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Low saturation fluence in a semiconductor saturable electroabsorber mirror operated in a self-biased regime

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Abstract

A Semiconductor Saturable Absorber Mirror utilising the electroabsorption effect in a self-biased stack of extremely shallow quantum wells is proposed and analysed theoretically and numerically. The saturation flux and recovery time of the proposed device when operated with picosecond incident pulses are shown to compare very favourably with existing all-optical constructions.

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Semiconductor Saturable Absorber Mirrors (SESAMs) are widely used for passive mode-locking (and Q-switching) in a large number of laser constructions (see [1–4] and the references in [4]). Most existing SESAMs operate via the all-optical absorption saturation mechanism in Quantum Wells (QWs)[1, 4]. For high frequency operation of passively mode-locked lasers, it is crucial for the SESAMs to have a small saturation fluence and a short recovery time [4]. On the other hand, the total absorption variation with power in SESAMs can be relatively modest, corresponding to a total reflectance variation ΔR of the order of several per cent [4, 5]. As has been experimentally shown, using Quantum Dots (QDs) in all-optical surface normal SESAMs allows obtaining a small saturation fluence ($\sim 2\mu J/cm^2$), while maintaining a short recovery time [6].

Here, we show that the electroabsorption effect in extremely shallow QWs (ESQWs) [7, 8] is very well suited for implementation of very low saturation fluence self-biased surface normal electroabsorptive SESAMs. For this purpose, we propose to use the electroabsorption effect in ESQWs in the spectral region where the absorption coefficient increases with electric field - that is, in the region which was up to now supposed to be unusable in ESQW electroabsorptive devices [8].

The self-biased SESAM, realised for example in the AlGaAs material system, is schematically shown in Fig.1. It comprises a simple P-i-N structure where a narrow-bandgap electroabsorptive i (n^0 or p^0) layer is placed between P- and N-doped wide-gap layers. This structure is grown on top of a high- reflectivity undoped AlGaAs DBR ($AlAs/Al_{0.1}Ga_{0.9}As$ in our specific case). The reflection coefficient of such a DBR with low optical losses can be made very close to one(see e.g. [9]). No voltage is applied to the device. The incident light has a photon energy slightly below the bandgap E_g of the i-layer.

The principle of operation of the saturable absorber in such a SESAM is very simple [10]. Light absorption in the i-layer is governed by the electroabsorption effect due to the built-in voltage V_b of the $P^+ - i - N^+$ structure. In steady state, the photocurrent generated due to this electro-absorption results in a voltage drop φ on the load resistance. Therefore, the voltage on the $P^+ - i - N^+$ junction decreases, which means a decrease in the electric field in the i-layer. This leads to a decrease in the electro-absorption. An increase of the radiation power increases the potential φ and thus reduces the voltage across the junction and, correspondingly, lowers the value of the electro-absorption coefficient α. Saturable Franz-Keldysh absorption of such a kind has been experimentally demonstrated, under steady-state operation, in a surface normal configuration in [11] and in a waveguide configuration in [12].

Next, we need to specify the nature of the electroabsorptive layer. Phenomenologically, any kind of electroabsorption effect in the spectral region where absorption coefficient increases with electric field allows saturable absorption to be realised. Quantum Confined Stark Effect (QCSE) in multiple quantum wells structures (MQWs) [13], which allows obtaining a large variation in absorption in this spectral region, is usually used for practical realisation of electroabsorption modulation. Achieving this large absorption variation alongside a short recovery time requires, however, high electric field values, meaning that a considerable voltage needs to be applied to the MQW structure. On the other hand, the Electroabsorption effect in Extremely Shallow Quantum Wells (ESQWs) in this spectral region, at electric fields sufficient for field ionization of excitons to take place yet still modest in absolute value ($\sim 2-5\cdot 10^4$ V/cm), provides a relatively large increase in the absorption coefficient in comparison with bulk material under only a moderate increase of the electric field [8]. Similar to the case in bulk semiconductors, the time t_{tr} of carrier transit through the space charge region of a ESQW structure remains small in a broad range of electric fields [14]. All these considerations facilitate the use of a saturable absorber mechanism in ESQW and thus make it possible to construct compact SESAMs combining a very low saturable fluence with a short recovery time.

The reflection coefficient R_S of the proposed SESAM is given by:

$$R_S = R_{DBR} \exp\left[-2\alpha(E)W_i\right] - \Delta R_{ns}, \tag{1}$$

where R_{DBR} is the DBR reflectivity, W_i is the thickness of the i-layer and ΔR_{ns} takes into account the nonsaturable losses due to absorption outside the i-layer. We assume that an antireflection coating is deposited onto the SESAM (see Fig. 1), with a reflectivity $R_{AR} < 10^{-3}$ (see e.g. [15]), which is low enough for us to ignore all standing-wave effects, effectively assuming $R_{AR} = 0$. The dependence of the electro-absorption coefficient $\alpha(E)$ on the the electric field in the i-layer is given by an expression typically used for Franz-Keldysh effect:

$$\alpha = \alpha_0 + \frac{a}{W_i}[V_b - \varphi] \exp\left[-\frac{E_0 W_i}{V_b - \varphi}\right], \tag{2}$$

where we have used for the electric field E the expression $E = (V_b - \varphi)/W_i$. α_0 is the background absorption coefficient for $E \approx 0$ and a and characteristic field E_0 are fitting parameters. We determine these parameters by fitting the available experimental data for AlGaAs/GaAs ESQW in which $100\mathring{A}$-thick GaAs wells are sandwiched between $60\mathring{A}$-thick $Al_{0.04}Ga_{0.96}As$ barriers [8]. Then, we estimate $\alpha = \alpha_w[(100\mathring{A})/(100\mathring{A} + 60\mathring{A})]$, where α_w is the effective absorption coefficient inside each well. The fitting of the experimental data presented in [8] gives $\alpha_0 \approx 100cm^{-1}$, $a \approx 0.09V^{-1}$ and $E_0 \approx 7.2 \cdot 10^4 V/cm$ at $\lambda = 0.873\mu m$.

The photocurrent i_{ph} is given by:

$$i_{ph} = \frac{eP_a}{\hbar\omega} = \frac{eP_{in}}{\hbar\omega}\left(1 - e^{-2\alpha W_i}\right) \approx \frac{eP_{in}}{\hbar\omega} 2\alpha W_i, \tag{3}$$

where e is the electron charge, $\hbar\omega$ is the photon energy, P_a and P_{in} are the optical power absorbed in the i-layer and the incident power, respectively.

We are interested in short optical pulses with a duration t_0 such that $t_{tr} << t_0 << \tau_{rec}$, where the potential φ recovery time τ_{rec} is determined by the diffusive conduction of the P^+ - and N^+ - layers [16] and can be evaluated as $\tau_{rec} = (R^p_{spr} + R^n_{spr} + R_{ext})C \approx R^p_{spr}C$, where $C(W_i, w)$ is the device capacitance, mainly determined by the capacitance of the $P^+ - i - N^+$ - junction, and R^p_{spr} and R^n_{spr} are the spread resistances of the P^+ - and N^+ - layers correspondingly, with $R_{spr} = R_s/8\pi$, R_s being the resistance per square [16]. Then,

$$\varphi(t) \approx \frac{1}{C}\int_0^{t_0} i_{ph}(t')dt'. \tag{4}$$

Using Eqns (2)-(4), we obtain $\frac{d\varphi}{dt} \approx \frac{2eW_i}{\hbar\omega C}\alpha(\varphi)P_{in}(t)$ and, after separation of variables, arrive at the final expression connecting φ to the incident energy fluence F_{in}:

$$\int_0^{\varphi} \frac{d\phi}{\alpha(\phi)} \approx \frac{2eW_i}{\hbar\omega C}\int_0^{t_0} P_{in}(t')dt' = \frac{2eW_iA_X}{\hbar\omega C}F_{in}. \tag{5}$$

where the SESAM cross-section is $A_X \approx \pi w^2$. Solving this transcendental equation for the potential φ gives us φ as a function of the incident fluence F_{in} (see Fig. 2(a)). Substituting the resulting dependence $\varphi(F_{in})$ into equations (2) and (1), we obtain the F_{in} dependences of the electro-absorption coefficient $\alpha(F_{in})$ (Fig. 2(a)) and the reflectivity $R_s(F_{in})$ (Fig. 2(b)), respectively.

We note that the dependences of both the potential φ and the absorption coefficient on the incident light fluence take a particularly simple form when we can assume that $\varphi << V_b$. In that case, we can approximate

$$\alpha(\varphi) \approx \alpha_{uns} - \left|\frac{\partial\alpha}{\partial\varphi}\right|\varphi \tag{6}$$

where the derivative is taken at $\varphi = 0$ and can be easily evaluated analytically, and $\alpha_{uns} = \alpha(\varphi = 0)$ is the unsaturated absorption. Then, we can obtain the expression for the potential in the form

$$\varphi(F_{in}) \approx \alpha_{uns} \left(\left| \frac{\partial \alpha}{\partial \varphi} \right|_{\varphi=0} \right)^{-1} \left[1 - \exp\left(-\frac{F_{in}}{F_{sat}} \right) \right], \tag{7}$$

where

$$F_{sat} = \left(\frac{2eW_i A_X}{\hbar\omega C} \left| \frac{\partial \alpha}{\partial \varphi} \right|_{\varphi=0} \right)^{-1} \tag{8}$$

and for the absorption, in the form

$$\alpha(F_{in}) \approx \alpha_{uns} \exp\left(-\frac{F_{in}}{F_{sat}} \right), \tag{9}$$

which is a well known phenomenological description of slow absorption saturation with a saturation fluence F_{sat}, widely used for QW and QD saturable absorbers (see e.g. [5] and references therein). An explicit expression for the parameter F_{sat} for our mechanism is easily obtained by evaluating $\left|\frac{\partial \alpha}{\partial \varphi}\right|$ at $\varphi = 0$; the result is

$$F_{sat} = \frac{\hbar\omega C}{2eaA_X} \frac{V_b}{V_b + E_0 W_i} \exp\left(\frac{E_0 W_i}{V_b} \right) \tag{10}$$

If the capacitance C is entirely determined by the SESAM layer structure then $C = \epsilon_0 \epsilon A_X / W_i$, with ϵ, as usual, being the relative dielectric permittivity of the semiconductor and ϵ_0,the dielectric permitivity of vacuum. In this case, the saturation flux F_{sat} does not depend on A_X, and the sole reduced parameter that determines F_{sat} is $W_i E_0 / V_b$. The dependence $F_{sat}(W_i E_0 / V_b)$ has a minimum at $W_i E_0 / V_b \approx 1.62$. With $V_b \approx 1.2V$, the minimum fluence is thus at $W_i \approx 0.27\mu m$. For the calculation of the curves shown in Fig.2, we have chosen a slightly smaller value $W_i = 0.2\mu m$, which only slightly compromises F_{sat} while the transit time t_{tr} for the holes is twice smaller than at $W_i = 0.27\mu m$. The $W_i = 0.2\mu m$-thick electroabsortive material consists of 12 ESQWs, i.e. of 13 barriers of $60\mathring{A}$-thick $Al_{0.04}Ga_{0.96}As$ and 12 wells of $100\mathring{A}$-thick GaAs.

We also assume in the calculations that the hole (electron) density in the doped P^+ (N^+) layer is $\sim (10^{17} - 10^{18}) cm^{-3}$. The carrier density in the i - layer is $\sim 10^{15} cm^{-3}$. Such carrier densities are typically used in modelling P-i-N electroabsorptive devices [17] and are indeed normal in both MOCVD and MBE grown undoped GaAs layers [18] [19] and undoped deep AlGaAs/GaAs QWs [19]. At such small carrier densities, the electrical field is approximately constant across the i-layer for $W_i \approx 0.2\mu m$ and $\varphi < 0.7V$ (see fig.2a)).

As can be seen from Figure 2, Eqns. (6) and (9) work well for low F_{in}. In a broader range of F_{in}, $\alpha(F_{in})$ is found to be described quite well by a heuristic expression

$$\alpha(F_{in}) \approx (\alpha_{uns} - \alpha_0) \exp\left(-\frac{F_{in}}{F_{sat}}\right) + \alpha_0, \tag{11}$$

with the same F_{sat} as in Eqn. (9) (see Fig.2a). This expression is mathematically equivalent to treating α_0 as unsaturable background absorption.

As can be seen from Fig.2b, the saturation fluence of the proposed SESAM is much smaller than the one of an all-optical QD device. This is unsurprising as the proposed SESAM belongs to the class of Self-Electrooptic-Effect Devices (SEEDs), for which the switching energy can be much smaller than the one achieved in genuinely all-optical devices [13]. For the specific device of Fig.1, the transit time is $\tau_{tr} \sim 3ps$ and is determined by the hole transit time. Then for a pulse duration of $t_0 \sim 5-10ps$ the recovery time can be as small as $\tau_{rec} \sim 10-20ps$. Such a value of τ_{rec} can be easily obtained for the proposed SESAM when $2w \sim 50\mu m (C \sim 1pF), d \sim 1\mu m$, and the doping level of the P^+ $Al_xGa_{1-x}As$ layer (with a small percentage of Aluminium) is $\sim 10^{18} cm^{-3}$. The recovery time τ_{rec} can be brought down to 5-10 ps, at the expense of a corresponding increase of J_{sat} (assuming the same pulse duration of $t_0 \sim 5-10ps$).

To conclude, we have proposed and analysed, numerically and analytically, a ESQW-based self-electrooptic-device type SESAM construction for operation with pisosecond pulses. Construction dependencies of the parameters of the proposed device have been discussed, and it has been shown that its saturation flux can be as low as $\approx 0.5\mu\text{J/cm}^2$, with the recovery time $\sim 10-20$ ps.

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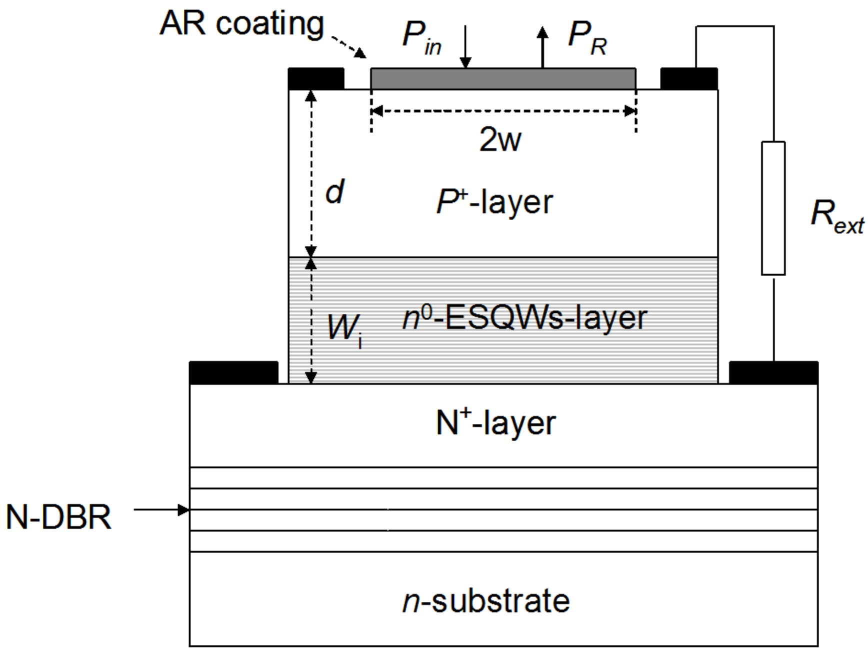

FIG. 1: Schematical view of a self-biased surface normal Extremely Shallow Quantum Well electroabsorptive self-biased SESAM. w is the radius of the light spot.

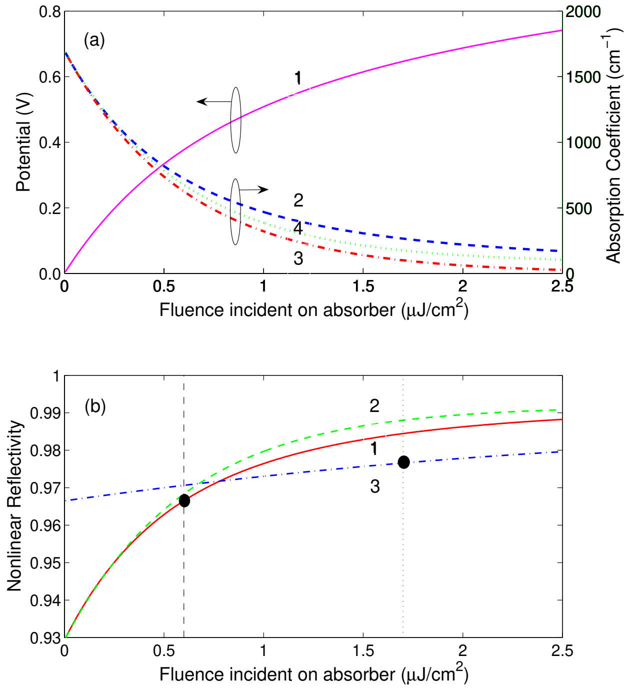

FIG. 2: a) Potential φ (curve 1) and absorption coefficient α (curves 2, 3 and 4) as functions of incident fluence F_{in}. Curves 1 and 2 are the exact solutions of Eqns.(2) and (5); curve 3 is the approximate solution (Eqns.(9)-(10)); curve 4 is the approximate solution(Eqns.(11) and (10)). (b) Reflectivity R_s as a function of incident fluence F_{in}: exact (curve 1) and approximate (curve 2) solutions. $R_{DBR} = 1$ and $\Delta R_{ns} = 0.005$. Experimental results for all optical QD SESAM from [4, 7] with $\Delta R_{ns} = 0.002$ are shown as *3*. Vertical lines denote the saturation fluences for SESAMs of the proposed type and that of [4, 7].