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Huge positive magnetoresistance in a gated AlGaAs/GaAs high electron mobility transistor structure at high temperatures

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Magnetoresistivity measurements on a gated AlGaAs/GaAs high electron mobility transistor (HEMT) structure were performed at high temperatures T. By changing the applied gate voltage V_g, we can investigate the observed huge positive magnetoresistance (PMR) at different effective disorder and density inhomogeneity within the *same* HEMT structure. The observed PMR value increases with increasing disorder in the depletion mode ($V_g \leqslant 0$). Moreover, the PMR value is *not* limited by the quality of the HEMT structure at $T=80$ K. Such results pave the way for low-cost, high-throughput GaAs-based HEMT fabrication for future magnetic sensing and recording devices fully compatible with the mature HEMT technology. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2906360]

AlGaAs/GaAs high electron mobility transistor (HEMT) structures have been attracting a great deal of interest because of their applications in low-noise, high-frequency amplifiers, in microwave and millimeter wave communications, in radar and radio astronomy, and in logic elements. In addition, the two-dimensional electron system (2DES) situated at the AlGaAs/GaAs interface is an ideal testing ground for interesting physics. For example, the fractional quantum Hall effect was first observed in the 2DES in a high-quality GaAs/AlGaAs HEMT structure.[1] Therefore, the AlGaAs/GaAs HEMT structure is extremely useful not only for applied sciences but also for basic research.

Devices showing large magnetoresistance (MR) are of promising applications as they can be used as magnetic sensors, logic elements, and magnetic storage and recording devices. For example, a read-head sensor can be realized based on tunneling MR[2] or giant MR (GMR)[3,4] in layered magnetic metals. Very recently, we have demonstrated that AlGaAs/GaAs HEMT structures show huge positive MR (PMR) at high temperatures.[5] The huge PMR can be described by a model based on macroscopic inhomogeneity within a two-dimensional semiconductor.[5,6] To fully realize its potentials as future magnetic devices, it is highly desirable to study how the MR value varies with changing the gate voltage V_g, effective disorder, and density inhomogeneity within the *same* gated AlGaAs/GaAs HEMT structure. In this letter, we shall present such measurements at high temperatures ($35\text{ K} \leqslant T \leqslant 80\text{ K}$). Interestingly, our experimental results show that in the depletion mode ($V_g \leqslant 0$), the MR value increases with increasing effective disorder and density inhomogeneity within our HEMT structure. We show that the PMR value is not limited by the quality of the HEMT structures at $T=80$ K. Such interesting results lay the foundation for mass-productive, low-cost and high throughput GaAs-based HEMT fabrication using, for example, metal-organic chemical-vapor deposition (MOCVD) for possible future magnetic devices fully compatible with the mature HEMT technology.

The gated HEMT structure LM4656 used in this work was made from an $Al_{0.33}Ga_{0.67}As$/GaAs heterostructure grown by molecular beam epitaxy (MBE). The following layer sequence is grown on a semi-insulating GaAs substrate: 1 μm undoped GaAs, 20 nm undoped $Al_{0.33}Ga_{0.67}As$, 40 nm Si-doped ($3.66\times10^{18}\text{ cm}^{-3}$) $Al_{0.33}Ga_{0.67}As$, and 10 nm undoped GaAs. At $V_g=0$, sample LM4656 has a 2DES density of $\approx 2.5\times10^{11}\text{ cm}^{-2}$ with a mobility of $\approx 7.5\times10^4\text{ cm}^2/\text{V s}$ for $T=0.3$ K. The experiments were performed in a top-loading He^3 cryostat equipped with a superconducting magnet. Since we are interested in the high-temperature resistivities of our device, the measurement temperature was chosen to be between 35 and 80 K. Four-terminal magnetoresistivity measurements $\rho_{xx}(B)$ were performed using standard ac phase-sensitive lock-in techniques. Over the whole measurement range, the gate-2DES leakage

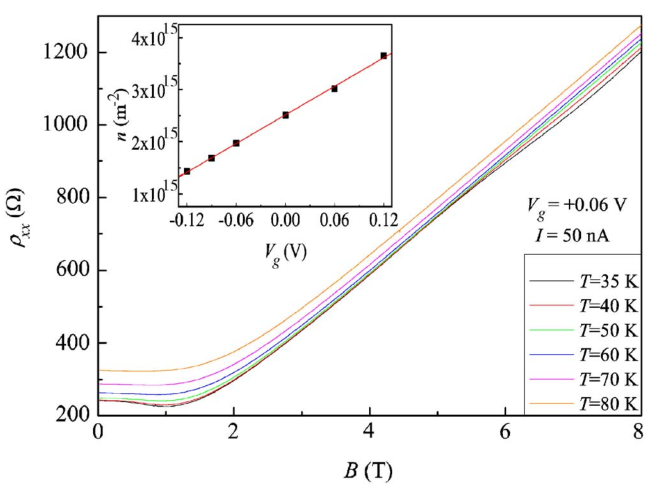

FIG. 1. (Color online) Magnetoresistivity measurements $\rho_{xx}(B)$ at various temperatures T. The inset shows the measured 2DES density n as a function of V_g. The linear fit is discussed in the text.

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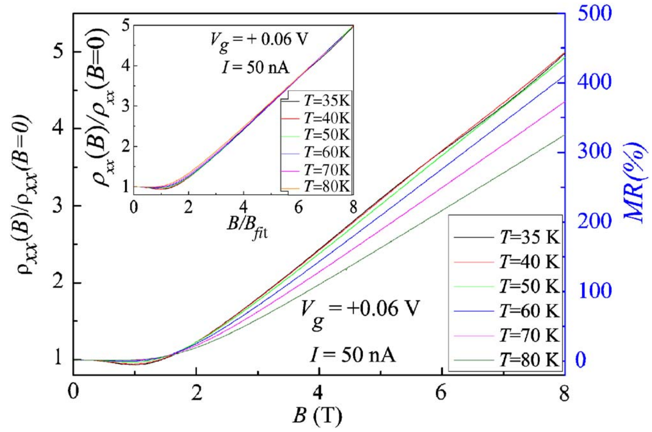

FIG. 2. (Color online) $\rho_{xx}(B)/\rho_{xx}(B=0)$ and $\mathrm{MR}=\Delta\rho_{xx}/\rho_{xx}=\rho_{xx}(B,T)-\rho_{xx}(0,T)/\rho_{xx}(0,T)$ as a function of magnetic field B at different temperatures T. The inset shows $\rho_{xx}(B)/\rho_{xx}(B=0)$ as a function of B/B_{fit} for various temperatures.

current is kept below 10 nA. The magnetic field B is applied perpendicular to the plane of the 2DES.

Figure 1 shows magnetoresistivity measurements $\rho_{xx}(B)$ at various T for $V_g=0.06$ V. For $B\geqslant 3$ T, almost linear PMR can be observed. The observed PMR becomes less pronounced at higher T but persists up to $T=80$ K. The inset to Fig. 1 shows the measured 2DES density n as a function of V_g. We can see that n shows a good linear dependence on V_g, consistent with the well-known parallel-plate capacitor model in which one is the Schottky gate and the other is the 2DES. The depth of the 2DES can be estimated to be about 75 nm. This is in excellent agreement with the as-grown value of 70 nm.

Figure 2 shows $\rho_{xx}(B)/\rho_{xx}(B=0)$ and the MR value which is defined as $\mathrm{MR}=\Delta\rho_{xx}/\rho_{xx}=[\rho_{xx}(B,T)-\rho_{xx}(0,T)]/\rho_{xx}(0,T)$ at different temperatures for $V_g=0.06$ V. We can see that both $\rho_{xx}(B)/\rho_{xx}(B=0)$ and MR decrease with increasing T. For $B=8$ T, the MR value is $>300\%$ even at the highest measurement temperature $T=80$ K. The weak negative MR at low fields can be ascribed to evidence for electron-electron interaction effects.[7] The inset to Fig. 2 shows $\rho_{xx}(B,T)/\rho_{xx}(0,T)$ as a function of B/B_{fit} for various temperatures. Here, B_{fit} is a parameter which scales the experimental results.[5] The collapse of the data is reasonable. Following the procedure described in Ref. 5, we are able to estimate the root mean square density inhomogeneity $\Delta n/n$ to be $\sim 12\%$ at $V_g=0.06$ V. Such a value is about a factor of 2 larger than those obtained in much higher mobility samples.[5]

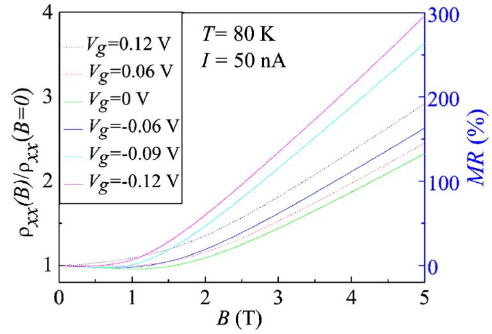

FIG. 4. (Color online) $\rho_{xx}(B)/\rho_{xx}(B=0)$ and $\mathrm{MR}=\Delta\rho_{xx}/\rho_{xx}=\rho_{xx}(B)-\rho_{xx}(B=0)/\rho_{xx}(B=0)$ as a function of magnetic field at various gate voltage for $T=80$ K.

We now describe our main experimental findings. Figures 3 and 4 show $\rho_{xx}(B)/\rho_{xx}(B=0)$ and MR as a function of magnetic field at various V_g for $T=35$ K and $T=80$ K, respectively. We can see that for the depletion mode ($V_g\leqslant 0$), both $\rho_{xx}(B)/\rho_{xx}(B=0)$ and MR increase with increasing negative gate voltage over the whole measurement range. The data for the enhanced mode ($V_g\geqslant 0$) do not seem to show a trend compared with those obtained for $V_g\leqslant 0$. It may be possible that in the enhanced mode, the zero-field resistivity is considerably smaller than those in the depletion mode, causing large MR and $\rho_{xx}(B)/\rho_{xx}(B=0)$ values. Since a HEMT device is normally operated in the depletion mode, we shall concentrate on the results for $V_g\leqslant 0$.

By studying $\rho_{xx}(B)/\rho_{xx}(B=0)$ as a function of B/B_{fit} at various temperatures for a fixed gate voltage, we are able to estimate $\Delta n/n$ as a function of V_g. Such results are shown in Fig. 5. We can see that in the enhanced mode ($V_g\geqslant 0$), $\Delta n/n$ is approximately constant. In the depletion mode ($V_g\leqslant 0$), $\Delta n/n$ shows a substantial increase with increasing negative gate voltage. Therefore, with increasing negative voltage, the effective disorder within our HEMT structure is vastly increased, thereby, resulting in a larger MR value.

We wish to point out that, however, our results do not imply that in order to optimize the PMR value, one should deliberately use a highly disordered structure. Suppression of weak localization and/or possible electron-electron interactions[7] can cause negative MR even at high

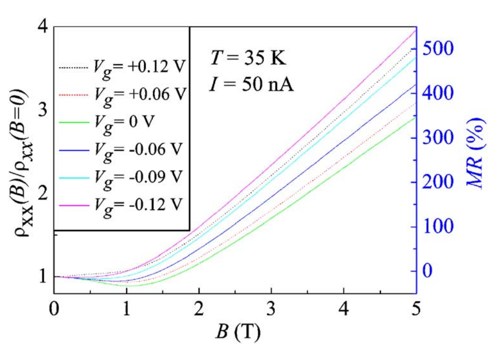

FIG. 3. (Color online) $\rho_{xx}(B)/\rho_{xx}(B=0)$ and $\mathrm{MR}=\Delta\rho_{xx}/\rho_{xx}=\rho_{xx}(B)-\rho_{xx}(B=0)/\rho_{xx}(B=0)$ as a function of magnetic field at various gate voltage for $T=35$ K.

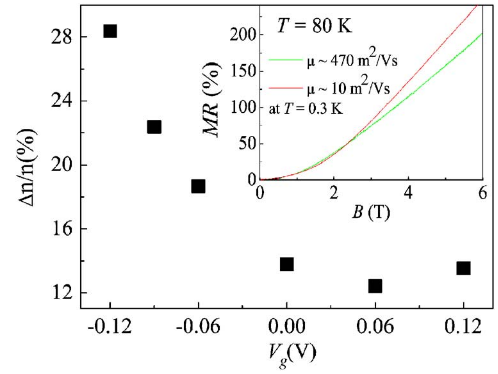

FIG. 5. (Color online) Determined density inhomogeneity $(\Delta n/n)(V_g)$. The inset shows MR of two samples with vastly different low-temperature mobilities.

temperatures, hindering observation of PMR in a low-mobility sample.

For potential applications as magnetic sensing and storage devices, it is highly desirable to achieve a large MR value at above liquid nitrogen temperatures. For this purpose, we replot the MR result for $V_g=0.12$ V, together with the result obtained from a much higher-quality HEMT structure, at $T=80$ K. The data for $V_g=0.12$ V is chosen so that the carrier densities of the two devices are identical in the inset to Fig. 5. For $B<2.5$ T, the MR values are almost identical, despite the large difference between their mobilities (a factor of ≈ 50 at $T=0.3$ K and a factor of $18.6/6.9 \approx 3$, even at $T=80$ K). For $B>2.5$ T, the lower-mobility sample even shows a larger MR value. Therefore, our data indicate that it does not require state-of-the-art MBE techniques for growing ultra high quality AlGaAs/GaAs HEMT structures[8–10] for the purpose of future magnetic devices.

It is particularly useful to achieve a reasonable MR value in the low field regime for practical device applications. It is known that a 50-nm-deep 2DES can be subject to a perpendicular magnetic field of ~ 0.55 T, introduced by a ferromagnetic film deposited above the 2DES.[11] By simply decreasing the depth of the 2DES to ~ 40 nm, such a ferromagnetic film can induce a perpendicular field of ~ 1.1 T, since the stray field experienced by the 2DES is inversely proportional to the cube of the film-2DES distance. At $B \sim 1.1$ T, the MR value of our HEMT device is $\sim 10\%$ at $V_g=-0.12$ V and $T=80$ K. This MR value is comparable to those of GMR devices (10%–20%) reported in the literature.[12,13] By depositing a ferromagnetic film on top of the HEMT structure and decreasing the 2DES depth, we may achieve the low field regime ($B \sim 1$ T) for potential and low-cost magnetic sensing and storage devices using GaAs-based HEMT structures.

In conclusion, we have presented magnetoresistivity measurements on a gated AlGaAs/GaAs HEMT structure at high temperatures. Huge positive MR is observed and persists up to $T=80$ K. The huge PMR can be described by a model based on macroscopic inhomogeneity within a two-dimensional semiconductor. In the depletion mode, the MR value increases with increasing negative gate voltage and effective disorder within our HEMT structure. This interesting effect can be ascribed to vastly enhanced density inhomogeneity (from $\sim 12\%$ to $\sim 28\%$) as estimated using a simple effective medium approximation model.[5,6] Interestingly, our results indicate that at above liquid nitrogen temperatures, the MR value is not limited by the mobility of the HEMT structure. Our results, therefore, pave the way for low-cost, high-throughput GaAs-based HEMT fabrication using, for example, MOCVD for future magnetic sensing and recording devices which are fully compatible with the mature HEMT technology in industry.

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