Characteristics of InAs/AlGaAs self-organized quantum dot modulation doped field effect transistors

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We have investigated the dc characteristics of InGaAs/AlGaAs modulation doped field effect transistors in which a layer of self-organized InAs quantum dots is inserted adjacent to the pseudomorphic quantum well channel. Distinct steps and a negative differential resistance are observed in the current–voltage characteristics at room temperature and lower temperatures. These are attributed to conduction through the bound states in the quantum dots. © *1998 American Institute of Physics.* [S0003-6951(98)02726-0]

Interest in low-dimensional quantum confined structures has been fueled by the richness of fundamental physical phenomena therein and the potential device applications.[1–6] In particular, ideal quantum dots can provide three-dimensional carrier confinement and resulting discrete states for electrons and holes. Interesting electronic properties related to the transport of carriers through the bound states and the trapping of electrons and holes can be used to realize a new class of devices such as the single-electron-transistor, multilevel logic element, memory element, etc.[7–9] We have investigated the temperature-dependent properties of an InGaAs/AlGaAs modulation doped field effect transistor (MODFET) in which a layer of self-organized InAs quantum dots is incorporated in parallel to the pseudomorphic quantum well channel. Distinct steps are observed in the transistor output and transfer characteristics at room temperature and a negative differential resistance (NDR) is also observed in the output characteristics for certain gate voltages.

Self-organized growth of quantum dots has been by far the most successful technique in fabricating semiconductor quantum dots.[10–12] During the epitaxial growth of highly strained material (lattice mismatch greater than 1.8%), under the *Stranski–Krastanow* growth mode, three-dimensional islands are formed after an initial two-dimensional wetting layer. These coherently strained defect-free three-dimensional (3D) islands are pyramidal in shape with dimensions (10–20 nm) suitable to form quantum dots. Optoelectronic devices such as lasers, detectors, and electro-optic modulators have been demonstrated[13–18] which distinctly show the quantum size effect in these quasi-zero dimensional structures. The electron transport through dots embedded in a transistor structure has also been studied.[19,20] In this letter we demonstrate the effect of conduction through the bound states in these quantum dots on the transport properties of an adjacent quantum well channel in a MODFET configuration.

The device heterostructure, grown by solid source molecular beam epitaxy (MBE), is shown in Fig. 1 along with the conduction band diagram. The GaAs buffer layer, top $Al_{0.15}Ga_{0.85}As$ layer and the n^+-GaAs contact layer were grown at 620 °C. The $In_{0.25}Ga_{0.75}As$ quantum well channel

layer, InAs quantum dot layer, and the $Al_{0.15}Ga_{0.85}As$ spacer layer were grown at 510 °C. The quantum dot layer consists of 2.5 monolayers (ML) of InAs grown at a rate of 0.1 ML/s. The density of dots formed under these growth conditions, measured by atomic force microscopy (AFM), is $\sim 5 \times 10^{10}$ cm^{-2}. Due to the small separation (2.5 nm), the electronic states in the quantum well and the quantum dot layer are coupled. It is evident from the band diagram that the channel as well as quantum dots are modulation doped by the Si dopants in the $Al_{0.15}Ga_{0.85}As$ layer. The sheet carrier density and mobility, as obtained by Hall measurement at room temperature, are 1×10^{12} cm^{-2} and 3500 cm^2/V s, respectively. The relatively low mobility is believed to be due to the poor interface between the channel and the spacer layer, grown at a relatively low temperature. A transistor heterostructure without the quantum dot layer was also grown for comparison. The sheet carrier density and Hall mobility in this sample are 1×10^{12} cm^{-2} and 6000 cm^2/V s, respectively. 0.3-μm-gate single recess field effect transistors (FETs) were fabricated by electron beam lithography. 1-μm-gate single recess FETs were also fabricated by standard photolithography. We have used wet chemical etching for gate recess, annealed Au/Ge ohmic metal for source–drain
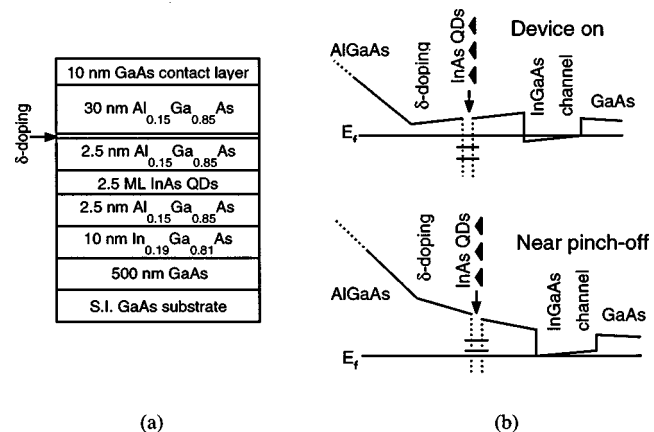

FIG. 1. Schematic of (a) transistor heterostructure grown by MBE and (b) the conduction band diagram of the transistor in conduction and near pinchoff.

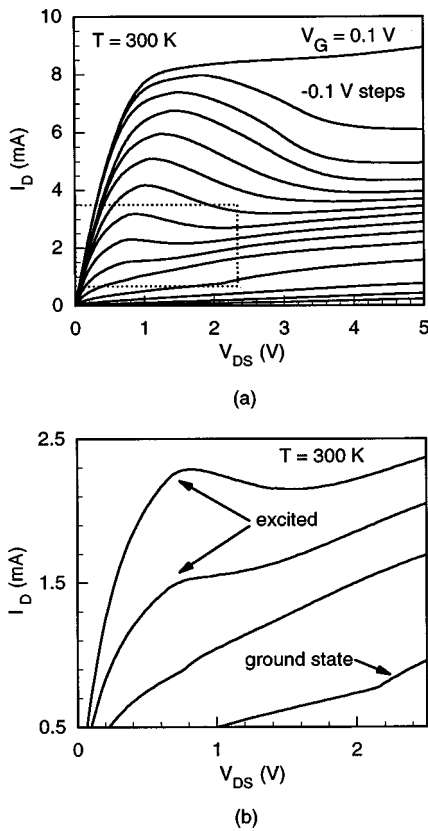[a]Electronic mail: pkb@eecs.umich.edu

FIG. 2. Quantum dot transistor ($L_{\text{gate}} = 0.3$ μm), (a) output characteristics ($I_D - V_{\text{DS}}$) and (b) a magnified region of the output characteristics showing nonlinear behavior and NDR for distinct gate voltages.

FIG. 3. Transfer characteristics of (a) 0.3-μm-gate QD transistor for varying V_{DS} and (b) the slope of the transfer characteristics as a function of gate bias.

contact, and Ti/Au for the Schottky gate. The gate width was 100 μm. The mounted 1-μm-gate devices were loaded in a closed cycle He cryostat for variable temperature measurements of their dc characteristics. The submicron gate devices were measured at room temperature with a dc probe station.

At room temperature, the drain current–voltage ($I_D - V_{\text{DS}}$) characteristics of the 0.3-μm-gate QD transistors, shown in Figs. 2(a) and 2(b), exhibit weak steps and a nonlinear behavior with varying gate voltage, with a strong negative differential resistance (NDR) region observed for certain values of gate bias. The transfer ($I_D - V_G$) characteristics, shown in Fig. 3, exhibit steps at two distinct values of V_G. The observed unique characteristics are a result of the additional conduction via the confined states of the quantum dots contributing to the conduction in the quantum well channel. This additional dot conduction is controlled by the gate bias, which changes the energy position of the Fermi level with respect to the bound states in the dot. The NDR region occurs close to the crossover of the Fermi level with the excited dot state and is believed to be due to the carrier escape from the excited state to the AlGaAs doping layer. The minimum NDR observed is 570 Ω. The energy level separation between the ground and excited states, ΔE, can be derived from the voltage separation, ΔV_G, between the steps in the $I_D - V_G$ characteristics using $\Delta E = \alpha \Delta V_G$. With $\Delta V_G \cong 1$ V and assuming α (the gate modulation coefficient) $\cong 0.1$,[21] we get $\Delta E \cong 80$ meV. From photoluminescence[22] and infrared absorption measurements[23] on similar In(Ga)As dots, we have determined the intersubband separation to be in the range of 60–100 meV, depending on the dot size and
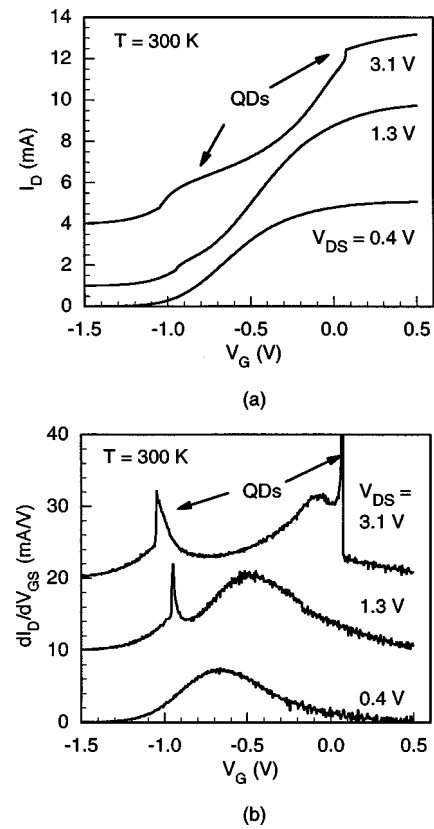
the barrier material. The current steps and the NDR are observed over a wide range of gate voltages, which is a result of the inhomogeneous distribution of dot energy levels that stems from the size distribution of the quantum dots themselves. The maximum transconductance of the devices, without including the current steps, is $g_m(\text{max}) = 120$ mS/mm. In comparison, all of the features mentioned above are not observed in a normal InGaAs/AlGaAs MODFET without the quantum dot layer.

Figure 4 shows the transfer characteristics of a 1-μm-gate device as a function of temperature. It should be noted that the heterostructure was grown and the device was fabricated separately from the submicron devices, leading to a different turn-on voltage. However, many of the same features are observed. The steps in these characteristics, due to bound state conduction in the dots, are more pronounced at low temperatures. As the temperature is increased the carrier leakage from the quantum dots increases. Evidence of such carrier leakage has been observed in self-organized quantum dot lasers.[24] Despite carrier leakage effects, step-like characteristics are clearly observed in the submicron devices at room temperature, showing their potential for room temperature applications. It is clear from Figs. 3 and 4 that the steps are not only a function of gate voltage but also the drain voltage. This means that a detailed two-dimensional charge control model is necessary in order to estimate the precise position of the Fermi level. The device characteristics described above can be made to approach those of a true single
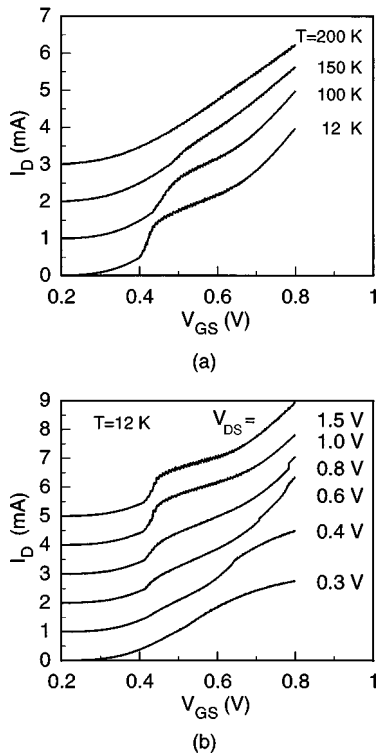
FIG. 4. Transfer characteristics of (a) 1-μm-gate QD transistor for varying temperature and (b) for varying V_{DS}.

electron transistor with partial or complete removal of the quantum well channel conduction, and also through reduction in device size where fewer dots lie under the active region.

In conclusion, we have demonstrated step-like transfer characteristics in a conventional InGaAs/AlGaAs MODFET structure with the addition of a layer of self-organized InAs quantum dots electronically coupled to the channel. These characteristics are observed at room temperature and are attributed to conduction via the bound states of the quantum dots.

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