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Localized strain reduction in strain-compensated InAs/GaAs stacked quantum dot structures

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The authors report the effect of localized strain in stacked quantum dots (QDs) with strain-compensation (SC) layers by evaluating the vertical coupling probability of QD formation between stacks measured as a function of spacer thickness. The localized strain field induced at each QD can be partially suppressed by SC layers, resulting in reduced coupling probability with moderate spacer thickness along with the improved QD uniformity and optical properties. The authors have simulated the local strain field along with subsequent QD formation and coupling probability based on a distributed surface chemical potential. By fitting the experimentally derived coupling probability to the modeled values, a 19% reduction of the localized strain field is obtained for the SC structures compared to the uncompensated structures. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2730732]

Formation of highly crystalline, densely stacked quantum dot (QD) structures (spacer thickness $t_s < 30$ nm) becomes important for QD-based optical devices such as lasers (including vertical cavity surface emitting lasers),[1] semiconductor optical amplifiers,[2] modulators,[3] sensors, or solar cells[4] to obtain higher modal gain than a single QD layer can provide. Such QD stacking introduces two types of strain, homogeneous and localized strain fields. Homogeneous strain, which initiated from wetting and cap layers, is similar to strain field in quantum well structure. The localized strain field initiated and propagates vertically from each individual QD, and induces vertically aligned columns of strain-coupled QDs for $t_s < 30$ nm. For $t_s > 40$ nm, the localized strain field becomes diffused and approaches a homogeneous distribution.[5] Accumulated strain can aggravate the internal loss of laser structures by introducing interfacial undulations between the active and *p*-cladding layers and defect formation.

We have so far reported improved optical properties and crystalline quality in stacked QD ensembles by embedding uniform tensile GaP layers between the compressively strained QD layers. The strain-compensation (SC) layers can both reduce overall strain more than 36%, verified by x-ray diffraction (XRD) analyses, and reduce defect density at each layer, as measured by microscopy methods.[5–8] Using SC layers, room-temperature (RT) ground state lasing at a wavelength of 1.27 μm has been demonstrated from a five-stack QD active with a low internal loss and a low threshold current density (J_{th}) of 108 $\mathrm{A/cm^2}$.[5–7] However, while SC layers can easily compensate the homogeneous strain field, it is more difficult to compensate localized strain especially in dense stacks.[9,10] Furthermore, the effect of localized strain is difficult to quantify since it cannot be directly measured by XRD analyses.

Many groups have investigated the strain effect of stacked QDs by varying the spacer thickness.[11–13] An analytical description of correlated island formation under strain fields has been provided by Xie *et al.*[13] This group has shown that self-assembled QDs induce a tensile strain field in the prospective cap layer grown above the islands. When $t_s < 50$ nm, which is within the strain dependent or strain-coupled range, the localized strain fields provide the driving force for vertically aligned QD formation. When $t_s > 50$ nm, the localized strain field becomes diffused and negligible. Subsequent indium deposition produces island formation that is independent of the underlying QDs and thus strain decoupled. The occurrence of strain coupling between adjacent QD layers can be observed and evaluated from microscopy images. Thus, it is possible to quantify localized strain field within SC structures by evaluating the strain coupling probability of QD formation as a function of the spacer thickness for both compensated and uncompensated structures.

In this letter, we report the effect of localized strain in stacked QDs with SC layers by evaluating the vertical coupling probability of QD formation between stacks. We show that the localized strain field is partially suppressed by SC layers, resulting in reduced coupling probability with moderate spacer thickness. Reduction of localized strain field also improves both QD uniformity and optical properties of SC active structures. The coupling probability is estimated from high-resolution scanning electron microscope (HRSEM) data and compared with simulated values based on QD formation in a surface chemical potential induced by a localized strain field. Based on this model, a 19% reduction of localized strain field is obtained in our SC structures compared to uncompensated QD layers.

Samples are grown by low pressure metal-organic chemical-vapor deposition at 60 Torr using trimethylgallium, trimethylindium, tertiarybutylphoshine, and tertiarybutyarsine. Growth is initiated on a GaAs (001) substrate with a 3000 Å GaAs layer at 680 °C, then the temperature is reduced and stabilized for active region growth within the range of 450–520 °C. All active regions consist of a 5 ML $\mathrm{In_{0.15}Ga_{0.85}As}$ buffer layer and a 3 ML InAs QD coverage. We study two sets of five-stack QD samples with varying spacer thickness, ranging from 15 to 45 nm, without SC and with 4 ML GaP SC layers. For the latter type of samples, the SC layers are located at 4 nm above each QD layer as in previous studies.[5] Details of growth optimization are ex-

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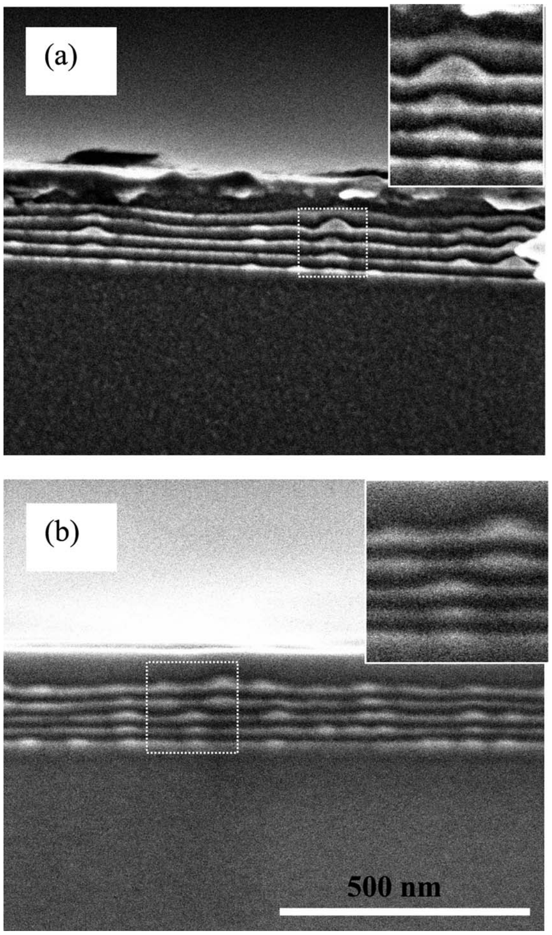

FIG. 1. Cross-sectional SEM images of five- stack QD ensemble with t_s =25 nm (a) without SC and (b) with SC layers showing reduction in coupling probability.

plained elsewhere.[8] Samples are characterized by HRSEM and RT photoluminescence (PL).

Figure 1 shows the [011] cross-sectional SEM images of a five-stack sample with t_s=25 nm (a) without and (b) with SC layers. From the material contrast, the structure without SC layers shows a strong coupling between QD layers with a coupling probability of 0.89. Details of the calculation for coupling probability are described in paragraphs below. The inset of Fig. 1(a) shows that the QD size increases approximately 20% in both width and height due to accumulated localized strain in the QD column. With the presence of SC layers, as shown in Fig. 1(b), the coupling probability reduces to 0.70 with improved QD size uniformity. The inset of Fig. 1(b) shows evidence of strain-decoupled QD formation and suggests compensation of localized strain field with the presence of SC layer.

Figure 2 shows RT PL of a five-stack QD ensemble with t_s=25 nm (as shown in Fig. 1) both with (solid) and without (dashed) SC layers. The corresponding full width at half maximum are 74–67 meV. The SC structure emits at λ =1280 nm, which is similar wavelength to that obtained from a single QD layer. The structure without SC emits at λ=1340 nm due to increased QD size. The integrated PL intensity of the SC sample increases by a factor of 1.62 compared to the uncompensated sample as a result of reduced nonradiative recombination centers. In addition, a small peak at λ=1360 has been observed from SC sample, due to bimodal QD formation, as described in our previous work.[5]

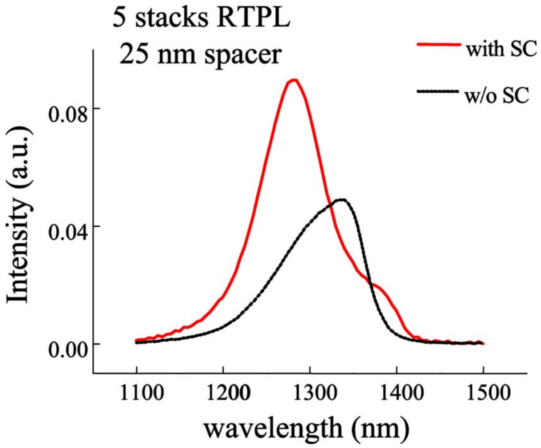

FIG. 2. (Color online) PL spectra comparing QD active regions with and without SC layers at t_s=25 nm showing improved emitting efficiency with SC layers.

Figure 3 shows a schematic illustration of the In atom migration process on the stressed surface. Assuming an isotropic crystal, where the strain interact in the same manner regardless of the crystal orientation, the two-dimensional localized strain component on the surface along x axis can be expressed by[13]

$$\varepsilon_{xx}^{\mathrm{GaAs}}(x,t_s) = 2A\varepsilon_0 \frac{r_0^3}{(x^2+t_s^2)^{3/2}}, \tag{1}$$

where r_0 is the radius of the equivalent spherical QD, t_s is a barrier thickness, $A=3B_{\mathrm{InAs}}/3B_{\mathrm{InAs}}+2E_{\mathrm{GaAs}}/(1+\upsilon_{\mathrm{GaAs}})$ =0.572 and ε_0 ($\sim$0.07) is the lattice mismatch between InAs and GaAs. This equation indicates a localized strain field which is very strong at the QD site, but reduces in intensity with vertical propagation. The strain field from a buried QD introduces an inhomogeneous distribution of surface chemical potential. Surface chemical potential for InAs as a function of strain on a flat GaAs surface can be described as[14]

$$\mu(x,t_s) = \mu_0 + \frac{\Omega_{\mathrm{InAs}}}{2E_{\mathrm{InAs}}}\sigma_\tau^2, \tag{2}$$

where μ_0 is the surface chemical potential of bulk InAs, Ω_{InAs} is the atomic volume, σ_τ is tangential stress at surface. From Eqs. (1) and (2), probability of QD formation on the top of buried QD depends on the distribution of surface chemical potential, which is a function of average lateral separation between QDs (l). The coupling probability is proposed by Xie *et al.*[13]

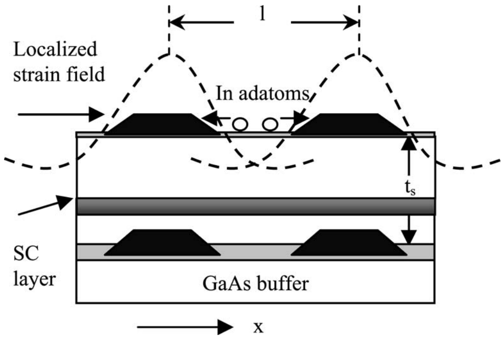

FIG. 3. Schematic illustration showing the indium atom migration process on the stressed surface.

$$P(t_s) = \frac{d}{l} + \left(1 - \frac{d}{l}\right)\frac{1}{Q}\frac{\sinh Q}{\cosh Q + t_s/r_0^3 l/8L_D A 2E_{\mathrm{InAs}} k_B T/\Omega_{\mathrm{InAs}}(xC_{11}^{\mathrm{InAs}}\varepsilon_0)^2 I/I - 1 \sinh Q}, \tag{3a}$$

$$I = (l^2/4t_s^2 + 1)^{3/2},$$

$$Q = (l - d)/2L_D, \tag{3b}$$

where QD widths of $d \sim 30$ nm and $l \sim 100$ nm are determined by atomic force microscopy results. The variable x represents the coefficient of strain field initiating from a buried QD to the upper surface such that $x = 1.0$ for a structure without strain-compensation layer.

The summarized coupling probability obtained from SEM as a function of spacer thickness is shown in Fig. 4. For closely stacked QDs ($t_s < 15$ nm), there is no difference in coupling probabilities between compensated and uncompensated structures due to the strength of localized strain field. The coupling probabilities in both structures are approximately 100%. For a thicker spacing ($t_s > 25$ nm), the localized strain field diffuses and we can observe that the coupling probabilities are suppressed by the SC layer. By combining Eqs. (1)–(3), using a diffusion length parameter L_D ($\sim$280 nm),[13] we can treat r_0 of Eq. (1) as the only unknown. A value of $r_0 = 6.1$ nm is found to be reasonable fitted with our experimental result for structure without SC (solid), as shown in Fig. 4. By using the same parameters and fitting to SC data, treating x as unknown, we obtain $x = 0.81$. This x value indicates 19% reduction of localized strain field with the presence of SC layers from experimental results. This amount of strain reduction is approximately half of the value in case of homogeneous strain compensation (36% reduction) obtained from XRD results.[5] This result indicates that compensation of localized strain is more difficult than homogeneous strain.

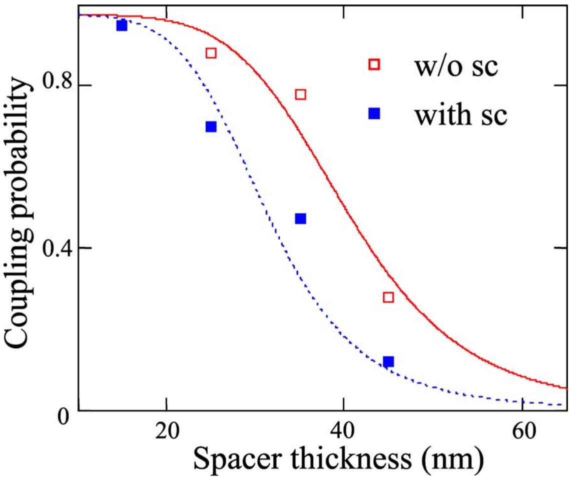

FIG. 4. (Color online) Experimental (squares) and simulation (line) results of coupling probabilities as a function of the spacer thickness.

In conclusion, we have reported a method for evaluating localized strain in SC QD structures. The localized strain field is initiated by buried QD and cannot be observed by normal XRD techniques since it is inhomogeneous within the matrix. As the strain field propagates vertically, the strain energy field diffuses and the maximum of the strain field reduces. Thus, probability of strain coupling between QD layers is inversely proportional to the spacer thickness. To evaluate the effect of SC layers on localized strain, we have studied a series of sample with different spacer thicknesses. We found that the strain coupling probabilities can be suppressed by SC layers, suggesting reduction of localized strain field from buried QD. A 19% reduction of localized strain is quantified for our SC structure by using a model based on nature of strain field induced QD formation. Localized strain reduction also results in improved QD uniformity and optical properties of SC active region, which would be important to the performance of QD lasers.

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