Structural investigation of light-emitting A3B5 structures grown on Ge/Si(100) substrate

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Abstract. In this paper we have investigated light-emitting diodes based on GaAs/InGaAs heterostructures grown on a Ge/Si(100) substrates. Ge layers were deposited by the "hot wire" method, and A3B5 layers were grown by the low pressure MOCVD. Structures were investigated by the methods of electroluminescence spectroscopy and electron beam induced current imaging in a scanning electron microscope. Technological ways to improve crystalline quality of active region of light-emitting structures grown on Ge/Si(100) substrate were shown.

1. Introduction

There is an increasing demand for Si substrates as the basis of optoelectronics devices, alternatively to GaAs [1]. Growing A3B5 semiconductor layers of proper crystalline quality on the Si substrate opens new prospects for the creation of such microwave devices, light-emitting diodes (LEDs), photodetectors, solar cells, etc. GaAs layers can be grown directly on the Si substrate, but due to the difference in the lattice parameter and the thermal expansion coefficient of GaAs and Si, layers contain structural defects of high density. A more prominent way is to use different buffer layers introduced between the Si substrate and the GaAs film. These layers should have intermediate values of the lattice parameter and thermal expansion coefficient. For instance, growth of Ge layers on Si and following growth of GaAs layers is a widespread technique.

Structures we produced are the basis for creation of hybrid A3B5/Si LEDs with ferromagnetic contact. We used ferromagnetic CoPt contact for the purpose of injecting spin-polarized carriers into active region resulting in emission of partially circularly polarized light at the room temperature [2]. The main problem of those hybrid diodes is low intensity of luminescence due to high density of defects. Two types of defects influence luminescence the most: threading dislocations and antiphase boundaries (APBs). Antiphase domain is a region where Ga and As sublattices are swapped forming a boundary propagating through structure [3]. We focused on technological ways to increase electroluminescence intensity by reducing significantly the density of APBs in the present paper.

Electron beam induced current (EBIC) in a scanning electron microscope has been exploited to investigate the structure of electrically active defects in our samples. This technique combines spatial visualization and high resolution detection of electrically active defects in a structure with the
2. Fabrication of structures

Epitaxial structures were grown on Si substrates with (100) orientation. At the first stage, intermediate layers were deposited on the substrate by the method of molecular beam epitaxy (MBE). First, 200 nm thick Si layer was grown at 800°C using a sublimation source. Second, the substrate temperature was decreased to 350°C and germane (GeH₄) was injected into the growth chamber at pressure of 4×10⁻⁴ Torr. Germane pyrolytically decomposes under these conditions in the region of the tantalum wire heated up to 1350°C temperature [5]. Atomic Ge precipitated on a substrate as a result of the pyrolytic decomposition of the germane, and 750 nm thick Ge layer was grown.

At the second stage, the A3B5 structure was grown at pressure of 50 mbar using the AIX 200RF MOCVD system. Precursors were used as follows: trimethylgallium for Ga, trimethylaluminum for Al, arsine for As, silane for n-type doping of buffer, and carbon tetrachloride for p-type delta-doping of cap layer. The technique and sequence of growth of A3B5 buffer layers coincided with those described in [6] where layers of the laser structure were formed after the growth of transition layers of AlAs/GaAs and thick n⁺-GaAs buffer. In the present work, the n-GaAs layer (n = 5·10¹⁷ cm⁻³) and the InGaAs quantum well (QW) were grown on top of heavily doped n⁺-buffer. Two structures were fabricated and investigated with the different modes of a buffer layer growth. In the first structure the buffer layer thickness was 2 μm and the growth temperature was 700°C (structure A). For the second structure fabrication, the buffer layer growth temperature was increased to 750°C and the buffer layer thickness was increased to 3 μm (structure B). In addition a set of 5 shallow InGaAs QWs were grown in the beginning of the structure B buffer layer fabrication to create a dislocation barrier.

3. Results and discussion

The photoluminescence (PL) spectra at room temperature (not shown) reveal a peak at 965 nm wavelength corresponding to recombination in the quantum well. At the same time, PL intensity is by one order of magnitude lower than intensity obtained on the control structure grown on a GaAs substrate. This situation is typical for A3B5 structures grown on Si substrate due to high density of electrically active defects in active region. Top CoPt contacts were deposited on sample surface [7] and the Ohmic contact was alloyed into the buffer layer away from CoPt contact for the electroluminescence (EL) study. The EL spectra are shown in figure 2. EL study shows that increase in doping level and in thickness of buffer layer as well as inclusion of InGaAs dislocation filters leads to EL intensity increase by more than an order of magnitude.

![Figure 1. Scheme of investigated LEDs.](image)

![Figure 2. EL spectra of A3B5/Ge/Si LEDs with CoPt contact at 77K.](image)
Structural investigations of LED structures with InGaAs/GaAs QWs were carried out by EBIC technique. Details of EBIC technique were described elsewhere [4]. Figure 3 shows EBIC micrograph of the LED structure A obtained at accelerating voltage of 35 kV. It can be noted that the images show a high density (about $10^8$ cm$^{-2}$) of defects with dark contrast, associated with threading dislocations. APBs consist of Ga-Ga and As-As bonds resulting in creation of large amount of non-radiative recombination centers and the whole antiphase boundary might result in closed loops with dark contrast on EBIC picture (figure 3). Shape of these loops remains the same as the accelerating voltage increases from 5 kV to 35 kV. This fact confirms association of the loops with APBs, which propagate from the initially formed transition layer to the surface.

At the same time, no loops presumably associated with APBs were observed for structure with thicker $n^+$-GaAs buffer and additional dislocation filter layers (figure 4). Absence of APBs might be a result of combination of several factors. The level of doping was raised in order to increase luminescence intensity. Greater level of doping was obtained by increasing mole fraction of silane in growth chamber as well as increasing temperature of substrate from 700°C up to 750°C. Self-annihilation of antiphase boundaries in GaAs epilayers on Ge substrates with 6° offcut was reported in [8]. In our case, industrially compatible Si(100) substrates without additional offcut were used, but it is reasonable to assume that APBs could self-annihilate at the same conditions: higher temperature and thicker A3B5 layer. Overall thickness of A3B5 structure with thicker buffer reaches 3.5 μm considering all transition layers and dislocation filters. In our case, EBIC signal was collected from the depth of 0.2-0.3 μm (space charge region (SCR) + minority carrier diffusion length). It is safe to say that if self-annihilation occurs at some point, it takes place beyond the signal collection depth of the EBIC technique.
The comparison of the images obtained at different accelerating voltages for structure B shows that they differ substantially. Large-scale inhomogeneities of current collection (bright regions in figure 4(a)) are revealed for EBIC images at high accelerating voltages, while such inhomogeneities are absent in EBIC micrographs at low energies of the primary electron beam (figure 4(b)). In some cases, these bright regions reach a size of $10 \times 10 \, \mu m^2$. At the same time, micrographs in the secondary electron imaging (SEI) mode have not revealed any defects on the surface, which allows us to state that the heterogeneity of the EBIC signal is not related to the surface.

To obtain additional information on nature of inhomogeneities revealed, dependencies of the EBIC collection efficiency on the accelerating voltage were measured both for the signal averaged directly over light regions and for the signal averaged over a large area. The latter procedure made it possible to minimize the contribution from the light regions at high accelerating voltages. Figure 5 shows these dependencies. It can be seen that for accelerating voltages greater than 10 keV, the curve for the light region lies higher than the curve obtained by averaging over a large area. This means that there is actually more current flowing in the light regions, as compared with the rest of the structure area at high accelerating voltages of the primary electron beam.

![Figure 5](image_url)

**Figure 5.** Normalized dependencies of the EBIC collection efficiency on accelerating voltage: hollow squares - a curve for a signal averaged over a large area, filled squares - for a light region.

According to the calculation of the band diagram of such a structure, the InGaAs QW is deep in the SCR, whose width is $\sim 0.1 \, \mu m$ at zero bias voltage, and, hence, cannot affect the EBIC collection efficiency. At the same time, it has been established from the simulation of the obtained dependences of the EBIC collection efficiency that the diffusion length of the minority charge carriers is comparable with the width of the SCR and varies in the range 0.1-0.2 μm. Thus, proceeding from the analysis, it can be assumed that the appearance of regions with an increased current flow may be associated with fluctuations in the SCR width caused by the heterogeneity of the $\delta$-layer of carbon. This assumption is also confirmed by the fact, that described inhomogeneities were not revealed in EBIC images of structure A, which does not include carbon $\delta$-layer.

In conclusion we have grown and investigated InGaAs/GaAs LED structure on Ge/Si(100) substrate. Although the EL intensity is relatively low compared to LED structures on native substrate, there is room for improvement. A combination of changes in LED growth technology led to obtaining a LED structure with APB-free active region. This effect in combination with variations in doping of structure led to significant increase in EL intensity of the LED.

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