Bandgap engineering of InAs/InGaAlAs quantum dashes-in-well laser structures: a surface photovoltage spectroscopy study

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Abstract. Room temperature surface photovoltage (SPV) spectroscopy is used to study the interband optical transitions and intermixing processes in InAs quantum-dash-in-InAlGaAs quantum-well structures grown on InP substrates. The intermixing is performed by nitrogen ion implantation followed by rapid thermal annealing at 700°C in nitrogen ambient. The effect of group-III intermixing to the interband optical transition energies in the structures is revealed by SPV spectroscopy and the results are confirmed by photoluminescence measurements. A differential bandgap blueshift as large as 93 meV (176 nm) is observed in the intermixed sample compared to the as grown one. The SPV investigation confirms that this intermixing technique is a powerful tool for achieving the required wavelength of 1.55 µm for telecommunication applications.

1. Introduction

Recently there has been an increasing interest in growing self-assembled InAs dots or dashes on InP substrate in order to achieve emission at wavelength above 1.3 µm [1,2] which is suitable for optical fiber telecommunication, gas sensing and molecular spectroscopy device applications. These quantum dot heterostructures usually emit at around 1.6 µm, while the wavelength required for telecommunication purposes is 1.55 µm. Therefore, for tailoring the material properties, various quantum dot intermixing (QDI) techniques have been utilized, such as impurity free vacancy disordering (IFVD) [3], impurity-induced disordering [4] and laser-induced intermixing [5]. The QDI techniques include as an important step a rapid thermal annealing of the structure, with the annealing temperature being a crucial factor in achieving interface grading and proper performance of the final device. As explained in [4], the nitrogen ion-implantation induced disordering (NIID) requires lower annealing temperatures compared to the IFVD technique, which is a major advantage for monolithic photonic integrated circuits on a single chip. For device applications using QDI, the investigation of the interdiffusion effect on the device characteristics is of prime importance. In this work we apply surface photovoltage (SPV) spectroscopy in order to investigate the absorption properties of NIID interdiffused InAs/InGaAlAs dash-in-well (DWELL) laser structures grown on a InP substrate.
2. Experimental details
The samples used in this study are InAs/InGaAlAs DWELL partial laser structures grown by molecular beam epitaxy. The active region consists of four undoped 5 monolayers (ML) thick InAs quantum dash (QD) layers, each one embedded within a 7.6 nm thick compressively strained In$_{0.64}$Ga$_{0.16}$Al$_{0.2}$As quantum well (QW) with a 15 nm thick tensile strained In$_{0.52}$Ga$_{0.48}$As barrier layer. The QD layers were grown 1 ML at a time, each ML followed by a 5-second growth pause. The growth was terminated after the topmost barrier layer. Between the active region and the substrate a partial separate confinement heterostructure (SCH) layer, consisting of a 160 nm thick undoped In$_{0.52}$Ga$_{0.28}$Al$_{0.2}$As, was grown on top of a 200 nm thick Si-doped (1x10$^{18}$cm$^{-3}$) In$_{0.52}$Ga$_{0.48}$As partial cladding layer. Both layers are lattice matched to the (100) oriented, S-doped (3x10$^{18}$ cm$^{-3}$), InP substrate and they are referred to as “partial” because there are no corresponding complementary layers above the active region. The band structure and the layer sequence are shown in figure 1.

For the intermixing process using the NIID technique, the samples were covered with 1-µm thick SiO$_2$ layer and the N implantation was performed at room temperature with a dose of 5x10$^{12}$cm$^{-2}$ and energy of 1500 keV, introducing the peak defect density center at 0.8 µm below the active region of the structure. This is the so called indirect implantation, which aims to minimize the damage cluster formations in the active region and possible degradation of the optical properties of the samples [6]. The SiO$_2$ layer was then removed using buffered oxide etch solution and the samples were annealed in a rapid thermal processor at 700°C for 2 min with no annealing cap to avoid any possible IFVD effect. The N implantation process and the diffusion of defects during the annealing are represented with arrows in figure 1. For comparison purposes we also studied a control sample annealed at the same conditions, but without ion implantation, as well as an as-grown sample.

The SPV measurements were performed using the metal-insulator-semiconductor (MIS) operation mode [7]. The semitransparent probe was a SnO$_2$ film evaporated on the bottom surface of quartz glass. During the measurement, the SnO$_2$ probe was used to press the sample against a ground copper platform. The optical excitation was performed using a 100 W lamp along with a SPEX grating monochromator ($f$ = 0.25 m, 600 l/mm) and an optical chopper. The probe signal with respect to ground was fed to a high-impedance unity gain buffer and then measured by an EG&G 5207 lock-in.
amplifier. Normally incident light chopped at 94 Hz was used. The light wavelength was scanned from the higher to the lower values keeping the photon flux constant (≈2x10^{14} \text{ cm}^{-2}\text{s}^{-1}) within ±2 % for all wavelengths. More details about the experimental setup and the measurement procedure can be found in [8]. The PL signal was excited by a 532 nm diode pumped solid state laser (1.5 kW cm^{-2}). The PL system used a 3 dB split multimode optical fiber coupler with a 62.5 µm fiber diameter as the signal probe, and a 0.25 m monochromator with an InGaAs photodetector to detect the luminescence. All PL and SPV measurements were performed at room temperature.

3. Results and discussion

The SPV formation processes in these complicated quantum heterostructures are discussed in detail in [9]. In brief, they include electron-hole pair generation, followed by thermal or field assisted tunnelling extraction of the photocarriers from the active region and their redistribution due to the built-in electric field over larger distances in the SCH and cladding layers.

Figure 2 summarizes the SPV and PL results on all the three samples. The SPV spectra are step-like features, whose energy ranges coincide very well with the positions of the corresponding PL peaks. As explained in [9], due to the homogeneous QD size distribution, each SPV steps is composed of a series of broad Gaussians [10] corresponding to the QD ground state as well as excited states optical transitions. The energy position of the ground states transition is in the range of the steep slope of the SPV step, where a weak shoulder can be seen (for the as grown and control samples). It can be determined more precisely from the position of the corresponding PL peak, which has been proven to reveal the ground state position (the peak does not shift with decreasing the excitation density). The PL spectrum of the as-grown and the control samples shows also a few excited state transitions, whose energies are situated in the region corresponding to the flat part of the SPV step.

![Figure 2. SPV (lines) and PL (lines & symbols) of as grown, control and N-implanted samples.](image-url)
Figure 2 shows that there is a total blueshift as large as 93 meV (176 nm) between the as grown and the N-implanted sample, calculated from the SPV step and PL peak positions. It is explained as follows. The N ion implantation introduces vacancies and interstitial defects in the sample, which effectively diffuse towards the active region (see figure 1) to enhance the thermally induced intermixing [6]. The intermixing of group-III atoms (mainly In and Ga) between the InAs QDs and the surrounding InGaAlAs QW modifies the compositional profile from an abrupt interface to a graded one, resulting in an interfacial graded potential. This leads to a blueshift of the bound states and the corresponding transition energies, as explained in [9]. For comparison, the blueshift of the control sample is only 41 meV (80 nm) because the intermixing in this case is due simply to grown-in defects diffusion during the annealing process. The net effect of N implantation is seen from the comparison between the spectra of the control and the N-implanted samples – the differential bandgap shift is also significant, namely 52 meV (96 nm), which proves again the role of the implantation induced defects in the intermixing process. It should be noted that in a previous work [9] we have reported the same amount of blueshift (52 meV) for similar samples but processed with the IFVD technique employing a 100°C higher annealing temperature.

The N implantation also leads to step narrowing in the SPV spectrum (approximately 50%) as well as to PL line width reduction (approximately 40%) as can be seen from the comparison of the spectra of the control and the N-implanted samples on figure 2. This is due to the improved homogeneity of the QD size distribution during the intermixing, which is in accordance with the results in [6]. Another possible reason for this narrowing could be the fact that after the intermixing the QD bound states become closer in energy (the potential well of the QD becomes shallower). This does not allow one to resolve the Gaussians corresponding to the ground and excited states transitions, which results in a smoother SPV step of the N-implanted sample revealing no shoulders (contrary to the SPV spectra of the other two samples).

4. Conclusion

We performed an SPV investigation of the NIID intermixing effect on the optical properties of partial InAs/InGaAlAs DWELL laser structures. The N-implanted sample shows a differential blueshift of 93 meV as compared to the as-grown sample, which shows the potential of the NIID technique for bandgap tuning of monolithic photonic devices using lower annealing temperatures compared to the IFVD technique. The results also highlight the advantages of using SPV spectroscopy as a nondestructive, contactless method to characterize optical transitions in complex semiconductor nanostructures at room temperature.

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