LUMINESCENCE CHARACTERIZATION OF GaAs SINGLE QUANTUM WELLS

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ABSTRACT

The peculiarities of the photo- and cathodoluminescence of MOVPE grown single quantum wells containing impurities are investigated. The investigations reveal monolayerfluctuations with a lateral extension of about 10 μm . The incorporation of carbon in the thicker islands is shown using micrographs of spectrally resolved cathodoluminescence. Extrinsic radiative transitions involving the impurities are found also in the barrier above that islands which contain impurities. These inhomogenities are proposed to be connected with dislocations emanating from the substrate and penetrating the sandwiched layer structure.

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1. INTRODUCTION

This paper is a report of single-quantum well characterization by means of photoluminescence (PL) and cathodoluminescence (CL) investigations. These two methods ensure complementary results with regard to the local and spectral resolution, the injection level dependencies and the imaging possibilities. About such measurements at MBE grown SQW's was reported in /1,2/.

AlGaAs/GaAs/AlGaAs unintentionally doped single quantum wells (SQW) in the present work were grown by low-pressure MOVPE. The grown layer structure is shown in Fig. 1. The electronic structure of a 7nm GaAs-well investigated is shown in Fig. 2.

Fig. 1

Fig. 2

CL excited with the primary electron energy of 20 keV was measured in the temperature range between 80K and 300K. It is interesting to note that the electron-hole pair generation function excited by the electron beam with a primary energy of 20 keV exhibits a maximum at distances of about 0.4 μm below the surfaces and decreases to about 50% at a depth of 1 μm . The 632.8nm line of a He-Ne laser was used to carry out PL measurements. The 1.96eV photons penetrate the barriers without any absorption and a local resolution comparable with the laser spot diameter ($\approx 3\mu\text{m}$) can be expected.

2. MICROPHOTOLUMINESCENCE

In Fig. 3 typical PL-spectra taken at different positions of the GaAs-SQW are shown.

Fig. 3

material, namely, the saturation of more distant pairs in favour of closer ones which produce higher-energy photons. For low excitation levels (curve c - $N = 1 \text{ W/cm}^2$) donor-acceptor pair transitions connected with the centre and edge of the well-located acceptors were resolved ($h\nu_c(D'A^*)^c = 1.672 \text{ eV}$, $h\nu_c(D'A^*)^e = 1.720 \text{ eV}$) in the impurity contaminated regions.

Fig. 4

Only one band due to the radiative decay of electrons and heavy holes associated with the lowest conduction and valence band sublevels ($h\nu_c(e-hh) = 1.806 \text{ eV}$; $\text{FWHM} = 20 \text{ meV}$) was observed on the regular quantum well (curve a). The luminescence band II at 1.745 eV was obtained with the strongly focused laser beam only and appears in a number of small regions of the sample (curve b and c). In those regions where band II is discernible a strong intensity of the low-energy band can be obtained also. Considering the similar behaviour of the high-energy bands I and II as the excitation density was varied and the above-mentioned features of band II, we attribute the 1.745 eV transition to a radiative decay of 2D electrons and heavy holes ($e-hh$) between the lowest conduction and valence band sublevels of thicker SQW regions with relative small lateral extensions ($\delta E = 239 \text{ meV}$). This hypothesis will be discussed later. As the pump level is increased the low energy band shifts to higher energy, typical for a $(D'A^*)$ transition in bulk

At higher temperatures only the $(e-hh)^I$ and the low-energy extrinsic transitions were observed. Two corresponding PL spectra are displayed in Fig. 3 recorded at $T = 180$ and 220 K . The decreasing peak energy of the $(e-hh)^I$ bands ($h\nu_c(180\text{K}) = 1.784 \text{ eV}$ and $h\nu_c(220\text{K}) = 1.767 \text{ eV}$) corresponds to the lowering of the energy gap with increasing temperature. The impurity correlated luminescence bands reveal peak positions independent of the pump level indicating the free to bound character of the extrinsic transitions in this temperature range (not shown). We attribute this bands ($h\nu_c(180\text{K}) = 1.659 \text{ eV}$ and $h\nu_c(220\text{K}) = 1.642 \text{ eV}$) to the radiative decay of 2D electrons with holes bound to acceptors located in the well centre (eA^*).

3. LOCAL LUMINESCENCE DISTRIBUTION

Fig. 5

Fig. 6

Two monochromatic CL micrographs are shown in Fig. 5 and 6 which were taken with a focused electron beam of the primary energy $E = 20$ keV and $T = 85$ K at the wavelengths of the $h\nu_c(e-hh)^I$ (Fig. 5) and extrinsic transitions (Fig. 6). As a result, in the $h\nu_c(D'A^*)$ picture (Fig. 6) the white islands contrast the local impurity distribution. The visible islands exhibit an extension up to $10\mu m$. An overlapping of the different contrast regions results from the carrier diffusion in the barrier and in the well. The overlapping is about $1.5 \mu m$. The striking feature is the complementary behaviour of the pictures taken with the peak wavelength of the $h\nu_c(e-hh)^I$ band and extrinsic transitions indicating the incorporation of the impurities in single regions of the quantum well with diameters in the μm range.

Additionally we measured the luminescence spectra excited with the electron beam in impurity contaminated regions. Two corresponding CL spectra recorded at $T = 85$ K are displayed in Fig. 7. The energy scale is listed with respect to the 3D energy gap of GaAs. The broad luminescence band generated on the impurity contaminated islands (dashed line) is caused by the convolution of the $(e-hh)^{II}$ and $(D'A^*)^C$ bands. The CL spectra outside of these islands (solid line) are governed by a band due to the $(e-hh)^I$ transition. The low energy shoulder indicates the diffusion of excess carriers to the impurity contaminated regions.

Fig. 7

Fig. 8

As a result, residual impurities were found in small quantum well regions, which realize a weaker confinement of the carriers than found in the regular quantum well. The observed transitions are shown in Fig. 8 (straight line:regular SQW, full line:impurity contaminated region). From the peak shift $\delta E(e-hh)^I \approx 300$ meV we conclude a seven monolayer thick regular quantum well. The lower confinement in the small quantum well regions could be due to a nine monolayer thick well.

3. THE NATURE OF THE IMPURITY

Although the chemical nature of the acceptor found in the SQW has not yet been determined, it is thought to arise from carbon on As site, since it usually appears in material prepared by MOCVD in GaAs and AlGaAs alloys. Taking the lowest energies at which the extrinsic peaks were observed in excitation dependent PL investigations at $T = 85$ K ($h\nu_C(D^+A^-)^C = 1.672$ eV) as the peak position in the low excitation limit the total activation energy of the acceptors and donors at the well centre was found as 74 meV. From the free to bound transition at temperatures $T > 110$ K the ionisation energy value of the well centre acceptor can be determined using the relation

$$E_a^C = E_{sb} - h\nu_C(eA^-) + \frac{1}{2}kT \quad (1)$$

where E_{sb} denotes the energy distance between the subband levels and $\frac{1}{2}kT$ results from the thermal distribution of the free carriers in the subband. The extrinsic bands appear in connection with the $(e-hh)^{II}$ transition. Consequently, we estimated the acceptor ionisation energy with regard to the heavy hole sublevel energy in the nine-monolayer SQW. Using (1) the ionisation energy of the acceptor located in the centre of the well amounts to 63 meV.

Fig. 9

4. DISCUSSION

Fig. 10 and Fig. 11 illustrate the local distribution of the extrinsic luminescence in the barrier and in the SQW at $T = 90$ K. It is interesting to note that the luminescence due to extrinsic transitions in the barrier and in the quantum well appears at the same lateral positions. Around these impurity containing regions the $(e-hh)^I$ transition dominates in the SQW and the free exciton luminescence band correlates with the X-minimum of the conduction band in the barrier /4/.

As a result, we conclude a wide regular seven monolayer thick quantum well with excellent interface quality. This well involves nine-monolayer thick impurity contaminated regions with lateral extensions in the micrometer range. Locally correlated impurity contaminated regions were also observed in the barriers and we conclude dislocations which grow through the wafer emanating from the substrate. The dislocation density in the range between 10^3 and 10^4 cm^{-2} corresponding to values found on low-quality substrates confirms this hypothesis.

Fig. 10

Fig. 11

This assignment was confirmed by the temperature dependence of the (eA^*) transition CL intensity. The intensity versus the inverse temperature is listed in Fig. 9. The theoretical curve was calculated using the relation for a two-level model:

$$I(eA^*; T) = I_0 [1 + A \exp(-E_a^C / kt)]^{-1}$$

The activation energy evaluated from Fig. 9 amounts to $E_a = 63 \text{ meV}$ in excellent agreement with the above found result. From the measurements a donor activation energy of 11 meV in reasonable agreement with the expectation for a donor localized in the well

/3/ can be concluded.