Shubnikov-de Haas oscillations in AlN/GaN/AlN quantum-wells on single-crystal AlN substrates

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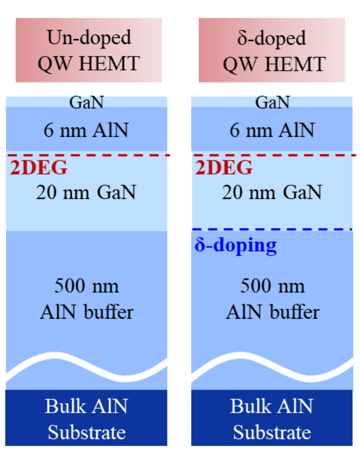
AlN/GaN/AlN quantum well high electron mobility transistor (QW HEMT) heterostructures feature large energy band offsets between GaN well of ≈ 20 nm surrounded by AlN back barrier of ≈ 500 nm and AlN top barrier of ≈ 5 nm. The AlN layers have no strain as they are grown on single-crystal bulk substrate, whereas the GaN channel is under a large compressive strain of -2.3%, which modifies its energy-momentum dispersion. The large discontinuity in spontaneous and piezoelectric polarization between GaN and AlN induces a 2D electron gas (2DEG) of high density (~$2\text{x}10^{13}$ cm^2) with highly populated electronic sub-bands. This undoped binary heterostructure typically exhibits electron mobilities of approximately 1200 cm^2/Vs at 10 K, limited by Stark-effect scattering from a) the strong internal electric field in the well, and b) Coulomb drag, and parallel conduction between the 2DEG and polarization-induced 2D hole gas (2DHG) present on opposite sides of the well forming a bilayer in undoped control samples [Figure 1 (a)].

To remove the 2DHG and reduce the electric field in the well, we incorporated n-type compensation δ-doping in the AlN/GaN/AlN heterostructure [Figure. 1 (b)], which resulted in enhanced Hall-mobilities of 854.1 cm^2/Vs at RT and 2240.2 cm^2/Vs at 10 K, and as a result record low sheet resistances (86.9 Ω/□ at 10 K) [Table. 1]. Shubnikov-de Haas (SdH) oscillations in the longitudinal magnetoresistance were observed in both heterostructures with an onset of ~ 8 Tesla [Figures. 2(a) and 2(b)]. The Fast Fourier Transform (FFT) of ΔR_{xx} reveals single oscillation frequency, indicating one sub-band occupation [inset of Figs. 2(c) and 2(d)]. Analysis of the FTT amplitudes indicates an electron effective mass $m^* \approx 0.26\ m_0$ for the un-doped QW and $\approx 0.28\ m_0$ for the δ-doped QW [Figures. 2(c) and 2(d)], slightly higher than ≈ 0.2-0.23 m_0 in conventional AlGaN/GaN heterostructures of lower 2DEG densities, possibly due to the compressive strain of the GaN channel and the strong nonparabolicity of the sub-band at high energies. Finally, δ-doped QW HEMTs exhibit twice the quantum scattering lifetime τ_q than the un-doped counterpart. A Dingle ratio $\tau_{classic}/\tau_q \cong 2.58$ at 2 K suggests the prevalence of short-range scattering potentials, likely arising from interface roughness (IR) scattering [Figures. 2 (e)-(f)].



QW HEMT	$n_s^{10\,K}$ (10^{13} cm^{-2})	$\mu^{10\,K}$ (cm^2/Vs)	$R_s^{10\,K}$ (Ω/□)
Un-doped	2.01	1211.5	255.9
δ-doped	3.21	2240.2	86.86

Figure 1. Schematics of the (a) un-doped and (b) δ-doped AlN/GaN/AlN heterostructures.

Table 1. 2DEG densities, mobilities and sheet resistances measured via Hall-effect at 10 K.

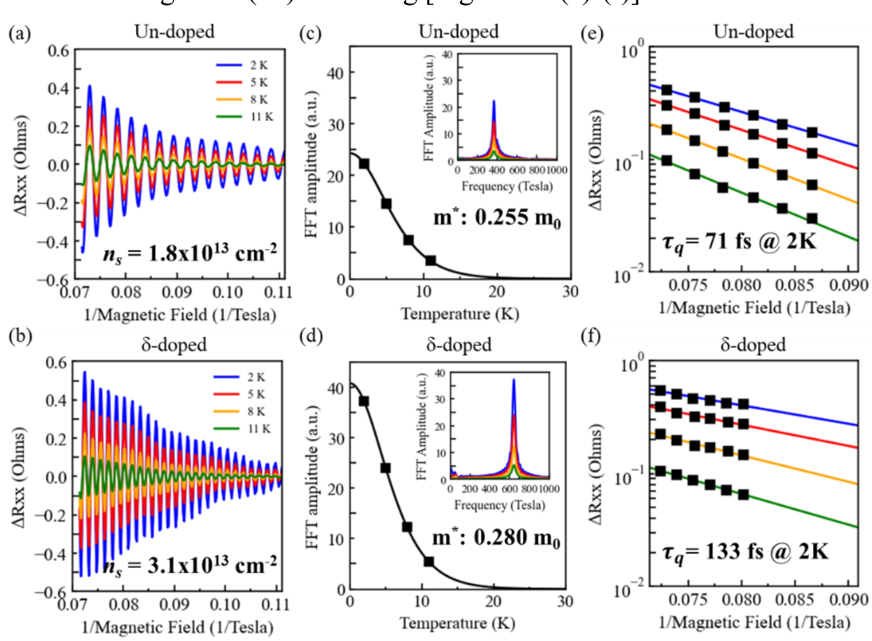


Figure 2. (a)-(b) SdH oscillations in the un-doped and δ-doped GaN QW heterostructures, respectively. The 2DEG densities extracted from the oscillation periods are consistent with the low-field Hall measurements. (c)-(d) Thermal damping of FFT amplitudes indicates electron effective mass in GaN QW heterostructures. Insets show the single oscillation frequency peaks from FFT analysis. (d)-(e) δ-doped GaN QW heterostructures exhibits longer τ_q than its undoped counterpart.