Optical non-linearities in III/V quantum dots

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ABSTRACT
We report all-optical switching due to state-filling in quantum dots (QDs). The switching energy is as low as 6 fJ since state-filling requires only 2 electron-hole pairs per QD. The single layer of InAs/InP QDs is inserted within a InGaAsP/InP waveguide, which is processed into a Mach-Zehnder Interferometric space switch (MZI). A 1530-1570 nm probe beam is switched by optical excitation of one MZI-arm from above. By exciting below the InGaAsP bandgap, we prove that the refractive index nonlinearity is entirely due to state-filling in the QDs.

Keywords: Quantum dots, all-optical switching, photonic switching, state-filling.

1. INTRODUCTION
Photonic switching has mainly been investigated in optical amplifiers [1]. All-optical switching in passive materials [2,3] usually requires a high switching energy, due to the small optical nonlinearities. Semiconductor quantum dots (QDs) are expected to provide improved all-optical nonlinearities [4,5] since a single electron-hole pair is able to induce transparency of the ground state transition, while 2 electron-hole pairs are able to completely fill the ground state level of the QD, thus already creating optical gain. At a usual QD-density of 1010/cm², a carrier density of 1010/cm² will generate transparency and thus also a large refractive index variation. This should be compared to a transparency carrier density of 1017/cm² for quantum wells or 1018/cm³ for bulk materials. Due to their delta-function-like density of states, QDs also show sharp excitonic absorption peaks with high peak absorption [5]. We investigate all-optical switching at 1550 nm due to state-filling in a single layer of InAs/InP QDs embedded in a InGaAsP/InP waveguide, which is processed into a Mach-Zehnder Interferometric space switch (MZI).

2. EXPERIMENTAL
The all-optical switching set-up is schematically shown in Fig. 1. The pump beam is a tunable optical parametric oscillator (OPO), which generates 200 fs pulses at 76 MHz repetition rate. The pump beam excites one of the two arms of the MZI from above, i.e. perpendicular to the substrate. The OPO (λ>1350 nm) excites carriers directly into the InAs/InP QDs, without exciting the bulk InGaAsP waveguide core or the InP waveguide cladding. The resulting state-

Figure 1: Schematic picture of the all-optical switching setup using a pump beam from the top to excite the QDs in the upper arm (in the shaded area) of the Mach Zehnder switch. The QDs are contained in the core of the InGaAsP/InP waveguides shown in the right panel, from which the switch is fabricated.
filling in the QDs leads to bleaching of the QD absorption. As a consequence of the Kramers Kronig relations, the absorption bleaching also results in a refractive index variation, which is necessary to partially switch the MZI. The switching is probed by a CW tunable semiconductor laser (1530-1570 nm). The probe beam is coupled into the MZI by microscope objectives. The probe output is focused onto a slit to spatially separate the two outputs of the MZI. The all-optical switching signal is acquired by chopping (2 kHz) the pump beam and measuring the demodulated probe output with a lock-in amplifier. The pump laser excites a surface area of approximately 600x25 μm² around the upper arm of the MZI, as schematically indicated in Fig. 1. Since we pump with a mode-locked OPO, generating carriers with a repetition rate of 76 MHz and a typical decay time [2, 6] of 55-65 ps, while we probe CW, we measure a time-averaged switching efficiency, estimated to be 0.5% of the peak switching efficiency. Great care has been exercised to avoid spurious contributions due to photoluminescence (PL) guided within the waveguide as well as unwanted thermal switching. The magnitude of the PL-contribution was regularly checked by fine-tuning the probe laser, thereby separating the oscillating interferometric switching signal from the constant PL background. Thermally activated switching is not expected for excitation energies below the InGaAsP bandgap where only 0.08 % of the pump light is absorbed [6] by the QDs, resulting in a heating power of 10 nW directly hitting the waveguide. The resulting heating of 0.6 mK results in a Δnthermal≤10⁻⁷, which is negligible compared to the observed refractive index nonlinearity.

3. SAMPLE AND PROCESSING

The QD sample was grown by Chemical Beam Epitaxy on a (100) oriented InP substrate. The QDs are prepared by Stranski-Krastanow growth by depositing 4.3 monolayers InAs at 500°C on top of a lattice matched GaₓIn1-xAs₀.₅₅P₀.₄₅ layer (x=0.25, y=0.55). The QDs are subsequently capped with 0.62 nm InP and annealed for 5 min in PH₃, thereby shifting the PL peak wavelength 100 nm down to 1500 nm [7]. Atomic Force Microscopy of similar uncapped InAs/InP QDs shows a density of 1.4.10¹⁰/cm². The single QD layer is embedded into a 370 nm thick Q1.3 InGaAsP waveguide core, which is covered with a 1.3 μm InP cladding, as shown in Fig. 1. Subsequently, 2x2 Mach-Zehnder Interferometric space switches [8,9] were fabricated, built on 3-dB Multi-Mode Interference input and output couplers. The length of the phase shifting section is 605 μm, with 30 μm separation between the arms.

4. RESULTS

The room temperature photoluminescence (PL) spectrum shown in the inset of Fig. 4, reveals an InGaAsP peak at 1300 nm and a QD PL peak at 1500 nm with 90 meV FWHM. The QD size distribution was intentionally kept this broad for obtaining a wavelength insensitive switching behaviour. The waveguide loss at 1550 nm is 30 dB/cm for TE and 11 dB/cm for TM-polarization, allowing photonic switching experiments with a 0.3 mW TM-polarized probe. Due to the large waveguide loss, Fabry-Perot effects due to reflections between the chip facets are small compared to the all-optical switching signal.
Figure 3: Demodulated probe transmission of versus pump power, showing QD all-optical switching at a pump wavelength of 1450 nm and at probe wavelengths indicated in the figure.

Fig. 3 shows the all-optical switching results for excitation of the QDs at 1450 nm and detection between 1530 and 1570 nm. The pump laser excitation density of 1W/cm² corresponds to a relative QD occupation of 1.4% at the highest power of 0.125 mW presented in Fig. 3. We claim that we observe predominantly all-optical switching, since the demodulated probe signals for the two outputs of the MZI are of similar magnitude and opposite sign, as expected for an induced phase shift. A bleaching of the QD absorption would result in increased probe transmission for both MZI outputs. A second argument for the observation of index of refraction nonlinearities are the strong oscillations of the demodulated probe transmission when we fine-tune the probe wavelength through the transmission characteristics of the MZI, which oscillate as a function of probe wavelength. Finally, at 1150 nm pump wavelength when we also excite the waveguide core, we could clearly observe switching from the cross to the bar output of the MZI on an infrared camera. This confirms that we don’t observe bleaching. At this excitation wavelength, a much larger fraction of the QDs is populated due to carrier capture from the waveguide core. An analysis of the data suggests that the observed switching at 1150 nm excitation wavelength is predominantly due to QD state-filling, while a small part might be due to InGaAsP bandfilling.

The probe wavelength dependence of the all-optical switching signal between 1530 and 1570 nm is also shown in Fig. 3. The switching efficiency is relatively wavelength insensitive due to the intentionally broad size distribution of the InAs/InP QDs. From the PL-spectrum, we observe that the QD PL varies less than 10% in the range 1470-1550 nm. A similar wavelength insensitivity is observed for the probe wavelength dependence.

The pump-wavelength dependence of the all-optical switching signal is presented in Fig. 4. The slow decrease of the all-optical switching signal with increasing pump wavelength confirms that the signal does not arise from the exponentially decreasing Urbach absorption tail from the InGaAsP. The switching behaviour thus cannot be explained by residual InGaAsP absorption. At the excitation density applied, we also do not expect bandfilling in the InAs wetting layer. Summarizing, we conclusively interpret the observed all-optical switching as being due to state-filling in the InAs/InP QDs.

5. SWITCHING EFFICIENCY

We finally estimate the switching efficiency of the all-optical switch. From the results presented in Fig. 3, we observe 2.6.10⁻⁴ rad phase shift at 0.125 mW pump power. Since 10% of this power directly excites the waveguide and the temporal duty cycle is 0.5%, we find a phase shift of 4.2 rad/mW incident power. We correct for the estimated 8.10⁻⁴ absorption strength [6] of a single QD-layer with an uncapped QD-height of 5-7 nm, yielding a maximum switching
efficiency of 5 rad/(μW absorbed power) or a required switching energy of 6 fJ for a π-phase change, assuming that all pump power is absorbed in the QDs. The estimated index of refraction nonlinearity is $n_2=0.08/(μW \text{ absorbed power})$.

We present the nonlinearity as a function of the absorbed laser power, since this is the relevant quantity for all-optical switching, when the pump beam excites one arm of the MZI through a separate third waveguide.

Figure 4: Pump wavelength dependence of the all-optical switching signal showing 2 measurement series. The inset shows the room temperature PL spectrum recorded at 256 mW/cm², showing the InAs/InP QDs luminescence at 1500 nm and the luminescence of the waveguide core at 1300 nm.

Figure 5: Quantum dot ground state transition in combination with the continuum background (Left panel) due to indirect in real space transitions between the wetting layer and the quantum dot confinement levels (Right panel).

6. DISCUSSION

A first interpretation for the observed pump wavelength dependence is Fig. 4 is as follows: at 1550 nm, the pump laser is only resonant with the ground state of the largest InAs/InP QDs, while 1400 nm light is able to excite both the ground states of the small QDs as well as the excited exciton and exciton-phonon states of the larger QDs. Assuming that the QD ground-state transition spectrally overlaps with QD the excited-state transition due to the broad QD size distribution, the total QD absorption is thus expected to decrease with increasing pump laser wavelength, in accordance with our experimental observation.

A second explanation for the increasing switching efficiency with pump photon energy is the continuum background, as schematically depicted in Fig. 5, which has also been observed in single QD photoluminescence excitation spectra (PLE). As first explained by Vasanelli et.al., the continuum background is due to indirect in real-space” transitions between the confined level inside the QD and the wetting layer as shown in Fig 5.
Figure 6: (Left) Cleaved-side photoluminescence spectrum taken at 5K, showing the photoluminescence due to the InGaAsP waveguide core layer at 1260 nm and the QD photoluminescence at 1430 nm, which is predominantly TE-polarized. A TM-polarized light-hole state is clearly not observed. (Right) State-filling in a QD bleaches not only the QD-transitions (vertical arrows) but also the “indirect in real-space” transitions (non-vertical arrows) between the wetting layer valence band and the electron ground state or between the QD hole ground-state and the wetting layer conduction band.

The observed increase of the switching efficiency with pump energy in Fig. 4 might well be due to this continuum background broadened by the QD size distribution.

We are now in a position to discuss the detailed switching mechanism. Since we probe the all-optical switching with a TM-polarized probe beam, the switching can be either due to (i) bleaching of the QD ground-state transition, (ii) bleaching of a confined light-hole transition or (iii) bleaching of the continuum background as shown in Fig. 6b. In all cases, the index of refraction variation is directly related to the absorption bleaching by the Kramers-Kronig transformations. We first checked whether there is a confined light-hole transition within the QD by performing a cleaved-side photoluminescence experiment as shown in Fig. 6a. A confined light-hole state was clearly not observed. A second possible origin of the TM-polarized optical nonlinearity would be the bleaching of the heavy-hole ground-state transition. As shown by Fig. 6a, the QD heavy-hole ground-state transition is also partially TM-polarized, meaning that the bleaching of this transition also generates a TM-polarized optical nonlinearity. We however expect a strong probe wavelength dependence of this nonlinearity since the index of refraction variation is expected to cross zero exactly at the line center of the QD heavy-hole transition. The observed probe wavelength insensitivity of the switching efficiency argues against this explanation.

Although we can not completely rule out that the observed nonlinearity is due to the bleaching of the confined heavy-hole transition, we believe that the increasing switching efficiency with pump photon energy points towards the bleaching of the continuum background. As depicted in Fig 6b, one or two confined electron-hole pairs within the QD are capable to also bleach the continuum background due to the “indirect in real-space” transition between a QD level and the wetting layer. It should be stressed that, in this case, a continuum band can be bleached with a single electron-hole pair. Since the transition between the wetting layer valence band and the lowest confined electron level inside the QD is expected not to be polarized, the bleaching of this background transition will also generate the TM-polarized index of refraction variation we observe. The bleaching of the continuum background is also expected to generate the observed wavelength insensitive switching efficiency. Finally, the bleaching of a continuum band with a single absorbed photon is expected to provide a very large index of refraction variation.

In conclusion, we observe all-optical switching in a Mach-Zehnder switch containing a single layer of QDs. The switching efficiency is 5 rad/(μW absorbed power). The pump wavelength dependence clearly shows that the all-optical switching is due to state-filling within the QDs. We finally emphasize that the excellent switching efficiency is obtained from a 600 μm long phase shifter with a single QD-layer.
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REFERENCES