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Development of 1300 nm GaAs-based microcavity light-emitting diodes

C. Möller, N. A. Maleev†, W. Passenberg, J. Böttcher, H. Künzel,
A. V. Sakharov†, A. E. Zhukov†, A. F. Tsatsul'nikov† and V. M. Ustinov†
Heinrich-Hertz-Institut für Nachrichtentechnik Berlin GmbH,
Einsteinufer 37, D-10587 Berlin, Germany
† Ioffe Institute, St Petersburg, Russia

Abstract. The present status of basic development steps towards AlGaAs/GaAs microcavity devices emitting at 1.3 μm is presented. An emission wavelength of the active medium of 1.3 μm was achieved by the implementation of self-organized InAs/GaInAs quantum dots. To match the wavelength tight control of the microcavity parameters was ensured by an improved layer thickness calibration procedure. Incorporation of a reverse-biased Si/Be-doped GaAs tunnel junction with record low junction resistance is expected to improve the lateral carrier distribution for intra-cavity contacted devices.

1. Introduction

An attractive way to fabricate vertical-cavity surface emitting lasers (VCSEL) and microcavity light-emitting diodes (MC-LED) for short-to-medium-haul fiber optical links is to combine Al(Ga)As/GaAs distributed Bragg reflectors (DBR) with a GaAs-based 1.3 μm emitting active medium in a single epitaxial growth run [1].

Self-organized In(Ga)As quantum dot (QD) heterostructures grown by molecular beam epitaxy (MBE) are promising candidates as an active region for GaAs-based 1.3 μm light emitting devices. Ground state emission at 1.3 μm was demonstrated using sub-monolayer deposition, low-rate growth, InGaAs barrier layers and InGaAs overgrowth [2].

For the successful growth of microcavity devices extremely precise control of the layer thicknesses is very crucial and thus requires extensive calibration procedures. We present a simple calibration technique for MBE systems which are not equipped with in-situ thickness control. In this contribution we demonstrate that QD microcavity devices for long-wavelength applications can be successfully grown using an optimised growth procedure of the active region combined with a relatively simple preliminary calibration technique.

2. MBE growth of multiple stacked InAs/InGaAs QDs

In this contribution we apply the MBE technique for the fabrication of Al(Ga)As/GaAs based microcavity structures which incorporate InAs/InGaAs QDs as active region. Recently, we have shown that improved MBE growth conditions for InAs QDs covered by InGaAs cladding layers allow the fabrication of structures which exhibit intense and narrow 300 K photoluminescence (PL) in the 1.3 μm wavelength range [3]. The most important advantages of this approach is that a QD density in each layer may be as high as $(3-5) \times 10^{10}$ cm^{-2}. To overcome the general problem of gain saturation, the QD planes may be successfully stacked by using relatively thick GaAs spacer layers (15–30 nm) without degradation of PL properties [4]. For samples with different numbers of QD planes the integrated PL efficiency at 300 K as a function of excitation power density (Ar^+ ion laser, 514.5 nm, 0.5–500 W/cm^2) was close to linear for all test samples. The onset of saturation of PL efficiency was observed only for the highest excitation power.

3. Layer thickness calibration

For MBE systems that are not equipped with in-situ thickness control we have developed a preliminary alternative calibration procedure for the layer thickness based on reference layers. A specific test structure for the DBR calibration consists of six pairs of AlGaAs/GaAs with a nominal layer thickness equal to one quarter of the operation wavelength ($\lambda/4n_i$, where n_i are the refractive indices of AlGaAs and GaAs) followed by the GaAs cavity of a nominal thickness of $\lambda/2n_i$. Two reflection spectra of each sample were measured consecutively, firstly the as-grown structure and secondly after selectively etching off the GaAs cavity layer and potentially one or several of the AlGaAs/GaAs DBR pairs. Comparing experimental and simulated reflection spectra delivers the individual real layer thicknesses. Thus, using this procedure only one test structure is necessary for growth rate calibration of GaAs and AlGaAs.

4. QD-based microcavity structures and MC-LEDs

The calibration procedure described was verified using several microcavity structures, containing also InAs/InGaAs QD active regions. As an example the experimental reflectivity spectrum for a structure containing a bottom 12-pair $Al_{0.85}Ga_{0.15}As$/GaAs DBR and a top GaAs(cavity layer)/air surface is presented in Fig. 1 and is labelled 'as grown'. Additionally depicted is a reflectivity spectrum measured after ion beam sputter-deposition of an additional 2-pair dielectric SiO_2/TiO_2 top mirror. The experimental 300 K PL spectra of both microcavity structures are additionally compared in Fig. 1 with a reference sample composed of the same active region without any optical resonator. The experimental reflection spectra and PL intensity ratios are close to the corresponding simulation results.

QD MC-LED samples were fabricated in intra-cavity contact geometry using proton implanted current apertures [4]. As shown in Fig. 2 the emission peaks of all devices investigated are centered in the projected wavelength range and exhibit a FWHM of approximately 13–26 nm depending on the active layer/top mirror parameters and have a circular output beam with a low divergence of less than 17° for the complete wavelength range and less than 10° for the resonant wavelength (angles measured at $1/e^2$ of the maximum intensity). The light output versus current characteristic is linear at low current values and saturates at current densities of about 100–200 A/cm^2. At 10 mA drive current the total top-side optical power emitted from a 40 μm diameter MC-LED was 5–7 μW. The corresponding power density is several times higher than previously published values [5].

5. Tunnel junctions in MCLEDs

High-quality tunnel junctions (TJ) open new possibilities for the design of MC-light sources, since they serve as an electron-hole converter. For intra-cavity contacted microcavity structures with oxidised current apertures, a tunnel junction (positioned at a node of the optical longitudinal field to minimise absorption) may be used as a high electron mobility layer to spread the carriers across the nearby aperture, ensuring improved lateral uniform current flow through the oxide-defined cavity.

The basic requirements for a TJ in a VCSEL are low resistivity, good thermal conductivity, temperature stability and long-term reliability.

To develop TJs, test samples were grown by MBE. The layer sequence consisted of a 400 nm low doped GaAs:Si buffer layer grown at 600°C on GaAs:Si substrate, followed by the tunnel region consisting of 100 nm n^{++} GaAs:Si and 100 nm p^{++} GaAs:Be, both layers homogenious doped and grown at reduced temperature (400°C). This reduces diffusion of

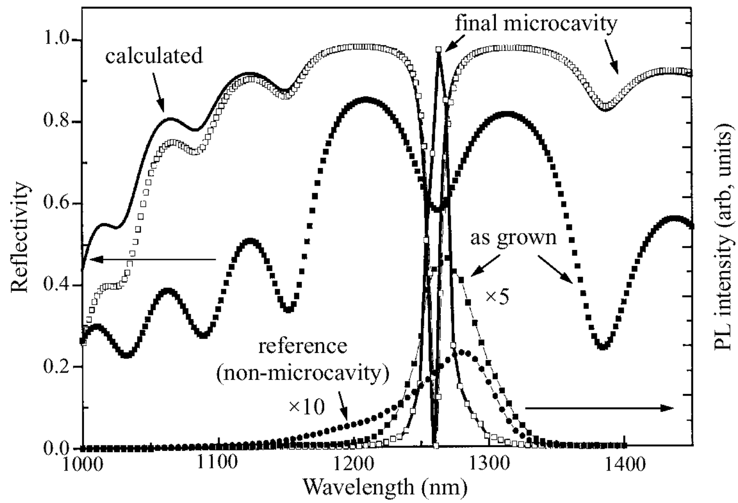

Fig. 1. Reflectivity and 300 K PL spectra taken at different stages during MC-LED layer deposition: as-grown MBE microcavity structure (black square) and after deposition of top SiO_2/TiO_2 DBR (square). For comparison, the 300 K PL spectrum of a reference active region without optical resonator (black circle) and the simulated reflectivity spectrum for the completed MC structure (solid line) are included.

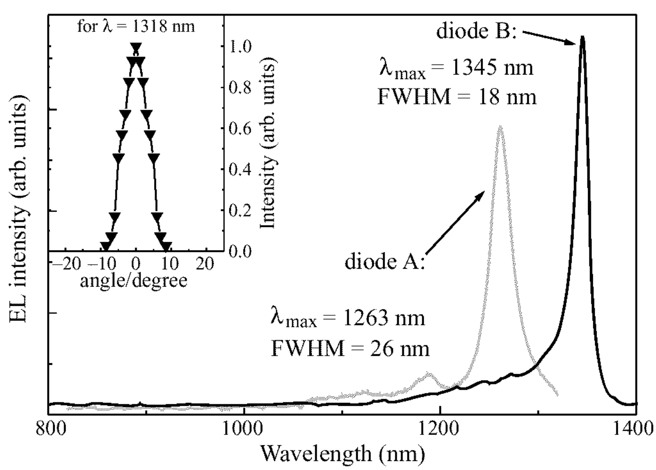

Fig. 2. 300 K CW-EL spectra of two 40 μm diameter MC-LEDs with InAs/InGaAs QD active layer emitting in the 1300 nm range (on-wafer measurement at a drive current of 10 mA). The insert shows a representative far field pattern for a mounted device (circular symmetry).

the dopants to achieve very abrupt junctions. The measured net carrier concentrations are 1.8×10^{19} cm^{-3} for silicon and 2×10^{20} cm^{-3} for beryllium. When the Si concentration is further increased, the dopant begins to substitute on the acceptor sites which results in self compensation, limiting practical net electron concentrations to 2×10^{19} cm^{-3}. On top we evaporated standard non-alloyed Ti/Pt/Au contacts, which we used as an etch mask to form 30×30 μm mesa. The back-side contact was fabricated by evaporating and alloying (400°C, 20 s) AuGe/Ni/Au.

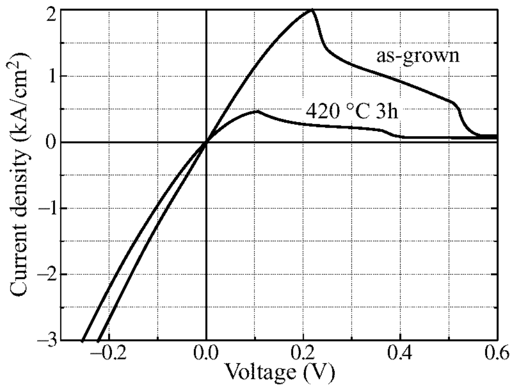

Fig. 3. Current-voltage characteristic of a 30×30 μm tunnel junction taken at room temperature, with and without tempering at 420°C for 3 hours.

The experimental I–V curves for the GaAs tunnel junction are shown in Fig. 3. The as-grown tunnel diode shows a zero-bias specific resistance of less than 7×10^{-5} W/cm^2, a peak current density of 1900 A/cm^2 and a peak-to-valley current ratio of ~19:1. To the authors knowledge this is the highest peak current density and lowest specific resistance ever reported for a GaAs tunnel diode. The results are in good agreement with calculated values.

By heat treatment of the sample at 420°C for 3 hours we simulated oxidisation process. The decrease of the peak voltage and the peak-to-valley current ratio (~6:1) is attributed to be directly related to the diffusion of the dopants. The junction is no longer abrupt, but the reverse current is still acceptably high. Under reverse-biased continuous current (cw) conditions both diodes are stable up to 15 kA/cm^2.

Summary

AlGaAs/GaAs microcavity structures incorporating self-organized InAs/InGaAs QD as active medium emitting at 1.3 μm were successfully grown by molecular beam epitaxy on GaAs substrates without the need to rely on any in-situ calibration technique. Fabricated intra-cavity contacted MC-LEDs demonstrate narrow electroluminescence spectra (FWHM $<$ 15 nm) accompanied by a circular output beam divergence of down to 10°. Thus, MBE-growth combined with intra-cavity design and top tunnel junction contact open new possibilities to design high-performance 1.3 μm microcavity light emitters.

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