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Hopping photoconductivity and its long-time relaxation in two-dimensional array of Ge/Si quantum dots

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Photoconductivity excitation kinetics has been studied in a two-dimensional array of Ge/Si quantum dots under illumination with different light wavelength. Both negative and positive photoeffects depending on dot occupations with holes were observed. Long-time conductivity dynamics (typically, $10^2 - 10^4$ sec at T=4.2 K) has been revealed as well as after switch on and switch off the illumination, displaying a sluggish temporal dependence. The observed effects were not suppressed by decreasing of the excitation energy below the silicon band-gap. For electronic glasses it was discovered that the more time under excitation the faster relaxation rate. Our results are explained by the different capture rate of electrons and holes by quantum dots, due to the presence of potential barriers created by positively charged Ge quantum dots.

1 Introduction Effective localization of holes in the valence-band of Ge quantum dots (QDs) and high density of Ge/Si (001) quantum dots ($1 \div 4 \times 10^{11}$ cm^{-2}) lead to charge transport through such a system at low (<20K) temperatures is dominated by variable-range hole hopping between dots [1]. Both the concentration and the mobility of charge carriers can determine the change of hopping conductivity under interband illumination. Provided the concentration affects conductivity stronger than mobility, one can expect different signs of photoconductivity for different hole filling factors because of the oscillating dependence of hopping conductivity on the charge state of dots [1]. In the opposite case it was predicted [2] that the hopping conductivity of the system excited from thermal equilibrium is always enhanced. It is unknown in advance whether the oscillating behavior of conductivity would modify this process. Moreover, there is good reason to think that the anomalous relaxation of photoconductivity can be observed in this structure. On the one hand, Ge quantum dots occupied with holes induce band bending, which corresponds to a potential barrier for free holes and a potential well for electrons. Different capture process of holes and electrons in quantum dots can results in long-time relaxation of hopping photoconductivity. On the other hand, anomalous dynamics of photoconductivity (PC) was obtained earlier in electronic glasses [2-3] and was explained by the influence of long-range interaction of localized carriers on the relaxation processes. Ge/Si QDs can be related to electronic glasses due to disordered arrangement of nanoclusters in two-dimensional plane and Coulomb interaction between holes localized in different quantum dots. In this paper we describe results that demonstrate anomalous dynamics of hopping conductivity in QDs system excited by illumination and propose a model that describes the experimental data.

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2 Experimental details Samples were grown by molecular beam epitaxy on a boron doped (001) oriented Si substrate. Ge layer with a nominal thickness of 8 ML was symmetrically embedded into 400 nm thick boron doped silicon region. To supply holes on the dots, a boron δ-doping Si layer was inserted 5 nm below the Ge layer. The concentration of boron was varied for different samples, which was allowed to change the average number of holes in dots. To avoid surface effects in photoconductivity measurements, Ohmic contacts were fabricated by Al evaporation into the preliminary etched pits followed by annealing at 400°C in N_2 atmosphere. Details of sample preparation and structural characterization have been described elsewhere [1]. To separate response from the dots, the test samples without Ge were grown under conditions similar to the dot samples. Photoconductivity experiments have been carried out using three light-emitting diodes (LED) with an emission maximum at the wavelength of 0.9, 1.3, 1.55 μm. To study the persistent photoconductivity (PPC) effect, the samples were kept at room temperature before each experiment. They were then cooled to their respective measurement temperature 13.3-4.2 K. All the data obtained under different conditions were taken in such a way that the system was allowed to relax to equilibrium.

3 Experimental results Interband illumination of such a system results in a complicated transient behavior of the photoconductivity during reaching illuminated or dark steady state. Our experiments involve the following procedure. The samples are cooled to the measuring temperature with a zero drain voltage, and are allowed to equilibrate for several hours. The time dependence of conductance under the condition of LED illumination (on) and stopping illumination (off) was taken several times serially. Figure 1a shows a typical conductance transient traces under interband illumination for two structures with different δ-boron doping at 4.2 K. In contrast to the test Si samples, in which the PC is always positive, both positive and negative photoeffects depending on dot filling factor are observed in dot samples. In both cases, kinetics of the recovery as well as of the decay is extremely slow. When the LED illuminates on the sample, the resistivity changes rapidly at the beginning and slowly at the end, while the residual photoconductance can persist for several hours after the light switch off. This phenomenon characterizes a typical effect [4] of persistent photoconductivity (PPC). The PPC level is about 90% of the initial PC value after more than 5000 seconds of decay. Long-time relaxation process was not observed in test samples containing no dots (Fig. 1b).

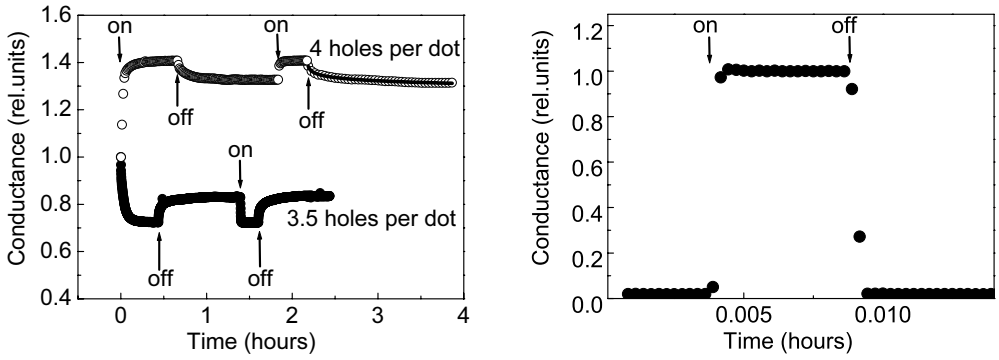

Fig. 1 a) Conductivity traces for the samples with different average numbers of holes per one Ge dot. The solid line is the fitting to the experimental data by a logarithmic law. b) Photoconductivity for the Si sample without Ge quantum dots.

As the behaviour of negative PC dynamics is similar to positive one, all further experimental data are presented only for the samples with positive PC. Figure 2 shows the conductance decay traces at different temperatures for λ=0.9 μm and demonstrates the quenching of the PPC effect at high temperatures.

Experimental data have been normalized to unity at $t = 0$ (at a moment when the illumination is terminated) according to $G_{PPC}(t) = (G(t) - G_d)/(G(0) - G_d)$. Here, $G(0)$ is the conductance level immediately after the termination of the excitation source, G_d is the initial conductance in the dark. Transient curves for illumination with different light wavelength are shown in Fig. 3. One can see that the illumination with photon energy below the silicon band-gap proved to be enough for stimulation of photoconductivity. We observed that the PC in saturation (inset of Fig. 3) is practically unaffected by changing of light intensity for LED with λ=1.55 μm.

To find an aging effect typical for glass systems [5], we studied the relaxation of photoconductivity after different time of excitation t_w (waiting time) for λ=1.3 μm (Fig. 4). A special case of aging, so called simple-aging, when $G(t,t_w)=G(t/t_w)$, has been recently observed in electronic glasses [5]. In general the relaxation in electronic glasses is more sluggish the longer the system is "aged". But when plotted as a function of t/t_w, the different $G(t,t_w)$ curves collapse onto a common plot that only weakly depends on other parameters. Figure 5 shows the G/G_{max} versus (t/t_w) and demonstrates the absence of aging effect under light illumination in quantum dot system. Moreover, the waiting time dependence in this system is opposite to that for the electronic glasses: the more the waiting time the faster the relaxation.

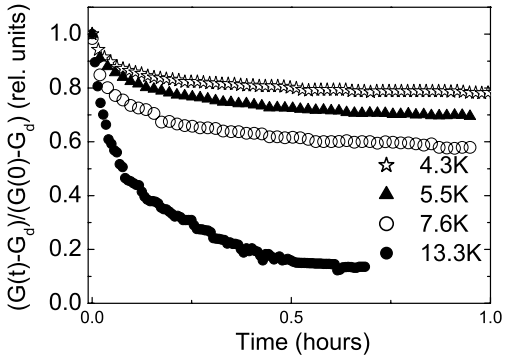

Fig. 2 PC decay at different temperatures, λ=0.9 μm.

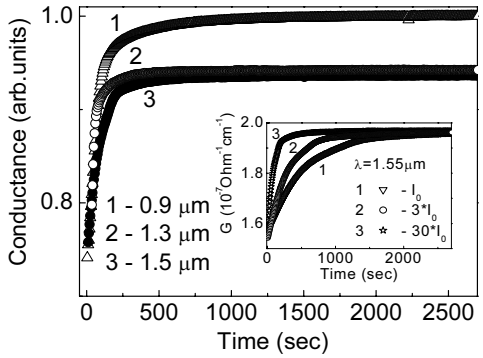

Fig. 3 PC buildup at different light wavelength λ and light intensities I_0 (inset), T=4.2 K.

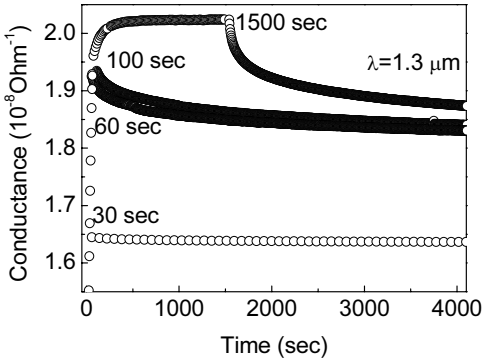

Fig. 4 PC relaxation after different waiting time, T=4.2K.

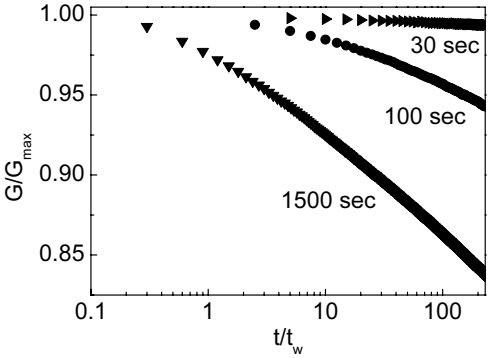

Fig. 5 Relaxation of G as a function of t/t_w, λ= 0.9 μm, T=4.2 K.

4 Discussion Non-equilibrium effects obtained under illumination of Ge/Si QDs structures seem to be quite different from the well-known properties of electronic glasses. In particular, we did not observe an aging effect, which is inherent feature for electronic glass; PC in QDs system changes sign with changing of the hole filling factor while PC in electronic glasses is always positive [2]. We suggest that the anomalous dynamics of PC is due to the variation of hole concentration rather than their mobility. The following model has been proposed [6] for explaining our earlier experimental observations for interband excitation. A sheet of quantum dots occupied with holes induces a band bending, which corresponds to a potential barrier for free holes and a potential well for electrons. When an electron-hole pair is photoexcited, electron is trapped by a dot while a hole cannot recombine with this electron because of the QD's repulsive potential. Recombination of electrons with equilibrium holes in Ge nanoclusters reduces the potential barrier for hole capture. Thus, under illumination, the hole trapping into QDs occurs in a condition of permanent decreasing of the potential barrier height. The stationary state set in, when the electron flux into dots becomes equal to that for the holes. After the light switch off, holes continue to be captured by QDs and the barrier height steadily rises. New conductive state resulting from the relaxation of the system after the light termination differs from the initial one, because the PPC is realized at low temperature when the hole trapping into the dots is strongly limited. It was shown in previous paper [6] that the experimental data for the interband excitation is well described by proposed model in additional assumption about the alignment of barrier heights, which, in turn, is a result of photohole capture into the dots. Waiting time effect behaves according to this model: when the barrier height is large (30 sec curve in a Fig. 4), holes are captured by QDs so slowly that the conductivity slightly relaxes to a corresponding PPC value. Long time illumination decreases the barrier height resulting in more effective hole capture and larger relaxation rate. Increase of the temperature rises the efficiency of hole trapping and suppresses the PPC effect.
In the framework of this concept the effects obtained under excitation with λ=1.3 and 1.55 μm can be explained only on the assumption of the presence of deep-level defects near the Si/Ge interface. The electrons excited from a defect level are trapped by QDs, which results in decreasing the hole number in QDs. For recovery of the initial state, an equilibrium electron in QDs should tunnel to a residual unoccupied defect state. Probability of this process depends on the barrier width, and is determined by charge state of dots. Further reasoning will be the same as for the case of interband excitation. However the fact that the relaxation times in both cases are of the same order seems to be questionable, because the band and impurity absorption should be quite different. At present we cannot say anything about the nature of defects, their concentration and absorption cross-section. In order to obtain the absorption coefficient for impurity centres close to the bandgap absorption at helium temperature, the photo-ionization cross-section must be ~ 10^{-15}cm^2 at the impurity concentration of about 10^{17} cm^{-3}.

5 Summary Long-time non-exponential kinetics of photoconductivity excitation and effect of persistent photoconductivity have been observed in *p*-type Ge/Si heterostructures containing Ge quantum dots. Our observations are explained rather by dependence of the hole capture into the quantum dots on dot charge state than by properties of electronic glasses.

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