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Conductance through chains of Ge/Si quantum dots: crossover from one-dimensional to quasi-one-dimensional hopping

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Parallel chains of germanium quantum dots were grown on a patterned silicon (100) substrate prepared by the combination of nanoimprint lithography and ion irradiation. Strong anisotropy of the conductance between the direction of the chains and the perpendicular one was observed; the current-voltage curves being essentially superlinear. At low bias voltage dependence of the conductance obeys the Arrhenius law indicating one-dimensional (1D) hopping. With increase of the bias this dependence crosses over to $G \propto \exp[-(T_0/T)^{1/2}]$ explained by a quasi-1D transport involving hopping between nearest neighboring chains.

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Progress in technology enables the realization of a wide variety of materials with one-dimensional (1D) structural and electronic properties perspective for applications in nanotechnology. They include carbon nanotubes, nanowires, polymers, conducting molecules, etc. Before applications of 1D structures may become practical, a number of fundamental problems need to be resolved. One of them is the effect of disorder on transport properties. Despite great progress in nanofabrication, the disorder is hard to get rid off, especially if a low-cost processing is desired. The disorder causes localization of electron states, so that the low-temperature transport in 1D systems is often dominated by hopping. In this case one can anticipate that temperature dependence of the conductance, $G(T)$, obeys the law

$$G(T) = \gamma T^m \exp[-(T_0/T)^x], \qquad (1)$$

where γ is a temperature-independent factor and the exponents m and $0 < x < 1$ depend on the hopping regime. If electron-electron interaction is not important then this is just the Mott's law for the variable range hopping (VRH) [1]. In this case γ, m, and T_0 are the material-dependent constants while x is related to the system dimensionality, d, as $x = (1+d)^{-1}$. For $d = 1$, $x = 1/2$. This formula, while applied to the 1D case, has immediately become a matter of controversy because a very important and nontrivial peculiarity of the 1D geometry – crucial role of highly resistive segments ("breaks") on the conducting paths – was overlooked [2–5]. A proper account of the breaks leads to the Arrhenius (activation) law for $G(T)$,

$$G(T) \sim \exp(-T_1/T), \qquad (2)$$

where T_1 is set by the highest barrier that occurs in the chain. Nevertheless a lot of the experiments on 1D systems show the hopping behavior described by the stretched exponential dependence similar to the Mott law (1) [6].

Several attempts were made to explain this dependence theoretically. One idea was to take into account hops between the nearest chains avoiding highest barriers. That makes the system not strictly one-dimensional [7, 8]. Another idea was assuming that the conducting system is a quasi-one-dimensional strongly anisotropic fractal [9]. This model, mostly suitable for polymers, also results in Eq. (1), but with different meaning of the parameter T_0. Furthermore, it has been shown [10] that role of the breaks decreases in sufficiently strong electric fields. Even more complicated behavior is expected when electron-electron interaction is important [11]. Therefore, the physical picture of electron transport in quasi-1D conductors is very rich and diverse.

In the present work we study the transport through a set of parallel chains of quantum dots (QDs), in which the regime of 1D transport is strongly dependent on the bias voltage. We show that in a weak electric field

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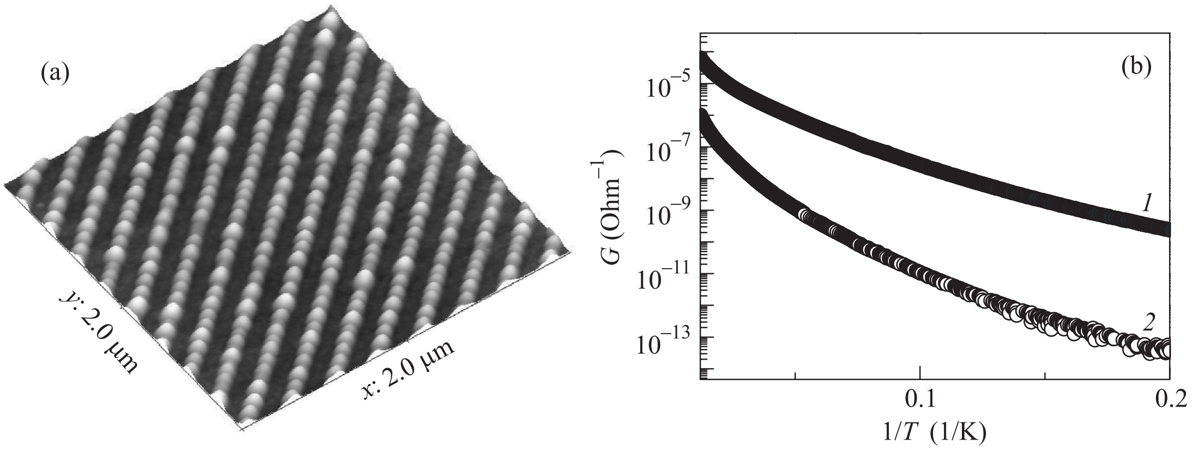

Fig. 1. (a) – AFM image of the structure under study. (b) – Temperature dependence of conductance measured along (1) and perpendicular (2) to the wires at bias voltage of 0.5 V

the hole transfer is limited by highly resistive tunneling barriers ("breaks") leading to the activation (Arrhenius) law (2), whereas increase of the bias voltages leads to a crossover to the variable range hopping (1). We call this regime the quasi-1D transport.

The samples under study were grown on a (001) p-Si substrate with a resistivity of 20 $\Omega\cdot$cm by molecular-beam epitaxy (MBE) of Ge. Before growth the pre-patterning of the Si surface was carried out using the original approach based on the combination of nanoimprint lithography [12] and ion irradiation proposed in our resent work [13]. After this process a periodically striped structure was observed, with the relief height about 30 nm and period about 180 nm.

Further molecular beam epitaxy (MBE) of Ge on the pre-patterned Si surface allowed us to create parallel wires of QDs with their one-dimensional density controlled by the growth regimes. 1 nm-thick Ge layer was deposited at 600 °C with a rate of 0.005 nm/s. To supply holes to the dots, a B-δ-doped Si layer was inserted 15 nm above the Ge QDs layer. The silicon cap layer has a thickness of 40 nm. Al metal source and drain electrodes were deposited on the top of structure and heated at 480 °C. The distance between the contacts was about 0.05 mm. The resistance both along and perpendicular to the QD chains was measured by the two-terminal method with a Keithley 6514 electrometer. A similar procedure carried out for a plain Si surface in which a 2D layer of QDs was formed leads to formation of very high quality Ohmic contacts with resistance much smaller that the resistance of the sample. Therefore, we expect that in our structure the measured conductance is determined by the transport via QDs. The temperature stability was controlled using Ge thermometer. Our QD structures can be roughly divided in two groups. The structures of the first type contain numerous QDs between the chains forming rather dense set of "bridges". In the structures of the second type the bridges are rare.

The Atomic Force Microscopy (AFM) image of a typical second-type structure is shown in Fig. 1a. This part of the structure does not contain visible bridges.

Fig. 1b demonstrates temperature dependence of the conductance measured along (curve *1*) and perpendicular (curve *2*) to the wires measured on different, but similar second-type samples at the bias voltage of 0.5 V. One can see that the anisotropy of the conductance reaches 4 orders of magnitude. Significant anisotropy indicates 1D character of the electron transport while a finite conductance in the perpendicular to the field direction evidences the presence of charge transfer between the chains. The anisotropy of the conductance in the first-type structures was much less.

In this paper we focus on the second-type structures where anisotropy of the conductance reaches 2–4 orders of magnitude. Measurements were performed on 4 samples and in what follows we demonstrate typical behaviors.

Shown in Fig. 2a are temperature dependences of the conductance measured at different bias voltages. Current-voltage curves at different temperatures are presented in Fig. 2b. They demonstrate a super-linear behavior typical for the hopping conductance [14, 15, 10]. It is a consequence of "tilting" of the potential by electric field leading to decrease of the effective barriers between the sites and facilitation inter-site transitions.

We have verified that the observed non-Ohmic behavior cannot be explained by heating of charge carriers involved in diffusive transport [16]. A hallmark of that

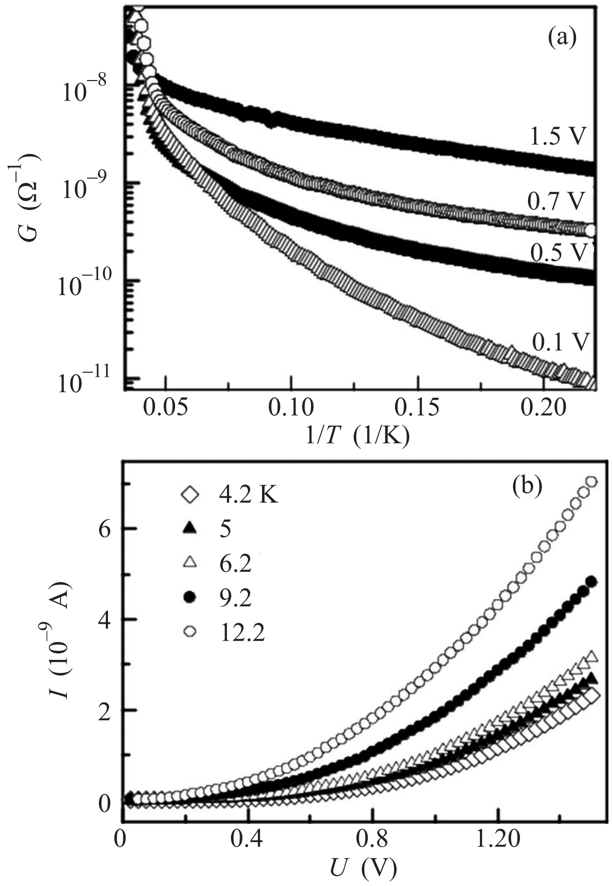

Fig. 2. (a) – Temperature dependences of conductance measured along the wires for different bias voltages. (b) – $I-V$ curves for different temperatures

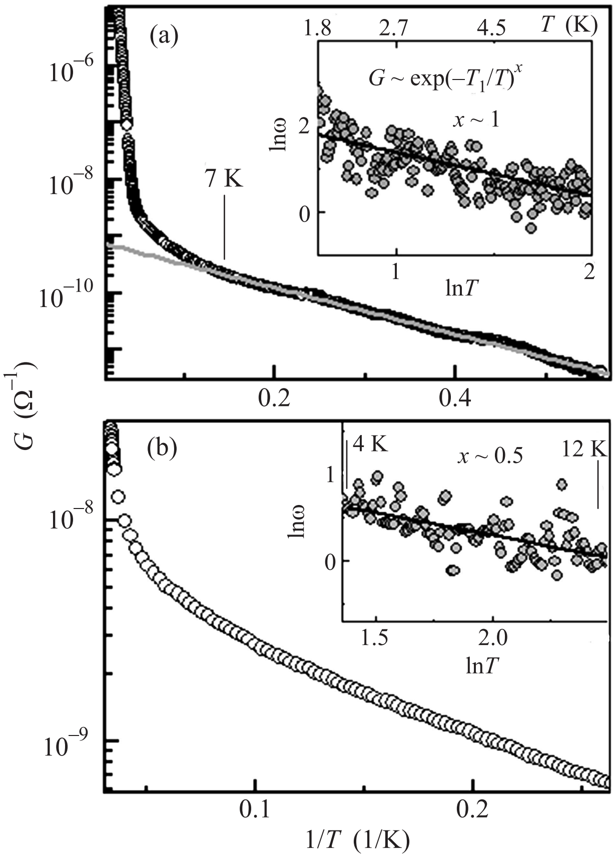

Fig. 3. Temperature dependences of the conductance for bias voltages of 0.7 V (upper panel) and 1.5 V (down panel). High-temperature parts correspond to activation to the valence band. Insets – $\ln w$ versus $\ln T$, solid lines – linear fits

regime is a universal relation between the conductance, dissipated power and temperature [17]. This relation is not met in our system. Based on combination of the above facts we conclude that the observed non-Ohmic behavior of conductance is due to the increase of the hopping probability and impact ionization that are the characteristic features of the hopping behavior.

To identify the hopping mechanism the temperature dependences of the conductance for the bias voltages of 0.7 and 1.5 V (Fig. 3) were analyzed using the method of the reduced activation energy [18]. Along this approach, we assume that the temperature dependence of the conductance is given by Eq. (1) and present the logarithmic derivative $w \equiv \partial \ln G(T)/\partial \ln T$ as the combination $m + x(T_0/T)^x$ containing 3 adjustable parameters. If $m \ll x(T_0/T)^x$ then $\ln w(T) \propto x \ln T$, so the slope of the $\ln w$–versus–$\ln T$ dependence provides the hopping exponent x.

A typical plot for the bias of 0.7 V is given as inset in the upper panel of Fig. 3. In the range 7–1.6 K the $G(T)$ dependence is well described by the Arrhenius law ($x = 1$) that typical for the strong localized 1D regime determining by the most resistive break in the wire. The activation energy was determined to be 0.8 meV. Increase of the bias voltage changes the behavior of conductance in such a way that in the temperature range 4–13 K the exponent x is close to 0.5 (lower panel of Fig. 3) corresponding to the Mott's law in a 1D system. That happens, in particular, when the current lines can avoid the breaks inside of the chain or increase of the hopping length in strong field can lead to including of neighboring chains to the percolation path. Below 4 K we observe the conductance that very weakly depends on the temperature at large bias. Such a behavior was observed in polydiacetylene [19] and explained by activation-free phonon-emission-assisted hopping conduction [14], which follows the non-Ohmic hopping conduction regime as temperature decreases. In this regime, due to "tilting" of the potential profile by the electric field, the hopping between the localized states always involves emission of a phonon and takes place to the states having lower energy.

Different models were used to describe the behavior of non-Ohmic conductance in 1D. The best description of our results for large bias is given along the model expecting quasi-1D VRH between nearest neighboring chains [7, 8, 20].

Assuming that there exists charge transfer between the nearest neighboring chains the authors present the dependence of the conductance on the bias voltage U in the form

$$\ln G = K(T)(U/L)^{1/2} + \mathrm{const}(U),\ K(T) \propto T^{-1/2}, \quad (3)$$

where L is the length of the sample. This behavior agrees with our results (see Fig. 4), where the depen-

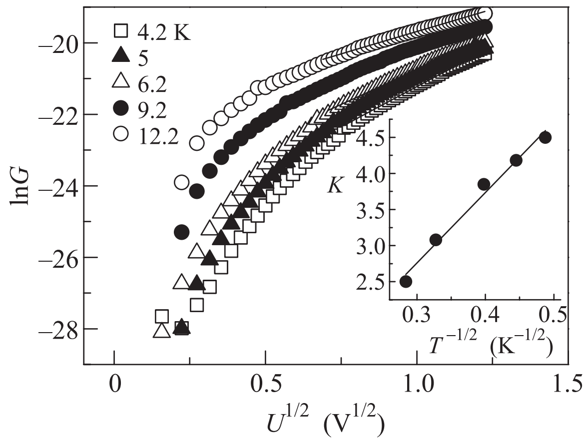

Fig. 4. The $\ln G(U^{1/2})$ dependences measured at different temperatures. Inset – K versus $T^{-1/2}$. The solid line is the least-squares fit to the linear dependence

dences $\ln(G)$ versus $U^{1/2}$ are plotted for different temperatures. The dependence $K(T^{-1/2})$ is shown in the inset.

We also tried to fit the experimental data by the prediction of the theory [10] based on the assumption of isolated wires. However the scaling following from that theory for intermediate and large bias was not observed.

The observed linear dependence $K(T^{-1/2})$ shown in the inset of Fig. 4 supports the transport mechanism based on the mode [7, 8] of quasi-1D VRH. However, this model predicts that at low bias one should observe the Mott-law temperature dependence, $G \propto \propto \exp\left[-(T_0/T)^{1/2}\right]$, while we observe the Arrhenius one, $G \propto \exp(-T_1/T)$, predicted for purely 1D hopping. We conclude that at low bias the inter-chain transport is suppressed by high barriers between the chains, while at high bias voltages the role of barriers is diminished resulting in the crossover to a quasi-1D behavior. It seems that the charge transport between the QDs belonging to the nearest chains occurs via inter-chain QDs, which are present even in the second-type samples. They are actually responsible for the conductance in the direction perpendicular to the chains.

Our samples demonstrate photoinduced switching of conductance followed by slow relaxation accompanied by so-called persistent photoconductance when the system does not return to the initial state even through several hours of the relaxation in dark. This behavior is similar to that observed in 2D arrays of Ge/Si QDs [21] and explained by the space separation of electron and holes in type-II QDs. Shown in Fig. 5 is kinetics of pho-

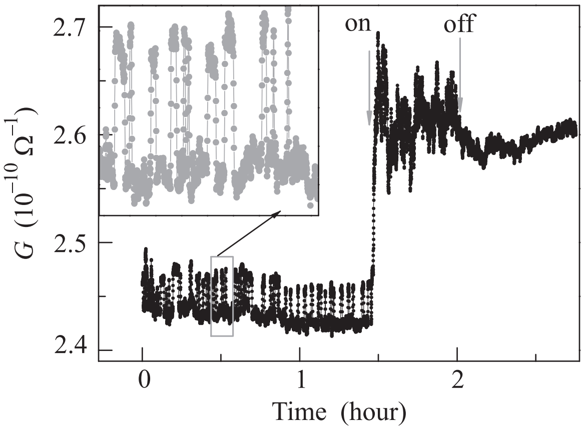

Fig. 5. Kinetics of photoconductance under illumination with 1.5 μm light. Inset – enlarged image of the two-level fluctuation in dark

toconductance under illumination with 1.5 μm light. In addition to the photoinduced switching there exist pronounced two-level fluctuations of the conductance in the dark state. These typically mesoscopic fluctuations evidence that the transport is dominated by few "bottlenecks", which can be restructured due to illumination.

The main conclusion of the present work is that in the studied arrays of QD chains the charge transport is due to 1D hopping along the chains at a small bias, which crosses over to a quasi-1D transport including inter-chain hopping between nearest neighbors at a large bias.

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