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Diminished nonradiative recombination in near-surface pseudomorphic $Si_{1-x}Ge_x/Si$ quantum wells

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1. Introduction

Strained silicon-based heterostructures have recently attracted considerable attention in the field of nanotechnology for potential use as electronic and optoelectronic devices. In the context of radiative recombination, compressively strained $Si_{1-x}Ge_x$ quantum wells (QWs) grown on Si(001) have been most widely studied. It is well established that their conduction band offset is so small that electrons are only weakly bound to the $Si_{1-x}Ge_x$ QWs as opposed to the quantum-confined holes [1].

Interestingly, this unique potential lineup allows negative charge build-up in the surface. We have recently identified the existence of charge imbalance due to surface charge build-up in the pseudomorphic $Si_{1-x}Ge_x$ QWs through the excitation power dependence of steady-state (cw) photoluminescence (PL) [2].

In this study, we explore time-resolved PL and temperature dependent PL in an attempt to highlight the role of charge build-up in the radiative recombination in the pseudomorphic $Si_{1-x}Ge_x/Si$ QWs.

2. Experimental

The sample was a nominally undoped pseudomorphic $Si_{0.85}Ge_{0.15}/Si$ double QW grown by molecular beam epitaxy on p-type Si(001). The DQW contains a surface-side QW (QW_2) (34 Å) capped with a Si layer (L_c = 0.6 μm) and a 68-Å-thick QW (QW_1) buried 3.5 μm away from the surface.

The sample was cooled in a closed-cycle refrigerator. Time-correlated single-photon-counting was used for the time-domain analysis. For detection, an infrared-sensitized InGaAs-based photomultiplier (Hamamatsu H9170-75) was used. The detection wavelengths were fixed at the no-phonon line, i.e., 1045meV for the QW_1 and 1067meV for the QW_2, respectively.

3. Results and Discussion

A double-logarithmic plot of the integrated PL intensities from the two QWs taken at 19-K is shown in Fig. 1 as a function of excitation power density. The QW_1 shows a clear tendency of saturation with increasing carrier density. The bimolecular recombination regime ($m \approx 2$) at weak excitation is followed by the excitonic regime ($m \approx 1$) and the Auger regime ($m \approx 2/3$) as the excitation power increases. In contrast, the QW_2 behaves differently. Clearly, we see an S-shaped anomaly, which will be explained in terms of the Shockley-Read-Hall (SRH) recombination [3][4]. As shown in the inset, due to the type-II band line-up of pseudomorphic $Si_{1-x}Ge_x/Si$ QWs, negative surface charge build-up occurs during photoluminescence experiment. This leads to local charge imbalance in the near-surface and in the QWs, which results in diminution of the otherwise active SRH recombination maximizing at an equal density of electrons and holes [3], and thus to an apparently enhanced internal quantum efficiency of luminescence of the *near-surface* QW results. Note that this occurs exclusively at a low level of excitation.

The PL decays of the DQW taken at various

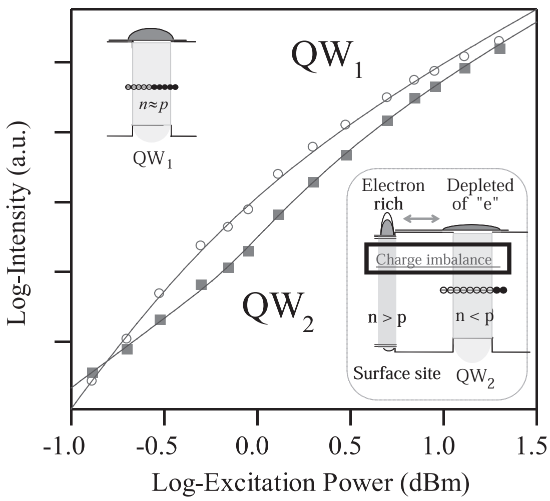

Fig. 1. Excitaion depencence of 19K-PL spectrum of $Si_{0.85}Ge_{0.15}/Si$ DQW with Lz=68Å (QW_1) and Lz=34Å (QW_2). The inset shows the charge imbanalce model in pseudomorphic $Si_{1-x}Ge_x/Si$ DQW. n and p are the densities of electrons and holes, respectively.

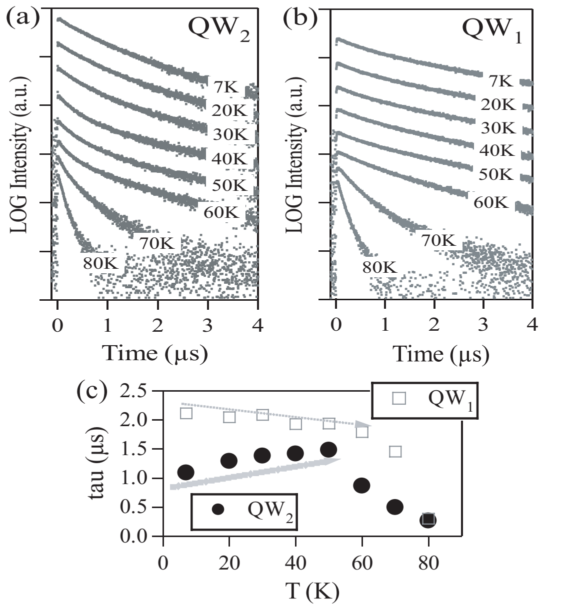

Fig. 2. Synopsis of the decays of the no-phonon PL in (a) QW_2 and (b) QW_1 as a function of temperature. (c) The decay time as a fuction of temperature are plotted.

temperatures are compared in Figs. 2(a) and (b). The excitation power was set at 0.1mW so that the SRH nonradiative recombination operates. The effective PL decay times, defined as the 1/e decay time, as a function of temperature are shown in Fig. 2(c). In the QW_1 (Fig. 2 (b)), the decay time decreases monotonically with temperature, which is in part attributed to thermal activation of the nonradiative (dissipative) recombination channel. As the temperature is raised above 50K, the QW begins to release holes up to the barrier band-edge of Si, which results in even steeper decays.

On the contrary, in the surface side QW (QW_2) (Fig. 2 (a)), the initial PL decay times increase up to 50K. This can be attributed to thermal distribution of electrons, *which is manifest only when the SRH pathways are diminished due to charge imbalance*. As a result, excitonic radiative recombination dominates.

This is consistent with the temperature dependence of cw PL as shown Fig. 3. The PL intensity of the QW_1 (Fig. 3(b)) decreases slowly with temperature due primarily to activation of nonradiative channels and in part to hole release, i.e., standard thermal roll-off. In contrast, the PL intensity of the QW_2 (Fig. 3(a)) remains almost unchanged up to 60K. The hole release only begins to be pronounced above 70 K. Importantly, the influence of the temperature is small at low excitation and temperature in the QW_2 which is the shallower of the two. It therefore turns out that the near-surface QW_2 has higher internal quantum efficiency at low excitation than the other (QW_1).

4. Conclusion

The diminution of the SRH recombination in near-surface pseudomorphic $Si_{1-x}Ge_x$/Si QWs was studied

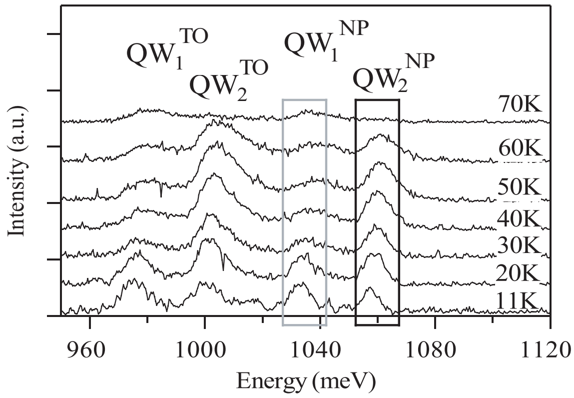

Fig. 3. Temperature dependence of cw PL spectra of DQW at low excitation.

in the time-domain. The results provide clear evidence for the predicted local charge imbalance due to charge build-up of the surface and the QWs.

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