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Quasi-one-dimensional Channel GaAs/AlGaAs Modulation Doped FET Using Corrugated Gate Structure

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This paper reports on the fabrication and characterization of a modulation-doped GaAs/AlGaAs FET with a corrugated gate structure in which the electron gas confinement has been changed from a conventional two-dimensional electron channel to an array of one-dimensional electron gas channels with negatively biased gate voltage. With this device, we observed the enhanced field effect mobility and transconductance oscillations in strictly-defined one-dimensional channels.

1. Introduction

In a one-dimensional electronic system, the motion of electrons normal to the channel is quantized, leading to size-quantization effects in transport properties of electrons. In 1980, Sakaki[1] theoretically analyzed the electron transport in such a system and showed the possibility of suppressed elastic scattering, thus increasing carrier mobility. More recently, Yamada[2] simulated the high-field electron transport in such a system by solving the Boltzmann equation and made a statement on electron energy confinement and the possibility of electron velocity runaway[3].

In this paper, we report on the results of conductance experiments on a corrugated gate GaAs/AlGaAs modulation-doped FET in which the electron gas confinement has been changed from a conventional two-dimensional electron gas channel to an array of one-dimensional electron gas channels.

2. Structure and Fabrication

Figure 1 shows a top view of our proposed device structure. It consists of a corrugated gate and two source-drain pairs. The corrugated gate structure was formed on a GaAs/AlGaAs modulation-doped heterostructure grown by MBE.

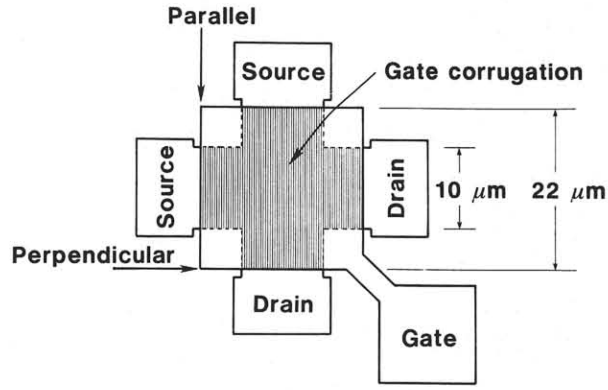

Fig. 1. Top view of the device.

Figure 2 shows the epilayer structure of the device. It has no spacer layer. The Hall mobility of the two-dimensional electron gas confined in the structure was measured as 2×10^4 $cm^2/V \cdot s$ at 77 K, with a sheet carrier concentration of 1×10^{12} cm^{-2}.

Figure 3 shows the schematic cross section of the corrugated gate structure. When a negative gate voltage is applied, the two dimensional electron gas changes into quasi-one-dimensional electron gases, because the two-dimensional electron gas is depleted at those areas without n^+-GaAs cap stripes.

Figure 4 is an SEM photomicrograph of the n^+-GaAs stripes we delineated. The stripes were formed using holographic He-Cd laser exposure and subsequent CCl_2F_2/He reactive ion etching (RIE) to selectively remove the n^+-GaAs. The stripes are spaced of 200 nm intervals and have a line width of about 50 nm.

3. Results and Discussion

Figure 5 shows the current-voltage characteristics of a transverse (having the channel perpendicular to the n^+-GaAs stripes) and a longitudinal (having the channel parallel to the n^+-GaAs stripes) FETs. These were measured at 5 K. The drain currents for these FETs completely saturate for drain voltages greater than 0.9 V. The gate length of these devices is 22 µm as shown in Figure 1.

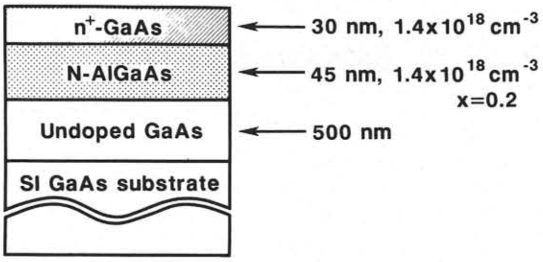

Fig. 2. Epilayer structure.

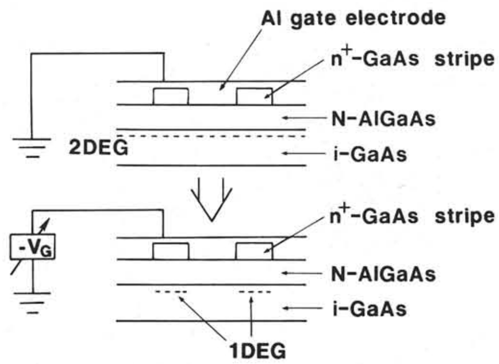

Fig. 3. Schematic cross section of this device.

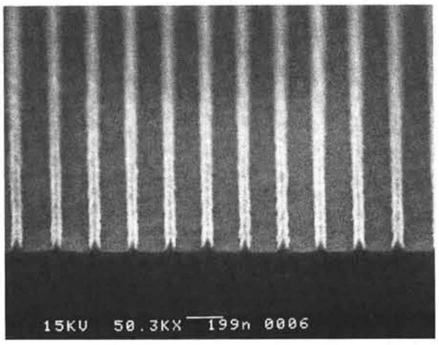

Fig. 4. SEM photomicrograph of the n^+-GaAs stripes.

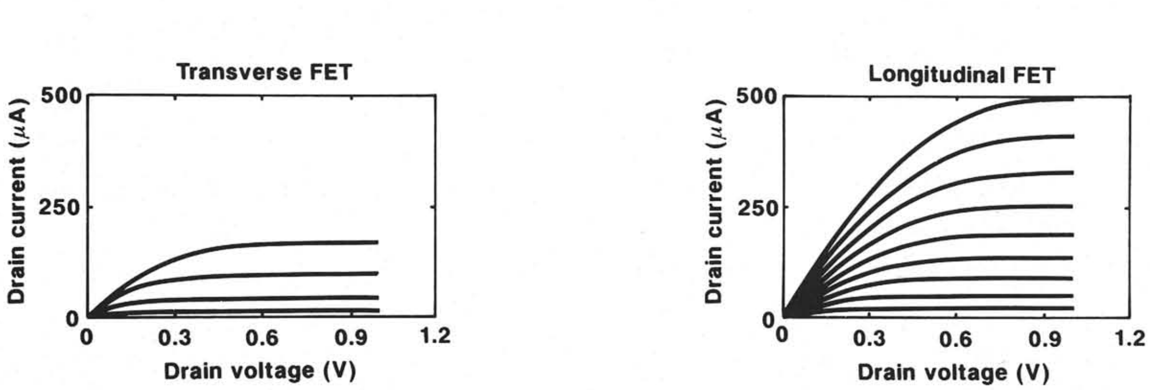

Fig. 5. I-V characteristic of transverse and longitudinal FETs at 5 K.

Figure 6 plots the transconductance measured as a function of the gate voltage for drain voltage of 0.9 V. The transconductance of the transverse FET decreases with increasing negative gate voltage and becomes zero at around -0.45 V. The transconductance of the longitudinal FET has finite values for negative gate voltages at around -0.45 V. This indicates that the channel changes from two-dimensional to quasi-one-dimensional at around -0.45 V. This was confirmed by gate capacitance measurements as follows.

Figure 7 plots the gate capacitance against the gate voltage for this device measured at a frequency of 1 MHz. The capacitance decreases sharply with increasing negative gate voltage from -0.2 V to -0.45 V, then monotonically decreases with increasing negative gate voltage. This further suggests that the transition from a two-dimensional channel to one-dimensional channels occurs at around -0.45 V, and the width of the one-dimensional channels decrease monotonically from -0.45 V to -1.0 V as the negative gate voltage varies.

With respect to the transconductance of a longitudinal FET in the one-dimensional channel regime, there is a critical change in the slope of the transconductance curve (K value) at around -0.85 V (shown by the arrow in Fig. 6). The capacitance monotonically decreased from -0.45 V to -1.0 V (see Fig. 7).

Since the gate length L_G of our device is 22 μm, the gradual channel approximation can be employed. The transconductance g_m in the saturation region (the source drain voltage was 0.9 V) is thus approximated by

$$g_m = 2K(V_G - V_T)$$

$$K = \frac{\mu_F C_G}{2 L_G^2}$$

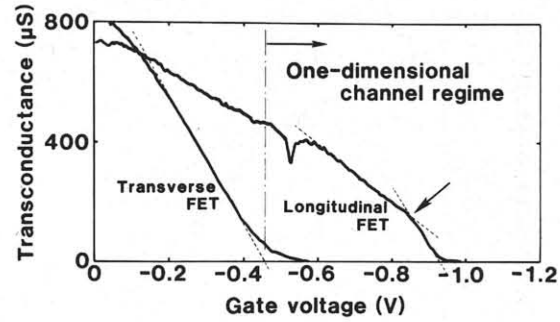

Fig. 6. Transconductance vs gate voltage at 5 K.

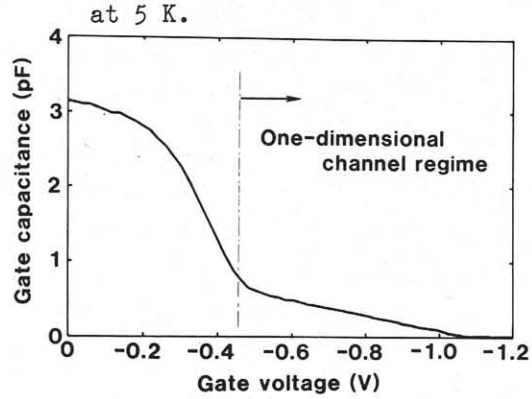

Fig. 7. Gate capacitance vs gate voltage at 5 K.

where V_G is the gate voltage, V_T the threshold voltage, C_G the gate capacitance of this device, and μ_F the field effect mobility. The slope of the transconductance (K value) is proportional to the product of the gate capacitance and the field effect mobility. Considering the monotonic decrease of the gate capacitance around -0.85 V, the critical change in the longitudinal transconductance slope (K value) is caused by the enhancement of the field effect mobility. The field effect mobility after the change in slope is estimated from the graph to be about three times that before the change in slope.

Figure 8 shows the transconductance of the longitudinal FET in the one-dimensional regime for a different sample. The similar critical change in slope is observed at around -0.7 V for this sample. Moreover, staircase-like oscillations are clearly visible for the negative gate voltage region from -0.7 V to -0.9 V.

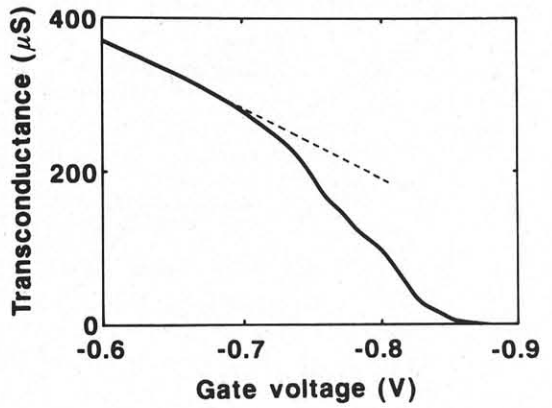

Fig. 8. Transconductance vs gate voltage at 5 K.

This oscillatory behavior can be understood as caused by the one-dimensional quantization of the channels as follows: For one-dimensional electronic system, the density-of-states (DOS) is given by

$$\rho(E) = \left(\frac{m^*}{2\hbar^2\pi^2}\right)^{1/2} \sum_{l\,m} \frac{1}{\sqrt{E - E_l - E_m}}$$

as reflected in Figure 9. When a negative gate voltage is applied, the Fermi level descends due to decreased carrier density, while the one-dimensional energy levels and intervals between them increase due to the decreased width of one-dimensional channels. These indicate that the Fermi level passes through successive one-dimensional levels as the negative gate voltage increases. When the Fermi level passes the minimum DOS , the available final states are most limited. Therefore, the substantial scattering rates change, thus the field effect mobility and transconductance become oscillatory.

Consequently, in this oscillatory regime, it is suggested that electrons are strictly-defined into the one-dimensional channels. Thus, the enhancement of the field effect mobility is considered to be caused by the transition from loosely-defined one-dimensional channels to strictly-defined one-dimensional channels.

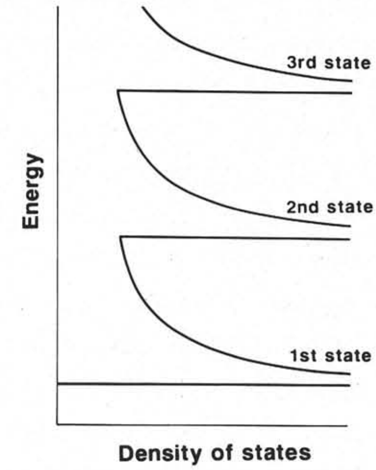

Fig. 9. Density of states in a strictly-defined one-dimensional electronic system.

4. Summary

A quasi-one-dimensional channel GaAs/AlGaAs modulation doped FET using a corrugated gate structure was proposed and fabricated. The gate of this device changes a two-dimensional channel to an array of one-dimensional channels. In the one-dimensional regime, we observed the enhancement of field effect mobility and transconductance oscillations. These are considered to be due to the size quantization effects occurring in strictly-defined channels.

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