Two-photon absorption photocurrent enhancement in bulk AlGaAs semiconductor microcavities

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We report on two-photon absorption (TPA) photocurrent in semiconductor microcavities. We experimentally show a substantial increase in the TPA photocurrent generated, at resonance, in a GaAlAs/GaAs microcavity designed for TPA operation at ~890 nm. An enhancement factor of ~12 000 of the photocurrent is obtained via the microcavity effect, which could have an important impact on the use of TPA devices for high speed switching and sampling applications. Our results also show the implications of the cavity photon lifetime on autocorrelation traces measured using TPA in semiconductor microcavities. © *2002 American Institute of Physics.*
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Two-photon absorption (TPA) in semiconductors has recently been shown to be a serious candidate for optical autocorrelation of short pulses and for all-optical switching and sampling of high speed optical data signals in optical time division multiplexed (OTDM) systems. Experiments using TPA for these applications have been performed at many different wavelengths, using different types of semiconductor devices.[1–3] However, because TPA is a very inefficient nonlinear process, it usually requires high intensity lasers or very long detectors, which could make the TPA nonlinearity unsuitable for use in practical autocorrelators and in optical switches and sampling devices for real telecommunication systems.

The use of a Fabry–Pérot microcavity greatly enhances the optical intensity and thus increases the nonlinear response of the embedded material. This was recently demonstrated[4] and the optical Stark (χ^3) effect was shown to be responsible for the high instantaneous reflectivity modulation.

We show here that by using a Fabry–Pérot microcavity, it is possible to greatly enhance the TPA photocurrent. We actually demonstrate that our active length of 0.27 μm is as efficient as 5.4 mm without a microcavity. A detailed theoretical study has already been undertaken,[5] so we focus here on the more technological aspects of the device. A similar effect has previously been shown in an organic material, aminopurine,[6] but the enhancement factor was only ~120 even though high reflectivity mirrors were used. One explanation for this lies in the fact that very short (100 fs) pulses were used which made them spectrally very broad compared with the cavity bandwidth, thus only a small fraction of the spectral range of the pulse is enhanced.

The device studied for TPA absorption is a GaAlAs PIN microcavity photodetector grown on a (001) GaAs (tilted 3°) substrate. It comprises a 0.27 μm $Ga_{0.7}Al_{0.3}As$ active region embedded between two $Ga_{0.5}Al_{0.5}As$/AlAs Bragg mirrors. The front p doped ($C\sim10^{18}$ cm^{-3}) mirror consists of 15.5 pairs, while the back n (Si$\sim10^{18}$ cm^{-3}) mirror contains 35.5 pairs designed for high reflectivity at 880 nm. The cavity resonance was measured at 890 nm and the reflectivity spectrum was in very good agreement with the simulations (the small discrepancies could be explained by small, a few Å, fluctuations in the layer thickness). The device was designed to show significant TPA response ($Eg/h\upsilon\sim1.27$), and low residual Franz–Keldysh absorption at high reverse voltages (estimated to be 0.1 cm^{-1} at 10 V).

The device studied was a 400 μm diam vertical structure etched to ~1 μm in an n-Bragg stack. A SiN layer was deposited to passivate the sides of the mesa and thus to limit the leakage current. A reverse breakdown voltage of 10 V was measured. A high reverse voltage may be needed to improve the overall dynamic range of the device and to reduce the response time (i.e., the time taken to sweep the photocarriers from the active region).

We have used a tunable Tsunami Ti:sapphire laser that delivers 1.6 ps pulses at a 82 MHz repetition rate. We have used standard lock-in techniques to measure the photocurrent. The load resistance was changed from 200 Ω to 20 kΩ to improve measurement sensitivity. Alignment was made by forward biasing the photodiode which then acts as a light emitting diode (LED) that emits at 700 nm. This method allowed us to quickly prefocus the laser spot onto the sample. The spot size was then adjusted by moving the microscope objective which was that mounted on a three-axis holder. The laser spot size in front of the objective was ~3.5

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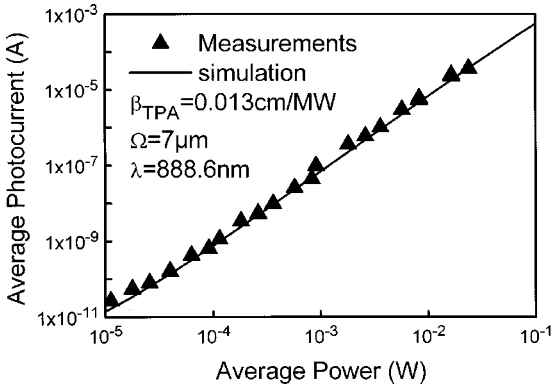

FIG. 1. Measured (triangles) and simulated (straight line) average photocurrent vs the average power.

mm, and the beam was polarized along the [100] axis. We used a 10×0.25 numerical aperture (NA) objective to focus the laser beam onto the device and the laser spot size $(1/e^2)$ was judged to be $\sim 7\ \mu$m. For the device measured the cavity linewidth was measured as 1.12 nm, consistent with the simulations. The resonant wavelength along the diameter of the 400 μm photodiode varied by approximately 0.18 nm and the spectral linewidth of the optical pulses was calculated to be around 0.51 nm by the transform limit approximation.

First, a photocurrent measurement was performed as a function of the incident power (Fig. 1) close to cavity resonance. As expected, a squared dependence of the photocurrent on the incident intensity is clearly observed, demonstrating the two-photon absorption process. We also show the simulation results, in which we took a TPA coefficient of $\beta = 0.013$ cm/MW and linear absorption of 0.1 cm^{-1} which is observed at low intensities.

Then, for a given incident average intensity of 14 mW, we performed a wavelength-dependent photocurrent measurement around the resonance, shown in Fig. 2. Experimental enhancement (a comparison with the same active material thickness and same incident power but with antireflecting mirrors) of close to 12 000 is reached, close to the simulation results that take the spectral dispersion of the pulses into account.

It is interesting to look at the impact of the cavity and the duration of the incident pulse on the TPA generated photocurrent, key factors in determining the optimal structures and operating conditions. This also shows that our structures are close to optimum for the ps duration pulses, which were available for the experimental measurements. The impact of

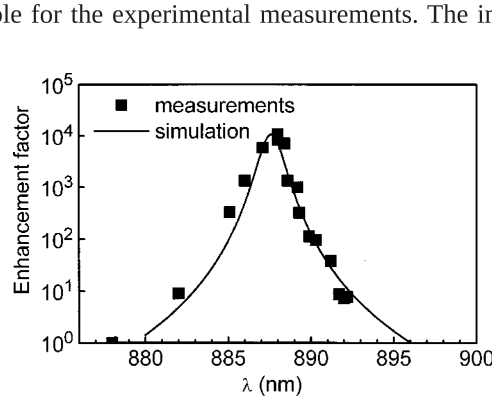

FIG. 2. Photocurrent vs the wavelength across the cavity's resonance.

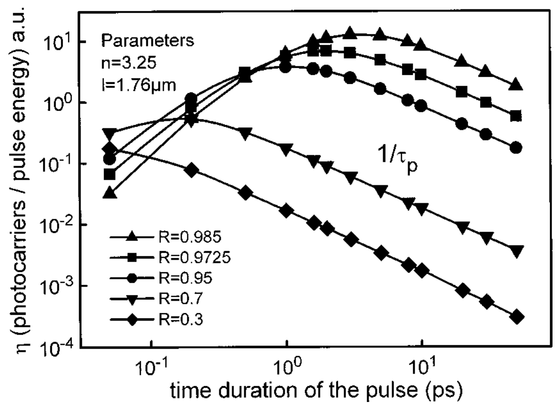

FIG. 3. Simulated photocurrent response (efficiency) vs the duration of the pulse for different cavity reflectivities. The cavity reflectivities given correspond to $R = (R_1^* R_2)^{1/2}$ where R_1 and R_2 are the front (back) mirror reflectivities, respectively. ℓ corresponds to the effective cavity optical thickness, which takes into account the optical field penetration into the Bragg mirrors.

the cavity is investigated by examining the photocurrent efficiency as a function of the cavity's reflectivity, $R = (R_1^* R_2)^{1/2}$ where R_1 and R_2 are the front (back) mirror reflectivities, respectively. We define the photocurrent efficiency as the ratio of the photocurrent to the pulse energy. The simulation was performed by calculating the time dependence of the electric field inside a given cavity with a defined effective length and effective index.

The general behavior seen in Fig. 3 can be explained simply as follows: when the pulse duration, τ_p, is smaller than the cavity photon lifetime, τ_c, the electric field inside the cavity does not reach steady state, thus the intensity is not fully magnified by the multiple reflections. In a similar way, it can be understood from a spectral (Fourier) point of view: when the pulse spectra are too broad compared to cavity finesse, only part of the spectrum is sufficiently magnified by the cavity effect. When the pulse duration reaches τ_c, the interference inside the cavity has time to build up and the cavity intensity magnification effect is sufficient. However, the efficiency of the photocurrent decreases as $1/\tau_p$, because TPA depends on the square of the intensity and the pulse intensity is inversely proportional to τ_p. When integrating over time, we of course get the $1/\tau_p$ dependence. This implies that the cavity effect can be used efficiently for pulses in the ps range for usual semiconductor microcavities (normally of μm length). In our case with cavity reflectivity, $R = 0.9725$, and using 1.6 ps pulses, we nearly reach the op-

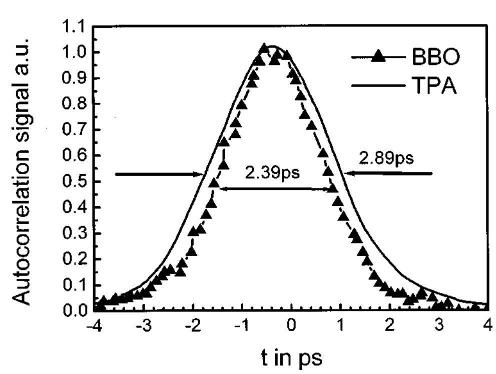

FIG. 4. Autocorrelation signal using a BBO crystal (triangles) and the TPA microcavity device (line).

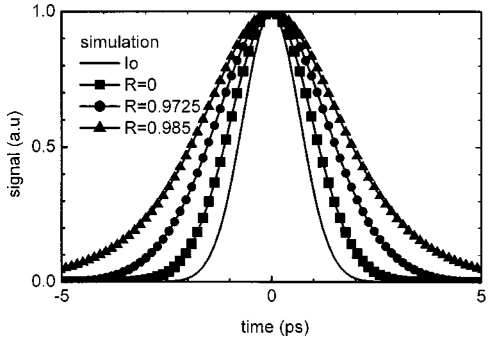

FIG. 5. Simulated autocorrelation signal for a Gaussian 1.6 ps (FWHM) pulse and different microcavity reflectivities. The line is the incident pulse, $I_0(t)$.

timal conditions for enhancement compared to in a noncavity ($R<0.7$) device.

The impact of the cavity on the dynamic response of the TPA microcavity device has also been investigated using autocorrelation measurements and the results were compared to a BBO crystal. As can be seen in Fig. 4, the cavity lifetime elongates the measured autocorrelation pulse width. Using a 1.6 ps pulse (the pulse width is believed to be 2.39×0.65 ps) an autocorrelation pulse width of 2.39 ps was recorded for the BBO crystal compared with 2.89 ps for the TPA device. Furthermore, the cavity effect also changes the autocorrelation trace to a more Lorentzian-like shape.

To check these measurements, the TPA response was calculated for a 1.6 ps full width at half maximum (FWHM) Gaussian pulse (Fig. 5) and it also shows the cavity lifetime effect on the autocorrelation trace for different mirror reflectivities.

In summary, we have shown that, by using a semiconductor microcavity, significant TPA enhancement can be achieved. We have also discussed the impact of the photon lifetime of the cavity structure on the speed of the devices and demonstrated these effects using an autocorrelation measurement. Furthermore, we have shown how the optimal cavity structure can be determined for applications. These initial results are encouraging for the use of TPA microcavity devices for all-optical switching and sampling of OTDM signals in future high speed optical communication systems.

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