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Electrically detected and microwave-modulated Shubnikov–de Haas oscillations in an $Al_{0.4}Ga_{0.6}N/GaN$ heterostructure

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We report the drastic enhancement pattern of Shubnikov–de Haas (SdH) oscillations observed in an AlGaN/GaN heterostructure by microwave modulation. The dependence of the SdH pattern on microwave power and temperature is investigated. The underlying mechanism is attributed to the effect of carrier heating. This technique helps study the transport properties of two-dimensional electrons in many wide-band-gap heterostructures, in which moderate mobilities and heavier electron effective mass (rapidly damping SdH amplitudes) are frequently encountered. 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. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1539286]

I. INTRODUCTION

Two-dimensional electron gas (2-DEG) systems based on semiconductor heterostructures are of great importance for applications in modern optoelectronic technology. One of the most frequently used tools to characterize the transport properties of a semiconductor system is the Shubnikov-de Haas (SdH) measurement. It is known that the conductivity depends on the density of states at the Fermi energy and oscillates as Landau levels shift to higher energies with increasing magnetic field. Observation of the oscillations requires that the thermal energy and the scattering-induced energy broadening be smaller than the Landau level separation. To detect SdH oscillations, the measurements must be performed at low temperatures, and the sample mobility needs to be relatively high. Many experimental techniques have been developed to enhance the sensitivity of the conventional SdH measurements. In the carrier-modulated SdH technique, the carrier concentration is modulated by a chopped laser beam. The carrier modulation is capable of enhancing the SdH pattern,[1,2] however, excess carriers generated by the light source make the exact determination of carrier concentration difficult.

The microwave-detected SdH technique is based on measuring the change in magnetoresistance due to the microwave absorption.[3–5] This technique is flawed by the fact that the SdH oscillations are less evident in σ_{xx} than in ρ_{xx}, since the SdH amplitudes decrease as $1/B^2$ for higher magnetic fields for σ_{xx}. It is shown that the sensitivities of the carrier-modulation technique and the magnetic-field-modulation technique are comparable.[6] The shortcoming of utilizing magnetic-field-modulation technique is that it is not easy to realize by conventional superconducting coil. Therefore, this technique is less effective for studying many structures in which carrier mobilities are low in most cases.

AlGaN/GaN heterostructures have attracted much attention in the past several years due to their unique material and electronic properties.[7–12] They have advantages including high thermal conductivity, high breakdown voltage, radiation resistance, chemical inertness, and mechanical stability. High-quality 2-DEG can form in the heterointerface because of the large band offset and the strong piezoelectric polarization in this material system. Therefore, the study of this material system contributes to the full realization of electronic devices capable of operating at high temperatures, high power densities, and in hostile environments. In this article, we report SdH measurements on a wide-band-gap AlGaN/GaN heterostructure based on a technique that can drastically enhance the SdH pattern without altering carrier concentrations.[13] The strengthened resolution comes from the additional modulation of microwave. The signal is detected electrically in phase with the microwave modulation. We studied the dependence on microwave power and 04 temperature. The enhancement mechanism is attributed to the hot carrier effect induced by microwave absorption and the suppression of the nonoscillatory background. We demonstrate that this technique is suitable for studying many wide-band-gap heterostructures in which moderate mobilities and heavier effective mass (rapid damping SdH amplitudes) are frequently encountered at relatively high temperatures or low magnetic fields, without altering the carrier concentration and without the risk of laser heating.

II. EXPERIMENT

The measurements were performed on a metalorganic-chemical-vapor-deposition-grown $Al_{0.4}Ga_{0.6}N/GaN$ hetero-

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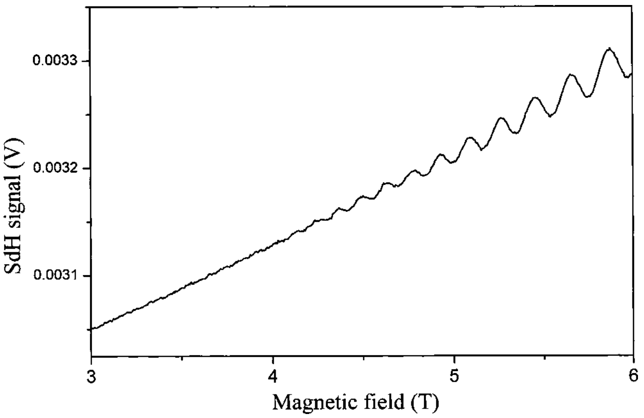

FIG. 1. (a) The conventional SdH oscillations on the AlGaN/GaN heterostructure taken at a temperature of 4.3 K. For clarity, only the range of magnetic fields higher than 3 T is shown.

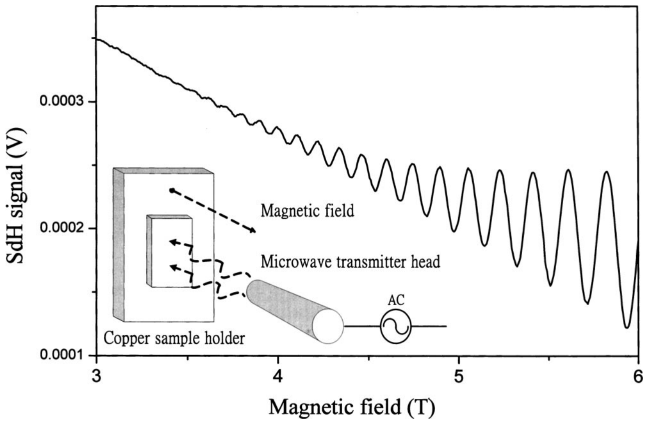

FIG. 2. The electrically-detected, microwave-modulated SdH oscillations at a temperature of 4.3 K for the same sample. The microwave frequency is 3 GHz. The onset of the SdH oscillations occurs at a lower magnetic field of 3.2 T. The inset shows the experimental configuration.

structure, which is of increasing importance for future electronic technology. The sample structure was grown on a sapphire substrate and consists of an undoped $250-\text{Å}$ $-$thick $\mathrm{Al_{0.4}Ga_{0.6}N}$, an undoped GaN of 2.5-$\mu$m thickness, and a GaN buffer layer. The dimensions of the sample is $4\ \mathrm{mm}\times 3\ \mathrm{mm}$. The Hall pattern was made with conventional optical lithography. By using a Cr metal mask, active orthogonal mesa regions of $80\ \mu\mathrm{m}\times 800\ \mu\mathrm{m}$ were patterned by inductively coupled plasma etching using $\mathrm{BCl_3}$ etchant. The specific contact sensitivities $\sim 10^{-6}\ \mathrm{ohm\,cm^{-2}}$ were measured by means of the transmission line method prior to the deposition of Ti/Al/Ni/Au (150 Å/2200 Å/400 Å/50 Å), using an electron beam evaporator in the background vacuum of better than 5×10^{-7} and then annealed at a temperature of 700 °C. The Hall mobility at 77 K is $1090\ \mathrm{cm^2/V\,s}$.

The sample was placed inside a 6-T Oxford superconducting magnet, and was immersed in liquid helium. Raising the temperature is done by a heater and a specific higher temperature can be maintained by a balance between the controlled heating and the injected liquid helium. The sample temperature is measured by a sensor placed directly on the other side of the sample holder.

For the microwave-modulated SdH measurements, the microwave was generated by a Gigatronics GT 9000 S microwave sweeper and guided to the sample surface by a microwave coaxial cable. No cavity and no special waveguide are needed in this way. The shape of the microwave pulses is a sine wave and the frequency range can be $2\sim 20$ GHz. The estimated microwave power density for a 10-dBm surface irradiation is $0.125\ \mathrm{W/cm^2}$. The oscillatory conductivity 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.

III. RESULTS AND DISCUSSION

Figure 1 shows the conventional SdH oscillations taken at 4.3 K. There is only one series of oscillations and the SdH oscillations can be resolved from 4.2 T. The two-dimensionality of the carriers has been verified by rotating the sample orientation against the magnetic field.

We now present our main experimental results. Figure 2 displays the microwave-modulated SdH pattern under the modulation of a 3-GHz microwave radiation at the same temperature. The inset shows the experimental configuration described above. The SdH pattern is considerably enhanced and the onset of oscillations is lowered to 3.2 T. Both SdH oscillations gave the same carrier concentration of $7.4\times 10^{12}\ \mathrm{cm^{-2}}$.

To understand the effect of microwave on the magnetotransport measurements, we measured the regular SdH pattern under continuous microwave radiation without modulation, as shown in Fig. 3. We first note that the nonoscillatory part of the magnetoresistance remains almost the same, which indicates that the microwave has little influence on the magnetoresistance background. Moreover, it is clear that the continuous microwave illumination reduces the amplitudes of the SdH oscillation. It is known that the amplitude of SdH oscillation depends sensitively on the temperature-dependent factor

$$A\sim Z/\sinh Z, \tag{1}$$

where $Z=2\pi^2 k_B T/\hbar\omega_C$, $\hbar$ is the reduced Planck constant, k_B is the Boltzmann's constant, cyclotron frequency ω_C

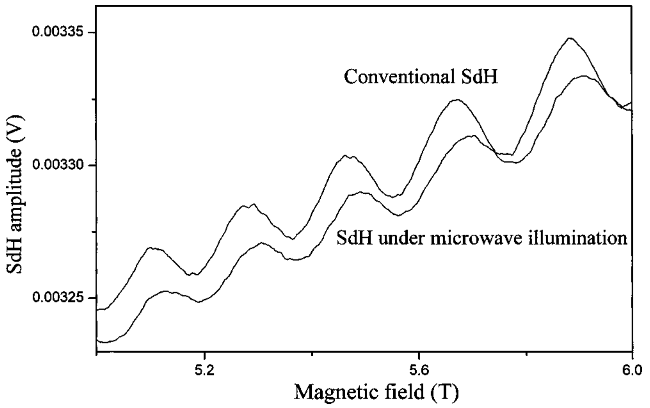

FIG. 3. Conventional SdH measurements with and without the continuous microwave illumination of 3.76 GHz.

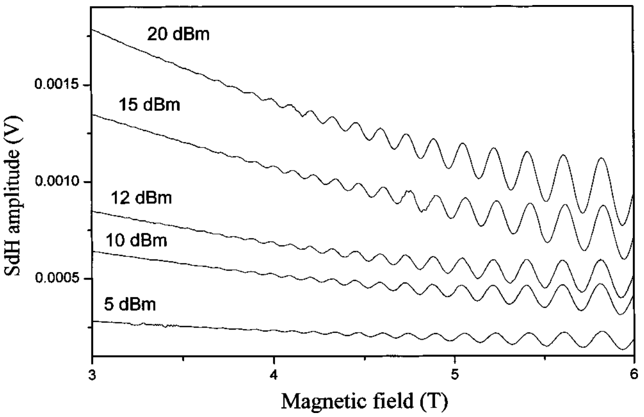

FIG. 4. The dependence of microwave-modulated SdH measurements on microwave power at temperature 4.3 K. The microwave frequency is 4 GHz.

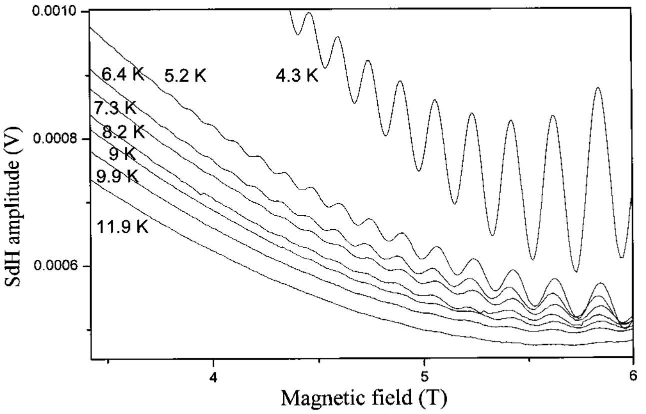

FIG. 5. The dependence of microwave-modulated SdH measurements on temperature with microwave frequency 3.75 GHz. The oscillation can still be observed at 9.9 K within available magnetic fields.

$=eB/m^*$, e is the electron charge, B is the magnetic field, and m* is the electron effective mass. Since the continuous microwave radiation decreases the SdH amplitude, our observation can be attributed to the hot carrier effect.[14] The free carriers near the Fermi level absorb the incident microwave and become hot carriers. These hot carriers possess an equivalent temperature that is higher than the lattice temperature. Hence the SdH amplitude diminishes compared with that obtained without microwave radiation. In the microwave-modulated SdH measurements, the detected signal is proportional to the change of ρ_{xx} under microwave modulation. Since the nonoscillatory background is not altered under microwave illumination, this background signal can be suppressed, and the remaining oscillatory part is enhanced. Therefore, the sensitivity of the measurement can be improved.

The dependence of the SdH pattern on microwave power is shown in Fig. 4. It is evident that the SdH amplitude increases with increasing microwave power. This result can also be interpreted in terms of the hot carrier effect described earlier. Increasing microwave power brings about higher carrier-equivalent temperatures and hence reduced SdH amplitudes under microwave radiation. Because the detected signal is proportional to the SdH amplitude difference, the microwave-modulated SdH pattern is enhanced.

Finally, the temperature-dependent, microwave-modulated SdH oscillations are shown in Fig. 5. The SdH oscillation can be observed at temperatures up to 10 K within the attainable magnetic field range. Considering the SdH-detected effective mass value of $0.23\,m_0$, [8–10] and a moderate mobility of $2500\,\mathrm{cm}^2/\mathrm{V\,s}$ at 4.3 K (roughly estimated from Fig. 1), the observation of SdH oscillations at this relatively high temperature clearly demonstrates the usefulness of the microwave-modulated SdH measurement.

IV. CONCLUSION

In summary, we report measurements of electrically detected microwave-modulated SdH oscillations in a wide-band-gap AlGaN/GaN heterostructure. We show that this experimental technique can greatly enhance the sensitivity of the SdH measurement. The dependence on microwave power and temperature is studied. The enhancement mechanism is attributed to the hot carrier effect induced by microwave absorption and the suppression of the nonoscillatory background. We demonstrate that this technique is suitable for studying many wide-band-gap heterostructures, in which moderate mobilities and heavier effective mass (rapid damping SdH amplitudes) are frequently encountered at relatively high temperatures or low magnetic fields. Furthermore, this technique has the advantage of unchanging carrier concentration, avoiding possible laser heating, and not requiring expensive high-energy laser facilities, compared with carrier-modulated SdH measurements.

ACKNOWLEDGMENTS

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