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LT-InGaAs Layer Grown for Near Surface SESAM Application

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We have developed a mode-locked diode-pumped Yb:KYW laser generating nearly band-width limited pulses as short as 101 fs using semiconductor saturable absorber mirror (SESAM). With the nonsaturable losses of 1.94% and the modulation depth of 1.48% the self-starting and stable mode-locking was observed. The nonsaturable losses are mainly related to As^0_{Ga}-CB transitions in InGaAs QW absorbing layer and low temperature defects. Low temperature defects are eliminated by using higher growth temperature and lower ratio of group V to group III beam equivalent pressure than typically used. The InGaAs layer was grown by molecular beam epitaxy at the temperature as high as 420 °C, under the V/III ratio as low as 10. No annealing was performed.

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1. Introduction

Semiconductor saturable absorber mirrors (SESAMs) suitable for ultrashort laser pulse generation require absorbing materials with a fast temporal response of the nonlinear saturable absorption and low nonsaturable absorption. Such feature which allows to obtain sub-ps response time exhibit epitaxial layers MBE grown at low substrate temperature (LT) under As-rich conditions [1]. The low temperature range is 220–350 °C and the value of V/III ratio is close to 20 [2]. It results in generation of the As antisite defects: the minority of ionized As^+_{Ga} and the majority of neutral As^0_{Ga}. Only the ionized As antisites act as the electron traps in the absorber material, which efficiently decrease the currier nonradiative recombination lifetime [3]. The absorption due to carrier excitation from the neutral As antisites to the conduction band (As^0_{Ga}-CB) is a major contribution to the parasitic nonsaturable losses [4]. The rest of absorption seems to be intimately related to the LT growth since it increases with As^0_{Ga} density. The lower growth temperature results in faster carrier trapping rate caused by higher As^+_{Ga} density but on the other hand it leads to higher total nonsaturable absorption due to higher density of As^0_{Ga} and other LT defects. Thus a compromise has to be found. There are two ways to reduce the nonsaturable absorption in the LT layers: optimisation of the growth condition itself and post growth annealing which is commonly used. Annealing of LT layers strongly reduces the density of the neutral As antisites and then total nonsaturable losses are related to the LT defects. However annealing deteriorates the interface sharpness and may cause the generation of the misfit dislocations in pseudomorphic absorber layer due to the plastic relaxation of the crystal.

The goal of our work was the optimisation of the (quantum well) QW absorber growth which allows to avoid annealing and to generate low but sufficient density of As antisite defects for fast trapping and recombination of electrons and simultaneously for strong reduction of the LT defect density.

2. Experiment

The heterostructures were grown in 32P RIBER MBE system on (100) oriented semi-insulating GaAs substrates. The growth temperature was controlled by a pyrometer and a thermocouple simultaneously. The samples were designed to investigate the influence of growth temperature T_G, V/III ratio and the interruption time t_I at the GaAs/InGaAs/GaAs interfaces on the response time of the InGaAs QW absorber layer.

The QW heterostructures consisted of 8 nm $In_{0.26}GaAs$ followed by 300 nm GaAs buffer layer and capped by 35 nm GaAs layer. The growth temperature of the buffer and cap GaAs layers was 530 °C and V/III ratio was 5. The varied epitaxial parameters of QW heterostructures such as the growth temperature T_G, V/III ratio and the interruption time t_I are listed in Table I.

In SESAM, the growth of absorbing region of 8 nm $In_{0.26}GaAs$ layer was performed by applying parameters optimized during the QWs investigations. In the growth direction the SESAM structure contains a 24-pair AlAs/GaAs distributed Bragg reflector (DBR), the

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TABLE I

Epitaxial growth parameters of the SQW and SESAM structures.

Samples	T_G [°C]	V/III	t_I [min]
QW1	450	5	3
QW2	450	6	3
QW3	450	7	3
QW4	450	8	3
QW5	420	6	3
QW6	420	10	4
QW7	400	10	4
QW8	400	9	6
SESAM	420	10	4

top quarter-wavelength layer of GaAs is extended by approximately an additional quarter-wavelength layer. The $In_{0.26}GaAs$ absorber layer is placed just beneath the surface and capped only by 5 nm GaAs layer. The structure is completed by the low-refractive index dielectric quarter-wave layer of SiO_2.

3. Results and discussion

The growth temperature of QW samples was chosen to be higher than the onset of the precipitation formation, which is commonly recognized at about 400 °C [5, 6]. It allows to assume that both As^0_{Ga} defects and the precipitations occur in the QW material grown under As excess conditions.

The transition energy of QW controlled by photoreflectance measurements is in a range of $1050 \div 1080$ nm.

The quantitative data on the carrier recombination in the analyzed QW were obtained by time resolved photoluminescence (TRPL). The applied TRPL technique is capable for measurements of carrier lifetimes as short as ≈ 10 ps [5, 7]. The measurements were performed using a mode locked Ti:sapphire laser emitting at 800 nm. The pulse duration is below 100 fs, and the repetition rate amounts to ≈ 82 MHz. The PL transient is detected by a synchro-scan streak-camera system equipped with an infrared enhanced cathode. From the measured data, we extract PL decay curves such as presented in Fig. 1a–c.

Time constants obtained by fitting these transients are given in Table II. Let us note that ≈ 8.0 ps for QW6–QW8 represents the present time resolution limit of the setup.

The measured results may be divided into two groups depending on their character. In the first group containing QW1–QW4 grown under low V/III ratio and at high temperature, two type of electron traps coexist: precipitates and ionized defects but the dominant ones are As^+_{Ga} defects. The photoexcited carriers at first are trapped at defects, which is described by "fast decay" constant. After, when the traps are saturated, part of captured

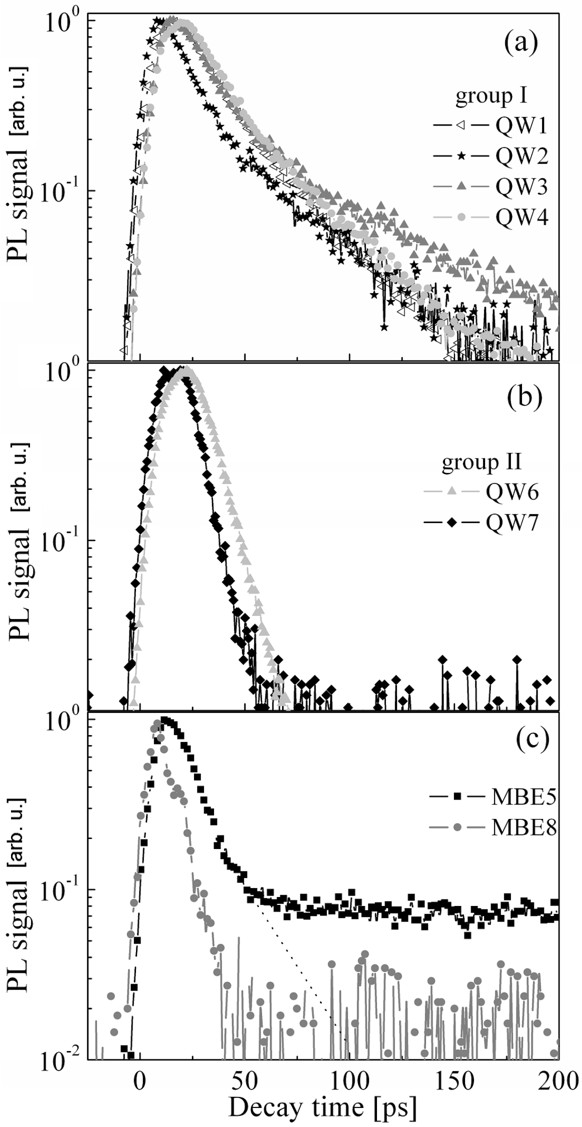

Fig. 1. PL transients for low temperature InGaAs QWs with "long" (a), "short" (b) and untypical (c) decay time.

electrons recombine with holes and the As^+_{Ga} traps become available to capture additional electrons from the conduction band. It leads to emptying of the conduction band and the PL transients approach zero, which represents "slow decay" constant. The small differences in V/III ratio during the growth produce negligible changes in the As^+_{Ga} defect densities in QWs.

The further reduction of the decay time from about 24 ps to 8 ps is obtained for second group of QWs (Fig. 1b). This is achieved by simultaneous decrease of the growth temperature from 450 °C to 420–400 °C, the increase of V/III ratio from 5 to 10 and the increase of the interruption time from 3 min to 4 min. Here the PL transients suffer from the absence of the slow-time component of the decay. It can be explained by the dominant role

TABLE II

The components of temporal responds of InGaAs QW layers.

Sample	"Fast" decay time [ps]	"Slow" decay time [ps]
QW1	20.0	32.6
QW2	17.4	43.5
QW3	21.7	60.9
QW4	23.9	39.1
QW5	14.8	"very" long
QW6	8.3	not present
QW7	7.4	not present
QW8	7.8	not present

of precipitations in the recombination processes. Lower growth temperature stimulates the As incorporation as the As_{Ga} antisite point defects and longer interruption time causes the increase of precipitation density. Then the density of the trap states for the electrons is sufficient to empty the conduction band of the InGaAs absorber without the long-time saturation effect.

Temporal responds of QW5 and QW8 differ from analysed characteristics. In case of QW5 sample, the "slow component" is represented by the straight line and the transient does not approach "zero". It is not understandable. The "fast component" of QW8 sample consists of three parts. It may indicate on three types of carrier traps but a quantitative analysis employing other measuring techniques as deep level transient spectroscopy (DLTS) is needed to confirm this hypothesis.

The shortest decay time of about 8 ps registered for QW6 and QW7 heterostructure is longer than reported for annealed LT-GaAs layers. The typical electron trapping time for annealed LT-GaAs used in SESAM structures is between 0.2 and 1.0 ps [8]. To increase the traps density but simultaneously to avoid the annealing drawbacks, we have proposed the indirect approach for SESAM performance. First, the InGaAs absorbing layer should be grown at higher temperature than commonly used to reduce the nonsaturable losses related to the defects generated in the crystal during the LT-growth. Then, the increase of the trap density can be obtained by employing the surface states of SESAM structure or/and by increase of the As precipitate density. These solutions were applied in SESAM heterostructures (Table I). SESAM was grown under the same technological conditions as the QW6 structure.

Mode-locked operation was tested in the common z-shaped astigmatically compensated cavity. The arm of the output coupler contained two prisms with a tip-to-tip distance of 39 cm. Focussing on the SESAM was realized by an $f = -150$ mm spherical mirror. The experiment was performed with Yb-doped potassium yttrium tungstate Yb:KY$(WO_4)_2$ (Yb:KYW) as a gain medium. The KYW crystal was pumped at 980 nm by a broad stripe laser diode. The intensity autocorrelation and frequency spectrum are shown in Fig. 2.

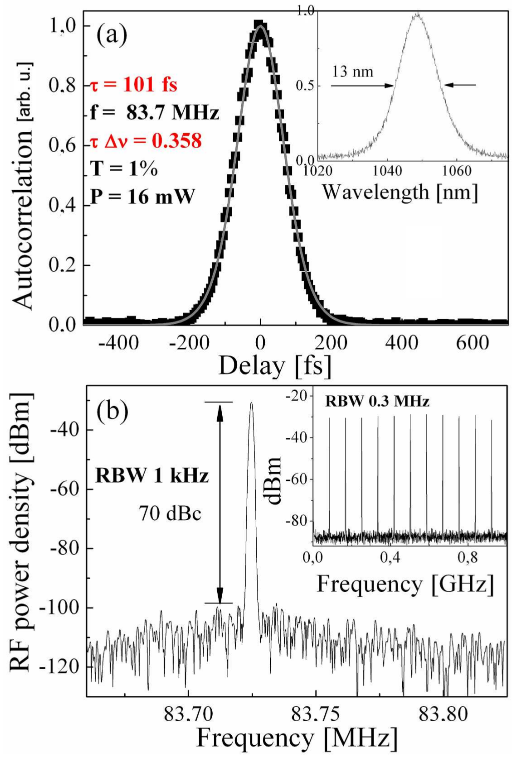

Fig. 2. Intensity autocorrelation and optical spectrum (inset) (a) and radio frequency spectrum of the mode-locked Yb:KYW gain medium with SESAM (b).

Using an 1% output coupler the shortest pulses of 101 fs with average 16 mW output power were registered. Similar results were reported by Paunescu et al. [9] and by Klopp et al. [10]. In the recorded frequency spectrum, no spurious modulations are visible down to 70 dBc, which indicates a stable CW mode locking. The time-band width product of 0.358 is slightly above the theoretical value of 0.315 for a sech^2 pulse shape.

4. Conclusion

The InGaAs absorber layer was grown at higher than commonly used temperature of 420 °C to reduce the defect density generated during LT growth. We think that these defects are responsible for the additional nonsaturable losses in annealed LT materials. Moreover, the V/III ratio of 10 was high enough to obtain the trapping time in sub-ps range and on the other hand, relatively low to maintain the pseudomorphic growth of strained InGaAs absorber layer. The optimisation of the LT growth conditions without annealing can be considered as an alternating way to obtain short pulse duration. We have demonstrated the stable self-starting passive CW mode locking of the Yb:KYW laser at about 1046 nm generating pulses as short as 101 fs.

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