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DX-centers and long-term effects in the high-frequency hopping conductance in Si-doped GaAs/$Al_{0.3}Ga_{0.7}As$ heterostructures in the quantum Hall regime: acoustical studies

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Abstract

It is discovered that both high-frequency (hf) hopping conductance and electron density in the 2D channel, n_s, in Si δ-doped and modulation-doped GaAs/$Al_{0.3}Ga_{0.7}As$ heterostructures at the plateaus of the integer quantum Hall effect depend on *cooling rate* of the samples. Furthermore, consecutive IR illumination leads to a *persistent hf hopping photoconductance*, which decreases when the illumination intensity increases, while n_s increases. The persistent hf hopping photoconductance occurs when the illumination frequency exceeds a threshold, which is between 0.48 and 0.86 eV. The results are attributed to two-electron defects (so-called DX-centers) located in the Si-doped layer of the $Al_{0.3}Ga_{0.7}As$ heterostructure.

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1. Introduction

Acoustical studies allow to determine the high-frequency (hf) conductivity of heterostructures, σ_{xx}^{hf}. In magnetic fields, corresponding to the middle points of the integer quantum Hall effect (IQHE) plateaus where the direct-current conductivity σ_{xx}^{dc} vanishes, the hf conductivity is finite and complex: $\sigma_{xx}^{hf} = \sigma_1 - i\sigma_2$ [1]. Both real σ_1 and imaginary σ_2 parts can be found from simultaneous measurements of the attenuation and velocity of a surface acoustic wave (SAW) interacting in a magnetic field with 2D electrons of the heterostructure. The experiment evidenced that $\sigma_2 \gg \sigma_1$.

According to Efros [2], these facts lead to the conclusion that the mechanism of hf conductance is *hopping*. As it follows from Ref. [3], the hf hopping conductivity in the 2D channel of the δ-doped GaAs/AlGaAs heterostructures seems to be effectively shorted out with the hf conductivity along the Si-δ doped $Al_{0.3}Ga_{0.7}As$ layer. It turned out that this value of the σ_{xx}^{hf} depends on both the rates of the sample cooling from room temperature to 4.2 K and

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consecutive IR illumination. The aim of the present work is to systematically study these phenomena.

2. Experimental results and discussion

SAW attenuation, Γ, and velocity variation, $\Delta V/V$, at a sound frequency $f = 30$–150 MHz, in a magnetic field up to 7 T, and at temperatures 4.2 and 1.5 K have been measured in GaAs/Al$_{0.3}$Ga$_{0.7}$As heterostructures $n_s = (1.5 - 7) \times 10^{11}$ cm^{-2}. n_s has been determined from Shubnikov–de Haas-type oscillations of Γ and $\Delta V/V$. Real, σ_1, and imaginary, σ_2, components of complex $\sigma_{xx}(\omega)$ were determined from the experimentally measured Γ and $\Delta V/V$ using the procedure outlined in Ref. [3]. During the measurements the process of the sample cooling has been strictly checked and controlled. In Fig. 1b the magnetic field dependence of real σ_1 and imaginary σ_2 parts of the hf conductivity $\sigma_{xx}^{\mathrm{hf}}$ of a GaAs/AlGaAs heterostructure with $n_s \approx 1.5 \times 10^{11}$ cm^{-2} is depicted. The Γ and $\Delta V/V$ values measured in the experiment and used for the calculations of $\sigma_{xx}^{\mathrm{hf}}$ are presented in the Fig. 1a.

Acoustic measurements require the sample to be placed either in vacuum or in a dilute gas. To reach the temperatures 1.5–4.2 K a dilute exchange gas (He^4, $p \sim 0.1$ Torr) was inserted into the chamber with a sample.

The cooling procedure was as follows. The chamber has been initially cooled inside the cryostat by cold gaseous He^4, and then liquid He^4 has been poured into the cryostat.

Different cooling regimes were studied, and in the following they will be referred to as *slow* and *rapid* cooling. In the first case, the exchange gas has been inserted from the very beginning, at the room temperature. Then the chamber was cooled during 1.5–2 h by cold gaseous He^4 down to 7–8 K, and finally liquid He was poured. In the second case, the chamber was initially evacuated and cooled first by gaseous and then by liquid He^4. At some temperature T_0, which actually depends on the pressure in the chamber, the exchange gas was inserted, and the sample cooled down to the 4.2 K during 5–10 min. The maximum cooling rate was at $T_0 \approx 77$ K.

The magnetic field dependences of σ_1 in the 2–4 T range and for different cooling rates are presented in Fig. 2. It is seen from the picture that with the variation of the cooling rate or the pre-cool temperature T_0 both the minimal σ_1 value and the minimum position change. The second fact implies a change in the electron density in the 2D layer. Then these samples were successively illuminated by calibrated doses from a micro light-emitting diode (LED) located near the samples in the evacuated camera. We used LEDs with several wavelengths: 0.8, 1.44, 2.6 and 5.3 µm.

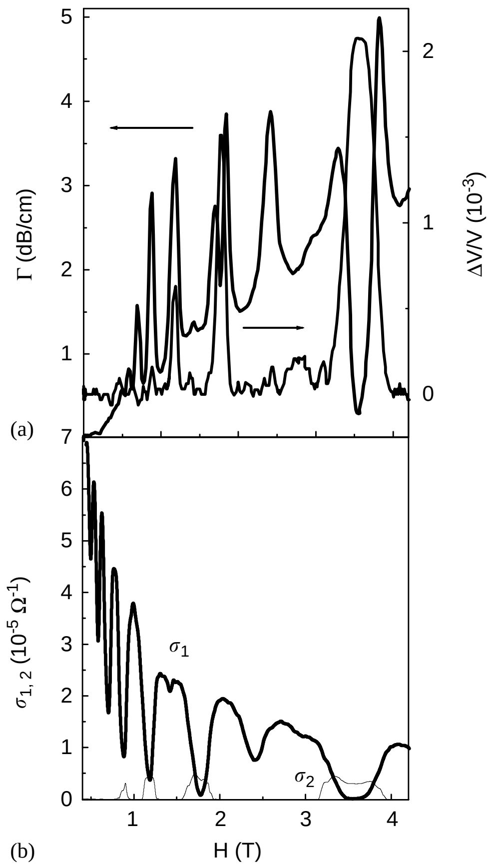

Fig. 1. (a) Magnetic field dependences of the SAW attenuation, Γ, and of the relative velocity change, $\Delta V/V$ for $f = 30$ MHz. (b) Components σ_1 and σ_2 of AC conductivity versus magnetic field H at $T = 1.5$ K. Sample: Si δ-doped GaAs/Al$_{0.3}$Ga$_{0.7}$As heterostructure, initial electron density $n_s \approx 1.5 \times 10^{11}$ cm^{-2}.

Magnetic field dependences of σ_1 at 4.2 K for the δ-doped sample with $n_s \approx 4 \times 10^{11}$ cm^{-2} illuminated with successive low portions of the 0.8 µm LED radiation are shown in Fig. 3 ($f = 30$ MHz). One can see from the figure that after successive short (< 10 s)

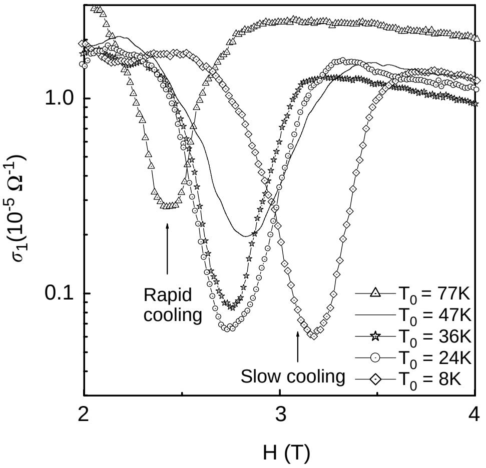

Fig. 2. Magnetic field dependences of σ_1 for $T=1.5$ K, $H=2$–4 T and different pre-cooling temperatures, T_0. All curves correspond to the filling factor $v=2$.

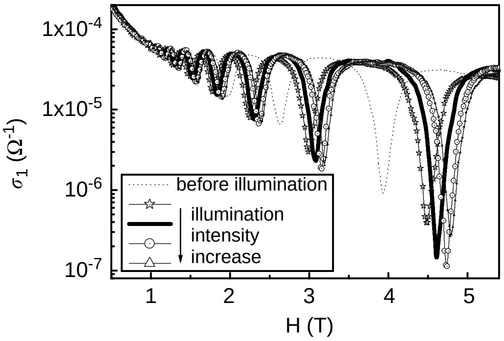

Fig. 3. Magnetic field dependences of $\sigma_1(\omega)$ after successive illumination, $\lambda=0.81$ μm, $T=4.2$ K, $f=30$ MHz.

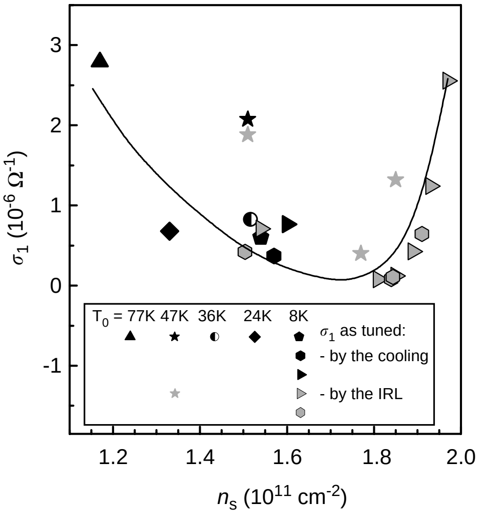

Fig. 4. Combined effect of cooling and successive illumination for $\sigma_1(\omega)$ which is plotted versus n_s tuned either by cooling, or by illumination. T_0 are different pre-cooling temperatures. δ-doped sample, $n_s \approx 1.5\times10^{11}$ cm^{-2}, $T=1.5$ K. The solid line is an eye-guided curve. Measurements are performed at $f=30$ MHz; $v=2$.

flashes of the LED the minima in σ_1 occur at successively different magnetic fields. This means that the carrier density *increases*, while the minimal value of σ_1 *decreases*. At the same time the conductivity maxima (determined by extended electron states) remain practically unchanged.

The second important feature is that there is a *threshold* in the persistent hf photoconductivity. Namely, the persistent photoconductivity has been observed only for the radiation quantum energy exceed some value between 0.86 and 0.48 eV (1.4 and 2.6 μm).

As we expected, [3] the set of experimental results indicates a significant role of the Si-doped layer $Al_{0.3}Ga_{0.7}As$ in the long-term effects.

To demonstrate these effects, we plot σ_1 and n_s obtained at different pre-cool temperatures T_0, both without and with subsequent IR illumination, in coordinates n_s-σ_1. The results a Si δ-doped sample with $n_s \approx 1.5\times10^{11}$ cm^{-2} are shown in Fig. 4. As is seen, most of the data collapse to a smooth curve, except of those marked my stars. According to our observation, these data correspond to a substantially different cooling procedure. The increasing part of $\sigma_1(n_s)$ is associated with the change of a conductivity mechanism. Consequently, we attribute the scatter in the data in Fig. 4 to some uncontrollable differences in the cooling procedure. We believe that such property, as well as the threshold in AC photoconductance support the idea that the electron states in the doped layer are just the so-called DX-centers [4]. These states are actually two-electron bound states stabilized by local lattice distortion. DX-centers were observed both in $GaAs/Al_{0.3}Ga_{0.7}As$ heterostructures and in $Al_xGa_{1-x}As$ films with $x>0.22$. They are considered to be responsible for DC persistent photoconductance in these systems, in which thresholds in the photon energy located between 0.6 and 0.8 eV were observed (Refs. [4,5], respectively).

In general, the defects responsible for the DX-centers have three charge states which differ by number of electrons occupying the center. Due to a local lattice distortion the two-electron state has the lowest energy if the two-electron correlation energy $|U|$ exceeds the thermal energy kT. As a result, at $T \ll |U|/k$ the defects are either occupied by two electrons and negatively charged (D_--centers) or empty and positively charged (D_+-centers). The D_--centers can be treated as *small bipolarons*.

Acoustic methods under conditions of the QHE provide a unique possibility to separate the contributions of the interface and doped layers. Indeed, at the QHE plateaus the electronic states in the interface layer are *localized* and their contribution to σ_{xx} is small. As a result, the contribution of the electron hopping in the *doped layer* becomes measurable [3]. We believe that the main mechanism leading to this contribution is due to tunneling transition of electron pairs (bipolarons) between a D_- center and an adjacent D_+ one.

3. Conclusions

An important conclusion of the work is that in the integer quantum Hall effect regime when σ_{xx}^{DC} tends to zero the AC conductance is associated with Si-doped layer $Al_{0.3}Ga_{0.7}As$. That does not give a possibility to study quantum effects in the 2D channel by AC methods directly.

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