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GaAs/AlAs multilayer cavity with Er-doped InAs quantum dots embedded in extremely thin strain-relaxed InGaAs barriers for ultrafast all-optical switches

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1. Introduction

Ultrafast all-optical switches operating at 1.55 μm are attractive devices for a high-bit-rate optical fiber communication system. Especially, planar-type GaAs/AlAs multilayer cavities with InAs quantum dots (QDs) embedded in strain-relaxed InGaAs barriers [1-3] is one of the desirable structures for the dense parallel processing and simultaneous multichannel demultiplexing. In this structure, a strong internal light electric field due to the cavity effects yields drastic enhancement of nonlinear phase shift in the half-wavelength (λ/2) cavity layer, which results in a strongly enhanced optical Kerr signal. In addition, the InAs QDs inserted into the λ/2 cavity layer have excellent nonlinearity around 1.55 μm because optical absorption in the QDs is extended to the wavelength range of 1.35-1.65 μm by using strain-relaxed $In_{0.35}Ga_{0.65}As$ barriers [4]. Another characteristic feature of the QDs is the fast decay (~ 18 ps) of the photo-generated carriers into the nonradiative centers arising from the crystal defects related to the lattice strain relaxation [4], which is useful for the reduction of the pulse pattern effect under high-bit-rate operation. Furthermore, the decay time can be further shortened (~ 3 ps) by Er-doping during the molecular beam epitaxy (MBE) of the InAs QDs with strain-relaxed InGaAs barriers [5]. Recently, we have grown the GaAs/AlAs multilayer cavity with the Er-doped InAs QDs embedded in the strain-relaxed InGaAs barriers for the ultrafast all optical switches [6]. However, a growth temperature of a top DBR multilayer was needed to increase to maintain the good structural quality of the sample. This decreases the number of the nonradiative centers and increases the number of slowly decaying carriers (> 300 ps) attribute to the radiative recombination process, which is not desired to the ultrafast all-optical switching.

One effective method to fabricate the good quality structure without increasing the growth temperature of the top DBR multilayer is to use a GaAs/AlAs multilayer cavity with a λ/2 AlAs cavity layer. Since the optical field is strongly enhanced at the center of the cavity layer in this structure, the Er-doped InAs QDs can be embedded in the thinly grown strain-relaxed InGaAs barrier. Note that in previously grown GaAs/AlAs multilayer cavity [2, 3, and 6], the optical field is strongly enhanced at the sides of the λ/2 cavity layer so that InAs QDs should be embedded in the thick (> 200 nm) strain-relaxed InGaAs barriers.

In this study, we fabricated the GaAs/AlAs multilayer cavity with the λ/2 AlAs cavity layer which includes the Er-doped InAs QDs embedded in the thinly grown strain-relaxed InGaAs barrier. Structural and optical properties were characterized by the scanning electron microscopy (SEM) and optical reflection measurements, respectively. Furthermore, time-resolved transmission change measurements were also performed to study the relaxation time of the photo-generated carriers in the Er-doped QDs.

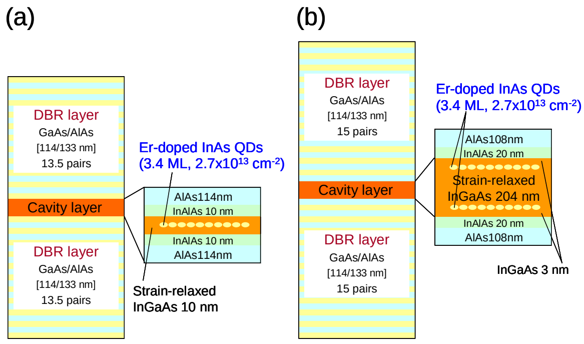

Fig. 1 Schematic of the GaAs/AlAs multilayer cavities with the Er-doped InAs QDs embedded in (a) thin (10 nm) and (b) thick (204 nm) strain-relaxed InGaAs barriers.

2. Multilayer Cavities with Er-Doped QDs

For comparison, two Er-doped QD cavities with thin and thick strain-relaxed InGaAs barriers were grown on a (100) GaAs substrate by a solid-source MBE, as shown in Fig. 1. For the thin strain-relaxed InGaAs barrier sample [Fig. 1(a)], 13.5-periods of bottom and top GaAs/ AlAs (114 nm/133 nm) distributed Bragg reflector (DBR) multilayers were grown at T_s = 580ºC and 480ºC, respectively. The λ/2 cavity layer, which includes single layered Er-doped InAs QDs (3.4 ML) embedded in a thin strain-relaxed InGaAs (10 nm) was grown at T_s = 480ºC. The Er-doped InAs QDs layer was designed to be positioned at the center of the λ/2 cavity layer, where the optical field is the strongest. For the thick strain-relaxed InGaAs barrier sample, 15-periods of bottom and top GaAs/AlAs (114 nm/133 nm) DBR multilayers were grown at T_s = 570ºC and 480ºC, respectively. The λ/2 cavity layer, which includes two layers of Er-doped InAs QDs (3.4 ML) embedded in thick strain-relaxed InGaAs (204 nm) was grown at T_s = 480ºC. Two layers of the Er-doped InAs QDs were designed to be positioned at the strongest region of the enhanced optical field in the λ/2 cavity layer. Er irradiation was performed

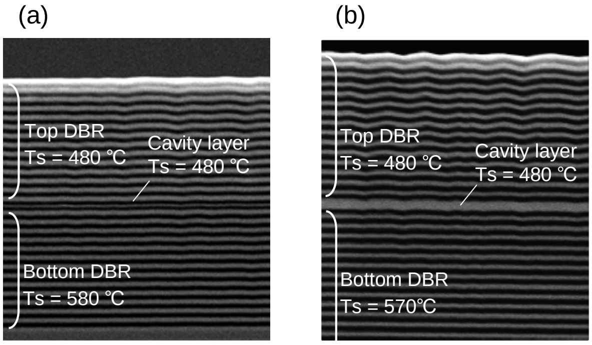

Fig. 2 Cross-sectional SEM image of the Er-doped QD cavities. Er-doped QD-cavity with the (a) thin and (b) thick strain-relaxed InGaAs barriers.

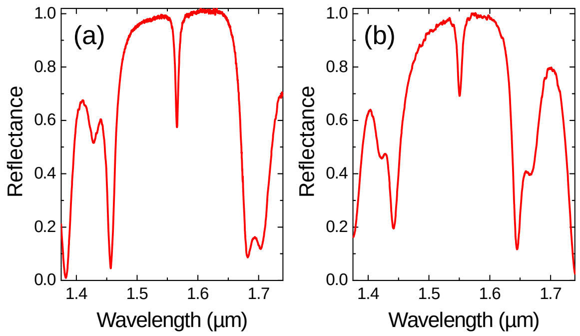

Fig. 3 Reflection spectra of the Er-doped QD cavities with the (a) thin and (b) thick strain-relaxed InGaAs barriers.

only when the QD layer was deposited in the both samples. All the QD layers had an Er sheet density of 2.7 × 10^{13} cm^{-2}.

3. Results and Discussions

Figure 2 shows cross-sectional scanning electron microscopy (SEM) images of the Er-doped QD cavities with thin and thick strain-relaxed InGaAs barriers. Although the top DBR layers were grown at low T_s of 480ºC, the smooth GaAs/AlAs interfaces were obtained by reducing the thickness of the strain-relaxed InGaAs barriers, as shown in Fig. 2(a). Figure 3 shows the reflection spectra for the Er-doped QD cavities with the thin and thick strain-relaxed InGaAs barriers. A clear cavity mode with transmittance of ~0.4 was observed at a wavelength of 1.55 μm in the center of the high reflection band for the for the Er-doped QD cavity with the thin strain-relaxed InGaAs barrier. On the other hand, round shaped stop-band structure with the relatively small transmittance of ~0.3 was observed for the Er-doped QD cavity with the thick strain-relaxed InGaAs barrier. The results of Figs. 2 and 3 indicate that the structural and optical properties were improved by the reducing the thickness of the strain-relaxed InGaAs barriers in the λ/2 AlAs cavity layer.

Time-resolved transmission changes were measured for the Er-doped QD cavities after removing the GaAs substrate by mechanical polishing and selective wet etching.

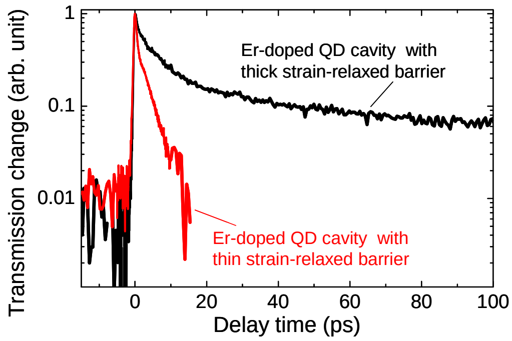

Fig. 4 Temporal profiles of normalized transmission change measured for Er-doped QD-cavities with thin and thick strain-relaxed InGaAs barriers. Top DBR multilayer of the thick strain-relaxed barrier sample was grown at 570 ºC.

Time-resolved measurement for the thick strain-relaxed barrier sample was performed using the same structure but top DBR multilayer grown at high T_s of 570ºC instead [6], because the sample with the top DBR multilayer grown at low T_s of 480ºC had the poor quality of DBR multilayer, as mentioned before. Figure 4 shows the temporal profiles of normalized transmission change measured for the Er-doped QD cavities with thin (T_s = 480ºC) and thick (T_s = 570ºC) strain-relaxed InGaAs barriers. Although only single or two QD layers were inserted into the λ/2 cavity, transmission changes caused by absorption saturation were clearly observed for both cavities. As seen in the figure, the time-resolved signal of the Er-doped QD cavity with the thin strain-relaxed InGaAs barrier showed a full width at half maximum (FWHM) of 1 ps, which is much smaller than that (4 ps) of the Er-doped QD cavity with the thick strain-relaxed InGaAs barrier. We also found that the slowly decaying carriers after 20 ps attribute to the radiative recombination process were extremely reduced by the thinly grown strain-relaxed InGaAs barrier in the cavity layer.

4. Conclusions

Er-doped QD cavities with thin and thick strain-relaxed InGaAs barriers were fabricated by MBE. Sample quality of the Er-doped QD cavity was improved by the reducing the thickness of the strain-relaxed InGaAs barriers in the λ/2 AlAs cavity layer. Extremely small FWHM of 1 ps with large reduction of slowly decaying carriers was observed for the Er-doped QD cavity with thin strain-relaxed InGaAs barrier in time-resolved transmission change measurements.

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