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ACOUSTOELECTRIC INVESTIGATION OF OPTICALLY INDUCED DEEP CENTERS IN GaAs/AlGaAs HETEROSTRUCTURES *

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The acoustoelectric interaction between a longitudinal acoustic wave and heterojunctions is used to investigate the deep centers in GaAs/AlGaAs heterostructures. The acoustoelectric response generated by the interface when acoustic wave propagates through the heterostructure reflects any changes in the charge distribution, connected also with the charged traps. The time developments of the acoustoelectric response after an optical excitation pulse reflect then relaxation processes associated with the thermal recombination of excited carriers moving towards their equilibrium state. The measured signal that is proportional to the nonequilibrium carrier density in the interface regions and can be used to the determination of activation energy and corresponding cross-section of deep centers. Planar GaAs/AlGaAs heterostructures with both two dimensional electron system (2 DES) and two dimensional hole system (2 DHS) were investigated by optically induced acoustic deep-level transient spectroscopy (OI A-DLTS). The method of computer evaluation of isothermal acoustoelectric transients was used in the A-DLTS technique. Several deep centers were found and their parameters were determined.

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1 Introduction

Characterization of deep centers in GaAs/AlGaAs heterostructures based high mobility devices is extremely important since the presence of defects significantly affects device performance. The use of acoustoelectric interaction has been recently proved valuable in the study of the deep centers in GaAs/AlGaAs heterostructures [1–4]. A transverse acoustoelectric signal (TAS) is generated across the heterostructure as a result of nonlinear acoustoelectric interaction between the surface acoustic wave (SAW) electric field and the free carriers in an interface region [1,2] and an acoustoelectric response signal (ARS) is observed at the heterojunction when a longitudinal acoustic wave (LAW) propagates through the heterostructure [3, 4]. Both the ARS and TAS are extremely sensitive to any changes in the space charge distribution in the interface region, also due to the trapped charge. After an injection pulse (optical or electrical) has been applied to the heterostructure, the acoustoelectric signal time development represents acoustoelectric transient which reflects relaxation processes associated with the thermal recombination of excited carriers moving towards their equilibrium state. By investigating the temperature dependence of the

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acoustoelectric transients characterizing the return to the thermodynamic equilibrium, the deep center parameters can be determined by the acoustic deep-level transient spectroscopy (A-DLTS) technique [5, 6].

Here we present the results obtained by the A-DLTS technique used for the deep centers investigation in GaAs/AlGaAs heterostructures with both two dimensional electron system (2 DES) and two dimensional hole system (2 DHS) using the LAW and optical excitation (OI A-DLTS)

2 Experimental procedure

The A-DLTS technique we used is based on the fact that the time development of the amplitude of the measured ARS after an injection optical pulse has been applied to the heterostructure is proportional to the nonequilibrium carrier density, so that the decay time constant associated with the relaxation of the acoustoelectric signal amplitude is a direct measure of the time constant associated with the relaxation processes of injected carriers [6].

The release of carriers from deep trap centers that leads to the thermal equilibrium on a new steady state has the dependence on time [7]

$$\Delta n(t) = \Delta n_0 exp(-t/\tau) \tag{1}$$

where Δn_0 represents the variation in trap occupancy due to the acoustoelectric field and τ is the time constant associated with the release of the carriers from deep centers when illumination is turned off. The measured acoustoelectric signal can be expressed then as follows

$$U_{ac}(t) = U_0 exp(-t/\tau) \tag{2}$$

Since this relation was obtained assuming only one deep center, the result can be readily generalized.

Comparing with the original version of A-DLTS that uses the analysis of the acoustoelectric transient signal after an injection pulse similarly as the Lang's DLTS developed for the capacitance transient [8] by means of a set of emission rate windows, the present technique is based on the computer-evaluated transients measured at fixed temperatures. The measurement technique allows a single transient to be sampled at up to 8 different sample rates permitting 3 to 4 decades of time constants to be observed in one thermal scan. The differential ARS δU_{ac} can be then monitored as a function of temperature and peaks with maxima at the temperature for which the emission rate is the same as the adjusted sample rate. Because it is necessary to analyze only enough data to obtain the required information, specifically, the time constants of the transient at each temperature, a data compression algorithm was applied.

Using the method of computer evaluation of isothermal acoustoelectric transients by applying a data compression algorithm in connection with the known relation expressing the temperature dependence of the relaxation time which characterizes the return to the thermodynamic equilibrium [5, 6] the activation energies and corresponding capture cross-sections can be determined from transient measurements of ARS.

The characters of the observed processes and corresponding deep centers can be determined from the following simple rule for the acoustoelectric response time development: If the charge

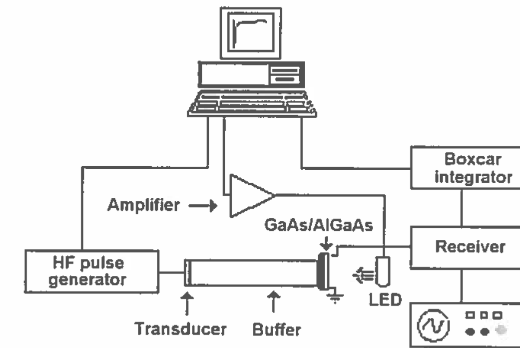

Fig. 1. The experimental setup to perform acoustoelectric response signal versus temperature measured under (after) illumination.

carriers are negative, their emission and capture cause an increase and decrease of the ARS, respectively. In the case of the positive charge carriers and the same processes the situation is opposite.

The experimental arrangement of A-DLTS technique is described in Fig. 1. The GaAs/AlGaAs sample heterostructure was acoustically bonded to a quartz rod buffer, on the other side of which was a $LiNbO_3$ transducer to generate a longitudinal acoustic wave of frequency 13,2 MHz by applying short HF pulses. The heterostructure worked as a receiver transducer. The ARS generated by the heterostructure was detected by a receiver system, selected by the box-car integrator and then recorded and stored by a computer. The acoustoelectric signal amplitude was recorded as a function of the temperature. The computer was used to trigger the apparatus, to drive the source of the excitation light pulses as well as to record and evaluate the isothermal transient acoustoelectric signals.

We have investigated three different GaAs/AlGaAs heterostructures, which have been grown by MBE on semiinsulating (SI) GaAs substrates and prepared in the form of planar structure with 2 DES (NU 169 and NU 1787) and 2 DHS (NU 1323) at heterojunction. The first relatively simple investigated heterostructure (NU 169) consisted of the following layers: SI buffer layer, 2 μm; undoped AlGaAs spacer layer, 20 nm; n-type doped AlGaAs layer with $1x10^{18}$ cm^{-3} Si, 40 nm; SI GaAs capping layer, 20 nm. The 2 DES was located at the interface between the SI GaAs layer and the AlGaAs spacer layer. Two ohmic contacts were made to reach the 2 DES layer. The schematic illustration of heterostructure arrangement is in Fig.2.

Another two heterostructures, NU 1787 and NU 41323 had similar layer structures consisting superlattice. The layer structure of the sample NU 1787 consisted of the following layers: undoped GaAs, 1 μm; superlattice GaAs (2.5 nm)/AlGa (2.5 nm), 50x; undoped GaAs, 0.5 μm; undoped AlGa, 50 nm; n-type doped AlGa with n = 5.10^{17} cm^{-3}, 80 nm; undoped

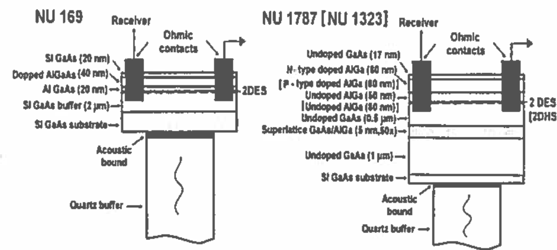

Fig. 2. Schematic illustration of experimental and layers arrangement of investigated GaAs/AlGaAs heterostructures.

GaAs, 17 nm. The third heterostructure (NU 1323) with 2 DHS contained: undoped GaAs, 1 μm; superlattice GaAs/AlGa, 5 nm (50x); undoped GaAs, 0.5 μm, AlGa layer, 80 nm; p-type doped AlGa layer with n = 5×10^{17} cm^{-3}, 80 nm; undoped GaAs, 17 nm. The 2 DES and 2 DHS were located between undoped GaAs and AlGa layers.

For the optical excitation (200 ms wide pulse) the IR-LED with the maximum in spectral characteristic of 900 nm and power density 60 mW/Sr was used.

3 Results and discussion

Representative optically induced A-DLTS spectra of all investigated samples with both 2 DES and 2 DHS obtained from acoustoelectric transients are illustrated in Fig.3. The A-DLTS spectrum of NU-169 sample contains three evident peaks representing three deep centers. The activation energies and corresponding capture cross-sections determined from the Arrhenius plots constructed for the individual peaks of A-DLTS spectra have the values: 0.29 eV (1), 0.26 eV (2), 0.21 eV (3) and 2.9×10^{-16} cm^2 (1), 5.2×10^{-16} cm^2, $1.8\times10^{-15}$$cm^2$ (3), respectively. While two of them, (1) and (2) have a donor character, the last center is acceptor type.

All obtained deep centers are well known from the measurements obtained by DLTS or other techniques, however never in the same composition. The deep centers with the energy level 0.29 eV was detected in GaAs/AlGaAs heterostructures [10], but also in GaAs layers prepared by MBE technique [11]. The deep center with energy 0.26 eV is known also as DX center [12], sometimes with energies of 0.25 – 0.28 eV. Deep center of acceptor character with energy 0.21 eV was detected in both GaAs/AlGaAs or GaAs layers prepared by MBE technique [12, 13]. Some measurements [12] indicated even internal structure of obtained peaks like superposition of two different peaks similar as in our OI A-DLTS measurements.

The appearance of two broader peaks corresponding to deep centers of different type with some structure of smaller peaks is the characteristic feature of A-DLTS spectra obtained on NU 1787 sample containing also 2 DES. The activation energies of 0.29 eV (a) and 0.10 eV (b) with corresponding cross-sections of 2.2×10^{-18} cm^2 (a) and 5.5×10^{-21} cm^2 (b), respectively were determined as parameters characterizing these deep centers. It should he noted that the A-DLTS

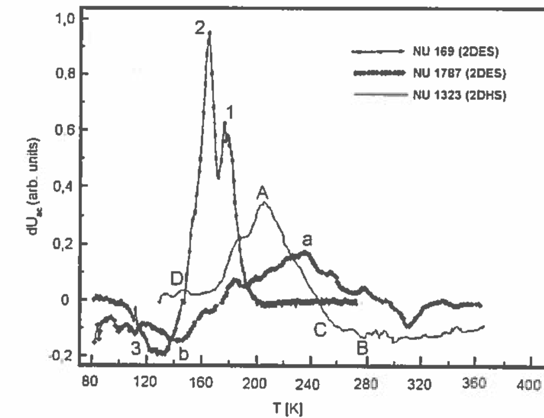

Fig. 3. A-DLTS spectra of investigated GaAs/AlGaAs heterostructures obtained for a relaxation time τ = 0.0368 s.

signal at this case was much smaller (presented A-DLTS spectrum is even ~ 2x amplified) comparing to previous spectrum and smaller peaks could not be easily used to deep centers characterization. The deep centers of acceptor type characterized by activation energy close to the value 0.1 eV and not detected in previous sample were obtained in GaAs/AlGaAs heterostructures by SAW technique using dc TAS [1] and also by ordinary DLTS measurements [10].

The A-DLTS spectrum of NU-1323 sample with 2 DHS recorded by applying an optical injection pulse contains one dominant peak (A) and three weaker ones (B-D). Using Arrhenius plots, the following activation energies and corresponding capture cross-sections were determined: 1.29 eV (A); 0.33 eV (B); 0.73 eV (C); 0.61 eV (D) and 1.8×10^{-19} cm^2 (B); 9.2×10^{-12} cm^2(C); 1.5×10^{-12} cm^2 (D), respectively. In spite the fact that some of the obtained deep centers (B-D) were registered also by other transient techniques using both electrical and optical pulse excitation [10, 13, 14], they are typical for acoustical transient measurements [1, 2, 10] and deep center (A) characterized with relatively high activation energy, 1.29 eV and large cross-section (~ 10^{-4} – 10^{-6} cm^2) is known, except acoustic transient measurements [2, 9], only from TSC measurements [15].

As it can be seen the obtained values of activation energies are mostly in good agreement with the values found by both optically induced and other transient spectroscopy techniques and attributed to deep centers or other defects. The experimental arrangement indicates that detected deep centers should be localized close to the 2 DES or 2 DHS. However, some features found only by acoustic transient spectroscopy still remain unclear.

4 Conclusion

In conclusion, the acoustoelectric investigation using the acoustic transient spectroscopy technique we presented can be successfully used to study the deep centers in GaAs/AlGaAs heterostructures. Several deep centers attributed to the interface states in GaAs/AlGaAs heterostructures with both 2 DES and 2 DHS were discovered and their parameters were determined. The observed A-DLTS peaks highness indicates also much lower concentration of deep centers in the heterostructures NU-1787 and NU-1323 comparing with the heterostructure NU-169. The presented and for deep centers investigation used acoustoelectric transient technique has also some advantages comparing with the other transient techniques: the acoustoelectric signal is produced directly by a heterojunction containing space charge so that any changes in its distribution are immediately reflected by the ARS; the number and thickness of individual insulating layers at the heterostructure does not influence obtained acoustoelctric response; the quality of the ohmic contacts does not play so important role as in electric techniques.

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PASSIVATION OF DEFECT STATES IN Si AND Si/SiO$_2$ INTERFACE STATES BY CYANIDE TREATMENT: IMPROVEMENT OF CHARACTERISTICS OF PIN-JUNCTION AMORPHOUS Si AND CRYSTALLINE Si-BASED METAL-OXIDE-SEMICONDUCTOR JUNCTION SOLAR CELLS *

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Defect states in Si can be passivated by cyanide treatment which simply involves immersion of Si materials in KCN solutions, followed by rinse. When the cyanide treatment is applied to pin-junction amorphous Si (a-Si) solar cells, the initial conversion efficiency increases. When the crown-ether cyanide treatment using a KCN solution of xylene containing 18-crown-6 is performed on i-a-Si films, decreases in the photo- and dark current densities with the irradiation time are prevented. The cyanide treatment can also passivate interface states present at Si/SiO$_2$ interfaces, leading to an increase in the conversion efficiency of $\langle$ITO/SiO$_2$/Si(100)$\rangle$ solar cells. Si-CN bonds formed by the reaction of defect states with cyanide ions have a high bond energy of about 4.5 eV and hence heat treatment at 800° C does not rupture the bonds, making thermal stability of the cyanide treatment. When the cyanide treatment is applied to ultrathin SiO$_2$/Si structure, the leakage current density is markedly decreased.

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1 Introduction

Defect states in the band-gap seriously degrade Si solar cell characteristics. In the case of amorphous Si (a-Si), an intrinsic layer (i-layer) with good characteristics has a defect density of the order of 10^{21}m^{-3}, but it increases to the order of 10^{23}m^{-3} with prolonged irradiation [1]. In the absence of defect states, almost an uniform electrical field is induced in the i-layer by charges in the n- and p-layers as shown in Fig. 1a. However, light irradiation generates defect states in the band-gap of a-Si. Photo-generated electrons and holes are trapped at the defect states near the n/i- and p/i-interfaces, respectively, and consequently the potential gradient in these regions becomes steep (Fig. 1b). However, the band in the middle of the i-layer becomes flat, and photo-generated electrons and holes recombine at the defect states, resulting in a decrease in the energy conversion efficiency. Due to the formation of defect states, photo- and dark conductivities of a-Si films greatly decrease with the irradiation time, as was observed by Staebler and Wronski in 1977 for

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