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# Cathodoluminescence characteristics of pseudomorphic modulation-doped quantum well AlGaAs/InGaAs/AlGaAs heterostructures at high carrier densities and their radiation damaging

© V.S. Khrustalev¶, A.V. Bobyl, S.G. Konnikov, N.A. Maleev, M.V. Zamoryanskaya¶¶

Ioffe Physicotechnical Institute, Russian Academy of Sciences,
194021 St. Petersburg, Russia

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Cathodoluminescence characteristics of modulation-doped transistor heterostructures AlGaAs/InGaAs/AlGaAs with the width of quantum well $\sim 12$ nm are investigated in this work. The investigation was conducted by means of cathodoluminescence generation depth changing, the depth depends on electron energy. So this fact permits to get cathodoluminescence characteristics from different depth of the investigated structure. The influence of $\gamma$-radiation with several doses on the cathodoluminescence spectra was examined.

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## 1. Introduction

Nowadays effects of the interaction between nonequilibrium carriers and two-dimensional electron and hole gas attract attention due to their usage in devices and possibility for the investigation of fundamental characteristics of two-dimensional systems. The adaptation of the method of local cathodoluminescence (CL) is very effective for investigation of nanostructures with a number of heterolayers, as such method permits to obtain CL characteristics with generation of nonequilibrium carriers at different depth due to variation of energy of bombarding electrons. As an example, for $A^{III}B^{V}$ materials the penetration is about 20 nm, when the energy of electron beam is 1 keV, and it increases to $1.1\,\mu$m when the energy is 15 keV.

The purpose of this work is local cathodoluminescence investigation of heterostructures AlGaAs/InGaAs/AlGaAs, which are used for production of ultrahigh frequency transistors. The following was investigated:

1) the modification of CL spectra due to energy of electron beam for transistor heterostructure and GaAs substrate;

2) time change of intensity peaks during long-duration irradiation with the cathode beam (with different electron beam's energy);

3) the influence of $\gamma$-irradiation with several doses on CL characteristics of heterostructure AlGaAs/InGaAs/AlGaAs.

## 2. Experimental technique

For CL study we used original CL system incorporated into electron probe microanalyzers MicroBeam Camebax (Cameca) [1]. This CL system consists of two spectrometers; one of these operates in near ultraviolet (UV) and visible ranges (5.5−1.8 eV), while the other is designed for the infrared (IR) (2.0−0.9 eV). Optomechanical systems of spectrometers are identical, the difference is in gitters and radiation detectors. CL system has high sensitivity and high spectral resolution of spectrometers (spectral resolution of 0.1 nm in UV and visible ranges and 0.2 nm in IR range).

The use of local CL method is effective for the investigation and monitoring of general properties of semiconductors. Beam focusing to $0.5\,\mu$m allows to realize local investigations of luminescent characteristics and to vizualize defects and doping pattern. The next very useful possibility of CL method is its depth resolution. The excitation depth depends on electron energy. So this fact allows to get CL characteristics from the different depth of the investigated structure. Electron probe microanalyzers MicroBeam Camebax allows to realize electron bombardment with energies from 1 to 40 keV.

## 3. Results

### 3.1. Investigated structure

In this work the results of CL investigation of transistor multilayer heterostructure AlGaAs/InGaAs/AlGaAs, which was grown in molecular beam epitaxy machine on GaAs substrate, are set out. In Tabl. 1 layers sequence, their width, composition and doping level with Si, which was set by the parameters of engineering process, are given. The channel of investigated structure is $\mathrm{In}_{y=(0.16-0.17)}\mathrm{Ga}_{1-y}\mathrm{As}$. The width of pseudomorphic channel is 12 nm. Band-gap energy is 1.2 eV.

### 3.2. Cathodoluminescence investigation of heterostructure AlGaAs/InGaAs/AlGaAs

Fig. 1 shows typical CL spectrum of heterostructure AlGaAs/InGaAs/AlGaAs (electron energy is 5 keV and absorbed current is 30 nA). There are two lines in this spectrum (at energies $E_1 = 1.25$ eV and $E_2 = 1.30$ eV), which are associated with transitions from the lowest two electron subbands to the highest hole subband (Fig. 2, $a$). The difference between the two lowest electron subbands is about 50 meV. This adjusts to theoretical calculation [2]. In spite of the selection rule, according to which transition

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¶ E-mail: vasya 3006@rambler.ru

¶¶ E-mail: zam@mail.ioffe.ru

**Table 1.** Parameters of investigated structure

| № | Layer | Composition, $x$ or $y$ | Width | Doping level, $\text{cm}^{-3}$ |
|---|---|---|---|---|
| 1 | GaAs substrate | | $350\,\mu$m | |
| 2 | Buffer layer GaAs | | 400 nm | |
| 3 | Superlattice $\text{Al}_x\text{Ga}_{1-x}\text{As/GaAs}$ ($\times 7$) | 0.24/0 | 2 nm/2 nm | |
| 4 | Buffer layer $\text{Al}_x\text{Ga}_{1-x}\text{As}$ | 0.24 | 100 nm | |
| 5 | High-concentration layer $n$-$\text{Al}_x\text{Ga}_{1-x}\text{As}$ | 0.24 | 4.5 nm | $\sim 2.5 \cdot 10^{18}$ |
| 6 | Spacer $\text{Al}_x\text{Ga}_{1-x}\text{As}$ | 0.24 | 2 nm | |
| 7 | Moderating layer GaAs | | 2 nm | |
| 8 | Channel $\text{In}_y\text{Ga}_{1-y}\text{As}$ | 0.16−0.17 | 12 nm | |
| 9 | Moderating layer GaAs | | 1.5 nm | |
| 10 | Spacer $\text{Al}_x\text{Ga}_{1-x}\text{As}$ | 0.24 | 2 nm | |
| 11 | High-concentration layer $n$-$\text{Al}_x\text{Ga}_{1-x}\text{As}$ | 0.24 | 13 nm | $\sim 2.5 \cdot 10^{18}$ |
| 12 | Barrier layer $n$-$\text{Al}_x\text{Ga}_{1-x}\text{As}$ | 0.24 | 10 nm | grad to $5 \cdot 10^{17}$ |
| 13 | Barrier layer $n$-$\text{Al}_x\text{Ga}_{1-x}\text{As}$ | 0.24 | 16.5 nm | $\sim 5 \cdot 10^{17}$ |
| 14 | Contact layer $n$-GaAs | | 10 nm | $\sim 1 \cdot 10^{18}$ |

from the second electron subband to the highest hole subband should be forbidden, the intensity of the second line is equal to the intensity of the first line. This fact accounts for asymmetry of quantum well, which led to space division of energy levels and breaching of the selection rule (Fig. 2, *b*) [3].

To investigate dependence of multilayer structure CL emission on the location of its generation, the spectra with the electron energies 15, 10, 5, 2.5 and 1 keV (absorbed current was not changed) was taken (Fig. 3). Approximate electron penetrations for several electron energies were calculated by the formula $X = 0.1\,E_0^{1.5}/\rho$ [4], where $X$ — electron penetration ($\mu$m), $E_0$ — electron energy (keV), $\rho$ — density ($\text{g/cm}^3$) (Tabl. 2). Fig. 4 shows the dependence of the CL intensity on the electron energy for the investigated structure.

**Table 2.** Theoretical estimate of electrons penetration

| Electron energy, eV | Penetration, $\mu$m |
|---|---|
| 15 | 1.08 |
| 10 | 0.59 |
| 5 | 0.21 |
| 2.5 | 0.07 |
| 1 | 0.02 |

High intensity in the cases of electron energy 2.5 and 5 keV is explained by the formation of most nonequilibrium carriers not far from the channel, so they recombine in preference there with emission (embedment depth of the channel, which was set by engineering process parameters, is about $0.05\,\mu$m).

Low intensity of CL emission in the case of electron energy 1 keV is explained by formation of most carriers in the first barrier and contact layers, so gradient of concentration in the second barrier layer prevents running of electrons to the channel and the most part of them recombine without emission in the near-surface layers.

In the cases of electron energies 10 and 15 keV most nonequilibrium carriers are generated deeply in the GaAs substrate. So to recombine with emission in the channel carriers should pass a long distance, during which most of them recombine without emission, so intensity of CL emission is low (as in the case of 1 keV energy).

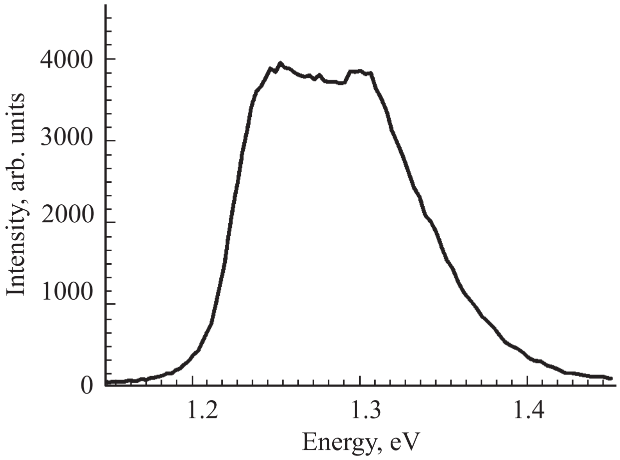

**Figure 1.** Cathodoluminescence spectrum in IR region. Electron energy 5 keV, absorbed current 30 nA.

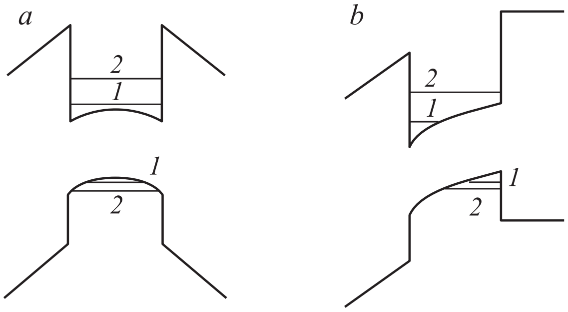

**Figure 2.** Position of energy subbands: *a* — case of symmetric quantum well; *b* — case of asymmetric quantum well. *1, 2* — two lowest electron subfands and two highest hole subfands.

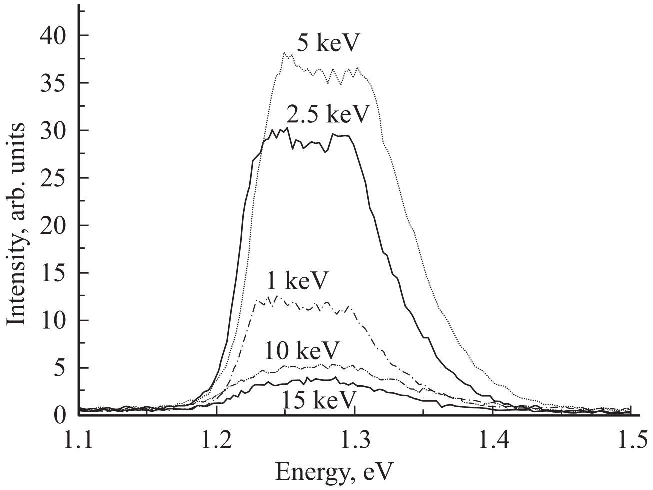

**Figure 3.** Cathodoluminescence spectra in IR region. Absorbed current 30 nA.

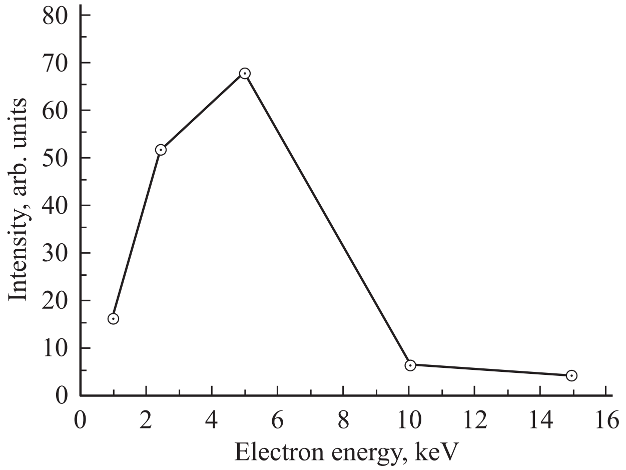

**Figure 4.** Dependence of maximum intensity of cathodoluminescence emission on the electron energy.

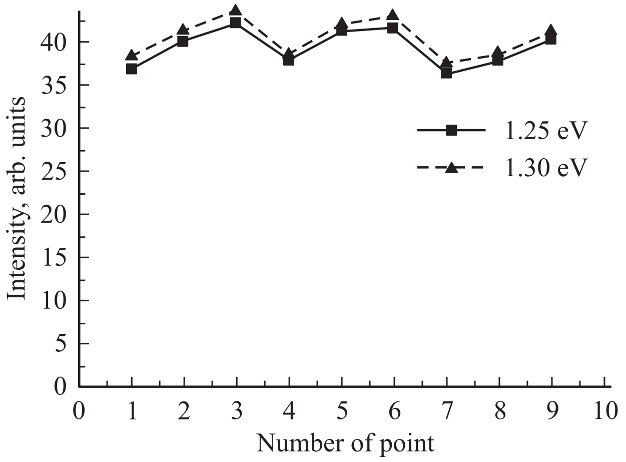

**Figure 5.** Space distribution of two cathodoluminescence peak intensities.

The investigation of the test structure such as substrate GaAs shows that in contrast to the investigated multilayer structure the intensity of CL emission increases monotonically with the increase of electron's energy in the range from 1 to 15 keV.

Locality of cathodoluminescent investigations permits to characterize the potential profile of the channel in each local structure microvolume and to predetermine profile spatial homogeneity. Fig. 5 shows the maximum intensities of two peaks of cathodoluminescent emission, which was generated in different points of the investigated heterostructure AlGaAs/InGaAs/AlGaAs. Dispersion for this structure does not exceed 10%. This fact justified the high degree of homogeneity of the investigated heterostructure parameters.

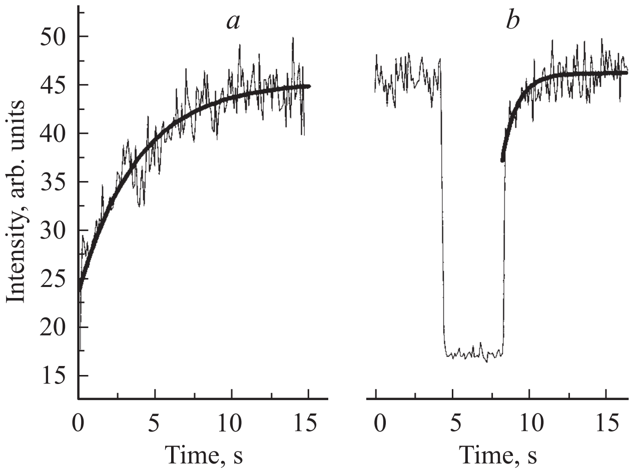

**Figure 6.** Time dependencies of peak intensity: *a* — in the case of the beginning of irradiation by cathode beam (3.6 s); *b* — in the case of irradiation after a short pause (1 s).

### 3.3. Intensity rise of cathodoluminescence emission of heterostructure AlGaAs/InGaAs/AlGaAs

In the process of heterostructure investigation the time dependence of CL emission was measured. For this purpose the spectrometer was adjusted to the maximum intensity of the emission and it registered intensity modification during long-duration irradiation by the cathode beam. Both peaks of the intensity rise were observed and the time of the rise was evaluated (Fig. 6, *a*). The dependence obtained was estimated by formula $I = I_0 - A\exp(-t/\tau)$, where $I$ — intensity (arb. units), $I_0$ — intensity of saturation, $t$ — time (s), $A$ and $\tau$ — parameters. Parameter $\tau$ (the rise time) characterizes the time of going to saturation. Fig. 7 shows the dependence of the rise time on the electron energy. The effect of the intensity rise can be explained by the defects annealing effect. The following experiment was made for confirmation. The investigated heterostructure was irradiated by a cathode beam during the time sufficient for going to saturation. In this case the rise time is about 3.6 s.

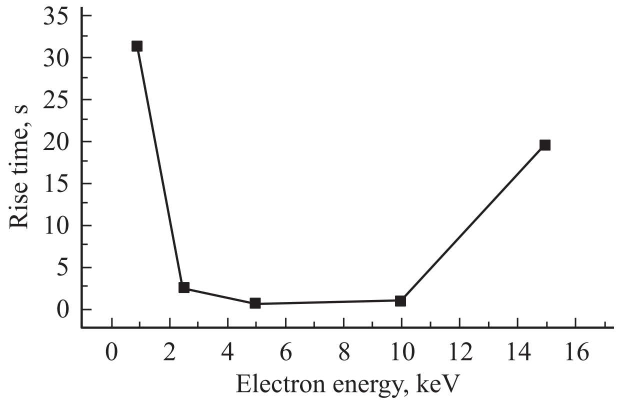

**Figure 7.** Dependence of the rise time on the electron energy.

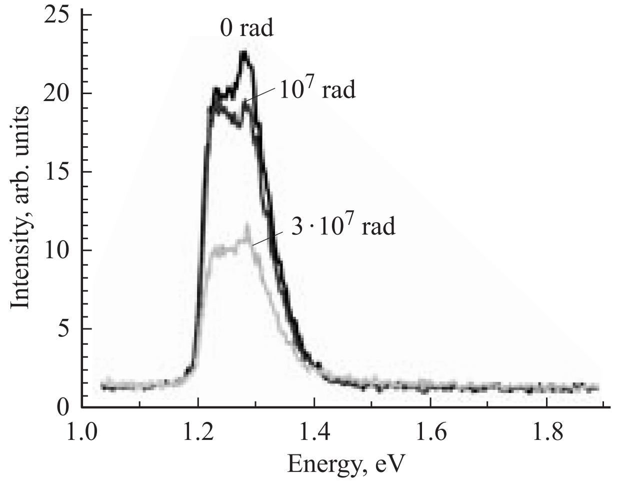

**Figure 8.** Cathodoluminescence spectra of AlGaAs/InGaAs/AlGaAs heterostructures irradiated with $\gamma$-rays with several doses.

After that the cathode beam was switched off and reclosed after 3 s (Fig. 6, *b*). After reclosing the intensity of the CL peaks immediately assumed the value, which is 10% less than before switching off, and recurred rising to saturation. The time of recurred rising is about 1 s. It is evident that this time is noticeably less than the time of the first rise. The result of this experiment confirms the interpretation of intensity rise as the structure defects annealing effect. The recurred rise can be explained by the presence of fractional relaxation of the structure defects in the irradiated region during the absence of the cathode beam.

### 3.4. Degradation investigation of heterostructure AlGaAs/InGaAs/AlGaAs under influence of $\gamma$-irradiation

The irradiation of heterostructures was executed with $\gamma$-quanta of $^{60}$Co at room temperature (irradiation energy was 1.25 MeV). For the investigation of the heterostructure degradation, CL of the same heterostructure irradiated with two doses ($10^7$ and $3 \cdot 10^7$ rad) was compared (Fig. 8). CL spectra of the irradiated heterostructures also consist of two peaks (their energies are the same as for unirradiated heterostructure). So it can be concluded that considerable modifications of the pseudomorphic InGaAs channel are absent in the cases of investigated doses of irradiation. Using $X$-ray diffraction and transmission electron microscopy, it was determined that if the dose radiation is $3 \cdot 10^7$ rad, then the breaking of planarity of the structure surface and the formation of dislocations happen [5]. In the case when the dose is $10^7$ rad, the spectrum slightly differs from the spectrum of unirradiated heterostructure, and for the dose $3 \cdot 10^7$ rad the peaks intensity is twice smaller. Such decrease can be explained by recombination without emission at a large amount of structure defects.

## 4. Conclusion

Cathodoluminescence characteristics of modulation-doped transistor heterostructures AlGaAs/InGaAs/AlGaAs with the width of quantum well $\sim 12$ nm were investigated in this work. Cathodoluminescence spectra of such structures consist of two peaks, which are associated with transitions from the two lowest electron subbands to the highest hole subband (their energies are about 1.26 and 1.30 eV). The shape of the cathodoluminescence spectra showed asymmetry of the potential profile of the quantum well.

The dependence of the spectra shape and the peaks intensities on the accelerating voltage (the electron energy) gave the embedment depth of the channel. This value coincided with the parameters of the engineering process successfully.

The influence of long-duration irradiation by the cathode beam on CL spectra was ivestigated, and the rise of peak intensities with the following going to saturation was observed. Such growth was justified by the structure defects annealing effect.

The investigation of CL spectra of transistor heterostructures, which were irradiated with $\gamma$-rays, showed the absence of a considerable modification in the conductive InGaAs channel. The sharp decrease of intensities of the both CL peaks after $\gamma$-irradiation with the dose $3 \cdot 10^7$ rad is connected with the formation of a large amount of defects in the surface layers.

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*Редактор Л.В. Шаронова*