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Control of photocurrent relaxation in GaAs/AlGaAs nanostructures

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Abstract. Strong influence of an interband carrier generation on deep states relaxation in GaAs/AlGaAs nanostructures has been found. Considerable variation of relaxation time, sign and amplitude of impurity photoconductivity (PC) signal has been detected at rather low interband excitation. In single quantum well structures the additional interband excitation results in strong (more, than 10^3 times) decrease of a deep states relaxation time. In modulation doped GaAs structures the interband generation results in long-time negative photoconductivity signal with decay time controled by the interband generation intensity. The effect may be used for the analysis of deep states distribution in GaAs/AlGaAs nanostructures.

Introduction

The changes of semiconductor conductivity at photoexcitation yield the information on deep centers (DC). In the inhomogeneous structures this process is accompanied by spatial separation of the excited carriers and DC by built-in electric field, that results in relaxation time change along with bulk charge accumulation and band edge lineup distortion. A quantum well is the "ideal" uniform system for DC studies because the uniform photoexcitation in the quantum well is realized both in impurities and fundamental absorption regions provided the excitation is performed by "cold" radiation, which do not excite interband and intracenter transitions in barrier layers.

Solving of the reverse problem, namely the relaxation processes analysis of the known DC in semiconductor structure with built-in electric field, allows one to receive the information about band edge positions and DC spatial localization. The purpose of our activity is to study the relaxation of well known DC — EL2 centre — in the GaAs/$Al_{0.3}Ga_{0.7}As$ nanostructures for analysis of the band edges behavior in nanostructure.

1. Experimental technique

For PC measurements we have used GaAs epitaxial layers uniformly doped by Si, Be and carbon, n-GaAs/$Al_{0.3}Ga_{0.7}As$ single quantum well structure with 20 nm wide well and n-GaAs $\langle\delta-\mathrm{Si}\rangle$ structures prepared by molecular beam epitaxy on i-GaAs substrates. Sheet carrier concentration and mobility at 77 K were $\sim 10^{12}$ cm^{-2}, and $\sim 6\times10^4$ cm^2/V·s and $\sim 6\times10^3$ cm^2/V·s for quantum well and δ-doped structures respectively.

Optical excitation was made simultaneously by two sources: pulse semiconductor laser of $h\nu = 0.38-2$ eV and CW He-Ne laser ($h\nu = 1.97$ eV) or quartz lamp armed by appropriate optical filters, background radiation was completely screened. The kinetics measurements were performed mainly with $h\nu = 0.87$ eV source which causes only in-center transitions in GaAs and practically does not excite DX centers in $Al_{0.3}Ga_{0.7}As$.

2. Results

The characteristics of PC signal mainly depended on conductivity type of the studied structure. Weak signal with onset photon energy ~0.8 eV and time constant < 10^{-6} s was found in p-type samples in the temperature range of 77–300 K. Background radiation had no effect on this signal.

Positive signal of impurity PC was observed for n-type structures at room temperatures. PC onset was found to be ~0.8 eV and the laser with $h\nu = 0.87$ eV was used further for excitation. As temperature was increased from 323 to 410 K, the relaxation time decreased from 7×10^{-3} to 6×10^{-5} s for all studied structures having a good fit to $\tau(T) = \tau_0 \exp(\Delta E/kT)$ equation with $\tau_0 = 1 \times 10^{-12}$ s and $\Delta E = 0.62$ eV.

Under background radiation with photon energy larger than band gap E_g both the time constant and the signal amplitude decreased. Even under relatively small intensity $\sim 10^{15}$ 1/(cm^2·s) this decrease was about three order of magnitude (Fig. 1(a,b)). Background radiation with $h\nu < E_g$ did not influence PC signal. The correlation between impurity PC signal amplitude and luminescence intensity of carbon ($h\nu = 1.49$ eV) was observed for uniformly doped samples.

Photoresponse signal characteristics at 77 K were drastically dependent on the structure configuration. The shape of photoresponse signal was not changed for GaAs/AlGaAs⟨Si⟩ quantum well structure as compared to that at room temperature, PC threshold being $\sim E_g/2$. For GaAs ⟨δ–Si⟩ structures the photoresponse shape changed essentially with the increase of CW irradiation with $h\nu > E_g$. First, the positive PC signal was detected, then the time constant started decreasing, and finally the PC signal became negative with the simultanious sharp increase of time constant. As CW irradiation intensity further increased, time constant of negative PC signal decreased (Fig. 1(c,d)). PC signal sign inversion occurred at 150 K at sufficiently high irradiation intensity. The threshold photon energy of impurity PC was

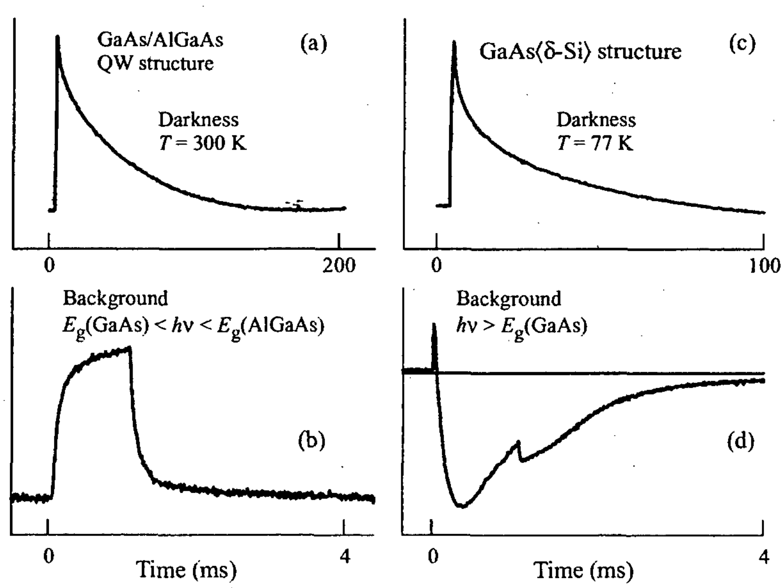

Fig. 1. Photoresponse signal for n-GaAs/AlGaAs single quantum well structure (a), (b) and n-GaAs⟨δ–Si⟩/GaAs (c), (d). Laser excitation with $h\nu = 0.87$ eV in darkness (a), (c) and under background CW-illumination with $h\nu = 1.97$ eV (b), (d).

$\sim E_g/2$, and for CW irradiation it coincided with E_g of GaAs.

3. Discussion

Experimental results are explained in frame of single-electron model of the deep donor level in GaAs. Energy diagram of the n-GaAs/AlGaAs structure is shown in the Fig. 2(a) along with DC configuration diagram, which can be described by [1]:

$$H = \Delta/2\Delta_0 + (\Delta_0 + \Delta)n + F(1 - n), \tag{1}$$

where Δ is the configuration coordinate, Δ_0 is the energy of DC level, F is the Fermi energy and n is the number of electrons coupled to DC ($n = 0, 1$).

3.1. *Model of positive PC signal*

Impurity PC in n-GaAs is excited as a result of ionization of filled DC. Excited electron and DC are not separated spatially, so the time of free electron capture from conductance band to empty DC is determined by the time needed to overcome the potential barrier ΔE in configuration space which is described by thermoactivation dependence.

Impurity PC in the p-type semiconductor is excited as a result of electron transition from valence band to the empty DC. Time constant of PC for p-GaAs is much less than that for n-GaAs and do not depend on the temperature because the potential barrier for electron to return to the band can be neglected (see Fig. 2).

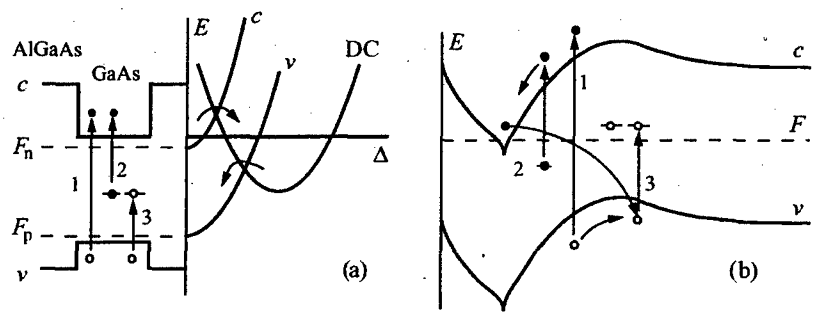

Fig. 2. Energy configuration of n-GaAs/AlGaAs quantum well structure combined with configuration diagram of deep center (a) and of n-GaAs⟨δ−Si⟩/GaAs structure (b). (1, 2, 3)—possible optical transitions.

Additional illumination of the n-GaAs structure by CW-radiation with $h\nu > E_g$ leads to the electron-hole pairs generation. Nonequilibrium holes are captured by DC's and cause their partial recharge. While DC relaxation rate is proportional to empty centers concentration this accelerate the PC relaxation. DC's are fully recharged under very high interband generation rate, so the electron transition from valence band to DC and its fast relaxation become the dominant process for impurity PC.

3.2. *Model of negative PC signal*

The negative PC arises in the inhomogenious in growth direction structures with built-in electric field, for example in n-GaAs⟨δ−Si⟩, HEMT-structures etc. (Fig. 2(b)), if some empty DC are present. The transition of electron from the valence band to empty DC leads to negative PC generation. Appeared hole recombines with electron in conducting channel through the contact areas of the structure within a time $\sim 10^{-6}$ s, that results in persistent negative PC. The generation of holes by CW-radiation with $h\nu > E_g$ creates the possibility for electrons to return to the valence band in the pauses between pulses of the radiation with $h\nu < E_g$ and makes the negative PC observable.

Empty DC can be formed in undoped buffer due to contamination of epitaxial layers with carbon, which forms deep donor EL2 center in complex with antisite Ga_{As} defect. When substituing the As atom, carbon acts as shallow acceptor and captures electrons from EL2 center. This is confirmed by correlation between PC amplitude and intensity of lumeniscence line of free carbon in studied samples.

We have performed numerical simulations of PC processes accounting all possible optical transitions (Fig. 2), recombination and relaxation channels. The comparison of experimental and simulated signals in dependence on excitation conditions allows to determine the charge state and to estimate the concentration of empty DC in the depth of the structure. It was found that the threshold temperature of negative PC signal generation is the most sensitive parameter for determination of DC concentration.

In summary, strong influence of interband carrier generation on the relaxation of impurity photoconductivity in A_3B_5 nanostructures has been detected. It has been demonstrated that the concentration of deep centers in the depth of structure can be determined by analysis of the photoconductivity signal.

Acknowledgements

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[1] I. I. Zasavitskii, B. N. Matsonashvili, O. A. Pankratov and V. T. Trofimov, *JETP Lett.* **42**, 3 (1985).