In this paper, we present an all-optical switch based on self-assembled GaAs/AlAs quantum dots (QDs) within a vertical cavity. Two essential aspects of this novel device have been investigated, which includes the QD/cavity nonlinearity with appropriately designed mirrors and the intersubband carrier dynamics inside QDs. Vertical-reflection-type switches have been investigated with an asymmetric cavity that consists of 12 periods of GaAs/Al_{0.8}Ga_{0.2}As for the front mirror and 25 periods for the back mirror. The thicknesses of the GaAs and AlGaAs layers are chosen to be 89 and 102 nm, respectively. To give a dot-in-a-well (DWELL) structure, 65nm dimension of Si was deposited within an 20nm AlAs QW. All-optical switching via the QD excited states has been achieved with a time constant down to 750 fs, wavelength tunability over 29.5 nm. These results demonstrate that QDs within a vertical cavity have great advantages to realize low-power consumption polarization-insensitive micrometer-sized switching devices for the future optical communication and signal processing systems.

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important to access to the nonlinear operation region of photonic materials, which usually requires high-power excitation. This becomes a well-known problem of the “power/speed tradeoff” [3]. To solve this problem, nanoscale materials such as self-assembled quantum dots (QDs) are particularly attractive due to their small volume as 3-D confined structures [4]. Atom-like carrier states in QDs with very high differential gain/absorption parameters are anticipated to generate high optical nonlinearity with ultralow power consumption. The carrier dynamics inside QDs will further limit the switching performance. To introduce in defect channels by using impurity doping or low-temperature growth techniques was previously suggested for QW and bulk materials [5]. These methods would reduce the absorption strength and hence degrade the optical nonlinearity. In comparison with this, discrete energy states in QDs offer another routing mechanism to manipulate the switching dynamics via energy states higher than ground QD states (GS). The fast carrier relaxation between QD states could be utilized to enhance the device performance.

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2. Principles of the Vertical Cavity QD Switch

Fig. 1(a) schematically illustrates the working principle of a QD switching device with a vertical Fabry–Perot (FP) cavity. The FP cavity consists of two DBR mirrors, which further includes multiple periods of alternating high- and low-index layers. The two DBR mirrors are named the front and back mirrors in this paper. Each individual layer of the DBR mirror has a thickness of \( \lambda/4 \), where \( \lambda \) is the operation wavelength. The cavity region between two DBR mirrors has a thickness \( L \) equal to an integral multiple of \( \lambda/2 \), which is the so-called \( \lambda \)-cavity structure.

The cavity reflectivity spectrum shown in Fig. 1(b) is numerically calculated by using a transfer matrix method (TMM) [6]. A narrow dip exists in the middle of the spectrum (FWHM = 33.35pm), which corresponds to the cavity resonant mode (or cavity mode in brief). Only the light in a narrow wavelength region at the cavity mode can penetrate the cavity. The high-reflectivity region with oscillating side lobes on both sides is the photonic bandgap, which is generated by the 1-D periodicity of the refractive index. When a control light pulse pumps the cavity mode, QDs inside the cavity are excited. The absorption saturation of QDs shifts the cavity mode and hence yields an optical switching process. Due to the Kramers–Kronig relation, if the pump light has a symmetric shape, the change of the refractive index is equal to zero at the central wavelength of the pump pulse. We have simply ignored the carrier heating effect because the switch is operated as a passive-type device and QDs are well separated spatially from each other. Only the absorption saturation is considered in the following theory.
As mentioned in the introduction, energy states higher than ground state (GS) in QDs are also utilized. In Fig. 1(b), QD absorption spectra are depicted with dotted curves. By adjusting the QD size and composition, optical emission from either GS or excite state (ES) can be selected. This provides a simple means to investigate the switching speed with respect to the intersubband relaxation of carriers. At the cavity resonant mode, the reflection from the front mirror can be fully cancelled by the effective reflection from the back mirror. This condition is named the “zero reflectivity condition” [1]. The differential reflectivity is a key parameter to evaluate the switching performance, which corresponds to the reflectivity variation with and without the optical pumping. As discussed later, the maximum differential reflectivity slightly departs from the zero reflectivity condition in the case of QD switches.

For a periodic structure, which comprises two consecutive layers of materials with different refractive indices, the total reflectivity at the cavity resonant wavelength $\lambda$ is derived as [7]

$$R = \left[ \frac{n_0 - n_H (n_H / n_L)^{2x}}{n_0 + n_H (n_H / n_L)^{2x}} \right]^2$$  \hspace{1cm} (1)

where $n_0$ is the refractive index of the incidence medium, $n_H$ and $n_L$ are the refractive indices of high- and low-index layers, respectively, and $x$ is the period number of the alternating high- and low-index layers. For the proposed structure shown in Fig. 1, the reflectivity of the front and back mirrors is given by

$$R_F = \left[ \frac{1 - n_H (n_H / n_L)^{2p}}{1 + n_H (n_H / n_L)^{2p}} \right]^2$$ \hspace{1cm} (2)

and

$$R_B = \left[ \frac{n_H - n_H (n_H / n_L)^{2q}}{n_H + n_H (n_H / n_L)^{2q}} \right]^2$$ \hspace{1cm} (3)

where $p$ and $q$ are the period of the front and back mirrors, respectively. When a $\lambda$-cavity is considered, the reflectivity at the cavity mode is expressed as [8]
where $\Gamma = 2 \int \alpha(l) \, dl$ is the total absorption in a cavity and $\alpha(l)$ is the absorption coefficient. $\Gamma$ is a dimensionless parameter, which comprises the total absorption strength inside the cavity with a certain electric field distribution. $R_{CM}$ reaches its minimum at $R_f = R_g e^{-2\Gamma}$. However, the $\Gamma$ value is extremely small for QD structures, normally on the order of $10^{-4}$[1]. A relatively high-finesse design needs to be addressed for QD switches.

3. Result and Discussion

Vertical-reflection-type switches have been investigated with an asymmetric cavity that consists of 12 periods of GaAs/Al$_{0.8}$Ga$_{0.2}$As for the front mirror and 25 periods for the back mirror. The thicknesses of the GaAs and AlGaAs layers are chosen to be 89 and 102 nm, respectively. To give a dot-in-a-well (DWELL) structure, 65nm dimension of Si was deposited within a 20nm AlAs QW. The nonlinear refractive index of Si is fixed $0.7 \times 10^{-13}$ cm$^2$/W [8]. The reflection spectra of the prepared DBR mirror is shown in Fig. 1(b) together with the absorption and photoluminescence (PL) spectra of the quantum dots Si was deposited within a 20nm AlAs QW. The reflectance of >99.5% is obtained in the fluorescence band region at $1460 < \lambda < 1640$ nm. Optically pumped photoluminescence (PL) spectra were taken under pulsed excitation using a center wavelength 1550nm.

The output PL intensity of quantum dots is plot as a function of wavelength as show in figure 2. The maximum output intensity is occurred around 1.535$\mu$m center wavelength. The Si was deposited within a 20nm AlAs QW with linear and nonlinear (Kerr type) have been increased photoluminescence (PL) intensity. We found that the PL intensity of Kerr type is increased about 1.3 times more than linear QDs at the wavelength 1535nm.

![Fig. 2. Cavity PL emission of QDs as functions of wavelength, dashed curve (---) present the Kerr-type and solid curve (---) present the linear of QDs](image-url)
In figure 3, we shows the power spectrum QD as a function of wavelength, we found that the spectrum resonance at 1.48\(\mu m\) with the output power -74.37dBm, FWHM 0.8nm, and the free spectral range (FSR) of power spectrum is 29.5nm. We found that the switch is fast at the around 1.325\(\mu m\) wavelength. The switching time (delay time) is about 275-ps as show in figure 4.

![Fig. 3. Power spectrum as a function of wavelength for QD wavelength tunable](image)

![Fig. 4. Reflectivity as a function of delay time for all-optical switches](image)

![Fig. 5. PL intensity as wavelength function for varies the wavelength center 0.98\(\mu m\), 1.20\(\mu m\), 1.31\(\mu m\), 1.55\(\mu m\) and 1.70\(\mu m\), respectively](image)
Transmission spectrum of the QDs vertical cavity designed as shown in Fig. 6 for varies the wavelength center 0.98\(\mu\)m, 1.31\(\mu\)m, 1.55\(\mu\)m and 1.70\(\mu\)m, respectively, we found that the minimum transmittance is occurred in 1.20 < \(\lambda\) < 1.36\(\mu\)m range and the maximum transmittance is appeared when the wavelength center is 1.31\(\mu\)m.

We found that at the wavelength center 1.55\(\mu\)m have been showed the maximum output power about -54dB with suitable for transmission data signal in frequency domain. Thus we chose this wavelength center for the transmission in frequency domain as shown in Fig. 7. We found that the FWHM transmittance at the wavelength center 1550nm is 29.21THz for broadband transmission spectrum.
4. Conclusion

In this paper, we present an all-optical switch based on self-assembled GaAs/AlAs quantum dots (QDs) within a vertical cavity. Two essential aspects of this novel device have been investigated, which includes the QD/cavity nonlinearity with appropriately designed mirrors and the intersubband carrier dynamics inside QDs. Vertical-reflection-type switches have been investigated with an asymmetric cavity that consists of 12 periods of GaAs/Al$_{0.6}$Ga$_{0.2}$As for the front mirror and 25 periods for the back mirror. The thicknesses of the GaAs and AlGaAs layers are chosen to be 89 and 102 nm, respectively. To give a dot-in-a-well (DWELL) structure, 65nm dimension of Si was deposited within a 20nm AlAs QW. All-optical switching via the QD excited states has been achieved with a time constant down to 275-fs, wavelength tunability over 29.5 nm. These results are demonstrated that QDs within a vertical cavity have great advantages to realize low-power consumption polarization-insensitive micrometer-sized switching devices for the future optical communication and signal processing systems.

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