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Photo-induced conductance fluctuations in mesoscopic Ge/Si systems with quantum dots

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Abstract. Nanometer sized SiGe quantum dot structures were used for the realization of infrared photodetectors working at extremely small photon fluxes. The sensitivity gain of the system to illumination is due to the fact that the hopping conductance via two-dimensional QD array strongly depends on the photoexcited charge trapped in the dots. Photo-induced conductance fluctuations in hopping regime were observed in both short/wide and long/narrow conductive channels. An optimized structure was determined by analyzing the time evolution of conductance in a frame of fluctuations count rate.

1. Introduction

A self-organizing growth technique, which includes a carefully controlled strained layer epitaxy at low (300°C) temperature, allows the formation of high density array of QDs with nanometer dimensions and homogeneous size distribution. The areal density of nanoclusters ($4 \times 10^{11} \text{ cm}^{-2}$) is large enough for the charge transport through such a system at low ($\leq 20\text{K}$) temperatures being dominated by hole hopping between dots [1]. It was shown that the hopping conductance in a densely packed array of Ge islands crucially depends on the occupation of the QDs by holes [2]. Thus, changing the QD charge state by illumination is expected to cause a change in the conductance of the array. In macroscopic samples with Ge/Si QDs both negative and positive photoresponse depending on dot filling factor were observed [3] under illumination with wavelength between 0.9-1.55 μm . Long-time conductance dynamics (typically, $10^2 - 10^4$ seconds at $T=4.2 \text{ K}$) has been revealed as well as after switching on and switching off the illumination, displaying a sluggish temporal dependence. It was found that the residual photoconductance could persist for several hours after the light switching off. Using these phenomena for mesoscopic samples, when the sample size is too small for self-averaging taking place, one can observe the physical processes corresponding to the unit events of network transformation. Thus, under weak illumination, a step-like change in the hopping conductance should be expected due to the charge changing by one carrier in one of the dots.

We present the experimental results of photo-induced conductance fluctuations in decanometer size QDs structures with different width and length of conductive channels.

2. Samples and experiment

The samples were grown on a (001) p-Si substrate by molecular-beam epitaxy of Ge in the Stranskii-Krastanov growth mode. The growth temperature for 10 monolayers (ML) Ge layer was 300°C and the growth rate was 0.2 ML/s. To supply holes to the dots, a boron δ -doped Si layer was inserted 5 nm below the Ge QDs layer. Electron-beam lithography was used to create the conductance channel, with their width and length being changed in the range of 70-500 nm. Quasi-one-dimensional, square and short samples were prepared and measured. Al metal source and drain electrodes were deposited on the top of structure and heated at 480°C to form reproducible Ohmic contacts. The system was excited by fiber coupled laser with 1.55 μm wavelength and 1 mW power value. To get extremely small light intensity, initial laser power was attenuated up to 60 dB. Time-resolved measurements were carried out at temperature 4.2 K and small currents ($10^{-12} \div 10^{-14}$ A) allowing to be in Ohmic regime. Any possible contact influence was prevented by using a four-point scheme for measuring the resistance traces. Photo-emf of contacts under illumination did not exceed 1% from the QD response. The temperature stability was controlled by Ge thermometer, the conductance change due to the temperature variation lay below the dark noise level.

3. Results and discussion

The scanning electron microscopy image of the sample with channel width w smaller than their length l is shown in a Fig1. The estimations of the correlation radius L_c of percolating network give their value of about micrometers. It means that all our samples has sizes smaller than L_c and conductance should reproduce the mesoscopic properties.

Figure 1. Scanned electron microscopy image of device with long and narrow conductive channel.

Figure 2. Conductance evolution of the mesoscopic sample with $l=100$ nm and $w=70$ nm. Inset is enhanced part of conductance curve.

Fig.2 shows the typical conductance traces for mesoscopic sample with $w=70$ nm width and $l=100$ nm length of the conductive channel under 30 dB attenuation of laser light. In the large-area sample measured in parallel (curve a), illumination causes a monotonic change of the conductance with time. Unlike macroscopic structures, in small-area samples, where conduction takes place through a mesoscopic size hopping network, the conductance evolves with time (curve b) in discrete steps (inset to Fig.2). We suggest that these steps correspond to changing of the individual QDs filling factor due to absorption of a single photon. Under 1.55 μm wavelength illumination, every photon absorbed in QD excites one electron from the dot, caused the addition of a single positive charge into dot. Generated electrons can be captured by another dot; as the result, the redistribution of carriers among different QDs occurs. The resulting new potential landscape leads to a new conductive path providing change of the conductance with time.

The behavior of mesoscopic samples is determined not only by their size but also by the channel geometry. In the presence of large fluctuations of the random potential, the sample resistance will be determined by exponentially rare regions of space containing no localized states within a few $k_B T$ from Fermi level. In quasi-one-dimensional structures, energetically unfavorable hops cannot be avoided, as in opposite limit of short and wide samples, the percolating cluster will be shunted by exponentially rare isolated chains of hops with conductances that are exponentially larger than the conductance of the infinite cluster. These chains are formed by localized states located at anomalously close distances from one another. Then, the sample conductance is determined by the highest resistance link of the best-conducting chain (the "critical" hop). Fig3 shows the evolution of conductance with time for three samples with different sizes and geometry of conductive channels under 30 dB attenuation of light. The sample a) corresponds to the quasi-one-dimensional structure ($l=500$ nm, $w=100$ nm), sample b) is a square one ($l=100$ nm, $w=100$ nm) and sample c) has the smallest channel width ($l=100$ nm, $w=70$ nm). One can see that the square sample is characterized by the largest average sheet conductance (Fig3). This result is the evidence that localized states which shunt the infinite cluster appear at small channel length. Since the probability for the formation of such a chain is an exponential function of l , a small change in the channel length should lead to a substantial change in conductance. The width of the channel determines the probability of appearance of the best-conducting chain. The more the width the larger the number of such chains should be.

Figure 3. Conductance tracks for three samples with different size of conductive channels.

Figure 4. Number of counts at different discrimination levels for the samples in dark (open symbols) and under illumination (full symbols).

Experimental kinetics data for dark and photo-excited parts of time-resolved conductance were analyzed in the frame of count rates at different threshold (discrimination) levels of fluctuation amplitude. The rate of steps was estimated by the following simple procedure. We found the zeros of the current derivative (with respect to time) responsible for the fluctuations and then determined the value of $\Delta G = G_2 - G_1$ between every two extremums. The fluctuation amplitude was estimated as a percentage of ΔG to the G_1 value. Then, we count the number of fluctuations with amplitude larger than some discrimination level. The results of such procedure for conductance tracks depicted in Fig3 are shown in a Fig4. The range of time was chosen to be 10000 seconds. One can see that the dark noise does not exceed 4-10% (open symbols in Fig4) whereas the amplitude of conductance fluctuations under illumination reaches more than 50% of magnitude. The largest number of fluctuations is observed not in the sample with largest area (long sample), but in square sample. It means that this kind of samples is more sensitive to the photon flux and can be used for creating of a single-photon detector.

To understand whether the photodetector is really working in the photon counting mode, we analyzed the dependence of the number of counts on the discrimination level at different light intensities, the result of its analysis is shown in Fig. 6. The inset in Fig.6 depicts the number of fluctuations counted for all used light intensities at discrimination level (10%) restricting dark and light noise. The data shows that the number of steps is linearly dependent on the light intensity, as expected for a single-photon process. It is worth to be mentioned that the persistent photoconductance effect, which accounts for $\sim 10 - 20\%$ of the conductance value in macroscopic samples, keeps the conductance constant after switching off the light in mesoscopic samples. This is advantageous, because in contrast to conventional avalanche photodiodes here after detection of one photon no reset of the system to its initial state is needed for the detection of the next photon.

Figure 5. Conductance evolutions for sample c) at different light intensity I

Figure 6. Number of counts for sample c) at different discrimination level. Inset- dependence of counts on I at level 10%.

The internal quantum efficiency of our device was estimated to be $\sim 17\%$ with taking into account the effect of oscillator force acceleration in quantum dot nanostructures. Large values of the oscillator strength and the exciton binding energy for type-II quantum dots with finite offsets was predicted by Rorison [4] and observed in the same Ge/Si QD structure [5] for $\sim 750-850$ meV exciton transitions that corresponds to the excitation wavelength used in this work. Strong oscillator strength of the Ge QDs was explained by electron leakage into the dots. However, a small thickness of Ge layer, absorbing the $1.55 \mu\text{m}$ wavelength light yields only $\sim 10^{-3}\%$ of external efficiency. To increase this value, the many-layers Ge structure and waveguide system is proposed to be used.

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