Nonuniform exciton localization in different GaAs quantum wells studied by spatially resolved cross-sectional cathodoluminescence

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1 Introduction

Excitonic radiative recombination in different GaAs quantum wells (QWs) is investigated by cross-sectional cathodoluminescence (CL) spectroscopy with high spatial resolution. By measuring spectrally discriminated CL intensities originating from the various QWs as a function of excitation position, the exciton bands of the individual QWs can be mapped to see how the respective CL intensities are influenced by the excitation position along the growth direction. We find that nonuniform capture of nonequilibrium electron-hole pairs by the QWs plays an important role for the exciton recombination, which strongly depends on the traversing pathway.

2 Experimental

The sample used for this study consists of three different QWs grown on an undoped GaAs (100) substrate by molecular beam epitaxy, prepared with growth interruption at the QW interfaces [4-6]. The nominal widths of the GaAs QWs, which are separated from each other by 36 nm thick Al0.2Ga0.8As inner barriers, amount to 7.8 nm (QW1), 5.5 nm (QW2), and 3.5 nm (QW3) starting from the substrate side. The three QWs and the two inner barriers are embedded in a pair of 72 nm Al0.3Ga0.7As barriers. This whole structure is additionally confined by 0.19 μm (surface side) and 0.43 μm (substrate side) Al0.1Ga0.9As outer barriers, forming a SCH configuration to avoid surface nonradiative recombination. These structures were grown nominally undoped with an estimated background doping level due to carbon below 1014 cm−3. Depth-resolved cross-sectional CL spectroscopy was performed on the cleaved edge of the sample in a scanning electron microscope at 6 K, using an electron beam energy of 3 keV and a beam current of 0.1 nA. A spectrometer with a focal length of 0.3 m and a cooled CCD array detector were used to disperse and detect the CL signal, respectively. The spatial resolution of the CL measurement amounts to about 50 nm.
3 Results and Discussion

Figure 1 shows a typical CL spectrum for excitation normal to the sample surface at 6 K. The CL intensity is plotted on a logarithmic scale. Five emission bands are observed due to QW1, QW2, QW3, the Al$_{0.2}$Ga$_{0.8}$As barrier layer, and an interface layer (IL) formed between the bottom Al$_{0.2}$Ga$_{0.8}$As and Al$_{0.3}$Ga$_{0.7}$As layers.

Figure 2 (a) Cross-sectional TEM image obtained with the chemically sensitive $g$=002 diffraction vector. (b) Intensity profile obtained after an average line-scan on the marked area in (a) clearly showing the presence of the IL.

A series of spot CL spectra for varying excitation positions (with a step length of 0.017 μm) were recorded by moving the electron-beam position across the heterostructure on the cleaved edge of the sample (CL line-scan). Figure 3 shows the integrated CL intensities of the four emission bands (QW1, QW2, QW3, and IL) at 6 K as a function of electron-beam position along the growth direction. The CL intensities of the $n=1$ exciton states of QW3, QW2, and QW1 exhibit successive maxima as the scan position moves towards the substrate exactly in order of the growth sequence and at the expected position. In Fig. 3, QW3 shows the highest CL peak intensity among the four exciton bands. We attribute it to the strongest confinement...
and to the efficient carrier sink due to resonant capture [7].

On the surface side of the 0.19 µm Al0.3Ga0.7As outer barrier (scan position at 0.0-0.2 µm), the CL intensities of the four bands are small due to surface nonradiative recombination, while they show characteristic and systematic differences on the substrate side of the 0.43 µm outer barrier (scan position at 0.5-0.8 µm). Note that, when the electron beam excites the bottom barrier center (e.g., for a position at 0.65 µm), the CL intensity for QW3 is smallest and the one for QW2 is smaller than that for QW1. This means that the generated carriers have difficulty to reach the QW3 layer due to intervening trapping sites of QW1 and QW2 during the diffusion processes. If the beam position is located further into the GaAs buffer layer (> 0.9 µm), the probability for the generated carrier pairs captured by the four bands is strongly reduced because of the existence of the GaAs carrier sink with a low band gap energy.

In order to examine the detailed distribution of the CL intensity as a function of excitation position, the logarithm of the CL intensities of the four bands is plotted in Fig. 4. Since the CCD detector does not allow to acquire the complete spectral range in one shot, two line scans along the same pathway were performed. For the first and second one, the spectra of the three QWs and the spectra of QW3 as well as IL have been acquired, respectively. Both profiles are then superimposed, where the CL intensity distribution of QW3 is used to calibrate both pathways. If we look at the bottom outer barrier region, the CL intensity of IL shows a single exponential decay as the excitation position moves away from the recombination site. Therefore, from this slope, we deduce a diffusion length $L = (D \tau)^{1/2}$ of 0.3 µm in agreement with the previous study [9]. In the outer barrier region far from the recombination sites (0.6-0.8 µm region), the CL intensities of QW1, QW2, and QW3 show a similar diffusion-limited exponential slope. However, the absolute CL intensity is significantly decreased as the excitation position moves away from the recombination site because of the existence of carrier trapping sites. As the number of carrier trapping sites between the excitation and detection positions is increased, the absolute CL intensity decreases. The CL intensity of QW3 farthest from the bottom outer barrier thus shows the lowest value. When the excitation position is closer to the trapping sites, the diffusion-limited transport is significantly modified for scan positions between 0.3 and 0.55 µm, for which the CL intensity distribution exhibits an increasing exponential slope for QW1 to QW3. That is, it becomes steepest for QW3 because of the additional shortening of the electron-hole pair lifetime by capture due to the existence of carrier traps of IL, QW1, and QW2. This change of the slope is easily understood in terms of the reduced lifetime of carriers by increasing the number of carrier trapping sites. If we look at the front outer barrier region (0.1-0.4 µm) in Fig. 4, a reversed tendency of the CL intensities is observed. That is, the CL intensity of IL is lowest and the slope is steepest. These results of the excitation position dependence of the CL intensity profiles indicate that the intensity of excitonic radiative recombination strongly depends on the traversing pathways and is not always uniform across the heterostructure.

4 Conclusion In summary, cross-sectional CL inten-
sity distributions due to excitonic radiative recombination
are investigated in GaAs QWs differing in their thickness
in a separate-confinement heterostructure configuration.
By measuring spectrally discriminated CL intensities
originating from the various QWs versus excitation posi-
tion, we are able to spatially resolve the exciton bands of
the individual QWs and to see how the respective CL in-
tensities are influenced by the excitation position relative
to the recombination site. The CL intensity distribution
limited by diffusion transport is observed, when there are
no intervening trapping sites. However, the existence of
trapping sites between the excitation and recombination
sites significantly affects the CL intensity distributions by
the capture of generated carriers. We thus find that exciton
localization into QWs is not always uniform and strongly
depends on the traversing pathway in inhomogeneous QW
systems.

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