Nonlinear optical effects in $\text{In}_x\text{Ga}_{(1-x)}\text{As}$ quantum systems for saturable absorbers

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Semiconductor saturable absorbers have been used successfully for mode-locking solid state lasers, fiber lasers and semiconductor lasers across a broad range of wavelengths. Quantum well (QW) saturable absorbers have been extensively studied for the mode-locking of solid state lasers, fully integrated semiconductor edge emitter lasers and Vertical External Cavity Surface Emitting Lasers (VECSELs). Other researchers have shown the advantage of using the excitons in QWs to improve the performance in edge emitting mode-locked lasers [1]. More recently, quantum dot (QD) saturable absorbers have been investigated for mode-locking VECSEL [2], solid state [3], and fiber lasers [4] because of their inherent advantage in having low saturation fluence, fast recovery times and broad absorption spectrum.

Unfortunately, most measurements reported in the literature quote external parameters for the saturable absorbers and fail to provide enough information to be able to extract the intrinsic properties of the absorbing material. Even devices with similar cavity configurations and absorbing materials seem to behave very differently.

In this study we present measurements of the intrinsic properties of three quantum systems: bound and excitonic QWs states, and QDs. We start by measuring the external properties of two saturable absorbers, one with QWs and the other with QDs. By fitting this measured external data, we then calculate the intrinsic properties of each of the three quantum systems and compare their merits as saturable absorbing materials.

Device fabrication

We have used components of a semiconductor external cavity laser to characterize the properties of QWs and QDs. The first device is an electrically pumped QW gain medium. A highly reflecting DBR and resonant cavity centered at 976nm were grown on a GaAs substrate by MOCVD. The cavity contains 3 sets of 3 $\text{In}_{0.16}\text{GaAs}$ QWs placed at consecutive antinodes of the standing wave pattern. Photoluminescence and absorption spectra show peaks for emission at 969nm and excitonic absorption at 976nm respectively. An antireflection coating deposited on top of the structure eliminates the sharp resonance and creates a similar standing wave enhancement factor across a broad range of wavelengths. The second device, used to characterize the QDs, consisted of a highly reflecting DBR grown by MOCVD and a cavity with two layers of $\text{In}_{0.5}\text{GaAs}$ QDs at an antinode of the standing wave. The QDs and cavity were regrown on the DBR by MBE. A combination of 2.5 pairs of Si_3N_4 and SiO_2 were deposited on the structure to shift the cavity resonance to 988nm and have a stronger interaction with the QDs.

Figure 1. Left - Measured external $R_{\text{lin}}(*)$, $R_{\text{ns}}(o)$ and $F_{\text{sat}}(+)$. Right - Non-linear reflectivity curve for the QD saturable absorber at 988nm.

Measurements

Using a Ti:Sapphire mode-locked laser producing 150fsec pulses at 80MHz, we have measured the non-linear reflectivity of both samples. We then fit the curves to a comprehensive equation to extract the saturation fluence and saturable absorption versus wavelength. The QW sample was heated to 70°C to move the exciton peak to longer wavelengths and match our laser's mode-locking window. Fig. 1 shows the measured linear reflectivity R_{lin} , the

non-saturable reflectivity R_{ns} , and the saturation fluence F_{sat} versus wavelength for the QW sample. It also shows the non-linear reflectivity curve of the QD sample at the resonance wavelength. The enhancement factor Γ_{avg} , defined as the average intensity of the standing wave at the QW or QD with respect a unity intensity input beam, was calculated for both samples at every wavelength using a simple transfer matrix program. The internal parameters of the absorbing material can then be calculated with the following equations [5],

$$\alpha(\lambda) = \frac{R_{ns}(\lambda) - R_{lin}(\lambda)}{\Gamma_{avg}(\lambda) \cdot N_Q} \quad (1)$$

$$F_{sat,int} = F_{sat,ext} \cdot \Gamma_{avg} \quad (2)$$

where α is the saturable absorption per layer of QWs or QDs, N_Q is the number of QWs or QD layers in the cavity and λ is the wavelength. Fig. 2 compares the internal parameters α and $F_{sat,int}$ versus wavelength for QWs and QDs.

Figure 2. Internal parameters for QWs α (+) and $F_{sat,int}$ (o) and for QDs α (•) and $F_{sat,int}$ (). The QD sample was only tested at the cavity resonance wavelength of 988nm.

The F_{sat} of a quantum state is a direct measure of the inverse of its absorption probability. Accordingly, the absorption probability is strongest in our QD states, closely followed by those of our excitons in QWs. However, the absorption probability decreases rapidly with shorter wavelength for bound states in the QWs. On the other hand, the saturable absorption α is proportional to the product of the absorption probability and the number of states accessible by a given wavelength. The number of accessible states will depend on the spatial density of QDs, the spatial density of excitons, and the density of states in energy of bound QW levels. Therefore, the spatial density of QDs, highly dependent on growth conditions, will determine the total saturable absorption. In our case, we can deduce that the spatial density of our QDs was lower than that of our QW excitons.

Conclusions

We have measured the external non-linear properties of QW and QD saturable absorbers and calculated the intrinsic properties of the quantum systems. We have found low saturation fluences of $8 \mu J/cm^2$ for the QDs, $17 \mu J/cm^2$ for QW excitons, and higher for QW bound states. Thus, QD absorbers are ideal for lasers requiring low saturation fluence and low modulation depths. On the other hand, excitons can also provide low saturation fluence with a higher modulation depth.

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