1 μm saturable absorber with recovery time reduced by lattice mismatch

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(Received 15 March 2006; accepted 13 July 2006; published online 18 August 2006)

Metamorphic growth of lattice mismatched InGaP on GaAs has been used to fabricate a fast semiconductor saturable absorber mirror operating at the 1060 nm wavelength range. The absorption recovery time could be reduced to ~5 ps without deteriorating the nonlinear absorption properties. The device was used to demonstrate self-starting operation of a mode-locked Yb-doped fiber laser and obtain high quality picosecond pulses. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2337278]

Semiconductor saturable absorber mirrors (SESAMs) are increasingly used to passively mode-lock a large variety of lasers.[1,2] In particular, mode-locked fiber lasers based on SESAMs are attractive due to their compact size, simple architecture, environmentally stable operation, and moderate cost. For efficient and self-starting mode locking, the absorption recovery time should attain values in the range of a few picoseconds to a few tens of picoseconds depending on the properties of the gain medium and the laser cavity design. An important aspect in controlling the absorber recovery time is the setting up of an optimal value for the absorber speed that provides the best self-starting capability and stability of the passive mode locking in a specific laser.[3] In particular, for very small recovery times, long pulses are insufficiently shaped and the start-up time increases dramatically with an increase in the absorber speed. On the other hand, with very long recovery times, the quasi-cw spontaneous radiation starts to saturate the absorber, thus decreasing its effective modulation depth and degrading its self-starting capability. This effect is especially strong in fiber lasers because of the high level of intracavity amplified spontaneous emission.

The recovery time of absorption in lattice-matched materials, typically used in SESAM growth, is of few hundreds of picoseconds or even nanoseconds. Therefore, the fabrication process of SESAMs includes special measures to reduce the recovery time. Amongst these, the most used are the low-temperature growth[4] and the ion irradiation.[5] Each of these techniques brings in certain tradeoffs related to fabrication complexity, degradation of the optical properties, and accuracy of tuning the recovery time to desired values. Recently, we have demonstrated an alternative solution for decreasing the absorption recovery time of 1.55 μm semiconductor saturable absorbers.[6] The method is based on controlling the crystalline quality of the absorbing material and thus the density of nonradiative recombination centers that are responsible for the fast response of the absorption. As an instrument to induce lattice defects within the active region we have used metamorphic growth of InP on GaAs. The absorption recovery time was controlled by changing the thickness of an InP "lattice reformation layer" grown on the GaAs-based distributed Bragg reflector (DBR) prior to the InGaAs/InP lattice-matched absorbing region. The method does not require any postgrowth technological actions and has the advantage of using high quality broadband GaAs/AlAs DBRs and GaAs substrates. In this letter, we extend the technique of reducing the recovery time via lattice mismatch management on another material system and demonstrate a fast SESAM operating at ~1060 nm.

Two SESAMs, termed SESAM 1 and SESAM 2, were grown by all-solid-source molecular beam epitaxy on *n*-GaAs (100) substrates. The generic structure of the SESAMs is presented in Fig. 1. The DBR consisted of 25 AlAs/GaAs pairs and had a stop band centered at 1.06 μm in both structures. An 80-nm-thick InGaP layer lattice mismatched to GaAs was used for introducing nonradiative re-

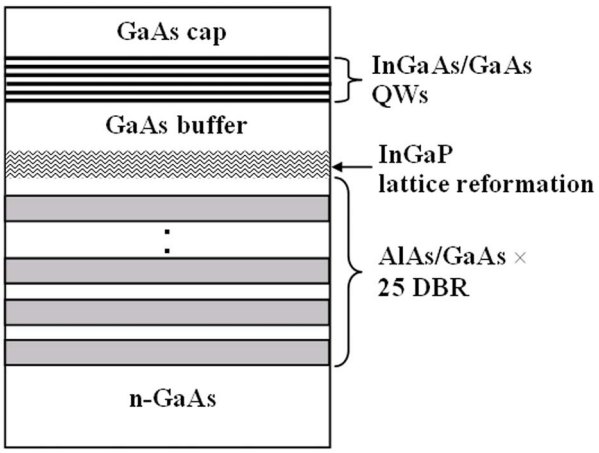

FIG. 1. SESAM structure with the absorption recovery time controlled via lattice mismatch engineering.

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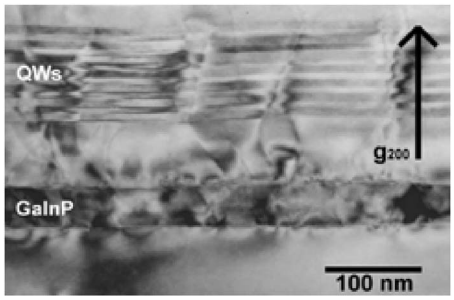

FIG. 2. TEM [200] bright field image of SESAM 1 from the lattice reformation layer, GaAs buffer, and QWs.

combination centers within the absorption region through misfit and threading dislocations. We should note that a high density of dislocations may result in excess loss and reduced nonlinearity. Therefore, the amount of defects should be limited to the level required for achieving the desired speed of the absorption recovery time. In the approach proposed here, the defect density within the active region can be controlled by both the lattice mismatch between the InGaP and GaAs and by the thickness of the GaAs buffer layer grown on InGaP before the quantum-well absorbing region. In our experiment the lattice mismatch between InGaP and GaAs that meet the aforementioned strategy was ~2.2%. The thickness of the GaAs buffer was 110 nm for SESAM 1 and 570 nm for SESAM 2. The absorption region comprised 7-nm-thick InGaAs/GaAs quantum wells (QWs) with photoluminescence peaked at 1080 nm. The structures were capped with GaAs.

The crystallographic lattice perfection of the SESAMs were studied by cross-sectional transmission electron microscope (TEM) using [200] bright field imaging and a Jeol JEM 2010 microscope. The TEM samples were prepared by mechanical polishing followed by Ar^+-ion milling. As expected, the TEM micrograph shown in Fig. 2 reveals the presence of lattice defects that propagate from the InGaP layer towards the quantum-well absorber. These defects act as fast nonradiative recombination centers reducing the absorption recovery time. For measuring the recovery time we have used a degenerate pump-probe setup.[7] These measurements were performed near the stop band center wavelength of the DBR. As shown in Fig. 3, the recovery time constants

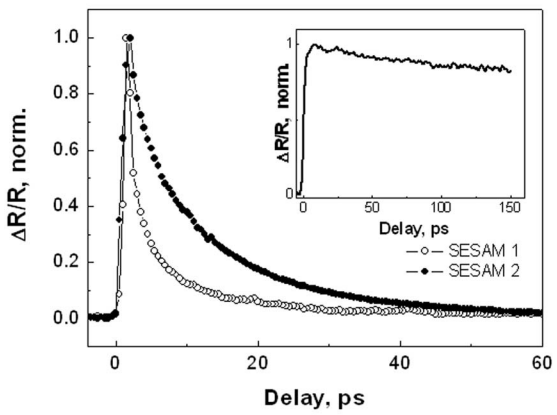

FIG. 3. Time resolved reflectivity response of SESAMs 1 and 2. Inset: recovery time for a typical "slow" SESAM structure without InGaP lattice reformation layer.

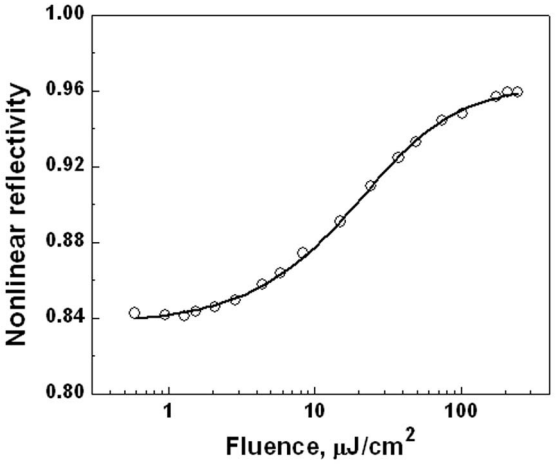

FIG. 4. SESAM 2 reflectivity as a function of the incident pulse energy fluence.

derived using single-exponential fitting are 4.9 ps for SESAM 1 and ~9.8 ps for SESAM 2. The longer recovery time of SESAM 2 could be explained by a smaller defect density in the quantum-well region owing to a thicker GaAs buffer layer. It is expected that by further increasing the thickness of the GaAs the recovery time would increase. However, we should note that thick buffers would inherently increase the length of the Fabry-Pérot cavity defined by the bottom DBR and top surface of the structure. This in turn would correspond to a small free-spectral range between the Fabry-Pérot resonances that could impair the mode-locking operation. For comparison, we have also measured the absorption recovery time for a SESAM structure with an active region similar to SESAMs 1 and 2 but without InGaP layer. In this case the characteristic time was longer than 200 ps, as shown in the inset of Fig. 3. The nonlinear reflectivity variation for the fast SESAM 1 measured at 1060 nm is shown in Fig. 4. By fitting the experimental data with a two-level saturable absorption model,[3] we have derived the values for the modulation depth ($\Delta R = 12\%$), saturation fluence ($F_{sat} = 13\ \mu J/cm^2$), and nonsaturable losses ($\alpha_0 = 3.8\%$). We should note that we have not observed any measurable degradation in the optical properties for the fast SESAM com-

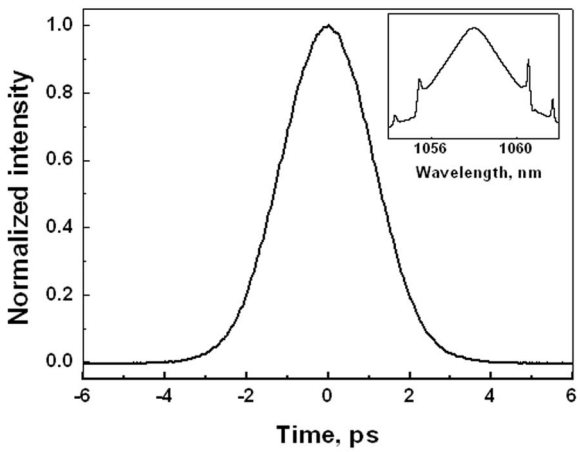

FIG. 5. Intensity autocorrelation traces of mode-locked pulses. Inset: corresponding optical spectrum.

pared to a slow structure (without InGaP layer).

To examine its performance to passively mode-lock a fiber laser, the fast SESAMs were used as end mirrors in an Yb-doped fiber laser cavity. The average cavity dispersion was set in the anomalous dispersion regime by a grating pair compensator. It was found that both fast SESAMs could reliably start passive mode locking resulting in pedestal-free 2.3 ps pulses. The pulse shape and the corresponding optical spectrum are shown in Fig. 5. To the contrary, the same laser could not be mode locked by a standard slow SESAM.

To investigate the stability of the SESAM parameters we have performed a rapid thermal annealing (RTA) at 400 °C for different times. This would eliminate the short-lived defects[8] and ensure reliable long-term operation. The measurement of the recovery time did not show any significant change after RTA, as can be inferred from Fig. 6. Thermally annealed samples were further tested in the fiber laser setup described previously. The mode-locked operation with annealed and as-grown samples showed similar behavior. However, to accurately verify the long-term stability of the samples when they are used within a mode-locked laser cavity, we would need to perform prolonged measurements.

In conclusion, we have demonstrated a method to fabricate fast SESAMs at 1060 nm by using metamorphic growth of InGaP on GaAs. This technology allows for reducing the absorption recovery time to picosecond level without degradation of the optical properties. The device was used to demonstrate self-starting operation of a mode-locked fiber laser and obtain high quality picosecond pulses.

This work is supported by the Finnish Academy of Sciences within the TULE-QUEST research program. The authors would like to thank Olli Tengvall for his support in fabricating the structures.

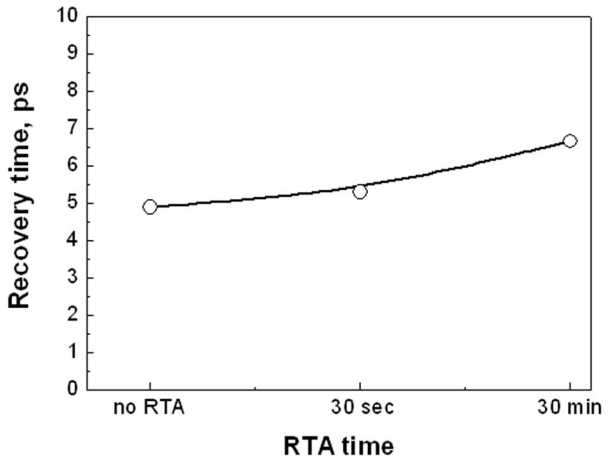

FIG. 6. Variation of the absorption recovery time with variation of annealing time.

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