Effects of N Incorporation on the Electronic Properties of GaAsN-Based Modulation-Doped Heterostructures

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Introduction:

Dilute nitride (In)GaAsN alloys are useful for applications in infrared laser diodes, high-efficiency solar cells, and high-performance heterojunction bipolar transistors. The addition of N to GaAs-based semiconductors decreases the bandgap energy without drastically affecting the lattice parameter. To date, literature reports have presented substantially lower electron mobilities for dilute nitride semiconductor alloys in comparison with those of (In)GaAs. Furthermore, for (In)GaAsN alloys, the electron mobility has been reported to decrease as the N incorporation increases. At present, the precise role of N in reducing the electron mobility is not well understood. In order to study nitrogen-related electron scattering effects in GaAsN, with minimal contributions from ionized impurity scattering, we are examining the transport properties of modulation-doped AlGaAs/GaAs(N) heterostructures, with Si dopants in the AlGaAs barrier layer spatially separated from the nominally undoped GaAs(N) channel layer. We will discuss the dependence of the mobility on carrier density, with a focus on the insulating phenomena associated with multiple scattering effects past a critical carrier density.

Experimental Procedure:

The heterostructures consisted of modulation-doped AlGaAs/GaAs(N) heterostructures grown via molecular beam epitaxy (MBE), on GaAs (001) substrates. An initial 500 nm thick GaAs buffer layer was grown at 580°C. After buffer layer growth, a 50 nm thick GaAs(N) channel was grown at 400°C. Next, a 5 minute pause was used to ramp the substrate temperature to 580°C, and layers of 1 nm GaAs, 20 nm undoped $Al_{0.3}Ga_{0.7}As$, 60 nm Si-doped $Al_{0.3}Ga_{0.7}As$, and 10 nm GaAs were then grown in succession. Carriers from the Si-doped AlGaAs layer migrated into the GaAs(N) channel and were confined in a triangular well, producing a two dimensional electron gas (2DEG). The undoped AlGaAs layer enabled spatial-separation of the 2DEG and the ionized impurities, thereby minimizing the Coulombic long-range scattering effects on the carriers [2]. The density of free carriers in the channel was further controlled by front gating, or by illumination at low temperature.

Electron transport measurements were implemented with eight-arm gated-Hall bars (1050 x 150 μm), fabricated by standard contact photolithographic processes, with e-beam evaporated Ni/Ge/Au/Ti/Au (200/325/650/200/2000 Å) contacts and Ti/Au (100/1000 Å) gates. The mesa and contacts/gate were defined using positive and negative photolithography and a phosphoric acid etch [6]. Prior to gate deposition, the contacts were annealed at 410ºC for 2 minutes in argon gas.

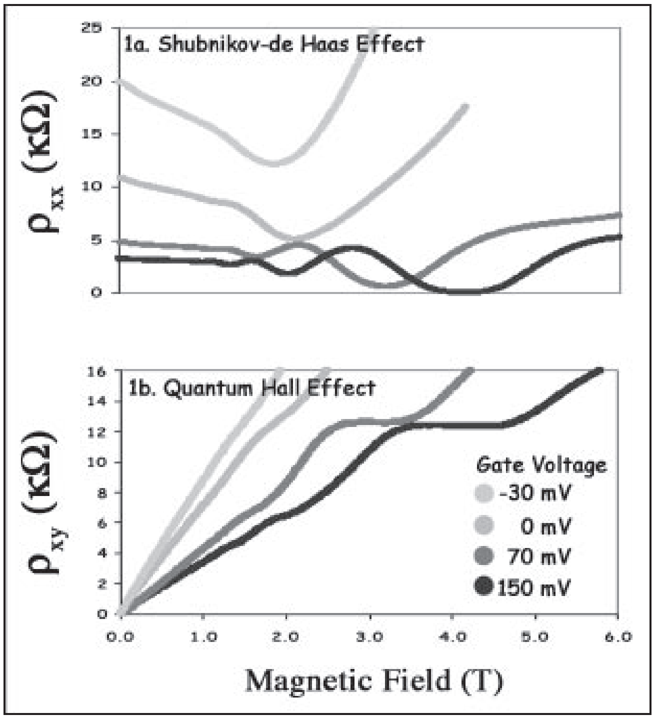

Figure 1: Magnetic field dependence of rxy and rxx, at T = 4.2K for a gate-controlled 2DEG.

Magnetoresistance measurements were performed at 4.2K, with the magnetic field swept from 0 to 7 Tesla in a superconducting NbTi magnet. To modulate the free carrier density in the 2DEG, the gate voltage was swept from -60 mV to 150 mV, and data were collected every 10 mV. A near-infrared light emitting diode was also used to illuminate the sample surface, to increase the free carrier density in the 2DEG, through the persistent photoconductivity effect [3].

Results and Conclusions:

In Figure 1(a), the minima of the Shubnikov-de Haas oscillations in the magnetoresistance data correspond to the Quantum Hall plateaus in Figure 1(b). Both of these quantum phenomena result from the increasing magnetic field altering the spacing between the Landau levels, thus sweeping the Landau levels with respect to the Fermi level. As the gate voltage decreases from 150 mV to -30 mV, the carrier density (resistivity) decreases (increases), and the Shubnikov de Haas oscillations and quantum Hall plateaus become less apparent, as shown in Figure 1.

From the gated resistivity and Hall effect measurements, we calculated the carrier density and carrier mobility at each gate voltage, shown in Figure 2. One characteristic of the relation between carrier density and mobility was the metal-insulator transition behavior due to multiple scattering effects at carrier densities below a critical carrier density (Nc). Based on the structure and doping level of our 2DEG, we predicted our critical carrier density to be around 7 x 10^{10}cm^{-2} [4]. The gated 2DEG data exhibited a deviation from power law dependence, recognized as the critical carrier density, at about 9 x 10^{10}cm^{-2} as shown in Figure 2.

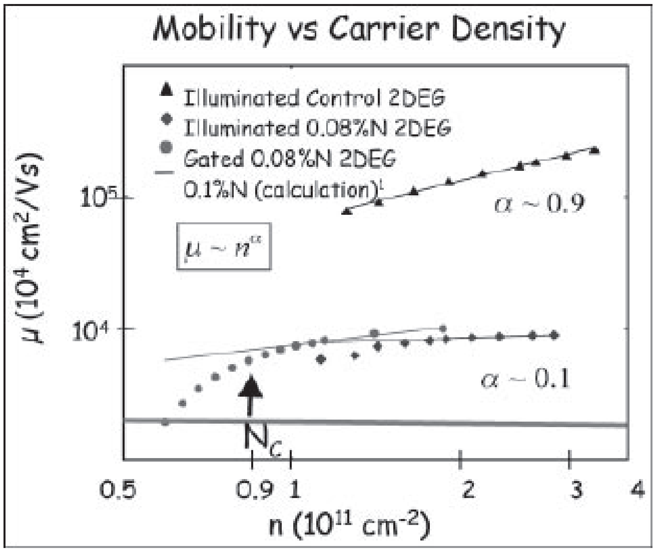

Figure 2: Electron mobility as a function of carrier density, measured at 4.2K.

The relationship between carrier density and carrier mobility for densities above 9 x 10^{10}cm^{-2} reveals information about the mechanisms of electron scattering by N atoms. The dependence of mobility on carrier density can be expressed as $\mu \sim n^{\alpha}$ [5]. The α values correspond to the slope of a linear-least squares fit to log (μ) vs. log (n). In the control 2DEG, $\alpha \sim 1$, suggesting remote ionized impurity scattering due to Coulombic interactions between the free carriers and the ionized impurities, is the dominant scattering mechanism. The mobility increases rapidly with n, due to increased screening of the ionized impurity potential. For the 0.08%N 2DEG, $\alpha \sim 0.1$, indicating ionized long-range scattering is likely not the dominant mechanism. The increased carrier density does not have the same screening effect on neutral scatterers, and therefore does not increase the mobility. For $n > N_c$, μ is independent of n, similar to calculations which assume N acts as a neutral independent local scatterer [1], as shown by the line in Figure 2. Thus, we tentatively conclude that N acts as a neutral, short-range scatterer.

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