Mid-infrared LEDs using $\text{InAs}_{0.71}\text{Sb}_{0.29}/\text{InAs}/\text{Al}_{0.25}\text{In}_{0.75}\text{As}/\text{InAs}$ Strained-layer Superlattice active layers

C. Van Hoof^a, Š. Németh^{a,h}, B. Grietens^a, K. Dessein^a, J. Genoe^a, P. Merken^a, G. Borghs^a,
F. Fuchs^c and J. Wagner^c

^a IMEC, Kapeldreef 75, B-3001 Leuven, Belgium

^h Microelectronics Department, FEI, STU, Ilkovičova 3, SK-81219 Bratislava, Slovakia

^c Fraunhofer-Institut für Angewandte Festkörperphysik, D-79108 Freiburg, Germany
e-mail: vanhoofc@imec.be

The use of strained-layer superlattices is a well-established technique to lower Auger recombination in the active layers of mid-IR LEDs and lasers. We have shown by temperature-dependent photoluminescence experiments that Auger recombination can be further reduced by incorporating InAs spacer layers inside symmetrically-strained InAsSb/InAlAs superlattices and that the thickness of the spacer is critical for the improved operation. The layers were grown by molecular beam epitaxy on (001) InAs substrates. The crystalline quality of the grown superlattices is demonstrated by means of transmission electron microscopy, atomic force microscopy, and X-ray diffraction measurements.

1. Introduction

Antimony containing A^{III}B^V compound semiconductor heterostructures have recently been of increasing technological interest due to their demonstrated application in a wide variety of high-performance electronic and optoelectronic devices. Especially mid-infrared (mid-IR) light-emitting diodes (LEDs) [1-3] are of interest because of their possible application in optical trace gas sensing and environmental sensing of atmospheric constituents [4]. Emission-wavelengths beyond 2.5 μm require the growth of ternaries such as InAsSb, InGaSb or InAsP on InAs or GaSb substrates. In recent works multiple quantum well (MQW) structures [5, 6] or even strained superlattices (SLS) have been used [7, 8] to achieve the wavelength range from 2 to 8 μm . LEDs operating in the mid-IR region suffer more from non-radiative recombination than LEDs operating in the near infrared region. The main recombination mechanism limiting the performance of mid-IR devices is Auger recombination [9, 10].

Auger processes are intrinsic and can not be suppressed by improving the quality and purity of the grown sample. Furthermore, the Auger rate decreases rapidly either for low temperatures or for high band-gap materials. Therefore the Auger recombination is more important in mid-IR devices than for example in the near-IR devices based on InGaAs strained layers. Quantum confinement has been used to reduce the Auger recombination in mid-IR lasers [11] where the increased effective mass in the growth direction is essential for the reduced Auger recombination. Auger lifetimes can be determined from optical pump-probe experiments [11] but an indirect measure is the reduction in photoluminescence (PL) intensity with increasing temperature [12]: whereas in bulk InAs (or InSb) the reduction in PL intensity between 10K and 100K was measured to be ≈ 25 (30 [13]), in type II n-i-p-i superlattices it was only a factor of 2.5.

2. Experimental procedures

The $\text{InAs}_{0.9}\text{Sb}_{0.1}/\text{InAs}/\text{In}_{0.85}\text{Al}_{0.15}\text{As}/\text{InAs}$ strained superlattices were grown (001) InAs substrates using conventional molecular beam epitaxy (MBE) system. The substrate preparation and growth procedures are described in detail in our work [14]. According to our earlier work, the necessity of precise control of composition and lattice parameters requires a number of test growth and calibration procedures [14]. Four different $\text{InAs}_{0.9}\text{Sb}_{0.1}/\text{InAs}/\text{In}_{0.85}\text{Al}_{0.15}\text{As}/\text{InAs}$ SLSs lattice matched to InAs were grown. The superlattices consist of 30 periods of $d(\text{InAs})$ nm $\text{InAs}/2.5$ nm $\text{InAs}_{0.9}\text{Sb}_{0.1}/d(\text{InAs})$ nm $\text{InAs}/2.5$ nm $\text{In}_{0.85}\text{Al}_{0.15}\text{As}$ where the thickness of the InAs spacer layers $d(\text{InAs})$ varies for the different samples between 0nm, 3nm, 7nm and 12nm.

The strained MQW LED was grown by MBE on a single side polished p^+ doped InAs substrate and consists of the following layers: 100nm InAs p^+ ($3 \times 10^{18} \text{ cm}^{-3}$), SLSs consisting 30 periods of 2.5nm $\text{Al}_{0.25}\text{In}_{0.75}\text{As}$ barriers, 12.5nm InAs spacer layers, 2.5nm InAs $_{0.71}\text{Sb}_{0.29}$ wells, and 12.5nm InAs spacer layers, 2.5nm $\text{Al}_{0.25}\text{In}_{0.75}\text{As}$ barrier, and 200nm InAs n^- ($2 \times 10^{18} \text{ cm}^{-3}$) top contact layer. The InAs spacer layers were grown at 400nm/h, the $\text{Al}_{0.25}\text{In}_{0.75}\text{As}$ layers were grown at 500nm/h, and the InAs $_{0.71}\text{Sb}_{0.29}$ layers were grown at 400nm/h, and the growth temperature was 450°C.

3. Structural and optical characteristics

Fig. 1: 10K PL spectra from four $\text{InAs}_{0.9}\text{Sb}_{0.1}$ / InAs / $\text{In}_{0.85}\text{Al}_{0.15}\text{As}$ / InAs SLSs with varying thickness of the InAs layers. As a reference the PL spectrum from a bulk InAs sample is also plotted.

870nm for d(InAs) = 12nm. Thus the low-temperature peak intensity alone does not substantiate a reduction of the Auger recombination. Therefore PL measurements were performed as a function of temperature.

Table 1 shows the reduction in PL intensity between 10K and 100K for the four samples and the reference bulk InAs sample. Whereas the PL intensity of the reference sample and the SL samples with 0 and 3 nm InAs spacers dropped approximately by a factor of 20, the wider spacer layer resulted in a slowly decreasing PL intensity with increasing temperature (a factor of 2 between 10K and 100K). The full temperature dependent PL intensity plots were also fitted using an expression for the bulk Auger recombination rate and involved only the activation energy for Auger recombination (expressed as a characteristic temperature T_0) as a fitting parameter and the resulting T_0 is added to the table.

Spacer layer thickness (nm)	Emission wavelength (μm)	PL variation between 10K and 100K ($\text{PL}_{10}/\text{PL}_{100}$)	Characteristic temperature T_0 (K)
Bulk InAs	3.05	≈ 25	120
0	2.79	18	115
3	3.29	19	85
8	3.5	2.5	353
12	3.84	1.8	445

Tab. 1: Emission wavelength, PL intensity reduction with temperature and characteristic temperature of the superlattice samples and the reference sample.

The origin of the reduction in Auger recombination is described in our further work [15].

Fig. 2: X-ray diffraction measurements demonstrating the structural quality of the $\text{InAs}/\text{InAs}_{0.67}\text{Sb}_{0.33}/\text{InAs}/\text{Al}_{0.24}\text{In}_{0.76}\text{As}$ SLs.

almost identical. The slight asymmetry of the superlattice diffraction pattern with respect to the InAs substrate reflex means that the whole layer stack is not strain balanced. The individual $\text{InAs}_{0.71}\text{Sb}_{0.29}$ layers show compressive strain of 4.79 % whereas the $\text{Al}_{0.25}\text{In}_{0.75}\text{As}$ layers show tensile strain of about 3.22 %.

The crystalline quality of the grown LED is also confirmed by high-resolution cross section TEM image (Figure 3). The TEM image clearly reveals that the interfaces between each layers are atomically sharp and can be estimated approximately 1 monolayer for all the interfaces. The absence of dislocations in the image proves that dislocation density is lower than about $5 \times 10^4 \text{ cm}^{-2}$. Furthermore the surface morphology of the LED structure was examined by atomic force microscope (AFM). The AFM measurements were conducted under ambient conditions. Although a native oxide layer has been formed on the surface, which is believed to be a few nm thick, the surface morphology remains clearly observable. The observed low value of the rms = 0.3 clearly demonstrates the smoothness of the surface (Figure 4).

Fig. 3: TEM image of an $\text{InAs}/\text{InAs}_{0.67}\text{Sb}_{0.33}/\text{InAs}/\text{Al}_{0.24}\text{In}_{0.76}\text{As}$ SLs.

X-ray diffraction measurements on the grown LED were performed on a diffractometer with Si (440) monochromator crystal using $\text{K}\alpha_1$ radiation. Figure 2 displays the diffraction pattern of a LED structure described above. The presence of a large number of satellite peaks and their narrow peak width demonstrates the high structural quality, in-depth homogeneity and interface sharpness of the sample. Even fringes due to the whole layer stack can be observed near to the InAs substrate reflex. A good agreement between measurement and simulation can be achieved for a layer stack consisting of 30 periods of 12.8nm $\text{InAs}/2.5\text{nm } \text{InAs}_{0.67}\text{Sb}_{0.33}/12.8\text{nm } \text{InAs}/2.5\text{nm } \text{Al}_{0.24}\text{In}_{0.76}\text{As}$. This shows that the nominal and actual layer structures are

Fig. 4: Atomic force microscopy images of an LED surface.

The 10K PL spectrum of the LED active layer is shown in Figure 5. The PL emission peaks at 0.26eV (4.77 μm) and the full-width at half-maximum is only 18 meV. Although the InAs top contact layer is transparent for the emission when operating the device as LED, ap-

Fig. 5: PL spectrum of the LED active layer obtained at 10K.

proximately 80% of the laser pump power is absorbed in the present PL measurement. This accounts for the comparatively lower PL intensity of this sample.

4. Summary

We have shown that Auger recombination can be reduced by incorporating InAs spacer layers inside symmetrically-strained InAsSb/InAlAs superlattices and that the thickness of the spacer is critical for the improved operation. Furthermore mid-infrared DH LEDs for electrical pumping purposes were grown. The excellent quality of the grown material has been demonstrated by means of PL, XRD, AFM measurements and TEM images.

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6. References

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