Temperature dependence of active photonic band gap in bragg-spaced quantum wells

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Abstract. A novel all-optical polarization switch of active photonic band gap structure based on non-resonant optical Stark effect bragg-spaced quantum wells was investigated and it could be compatible with the optical communication system. The theory is based on InGaAsP/InP Bragg-spaced quantum wells (BSQWs). Mainly through the design of the InGaAsP well layer component and InP barrier thickness to make the quantum-period cycle meet the bragg condition and the bragg frequency is equal to re-hole exciton resonance frequency. When a spectrally narrow control pulse is tuned within the forbidden gap, such BSQWs have been shown to exhibit large optical nonlinearities and ps recovery times, which can form T hz switch. However, the exciton binding energy of InGaAsP will be automatically separate at room temperature, so the effect of all-optical polarization switching of active photonic band gap bragg structure quantum wells can only be studied at low temperature. By a large number of experiments, we tested part of the material parameters of BSQWs in the temperature range 10-300K. On this basis, the InGaAsP and InP refractive index changes with wavelength, InP thermal expansion coefficient are studied and a relationship equation is established. Experimental results show that the bragg reflection spectra with temperature mainly is effected by InP refractive index changes with temperature. Our theoretical study and experiment are an instruction as a reference in the designs and experiments of future practical optical switches.

1.Introduction
As the rapid development of the optical communication, the demand for ultrafast switching is increasingly urgent. However the response time of traditional switches are limited by a variety of inevitable factors. Whereas all-optical switches have attracted more and more interests because of their favorable optical characteristics and much faster switching speed. All-optical polarization switches that make use of nonlinear optical effects in semiconductor multiple quantum wells have exhibited potentials for the application in many fields[1].
The InGaAsP/InP system is the essential for the efficient operation of a number of optoelectronic and transport devices[2]. The all-optical polarization switches adopting InGaAsP/InP bragg spaced quantum wells (BSQWs) is investigated because it can be compatible with the optical communication system. The exciton binding energy of InGaAsP is 3meV in 20K, but it is automatically separated in room temperature, so the optical switch can only be achieved at low temperatures. But, a study of the temperature behavior of the InGaAsP /InP system is lacking.
In this article we report a detailed study of 20 periods InGaAsP/InP BSQWs fabricated by low pressure metal-organic chemical vapor deposition (LP-MOCVD). We have measured the
photoluminescence (PL) spectra of InGaAsP/InP BSQWs in the temperature range 10-300K. In order to understand the temperature behavior of the quantized transitions, we propose a model that takes into account the temperature-induced modification of the exciton energy. And also we have measured the reflection spectra of InGaAsP/InP BSQWs in the temperature range 10-300K. Therefore, through our work we can change some parameters to promote the peak of exciton spectra to equal to the reflection spectra of the BSQWs, which can form THz switch.

2. Experiment details

The BSQWs was fabricated by the LP-MOCVD method in a conventional, horizontal reactor, using trimethylindium, triethylgallium, AsH3,PH3. PH3 diluted to 25% and AsH3 diluted to 5% in H2 as source materials. The 20 periods InGaAsP/InP BSQWs sample was grown on undoped (001) InP substrate. Growth began with a 150nm InP buffer layer, followed by the 8nm In0.76Ga0.24As0.3P0.7 quantum well and 174nm InP barrier layer with all layers undoped. The structure schematic of BSQWs is shown in Figure 1. The LP-MOCVD growth conditions: the chamber pressure is 150mbar, the growth temperature is 620 °C, V/III ratio is 240, the growth rate is 0.3nm/s and 30-seconds growth stop at the quantum well interfaces. Nominal InGaAsP alloy composition was estimated from PL measurements and double x-ray diffraction measurements of the thick layer which were grown under the same conditions. The same thick layer was also used to measure the InGaAsP growth rate. The growth conditions indicated well width 174±0.4nm.

![Figure 1. The structure schematic of BSQWs](image)

For forming resonance frequency, the width of well and barrier have to meet the modified bragg condition:

\[
n_{b}d_{b} + \frac{1+\rho}{1-\rho} n_{w}d_{w} = \frac{\lambda}{2}
\]

(1)

Where, \(n_{b}, n_{w}\) are the refractive indices of barrier and well, \(d_{b}, d_{w}\) are the width of barrier and well,, \(\rho\) is the Fresnel coefficient. \(\lambda\) is quantum well excitonic resonance wavelength[3].

This switch operated by a circularly polarized control pulse to induce circular dichroism and birefringence in multiple quantum wells, and the absorption coefficient and index of refraction for right and left circularly polarized light are different. So this circular anisotropy changes the polarization state of the linearly polarized signal pulse. The change in the signal polarization is subsequently converted to a modulation of the signal amplitude by additional polarization sensitive elements.

The PL measurements were performed with an Ar+ laser(\(\lambda=514.5\)nm) as the excitation source. The signal was dispersed by a 1 m spectrometer and detected by a liquid-nitrogen-cooled Ge p-i-n
photodiode which using conventional lock-in techniques[4]. The sample temperature was maintained in a continuous flow helium cryostat operating in the 10-300 K range.

Displayed in Figure 2 are the PL spectra of the BSQWs for the Photoluminescence spectra at 10, 50, 90, 120, 150, 200, and 300 K. The dominant PL peak positions shift to lower energies and the linewidths broaden with increasing temperature. The maximum of the PL spectra is due to the $E_{1H}$ transition between the $n=1$ electron subband and the $n=1$ heavy-hole subband. At room temperature the light-hole exciton peak $E_{1L}$ can also be seen and its intensity falls with the decrease of the temperature. In 10K, $E_{1L}$ reduction disappeared and just have a sharp perfect spectra, which is the $E_{1H}$ transition only be excited and that is what we want.

To facilitate comparison of PL spectra at different temperatures, the measured peak of each temperature PL spectra are drawn in Figure 3. Below 80K a small shift is observed with decreasing temperature. Using Varshni’s equation to fit the experimental data

$$E_{1H}(T) = E_{1H}(0) - \alpha T^2 / (\beta + T)$$

(2)

where $T$ is the absolute temperature measured in K.

$E_{1H}(0)$ is the $n=1$ electron subband to the $n=1$ heavy energy gap at 0 K, and $\alpha$ and $\beta$ are adjustable parameters. Using Varshni’s equation to fit the experimental data, the obtained values of $\alpha = -0.0008579 \text{eV/K}$ and $\beta = 952.2 \text{K}$.

**Figure 2.** Photoluminescence spectra for the sample at various temperatures. The transition between the $n=1$ electron subband to the $n=1$ heavy flight hole subband is labeled $E_{1H}$. 

![PL Spectrum Diagram](image)
Described in the front of this paper, the BSQW structure is a periodically spaced sequence of quantum wells forming a one-dimensional photonic crystal, thus forming a strong reflection at the range of bragg spaced resonance frequency. We have measured the reflection spectra of BSQWs for the spectral range at 10, 50, 90, 120, 150, 200, and 300 K, which are Shown in Figure 3. The dominant reflection spectra peak positions shift to lower energies and the linewidths broaden with increasing temperature.

The refractive indices and thermal expansion changes of InP and InGaAsP in the infrared have been studied by many researchers. There is generally good agreement among most of the studies on the values of the room-temperature refractive indices, but at some temperatures and wavelengths, no values are available. In our optical switch we can achieved in a temperature range, not just a
temperature dot. We can use the infrared laser interferometric thermometry (IRLIT) to measure the temperature of semiconductor wafers. In IRLIT, a low-power infrared laser which the photon energy is below the band-gap energy of a semiconductor is directed at the wafer of known thickness $h$ which is must polished on both sides. The intensity of an infrared laser beam is transmitted through, or reflected off, and the sample of semiconductor wafer was measured as the sample temperature was slowly varied. Either the reflected or transmitted intensity is measured by a same photodiode. As the temperature of the wafer is increased or decreased the optical path length $nh$ within the wafer increases or decreases, that can cause interference between the reflections in the front and back surfaces. The direction of temperature change can be measured by exploiting variations in wafer thickness, or by modulating the laser wavelength. The change of the optical path length in the semiconductor is dominated by the temperature dependence of $n$,

$$\beta(T) = \frac{1}{n} \frac{dh}{dT}$$

(3)

with a smaller contribution from thermal expansion,

$$\alpha(T) = \frac{1}{h} \frac{dh}{dT}$$

(4)

where $n$ is the sample refractive indices, $h$ is the sample thickness.

Because the interferograms are dominated by changes in the refracion index, $\beta(T)$ can be obtained by subtracting the contribution of $\alpha(T)$ from the interferometric data[5]. Since $\alpha(T)$ is small relative to $\beta(T)$, and well known $\beta(T)$ can be obtained with good accuracy. Using the experimental data in Ref. 19 we have calculated the coefficients of the polynomial expressions for $\alpha(T)$ and $\beta(T)$.

The peak of bragg reflection spectra and the previous calculation on the same graph are shown in Figure 4.

![Figure 5](image_url)

**Figure 5.** Temperature dependence of the Bragg reflection spectra energies for the InGaAsP/InP BSQWs. The dots are experimental test value. The curve is Simulation to Eq.1.
Because $\alpha(T)$ and $\beta(T)$ are increase with increasing temperature[6], result in the dominant bragg reflection spectra positions shift to lower energies and the linewidths broaden with increasing temperature. Computation show that the bragg reflection spectra with temperature mainly is effected by InP refractive index changes with temperature. Through the graph we can see that the bias of theoretical calculations and actual test results is small, within the experimental requirements. Our theoretical study and experiment are an instruction as a reference in the designs and experiments of future practical optical switches.

3. Conclusions
In conclusion, The temperature dependence of PL and reflection spectra in InGaAsP/InP BSQWs has been investigated experimentally and theoretically. The theoretical calculation is in good agreement with experimental results and it is shown that the dominant PL and reflection spectra peak positions shift to lower energies and the linewidths broaden with increasing temperature. However, the changes slope of PL spectra is much faster than that of reflection spectra. So we can design the components of BSQWs, reach the PL spectra peak and the bragg reflection spectra peak intersect within the range at 10 - 80K. The value of this experiment is that it is proved to be the possibility of all-optical polarization switches based on the InGaAsP/InP BSQWs structure, mainly through the design of the InGaAsP well layer component and InP barrier thickness to make the quantum-period cycle meet the bragg condition and the bragg frequency is equal to re-hole exciton resonance frequency. This study can be used as a basis of experimental research of all-optical spin-dependent polarization switching in BSQWs.

Acknowledgements
This work was Supported by the National Natural Science Foundation of China (Grant No. 60877040), National High Technology Research and Development Program of China (Grant No. 2008AA03Z404) and National Basic Research program of China (Grant. 2010CB923204).

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