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AC-hopping conductance of self-organized Ge/Si quantum dot arrays

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Abstract

Dense ($n = 4\times10^{11}\,\mathrm{cm}^{-2}$) arrays of Ge quantum dots in a Si host were studied using attenuation of surface acoustic waves (SAWs) propagating along the surface of a piezoelectric crystal located near the sample. The SAW magneto-attenuation coefficient, $\Delta\Gamma = \Gamma(\omega, H) - \Gamma(\omega, 0)$, and change of velocity of SAW, $\Delta V/V = (V(H) - V(0))/V(0)$, were measured in the temperature interval $T = 1.5$–$4.2\,\mathrm{K}$ as a function of magnetic field H up to 6 T for the waves in the frequency range $f = 30$–$300\,\mathrm{MHz}$. Based on the dependences of $\Delta\Gamma$ on H, T and ω, as well as on its sign, we believe that the AC conduction mechanism is a combination of diffusion at the mobility edge with hopping between localized states at the Fermi level. The measured magnetic field dependence of the SAW attenuation is discussed based on existing theoretical concepts.

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Keywords: Quantum dots; High-frequency transport

1. Introduction

We study Si samples with high-density ($n = 4\times10^{11}\,\mathrm{cm}^{-2}$) arrays of Ge quantum dots (QD). According to Ref. [1], the low-temperature DC conductance of such samples is due to variable range hopping between different QDs. In such dense systems the long-range Coulomb interaction is very important, mainly because its influence on the electron density of states [2]. Both, the density of states and the DC conductance, are sensitive to decay length of the electron states localized on the QD. Hence, it is tempting to find the electron

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localization length by an independent method. To fulfill this task we study attenuation of surface acoustic waves (SAWs) propagating near the QD array as a function of external magnetic field. SAW attenuation allows one to determine the AC conductance of the array, $\sigma(\omega)$, which depends on the localization length. The external magnetic field shrinks the electron wave function, and the consequent shortening of the localization length results in a decrease in the SAW attenuation.

We are aware only of one experiment [3], in which SAW attenuation in a GaAs/AlGaAs array of relatively large (250–500 nm) QDs was studied. In these samples QDs were fabricated using holographic lithography with subsequent ion etching. The authors interpreted their results assuming relaxational absorption within individual QDs [4]. One can expect this mechanism to be very weakly dependent on magnetic field, so that the magnetic field dependence of the attenuation would not manifest itself in relatively weak magnetic fields. Consequently a dependence of the SAW attenuation on magnetic field at weak fields can be mostly ascribed to inter-dot transitions.

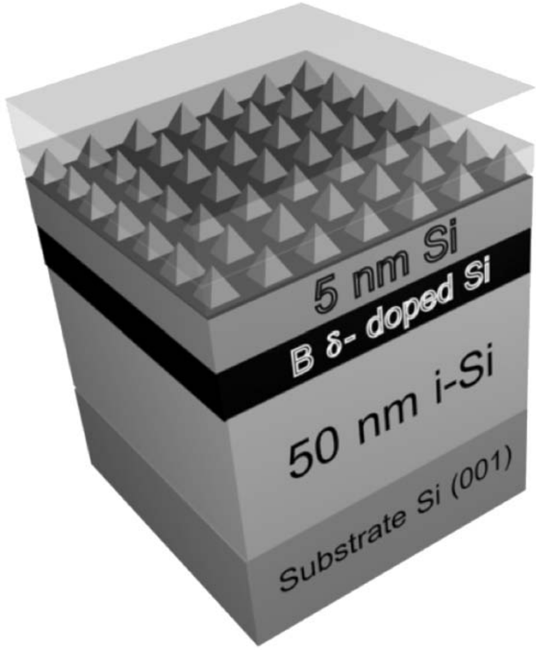

Fig. 1. Scheme of the quantum dot array.

2. Experimental results

We have measured variation of the attenuation coefficient, $\Delta\Gamma = \Gamma(\omega, H) - \Gamma(\omega, 0)$ and change of velocity of SAW $\Delta V/V = (V(H) - V(0))/V(0)$— in B-doped "Ge in Si" dense ($n = 4 \times 10^{11}\,\mathrm{cm}^{-2}$) QD arrays in magnetic field $H \leqslant 6\,\mathrm{T}$.

The samples were grown by MBE method on the (0 0 1) Si-substrate. Firstly, a 50 nm buffer layer of intrinsic Si-doped with B with $N = 2.4 \times 10^{12}$ cm^{-2} (6 holes per QD) was grown. Then a 5 nm undoped Si layer was grown, on top of which 8 Ge monolayers were placed. This structure was covered by a 30 nm i-Si layer. The self-organized Ge QDs had pyramidal shape with a height of 15 Å and square $100 \times 100\,\mathrm{Å}^2$ base (Fig. 1).

In our experiments the sample was pressed to a piezoelectric $LiNbO_3$ crystal by a spring, and SAW propagated along the crystal surface (Fig. 2). In such geometry the SAW is coupled to the holes only by electric fields, and a direct mechanical coupling turns out to be not very important [5,6]. The SAW frequency was in the range 30–300 MHz, and the input intensity varied

Fig. 2. Scheme of the acoustoelectric device. The electric field of a surface acoustic wave propagating on the surface of a piezoelectric substrate acts on a low-dimensional electron system "embedded" into the sample close to its surface. This "hybrid" geometry allows applying a sliding electrostatic potential to the electron/hole system in non-piezoelectric materials.

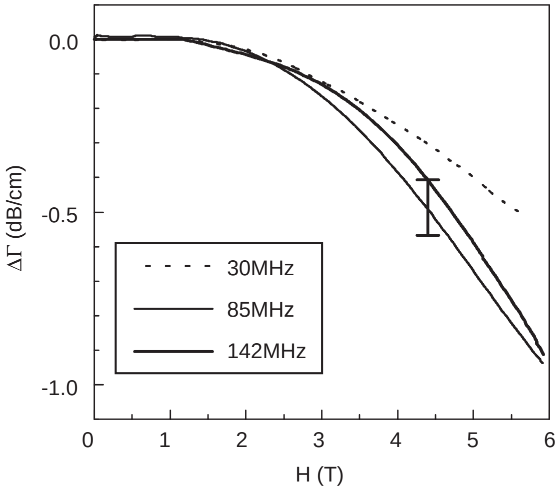

Fig. 3. Dependence of $\Delta\Gamma = \Gamma(\omega, H) - \Gamma(\omega, 0)$, $T = 4.2\,\mathrm{K}$.

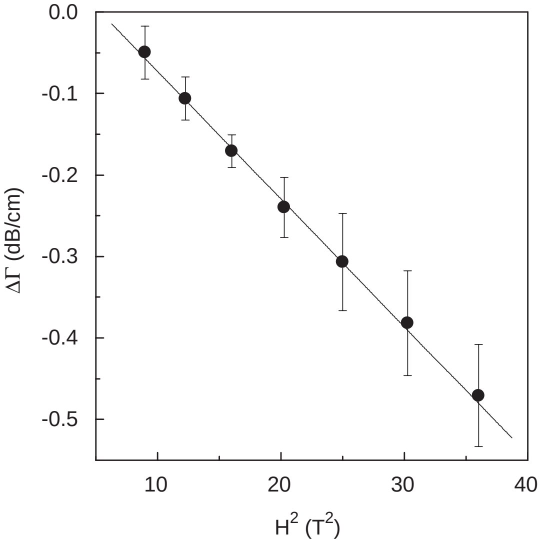

Fig. 4. Illustrative dependence of $\Delta\Gamma$ on H^2, $f = 30\,\mathrm{MHz}$, $T = 4.2\,\mathrm{K}$.

between 3×10^{-6} and 3×10^{-3} W/cm. Since $\Delta\Gamma$ is small even at $H = 6\,\mathrm{T}$ (about few %), two methods were used to determine the SAW attenuation—direct measurement of the SAW amplitude U at the receiver and comparison of this amplitude with the amplitude U_0 of another signal, which passed through the receiver's amplifier avoiding the sample. In the second case the result is just the ratio U_0/U.

DC conductance was measured in this sample in the temperature interval 4.2–25 K without magnetic field. In this temperature interval it obeys the law $\sigma^{\mathrm{DC}}(\Omega^{-1}) = 7.8 \times 10^{-5} \exp[-(282/T)^{0.5}]$. This dependence is compatible with the variable range hopping in the Coulomb gap regime (Shklovskii–Efros mechanism [7]). Having in mind the values of the DC conductance, we expect that in the relevant frequency range the AC conductance of the sample is $<10^{-7}\,\Omega^{-1}$. At such values of conductance the screening of SAW electric field by the layer of QDs is not important, and the attenuation is just proportional to real part of the complex conductance, $\Gamma(\omega) \propto Re\sigma_{xx}(\omega)$.

The measured magneto-attenuation $\Delta\Gamma$ as a function of H for different SAW frequencies is shown in Fig. 3. One can see that the attenuation *decreases* with magnetic field, $\Delta\Gamma < 0$. The absolute value of $\Delta\Gamma$ is proportional to H^2 (Fig. 4).

To make the method useful for quantitative studies of the material one has to extract $\Delta\sigma(\omega)$ and find its frequency and temperature dependences. For this purpose we employ the model of Ref. [8], which presents the system as a combination of semi-infinite substrate and sample divided by a vacuum clearance with thickness a. For $\sigma < 10^{-7}\,\Omega^{-1}$:

$$\Delta\Gamma = \frac{\Delta\sigma A(q) q \mathrm{e}^{-2qa}}{2[(\varepsilon_0 + \varepsilon_1)(\varepsilon_s + \varepsilon_0) - (\varepsilon_1 - \varepsilon_0)(\varepsilon_s - \varepsilon_0)\mathrm{e}^{-2qa}]^2}, \tag{1}$$

$$A(q) = 8.68\,\frac{K^2}{2}\,8(\varepsilon_0 + \varepsilon_1)\varepsilon_0^2\varepsilon_s,$$

where q is the SAW wave vector, K^2 is the electromechanical coupling constant of the substrate ($LiNbO_3$), $\varepsilon_1 = 51$, $\varepsilon_0 = 1$, $\varepsilon_s = 12$ are the dielectric constants of $LiNbO_3$, vacuum and the sample, respectively. The clearance $a = 3 \times 10^{-5}$ cm was determined using the well-known thin-film light interference method.

The frequency dependence of the conductivity $\Delta\sigma$ in magnetic field $H = 6\,\mathrm{T}$ at $T = 4.2\,\mathrm{K}$ was obtained using Eq. (1). It has been found that there is no pronounced frequency dependence of

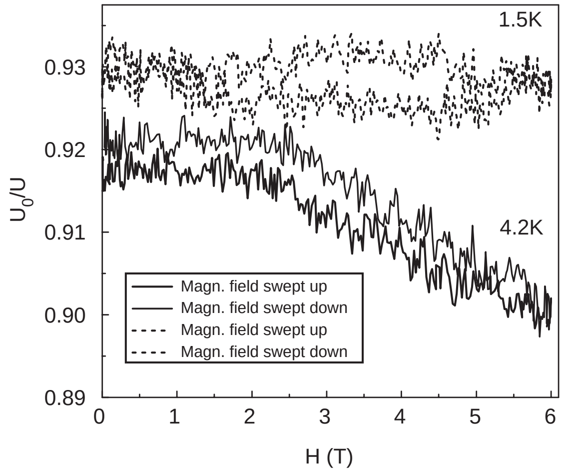

Fig. 5. Dependence of measured in experiments value of U_0/U on magnetic field at $T = 1.5$ and 4.2 K, $f = 87$ MHz.

$\Delta\sigma$ in the frequency range 30–270 MHz within our experimental error.

To get an idea about temperature dependence of the magneto-attenuation we compare the ratio U_0/U at a frequency of 87 MHz for temperatures 4.2 and 1.5 K (Fig. 5). Decrease of this ratio with increase of H means decreasing of the SAW attenuation. At $T = 1.5$ K the SAW attenuation is practically magnetic field-independent. Different curves correspond to increasing and decreasing branches of the magnetic field cycle in the range 0–6 T.

As regards the measurements of the velocity of SAW in a magnetic field, it was too small to be measured (we can measure relative change of velocity to within 5×10^{-5}).

3. Discussion

We have observed negative SAW magneto-attenuation, which is proportional to H^2 in magnetic fields up to 6 T and in the temperature range 1.5–4.2 K. The real part of magnetoconductance, $\Delta\sigma$, obtained from the raw data using the three-layer model [8], is also negative and proportional to H^2. It increases with temperature and almost frequency-independent.

Simple estimates show that the observed behavior cannot be allowed for taking into account only intra-dot transitions. Indeed, the inter-level distances in the small dots significantly exceed both $\hbar\omega$ and kT. Thus we are left with two mechanisms: (i) tunneling or thermally activated hopping between the states localized in different dots forming pairs; (ii) activation to the mobility edge, as in the case of the Coulomb-gap-mediated DC conductance.

In the first case, the theory (see Ref. [9] for a review) predicts a crossover from close-to-linear in frequency and temperature-independent to frequency-independent, but temperature-dependent $\Delta\sigma$. This crossover takes place at $\omega\tau \approx 1$, where $\tau(T)$ is the typical relaxation time for the inter-dot transitions. Another feature of the inter-dot hopping is the big imaginary-real parts ratio of the complex conductance, $\mathrm{Im}\,\sigma(H,\omega)/Re\ \sigma(H,\omega) \gg 1$. The imaginary part of the magnetoconductance can be, in principle, extracted from the measured SAW velocity V. However, the variation of the velocity in magnetic field is too small to be measured at present time.

In the second case the ratio $\mathrm{Im}\,\sigma(H,\omega)/Re\ \sigma(H,\omega) \ll 1$, and the AC magnetoconductance should be close to the DC one. This behavior could be the case at low enough frequencies [10], when the distance between the relevant localized states, $r_\omega = \xi\sqrt{T_0/T}$ ($\xi \simeq 10^{-6}$ cm is the localization length, $T_0 \simeq 280$ K) is comparable with the hopping length for the DC VRH conductivity, $r_T = \xi \ln(I_0/kT)$, where $I_0 \simeq 200$ meV is of the order of energy of the hole excited state in QD. Crude estimations show, that in our experiment $r_\omega \approx 6 \times 10^{-6}$ cm has indeed the same order of magnitude as $r_T \approx 8 \times 10^{-6}$ cm. Consequently, it seems to be difficult to discriminate between the processes at the mobility edge and the processes involving localized states.

4. Conclusions

For the first time, AC magnetoconductance in a Ge-in-Si QD array is measured using the SAW technique. Mechanism of AC conductivity is probably a combination of diffusion at the mobility edge with hopping between localized states at the Fermi level.

Acknowledgements

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