Magnetotransport Characterization of a Two-Dimensional Electron System in an AlGaN/AlN/GaN Heterostructure

Shubnikov–de Haas (SdH) oscillations are quantum oscillations observed in the longitudinal electrical resistivity of materials subjected to low temperatures and strong magnetic fields. These oscillations arise due to the quantization of electronic energy levels into Landau levels (LLs), which leads to periodic variations in the density of states at the Fermi level as the magnetic field is varied. The frequency of SdH oscillations is inversely proportional to the magnetic field and directly related to the extremal cross-sectional area of the Fermi surface perpendicular to the field direction.

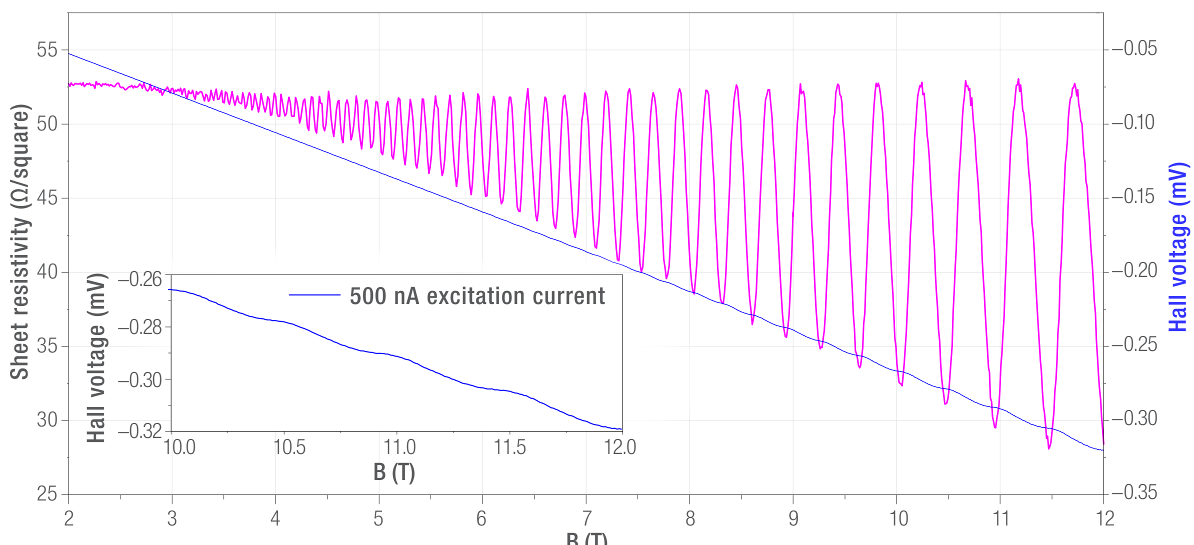


Figure 1

Sheet resistivity and Hall voltage are shown as a function of applied external magnetic field. The inset shows Hall voltage at higher magnetic fields.

SdH measurements are a powerful tool for probing electronic properties of materials. They enable the extraction of key parameters such as carrier concentration, mobility, scattering times, and effective mass, and provide insights into the geometry of the Fermi surface. This phenomenon has been widely observed in systems such as two-dimensional electron gases (2DEGs), graphene, van der Waals heterostructures, semiconductors, topological insulators, and metals.[1-5] Recently, SdH oscillations have also been reported in Kondo insulators,[6] where a well-defined Fermi surface is traditionally absent. This unexpected observation has sparked significant theoretical interest, prompting new models to explain quantum oscillations in insulating systems.

Experiment

In this work, SdH measurements were performed on an AlGaN/AlN/GaN heterostructure using a Lake Shore DryMag™ superconducting magnet platform with a 12 T superconducting magnet and a sample space operating down to 1.5 K. The device was mounted perpendicular to the magnetic field on a Hall sample holder outfitted with cryogenic triaxial cabling, and measurements were carried out using a Lake Shore M91 FastHall™ controller. Field and temperature were programmatically controlled and data collected through a sequence written in MeasureLINK™ software. All measurements were performed at device temperature of 1.6 K.

Before starting the Hall measurements, a quick contact check was executed to ensure that all contacts made with the device and the sample holder pins are intact. Then low field Hall measurements were performed to extract sheet carrier concentration, n_H ,and mobility, μ_H. At 1.6 K, this sample has a μ_H ~10,000 cm^2/Vs with n_H is in the order of ~10^{13}/cm^2.

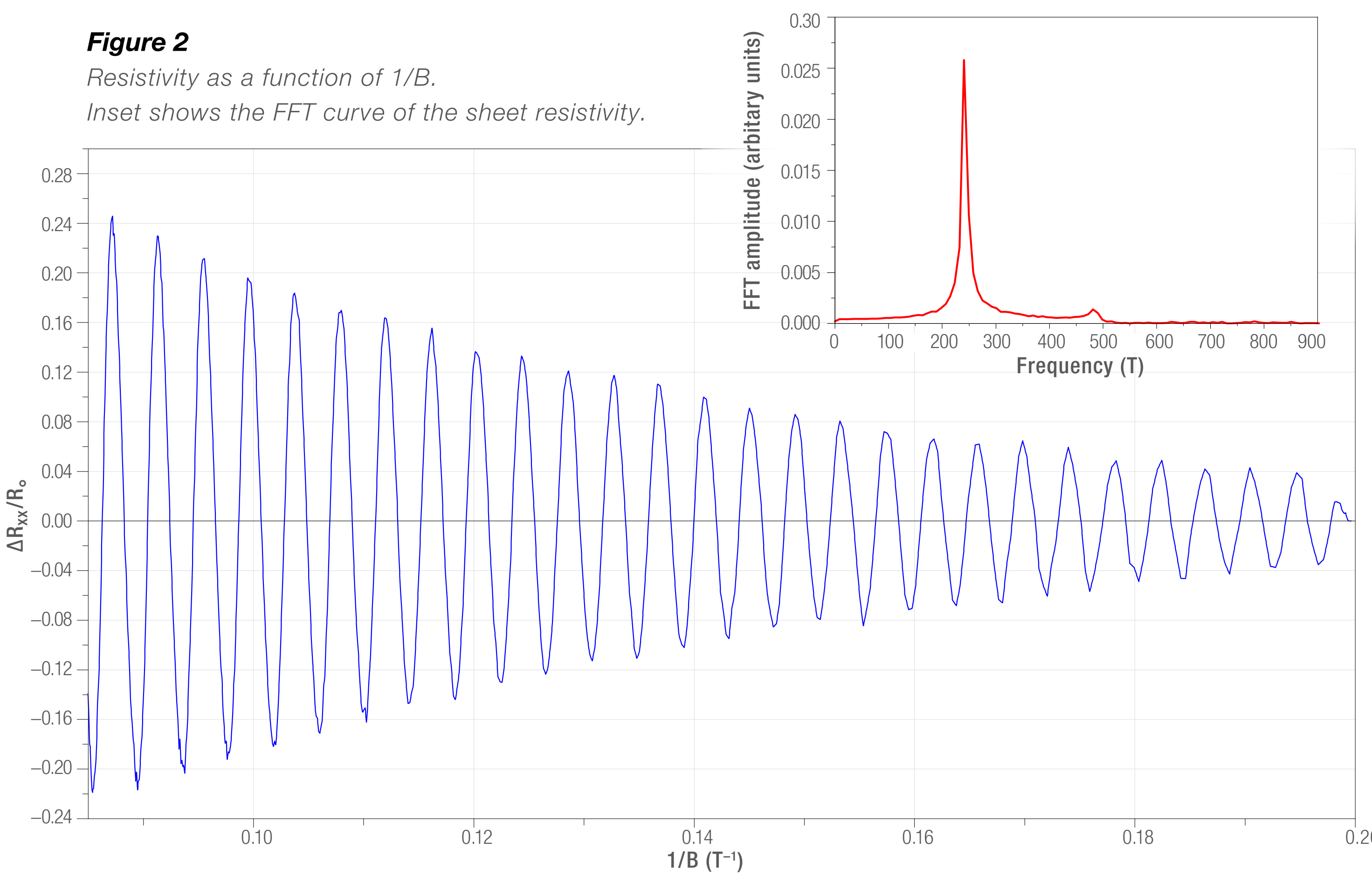
At higher fields, the onset of SdH oscillations is evident at fields greater than 4 T whereas the Hall voltage plateaus can be observed >7.5 T. The observed Hall voltage plateaus at the ρ minima point to the emergence quantum Hall effect in this 2DEG device; however, the plateaus have a finite slope suggesting the presence of dissipation states.[7]

Results and Discussion

To simplify the extraction of the transport parameters, the non-linear resistivity background was first removed from the measured SdH oscillation data. Here the sheet resistivity is normalized by the zero-field value, then plotted versus inverse field, and interpolated to achieve even data intervals in 1/B. The interpolated data is smoothed using an adjacent-averaging method to remove the SdH oscillations, leaving only the background resistivity. **Figure 2** shows a plot of corrected $\Delta R_{xx}/R_o$ after the background is subtracted.

Figure 2

Resistivity as a function of 1/B.
Inset shows the FFT curve of the sheet resistivity.



The inset of the figure shows the Fourier transform curve, and the frequency (B_f) of the oscillation extracted from FFT is ~240 T. The SdH carrier concentration computed from equation, $n_{\mathrm{SdH}} = 2eB_f/h$ where h is the Planck's constant and e is the electron charge ~$1.16 \times 10^{13}/cm^2$ which is in good agreement with the carrier concentration measured at low fields.

To obtain quantum scattering time, τ_q, a Dingle plot (**Figure 3**) is generated using the known expression[8]:

$$ln\left(\frac{A\,sinhX}{X}\right) = C - \frac{\pi m^*}{e\tau_q}$$

where $A = \frac{\Delta R}{4R_0}$, and $X = \frac{4\pi^3 k_B T}{\hbar\omega_c}$.

Here k_B is the Boltzmann constant and the cyclotron frequency, $\omega_c = eB/m^*$, is inversely proportional to the effective band mass, m^*.

A quantum scattering time τ_q of 0.27 ps was extracted from the slope of the Dingle plot, while the classical scattering time, τ_c, of 1.19 ps was calculated from the equation

$$\tau_c = \frac{m^* \mu_H}{e}$$

For both scattering times, an estimated effective band mass ratio of 0.21 was used. The ratio of $\frac{\tau_c}{\tau_q}$ can predict the scattering mechanisms in a 2D electron system—for material systems with higher scattering time ratios, ionized impurity scattering is often considered the primary scattering mechanism. Near unity scattering time ratios, like the ratio of 4.4 in this work, is indicative of interface roughness as the principle scattering mechanism.[9,10]

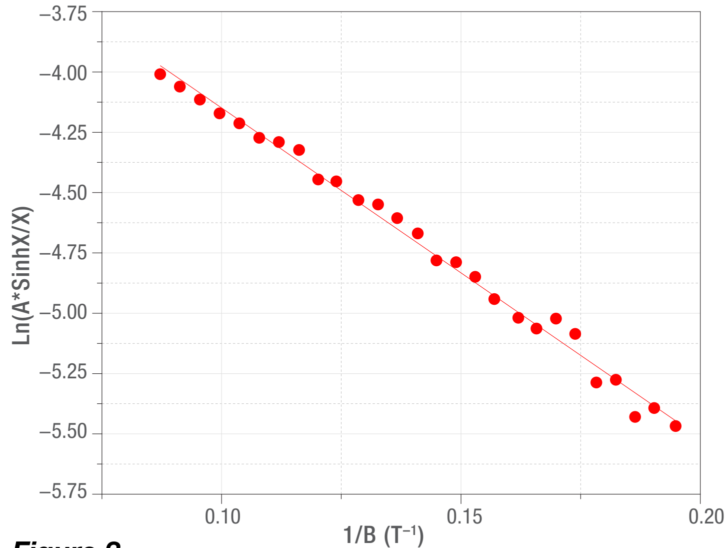


Figure 3

Dingle plot of SdH oscillation amplitude at 1.6 K vs 1/B.

Conclusion

The magnetotransport measurements performed on the AlGaN/AlN/GaN heterostructure reveal clear signatures of Shubnikov—de Haas (SdH) oscillations and the onset of the quantum Hall effect at low temperatures and high magnetic fields. The extracted carrier concentration from SdH analysis aligns well with low-field Hall measurements, validating the consistency and reliability of the experimental data. Furthermore, the quantum and classical scattering times, along with their ratio, suggest that interface roughness scattering is the dominant mechanism limiting mobility in this 2DEG system. The observed transport behavior provides valuable insights into the interplay between material structure and scattering mechanisms, which is critical for optimizing device performance in high-speed and high-frequency electronic applications.

References

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