Antimonide semiconductor saturable absorber for 1.5 µm

R. Grange, O. Ostinelli, M. Haiml, L. Krainer, G.J. Spühler, M. Ebnöther, E. Gini, S. Schön and U. Keller

Self-starting continuous-wave passive modelocking of an Er:Yb:glass laser at 1535 nm is demonstrated with the first antimonide semiconductor saturable absorber mirror (SESAM). The Er:Yb:glass laser produces 20 ps pulses at 61 MHz. This laser was used to characterise the nonlinear optical parameters of the metal organic vapour phase epitaxy grown SESAM.

Introduction: Broadly tunable pulse generating laser sources around 1.55 µm are required for telecomms applications. However, working semiconductor saturable absorber mirrors (SESAM)s [1] at this wavelength are more challenging, especially for high repetition rate lasers [2]. In contrast to fibre lasers [3–5], modelocking of low gain solid-state lasers (such as Er:Yb:glass) requires low modulation depths of the nonlinear reflectivity to overcome Q-switching instabilities [6]. AlGaAsSb is a novel long-wavelength semiconductor saturable absorber material with wide bandgap tunability. Lattice-matched to InP, its bandgap varies from 0.8 to 2.3 eV with increasing Al content. In contrast to InGaAsP lattice-matched to InP, the absorption edge of AlGaAsSb is not as steep [7, 8]. Therefore, it enables the modulation depth to be chosen to be as small as required by operating the absorber in the pronounced band tail, which is not present in the InGaAsP system. So far, antimonides have been grown by molecular beam epitaxy (MBE) mainly on GaSb substrates [9], and only recently the more challenging metal organic vapour phase epitaxy (MOVPE) growth of an AlGaAsSb/InP distributed Bragg reflector (DBR) on InP substrate was achieved [10]. In this Letter, we demonstrate the first AlGaAsSb SESAM. The device passively modelocked a 60 MHz Er:Yb:glass laser.

Design and growth parameters: The antimonide SESAM is based on 60 Bragg pairs of InP/InGaAsP grown on an InP (100) substrate by an AIX 200/4 MOVPE. On top of the DBR a 100 nm InP spacer layer, a 10 nm $Al_{0.04}Ga_{0.96}As_{0.52}Sb_{0.48}$ absorber (nominal stoichiometry), and a 10 nm InP cap layer were grown with H_2 atmosphere at 100 mbar and 565°C. Phosphine (PH_3), arsine (AsH_3), trimethylantimony (TMSb), trimethylindium (TMIn), trimethylgallium (TMGa) and trimethylaluminum (TMAl) were used as precursors. The antimonide absorber was grown at a ratio between the group V and group III elements (V/III) below 1. Growth rate calibration was carried out by online reflectance spectroscopy (EPI–R) and X-ray diffraction (XRD) on test structures. Note that photoluminescence (PL) spectra of the SESAM are strongly affected by the underlying DBR. Therefore, PL spectra were taken from AlGaAsSb test structures of about 110 nm thickness on plain InP substrates. They showed emission peaks around 1.5 µm with a full width at half maximum (FWHM) of about 150 nm at room temperature.

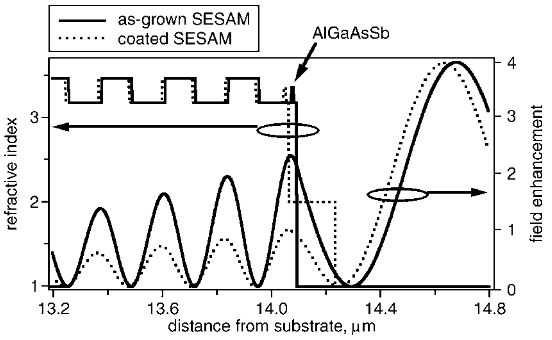

Fig. 1 *Refractive index and field enhancement of as-grown and coated SESAMs*
Bulk refractive indexes at 1535 nm used for calculations: $n_{InGaAsP} = 3.46$, $n_{InP} = 3.17$, $n_{AlGaAsSb} = 3.35$

The as-grown SESAM is partially resonant with a field enhancement in the absorber of 2.30 at 1535 nm, which means that the square of the electric field in the absorber is 2.3 times higher than the square of the incident field. The intensity in the absorber with refractive index 3.35 is consequently 7.7 times higher than the intensity of the incident beam. A 170 nm SiN_x single-layer coating was deposited by plasma enhanced chemical vapour deposition (PECVD) to decrease the field enhancement in the absorber down to 0.98 (Fig. 1), which is more suited for operation in our Er:Yb:glass laser. The small shift between the two designs is due to a slightly different radial layer thickness across the wafer.

Optical characterisation: Knowledge of the nonlinear optical SESAM characteristics at given pulse parameters is essential to evaluate the behaviour of the device in the laser cavity and to optimise both accordingly. To perform the measurement of the typical macroscopic parameters of a SESAM (saturation fluence, modulation depth, nonsaturable losses and recovery time) [11], we use the output of the modelocked laser with the coated AlGaAsSb absorber (see laser performance below). Using this source, we obtain the exact parameters of the SESAM performing in the laser cavity [12]. Fig. 2 shows for the as-grown and the coated design a modulation depth of 1.46 and 0.65%, low nonsaturable losses of 0.02 and 0.28% with an estimated error of ± 0.05% and a saturation fluence of 34 and 47 µJ/cm^2, respectively. Further adjustment of the AlGaAsSb absorber composition should allow for even smaller modulation depths.

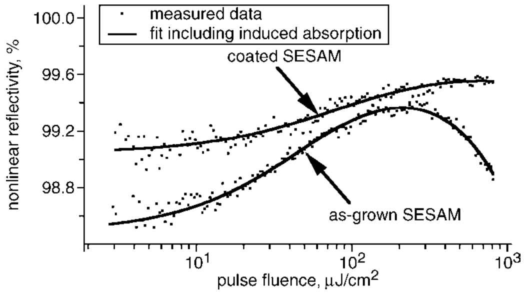

Fig. 2 *Nonlinear reflectivity against incident pulse fluence of as-grown and coated SESAMs*

Fig. 3 shows the standard pump-probe measurements with a recovery time of about 125 ps for the slower part of a double exponential fit. Note that even decay times of about 100 ps are sufficient to modelock multi-GHz lasers [13]. Nevertheless, we have already grown AlGaAsSb absorber layers on plain substrates with increased defect densities and sub-picosecond decay times. We will apply these growth conditions to AlGaAsSb absorbers on DBRs to optimise the recovery time.

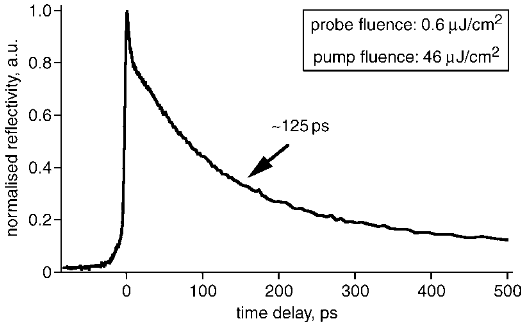

Fig. 3 *Measured recovery time of as-grown SESAM with standard pump-probe setup*

Laser performance: Stable modelocking was obtained with both as-grown and coated SESAMs. The microwave spectra in Fig. 4 demonstrate clean CW modelocking without Q-switching instabilities [6] at a repetition rate of 60.7 MHz with the coated SESAM. A sech^2-pulse duration of 20 ps was measured at a central wavelength of 1535 nm (Fig. 5). An average output power of 80 mW with 630 mW incident pump power was obtained with the coated SESAM and a 3% output coupler. Replacing the SESAM with a high reflector resulted in an output power of 89 mW, demonstrating the low losses of the antimonide SESAM. No degradation of the SESAM was observed over several hours, which provides a stable source that was used for several experiments (recall that we performed our optical characterisation with this laser source).

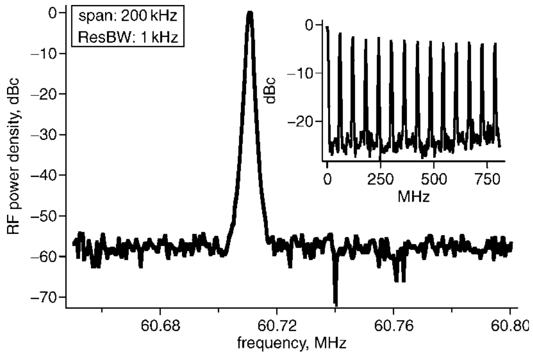

Fig. 4 *Microwave spectra span 200 kHz (1 kHz ResBW)*

Inset: Span: 800 MHz (1 MHz ResBW)

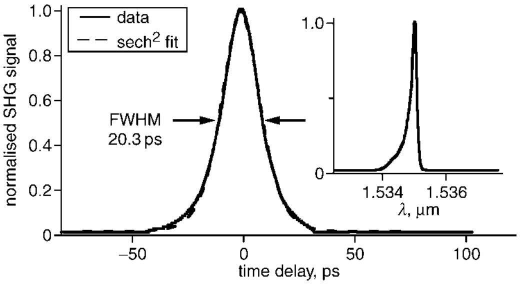

Fig. 5 *Autocorrelation signal*

Inset: Optical spectral density against wavelength

Conclusions: We have grown and characterised the first antimonide SESAM. AlGaAsSb is a very promising material for long wavelength nonlinear optical device applications. The strongly broadened bandedge can be exploited for saturable absorber designs lattice-matched to InP. The MOVPE grown device with AlGaAsSb absorber on an InGaAsP/InP Bragg mirror self-started stable passive modelocking of a 1.5 µm Er:Yb:glass laser. Investigation of test structures with different compositions and growth parameters will be applied to optimise future SESAMs for shorter pulse durations and higher repetition rates.

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R. Grange, M. Haiml, L. Krainer, G.J. Spühler, S. Schön and U. Keller (*Ultrafast Laser Physics, Institute of Quantum Electronics, Swiss Federal Institute of Technology (ETH), Wolfgang-Pauli-Str. 16, 8093 Zürich, Switzerland*)

O. Ostinelli (*Avalon Photonics, Badenerstrasse 569 PO Box, 8048 Zürich, Switzerland*)

M. Ebnöther and E. Gini (*FIRST Center for Micro- and Nanoscience, Swiss Federal Institute of Technology (ETH), Wolfgang-Pauli-Str. 10, 8093 Zürich, Switzerland*)

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