Semiconductor quantum well based shutters for NIR laser mode-locking with $\sim$ GHz repetition rate

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Abstract. Fast semiconductor shutters based on coupled wells were designed in the search for reliable, compact and cheap key element of GHz repetition rate NIR lasers passive mode-locking. Stable 0.98 GHz repetition rate 200-fs Yb:KYW laser pulses were demonstrated for SESAM including semiconductor reflector and a layer of quantum wells. The damage threshold estimate for the SESAM is $\sim$ 8.87 mJ/cm$^2$. Other type of shutter – DSAM – was developed with dielectric reflector and the layer of quantum wells transferred over reflector. The measured recovery time was about 2-3 ps for both types of saturable absorbers. The efficiency relative to the incident pump power was 57% for the SESAM and 19% for the DSAM. Average output power of 2.54 W for the all-semiconductor shutter (SESAM) and of 0.92 W for the dielectric mirror with a saturable absorber (DSAM) were obtained. Actual state of the art for the shutters design is considered.

1. Introduction
Femtosecond lasers are requested in many areas of fundamental science and applications. Their applications field covers research of fast transient processes in various media and in a wide spectral area, in biological and medical imaging (in particular, optical coherent tomography), in optical communication, in high-precision coordinate-temporal measurements of ground and cosmic location objects, in metrological support of high-technology branches of industry, etc. Briefly speaking, compact, reliable, cost-effective ultra-short pulse lasers are requested.

An idea of how to get ultra-short pulse is known since 70-th of the past century [1] – the synchronization of longitudinal modes of laser (mode locking technique); this method was firstly demonstrated in the system “dye laser + saturable absorber solution”. Today we know several approaches to the mode locking. Active mode locking can be realized by placing acousto-optic modulator inside a laser cavity, and this technique is well suited to high gain lasers. Passive mode locking can use Kerr lens effect; this approach is sensitive to laser cavity adjustment, and it needs high intensity of radiation to create remarkable beam deformation because of nonlinear change of refraction index. Passive mode locking via saturable absorption acquired new life due to idea to apply SEmiconductor Saturable Absorption Mirror (SESAM) [2]. Today, the SESAM became a key element of laser mode locking, and it provides self-starting self-sustainable mode locking regime without Q-switch for a wide class of lasers from NIR to MIR.

To introduce our activity in this area of research, some examples of SESAMs designed for lasers with low repetition rate of ultra-short pulses will be given below. From the large variety of
semiconductor nanostructures (quantum wells, quantum dots, dots-in-wells etc.), we chose the quantum wells (QW). For application in compact femtosecond lasers, the QW based SA are the most reliable, because they can operate at much higher working radiation intensity.

2. Shutter based on single quantum well

At the first step, we chose a QW of the 1-st type (both electrons and holes are confined) with ideal lattice matching between the well and the barrier materials. This is a quite rare case. Usually, there is no lattice matching, and the quantum well layers are under mechanical stress. Fig.1 shows energy diagram of single quantum well InGaAs between InP barriers. The band gaps are indicated for materials of barriers (InP) and quantum well (In$_{0.53}$Ga$_{0.47}$As). Dashed arrow shows transition between minimal energy quantization levels of heavy hole ($1_{hh}$) and electron ($1_{e}$). The possibility of exciton localization in this QW seems attractive because the excitonic transition is easy saturable.

![Energy diagram of the first type single quantum well.](image)

SESAM mirror for Cr:YAG laser (1.4 – 1.6 micrometers) was produced via hybrid technology (1-st type single QW was transferred onto dielectric reflector and sapphire substrate, and had an antireflective coating from the QW side. The In$_{0.53}$Ga$_{0.47}$As layer of 6 nm thickness is single QW between InP barriers. QW is located at the maximum of standing wave pattern. By using this shutter, and by thorough group delay dispersion (GDD) compensation, 27 fs pulses were obtained, which corresponded to 5 oscillations of carrier frequency only [3]. However, the output power of laser was low, and a saturable loss was comparable with non-saturable one.

3. Shutter based on several isolated quantum wells

As the next step, the combination of several functions (semiconductor total reflector + saturable absorber + GDD compensator) was realized in SESAM for Nd$^{3+}$:KGd(WO$_4$)$_2$ (Nd:KGW) laser (central wavelength of 1.06 microns) [4]. In this case, two quantum wells of In$_{0.25}$Ga$_{0.75}$As were used, and they were separated by thick (of about 23 nm) barriers of GaAs. Stable mode locking regime was provided by this all-in-one all-semiconductor mirror. Repetition rate was 70 MHz, and pulse duration was of about 0.6 ps. Laser crystal Nd:KGW is not very efficient; besides, slow trend of mode locked pulses was observed, probably, due to thermal lens generated in the laser crystal.

Ytterbium lasers Yb$^{3+}$:KY(WO$_4$)$_2$ operating around 1.04 microns demonstrate high efficiency with diode laser pumping. In collaboration with colleagues from Belarus, we developed SESAM for Yb:KYW laser (look [4]) based on several isolated quantum wells separated by thick barriers which prevents overlapping of wave functions from neighbor wells. Its kinetics could be approximated by biexponential low with two distinct relaxation times: $\tau_1$ corresponding to ionization of photo-generated excitons localized in quantum wells (usually about 0.4 ps), and $\tau_2$ which reflects final relaxation due to
electron-hole (e-h) recombination (for this SESAM, about 200 ps). Just the relaxation time τ₂ (known also as recovery time) determines either the shutter operation is enough fast. For this SESAM, laser intensity provoking optical damage was estimated as 10 GW/cm². Further, we used Yb:KYW laser in our work [5].

When thinking about shutters for the compact lasers, it was necessary to accelerate e-h recombination, recovery time of SESAM should be shorter, SESAM should be faster.

Acceleration of e-h recombination can be obtained by creation of additional electron-hole recombination centers (in particular, point defects). This can be done via post-growth irradiation of the shutter by heavy ions beam [6], or by doping of well and barrier materials by another atoms [7], or by intentional defects generation in a course of molecular beam epitaxy (MBE) due to lattice mismatching [8]. All above mentioned approaches induce partial degradation of the sample crystal lattice. This, in turn, reduces (or eliminates totally) contribution of localized excitons into absorption spectrum. However, just this contribution is able to provide absorption saturation at low intensity of working radiation (so called “easy start of mode locking”).

We carried out experiment using another way of e-h recombination acceleration; we investigated UV laser post-growth treatment of SESAM. For this goal, excimer XeCl laser operating at the wavelength of 308 nm was used (UV quantum energy was 4.03 eV, pulse duration 15 ns, maximum intensity of 13 MW/cm², repetition rate of 1 Hz). Effect of UV radiation was detected via photoluminescence (PL) spectra and via reflectivity kinetics of the samples before and after irradiation. UV laser modification of PL and kinetics change proved threshold-like process [9]. Recovery time shortened from 100-200 ps to 10-20 ps (almost by two orders of magnitude). We carried out X-ray diffraction testing; X-ray source operated at the wavelength of 0.154 nm with the beam size 1.5mm×0.1 mm. Monotonous changes in diffractive curves can not be attributed to the influence of UV irradiation, that is rather initial MBE growth in-homogeneity. Hence, the structure changes take place in a thin surface layer of about 5-10 nm thickness (not detectable for X-ray diffraction). This value correlates with the penetration depth of UV laser radiation: approx 13 nm (estimated by using absorption coefficient 7.72×10⁵ cm⁻¹). So, the mechanism of e-h recombination acceleration proved the same as in the previous works cited above, i.e. generation of point defects, in this case – assisted by UV laser [10].

The results on the post-growth UV laser treatment of SESAMs seemed promising. But, the nature of recovery time shortening is again the e-h recombination acceleration due to point defects generated by UV laser radiation. The semiconductor lattice is damaged; besides, we don’t know the behavior of point defects under high intensity working NIR radiation.

We needed some other approach to recovery time shortening which maintains ideal crystal quality of semiconductor structure. The first step was design of quantum wells separated by super-lattice barriers.

4. Shutter based on quantum wells with super-lattice barriers

Low band gap material In₀.₂₅Ga₀.₇₅As insertions into the barriers should promote the charge carriers tunneling between the quantum wells, and this should accelerate the recovery of optical shutter. Absorption spectra of layer of quantum wells In₀.₂₅Ga₀.₇₅As (15 nm thickness) separated by thick barriers AlAs (23 nm thickness) showed narrow spectral peak (about 20 nm spectral width) attributed to excitonic contribution. The layer of the same quantum wells separated by super-lattice barriers (quantum well 15 nm of In₀.₂₅Ga₀.₇₅As and barrier consisted of 3ML AlAs/8ML well/2ML AlAs/8ML well/3ML AlAs, where ML means monolayer, and well is In₀.₂₅Ga₀.₇₅As) had much wider spectrum (of 100 nm spectral width), and its kinetic gave the recovery time of about 8 ps [11]. On the base of this nanostructure, SESAM for Yb:KYW laser with super-lattice barriers and low non-saturable loss was made [12]. Pulses were close to spectral-limited ones with the time-bandwidth product of about 0.319. Maximum average power was 1.57 W, which is comparable to CW regime power of 1.62 W. Pulse repetition rate was 70 MHz with the peak power of 171 kW and pulses duration of 115 fs.
5. Shutters for compact NIR lasers

Taking into account previous experience, we can generate a list of requirements to optical shutters for passive mode locking in compact lasers. The shutter should provide saturable absorption (modulation depth) of necessary level; it should reveal fast saturation and recovery (especially for femtosecond lasers with fast repetition rate); it should demonstrate high reflectivity in spectral area of the laser gain (possess wide spectral range and high quality reflectors); it should be of low non-saturable loss (be of good optical quality); it should be resistive to intense working radiation; it would be desirable to obtain shutter of long lifetime and of low cost, etc.

Actually, two basic constructions of shutters for compact Yb:KYW laser were created. The first one is monolithic SESAM including semiconductor reflector grown over GaAs (001) epi-ready substrate (made of 20 pair of quarter-wavelength layers of GaAs and AlAs) and a layer of 3 quantum wells (27 ML of In_{0.25}Ga_{0.75}As) separated by thin barriers (5 ML of GaAs). This shutter could provide maximum modulation depth of 10%, which was tested by linear absorption spectrum of the sample covered by anti-reflecting layer of Y_2O_3 (of quarter-wavelength thickness). In order to adopt the shutter to a given Yb:KYW laser, upper dielectric mirror was sputtered over the anti-reflecting coating (in our case, we used alternation of ZrO_2 and SiO_2 quarter-wavelength layers); so, when finished by additional dielectric layers, the structure gives modulation depth of about 1%. Another shutter, DSAM, included dielectric reflector attached to metal substrate, and the same layer of 3 quantum wells transferred onto dielectric reflector.

Each of the shutters, SESAM and DSAM, has some advantages and drawbacks. Let’s consider specific features of reflectors used in the two shutters. For SESAM with 3 QW as saturable absorber, reflectivity optical table is of 110 nm width. DSAM shows reflectivity optical table is of 210 nm width. SESAM manifests lateral in-homogeneity of reflectivity optical table spectral position. Dielectric reflectors prepared via sputtering in vacuum show high lateral homogeneity. So, dielectric mirror has reflectivity table width twice larger than the semiconductor one, it is homogeneous, and semiconductor mirror (MBE grown of super-clean materials) is much more expensive.

To estimate how fast the shutters are, a single wavelength technique pump-probe with double modulation was used [13]. Saturating and probe beams of Yb:KYW laser (FL-1000, Minsk, Belarus, 1040 nm central wavelength, 130 fs pulse duration, repetition rate about 70 MHz) were chopped by mechanical choppers at two different non-multiple frequencies F_1 and F_2 stabilized at the accuracy of 1 Hz. The probe radiation pulse could be delayed relative the saturating pulse by time interval from -10 ps to +40 ps. The idea to detect nonlinear response of a sample reflectivity at the sum frequency F_1+F_2 was realized via generation of the reference signal at the sum frequency (from reference signals generated by optron pairs of each chopper) and by application of radio-filter at the sum frequency to detect the probe beam radiation. This approach permitted to eliminate completely scattered radiation of saturating beam. The set-up allowed us to get the minimal relative reflectivity change detection of about 5×10^{-6}.

Kinetic curves of quantum wells reflectivity show bi-exponential decay in the limit of low intense saturating radiation only. A phenomenological model of the kinetics of reflection of a semiconductor mirror with quantum wells was developed, which takes into account the contribution of two subsystems: excitons and electron-hole pairs [14].

The model makes it possible to compare with experimental data. For SESAM and DSAM designed for compact Yb:KYW laser we got the following relaxation parameters: \( \tau_1=0.4 \) ps (ionization time of excitons), \( \tau_2=2-3 \) ps (electron-hole recombination time), and \( \tau_3=0.8 \) ps (quasi-equilibrium installation time in manifold of un-correlated electrons and holes) [15].

Both types of shutters, SESAM and DSAM, were tested in compact Yb:KYW laser operating under optical pumping of CW diode laser at 980 nm. GDD was compensated by two elements based on Gires-Tournois interferometers. For both shutters, stable mode locking regime was obtained, and pulses duration was about 200 fs [15].
Efficiency of both shutters was estimated at 720 MHz repetition rate. For our SESAM, efficiency was 57% (some higher than for commercial SESAM), and maximum average output power was of 2.54 W. DSAM proved some worse: 19% of efficiency, and maximum average output power was of 0.92 W.

For SESAM, the shortening of laser cavity was carried out up to repetition rate of 970 MHz, and mode locking regime retained stable with high signal-to-noise ratio for central spectral component corresponding to the inter-mode distance. Side-band patterns appeared near the central component at repetition rate of 982.65 MHz. Parameters of working radiation under these conditions were used to estimate the optical damage threshold for our SESAM at the level of surface energy density of about 8.9 mJ/cm².

![Fig.2. Comparison of average output power in mode locking regime with 2 samples of DSAM with output power in CW regime with total reflector.](image)

For DSAM, the optical quality can be estimated by comparison of the average output power in mode locking regime with output power in CW regime with total reflector placed in spite of DSAM. Results presented in Fig. 2 demonstrate good reproducibility of two DSAM samples. However, they are still far from the limit of low non-saturable loss.

6. Conclusion

To summarize, we can state the following. Stable mode-locking up to 0.98 GHz repetition rate in Yb:KYW laser was demonstrated with SESAM based on coupled quantum wells (with thin barriers). Layer of quantum wells separated by thin barriers transferred onto dielectric reflector showed recovery time acceptable for passive mode locking in compact femtosecond lasers of NIR spectral area. DSAM needs further improvement, but it is promising in design of cheap and fast optical shutters for NIR lasers mode-locking.

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