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Picosecond Optical Bistability of ZnS–ZnTe/GaAs Multiple Quantum Wells on Reflection at Room Temperature

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The optical bistability with picosecond switching time in ZnS-ZnTe/GaAs multiple quantum wells (MQWs) on reflection at room temperature has been studied for the first time. The research results indicate that the switching threshold from high to low state and contrast ratio for the optical bistability are about 1.2 MW/cm^2 and 3:1, respectively. The major nonlinear mechanism for the optical bistability is due to the change of refractive index caused by the band filling effect.

KEYWORDS: optical bistability, ZnS–ZnTe MQWs, band filling effect

1. Introduction

Optical bistability of semiconductor superlattices has recently become an interesting research topic. In particular the optical bistability in semiconductor superlattices with Fabry-Perot (F-P) cavity optimized for operation on reflection has many distinct advantages over those used in transmission, such as the reduced effect of loss and infinite contrast ratio.[1] We have reported the reflection optical bistabilities in ZnSe–ZnS/GaAs multiple quantum wells (MQWs) with nanosecond switching time[2] and in ZnSe–ZnTe/GaAs with picosecond switching time.[3] So far, the picosecond optical bistability in ZnS–ZnTe/GaAs MQWs on reflection still has not been reported. ZnS–ZnTe/GaAs MQWs can cover a wide spectral range from red to blue by changing the well and barrier widths in the ZnS–ZnTe MQWs, and can be expected to be used in optical bistable devices. In this paper, we report the first observation and study of the optical bistability with picosecond switching time in ZnS–ZnTe/GaAs MQWs on reflection at room temperature.

2. Experimental Results and Discussion

The samples studied here are ZnS–ZnTe MQWs of total thickness of 2 μm grown by metalorganic chemical vapour deposition (MOCVD) on GaAs substrate which consists of 100 periods of 5 nm ZnTe wells and 15 nm ZnS barriers. The excitation source is a Nd:YAG laser producing 1 ns pulses at a wavelength of 532 nm with repetition rate of 1 Hz. The time dependence of incident and reflection pulses is received simultaneously using a M176 high-speed streak camera with 2 ps response time. The experimental setup is shown in Fig. 1.

Figures 2(a) and 3(a) show the normalized temporal shapes of incident I_0 and reflection I_r pulses in the ZnS–ZnTe/GaAs MQWs at room temperature in the condition of low and high incident intensities, respectively, and Figs. 2(b) and 3(b) give the resulting hysteresis loops $I_r=f(I_0)$. The experimental results show that the temporal shapes of the incident I_0 and reflected I_r pulses are quite similar under low incident light intensities. However, the 1 ns incident I_0 pulse is compressed into 600 ps reflection pulse under high incident light intensities. This fact indicates that the dependence of the reflection intensities I_r on the incident intensities in the case of low and high incident light intensities is linear and nonlinear, respectively.

In our earier study,[4] we determined that the smooth faces of front and back in ZnSe–ZnS MQWs with high quality can form a simple F-P cavity. Therefore, the major positive feedback mechanism for the optical bistability obtained here can be explained by the effect of a simple F-P cavity from both faces of ZnS–ZnTe MQWs. For a F-P cavity, the optical bistability should be pure absorption or dispersive. The condition for the

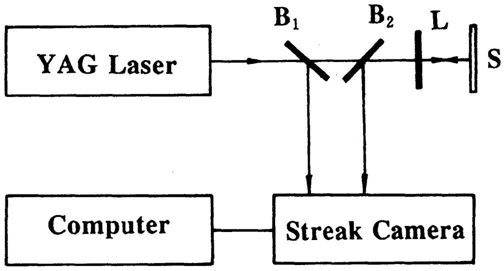

Fig. 1. Schematic diagram for measurement of optical bistability in ZnS–ZnTe MQWs on reflection at room temperature; (B) beam splitter; (L) lens; (S) sample.

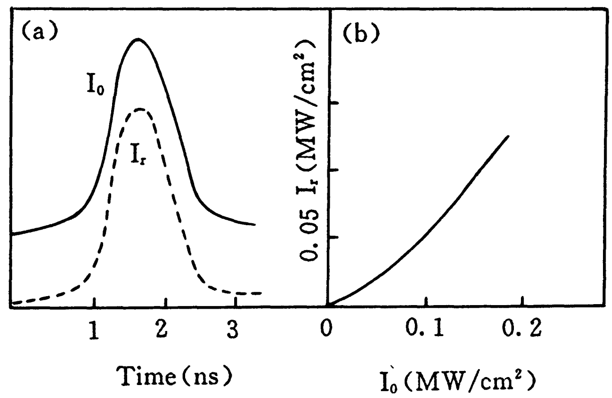

Fig. 2. Time dependence of the temporal shapes of the incident (solid curve) I_0 and reflected (dashed curve) I_r pulses (a) in ZnS–ZnTe MQWs on GaAs substrate at room temperature under low excitation densities. The resulting hysteresis (b).

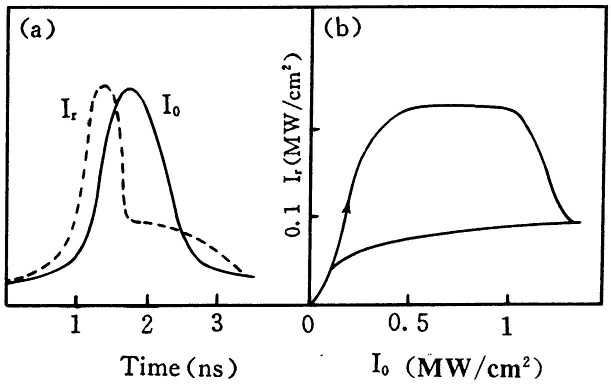

Fig. 3. Time dependence of the temporal shape of the incident (solid curve) I_0 and reflected (dashed curve) I_r pulses (a) in ZnS–ZnTe MQWs on GaAs substrate at room temperature under high excitation densities. The resulting hysteresis (b).

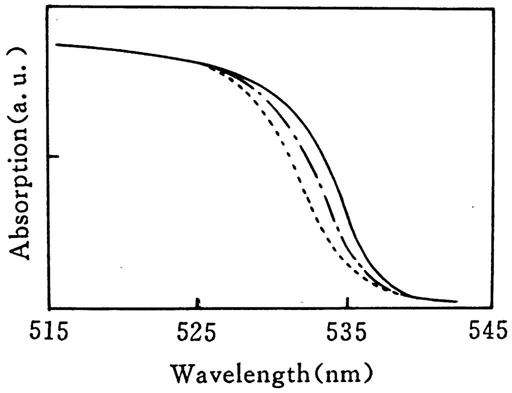

Fig. 4. The absorption spectra of ZnS–ZnTe MQWs at room temperature under different pump intensities; $I=0$ (——), 0.5 (– – –) and 1 MW/cm² (------).

pure absorption optical bistability is[5]

$$\frac{\alpha_0 L}{T+\alpha_b L}\geqslant 8, \tag{1}$$

where $\alpha_0 L$ and $\alpha_b L$ are the linear and unsaturable absorptions, respectively and T is transmission of every face in the F-P cavity. In our case, $\alpha_0 L$ and T are about 0.2 and 0.6, respectively. Obviously, the critical condition for the pure absorption optical bistability is not satisfied in the case for any value of $\alpha_b L$. Therefore, the optical bistability obtained here in the ZnS–ZnTe/GaAs MQWs is dispersive; that is, the major nonlinear mechanism for the optical bistability in the ZnS–ZnTe/GaAs MQWs is due to the change of refractive index in the ZnS–ZnTe MQWs.

In order to study the origin of the change of the refractive index in the ZnS–ZnTe/GaAs MQWs, the band edge absorption spectra are measured at room temperature by a pump-probe technique, as shown in Fig. 4. The pump and probe lights are the 337.1 nm line of a N_2 laser and the tunable dye laser from 510 to 545 nm obtained by using the Coumarin-480 pumped by the 337.1 nm line of the N_2 laser. When the pump intensity reaches 1 MW/cm², the blue shift of band edge absorption is observed in the experiment. On the basis of the nonlinear theories, the major nonlinear mechanisms are the excitonic nonlinear effect and band edge nonlinear effect. In our case, the excitonic absorption in the ZnS–ZnTe/GaAs MQWs is not observed at room temperature; therefore, the excitonic nonlinear effect does not play a major role. On the other hand, the red shift of band edge absorption caused by the heat effect in the ZnS–ZnTe MQWs was not observed, either. Therefore, the heat effect does not play a major role in the optical bistability. The nonlinearities due to band-gap effect include band filling and band shrinkage,[6,7] in which the band filling and band shrinkage appear the blue and red shifts of absorption edge in the absorption spectrum, respectively. On the basis of the above analytical result and the experimental results obtained from the absorption spectra under different pump intensities in the ZnS–ZnTe MQWs, we attribute the major nonlinear mechanism for the optical bistability obtained here to the band filling effect. For a F-P cavity operation in reflection, the reflectivity of the F-P cavity is[8]

$$E=\frac{E+F\sin^2\varphi}{1+F\sin^2\varphi}. \tag{2}$$

In our case, the absorption loss of intensity in the ZnS–ZnTe MQWs is about 0.2 at 532 nm, and the reflectivities of both natural faces in the ZnS–ZnTe MQWs are about 0.4. Therefore, the reflectivity of the simple F-P cavity is

$$R=\frac{2.8\sin^2\varphi}{1+2.8\sin^2\varphi} \tag{3}$$

where

$$\varphi=\left(\frac{2\pi}{\lambda}\right)nL \tag{3.a}$$

and

$$n=n_0+\Delta n. \tag{3.b}$$

Here λ and L are the incident wavelength and the cavity length, respectively. n_0 and Δn are the background refractive index and the change in the refractive index due to the increase of the incident intensity, respectively. According to the Kramers-Kronig relationship, the band filling effect will cause the change in refractive index. The change in refractive index will cause a change in the reflectivity R. When the incident intensity in the ZnS–ZnTe MQWs is high enough, the positive feedback required for the optical bistability can be achieved by the simple F-P cavity with the change of refractive index due to the band filling effect.

3. Conclusions

We have studied the optical bistability with picosecond switching time in the ZnS–ZnTe/GaAs MQWs on reflection at room temperature for the first time, and the switching threshold and the contrast ratio for the optical bistability are about 1.2 MW/cm² and 3:1, respectively. Based on the experimental results obtained here and the theories of nonlinearities and F-P cavity, we attribute the major nonlinear mechanism for the optical bistability to band filling effect, and the major positive feedback for the optical bistability to the simple F-P cavity with the change of refractive index due to the band filling effect. The high switching threshold can be considered by the low reflectivities in the simple F-P cavity. To optimize the F-P cavity,[9] the optical bistability in the ZnS–ZnTe/GaAs MQWs can be expected to become a useful switching device with low switching intensities, fast response time and high contrast ratio.

Acknowledgements

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