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Dilute nitride absorbers in passive devices for mode locking of solid-state lasers

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Abstract

We report on the growth, material and nonlinear optical properties of GaInNAs quantum wells (QWs) used in semiconductor saturable absorber mirrors (SESAMs) for passive mode locking of solid-state lasers in the telecommunication wavelength range from 1.3 to 1.55 μm. The antiresonant SESAMs were grown by molecular beam epitaxy with a nitrogen concentration of 1.6% and 2.6%, respectively. They were subject to rapid thermal annealing to fine-tune the absorption wavelength by blueshifting the photoluminescence wavelength. The appearance of QW intermixing upon thermal annealing was studied by X-ray rocking curve measurements. The thermal annealing procedure was proved not to alter the GaInNAs SESAM by QW intermixing for temperatures up to 800 °C. Optical characterization was applied to investigate the nonlinear SESAM properties. Degenerate pump-probe experiments revealed similar recovery times for both SESAMs in the tens of picoseconds range. We demonstrated stable self-starting passive cw mode locking with sub-10 ps pulses at 1314 and 1534 nm.

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1. Introduction

Semiconductor saturable absorber mirrors (SESAMs) are powerful devices to easily self-start and passively cw mode-lock solid-state lasers without the Q-switching instabilities [1,2]. Passive cw mode locking with ultrashort laser pulses below 10 fs was demonstrated with monolithically grown SESAMs in a Ti:sapphire cavity at 800 nm [3]. However, high-quality SESAMs for longer wavelengths (1.3–1.55 μm) remained a challenge due to the lack of a proper material lattice-matched to GaAs-based Bragg mirrors. So far, only SESAMs with highly strained InGaAs quantum wells (QWs) provided absorption in this particular wavelength range. More than 40% indium was needed to match a wavelength of 1.3 μm. The consequence was a high mismatch strain accompanied by an

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increased defect concentration and a reduced surface quality causing insertion losses during laser operation [4]. Recently, dilute nitrides have attracted strong attention for laser devices in the telecommunication wavelength range between 1.3 and 1.55 μm [5,6]. Alloying a few percent of nitrogen to InGaAs has two advantages: a redshift of the absorption wavelength and a reduction of the lattice mismatch to GaAs. The drawback is that the nitrogen incorporation decreases the crystalline quality, which is a big challenge for the fabrication of active devices. However, SESAMs are passive devices relying on fast defect-induced nonradiative carrier recombination to allow for short pulse generation. GaInNAs SESAMs for 1.3 and 1.55 μm have been successfully fabricated lately [7–9]. In fact, we were able to demonstrate their superior properties in terms of low losses and low saturation fluence at 1.3 μm and to provide a comprehensive study of their nonlinear optical properties [7]. In this paper, we now report on the growth and material properties of GaInNAs SESAMs at both 1.3 and 1.55 μm telecommunication wavelengths. All SESAMs had fast recovery times and demonstrated stable self-starting passive cw mode locking of solid-state lasers with sub-10 ps pulse durations.

2. Experimental procedure

$Ga_xIn_{1-x}N_yAs_{1-y}$ single QW and SESAM devices with $x = 0.65$ and $y = 0.016$ and 0.026, respectively, were grown by molecular beam epitaxy in a GEN III system using gallium and indium solid sources, an arsenic valved cracker and a nitrogen RF plasma source. A growth temperature of about 450 °C monitored by diffused reflectance spectroscopy (DRS) was applied. Reflection high-energy electron diffraction (RHEED) was used to qualitatively evaluate in situ interface properties and growth mode. X-ray rocking curve (XRC) and photoluminescence (PL) measurements at room temperature were carried out to verify stoichiometry, crystallinity and device design. Post-growth ex situ rapid thermal annealing (RTA) was applied to the samples at 600–800 °C for 1 min under N_2 flow. The samples were capped with GaAs pieces to avoid evaporation of arsenic from the sample surface.

Single QW samples consisted of a 10-nm GaInNAs QW capped with 65 nm GaAs. Two antiresonant GaInNAs SESAMs were grown on differently centered distributed Bragg reflectors (DBRs). The first SESAM consisted of a 30-pair AlAs/GaAs (DBR) centered at 1290 nm, a 79-nm GaAs spacer layer, a 10-nm GaInNAs saturable absorber layer with 1.6% N, and a 122-nm GaAs cap layer. The second SESAM consisted of a 35-pair AlAs/GaAs DBR centered at about 1590 nm, an 80-nm GaAs spacer layer, a 10-nm GaInNAs saturable absorber layer with 2.6% N, and a 134-nm GaAs cap layer. Both GaInNAs SESAMs were subject to RTA at 600 and 550°C, respectively, in order to shift the PL emission wavelength to the desired wavelength range for laser testing, i.e. 1330 and 1556 nm, respectively.

Degenerate pump-probe experiments were performed using 80 MHz, 280 fs pulses from a commercial optical parametric oscillator (OPO) at 1314 nm and 61 MHz, 5 ps pulses from Er:-Yb:glass laser (ERGO) at 1534 nm to observe the time response of the SESAMs. Laser performance was tested in a Ti:sapphire–pumped Nd:YLF standard delta cavity at 1314 nm and in a 61 MHz ERGO at 1534 nm.

3. Results and discussion

GaInNAs QWs and SESAMs were grown at the same growth temperature with the same indium content but different nitrogen fluxes. The increasing amount of incorporated nitrogen decreased the lattice mismatch, and the shallow QW peak in the XRC spectrum moved closer to the GaAs substrate peak as shown in Fig. 1. The lower nitrogen concentration of about 1.6% corresponded to an as-grown PL emission wavelength of about 1370 nm while the incorporation of about 2.6% nitrogen shifted the PL wavelength to about 1580 nm. For GaInNAs with 1.6% N, two-dimensional growth was observed by RHEED throughout the whole QW, while a further increase in the nitrogen content caused some roughening of

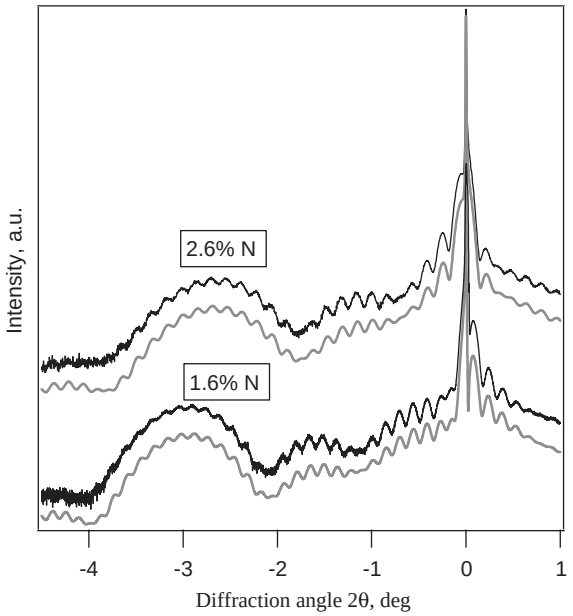


Fig. 1. XRC spectra (black line) and fit (grey line) of a GaInNAs quantum well with 1.6% N and 2.6% N, respectively. Measured spectra and fits are offset for purpose of better illustration.

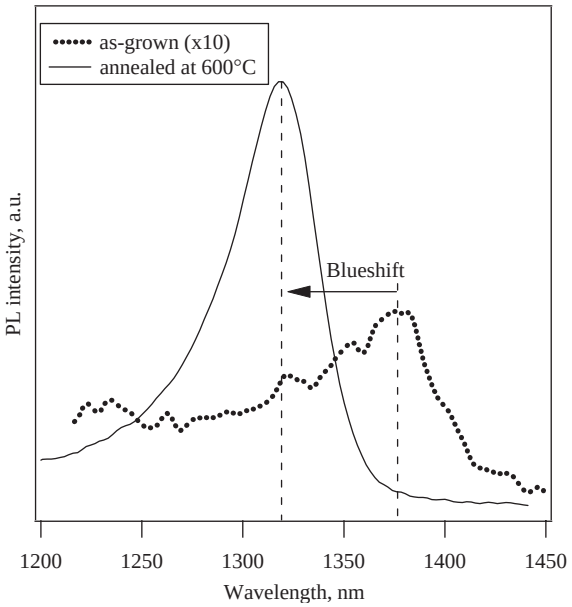
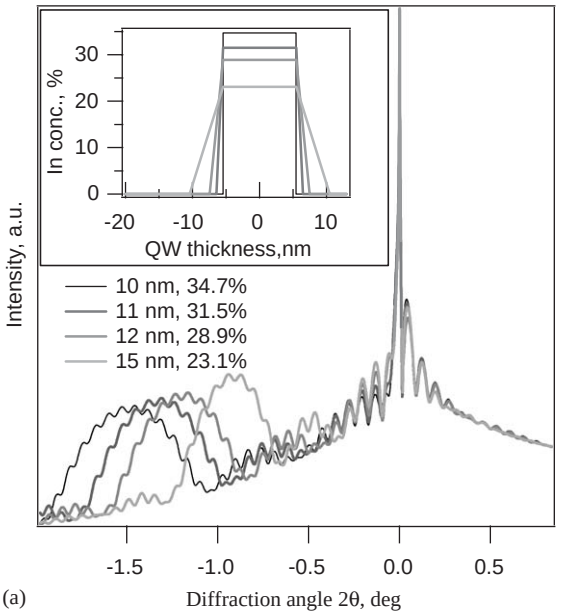


Fig. 2. PL blueshift of about 50 nm for a GaInNAs QW upon RTA at 600 °C for 1 min.

the growth interface towards the end of the QW growth.

RTA generally improved the crystal quality as observed by an increase in the PL intensity. Samples containing 1.6% N showed higher PL intensities upon annealing than samples with 2.6% N. In addition, thermal annealing blueshifted the as-grown PL wavelength as shown in Fig. 2. This wavelength blueshift can be attributed to a nearest neighbour reconfiguration [10] and/or QW intermixing. However, QW intermixing would alter the QW thickness and stoichiometry. Detailed information would be necessary for proper device design. The inset of Fig. 3a presents a simulation of concentration profiles for indium, which diffused out of a GaInNAs QW. The indium concentration in the original QW decreased from about 35% to about 23% with ongoing diffusion while the FWHM of the QW thickness increased from initially 10 to 15 nm. In Fig. 3a, the corresponding XRC simulations are shown. A distinct change in the QW peak position can already be observed for very small amounts of indium diffusing out of the QW and hence allows for a sensitive analysis of diffusion after annealing. In Fig. 3b, XRC spectra of GaInNAs QW samples together with their fits before and after annealing at different temperatures are presented. We did not observe any change for RTA temperatures up to 700 °C. Only at 800 °C, the XRC spectrum changed due to the fact that arsenic evaporated from the surface. The thickness of the GaAs cap layer was reduced from 65 to 3 nm according to the fit of the XRC spectrum. However, the QW peak itself did not experience any change. Therefore, the PL blueshift is assumed to be caused by a change in the nearest neighbour configuration and not by QW intermixing.

The temporal decay obtained from pump-probe experiments is a measure for the defect concentration related to carrier trapping. Fig. 4 shows the normalized time response of the annealed anti-resonant SESAMs. Interestingly, the temporal decay is with 20–30 ps, similar for both SESAMs. Since the increase in the PL intensities after annealing was smaller for samples with higher nitrogen content a much larger difference in the trap concentration was expected. The similarity in



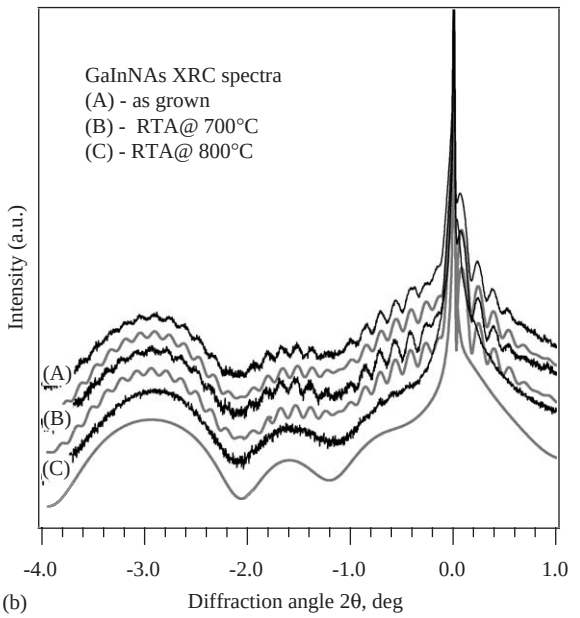


Fig. 3. (a) Simulated XRC spectra for different In concentrations and FWHMs of GaInNAs QW thickness based on the concentration profiles given in the inset. Inset: Concentration profiles of indium diffusing out of a GaInNAs QW upon thermal annealing. With increasing diffusion the In concentration in the QW decreased while the FWHM of the QW became larger. (b) Measured XRC spectra with the corresponding fit for as-grown and differently annealed GaInNAs QW samples.

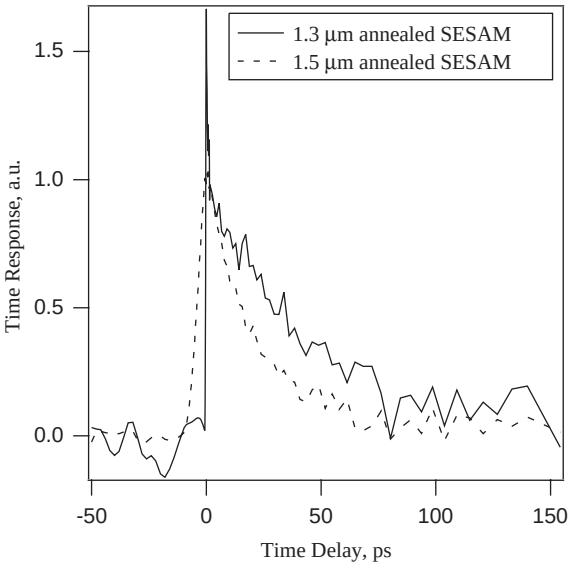


Fig. 4. Time response of two antiresonant GaInNAs SESAMs. 1.3-μm SESAM: measured with 280-fs pulses at 1314 nm; 1.5-μm SESAM: measured with 5-ps pulses at 1534 nm.

the recovery time pointed out that additional incorporation of 1% nitrogen did not create a significantly higher defect concentration relevant for recovery from absorption saturation after annealing.

The performance of the SESAMs was tested in a Nd:YLF:laser and Er:Yb:glass laser, respectively. We obtained clean stable self-starting fully passive cw mode locking with both SESAMs. Pulse durations as short as 6.7 ps at 1314 nm and 5 ps at 1534 nm fitted with a sech^2 function were measured. These short pulses are well-suited for fast data transmission in 1.3- and 1.5-μm telecommunication systems.

4. Summary

In conclusion, we fabricated antiresonant GaInNAs SESAMs for the telecommunication wavelength range from 1.3 to 1.55 μm. The SESAMs differed in their nitrogen concentration to match the desired wavelength. They were subject to rapid thermal annealing to fine-tune the absorption wavelength. The thermal annealing procedure was proved not to alter the GaInNAs SESAM

by QW intermixing for temperatures up to 800 °C. Optical characterization provided a similar recovery time for both SESAMs in the tens of picoseconds range. We demonstrated stable self-starting passive cw mode locking with sub-10 ps pulses at 1314 and 1534 nm.

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