ISSN 1063-7842, Technical Physics, 2015, Vol. 60, No. 3, pp. 432–436. © Pleiades Publishing, Ltd., 2015.
Original Russian Text © N.S. Zayats, R.V. Konakova, V.V. Milenin, G.V. Milenin, R.A. Red'ko, S.N. Red'ko, 2015, published in Zhurnal Tekhnicheskoi Fiziki, 2015, Vol. 85, No. 3, pp. 114–118.

PHYSICAL ELECTRONICS

Microwave-Radiation-Induced Structural Transformations in Homo- and Heterogeneous GaAs-Based Systems

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Received January 16, 2014; in final form, July 9, 2014

Abstract—The effect of microwave irradiation (f = 2.45 GHz, 1.5 W/cm^2, t = 1 or 2 min) on the reflectance and photoluminescence spectra of the epitaxial n–n^+-GaAs and Au-n–n^+-GaAs structures is studied. Short-term microwave irradiation is shown to cause long-term nonmonotonic changes in the spectral characteristics, which can result from the structure modification of the near-surface regions in the epitaxial films. The long-term changes of the optical spectra of the structures that occur after microwave irradiation are explained.

DOI: 10.1134/S1063784215030299

1. INTRODUCTION

The change in the microstructure and the chemical and phase composition of semiconductors under the action of electromagnetic fields is one of the promising trends in the modification of their physical properties. The basic investigations in this field have been performed using static or relatively low-frequency fields. The studies of the properties of semiconductors and the related devices in microwave electromagnetic fields are scarce and mainly belong to microelectronic devices of various types [1]. It was shown that semiconductor devices placed in powerful high-frequency electromagnetic fields undergo an electrical or thermal breakdown, diffusion mixing, and chemical reaction at interfaces; these phenomena eventually causes the degradation of microelectronic devices.

However, an increase in the structural homogeneity and the removal of undesired defects in semiconductors and the related devices are observed in some cases under certain irradiation conditions [2–5]. These effects were associated with microwave-radiation-induced gettering and restructuring of impurity defects in semiconductors, and the processes of structural relaxation continued after the end of microwave irradiation [6]. The mechanisms of these effects are still unclear and cannot be explained in terms of the thermal action of an electromagnetic field, since the performed investigations did not detect a significant increase in the material temperature during microwave irradiation.

The purpose of this work is to study the optical characteristics of GaAs-based semiconductor structures in order to reveal the transformation of the defects induced by the athermal action of microwave radiation.

2. EXPERIMENTAL

We studied epitaxial n–n^+-GaAs structures with a 3-μm-thick n layer and a 300-μm-thick n^+ substrate that were doped with Te. The free carrier concentrations in the epitaxial film and the substrate were 5×10^{16} cm^{-3} and 1×10^{18} cm^{-3}, respectively. A 10-nm-thick golden film was deposited onto some structures by electron-beam evaporation at a temperature of 250°C in a vacuum of 10^{-4} Pa.

We studied photoluminescence (PL) spectra recorded at 77 K and optical reflectance spectra recorded at room temperature. With the computer-assisted experimental device used to study PL spectra, we were able to perform measurements in the spectral region 0.6–2.0 eV during light excitation at $h\nu \geq 2$ eV. The light absorption coefficient at the given photon energy was 10^5 cm^{-1} [7].

The spectral dependences of reflectance were measured on a modified KSVU-23 spectrometer equipped with an IPO-76 reflection attachment in the range 800–1150 nm.

Samples were treated in the working chamber of a microwave oscillator in air at a frequency of 2.45 GHz and an output power of 1.5 W/cm^2. The irradiation time was 60 and 120 s. To prevent heating of a sample, the irradiation dose was accumulated in a steplike manner, the irradiation time was 3 s, and the time interval between treatments was 5 s.

The spectral dependences of reflectance were studied on the n–n^+-GaAs structures. PL spectra were measured on Au-n–n^+-GaAs structures during excitation on both the side of the thin metallic layer and the backside of the heavily doped GaAs substrate. The spectral dependences of PL and the nature of radiative recombination bands were analyzed with allowance for the experimental data systematized in [7].

3. RESULTS AND DISCUSSION

3.1. Effect of Microwave Irradiation on the Optical Properties of the Epitaxial n–n⁺-GaAs Structures

Figure 1 shows the spectral dependences of reflectance R before and after microwave irradiation for 1 min. These dependences have the shape that is typical for a GaAs film grown in a GaAs substrate with optical constants that differ from those of the film. The oscillating character of R in the spectral region outside the fundamental absorption is of interest. This interference pattern appears when the incident radiation is reflected from the epitaxial film surface and lower layer (including the transition zone); therefore, its parameters (density and peak-to-peak amplitudes of extrema, interference pattern contrast) reflect the degree of structural–morphological homogeneity of the reflecting layers that form the resulting reflectance spectrum.

No substantial changes were detected in the spectral dependences of R at the initial stage after microwave irradiation was turned off. The most pronounced changes in the optical spectra of the epitaxial structures are observed as an aftereffect after microwave irradiation is turned off. They manifest themselves in a change of the reflectance and in the shape of an interference pattern. It was found that the microwave-radiation-induced restructuring of the epitaxial layers was completed ~30 min after microwave irradiation was turned off, and neither R nor the interference pattern changed upon further storage (Fig. 1).

When analyzing the spectral curves, we can calculate effective epitaxial layer thickness d by the formula [8]

$$d = \frac{Mn\lambda_1\lambda_2(\lambda_2 - \lambda_1)}{2}, \quad (1)$$

where M is the number of oscillations between two interference extrema corresponding to wavelengths λ_1 and λ_2 and n is the refractive index of GaAs (3.4) [9]. The table gives the results of calculating d for various time intervals after microwave irradiation.

These results demonstrate that the film thickness decreases upon storage after microwave irradiation. This unusual result is likely to indicate that the assumption of a sharp reflecting film–substrate interface is not valid in real epitaxial structures; that is, extended transition zones, which differ from the contacting layers in chemical composition and structure, form at interfaces. As a result, the character of an interference pattern is determined by the following two factors: the epitaxial layer thickness and the parameters of the transition zone at an interface. For long storage time, the reflectance spectrum acquires the shape that corresponds to a one-layer interference model (effect of the transition zone may be neglected), and the spectral position of extrema makes it possible to estimate the “true” epitaxial film thickness (~3 μm).

Thus, we can assume that the transition zone parameters and, hence, the conditions of light reflection at the interface change as a result of microwave irradiation. This conclusion is supported by [10], where short-time microwave irradiation was shown to induce long-term processes of defect and impurity redistribution, which were most intense in regions with a high degree of structural imperfection (near crystal surfaces and interfaces).

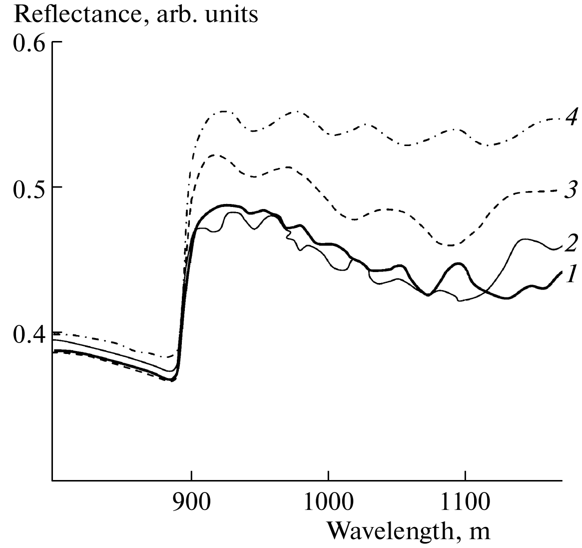

Fig. 1. Optical reflectance spectra of the epitaxial n–n^+ structures of gallium arsenide before and after microwave irradiation: (*1*) initial, (*2*) right after microwave irradiation, (*3*) in 30 min, and (*4*) 1.5 and 24 h after irradiation.

3.2. Effect of Microwave Irradiation on the PL Spectra of the Near-Contact Regions of the Au-n–n⁺-GaAs Structures

As shown in Section 3.1, microwave irradiation changes the parameters of the interface in the n–n^+-GaAs homoepitaxial structure. We assume that the structural evolution effects induced by the microwave fields at metal–semiconductor (MS) interfaces should also manifest themselves in heterogeneous thermodynamically nonequilibrium MS structures.

As in indicator of changes in the defect structure of the near-contact regions after microwave irradiation, we used the spectral dependences of PL excited by strongly absorbed light. PL spectra were recorded from

Values d calculated by Eq. (1)

Film thickness μ	Time, h
5	Initial
7	0.1
3	1.5
3	24

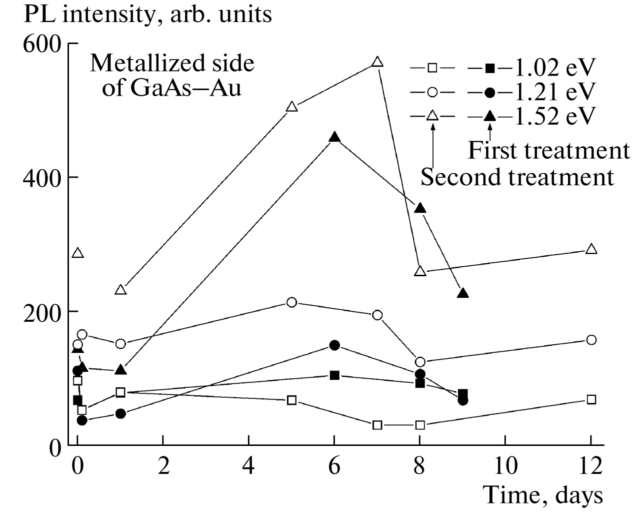

Fig. 2. PL band intensities of Au–GaAs vs. the storage time.

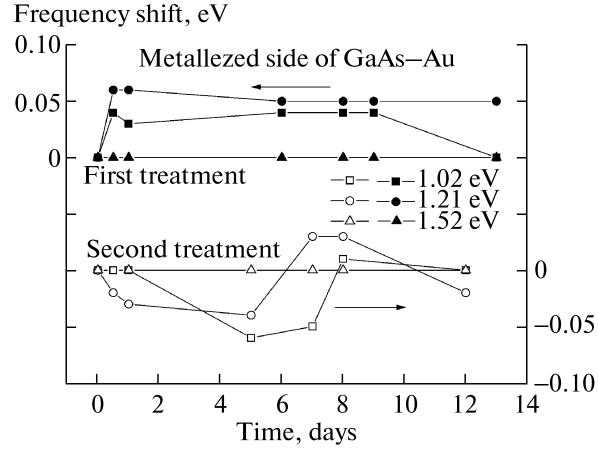

Fig. 3. Change of the frequency position of PL peaks after the end of microwave irradiation.

both the side of the thin metallized layer and the backside of the heavily doped substrate.

The PL spectra of the initial samples obtained from the side of metallization are close to the PL spectra of the epitaxial GaAs layers [11] and agree with the PL spectra of the same objects presented in [12]. The PL spectra of the epitaxial films have an edge band at $h\nu_{max} \approx 1.52$ eV and broad bands at $h\nu_{max} \approx 1.02$ and 1.21 eV, which are related with local states in the bandgap. As in [12], we attribute these bands to radiative recombination at donor–acceptor (DA) pairs formed by gallium vacancies and impurities.

Two bands at $h\nu_{max} \approx 1.06$ and 1.27 eV in the impurity PL range were detected from the backside of the substrate, and their nature is caused by the complexes that appear during the interaction of structural defects with impurities [13]. The edge band was not detected, which is likely to be related to a high imperfection of the near-surface layer because of the process of substrate preparation for epitaxial growth, since the back surface of the substrate was less carefully prepared as compared to the front (growth) surface and had a high level of structural imperfections, which played the role of an internal getter for structural defects and impurities in growth processes.

We first consider the changes that occur in the PL spectra of the epitaxial film after microwave irradiation for various times. It was found that microwave irradiation did not result in the formation of new radiative recombination centers and affected the intensities of both the initial edge and impurity bands (Fig. 2). These changes are observed in a certain time interval (several minutes) after microwave irradiation and have a long-term oscillating character. Note that a microwave field selectively affects the impurity bands: the band at $h\nu_{max} \approx 1.21$ eV changes most strongly, and its nature is related to V_{Ga}–D_{As} DA pairs [7].

The change of the impurity band intensities is accompanied by small frequency shifts of their maxima at the initial stage of long-term relaxation (Fig. 3).

Repeated exposure in a microwave field leads to long-term changes in the radiative recombination band intensities that are qualitatively similar to those during primary exposure (Fig. 2). We note a certain increase in the edge and impurity ($h\nu_{max} \approx 1.21$ eV) band intensities and a weakening of the band at $h\nu_{max} \approx$ 1.02 eV, which is related to an uncontrollable copper impurity [7]. A nonmonotonic shift of the frequency positions of the PL impurity band maxima is detected in this case (Fig. 3).

Thus, short-term microwave irradiation leads to long-term (several days) changes in the structural characteristics of the near-surface regions in the epitaxial films. This phenomenon has not been explained using a general model. The detected structural transformations are assumed to be caused by the fact that some impurities and native defects during epitaxial layer growth are in a state that does not correspond to thermodynamic equilibrium. Microwave irradiation promotes structural-impurity transformations due to the stimulation of gettering and complex formation processes, which are induced by the action of a microwave field on the defect subsystem of a crystal [13, 14].

The uncorrelated disproportionate changes of the impurity band intensities point to the fact that both radiative and non-radiative recombination channels change during microwave irradiation under experimental conditions. The changes in the PL spectra after repeated irradiation indicate that the energy parameters of structural transformations (the energy of destruction of defect complexes (including DA pairs), the activation energy of defect and impurity diffusion, etc.) are high enough for the defect structure of the crystal to correspond to an equilibrium state after irradiation. This finding is also supported by the data obtained for the substrate material (Figs. 4, 5).

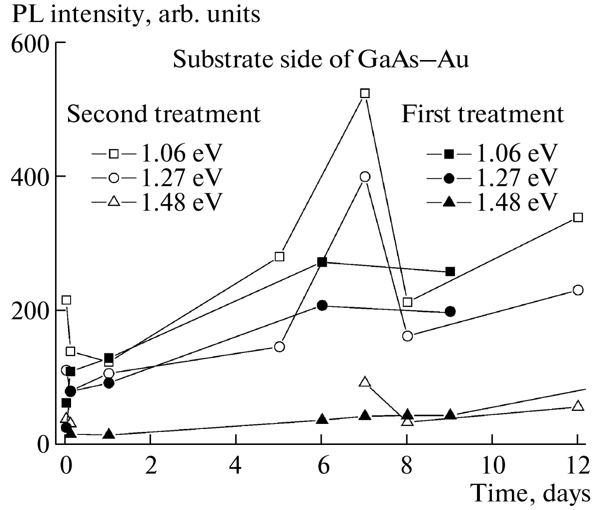

Fig. 4. PL band intensities of the GaAs substrate vs. the storage time.

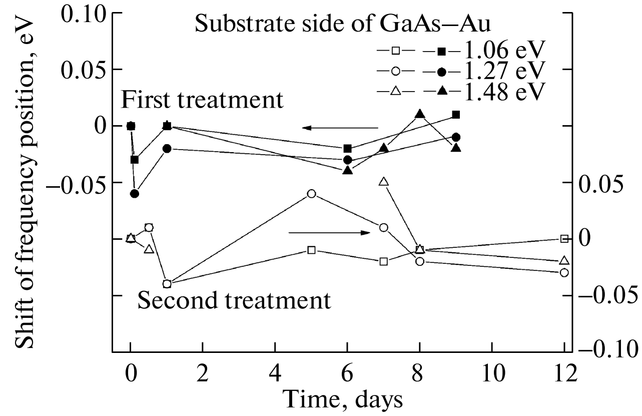

Fig. 5. Change of the frequency position of the PL peaks of the GaAs substrate after the end of microwave irradiation.

Let us consider the effect of microwave irradiation on the radiative recombination of the heavily doped substrate in more detail. As in the case of the epitaxial films, microwave irradiation results in long-term relaxation of the impurity band intensities after the end of irradiation, and the increase of the impurity band intensities has a symbate character. This irradiation weakly affects the near-edge band intensity ($h\nu_{max} \approx$ 1.48 eV), which is significantly lower than that of the epitaxial film.

The symbate change of the impurity band intensities is most likely to be due to changes in the concentration of non-radiative recombination centers. However, the changes of the fluxes of recombinating carriers through local centers of different origins are disproportionate, which can result from a selective action of microwave irradiation on these centers, in particular, the enhancement of the formation of complexes from structural defects with a Cu impurity gettered by the mechanically distorted near-surface layer on the backside of the substrate.

The detected small shifts of the radiative recombination band maxima can be related to different distances between donors and acceptors in complexes and to apparently nonequivalent donor and acceptor positions in the lattice because of a high concentration of point and extended defects induced by microwave irradiation (Fig. 4).

After repeated microwave irradiation, the long-term changes of the PL band intensities differ from the primary changes (Fig. 3). First, a jumplike symbate change of the impurity band intensities is observed at a storage time of ~7 days. Second, the process of long-term relaxation has a pronounced oscillating character. Moreover, the band at $h\nu_{max} \approx 1.48$ eV is more pronounced.

Thus, a high oversaturation concentration of impurities and nonequilibrium point defects is assumed to be caused by microwave irradiation in the near-surface layers of the semiconductors. The concentration and distribution of defects depend on the initial structural state of the near-surface layers and, hence, can be substantially different in the epitaxial layer and the substrate, which leads to differences in their PL spectra. In time, the concentration of excess defects relaxes due to trapping by sinks or complex formation. Since the restructuring of defects and impurities occurs via diffusion and interaction with structural defects [15], the PL band intensities change for a long time after a microwave field is turned off (Figs. 2, 3).

To explain the long-term relaxation qualitatively, we consider the following simplified model. Our experimental results demonstrate that microwave irradiation does not cause new radiative recombination centers and only changes the concentration of the existing centers. The change in their concentration is associated with a change in non-radiative recombination centers.

If we assume that the transformation of the defect–impurity structure of the semiconductor after the end of microwave irradiation changes the rates of radiative recombination and non-radiative recombination so that the contribution of radiative recombination increases mainly due to a decrease in the efficiency of a non-radiative channel and vice versa, a periodic undamped process of changing the concentrations of both radiative and non-radiative recombination centers should occur. However, as follows from the experimental data, the transition of the system to a quasi-equilibrium (stationary) state proceeds via damped oscillations; that is, the time changes of the recombination center concentration represent aperiodic oscillations and can be described by a differential oscillation equation with a dissipative term [15]. For the limiting values of the damping parameter (i.e., the quantity reciprocal to the relaxation time), which is determined by changes in the concentration of non-radiative recombination centers due to both gettering and the formation of complexes from impurities and point defects, the changes of the concentration of non-radiative centers can be as follows [15]:

(a) They can be damped and aperiodic at long relaxation times.

(b) At short relaxation times, aperiodic damping toward an initial steady state takes place.

Since the time evolution of the impurity band intensities depends on both the concentration of radiative recombination centers and the concentration of non-radiative recombination centers, the damped oscillating character of the latter centers would lead to oscillating changes in the impurity PL bands, which was experimentally detected.

4. CONCLUSIONS

Our optical investigations demonstrate that microwave irradiation leads to changes in the impurity–defect composition of the near-surface regions and interfaces, which have a long-term oscillating character. As noted in [16], the detected structural changes can result from a specific athermal mechanism of activation of the microwave-field-induced diffusion processes. As noted in [16], microwave irradiation of a crystal creates an additional driving force, which increases the mass transfer in the crystal and, hence, leads to the accumulation of structural defects and impurities in the near-boundary regions in the crystal. This state is nonequilibrium and its evolution is determined by the interaction of defects and impurities and absorption at sinks.

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Translated by K. Shakhlevich