



Microwave-modulated Shubnikov–de Haas oscillations in a two-dimensional GaN electron gas

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Abstract

We report the drastic enhancement of Shubnikov–de Haas (SdH) oscillations observed in a GaN/AlGaN heterostructure by microwave modulation. The dependence of the SdH pattern on microwave power and temperature are investigated. The underlying mechanism is attributed to the effect of carrier heating. This technique helps study the transport properties of two-dimensional electrons in a GaN/AlGaN heterostructure. In addition, this method has the advantage of keeping the carrier concentration fixed and not requiring expensive high-energy laser facilities compared with carrier-modulated SdH measurements.

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The Shubnikov–de Haas (SdH) oscillatory magnetoresistance is one of the most frequently used tools for determining the transport properties of a two-dimensional electron gas (2DEG) in semiconductor heterostructures. Observation of the oscillations requires that the thermal energy and the scattering-induced energy broadening be smaller than the Landau level separation. Therefore, the SdH technique is not suitable for the measurement at high temperatures or for samples with relatively low mobilities. Many experimental techniques have been developed to enhance the sensitivity

of the conventional SdH measurements. For example, the carrier modulated SdH technique [1,2], which is based on measuring the changes in magnetoresistance by a chopped laser light source. However, because the additional laser source can generate excess carriers, it is very difficult to obtain the exact carrier concentration as well as to determine the underlying mechanism of the enhanced SdH pattern.

We present a novel technique that can greatly enhance the SdH pattern without changing the carrier concentration. The enhanced SdH pattern is obtained by recording the changes in the quantum oscillations of magnetoresistance due to microwave radiation. We demonstrate that this technique is suitable for studying the magnetoresistance at relatively high temperature and in samples with moderate mobilities.

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The measurements were performed on a metal-organic chemical vapor deposition (MOCVD) grown GaN/Al_{0.4}Ga_{0.6}N heterostructure. A high-quality 2DEG can form in the GaN/AlGaN heterointerface because of the large band offset and the strong piezoelectric and spontaneous polarization in this material system. The sample was grown on a sapphire substrate and consists of an undoped 250 Å thick Al_{0.4}Ga_{0.6}N, an undoped GaN of 2.5 μm thickness, and a GaN buffer layer. The carrier concentration of the sample is $7.4 \times 10^{12} \text{ cm}^{-2}$ and the electron mobility is $2500 \text{ cm}^2/\text{V s}$ at 4.3 K. The sample was placed inside a 6 T Oxford superconducting magnet, and was immersed in liquid helium. Raising the temperature is done by a balance between the controlled heating and the injected liquid helium. For the microwave-modulated SdH measurements, the microwave was generated by Gigatronics GT 9000 S microwave sweeper and guided to the sample surface by a microwave coaxial cable. It is worth mentioning that no cavity and no special waveguide are needed in this way. The oscillatory resistivity caused by a sweeping magnetic field was measured by a conventional lock-in amplifier with a reference frequency provided by a function generator modulating the microwave output.

To understand the effect of microwave on the magnetotransport measurements, we first measured the regular SdH pattern under continuous microwave radiation without modulation. The sample is set under a perpendicular magnetic field B and an applying microwave is guided to the sample surface. The frequency of microwave is 3.75 GHz and the power is 20 dBm.

We find that the continuous microwave illumination reduces the amplitudes of the SdH oscillation. Moreover, the nonoscillatory part of the magnetoresistance remains almost the same, which indicates that the microwave has little influence on the magnetoresistance background. It is known that the longitudinal resistivity ρ_{xx} in the SdH oscillation is given by [3–6]

$$\rho_{xx} = \rho_0 \left[1 + 4D_T(X) \exp\left(-\frac{\pi}{\omega_c \tau_q}\right) \right].$$

We know the temperature-dependent term is $D_T(X) = X/\sin hX$, where $X = 2\pi^2 k_B T / \hbar \omega_c$, the cyclotron frequency $\omega_c = eB/m^*$, where m^* is the electron effective mass. Therefore, the amplitude of

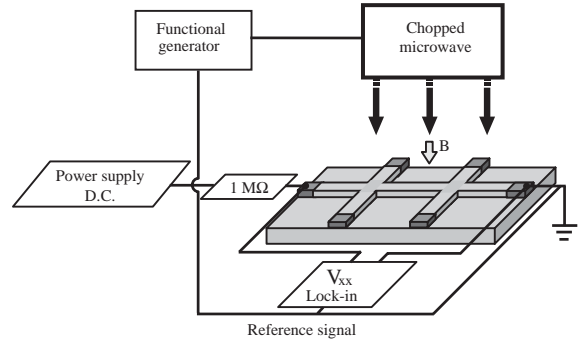


Fig. 1. The diagram of the experimental setup. The frequency and power of the microwave are 3.75 GHz and 20 dBm. Moreover, the frequency of the functional generator is 1.02 kHz.

the SdH oscillations is given by

$$\Delta\rho_{xx} = 4\rho_0 D_T(X) \exp\left(\frac{-\pi}{\omega_c \tau_q}\right),$$

that depends on the carrier temperature-dependent factor $D_T(X)$. We can easily find that $D_T(X)$ decreases progressively with increasing temperature T . We thus observe the reduction of the SdH oscillatory amplitude under the illumination of continuous microwave. Our observation can be attributed to the effect of carrier heating [7,8]. The free carriers near the Fermi level absorb the incident microwave and become hot carriers. When considering the thermal energy with background temperature (4.3 K) in liquid helium, that provides about 0.4 meV smaller than the band gap energy of GaN ($\approx 3.5 \text{ eV}$). However, the frequency of the microwave is 300 MHz \sim 300 GHz, we have electric energy $E = \hbar\nu \approx 10^{-3} \text{ meV}$. Therefore, we provide the energy to the carriers but do not excite electrons in the valance band. These hot carriers possess an equivalent temperature that may be higher than the lattice temperature, since the sample is immersed in liquid helium at 4.3 K. Hence, the SdH amplitude decreases compared with that obtained without microwave radiation.

In the last section, we see that the SdH amplitudes decrease under microwave radiation. This is not what we want. We want to enhance the sensitivity of the SdH measurements, so we will consider the modulated microwave illumination in this section.

Fig. 1 shows the diagram of the experimental setup. The oscillatory longitudinal resistivity caused by sweeping the magnetic field was measured by a lock-in amplifier with a reference frequency provided by a function generator modulating the microwave

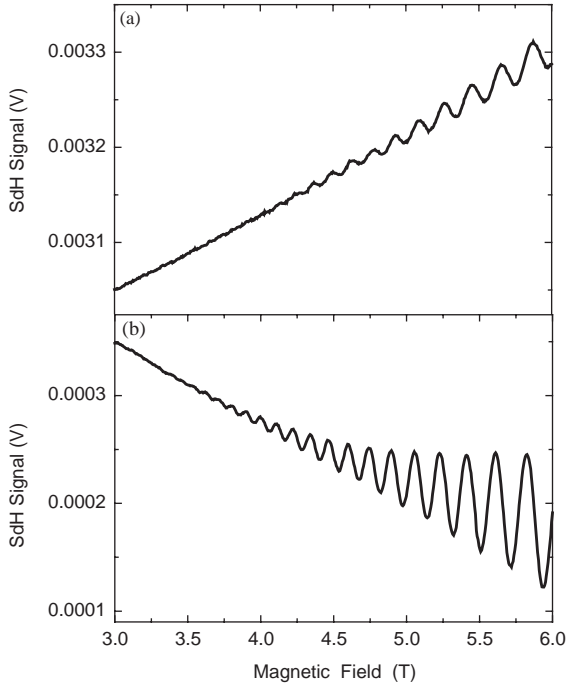


Fig. 2. (a) The conventional SdH oscillations on the GaN/Al_{0.4}Ga_{0.6}N heterostructure taken at a background temperature of 4.3 K. (b) The microwave-modulated SdH pattern under the modulation of a 3 GHz microwave radiation at the same temperature of 4.3 K.

output. We now have a chopped microwave radiation. The experimental technique that we used leads to a SdH signal that is proportional to the change of voltage drop along the sample with and without microwave illumination. Without illumination the electron temperature T_e is equal to the lattice temperature T_L . During the microwave pulse the electrons are heated from $T_e = T_L$ to $T_e > T_L$. After the end of the microwave pulse the electrons relax to $T_e = T_L$ again. The higher the T_e during illumination, the larger the difference between the oscillatory SdH amplitudes will be, whereas, the nonoscillatory background remains the same. Thus, our experimental technique suppresses the nonoscillatory magnetoresistance and make it possible to observe directly the oscillatory part.

Fig. 2(a) shows the conventional SdH oscillations on the GaN/Al_{0.4}Ga_{0.6}N heterostructure taken at a background temperature of 4.3 K. The SdH oscillations can be resolved from 4.2 T. Fig. 2(b) displays the microwave-modulated SdH pattern under the modulation of a 3 GHz microwave radiation at the same

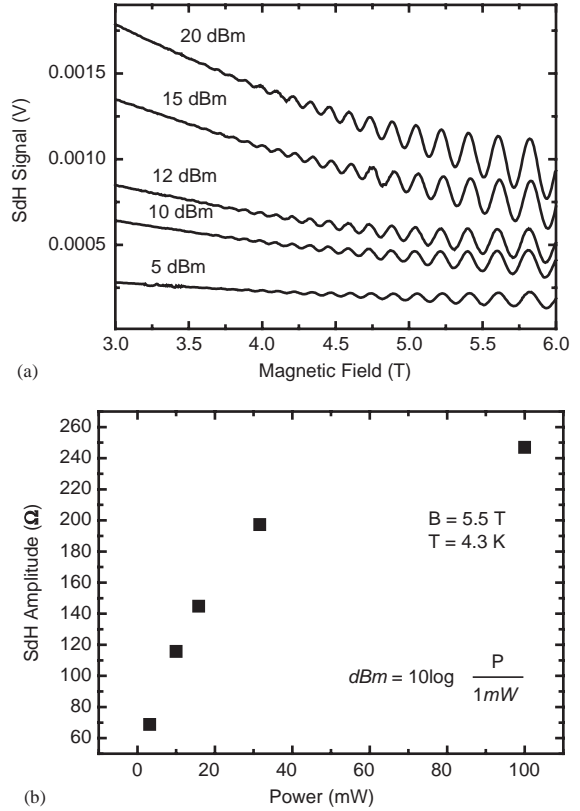


Fig. 3. (a) The dependence of microwave-modulated SdH measurements on microwave power at temperature 4.3 K. The microwave frequency is 4 GHz. (b) The SdH amplitudes as a function of applying microwave power at a constant magnetic field ($B = 5.5$ T).

temperature. We can see that the SdH pattern is considerably enhanced and the onset of the oscillations is lowered to 3.2 T.

If we consider the difference between ρ_{xx} with and without microwave illumination, which is

$$\begin{aligned} &\rho_{xx}(T) - \rho_{xx}(T + \Delta T) \\ &= 4\rho_0 \exp\left(-\frac{\pi}{\omega_c \tau_q}\right) [D_T(X) - D_{T+\Delta T}(X)]. \end{aligned}$$

Then the amplitude of the SdH oscillation sensitivity depends on the temperature-dependent factor $D_T(X) - D_{T+\Delta T}(X)$, that is an increasing function with increasing ΔT . Now we have an enhanced amplitude of the SdH oscillations, as shown in Fig. 2(b). Therefore, the sensitivity of the SdH measurement can be improved.

Fig. 3(a) shows the dependence of the SdH pattern on microwave power (5 ~ 20 dBm). It is evident

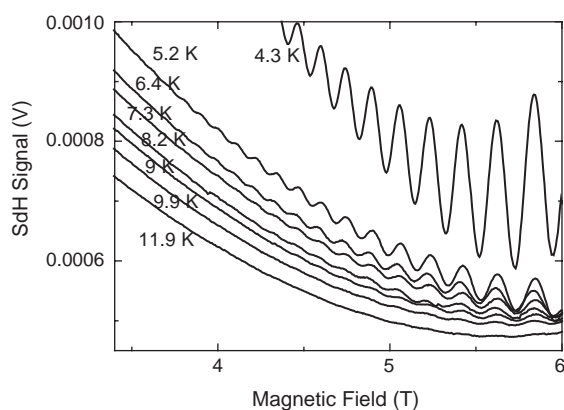


Fig. 4. The dependence of microwave-modulated SdH measurements on temperature with microwave frequency 3.7 GHz and microwave power 20 dBm.

that the SdH amplitude increases with increasing microwave power. This result can also be interpreted in terms of the electron heating effect from microwave absorption. The amount of electron heating is increased as microwave power is increased. Therefore, increasing microwave power brings about higher carrier-equivalent temperatures. The higher the electron temperatures during illumination, the larger the difference between the oscillatory SdH amplitude will be. Thus, the microwave-modulated SdH pattern is enhanced.

Fig. 3(b) shows the SdH amplitudes as a function of applying microwave power at a constant magnetic field ($B = 5.5$ T). We can see that with increasing incident microwave power, the SdH amplitude shows a drastic increase and then exhibits a small increase at the highest microwave power. Increasing the incident microwave power increases the electron temperature. Thus the difference between the electron temperature and lattice temperature $D_T(X) - D_{T+\Delta T}(X)$ increases, giving rise to an enhancement of the SdH amplitude.

Finally, we also increase directly the temperature of the sample to see the effect of microwave-modulated SdH oscillations. Fig. 4 shows the dependence of microwave-modulated SdH measurements on temperature. We see that the SdH amplitudes decrease with increasing sample temperature. At a fixed microwave power, increasing the lattice temperature decreases the difference $D_T(X) - D_{T+\Delta T}(X)$,

resulting in a smaller SdH amplitude. However, the SdH oscillatory signal can be observed at a temperature up to about 10 K. Moreover, considering the electron mobility of the studied GaN/AlGaIn sample is not too large ($\mu = 2500$ cm²/V s at 4.3 K), the observation of SdH oscillations at this relatively high temperature clearly demonstrates the usefulness of the microwave-modulated SdH measurement.

In conclusion, we report the observation of the enhancement of SdH oscillations by measuring the changes in magnetoresistance due to microwave illumination. We show that this experimental technique can greatly enhance the sensitivity of the SdH measurement. According to the studies of the dependence on microwave power and temperature, we attribute the mechanism of the enhancement to the hot carrier effect induced by microwave absorption and the suppression of the nonoscillatory background. By measuring the microwave-modulated transport in a GaN/AlGaIn heterostructure, we demonstrate that this technique can be used to study the magnetoresistance of samples with moderate mobility at relatively high temperatures or low magnetic fields.

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