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Enhancement of Subnikov-de Haas Oscillations by Microwave Radiation

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We report for the first time that the Subnikov-de Haas(SdH) pattern can be greatly enhanced by recording the changes in the quantum oscillations of magnetoresistance due to microwave radiation. In order to understand the origin of the enhancement, the dependence of the enhanced SdH signal on temperature, microwave frequency and power has been studied. It is concluded that the enhancement can be attributed to the effects of free carrier absorption and the suppression of the nonoscillatory magnetoresistance. The technique shown here can be used to detect the SdH oscillations at relatively high temperature and in samples with moderate mobilities without perturbing the carrier concentration.

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It is well known that the Subnikov-de Haas(SdH) oscillatory magnetoresistance is a powerful tool for determining tansport parameters in semiconductor heterostructures, such as the carrier concentration in the subbands of the two-dimensional electrons gas (2DEG), the effective mass and quantum lifetimes. Due to the Landau level broading, the SdH technique is not suitable for the measurement at high temperature or in samples with low mobilities. To enhance the sensitivity of the SdH technique, a modified method that is based on measuring the changes in magnetoresistance by a chopped laser light source has been developed [1]. However, because the additional laser source can generate excess carriers, it makes very difficult to obtain the exact carrier concentration as well as to determine the underlying mechanism of the enhanced SdH pattern.

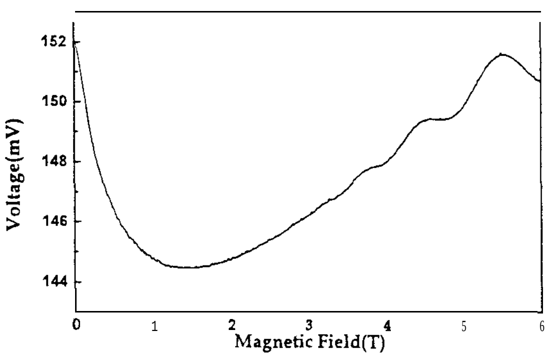
In this Letter, we present a novel technique which can greatly enhance the SdH pattern without changing the carrier concentration. The enhanced SdH pattern is obtained by recording the changes in the quantum oscillations of magnetoresistance due to microwave radiation. The underlying mechanism of the enhancement has been studied by the dependence of the enhanced SdH signal on temperature, microwave frequency and power. We concluded that the enhacement is due to the effects of free carrier absorption and the suppression of the nonoscillatory magnetoresistance. We point out that the technique shown here can be used to study the magnetoresistance at relatively high temperature and in samples with moderate mobility.

The experimental setup is similar to a conventional SdH equipment with an additional microwave source which is modulated by a function generator. The sample is placed near the transmitter head of a microwave coaxial cable, and no cavity or waveguide system is needed. The sample is cooled down in a 7T Oxford superconducting magnet and measured under Faraday geometry. The change in the longitudinal voltage drop is measured by a lock-in amplifier with the reference frequency provided by the function generator.

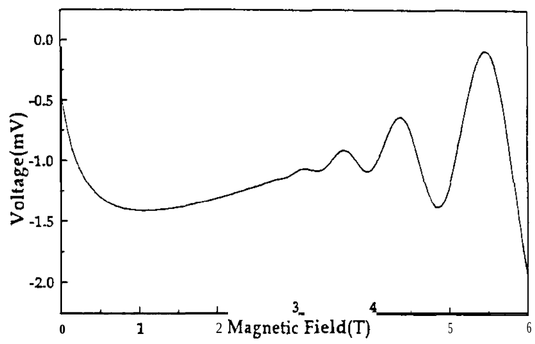
The samples used in this study were grown on n-type (001) silicon substrates at 550 ^oC using a home-made hot-wall multi-wafer ultrahigh-vacuum chemical vapour deposition system. The construction and operation of our system is similar to that which has been reported elsewhere [2]. The modulation-doped two-dimensional hole gas (2DHG) structures consist of a 1 μm undoped Si buffer layer, a 250 Å $Si_{0.71}Ge_{0.29}$ layer, a 100 Å undoped Si spacer, and a 1 μ_m B-doped Si layer. Details of the growth technique used and the results of the structural characterization have been described in our previous publication [3]. The concentration of the 2DHG formed in the SiGe layer due to charge transfer from the B-doped Si layer was determined to be 1.05 x 10^{12} cm^{-2} from SdH measurements.

Figure 1(a) and (b) show the regular SdH measurement and the modulated SdH pattern under the illumination of a 25GHz microwave radiation with a power of 10dbm, respectively. Both spectra were taken at 4.2K on the same SiGe quantum well sample. We can clearly see that the enhancement of the SdH pattern by the modulated microwave radiation is quite obvious. A comparion of Fig. 1 (a) and (b) indicates that both spectra have the identical frequency of oscillation which give a carrier concentration of 1.05 x 10^{12} cm^{-2} in the 2DHG.

In order to explore the underlying mechanism of the enhanced SdH pattern, let us look at the magnetoresistance measurement under continuous microwave illumination without modulation as shown in Fig. 2(b). Compared with the spectrum of Fig. 2(a) obtained in



(a)



(b)

FIG.1. SdH oscillations at 4.2 K on a modulation-doped SiGe/Si quantum well with $n = 1.05 \times 10^{12}$ cm^{-2} and μ_h = 7500 cm^2/Vs. (a) regular SdH, and (b) modulated SdH under microwave illumination.

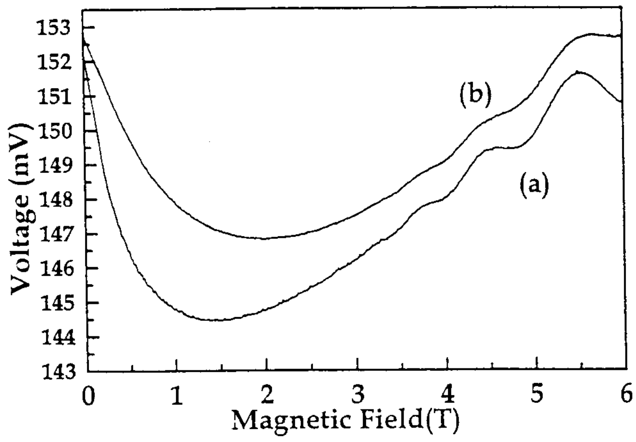


FIG. 2. SdH oscillations at 4.2K on a modulation-doped SiGe/Si quantum well. (a) and (b) are the measured results without and with continuous microwave illumination, respectively.

the dark, the illumination of microwave radiation reduces the oscillatory amplitude in the SdH pattern, whereas the nonoscillatory background remains the same, more or less. This result provides a reminiscence of free carrier absorption [4], in which the free carriers near the Fermi level absorb the incident radiation and become hot carriers. These hot carriers have an equivalent temperature T_h which is higher than the lattice temperature T_l. Because the SdH amplitude A depends sensitively on the carrier temperature as given by [5]

$$A \propto \frac{X}{\sin hX},$$

where $X = 2\pi^2 kT_h/\hbar\omega_c$, k is Planck constant, and ω_c is cyclotron frequency, we thus observe the reduction of the oscillatory amplitude under the illumination of microwave radiation. The exprimental technique which we used measures the changes of magnetoresistance due to microwave radiation. The recorded signal is proportional to the difference between the voltage drop along the sample with and without microwave illumination. Because the nonoscillatory background remains the same during illumination, our experimental technique can suppress the nonoscillatory signal and detect directly the oscillatory part. Thus, the observed oscillatory SdH pattern is enhanced.

To further confirm the effect of free carrier absorption, we performed the dependence of the enhanced SdH pattern on the frequency of microwave radiation as shown in Fig. 3. We can see that the amplitude of the SdH oscillations increases with increasing microwave frequency, in which the microwave power is fixed at 10 dbm for each microwave radiation. It is quite interesting to note that the enhacement factor of the SdH amplitude follows approximately the square root of microwave frequency as expected for free carrier absorption [4]. In addition, we studied the dependence of the enhancement on microwave power as shown in Fig. 4. It is found that the SdH amplitude increases with increasing microwave power. This behavior can also be easily understood according to the effect of free carrier absorption as described above. With increasing incident microwave power, the carrier

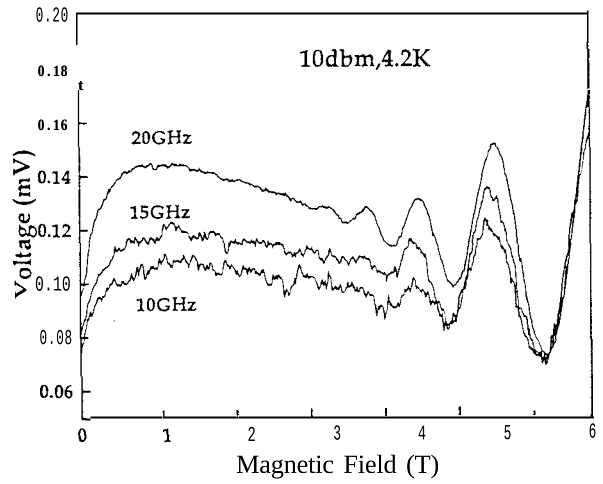


FIG. 3. Dependence of modulated SdH oscillations on microwave frequency, taken at 4.2 K. The power is fixed at 10 dbm for each microwave radiation.

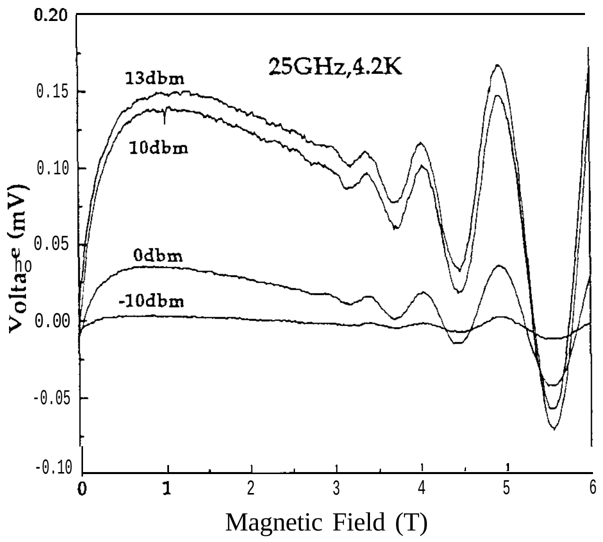


FIG. 4. Dependence of modulated SdH oscillations on microwave power, taken at 4.2 K. The microwave frequency is fixed at 25 GHz.

temperature T_h is also increased. The higher T_h during illumination, the larger the difference between the oscillatory SdH amplitudes will be. Thus, the enhancement factor is increased.

Figure 5 displays the measurements of the modulated SdH oscillations at different temperatures. We can still observe SdH oscillations at 13 K. Considering the hole mobility of the studied SiGe sample is not too large ($\mu_h = 7500$ cm^2/Vs at 4.2 K), the observation

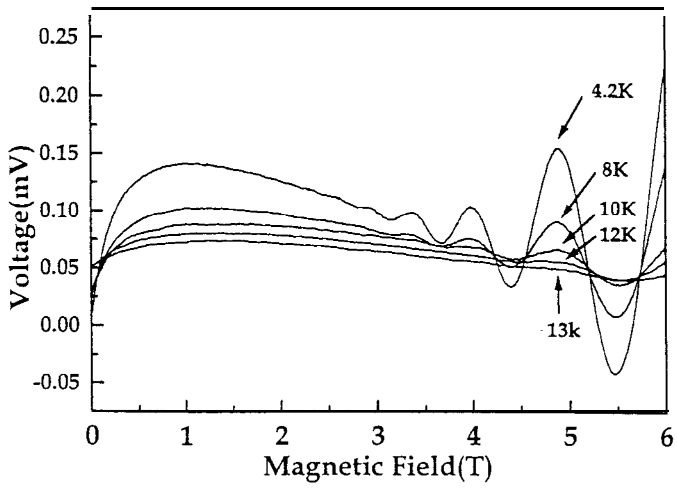


FIG. 5. Temperature dependence of modulated SdH oscillations under a 25 GHz microwave illumination.

of SdH oscillations at this relatively high temperature demonstrates the advantage of the modulated SdH measurement under microwave radiation.

In summary, we report the observation of the enhacement of SdH oscillations by measuring the changes in magnetoresistance due to microwave radiation. According to the studies of the dependence on microwave power, microwave frequency, and temperature, we attribute the mechanism of the enhancement to the effect of free carrier absorption and the suppression of the nonoscillatory background. By the measurement of a modulation-doped SiGe quantum well, we demonstrate that this technique can be used to study the magnetoresistance of samples with moderate mobilities at relatively high temperatures.

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