Growth parameter optimization for fast quantum dot SESAMs

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Abstract: Semiconductor saturable absorber mirrors (SESAMs) using quantum dot (QD) absorbers exhibit a larger design freedom than standard quantum well absorbers. The additional parameter of the dot density in combination with the field enhancement allows for an independent control of saturation fluence and modulation depth. We present the first detailed study of the effect of QD growth parameters and post growth annealing on the macroscopic optical SESAM parameters, measuring both nonlinear reflectivity and recombination dynamics. We studied a set of self-assembled InAs QD-SESAMs optimized for an operation wavelength around 960 nm with varying dot density and growth temperature. We confirm that the modulation depth is controlled by the dot density. We present design guidelines for QD-SESAMs with low saturation fluence and fast recovery, which are for example important for modelocking of vertical external cavity surface emitting lasers (VECSELs).

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References and links

1. U. Keller, K. J. Weingarten, F. X. Kärtner, D. Kopf, B. Braun, I. D. Jung, R. Fluck, C. Hönninger, N. Matuschek, and J. Aus der Au, "Semiconductor saturable absorber mirrors (SESAMs) for femtosecond to nanosecond pulse generation in solid-state lasers," IEEE J. Sel. Top. Quantum Electron. 2, 435-453 (1996).
2. U. Keller, "Recent developments in compact ultrafast lasers," Nature 424, 831-838 (2003).
3. C. Hönninger, R. Paschotta, F. Morier-Genoud, M. Moser, and U. Keller, "Q-switching stability limits of continuous-wave passive mode locking," J. Opt. Soc. Am. B 16, 46-56 (1999).
4. U. Keller, "Ultrafast solid-state lasers," in Landolt-Börnstein. Laser Physics and Applications. Subvolume B: Laser Systems. Part I., G. Herziger, H. Weber, and R. Proprawe, eds. (Springer Verlag, Heidelberg, 2007), pp. 33-167.
5. O. Qasaimeh, W. D. Zhou, J. Phillips, S. Krishna, P. Bhattacharya, and M. Dutta, "Bistability and self-pulsation in quantum-dot lasers with intracavity quantum-dot saturable absorbers," Appl. Phys. Lett. 74, 1654-1656 (1999).
6. A. Garnache, S. Hoogland, A. C. Tropper, J. M. Gerard, V. Thierry-Mieg, and J. S. Roberts, "Pico-second passively mode locked surface-emitting laser with self-assembled semiconductor quantum dot absorber," CLEO/Europe-EQEC, postdeadline paper (2001).
7. E. U. Rafailov, S. J. White, A. A. Lagatsky, A. Miller, W. Sibbett, D. A. Livshits, A. E. Zhukov, and V. M. Ustinov, "Fast quantum-dot saturable absorber for passive mode-locking of solid-state lasers," IEEE Photon. Technol. Lett. 16, 2439-2441 (2004).
8. A. A. Lagatsky, F. M. Bain, C. T. A. Brown, W. Sibbett, D. A. Livshits, G. Erbert, and E. U. Rafailov, "Low-loss quantum-dot-based saturable absorber for efficient femtosecond pulse generation," Appl. Phys. Lett. 91, 231111 (2007).
9. D. Lorenser, H. J. Unold, D. J. H. C. Maas, A. Aschwanden, R. Grange, R. Paschotta, D. Ebling, E. Gini, and U. Keller, "Towards Wafer-Scale Integration of High Repetition Rate Passively Mode-Locked Surface-Emitting Semiconductor Lasers," Appl. Phys. B 79, 927-932 (2004).
10. G. J. Spühler, K. J. Weingarten, R. Grange, L. Krainer, M. Haiml, V. Liverini, M. Golling, S. Schön, and U. Keller, "Semiconductor saturable absorber mirror structures with low saturation fluence," Appl. Phys. B 81, 27-32 (2005).
Since the early 90’s, picosecond and femtosecond lasers have made a large impact both in fundamental science and industrial applications. Today, many ultrafast diode-pumped solid-state lasers are used in a variety of applications ranging from laser micromachining and laser printing to medical laser applications such as laser-assisted in situ keratomileusis (LASIK). These lasers are capable of producing ultrashort pulses that can be used to perform precise and accurate operations with minimal damage to surrounding tissue.

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state lasers rely on passive modelocking using a semiconductor saturable absorber mirror (SESAM) [1, 2]. A SESAM is a high reflector with an integrated semiconductor saturable absorber. Semiconductor absorber materials are ideally suited to initiate and stabilize pulse formation because they cover a broad wavelength range from the visible to the infrared, and can be manufactured to provide sufficiently fast recovery time in the picosecond or even femtosecond regime. Their integration into a mirror structure provides a large design freedom to tune the relevant absorber parameters, which is important to overcome modelocking instabilities such as Q-switched modelocking (QML) [3].

So far, most SESAMs employ quantum-well absorbers, which enabled stable modelocking of various laser materials operating in the femtosecond and picosecond regime [4]. Recently, there has been an increasing interest in quantum dot (QD) based SESAMs because the strong localization of the wave function leads to an atom-like density of states that enables novel SESAMs with tunable optical properties. QD saturable absorbers were first used to modelock semiconductor edge emitters in 1999 [5], two years later in 2001 the first QD-SESAM is reported by Garnache et al. [6]. Rafailov et al. reported fast recovery dynamics, which can be beneficial for achieving shorter pulse durations [7] and pulse durations as short as 114 fs have been shown [8]. Another advantage of the QD-SESAM is the lower density of states and the additional parameter of the dot density which allow for low saturation fluence at moderate modulation depth. This is challenging to realize with QW-SESAMs [9, 10].

QD-SESAMs were particularly successful for modelocking vertical external cavity surface emitting lasers (VECSELs). Optically pumped VECSELs overcome limitations of semiconductor edge emitters, combining high output power and excellent transverse beam quality [11]. VECSELs modelocked with QW-SESAMs achieved up to 2.1 W average output power [12]. In contrast to diode-pumped solid-state lasers, a semiconductor gain material exhibits dynamic pulse-to-pulse gain saturation [4]. In order to achieve stable modelocking, the absorber needs to saturate at lower pulse energies than the gain. The gain structure in VECSELs typically consists of several QWs, with a saturation fluence similar to the QW used in standard SESAMs. Stable pulse formation is usually achieved by strong focusing onto the QW-SESAM (10-40 times smaller area than in the gain), which limits the geometrical size and restricts the maximum achievable repetition rate [13, 14]. The additional design freedom of QD-SESAMs supports lower saturation fluence to achieve modelocking with similar mode areas on SESAM and VECSEL. This resulted in modelocked VECSELs with record-high repetition rates up to 50 GHz [13]. Moreover, the similar mode areas enabled the integration of the QD saturable absorber directly into the VECSEL structure. This new class of ultrafast lasers is referred to as modelocked integrated external-cavity surface-emitting laser (MIXSEL) [15]. In the MIXSEL, modelocking is achieved from a simple, straight cavity, which has the potential for monolithic integration and cost-efficient wafer-scale mass production.

In this paper, we present the first detailed study of the effect of QD growth parameters on the macroscopic optical SESAM parameters. We measured the nonlinear reflectivity and the recovery dynamics of various QD-SESAMs with different dot densities and growth temperatures. Our MIXSELs currently use a lower growth temperature for the QD-region than for the gain region. We therefore also investigate the effect of post-growth annealing on the QD properties. Moreover, we present design guidelines for QD-SESAMs with low saturation fluence and fast recovery.

The paper is organized as follows. In Section 2 we discuss the QD-SESAM design and growth and describe our set of samples. In the next section, we present the nonlinear reflectivity measurements and demonstrate that the dot density directly influences the total change of reflectivity. In Section 4 the recovery dynamics are discussed, which vary strongly according to the dot density. In Section 5, we measure the influence of annealing and present QD-SESAMs with excellent performance in terms of low saturation fluence. Finally, we
discuss design guidelines for combining low saturation fluence, optimum modulation depth, and fast recovery.

2. SESAM design and growth

As mentioned before, a SESAM is a high reflector with an integrated semiconductor saturable absorber, see Fig. 1(a). A semiconductor absorbs light when the photon energy is sufficient to excite carriers from the valence band to the conduction band. At sufficiently high pulse energies the absorber is saturated because possible initial states of the pump transition are depleted while the final states are partially occupied, as a result the reflectivity of the device increases. The SESAM has several important parameters, see Fig. 1(b): the modulation depth $\Delta R$, i.e. the difference in reflectivity between a fully saturated and an unsaturated SESAM, the nonsaturable losses $\Delta R_{\text{ns}}$ and the saturation fluence $F_{\text{sat}}$, which is the pulse fluence (pulse energy per area, $F_p$) for which the SESAM is saturated. All SESAMs have a maximum achievable reflectivity. If the fluence is larger than a certain value the reflectivity decreases, for example through two-photon absorption (TPA), but also other effects [16, 17]. The parameter describing the induced absorption is $F_2$, which is the fluence where the reflectivity has dropped to 1/e due to induced absorption [16, 17]. It can be influenced by the SESAM design and depends on the semiconductor material composition, pulse duration, and wavelength of the laser. The reflectivity as function of the fluence can be modeled with [18]

$$R(F_p) = R_{\text{lin}} \ln \left[ 1 + \frac{R_{\text{lin}}}{R_{\text{ns}} \left( e^{F_p/F_{\text{sat}}} - 1 \right)} \right] \frac{F_p}{F_{\text{sat}}},$$

(1)

with $R_{\text{lin}}$ the linear reflectivity of an unsaturated SESAM and $R_{\text{ns}}$ the reflectivity of a saturated SESAM (in absence of induced absorption).

The relative field strength in the absorber section can be controlled by the design of the structure Fig. 1(a). Especially for lasers operating at high repetition rates, resonant designs were proposed. The enhanced field strength in the absorber section leads to a reduction of the saturation fluence [10], on the other hand it equally increases the modulation depth. By changing the field enhancement, the product $F_{\text{sat}} \cdot \Delta R$ cannot be altered: The absorbed pulse fluence in a SESAM is $F_p [1-R(F_p)]$, for a transparent SESAM ($F_p \to \infty$) this converges to

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Fig. 1. (a) The design of the QD-SESAM. The structure contains a 25-pair distributed Bragg reflector with a saturable absorber section grown on top. The antiresonant structure can be changed to a resonant structure by removal of the two top layers (with $\lambda/4$ optical thickness). (b) Reflectivity of a SESAM as function of the incident pulse fluence. Initially, the reflectivity increases with the pulse fluence. Induced absorption, described by the $F_2$ parameter [16, 17], can lead to a roll-over and decreases the reflectivity for high fluences. The blue curve has a small induced absorption parameter $F_2$ (fs-pulses), the green curve has a large $F_2$ (ps-pulses) and for the red curve $F_2 = \infty$. Please note that if the recovery time is smaller than the pulse duration, the saturation fluence increases slightly for longer pulses, which is not illustrated in this graph.
\(F_{\text{sat}} \Delta R\) (assuming \(\Delta R_{\text{ns}} = 0\) and \(F_2 = \infty\)). Thus \(F_{\text{sat}} \Delta R\) is the energy needed to completely saturate the SESAM. This energy must be proportional to the number of states in the absorber, since these states have to be filled with carriers for transparency. If one does not change the density of states, the absorbed pulse fluence to obtain complete saturation stays the same and the product \(F_{\text{sat}} \Delta R\) is maintained. The only solution to reduce both \(F_{\text{sat}}\) and \(\Delta R\) is to reduce the density of states. Using QWs, this is difficult; with QDs the number of states is simply proportional to the dot density.

We used QD-SESAMs with resonant designs and low saturation fluence before to increase the repetition rate of passively modelocked VECSELs to 50 GHz [13] and to demonstrate the first MIXSEL [15]. The employed QD-absorbers were designed for an operation wavelength of 960 nm. In this study, we use similar QD-absorbers, however, all presented SESAMs are antiresonant. In contrast to a resonant design, the electrical field in the QD layer is insensitive to small growth errors and a variation of the wavelength, which allowed us to study their optical properties over a range of more than 40 nm. An antiresonant design leads to a larger saturation fluence and lower modulation depth, and modelocking experiments with the same beam waist on SESAM and gain structure (which is necessary at higher repetition rates) is not possible. To overcome this, we introduce a new design which provides both resonant and antiresonant samples from one single growth run. As-grown the SESAM is antiresonant, but we can make the device resonant by selectively wet etching the last AlAs and GaAs layer away. We experimentally verified that this procedure leads to a decrease of the saturation fluence by a factor of 10, while the modulation depth increases by the same factor.

The SESAMs were grown on (100) GaAs substrates using a VEECO GEN III molecular-beam epitaxy (MBE). The distributed Bragg reflector (DBR) is a 25 pair AlAs/GaAs mirror and has a theoretical reflectivity of 99.98%. On top of the DBR the QD section is grown: first a spacer is needed to place the QDs in the anti-node of the electrical field. We chose AlAs instead of GaAs since GaAs has a smaller bandgap and therefore the two-photon absorption is significantly stronger. The InAs QDs are embedded between two thin GaAs layers (20 nm thickness each). After the first GaAs layer the substrate temperature is decreased to the desired temperature and during the growth of the second layer the temperature is ramped up.

The InAs QDs are grown using Stranski-Krastanov growth, which depends on the following parameters: substrate temperature, arsenic pressure, growth rate in number of monolayers per second (i.e. ML/sec) and indium monolayer coverage (ML coverage). The indium coverage is controlled by the opening time of the indium source shutter, a longer shutter time results in higher ML coverage, which again results in a higher dot density [19]. For the study, we grew the QDs at temperatures of 380°C, 400°C and 430°C, all other layers are grown at 600°C. In our MBE, the growth temperature is measured using band-edge absorption, giving a very good reproducibility and an accuracy of \(\pm 2\) °C.

During the evaluation, we observed an influence of the growth temperature on the recovery. However the ML coverage is the dominant effect and the general tendencies are similar for the sample sets with different growth temperature. Therefore, in this paper, we focus on QD-SESAMs grown at 400°C. We compare 5 samples grown with a 30, 35, 40, 45 and 50 seconds Indium shutter time. With the used growth rate of 0.053 ML/sec we obtain 1.6, 1.9, 2.1, 2.4 and 2.7 ML coverage. QDs are formed when the thickness of the InAs layer exceeds 1.5 MLs [20], so the first sample is just above this threshold.
3. High precision reflectivity characterization

The antiresonant samples have a relatively small modulation depth (< 1%) and a high precision setup is needed to measure the nonlinear reflectivity. The setup we use for this purpose has an accuracy of 0.05% for the reflectivity and a dynamic range (incident pulse fluence) of four orders of magnitude [18]. The laser source is a modelocked wavelength-tunable Ti:sapphire laser with a 80 MHz pulse repetition rate. The 140-fs pulses (measured directly after the laser) are nearly transform limited with a time bandwidth product of 0.34. In Fig. 2, we show nonlinear reflectivity measurements of our QD-SESAMs at a laser center wavelength of 960 nm. The absolute reflectivity was calibrated with a dielectric high reflectivity (HR) laser mirror, which reflectivity was assumed to be 100%. In reality, the reflectivity of the HR was even below the SESAMs, causing slightly negative $\Delta R_{ns}$.

The measurement data (dots) is fitted (solid lines) with the fit function (1). The SESAMs behave as expected, by increasing the ML coverage (dot density) the modulation depth also increases. The modulation depth is proportional to the dot density, while the saturation fluence remains constant. The microscopic definition of $F_{sat}$ we use is: $d\alpha / dt = -(I / F_{sat}) \alpha$, with $I$ the incident pulse intensity and $\alpha$ the (intensity) absorption coefficient of the QD layer. As a result, $F_{sat}$ only describes a relative change of the absorption given the incident intensity and this is independent of the number of dots. The rollover also remains constant, the $F_2$ parameter is between 405 and 483 mJ/cm². The rollover depends on the pulse duration of the laser and the design of the structure, i.e. the integrated intensity in the GaAs layers, which is similar for all structures [17]. Note that the measurements were done with a Ti:sapphire fs-laser, lasers operating in the ps regime have less induced absorption and therefore the rollover would occur at a higher fluence.

![Graph showing nonlinear reflectivity measurements of QD-SESAMs done at 960 nm with 140 fs pulses, the upper curve has the smallest ML coverage (dot density) and therefore the smallest modulation depth. By increasing the dot density the modulation depth also increases while the saturation fluence maintains constant. The table shows the obtained fit values, for a discussion on the relative errors please refer to [18].](image-url)

| ML  | $F_{sat}$ (mJ/cm²) | $\Delta R$ (%) | $\Delta R_{ns}$ (%) | $F_2$ (mJ/cm²) |
|-----|-------------------|----------------|---------------------|---------------|
| 1.6 | 66.5              | 0.26           | -0.002              | 405           |
| 1.9 | 71.2              | 0.48           | -0.042              | 457           |
| 2.1 | 70.7              | 0.74           | -0.092              | 482           |
| 2.4 | 65.7              | 0.77           | -0.032              | 443           |
| 2.7 | 78.4              | 0.88           | 0.004               | 483           |
We also investigated the wavelength dependence of the saturation parameters. A flat spectral response is important for realizing ultrashort pulses with broad optical spectrum. The saturation fluence and modulation depth have been measured for three different wavelengths (940 nm, 960 nm and 980 nm) and are shown in Fig. 3.

The measurements show a slight reduction of the modulation depth for longer wavelengths. The photoluminescence (PL) peak of the samples is around 1050 nm so we have both ground state (GS) absorption and excited state (ES) absorption. By increasing the wavelength, we have less ES absorption and more GS absorption, since ES absorption is stronger than GS absorption the total absorption decreases [21]. The average saturation fluence is 51.4, 70.5 and 44.5 µJ/cm² at 940, 960 and 980 nm. We conclude that the wavelength and ML coverage have no strong influence on the saturation fluence, only by increasing the field enhancement, the saturation fluence can be decreased.

4. Recovery dynamics

The SESAM recovery influences the pulse duration in a modelocked laser. In order to realize shortest pulse duration, fast recovery has to be achieved [22]. For GaAs absorbers fast recovery has been achieved by low-temperature growth (below 350°C) to create point defects to trap the carriers [23, 24]. Low-temperature growth is not required for QDs to have fast recovery times. Rafailov et al. have measured recovery times of approximately 1 ps [7]. The pump probe response exhibits a large fast component which quickly drops to 20% of its original value and is followed by a slow component > 100 ps. These two clearly distinguishable recovery processes are also present in our samples. Moreover, we observed that the time constants and relative ratio strongly depends on the growth conditions.

The recovery is measured with a pump probe setup as shown in Fig. 4(a). We use the same laser source as for the saturation measurements for better comparison. A beam splitter generates a pump and a probe beam. The pump beam hits the sample first under a small angle, after a variable delay the probe beam reflects off the sample and is measured with lock-in detection. The five samples are measured at 960 nm and shown in Fig. 4(b). The normalized pump probe response can be fitted well with the two time constants

$$\Delta R_{pp}(\tau) = Ae^{-\tau/\tau_{slow}} + (1-A)e^{-\tau/\tau_{fast}}, \quad (2)$$

where \(A\) is the amplitude of the slow component with time constant \(\tau_{slow}\) and \((1-A)\) the amplitude of the fast component with time constant \(\tau_{fast}\). For fast recovery a small slow
component (A ≈ 0) is favorable because then the slow component is not that significant anymore. Another option is a strongly reduced time constant $\tau_{\text{slow}}$, e.g. like measured for the 2.7 ML sample in Fig. 4(b).

The slow component is determined by carrier recombination and carrier escape. The sample grown with 1.6 ML coverage has a slow component of approximately 500 ps which is the expected recombination time for InAs QDs [25]. The measurement shows that by increasing the ML coverage the recombination becomes faster, which can be explained by a higher defect density and thus a faster recombination [26], or a higher interdot transfer probability because of the smaller distances between the dots [27].

The fast processes are due to transitions in the dots. There are several processes that can explain the fast relaxation mechanism. Auger processes are much more likely than phonon relaxation [28], and recovery times of 0.5 ps have been measured [29]. Another very fast process is thermal hole activation [30] where the hole is removed and stimulated recombination drops (a SESAM is saturated when the stimulated emission is equal to the absorption). We measured a fast relaxation time constant $\tau_{\text{fast}}$ between 0.7 and 1.2 ps.

In Fig. 5(a), the response is shown for the 1.6 ML sample pumped at different fluences ranging from 20 to 450 µJ/cm$^2$. It is obvious that by increasing the pump fluence the sample saturates more and thus the peak becomes higher. At low pump fluences the normalized response is identical ($\tau_{\text{slow}}, \tau_{\text{fast}}$ and $A$ are constant). At higher fluences the shape of the recovery changes. For the extreme case (450 µJ/cm$^2$) the reflectivity increases again after a time of 0.9 ps, which is different from the measurements at lower fluences. A second maximum is observed after a time of 14 ps. This is most likely caused by the carriers generated in the GaAs around the dots by two photon absorption which after a few picoseconds are captured in the dots. This agrees with the capture time of 31 ps measured by other groups [31]. TPA in pump probe measurements have already been reported in [32]. Please note that TPA is strongly reduced for longer pulses, and the variation of $A$ with pump fluence will be substantially lower. We expect that the normalized response would remain constant even at 450 µJ/cm$^2$, if pump pulses > 500 fs would be used.

In Fig. 5(b), the amplitude of the slow component $A$ is studied as function of ML coverage and wavelength. We used a constant pump fluence of 50 µJ/cm$^2$, for which TPA is negligible. The smallest $A$, which means a dominant fast recovery process, is obtained for
samples just over the QD formation threshold (1.5 ML). Increasing the ML coverage increases the significance of the slow component. At a longer wavelength (the red curve) a smaller $A$ is obtained, therefore this operation regime is preferable for short pulse operation. This is consistent with the findings presented in [7], an $A = 20\%$ is measured for a wavelength 30 nm below the PL peak.

5. Annealing studies

A key element for realizing the first MIXSEL [15] was a detailed study on post-growth annealing of QD saturable absorbers. In the MIXSEL design, the QD saturable absorber layer is placed in the middle of the structure and is annealed during several hours of subsequent growth at 550°C – 600°C. This changes the dot composition (indium out diffusion) and size, resulting in a blue shift of the absorption and PL emission wavelengths [33]. Post-growth annealing of SESAMs is also a simple way to optimize SESAM parameters without the need for expensive and time consuming growth. We therefore also studied the effect of post-growth annealing on our quantum dot samples.

The surfaces of the samples are capped with 100 nm SiO$_2$ during the annealing to avoid surface damage due to As evaporation. After the annealing the caps are removed with reactive ion etching. The samples are annealed at 625°C (temperature measured with a pyrometer having an accuracy of 5%) using rapid thermal annealing (RTA).

Fig. 6. (a) Photoluminescence spectra of the 1.6 ML QD sample before and after annealing, the two peaks are ground state (GS) and wetting layer (WL). (b) Blueshift of the PL peak as function of annealing time for a QD sample grown at 400°C. The samples are grown without a DBR.
We first studied the effect of the annealing time by observing the shift of the PL peak wavelength as function of annealing time. During the first minutes, the PL wavelength strongly shifts to shorter wavelength by several tens of nanometers, afterwards we observe a linear shift of 4.7 nm/hour, the blue shift is shown in Fig. 6. All presented measurements afterwards are for an annealing time of one hour. For longer annealing times, similar results are expected.

The PL of the annealed 1.6 ML sample showed a strong blue shift to a center wavelength of 953 nm after 1 hour of annealing at 625°C, with the result that the modulation nearly vanished and the saturation fluence was not measurable anymore. The modulation depth of the other samples with larger indium coverage remained nearly unaffected by the annealing, but their saturation fluence was strongly reduced. The reduction of the saturation fluence is the strongest for the samples with the least ML coverage, we observed a reduction by up to a factor of 9. The samples with higher ML coverage showed only a reduction by a factor of 1.3, see Fig. 7(a). Additionally, we observed a clear decrease of the slow recovery component (reduction of $A$) with an average of 18%, which can be explained by the blue shift. In Section 4, a smaller $A$ was also observed at longer wavelengths, i.e. closer to the PL peak. The change of the slow recombination time constant ($\tau_{slow}$) is not consistent, the samples with 1.9 and 2.1 ML became slower and the samples with 2.4 and 2.7 ML became faster, see Fig. 7(b).

In Fig. 7 (c) and (d) the result of the annealing is shown for the 1.9 ML sample. The saturation fluence reduces from 63.6 to 7.2 $\mu$J/cm$^2$, while the modulation depth stays constant at 0.5%. This gives a sample with $F_{sat}\cdot\Delta R = 36$ nJ/cm$^2$, a factor 10 smaller than InGaAs QWs and comparable to GaInNAs QWs operated within the band tail [34].
6. Conclusions

We studied the effect of dot density and post-growth annealing on quantum dot SESAMs. QD-SESAMs have an additional degree of design freedom compared to quantum well SESAMs. We experimentally demonstrated that the modulation depth can be tuned with the ML coverage (i.e. QD density) while the saturation fluence is constant, as predicted by theory. Due to its inherent inhomogeneous size distribution, the dots have broader uniform spectral properties than quantum wells. Nevertheless, the modulation depth increases slightly when operated at shorter wavelengths due to excited state absorption. The pump-probe measurements show that higher dot density results in faster recombination most likely because of defect recombination. For fast recombination, a small amplitude of the slow component is preferred, but care has to be taken when evaluating the measurements since the amplitude depends on the pump fluence. To enhance the fast component, the quantum dots should be grown close to the QD formation threshold and operated at a wavelength close to the PL peak. Post-growth annealing allows to further reduce the saturation fluence. Moreover, the fast component becomes even more dominating.

Modelocked high repetition rate VECSELs require SESAMs with low saturation fluence (< 10 µJ/cm²) and a modulation depth of typically 1%. For achieving short pulse durations, fast recovery is necessary. Our study shows that the optimum design parameters for this case are apparently obtained by growing around 2 ML InAs coverage and subsequent annealing. This gives also a small saturation fluence which is favorable for modelocking VECSELs, the small modulation depth can be increased by growing more than one absorber layer if necessary.

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