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Quantum dot micro-LEDs for the study of few-dot electroluminescence, fabricated by focussed ion beam

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Abstract

We present first results from a micrometer sized micro-LED fabricated for the electroluminescence (EL) investigation of very few to one self-assembled quantum dot. Utilizing focussed ion beam (FIB) implantation we were able to fabricate a LED consisting of crossed p- and n-doped stripes of a few micrometer width. Confined between both stripes is a layer of quantum dots symmetrically embedded in a thin i-layer. We show that good quality quantum dots can be grown on FIB implemented regions and present first EL spectra which agree very well with PL measurements. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Focused ion beam (FIB) implantation is a suitable technology for the fabrication of laterally structured semiconductor devices and—in particular—lateral doping patterns. We use FIB to fabricate novel opto-electronic devices, e.g. a very sensitive photo conducting detector for single photon detection [1]. Even a micro-LED-array could be fabricated easily. All these devices contain buried doping stripes, written by FIB.

In this paper we present a micro-LED made of crossed doping stripes for electroluminescence (EL) investigations on few quantum dots.

EL from an ensemble of dots always shows an inhomogenously broadened spectra. Although it is possible to get detailed information on the energetic position of electron and hole levels, EL measurements on single quantum dots should provide additional information, e.g. on many-body effects related to the number of occupied electron and hole levels. Due to the difficulties in contacting one single quantum dot, there are only a few reports on single quantum dot spectroscopy. Zrenner et al. obtained EL results from single dots by STM injection [2], and Itskevich et al. reported EL from individual dots that were embedded in a very small, cross-shaped pin-diode, that was fabricated by selective wet chemical etching [3].

Our approach to single dot spectroscopy is somewhat similar. We also embed our quantum dot layer in a pin-diode. However, we believe that using FIB

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technology for the fabrication of crossed doping stripes is less complicated than using photolithographical methods requiring underetching. Combining FIB technology and conventional photolithography allows us to define two narrow doped stripes (with p- and n-doping, respectively) where the top stripe is oriented perpendicular to the buried stripe. On top of the layer containing the p-doped stripe, but below the n-doped stripe, a layer of quantum dots can be grown. The dot layer is symmetrically embedded within an undoped layer of 50 nm GaAs. The cross-section area of the two stripes forms a micro-pin-LED with few quantum dots in the active region. Our goal is to achieve contact to one single dot in this active region and to study EL from within the cross section.

Reducing the stripe widths to 1 μm and assuming the strongly three-dimensional character of the space-charge potential of the crossed stripes, the number of dots close to its saddle point should be in the order of one.

In this paper we present first results on room temperature operation of our micro-LED including electrical characterization and first EL- and PL-spectra.

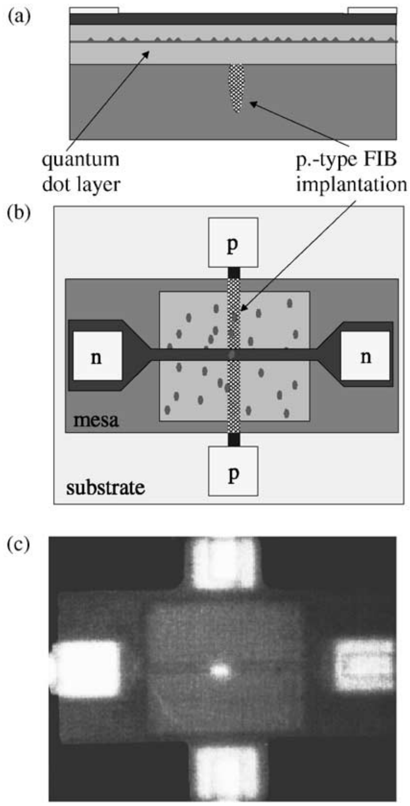

Fig. 1. (a) Schematic cross section of the micro-LED. (b) Schematic top view showing the arrangement on the p-doped stripe written by FIB and the n-stripe. (c) Room temperature luminescence from the cross section (10×10 μm) of a micro-LED.

2. Experimental

The micro-LEDs are fabricated by first growing an intrinsic buffer layer on a epi-ready GaAs substrate in an MBE. In this layer we define narrow (of the order of some micrometers or less), highly p-conducting stripes by using FIB implantation. Be^+ ions from a liquid metal ion source at an energy of 100 keV are used. The implantation doses are in the range from 10^{13} to 10^{14} cm^{-2}.

After dopant implantation and vacuum transfer back to the MBE the remaining layers are grown by MBE, including the quantum dot layer embedded symmetrically in 50 nm of i-GaAs. To ensure dot growth after the implantation we found it necessary to protect the surface during the transfer and the implantation by 30 nm of an amorphous As-layer grown before the sample is transferred into the FIB-machine. Before starting the regrowth, the As-protection layer is removed by heating the substrate to 400°C. In an additional high-temperature step up to 650°C for up to 3 min the defects induced by the ion beam are annealed. Subsequently, the lower i-layer, the InAs dot-layer, the top i-layer and the highly n-doped top-layer are grown (Fig. 1(a)). Finally, the n-layer is structured by conventional photo lithography and wet chemical etching to define narrow n-stripes perpendicular to the FIB-written p-stripes. After deposition of ohmic n- and p-contacts the devices are electrically separated by etching into the semi-insulating substrate.

3. Results

In order to test the dot growth on FIB implanted GaAs substrate, PL measurements were performed before processing the sample. PL signals were taken on both spots where no implantation and where implan-

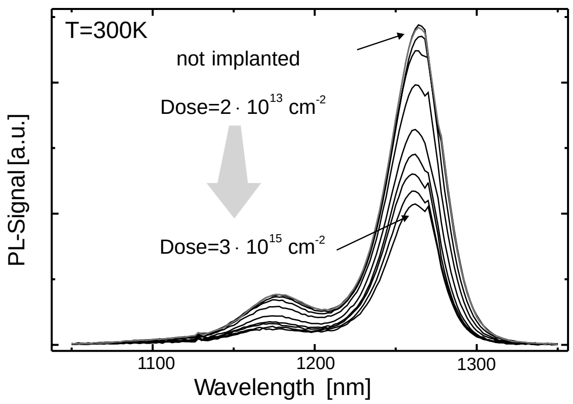

Fig. 2. PL measurements from quantum dots grown on regions where focussed ion beam implantation of Be^{+} ions of different doses (2×10^{13}–3×10^{15} cm^{-2}) was performed.

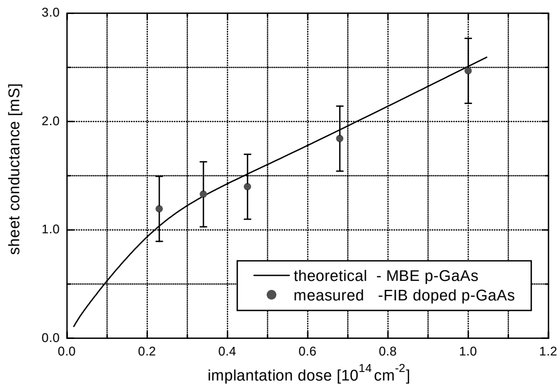

Fig. 3. Sheed conductance of p-stripes with different implantation dose. The theoretical model incorporates hall mobilities from p-doped MBE material and the depth distribution of the Be ions as obtained from SIMS measurements.

tation with different ion beam doses was performed. There is no dependence of the PL signal on the spot position for areas where no implantation was made, indicating homogenous dot growth over the wafer.

On spots where Be ions were implantated we found that with increasing implantation dose the intensity of the PL signal decreases steadily. However, the peak positions and the shape of the inhomogenously broadened spectra remain the same (Fig. 2). This indicates that except for extremely high ion beam doses of the order of 10^{15} cm^{-2} we still have growth of very good quality quantum dots in regions where ion beam

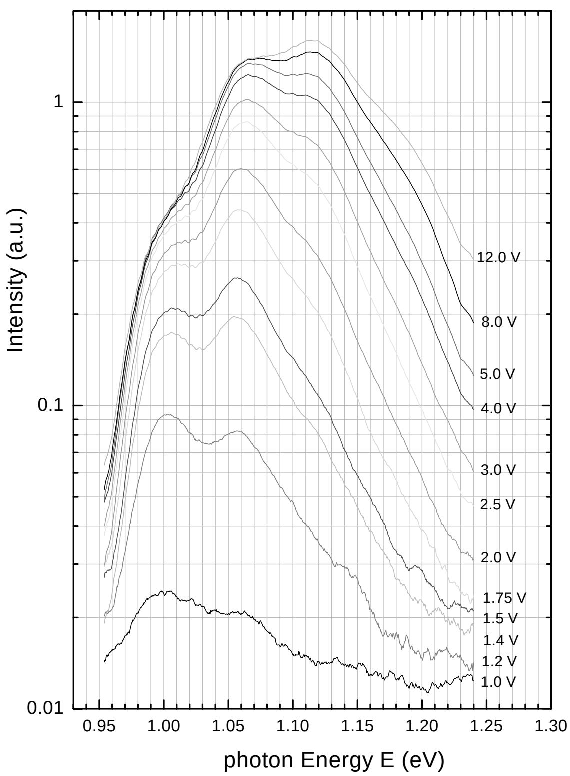

Fig. 4. Room temperature EL spectra from the quantum dot micro-LED for different forward bias.

implantation was performed. This is also confirmed by REM images taken from those regions.

After the processing an electrical characterization of our samples was performed. Our micro-LEDs show good I–V characteristics, with low reverse currents in the range of some microamperes. The conductance of the p-stripes was measured and found to be in good agreement with what we would expect from the hall mobilities for Be-doped GaAs and the stripe geometries (Fig. 3). The model incorporates the depth distribution of the Be ions obtained from secondary ion mass spectroscopy (SIMS). Hall mobilities from FIB implanted material agree very well with mobilities obtained from high-quality p-doped MBE material. We found close to 100% dopand activation in the implanted regions for all implantation doses.

For forward bias we obtain luminescence that strictly remains confined to the cross-sectional area. Fig. 1(c) demonstrates the room temperature operation of our first micro-LED with a (relatively) large cross-sectional area of $10 \times 10\ \mu m^2$. The EL-spectra (Fig. 4) of our first micro-LED show that luminescence starts at 1.0 V, i.e. at $U_{pn} < E_g$ in GaAs and attains about 10% of its maximum value already at 1.4 V. For $U_{pn} < 3$ V only dot luminescence and no GaAs or wetting layer luminescence is observed. Four transitions are observable. Ground state transition occurs at 1.006 eV and the spacing between the different transitions is about 55 meV. With increasing bias the ground state transition and the transition of the first excited state show saturation effects.

4. Outlook

In conclusion, we were able to show that the growth of good quality quantum dots is possible in regions where FIB implantation was performed with doses up to $10^{15}\ cm^{-2}$. We presented first results from our micro-LED and we obtained some promising results already at room temperature. Although we are able to obtain dot spectra from our micro-LED, we have not achieved single-dot spectroscopy yet since still some 10^4 dots can be found in the cross section of $100\ \mu m^2$. However, reducing the stripe widths down to 1 μm or less presents no technological challenge. By using such optimized devices and by performing measurements at low temperature we expect to see interesting results from few or even single dots soon.

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