AC Conductance in Dense Array of the Ge$_{0.7}$Si$_{0.3}$ Quantum Dots in Si

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Complex AC-conductance, $\sigma^{AC}$, in the systems with dense Ge$_{0.7}$Si$_{0.3}$ quantum dot (QD) arrays in Si has been determined from simultaneous measurements of attenuation, $\Delta \Gamma = \Gamma(H) - \Gamma(0)$, and velocity, $\Delta V/V = (V(H) - V(0))/V(0)$, of surface acoustic waves (SAW) with frequencies $f = 30$-300 MHz as functions of transverse magnetic field $H \leq 18$ T in the temperature range $T = 1$-20 K. It has been shown that in the sample with dopant (B) concentration $8.2 \times 10^{11}$ cm$^{-2}$ at temperatures $T \leq 4$ K the AC conductivity is dominated by hopping between states localized in different QDs. The observed power-law temperature dependence, $\sigma_1(H = 0) \propto T^{-1.4}$, and weak frequency dependence, $\sigma_1(H = 0) \propto \omega^2$, of the AC conductivity are consistent with predictions of the two-site model for AC hopping conductivity for the case of $\omega \tau_0 \gg 1$, where $\omega = 2\pi f$ is the SAW angular frequency and $\tau_0$ is the typical population relaxation time. At $T > 7$ K the AC conductivity is due to thermal activation of the carriers (holes) to the mobility edge. In intermediate temperature region $4 < T < 7$ K, where AC conductivity is due to a combination of hops between QDs and diffusion on the mobility edge, one succeeded to separate both contributions. Temperature dependence of hopping contribution to the conductivity above $T^* \sim 4.5$ K saturates, evidencing crossover to the regime where $\omega \tau_0 < 1$. From crossover condition, $\omega \tau_0 (T^*) = 1$, the typical value, $\tau_0$, of the relaxation time has been determined.

I. INTRODUCTION

Understanding of AC conductivity of low dimensional semiconductor structures is important both for fundamental science and nanodevice applications. Though the surface acoustic waves (SAW) technique has been successfully applied for AC conductivity measurements in two dimensional systems, only limited number of works aim at zero-dimensional objects$^{1,2}$. Here we report our results on the interaction between arrays of Ge$_{0.7}$Si$_{0.3}$ dots in Si with surface acoustic waves.

A layer containing a dense ($3 \times 10^{11}$ cm$^{-2}$) self-assembled array of Ge$_{0.7}$Si$_{0.3}$ quantum dots has been grown on a B delta-doped Si substrate and then covered by a 2000 A Si layer (Fig. 1). The dots were square pyramids with $120 \times 120 \, \text{Å}^2$ in base and 12 Å in height. Three samples with distinct B concentrations - $6.8 \times 10^{11}$ cm$^{-2}$ (sample 1), $8.2 \times 10^{11}$ cm$^{-2}$ (sample 2), and $11 \times 10^{11}$ cm$^{-2}$ (sample 3) - were investigated.

We studied the influence of an external magnetic field on the attenuation and relative velocity change for a SAW propagating along a surface of a piezoelectric lithium niobate platelet, when a sample with the quantum dots array was pressed to the surface (Fig. 2). The AC electric field accompanying the SAW penetrated into the sample, while no mechanical strain in the semiconductor sample was produced. The applied magnetic field of up to 18 T

![Layer scheme of the sample containing a dense array of Ge$_{0.7}$Si$_{0.3}$ quantum dots.](image-url)
was perpendicular to the quantum dots layer, and therefore to the SAW wave vector. The measurements were performed in the temperature range 1-20 K and in the SAW frequency range from 30 to 300 MHz.

II. EXPERIMENTAL RESULTS AND DISCUSSION

In the temperature interval between 1 and 5 K, see Fig. 3 (a-b), the SAW attenuation decreases, while the SAW velocity increases with magnetic field. We ascribe these behaviors to the inter-dot AC hopping conduction, described by the conventional two-site model. According to this model, variations of the SAW attenuation and velocity with magnetic field is due to shrinking of the localized wave functions of the states involved into hopping. The theory predicts that in low magnetic fields both $\Delta\Gamma = \Gamma(H) - \Gamma(0)$ and $\Delta V/V = (V(H) - V(0))/V(0)$ are proportional to $H^2$, while at high fields both quantities are proportional to $H^{-2}$, and therefore both the attenuation and velocity saturate. Our experimental data agree with these predictions.

Moreover, since $\Delta\Gamma \mid_{H \to \infty} = -\Gamma(0) + A/H^2$ one can find the zero-field attenuation, $\Gamma(0)$. A similar procedure can be used to determine $\Delta V(0)/V$. Thus, simultaneous measurement of $\Delta\Gamma(H)$ and $\Delta V(H)$ allows us to implement the procedure described in Refs. 4, 5 for determining the zero field AC conductance, $\sigma = \sigma_1 - i\sigma_2$, Fig. 4, for different temperatures and SAW frequencies. It has been found that both $\sigma_1$ and $\sigma_2$ are frequency-independent with accuracy 15% and 25%, respectively. Power-law temperature dependence of conductance, $\sigma_1(H = 0) \propto T^{2.4}$, and its independence of frequency agree with predictions of the two-site model for the case $\omega \tau_0 \gg 1$, where $\tau_0$ is the population relaxation time for a typical pair of dots giving contribution to the conductance.

At higher temperatures the sign of $\Delta\Gamma$ changes from negative to positive. At the same time, the two-site model predicts the crossover to the regime $\omega \tau_0 \ll 1$, where $\Delta\Gamma$ should saturate as a function of the temperature. To explain the experimental temperature dependence we assume that with temperature increase an additional conduction mechanism - carrier activation to the mobility edge - emerges and becomes dominant. As it follows from the experimental data, at higher temperatures the real part of the conductivity follows the activation law, $\sigma_1(H = 0) \propto \exp(-E_a/k_BT)$, with $E_a=2.5$ meV.

At intermediate temperatures, $4 < T < 7$ K, the AC conductivity in the sample 2 is a combination of hops between quantum dots and diffusion at the mobility edge. Extrapolation of the activation dependence to lower temperatures, Fig. 5, allowed us to extract the hopping contribution, $\sigma_1^h$, in the whole temperature range, Fig. 6. It is seen that $\sigma_1^h$ saturates as a function of the temperature...
at temperatures higher than $T^* \sim 4.5$ K, evidencing transition to the regime where $\omega \tau_0 < 1$. It follows from the crossover condition, $\omega \tau_0(T^*)=1$, that $\tau_0(T^*) \approx 5 \times 10^{-9}$s.

It is worth noting that the two-site model predicts $\sigma_2$ to be greater than $\sigma_1$, however, that is not the case in the experiment. We hope that a more sophisticated model allowing for the properties of dense arrays will provide better quantitative description of the experimental situation.

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