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Excitation wavelength dependence of carrier relaxation in self-assembled InAs quantum dots embedded in strain-relaxed $In_{0.35}Ga_{0.65}As$ barrier layers

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1. Introduction

An ultrafast all-optical switch using the nonlinear optical response is one of key devices in the high-bit-rate optical fiber communication system. InAs quantum dots (QDs) in 1.5 µm waveband are desirable materials for nonlinear phase shifter [1] in the optical Kerr gate switch. However, the pattern effect caused by a slow decay (around a nano-second) of generated free carriers by pump light is a crucial problem for a high-bit-rate operation. In our recent study [2], fast carrier relaxation of 18 picoseconds at 1.5 µm waveband was demonstrated in self-assembled InAs QDs embedded in the strain-relaxed $In_{0.35}Ga_{0.65}As$ barriers grown by molecular beam epitaxy (MBE). The observed fast decay is considered to come from carrier relaxation into the nonradiative center arising from the misfit dislocations in the strain-relaxed barriers. It can be expected that the carrier relaxation should be strongly dependent on excitation wavelength, because carriers are excited in the different-size QDs.

In this paper, excitation wavelength dependence of the carrier relaxation was studied for self-assembled InAs QDs embedded in the strain-relaxed $In_{0.35}Ga_{0.65}As$ barriers. Decay of photo-generated carriers in the QD sample was characterized by time-resolved absorption saturation measurements based on a pump-probe technique.

2. InAs QDs embedded in strain-relaxed barriers

InAs QD structures were grown on semi-insulating GaAs (100) substrates by a solid-source MBE. After the buffer layer growth [GaAs/AlAs (220 nm/130 nm)] at 580ºC, the substrate temperature was lowered to 400ºC. Then 20-nm-thick $In_{0.35}Al_{0.65}As$, 3-nm-thick $In_{0.35}Ga_{0.65}As$ layers and the 3.4 monolayer (ML) InAs QDs were grown under an As_4 pressure of 1×10^{-5} Torr. Growth rates of InAs and $In_{0.35}Ga_{0.65}As$ ($In_{0.35}Al_{0.65}As$) were 0.35 and 1 µm/h, respectively. In order to study the optical properties of InAs QDs embedded in strain-relaxed barriers, we grew the 20-layer stacked InAs QDs separated by 20-nm-thick strain-relaxed $In_{0.35}Ga_{0.65}As$ barriers, as shown in Fig.1.

Figure 2 (a) and (b) show the AFM images of the single InAs QD layer on the lattice-relaxed barrier and the QD layer formed on after 20-layer stacked QDs. The average height and density of the QDs for the single QD layer were 8 nm and 4×10^{10} cm^{-2}, respectively. On the other hand, lower density (1×10^{10} cm^{-2}) and larger size (an average height of 10 nm) of the QDs was observed for the 20-layer stacking case. Moreover, the underling $In_{0.35}Ga_{0.65}As$ strain-relaxed layer showed a relatively undulated surface. Further improvement in growth conditions and precious control of the strain is necessary for stacking of the QD layers with better uniformity.

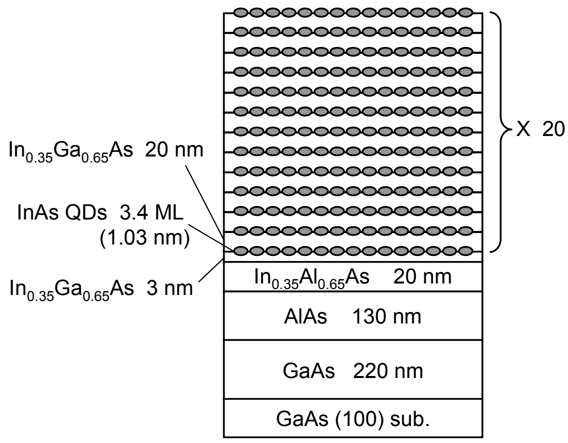

Fig. 1 Schematic illustration of the 20-layer stacked InAs QDs (3.4 ML) separated by 20-nm-thick strain-relaxed $In_{0.35}Ga_{0.65}As$ barriers.

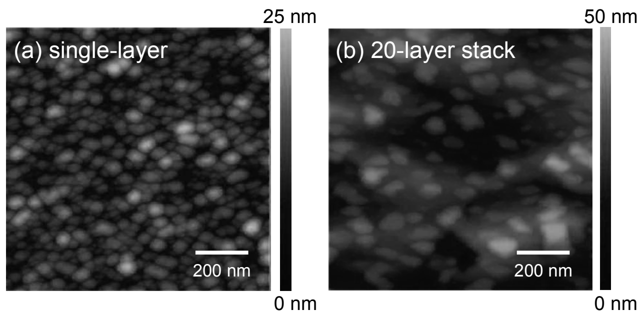

Fig. 2 AFM images of (a) the single InAs QD layer and (b) the QD layer formed on after 20-layer stacked InAs QDs.

3. Optical properties

Figure 3 shows the room-temperature (RT) optical absorption and photoluminescence (PL) spectra of the 20-layer stacked InAs QDs embedded in strain-relaxed barriers. Optical absorption of the QD sample was obtained after the thickness of GaAs substrate was reduced to ~40 µm by mechanical polishing. Optical absorption in the InAs QDs was clearly observed in the wavelength range of 1350-1650 nm. On the other hand, extremely weak PL emission from the QDs was observed around a longer wavelength of 1780 nm. This result indicates that radiative recombinations are possible only for the large-size QDs because of the strong carrier confinement. Moreover, it can be considered that carriers generated in the small-size QDs more easily relax into the nonradiative centers arising from the misfit dislocations in the strain-relaxed barriers.

Figure 4 shows the time-resolved transmission change (RT) of the 20-layer stacked InAs QDs measured by pump and probe method at different excitation wavelengths (λ = 1350, 1450 and 1550 nm). We used ~100 fs laser pulse with 100 kHz reputation rate, and the intensities of pump and probe beam were 2 and 0.05 mW, respectively. Temporal behavior of the transmission change due to the absorption saturation consists of two decay components for λ = 1450 and 1550 nm, while only a single fast decay was observed for λ = 1350 nm. The fast decay component (τ ~ 12-17 ps) is considered to come from carrier relaxation into the nonradiative centers arising from the misfit dislocations. The slow decay component (τ > 100 ps) attributed to the radiative recombination process is well suppressed comparing to the fast component, which is more significant for shorter excitation wavelength. Moreover, decay time of the fast component becomes faster as the excitation wavelength is shortened. A single exponential decay with a very fast decay time of 12 ps was observed when λ = 1350 nm. These results indicate that the generated carriers in the smaller-size QDs more easily escape into the nonradiative centers, and the number of radiative QDs, which keep carriers with long lifetime, is larger in the larger-size QDs. This is consistent with results of the absorption and PL measurements mentioned above. The small-size InAs QDs embedded in the strain-relaxed barriers are favorable for reduction of the pattern effect of ultrafast nonlinear optical switching application.

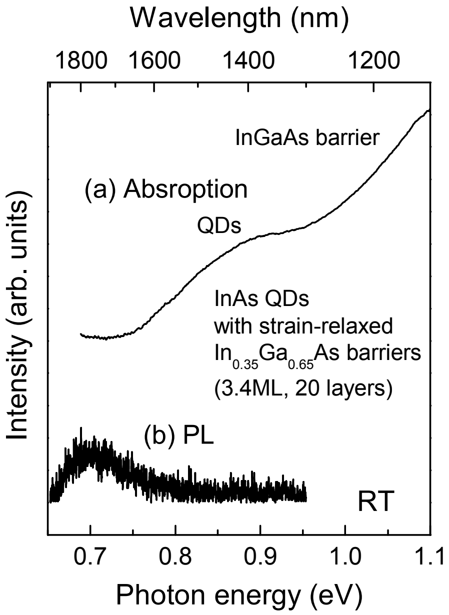

Fig. 3 Optical absorption and PL spectra of the 20-layer stacked InAs QDs embedded in strain-relaxed $In_{0.35}Ga_{0.65}As$ barriers.

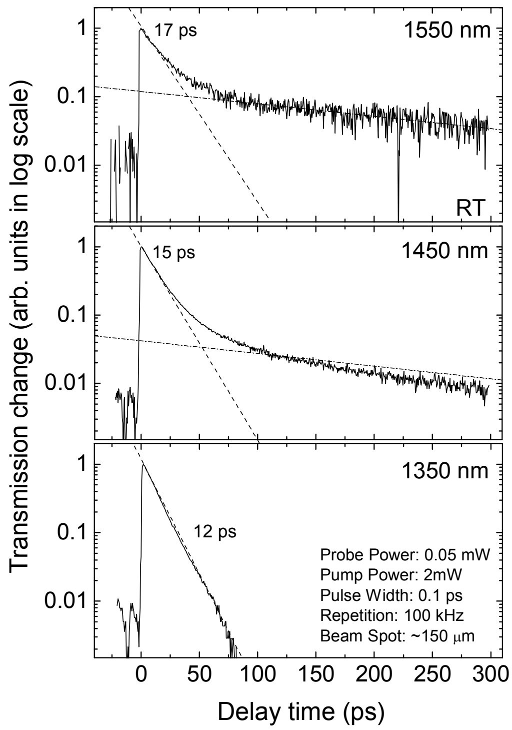

Fig. 4 Delay-time dependence of transmission change measured at excitation wavelengths of 1350, 1450 and 1550 nm.

4. Conclusions

Excitation wavelength dependence (λ = 1350-1550 nm) of carrier relaxation in self-assembled InAs QDs embedded in strain-relaxed $In_{0.35}Ga_{0.65}As$ barriers was investigated by time-resolved saturable absorption measurements. Fast (τ ~ 12-17 ps) and slow (τ > 100 ps) decay components corresponding to the nonradiative and radiative recombination processes, respectively, were observed. Suppression of the slow decay component was more significant for the shorter wavelength excitation, and decay time of the fast component becomes faster as the excitation wavelength is shortened. These results indicate that the generated carriers in the smaller-size QDs more easily escape into the nonradiative centers, and the number of radiative QDs is larger in the larger-size QDs. The small-size InAs QDs embedded in the strain-relaxed barriers are expected to reduce the pattern effect of ultrafast all-optical switching using nonlinear optical responses of the InAs QDs.

References

[1] H. Nakamura, K. Kanamoto, Y. Nakamura, S. Ohkouchi, H. Ishikawa, and K. Asakawa, J. Appl. Phys. **96** (2004) 1425.

[2] T. Kitada, T. Mukai, T. Takahashi, K. Morita and T. Isu, submitted to *15th International Conference on Molecular Beam Epitaxy* (2008).