Intraband absorption and interband photoconductivity transients in Ge/Si quantum dots

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Abstract. In this work a series of relaxation curves of photoinduced intraband absorption and interband photoconductivity were measured in Ge/Si quantum dots in the temperature range from 80 K to 300 K and at different levels of the interband excitation. The low-temperature experimental curves show a two-step decay of a population of quantum dots. At high temperatures there is only one decay component. A simultaneous analysis of photoinduced intraband absorption and interband photoconductivity relaxation curves shows that quantum dots act as traps for non-equilibrium holes only at low temperatures.

1. Introduction

Nanostructures with Ge/Si quantum dots are considered as a promising material for the development of new optoelectronic devices. This is due to their optical properties in the near and mid-infrared range. This work is devoted to studying the relaxation of nonequilibrium charge carriers in structures with Ge/Si quantum dots after a short high-power optical interband excitation.

2. Experimental setup and samples

A structure with self-assembled Ge/Si quantum dots (QD) MBE-grown on a Si (001) substrate was studied. The structure contains 10 periods of quantum dot layers formed in the growth regime similar to the one described in [1]. Quantum dots have a pyramidal shape with an average height of 2.7 nm, and an average base size of 14 nm. No intentional doping was performed.

In our experiment, the non-equilibrium charge carriers are excited in the structure by a 10-nanosecond pulse laser with a wavelength of 532 nm. Dynamics of the population of the quantum dot states was studied by means of the mid-infrared intraband absorption decay measurements. The wavelength of the mid-IR radiation was tuned to resonance corresponding to the hole transitions from the QD ground state to the continuum of states. We measured a signal of the pump-induced change of optical mid-infrared transmission ΔT that is directly proportional to the absorption for small ΔT values.

At the same time, the interband photoconductivity signal decay was measured. The photoconductivity measurements allowed us to uncover the overall relaxation processes of free bulk carriers in the structure. The experimental setup provided the time resolution of 100 ns.

3. Experimental results

The series of relaxation curves of photoinduced intraband absorption and interband photoconductivity $\Delta\sigma$ after a short excitation pulse were measured in the temperature range from 80

K to 300 K at different interband excitation levels. The absorption decay curves for the maximum excitation power are plotted in figure 1 for low and high temperatures as time dependencies of the optical transmission change ΔT together with the interband photoconductivity signals $\Delta\sigma$ in the same semi-log scale.

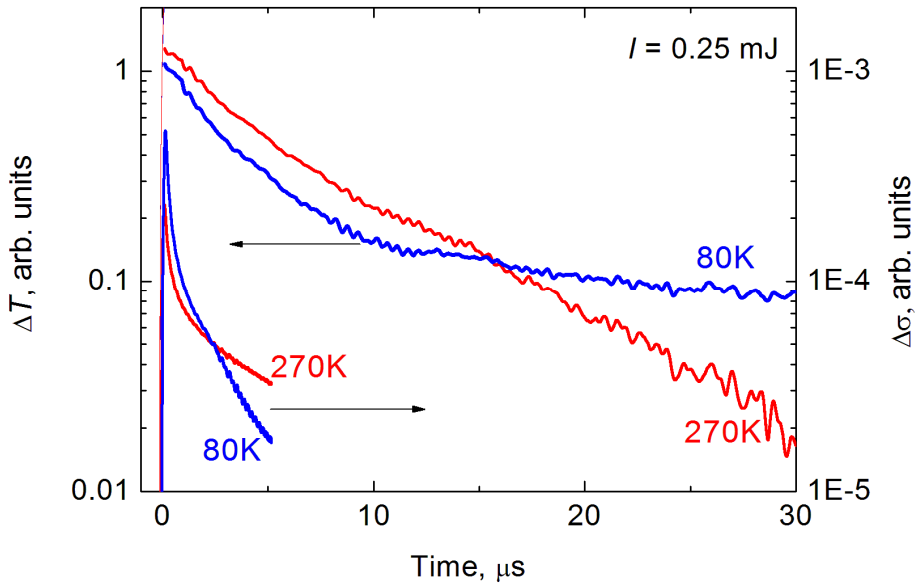

Figure 1. Time dependencies of the photoconductivity (right axis) and the photoinduced mid-IR absorption (left axis) signals after a pulsed excitation $I = 0.25$ mJ at two temperatures.

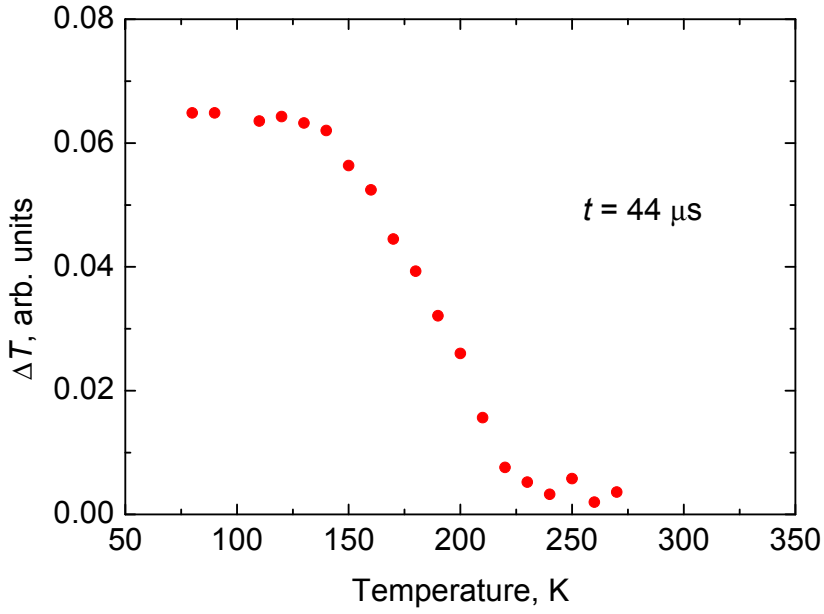

Figure 2. The dependence of the photoinduced absorption signal upon the temperature 44 microseconds after the excitation pulse. At low temperatures, the probability of ejection of holes from the quantum dot is small. This probability increases with temperature and holes begin to leave the dots. At room temperatures, there are no photoexcited carriers inside the dots.

The interband photoconductivity shows a non-linear recombination at the initial stage. Exponential parts of the photoconductivity decay curves have the characteristic decay times less than 10 μs for both temperatures.

The slope of the high-temperature absorption decay curve is comparable with the corresponding exponential part of the photoconductivity curve slope. Thus, the population of the QD ground states follows the bulk non-equilibrium charge carrier density which determines the photoconductivity.

In contrast, the low-temperature absorption relaxation curve approximately follows the exponential part of the photoconductivity decay only within the first 10 μs. Next, the absorption curve demonstrates a two-exponential decay behaviour with a slow relaxation time about one order of magnitude larger than the fast one. This experimental result clearly shows the presence of holes inside QDs when the bulk carrier density has already relaxed. Quantum dots act as traps for bulk charge carriers only at low temperatures, whereas at high temperatures this effect disappears. This behaviour can be clearly seen in figure 2, where the temperature dependence of the photoinduced absorption signal (proportional to the number of holes captured to QDs) 44 μs after the excitation pulse is plotted. We attribute this effect to the thermal escape of holes from the dots and their drag by the bipolar diffusion current of bulk charge carriers.

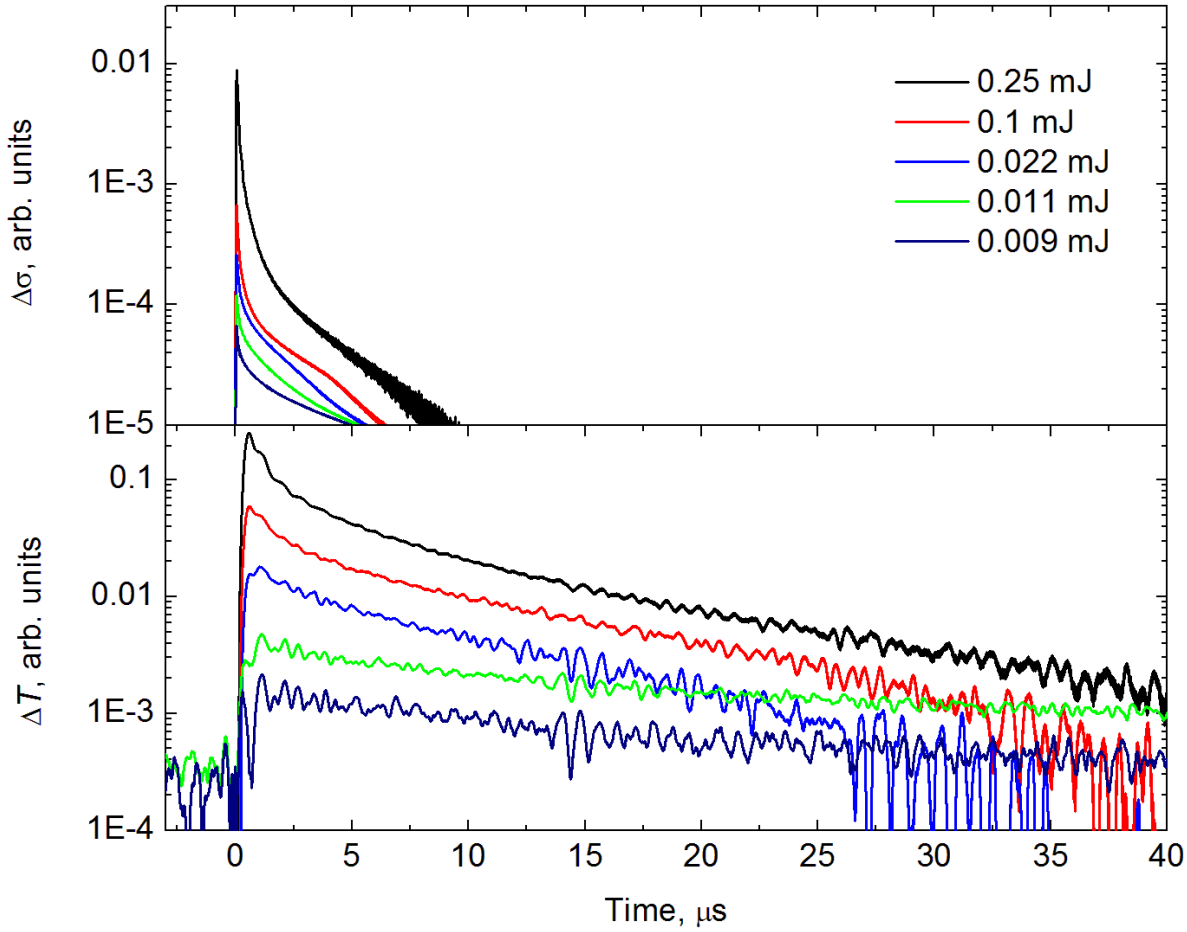

Figure 3. The time dependencies of photoconductivity (top panel) and photoinduced absorption (bottom panel) signals at different pump intensities at a temperature of 80 K.

The measured low-temperature time dependencies of the photoconductivity and photoinduced absorption signals are plotted in figure 3 for different excitation powers. The photoconductivity decay curves depend weakly on the excitation level, showing approximately the same characteristic decay times of the bulk carrier density below 10 μs for all excitation powers. However, the character of the absorption decay curves changes with the decrease of the excitation. Namely, there are no fast decay components for low-excitation QD population decay curves, but the characteristic decay time for the slow component becomes higher with the decrease of the excitation.

We attribute the disappearance of the fast QD population decay component at low excitation levels to the relatively low average energy of the bulk holes in the Si valence band, which becomes lower than the strain-induced energy barrier for hole capture to the QD (see, for example, [2] for details on the Ge/Si QDs heterointerface profile). The dependence of the slow relaxation time (which, in fact, is the lifetime of holes inside the QD) upon the excitation level can be related to the different QDs charge states since the total number of hole states in a QD is much higher than the total number of electronic states in strain-induced potential wells on a Si side of the QD interface [2].

4. Conclusion

In this work, we demonstrate experimentally that Ge QDs in a Si matrix effectively act as traps for non-equilibrium photo-excited holes only at low temperatures. The population of QDs follows directly the time dependence of the bulk photo-excited charge carrier density in silicon at high temperatures, so there are no holes in QDs when there are no holes in the bulk Si valence band. The characteristic lifetime of holes in QDs can be as long as 50 μs, and depends highly on temperature and initial excitation level.

Acknowledgements

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