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A GaAs/AlAs multilayer cavity with InAs quantum dots embedded in strain-relaxed barriers for planar-type optical Kerr gate switches

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1. Introduction

Ultrafast all-optical switches operating in the 1.55 μm waveband are among the most important devices in high-bit-rate optical fiber communication systems. The planar-type switches are especially attractive for dense parallel processing and simultaneous multichannel demultiplexing. Recently, we have proposed planar-type optical Kerr gate switches based on GaAs/AlAs multilayer cavity structures. [1] The strong internal light intensity due to the cavity effect yields drastic enhancement of nonlinear phase shift in the half-wave length (λ/2) cavity layer. Moreover, the optical Kerr signal intensity caused by the nonlinear phase shift can be further enhanced by using excellent nonlinear materials only in the λ/2 cavity layer. InAs quantum dots (QDs) in the 1.55 μm waveband are one of desirable nonlinear materials in the λ/2 cavity layer, since state filling in the QDs at low-excitation-power results in the large nonlinear refractive index change. [2,3] However, a slow decay (~ ns) of photogenerated carriers in the QDs is a crucial problem for the high-bit-rate operation because it leads to a strong dependence of response signal intensity on the pattern of pulse trains (pattern effect). In our recent study, self-assembled InAs QDs were successfully formed on strain-relaxed $In_{0.35}Ga_{0.65}As$ barrier by molecular beam epitaxy (MBE). [4] The 20-layer stacked InAs QDs with strain-relaxed barriers showed optical absorption in the wavelength range of 1.35-1.65 μm. The fast carrier relaxation of 12-18 ps was demonstrated for the excitation wavelength of 1.35-1.55 μm, [5] which comes from carrier relaxation into the nonradiative centers arising from the crystal defects related to the lattice-relaxation.

In this paper, we report on successful fabrication of the GaAs/AlAs multilayer cavity structure with InAs QDs embedded in strain-relaxed barriers grown by MBE. Two InAs QD layers were inserted into the λ/2 cavity layer consisting of the strain-relaxed $In_{0.35}Al_{0.65}As$ and $In_{0.35}Ga_{0.65}As$ barriers. Decay of phtogenerated carriers in the QD-cavity sample was characterized by time-resolved transmission change measurement based on a pump-probe technique.

2. MBE growth

The QD-cavity sample (Fig. 1) was grown on a semi-insulating (100) GaAs substrate by solid-source MBE. Native oxide on the GaAs substrate was removed by heating up to a substrate temperature (T_s) of 630ºC under As_4 atmosphere in a growth chamber of Varian GEN-II MBE system. After the growth of buffer layers containing AlAs/ $Al_{0.3}Ga_{0.7}As$ (5 nm/232 nm) etch-stopper structure, which is essential for selective removal of the GaAs substrate, [6] a 13-period bottom GaAs/AlAs (111 nm/130 nm) distributed Bragg reflector (DBR) multilayer was grown at T_s = 580ºC under an As_4 pressure of 1×10^{-5} Torr. Then, the λ/2 cavity layer, which includes two layers of self-assembled InAs QDs (3.4 ML) embedded in strain-relaxed $In_{0.35}Ga_{0.65}As$, was grown at T_s = 400°C. Relaxation of the lattice-strain was induced in the bottom $In_{0.35}Al_{0.65}As$ (20 nm) nucleation layer, and the upper $In_{0.35}Al_{0.65}As$ layer was also grown for the structural symmetry. Finally, the 13-period top GaAs/AlAs DBR multilayer was grown at T_s = 400ºC. Growth rates of InAs and $In_{0.35}Ga_{0.65}As$ ($In_{0.35}Al_{0.65}As$) used for the QD formation were 0.35 and 1 μm/h, respectively. On the other hand, the growth rate was 1 μm/h both for GaAs and AlAs layers used in the top and bottom DBR multilayers.

Figure 2 shows cross-sectional AFM image of the QD-cavity sample. Smooth GaAs/AlAs interfaces were clearly observed both in the top and bottom DBRs in spite that the in-plane lattice constant was expanded after the growth of the bottom InAlAs nucleation layer. Low-temperature (T_S = 400ºC) growth of the top GaAs/AlAs DBR is considered to be favorable to form the smooth interfaces.

Reflection spectrum of the QD-cavity sample is shown in Fig. 3. A single cavity mode was clearly observed at a wavelength of 1.46 μm in the center of the high reflection band, indicating good optical quality of the cavity structure.

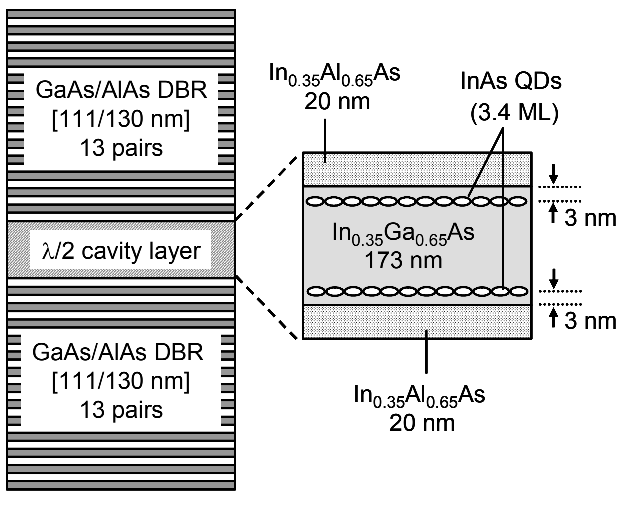

Fig. 1 Structure of the GaAs/AlAs multilayer cavity with InAs QDs embedded in strain-relaxed barriers.

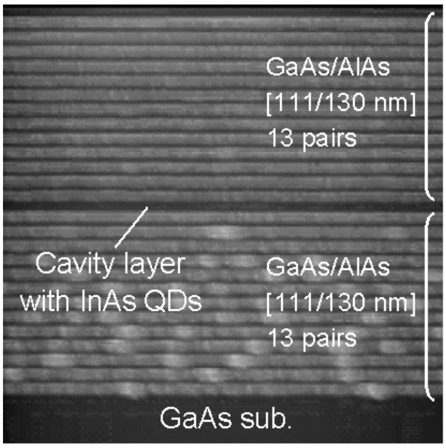

Fig. 2 Cross-sectional AFM image of the QD-cavity sample.

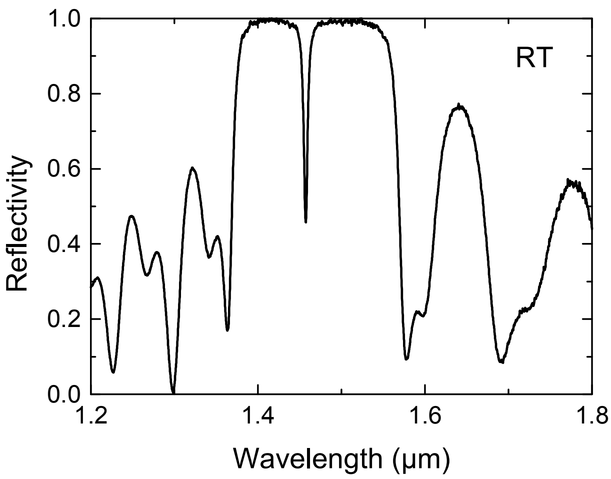

Fig. 3 Reflection spectrum of the QD-cavity sample.

3. Time-resolved transmission change measurement

Temporal behavior of the absorption saturation was studied for the QD-cavity sample after removing GaAs substrate. Before the substrate removal, the QD-cavity sample was mounted on a 1-mm-thick glass substrate using optical adhesive. After curing by UV light, the sample was mechanically polished to thin the GaAs substrate down to ~ 100 μm. The remaining substrate was then removed by selective wet etching using a citric acid-based etchant. [6] Finally, the sample was dipped in a buffered hydrogen fluoride (BHF) solution to remove the oxide layer.

Time-resolved transmission change was measured by a pump-probe method using 0.1 ps pulses with a 100 kHz repetition rate. The center wavelength was tuned in the cavity mode (λ = 1.46 μm). The incident pump beam was nearly collinear with the probe beam, and a mechanical delay stage was used for time delay scanning. Incident powers of the pump and probe beams were 2 and 0.05 mW, respectively, and they were focused on an area of about 140 μm diameter of the sample surface. Figure 4 shows the temporal profile of the transmission change measured at room-temperature. Note that transmission change caused by the absorption saturation was clearly observed in spite that only two QD layers were inserted into the λ/2 cavity layer. This implies that the QD-cavity structure efficiently enhances optical nonlinearity of the InAs QDs. Fast (~ 16 ps) and slow (~ 200 ps) decay components observed in Fig. 4 are attributed to nonradiative and radiative processes of phtogenerated carriers in the QDs, respectively. The fast decay component resulting from the nonradiative process is dominant because numerous crystal defects related to the lattice-relaxation are induced in the λ/2 cavity layer.

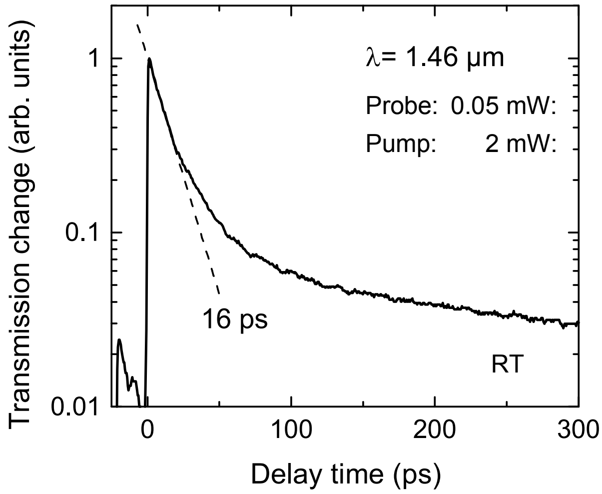

Fig. 4 Transmission change measurement as a function of pump-probe delay.

4. Conclusions

GaAs/AlAs multilayer cavity with self-assembled InAs QDs embedded in strain-relaxed barriers was successfully grown by MBE. Smooth GaAs/AlAs interfaces were formed both in the top and bottom DBRs in spite that the in-plane lattice constant was expanded during the cavity layer growth. Although only two layers of the InAs QDs were inserted into the λ/2 cavity layer, transmission change caused by the absorption saturation was clearly observed in the pump-probe measurement. Fast (~16 ps) decay component, which comes from carrier relaxation into the nonradiative centers arising from the lattice-relaxation, was dominant in the temporal profile of transmission change. Enhanced optical nonlinearity and fast carrier relaxation observed in the QD-cavity sample are promising characteristics for planar-type all-optical Kerr gate switches.

References

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