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Hopping magnetoresistance in two-dimensional arrays of Ge/Si quantum dots

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The temperature and magnetic field dependences of the conductivity associated with hopping transport of holes over 2D arrays of Ge/Si quantum dots with various filling factors are studied experimentally. A transition from the Efros-Shklovskii law for the temperature dependence of hopping conductivity to the Arrhenius law with an activation energy equal to 1.0-1.2 meV is observed upon a decrease in temperature. The activation energy for the low-temperature conductivity increases with the magnetic field and attains saturation in fields exceeding 4 T. It is found that the magnetoresistance in layers of quantum dots is essentially anisotropic: the conductivity decreases in magnetic fields oriented perpendicular to a dot layer and increases in a field whose vector lies in the plane of the sample. The absolute values of magnetoresistance for transverse and longitudinal field orientations differ by two orders of magnitude. Effect of spin correlations on the hopping magnetoresistance is discussed.

1 Introduction Analysis of fundamental aspects of charge transport as well as Coulomb and spin correlations in semiconductor nanostructures forms the basis for the development of nanoelectronics — one of the latest trends in the physics and technology of nanometer-size electronic devices. The layers of self-organized quantum dots (QDs) obtained as a result of heteroepitaxy of elastically strained systems are the most suitable objects for studying 2D hopping transport as well as the role of Coulomb correlations in a system of localized electrons. This is due the fact that (i) QDs lie exactly in the same (growth) plane and the disorder factor associated with disorder in the vertical (growth) direction of the nanostructure is absent; (ii) introducing electrons or holes into QDs, it is possible to controllably obtain 2D ensembles of localized charge carriers in apriori known quantum states with preset wave functions; (iii) since, as a rule, the ratio of the height to the lateral size in self-assembled QDs is much smaller than unity, the wave functions of charge carriers in QDs are strongly anisotropic and two-dimensional in contrast to those for impurities. A typical example of self-organized QDs is Ge QDs in Si(001) matrix. Ge/Si(001) QDs exhibit a type-II band-edge line-up: the localization inside the dots occurs only for holes, whereas the dots form potential barriers for electrons. The energy levels of the hole bound states in the dots are rather deep. For example, the ground state energy of hole confined in a pyramid-shaped Ge QD with a lateral size of $\sim$ 10 nm is about 300 meV [1]. Thus at low temperatures charge transport along arrays of Ge/Si QDs is dominated by 2D hole hopping between the dots. In this work we describe a set of experiments aimed at investigation of the mechanism of charge transport at different temperatures and magnetic fields in 2D arrays of Ge/Si QDs.

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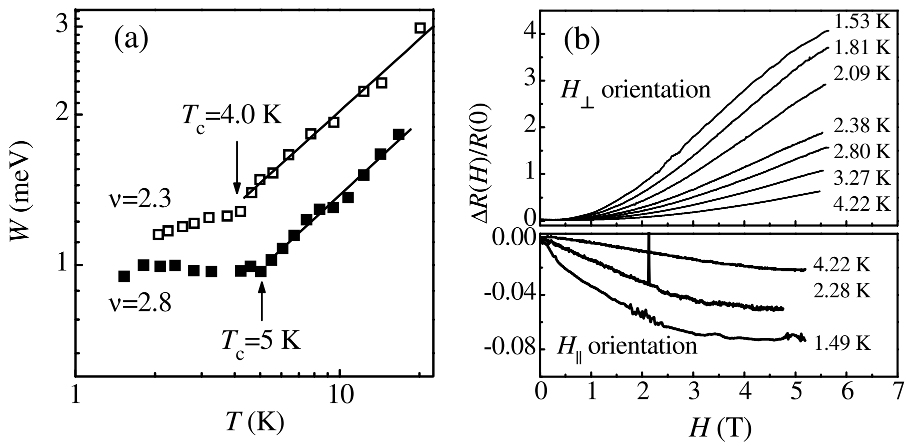

Fig. 1 (a) Temperature dependence of the hopping conduction activation energy plotted in the log–log scale. Solid lines describe the approximation of experimental data on $W(T)$ by $W(T) = xk_BT^{1-x}T_0^x$. (b) Relative variation of the resistance in a magnetic field at various temperatures for a Ge/Si QD sample with QD filling factor $\nu = 2.8$. The magnetoresistance was measured in a magnetic field which was perpendicular ($H_\perp$ orientation) or parallel ($H_{||}$ orientation) to the plane of the structure.

2 Samples Ge/Si heterostructures with self-assembled Ge QDs were fabricated by molecular-beam epitaxy in the Stranskii-Krastanov growth mode on (001)-oriented Si substrates. A Ge layer 8 monolayer thick (~ 10 Å) was introduced into the 250-nm epitaxial p-Si layer (boron concentration $\sim 10^{16}$ cm^{-3}) at a distance of 50 nm from the substrate. This produces spontaneous formation (self-assembling) of Ge nanoclusters randomly distributed in the plane. The average size of the dot base length is around 12 nm, the height is ~ 1 nm. The areal density of the dots is $n_{QD} \approx 4 \times 10^{11}$ cm^{-2}. To supply holes on the dots, a boron δ-doping Si layer was inserted 10 nm below the Ge QD layer. The concentration of boron was varied for different samples, which was allowed to change the average dot filling factor ν. To separate response from the dots, the reference samples were grown under conditions similar to the dot samples, except no Ge was deposited. Our measurements showed that the values of both conductance and relative magnetoresistance of the reference samples are about two orders of magnitude smaller than those of the samples with Ge QDs, which indicates a decisive role of the dots in the observed peculiarities of charge transport. Preparation and measurement details have been published elsewhere [2].

3 Temperature dependence of conductivity In general, the temperature dependence of the conductivity for variable-range hopping (VRH) is given by $\sigma(T) = \sigma_0 \exp[-(T_0/T)^x]$, where, in the 2D case in the absence of long-range Coulomb interaction, the exponent $x = 1/3$. VRH conductivity in the presence of long-range Hartree interaction between localized single-particle excitations obeys the Efros-Shklovskii law with $x = 1/2$. In order to obtain detailed information on the functional dependence $\sigma(T)$, we analyzed the temperature dependence of the activation energy which is defined as $W(T) = \partial \ln \sigma(T)/\partial(1/k_BT) = xk_BT^{1-x}T_0^x$, where k_B is the Boltzmann constant. In this approach, we have $\log W(T) = A+(1-x)\log T$ and $A = \log(xk_BT_0^x)$. Plotting $\log W$ as a function of $\log T$, one can find the hopping exponent x from the slope of the straight line. Typical plots of $\log W(T)$ versus $\log T$ for several samples are given in Fig. 1(a). It can bee seen that the activation energy at high temperatures decreases with T; i.e., the VRH regime is realized. At temperatures below $T_c = 4 - 5$ K, the activation energy becomes virtually independent of temperature. Approximation of high-T data by straight lines gives hopping exponent $x = 0.52 \pm 0.03$ and $x = 0.50 \pm 0.03$ for samples with $\nu = 2.3$ and 2.8, respectively. This means that the value of x changes from $x = 1/2$ to x 1 upon system cooling.

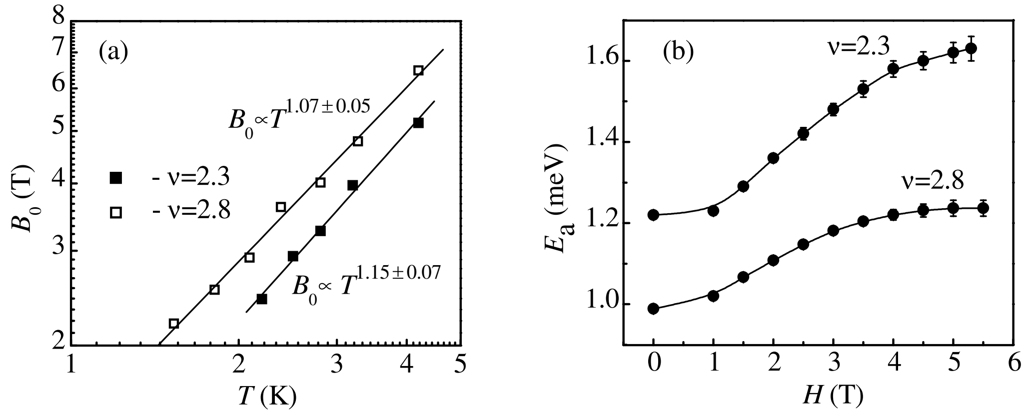

Fig. 2 (a) Values of characteristic magnetic field B_0 obtained by approximating the low-field experimental data by $\ln(R(H)/R(0)) = H^2/B_0^2 - H/H^*$ for various temperatures. Solid lines show the results of approximation of experimental $B_0(T)$ dependencies by a power function. (b) Magnetic field dependence of the low-temperature activation energy (in order to determine E_a, the $\sigma(T)$ data were taken at $T < 4$ K).

4 Magnetoresistance The magnetoresistance (MR) for the Ge/δ-Si:B sample with $\nu = 2.8$ is shown in Fig. 1(b). MR is positive in a transverse magnetic field and negative in a longitudinal magnetic field. The relative MR for the transverse orientation appears to be by two orders of magnitude larger than the value of $|\Delta R(H)/R(0)|$ for fields parallel to the plane of the structure. Such a giant anisotropy indicates an "ideal" 2D nature of hopping transport in QD layers. In what follows, we will confine ourselves to the discussion of experimental data for the $H_\perp$ field orientation only. A detailed analysis shows that the magnetic-field dependence $R(H)$ of the resistance for QD samples in a region of weak fields can be approximated by $\ln(R(H)/R(0)) = H^2/B_0^2 - H/H^*$. The negative term linear in H takes into account the presence of a negative MR in the vicinity of zero and is probably associated with suppression of destructive interference of different tunneling paths in a magnetic field [3]. As the magnetic field increases, the MR rapidly changes its sign and becomes positive. The positive contribution is usually related to shrinkage of the wave functions of localized carriers in directions perpendicular to the magnetic field [4]. The values of characteristic fields B_0 are shown in Fig. 2(a). It was found that parameter B_0 for both samples is a nearly linear function of temperature. Measurements of the temperature dependence of conductance demonstrate that the activation nature of charge transport is also preserved in a magnetic field. Figure 2(b) shows the low-T activation energy E_a determined from the slope of the experimental curves plotted in Arrhenius coordinates. It turns out that the value of E_a increases in a magnetic field and tends to saturate at $H > 4$ T.

5 Discussion The simple activated law of the type $\sigma(T) = \sigma_0 \exp(-E_a/k_B T)$ in the regime of hopping conduction is usually attributed to the nearest-neighbor hopping in impurity band. In our case, this conduction mechanism cannot explain the experimental results for the following reasons. First, the mechanism of conduction over the nearest neighbors must be replaced by variable range hoping conduction upon cooling. Our experiments reveal the reversed situation. Second, when the nearest-neighbor hopping conduction through impurity states takes place, the characteristic magnetic field B_0 is independent of temperature and depends only on density of sites [5]. However, Ge/Si samples with QDs exhibit a linear relation between B_0 and T [see Fig. 2(a)]. The above arguments suggest that the energy states of holes are absent in the vicinity of the Fermi level in a band of width $2E_a$; in other words, the hole density of states contains a small (~ 1 meV) "hard" gap which increases in a magnetic field. The origin of this gap is still unclear and deserves further investigations. It can be probably attributed to formation of electronic polarons as a result of many-particle excitations in 2D Coulomb glasses [2].

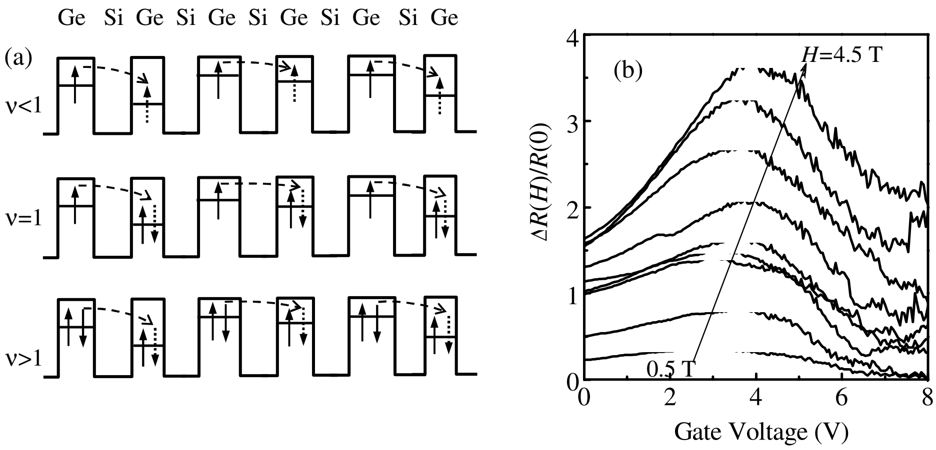

Fig. 3 (a) The schematic sketch of the valence band profile along the layer of Ge/Si quantum dots and the interdot hole transitions (arrows denote hole spin orientation) in the presence of magnetic field at various dot filling factors ν. (b) Experimental magnetoresistance of Ge/Si MOSFET as a function of gate voltage in different magnetic fields. The field varies from 0.5 T to 4.5 T with an increment of 0.5 T. Data were taken at $T = 4.2$ K.

6 Spin effects in hopping magnetoresistance The localized states of holes in the Ge QD are characterized by the angular momentum **J** and its projection J_z on the growth direction z. This projection can be considered as an analog of electron spin for hole states [6]. In this section we will show how the hole spin can affect magnetoresistance in the hopping regime of charge transfer. The idea of this experiment is based on the results of recent theoretical calculations which have demonstrated that probability of interdot tunneling processes with spin-flip for the hole states in 10-nm sized Ge QDs is two orders of magnitude smaller than that with spin conservation [6]. For simplicity, we will consider only the ground hole state with the maximum occupation $\nu = 2$ disregarding excited states due to the large ($\sim$ 50–70 meV) energy-level separation and neglect the intradot Coulomb correlations. When a magnetic field is applied, all hole spins in the system become polarized. For the average dot filling factor $\nu < 1$ and $\nu > 1$ the hopping of holes between QDs occurs with spin conservation [Fig. 3(a), top and bottom panels]. When $\nu \approx 1$, the hopping transition is accompanied by the spin-flip process [Fig. 3(a), middle panel] which certainly has a much lower probability. The suppression of hopping process by a magnetic field gives rise to a positive MR resulting in a resonant increasing of the hopping MR at $\nu \approx 1$ due to spin correlations. This prediction has been checked for a Ge/Si metal-oxide-semiconductor field-effect transistor (MOSFET) containing remotely doped Ge dots in a buried active channel. The average filling factor of the QD array was varied by the gate potential V_g down to $\nu = 0$. Experimental results are shown in Fig. 3(b). The MR peak emerging in a magnetic field and superimposed on the positive magnetoresistance is really observed at $V_g \simeq 4$ V. We suppose that the positive background is due to the wave function shrinkage effect while the MR peak is related to the spin correlations described above.

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