Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp1282-1283

Quantum Dots in a Vertical Cavity for All-Optical Switching Devices

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1. Introduction

Self-assembled quantum dots are predicted to be a promising candidate for the next-generation photonic devices due to their unique nature of three dimensional confined carrier states.[1] As an optical nonlinear medium, self-assembled InAs/GaAs QDs have been proposed for optical switching with ultra-low power consumption in a Mach-Zehnder interferometer.[2, 3] However, the low density of QD states requires a very long lateral dimension for such lateral transmission type devices and this makes it difficult to integrate into a compact device. For this reason, a vertical structure which can realize low-power, polarization-insensitive, and micrometer-size switching device is desirable.[4]

In this work, we have developed for the first time a reflection-type vertical cavity structure for ultra-fast optical switching which utilizing the nonlinear absorption saturation in self-assembled InAs/GaAs QDs. An all-optical switching device using InAs QDs within an asymmetric GaAs/$Al_{0.8}Ga_{0.2}As$ vertical cavity has been designed and fabricated. Switching times of 32~80 ps have been demonstrated by this structure.

2. Structure Design

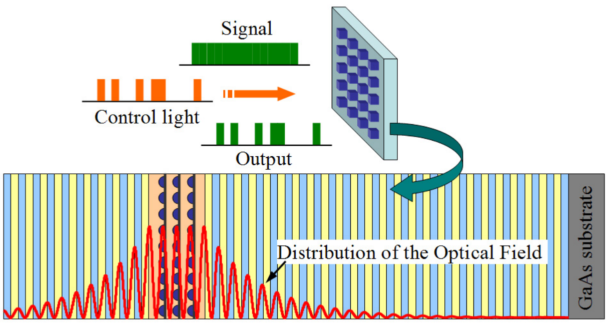

Figure 1. Schematic diagram of all optical switching using QDs as an optical nonlinear source. The vertically aligned Fabry-Pérot cavity consists of 10/25 periods of GaAs/AlAs for the front/back mirrors. Optical field distribution inside the cavity has been shown by an oscillation curve. InAs QD layers are placed at anti-nodes of the optical field.

Figure 1 describes the operation principle of a vertical-cavity QD switch. When a train of optical pulses are injected into the front mirror of a Fabry-Pérot (FP) cavity, saturated absorption of InAs QDs will shift the energy of the cavity resonant mode. This yields a fast modulation of the signal reflection. Based on this mechanism, InAs/GaAs QDs have been integrated into an asymmetric vertical cavity, which consists of 12 periods of GaAs/$Al_{0.8}Ga_{0.2}As$ for the front mirror and 25 periods for the back mirror. A transfer matrix method (TMM) has been employed to aid the design. Fig. 1 shows the calculated spatial distribution of the optical electric field intensity inside the FP cavity. An optical intensity enhancement of 22 times inside the cavity is obtained from the simulation of this structure.

3. Experimental Results and Discussion

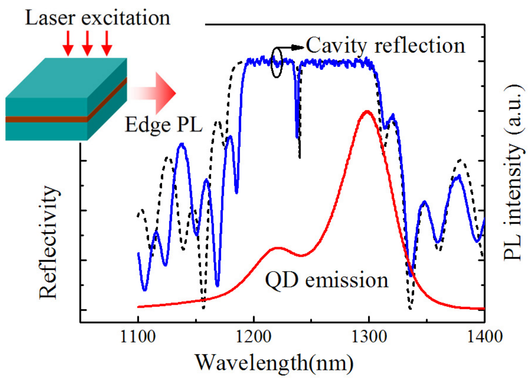

Figure 2. Cavity reflection and PL emission of QDs. For cavity reflection spectra, the solid curve presents experimental results whilst the dashed curve is the theoretical design. The inset shows a edge PL alignment to record the QD emission.

The QD wafer was grown on a GaAs (001) substrate by molecular beam epitaxy (MBE) in an Oxford Instruments V90 system. The InAs QD layers were prepared utilising the Stranski-Krastanow growth mode by depositing 2.6 ML of InAs within an 8 nm $In_{0.15}Ga_{0.85}As$ quantum well to give a dot-in-a-well (DWELL) structure. 3 layers of InAs QDs were placed at anti-node positions of the optical field. The cavity reflection spectra from both experiments and calculations as well as the QD photoluminescence (PL) emission spectrum are shown in Fig. 2. By measuring edge-emission PL, emission peaks of InAs QDs were observed with the ground state (GS) at 1298 nm and the first excited state (ES) at 1220 nm. The reflection spectrum gives a cavity resonant mode with a finesse value of ~600. The cavity mode wavelength is 1238 μm which is close to the QD ES. The dashed curve in Fig. 2 indicates a theoretical design carried out by the TMM simulation. It is well matched by the experimental results.

A conventional pump-probe measurement has been carried out at room temperature to study the switching performance of the QD sample. A pump beam is generated by an optical parametric oscillator (OPO), which provides 130 fs optical pulses with 80 MHz repetition rate. The pump beam excites the front mirror of the FP cavity at the wavelength of cavity resonant mode, while the differential reflectivity is measured by a probe signal beam with a much lower power than the pump beam. An optical delay line controls the time difference between the pump and probe beams, which has a time resolution of 80 fs. A switching process with a time constant of 23 ps has been demonstrated as shown in Fig. 3

Another wafer has been prepared for comparison, with a GS emission peak at 1220 nm and a cavity resonant mode at 1225 nm, obtained by varying the parameters of QD layers and mirrors. This GS switching sample shows a switching time of 80 ps, which presents results comparable with previously reported values for a QD switch using two-dimensional photonic crystal waveguides.[3] The significantly faster response for the ES sample can be explained by the rapid intersubband relaxation of carriers. When an ultra-fast optical pulse pumps at the ES, the absorption of the ES becomes saturated. This switches on the reflection of the signal light. When the pump light is removed, a fast relaxation of carriers into the GS recovers the absorption at ES and this gives a more rapid switch-off of the reflection signal. As a consequence, a faster switching time is suggested and has been experimentally demonstrated now.

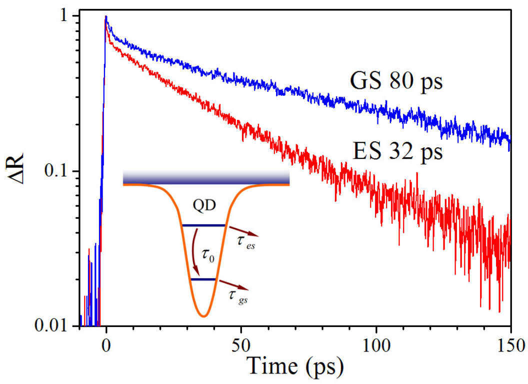

Figure 3. Differential reflectivity as a functionof delay time between pump and probe pulses. The inset shows the carrier dynamics inside a QD.

If we assume that the total carrier escape rate via recombination and thermalization is same for both the GS and ES, the carrier decay times of the GS (τ_{gs}) and ES (τ_{es}) satisfy $1/\tau_{es} = 1/\tau_{gs} + 1/\tau_{rel}$, where τ_{rel} is the carrier relaxation time from ES to GS. By this simple means, a carrier relaxation time of ~53 ps can be predicated in our QD samples. It should be noted that we have simply assumed that there is no remaining carrier in GS during the ES switching process. In a non-ideal case, carriers remaining in GS will accumulate and the relation among delay times deviates from the above relation. Therefore, we can expect an actual relaxation time shorter than 53 ps. Faster sweep out of remaining carriers from the GS (e.g. by introducing non-radiative recombination channels) would be effective to speed up the switching in both cases using GS and ES.

3. Summary

We have proposed an all-optical switch device based on self-assembled InAs QDs within a GaAs/AlAs vertical cavity structure. Pump-probe measurement has shown a switching time of 80 ps via QD GS and 32 ps via QD ES. The fast inter-sublevel transition of carriers inside QDs helps the switching process. These results support that QD materials are suitable for compact ultra-fast all-optical switches and will finally provide cheaper, faster, and reduced power consumption devices for future high-bit-rate telecommunication systems.

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