<th>$g_{mL}^{\text{max}}$ (mS/mm)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>300 K</td>
</tr>
<tr>
<td>HEMT</td>
<td>10.6</td>
</tr>
<tr>
<td>UNIFET</td>
<td>20.5</td>
</tr>
</tbody>
</table>
FIGURE CAPTIONS

Fig.1. Band structure of a quantum wire. $E_1, E_2,$ ... are the 1D subbands.
Fig.2. Layer sequence of a pseudomorphic heterostructure.
Fig.3. Schematic cross section of deep mesa-etched quantum wires.
Fig.4. Top view of a UNIFET.
Fig.5. I-V characteristics of UNIFET at ambient temperature.
Fig.6. I-V characteristics of conventional HEMT at ambient temperature.
Fig.7. Extrinsic transconductance $g_m$ of UNIFET and conventional HEMT at ambient temperature in the saturation regime.
Fig.8. Low-field transconductance of UNIFET at three temperatures.
Fig.9. Low-Field transconductance of conventional HEMT at three temperatures.