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Giant mesoscopic photoconductance fluctuations in Ge/Si quantum dot system

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We studied the impact of weak photon flux on the electron transport in strongly localized quantum dot system. Exploring devices with narrow transport channels lead to the observation of giant fluctuations of the photoconductance, which is attributed to the strong dependence of hopping current on the filling of dots by holes. This phenomenon has the potential to detect a single photoexcited carrier for a wide range of wavelength. In our experiments, single-photon mode operation is indicated by the linear dependence of the frequency of photoinduced fluctuations on the light intensity and the steplike response of conductance on the pulse excitation. © *2011 American Institute of Physics*. [doi:10.1063/1.3574022]

Two-dimensional electron gas (2DEG) and two-dimensional hole gas in silicon based materials, including inversion layer or accumulation layer field-effect transistors, SiGe quantum wells and strained Si layers, belong to the best studied systems due to their impact in modern communication technology. Experiments mapping out the gate bias voltage, temperature, electric field, and magnetic field dependences of the conductance have been made over a very wide range of carrier concentrations. The conductivity regimes found, reach from being metallic, to weakly localized and even to the hopping conduction.[1] The hopping transport regime can be explained by the disintegration of the 2D system into paddles of carriers in the valleys of a potential landscape. The interest in the hopping transport arose, when it was realized that the conductance in mesoscopic devices is not given by averaging over all possible paths of conduction, but along current lines providing the lowest resistance.[2] It becomes clear, that hopping conductance in mesoscopic devices will drastically depend on modifications of the potential of localized states, thus giving rise to the design of a new class of devices being able to sense single charges. In this respect, an interesting approach was proposed by Beattie *et al.*[3] The authors tuned the potential landscape of a 2DEG being in hopping regime, by an optical control of the charge occupancy of a quantum dot (QD) layer adjacent to the 2DEG. Under weak illumination they observe steplike increments in conductance of 2DEG caused by the discharging of individual dots by a single photoexcited electron.

In this work the optical modulation of the occupancy of a Ge/Si QD layer was used to observe giant fluctuations of hopping current flowing directly through the 2D array of QDs. To realize this type of transport, a very dense array of QDs with nanometer dots and a relative homogeneous size distribution is required.[4] The characteristic feature of hopping transport in a QD layer is an extremely strong dependence of the conductance on the occupation of QDs by carriers. It was shown[4] that the conductance in a Ge/Si QD layer is changed nonmonotonously by more than six orders of magnitude, upon variation in the average QD filling ranging from 0.5 to 6 holes per dot. Thus, adding or removing single charges from individual QDs should force the conductance to change. Previously, we showed[5] that illumination of macroscopic samples with QDs results in a photoconductance (PC), with their sign and magnitude being depended on the initial filling of the QDs with holes. The average change in the conductance under 0.9–1.55 μm wavelength illumination was 10%–20%.

Here we study the conductance in mesoscopic structures, hence the most favorable current path depends strongly on the exact realization of the random potential, i.e., on the charge state of every individual dot. Thus, under weak illumination we expect to observe a steplike change in the conductance, corresponding to the physical process of adding/removing a single charge to a dot. Indeed, employing this idea to Ge/Si QD devices with a size, much smaller than the correlation length of the percolation network, the present work demonstrates conductance fluctuations reaching up to 70% induced by single photons.

The samples were grown on a (001) p-Si substrate with a resistivity of 20 $\Omega\cdot$cm by molecular-beam epitaxy. A silicon buffer layer is followed by ten monolayers of Ge grown at 300 °C in the Stranskii–Krastanov growth mode. As a result, the areal density of the dots was shown to be $\sim 4\times 10^{11}$ cm^{-2}. To supply holes to the dots, a boron δ-doped Si layer was inserted 5 nm below the Ge QD layer. A silicon capping layer with 40 nm thickness covers the QDs. Electron-beam lithography and reactive ion etching were used to create the conductive channel with the length $l=100$ nm and width w being varied in the range of 70–200 nm. Al metal source and drain electrodes were deposited on the top of the structure and annealed at 480 °C to form Ohmic contacts. The system was illuminated by fiber coupled laser with 1.55 μm wavelength and 0.5 mW power. To get extremely weak light intensity, the initial laser power was attenuated up to 40 dB. Time-resolved measurements were carried out using four-point scheme at the temperature

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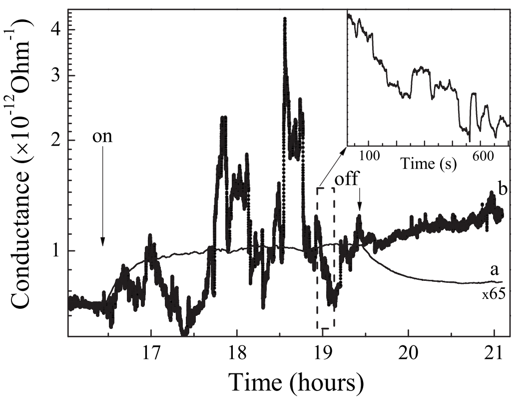

FIG. 1. Conductance evolution for the sample with $w=70$ nm under illumination. The inset is an enhanced part of the conductance curve. Line (a) depicts the conductance vs time for the corresponding macroscopic sample.

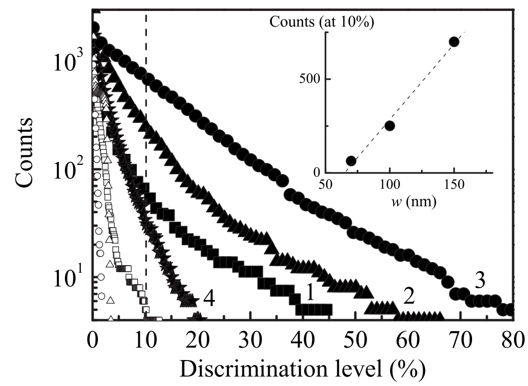

FIG. 2. Counts of conductance steps per 10 000 s at different discrimination levels for the samples with different w: 1–70, 2–100, 3–150, 4–200 nm, in dark (open symbols) and under illumination (full symbols).

of 4.2 K and small currents ($10^{-12}-10^{-14}$ A) allowing to be in Ohmic regime.

The typical conductance track under weak photon flux (30 dB attenuation of light) is shown in Fig. 1 for the sample with $w=70$ nm. In a large-area sample measured in parallel (curve a), illumination causes a monotonic change in the conductance with time. Unlike macroscopic structures, in the small-area samples, the conductance evolves with time (curve b) in discrete steps (inset to Fig. 1). We suggest that these steps correspond to a redistribution of charges in the QD array arising from the change in individual QD filling factor due to the absorption of a single photon. Under 1.55 μm wavelength illumination, every photon absorbed in a QD creates an electron-hole pair. Due to the type II band alignment in Ge/Si QD structures, the hole remains in the dot due to the strong confinement, whereas the excited electron may find a potential minimum in the vicinity of the dot and recombine with a hole in another dot. As a result, a redistribution of carriers among QDs of the array occurs. The resulting new potential landscape leads to a new conductive path providing a steplike change in the conductance with time. Due to nonmonotonic dependence of hopping conductance on QD occupancy, we observed both positive and negative steps in the conductance traces. Relaxation processes that are usually responsible for the appearance of downward steps,[6] have negligible contribution due to persistent PC effect, which is a characteristic feature for the structures under study.[5]

In order to clearly discriminate the steps in the conductance due to photoexcitation from fluctuations of the dark current, the experimental data of the time-resolved conductance of dark and photoexcited measurements were analyzed in the frame of count rates at different threshold (discrimination) levels of fluctuation amplitude. In detail, the height of steps in the conductance $G(t)$ was analyzed by determining the value at the beginning (G_1) and the end (G_2) of the step. The step height $\Delta G=G_2-G_1$ was set in relation to the G_1 value and the ΔG was measured as a percentage of G_1. Then, we counted the number of steps with an amplitude larger than some discrimination level. The range of time for analyzing was chosen to be 10 000 s. Figure 2 demonstrates the results of the analysis of the number of steps for four samples with different width (70, 100, 150, and 200 nm) of conductive channel. It is evident that fluctuations due to the dark noise do not exceed 4%–10% (open symbols in Fig. 2) of G_1 for all samples, whereas the step height in conductance under illumination reaches more than 70%. Thus, the steps due to photon absorption can be identified and counted by setting an appropriate discrimination level larger than 10%. The number of such steps in dependence on the channel width is shown in the inset to Fig. 2. For the samples with a channel width of 70, 100, and 150 nm a linear dependence is found intercepting the x axis at ~60 nm. It is assumed that the distance of 60 nm/2=30 nm from every vertically etched surface is depleted by surface states and the conductive width of the channel is given by subtracting 60 nm from the physical width. This hypothesis is justified by the estimations of the depletion length with the impurity concentration corresponding to the QD density. The obvious difference of the behavior of the device with the 200 nm wide channel is most likely determined by the appearance of "optimal" chains shunting the conductive cluster. According to the Raikh and Rusin model,[7] such a chain is characterized by the maximum value of the product of its conductance and the probability of formation and can occur when the channel width exceeds the chain size. The conductance of a sample with those optimal chains is expected to increase significantly and should be rather smooth, i.e., with little fluctuations. In fact, the sample with $w=200$ nm demonstrates not only the smallest number of conductance fluctuations, but its conductance is significantly higher than that for all other samples under investigation.

To study whether the steps in the conductance of the device can be attributed to absorption of single photons or not, the dependence of the amount of steps on the light intensity I, setting the discrimination level to 10%, was analyzed. Figure 3 shows the time dependence of the conductance for the sample with $w=70$ nm for three values of I. It is worth mentioning that the persistent PC effect[5] in mesoscopic samples keeps the conductance constant after switching off the light. This is advantageous for photon detection because, in contrast to the conventional avalanche photodiodes, here no reset of the system to its initial state is needed after the detection of a photon. The inset to Fig. 3 depicts the number of steps, counted for three used light intensities as a function of the number of absorbed photons. The latter was estimated taking into account experimentally obtained absorption data of similar Ge/Si QD structures[8] for excitation energies at ~750–850 meV, which corresponds to the light wavelength used in this work. The data in the

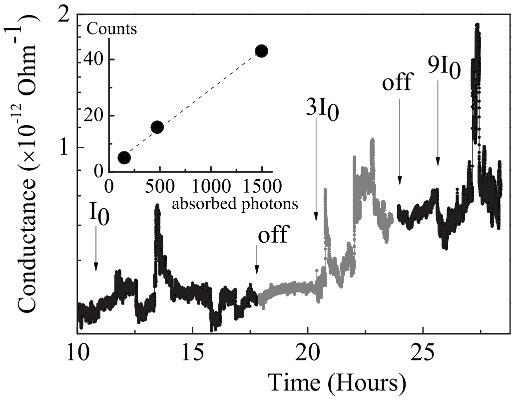

FIG. 3. Conductance for sample with $w=70$ nm at different light intensity I. Inset–dependence of counts on I at discrimination level of 10%.

inset of Fig. 3 give evidence that the number of steps is linearly dependent on the photon flux, as expected for a single-photon process.

Further evidence that steps in the conductance are induced by the absorption of single photons is given in Fig. 4. Here, the samples were subject to pulsed excitation using the pulse duration time, light intensity and the delay between pulses as parameters. Figure 4 shows the time dependence of the conductance for 10 s pulse excitation with a light power of ~0.25 μW for the sample with $w=200$ nm. In this case every pulse causes a single steplike change in the conductance. The estimation shows that this structure absorbs several photons per pulse, thus the internal efficiency is sufficiently high. However, the external efficiency of the photon detection remains low and efficient light trapping is required in the Si/Ge system to design a suitable single photon detector.

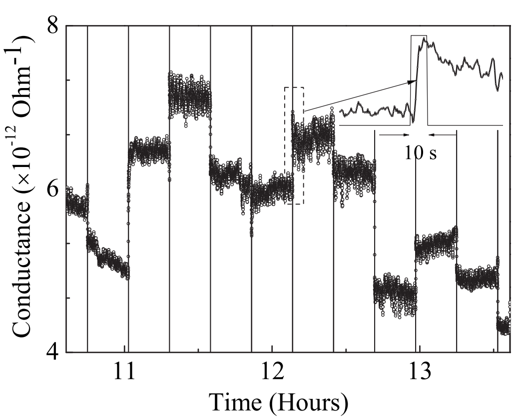

FIG. 4. Kinetics of conductance for the sample with $w=200$ nm under pulse excitation. Inset–enlarged image of single-pulse reaction.

In conclusion, we illuminated 2D mesoscopic structures with embedded Ge/Si QDs by a weak flux of infrared light. Giant (up to 70%) steplike switching of the conductance was observed. The magnitude of the current fluctuations and thus the sensitivity for single photon absorption can be controlled by the size of the transport channel, as well as by initial filling of dots by holes. It is proposed to embed such Si/Ge QD devices in light trapping structures to overcome the drawbacks of low external quantum efficiency and, thus, the obtained phenomena may pave the path for improved single photon detectors suitable for quantum information technology. This kind of detector has the potential to overcome the disadvantages typical for conventional avalanche photodiodes, such as afterpulses. Moreover, since the photodetector proposed in this work will directly sense a single photoexcited carrier, it would save the spin, thus providing a prerequisite for quantum information.

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