Undoped high mobility two-dimensional hole-channel $GaAs/Al_xGa_{1-x}As$ heterostructure field-effect transistors with atomic-layer-deposited dielectric

T.M. Lu,[1,*] D.R. Luhman,[1] K. Lai,[1,†] D.C. Tsui,[1] L.N. Pfeiffer,[2] and K.W. West[2]

[1]*Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544*
[2]*Bell Laboratories, Lucent Technologies, 700 Mountain Avenue, Murray Hill, New Jersey 07974*

We have fabricated undoped p-channel $GaAs/Al_xGa_{1-x}As$ heterostructure field-effect transistors with nearly ideal drain current-voltage characteristics, using atomic-layer-deposited Al_2O_3 as the dielectric, and measured their transport properties. At 0.3K, the densities and mobilities of the two dimensional holes can be tuned up to $2.9\times10^{11}/cm^2$ and $6.4\times10^5 cm^2/Vs$ respectively. The variable density high mobility two-dimensional hole system provides a large parameter space for the study of two-dimensional physics. Appl. Phys. Lett. **90**, 112113 (2007)

High mobility two-dimensional electron gases (2DEGs) have benefited research in condensed matter physics and brought about many interesting physical phenomena [1]. Conventionally there are two ways of realizing 2DEGs. Modulation-doping is the most widely used technique for $GaAs/Al_xGa_{1-x}As$ heterostructures, in which electrons transfer from dopants in the barrier layer to the heterojunction interface and form the high mobility 2DEG. Metal-oxide-semiconductor field-effect transistors (MOSFETs) are quite popular for Si-based systems, utilizing a high quality thermal oxide not available in other semiconductors. In a MOSFET, the 2DEG is induced at the interface of the semiconductor and the amorphous oxide by an electric field. The nature of disorder in the two types of 2DEGs is significantly different and is expected to have impact on their physical properties.

Fabrication of enhancement-mode (e-mode) GaAs transistors has proved to be a difficult task, primarily due to the lack of a good thermal oxide on GaAs surfaces [2]. The heterostructure-insulated-gate field effect transistor (HIGFET), whose insulating layer is molecular beam epitaxy (MBE) grown $Al_xGa_{1-x}As$, is so far the only widely studied GaAs-based e-mode device [3, 4]. Different variations of the HIGFET have also been demonstrated [5–8]. However, the insulating layer has an intrinsically small barrier height. Significant leakage current flows at large gate voltages and limits the tunable density range of the 2D carriers.

Recently, Willett *et al.* [9] have demonstrated high mobility 2DEGs in undoped $GaAs/Al_xGa_{1-x}As$ heterostructures, using plasma-enhanced-chemical-vapor-deposited Si_3N_4 as the dielectric. There, the insulating layer is deposited after contacts are formed, preventing a short circuit between gate and contacts. An overlaid gate on both the 2D mesa and the contacts, when biased positively, draws electrons from the contacts and creates a 2DEG at the $GaAs/Al_xGa_{1-x}As$ interface. An electron mobility of $8\times10^6 cm^2/Vs$ was demonstrated at the highest density of $2.4\times10^{11}/cm^2$, comparable to that of the 2DEG in modulation-doped heterostructures. However, we note that in Ref. 9, the effective capacitance was less than 25% of the ideal value derived from the parallel capacitor model, indicating the presence of interface states. It is also known that plasma is harmful to the quality of the 2D electrons and degrades the mobility [10, 11].

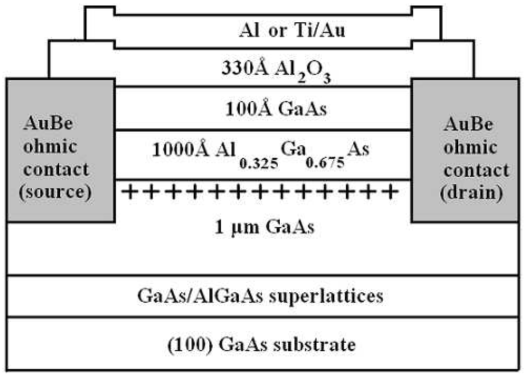

FIG. 1: Schematic view of the device structure of an undoped p-channel GaAs heterostructure transistor. The "+" signs denote the capacitively induced 2D hole layer.

In recent years, there has been much interest in using atomic-layer-deposited (ALD) Al_2O_3 as the insulator on GaAs-based devices [12, 13]. Employing a process similar to that described in Ref. 9, we have fabricated e-mode p-channel GaAs FETs on the (100) surface of undoped $GaAs/Al_xGa_{1-x}As$ heterostructures, using ALD Al_2O_3 as the dielectric. A high mobility two-dimensional hole gas (2DHG) is capacitively induced at the $GaAs/Al_xGa_{1-x}As$ interface, when the gate voltage is more negative than the threshold voltage V_T. The 2D hole density (p) varies linearly with the gate voltage up to $2.9\times10^{11}/cm^2$, and within this range, the leakage current remains virtually zero. At T=0.3K, the mobility increases with p and reaches $6.4\times10^5 cm^2/Vs$ at the highest density. The high quality of the 2DHGs is demonstrated by the observation of the integer and fractional quantum Hall effects (IQHEs and FQHEs).

Figure 1 shows the device structure schematically. The heterostructure consists of $1\mu m$ undoped GaAs, 1000Å $Al_{0.325}Ga_{0.675}As$ barrier layer, and 100Å GaAs cap layer grown on top of a semi-insulating (100) GaAs substrate by MBE. There are no intentional dopants

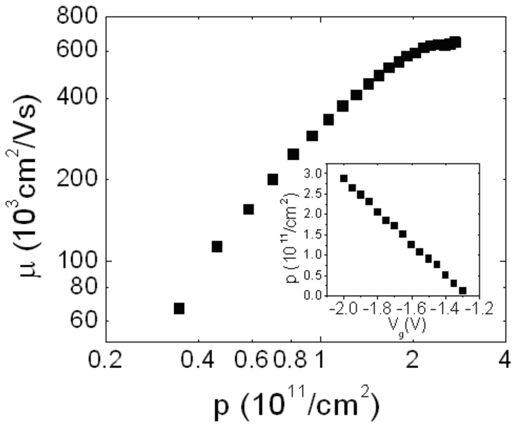

FIG. 2: μ vs p measured at T=0.3K. μ increases with p, and saturates for $p > 2.3\times10^{11}/\mathrm{cm}^2$. Inset: p vs. V_g. p is linearly dependent on V_g, with an effective capacitance of 63nF/cm^2. The density is determined from quantum oscillations in the longitudinal magnetoresistance.

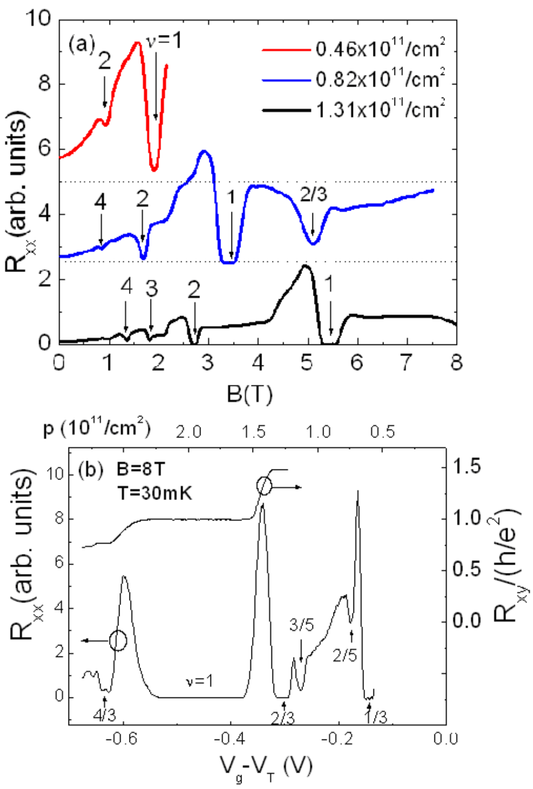

FIG. 3: (Color online) (a)Magnetoresistance R_{xx} at different densities at 0.3K. Curves are shifted vertically for clarity. The dotted lines represent the baselines for the top two traces respectively. (b)The IQHEs and FQHEs at B=8T. The gate voltage is converted to the density and the filling factor using the effective capacitance.

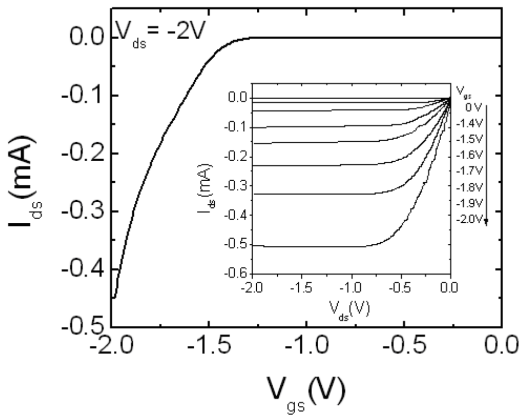

FIG. 4: I_{ds} vs. V_{gs}. A threshold voltage of -1.3V is observed, above which no current flows. Inset: Drain-source current-voltage characteristics.

throughout the heterostructure. The wafer was cut into 4mm $\times$ 4mm squares. The sample was first cleaned with dilute NH_4OH solution, and then treated with UV/O_3 for 5 minutes. After the contacts were defined photolithographically, 1500Å/150Å AuBe/Au was e-beam deposited on the sample, followed by a lift-off process. The sample was annealed in forming gas (90% N_2 + 10% H_2) at 500℃ for 3 minutes so that AuBe formed good ohmic contacts to the 2DHG. 300 cycles of ALD Al_2O_3 were then deposited over the top surface at 300℃ in a Cambridge NanoTech ALD system. Finally, the gate was defined by photolithography and e-beam deposition of either 2500Å Al or 50Å/2000Å Ti/Au. For DC magneto-transport measurements, the gate was a 400μm $\times$ 400μm van der Pauw square; for transistor characteristics, the width and length of the gate were both 600μm.

The magneto-transport properties were measured in the dark in a ^{3}He cryostat and a dilution refrigerator with a base temperature 0.3K and 20mK respectively, using standard low frequency (1-11Hz) lock-in techniques with excitation current less than 10nA. The density of 2D holes, determined from quantum oscillations in the longitudinal resistance (R_{xx}), varies linearly with the gate voltage (V_g), as shown in the inset of Fig. 2. The effective capacitance C_{eff} is 63nF/cm^2, within 10% of the expected value 69nF/cm^2 derived from the parallel capacitor model. The high quality interface between the ALD oxide and the heterostructure is confirmed by the nearly ideal capacitance. The threshold voltage (V_T) is $\sim$ -1.25V, above which no 2D holes are present at the GaAs/Al$_x$Ga$_{1-x}$As interface, as expected for an e-mode device. We note that V_T varies slightly from cooldown to cooldown, a common feature for devices operating at low temperatures [14]. The dependence of mobility (μ) on p and the effective capacitance, however, remains the same for each cooldown.

The mobility increases with p and saturates at

6.4×10^5cm^2/Vs for p greater than 2.3×10^{11}/cm^2, as shown in Fig. 2. As can be seen from the curvature of the data, the dependence of μ on p does not follow a simple power law $\mu \sim p^\alpha$, contrary to other high mobility 2DHGs [3, 15]. Nevertheless, we extract the exponent α piecewise so that a first-order comparison between our devices and other structures can be made. The values of α range from 1.6 to 0.9 for densities smaller than 2.0×10^{11}/cm^2, and are much larger than that reported previously for HIGFETs [3] and modulation-doped structures[15], suggesting a different dominant scattering mechanism in our devices. Having no intentional dopants, our devices are expected to have a different type of disorder than modulation-doped structures. The primary difference between our devices and HIGFETs is the cleanness of the interface between the insulator and the heterostructure. In a HIGFET, the insulator itself is part of the heterostructure and is almost free of imperfections. In our devices, the ALD oxide is deposited after the heterostructure growth. The interface, in spite of the nearly ideal capacitance, may contain defects, trapped ions, and charged interface states, which may become the dominant disorder when the material itself is ultra clean. The effect of interface pretreatment on mobility is currently under investigation.

Figure 3 (a) shows R_{xx} as a function of magnetic field (B) for three densities at 0.3K. Vanishing minima near integer fillings confirms the high-quality and uniformity of the 2DHG, and rule out the existence of a parallel conducting channel. For high densities, beating in R_{xx} at low B is observed (too small to be seen in Fig. 3), a common feature of a high mobility 2DHG in an asymmetric quantum well[16]. In addition to scanning B, the QHEs can be studied by sweeping the density as well, a distinct advantage of density-tunable devices. Figure 3 (b) shows such a sweeping at B=8T at 30mK. As the density increases, the Landau levels are gradually filled. The IQHEs are observed at integer fillings, when the Fermi level lies in the gaps of the Landau levels, while the FQHEs occur at odd-denominator filling factors, due to electron-electron interaction. We convert V_g to p, using the linear equation p=$C_{eff} \times (V_T - V_g)/e$, where e is the elementary charge. p is then converted to the filling factor, defined as ν=$p/(eB/h)$, where h is Planck's constant. The minima in R_{xx} align satisfactorily with ν=4/3, 1, 2/3, 3/5, 2/5, and 1/3, exactly where the IQHEs and FQHEs are expected to be observed. We also note that the density corresponding to ν=1/3 at B=8T is only about 6.4×10^{10}/cm^2. The fact that the minimum at ν=1/3 at such low density reaches zero implies the exceptional quality of the 2DHG.

Apart from the possible applications for studying 2D physics, e-mode high mobility transistors are of practical importance as well, as they are the building blocks of complementary GaAs circuits. To demonstrate transistor operation, the drain current-voltage characteristics were measured at 4K. In the inset of Fig. 4, the drain-source current-voltage traces at several gate voltages are shown. Except for the trace with V_{gs}=0V, the drain-source current $|I_{ds}|$ increases with $|V_{ds}|$ approximately quadratically at small $|V_{ds}|$. $|I_{ds}|$ saturates when $|V_{ds}|$ is larger than a characteristic value. The saturation current is shown in Fig. 4, where V_{ds} is fixed, and V_{gs} is swept from 0V to -2V. A threshold voltage is evident around $|V_{gs}|$=1.3V, below which no drain-source current flows.

In summary, we have fabricated undoped high mobility 2D p-channel GaAs/Al$_x$Ga$_{1-x}$As heterostructure FETs with ALD dielectric. 2D holes can be induced capacitively at the GaAs/Al$_x$Ga$_{1-x}$As interface. The IQHEs and FQHEs are observed, indicating the high quality of the 2DHGs. The operation of e-mode p-channel transistors has also been demonstrated. The high mobility 2DHGs realized in such devices provide a unique system with a different type of disorder, and are expected to bring us more insight into 2D physics.

A portion of this work was performed at the National High Magnetic Field Laboratory, which is supported by NSF Cooperative Agreement No. DMR-0084173, by the State of Florida, and by the DOE. The work at Princeton University is funded by the Princeton MRSEC (NSF-DMR0213706) and the AFOSR (FA9550-04-1-0370, Donald Silversmith).

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* Electronic mail: tmlu@princeton.edu
† Present address: Department of Applied Physics, Stanford University, Stanford, California 94305

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