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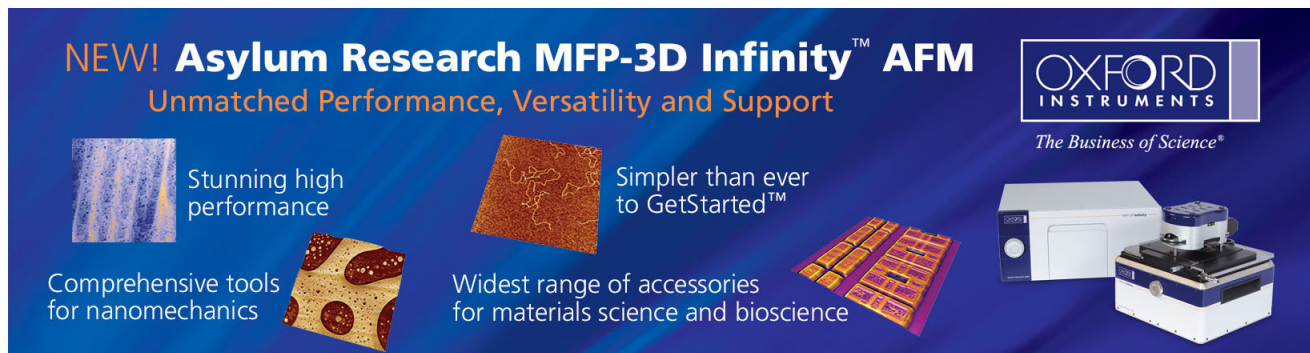
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Effects of tensile, compressive, and zero strain on localized states in AlInGaN/InGaN quantum-well structures

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The recombination dynamics of optical transitions as well as strain effects in AlInGaN/In_{0.08}Ga_{0.92}N quantum wells (QWs) were studied. QW emission energy, photoluminescence decay behavior, photoluminescence emission line shape, and nonradiative recombination behavior were found to be strong functions of strain as well as localization. The degree of carrier localization was inferred by modeling several aspects of optical behavior obtained from variable temperature time-resolved photoluminescence experiments. According to the modeling results, the degree of localization was found to be a minimum for unstrained QWs and increased as either tensile or compressive strain increased, indicating that InGaN QW microstructure is a function of the lattice-mismatch-induced strain experienced during deposition. © 2002 American Institute of Physics. [DOI: 10.1063/1.1469219]

Optical transitions in InGaN quantum-well (QW) structures play an important role in nitride light-emitting devices. It has been proposed that the luminescence originates from localized states at potential minima or quantum dots due to fluctuations of indium composition in the InGaN QW.¹ Others have argued that the optical transitions originate from QW states under the influence of the strain-induced piezoelectric field.² These previous studies were carried out with the InGaN well subjected exclusively to compressive stress as part of GaN/InGaN QW structures.

In the present work, we will study the optical transitions in InGaN QWs subjected to compressive, tensile, and zero stress. This can be realized through the use of AlInGaN quaternary alloys. We have previously reported the use of strain engineering to control the emission wavelength, emission intensity, and two-dimensional electron gas (2DEG) properties in AlInGaN/InGaN QW structures.^{3,4} Now, we report on the effect of strain on InGaN composition fluctuation by studying carrier lifetime, photoluminescence (PL) emission spectra, and activation energy for nonradiative transitions in the AlInGaN/InGaN QW structures.

AlInGaN/InGaN single-QW structures were grown by metalorganic chemical vapor deposition. The details of growth conditions and test structure used to vary the lattice-mismatch-induced strain experienced by an InGaN QW have been previously reported.^{4,5} The growth parameters were adjusted so that the In_{0.08}Ga_{0.92}N well was subjected to biaxial strain ranging from -0.86% (compressive) to 0.35% (tensile). Time-resolved photoluminescence of these variably strained InGaN quantum wells was performed to study the recombination mechanisms.

InGaN QWs are known to contain some degree of carrier localization due to compositional inhomogeneities. Ac-

cording to the model of Osinski *et al.*, the effect of these fluctuations on the band structure can be represented by a Gaussian density of states (DOS) characterized by a broadening term σ , related to the degree of fluctuation.⁶ In the presence of such localizing effects, the temperature dependence of the QW emission energy does not follow the same temperature dependence of the band gap. The peak emission energy variation with temperature is given by:⁷

$$E_{\text{QW}}(T) = E_{T=0} - \frac{2\alpha}{\exp(\Theta/T) - 1} - \frac{\sigma^2}{kT} \quad (1)$$

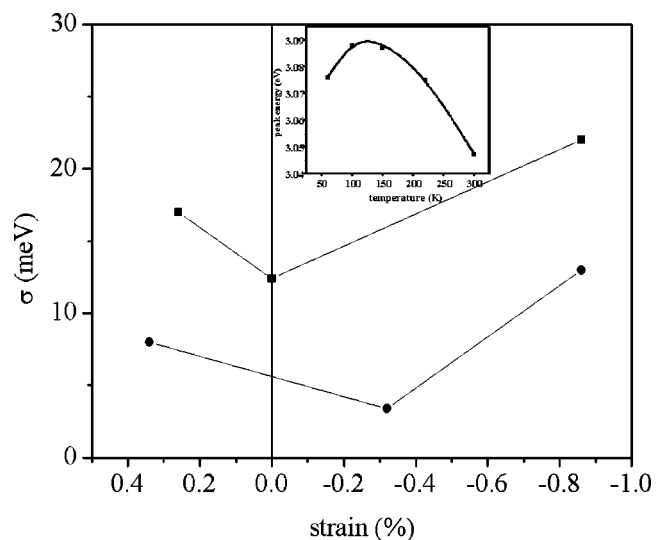


FIG. 1. Localizing parameter for peak energy position, σ , versus strain for (squares) 3 nm QWs and (circles) 9 nm QWs. (Inset) Experimental data for 3 nm unstrained QW are presented by squares and the line represents the best fit to Eq. (1) using " σ " as the fitting parameter.

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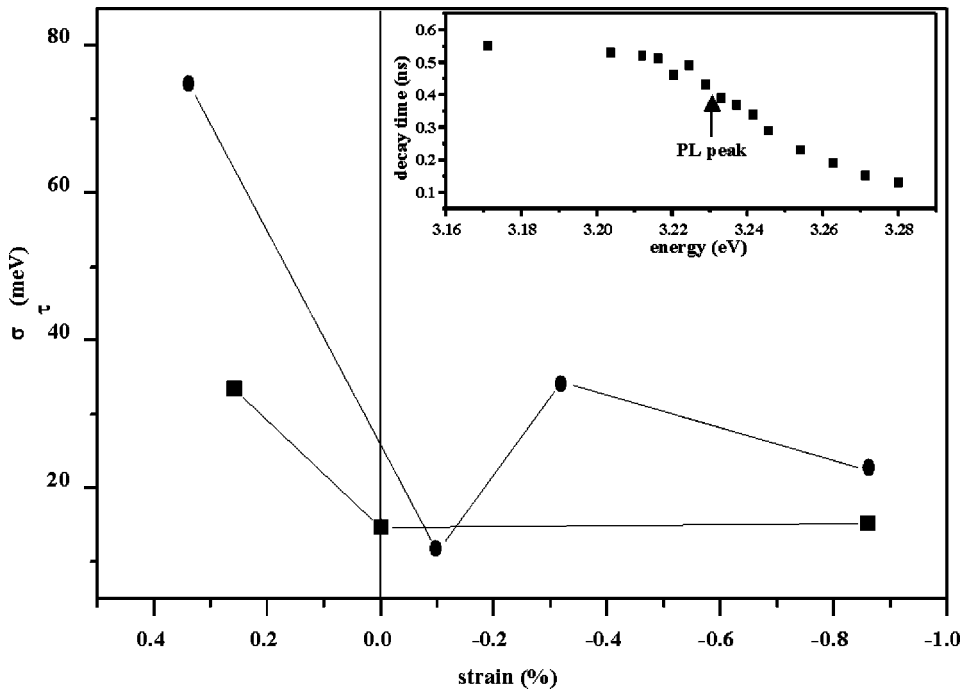


FIG. 2. Plot of localizing parameter σ_τ versus strain for (squares) 3 nm QWs and (circles) 9 nm QWs. (Inset) PL decay time versus energy for 9 nm QWs under -86% compressive strain.

where $E_{T=0}$ is the QW transition energy at 0 K and σ^2 reflects the degree of carrier localization. The parameters α and Θ measure the strength of the electron–phonon coupling and the average phonon temperature, respectively.

This relationship was used to model the temperature-dependent QW emission peak measured and shown in Fig. 1 inset with σ as the fitting parameter. Figure 1 shows the dependence of the best-fit σ for the 3 and 9 nm QWs versus strain. The degree of localization, reflected by the magnitude of σ , is smallest for the least strained sample and increases as strain increases.

Another means to observe the effects of carrier localization is through the energy dependence of the PL decay time. In Fig. 2 inset, the effective PL decay time is plotted versus energy for the 9 nm QWs under no strain and compressive strain, respectively. For the strained QW, the lifetime increases at energies below the QW peak emission energy. This was observed whether the well is under tensile or compressive strain. For the unstrained QW, the lifetime actually decreases at energies about 20 meV below the peak emission energy. This behavior is understood when the effects of carrier localization are considered as follows: The decay time reflects both recombination and carrier transfer to localized states, thus the decay time, or effective lifetime, variation with transition energy can be expressed by the following relationship:⁸

$$\tau(E) = \frac{\tau_{\text{radiative}}}{1 + \exp[(E - E_0)/\sigma_\tau]}, \quad (2)$$

where E_0 is an energy corresponding to the point where $\tau(E)$ equals $\tau_{\text{radiative}}$ and σ_τ is a parameter that reflects the degree of localization, though it is not necessarily the same as the σ used in Eq. (1). We fit Eq. (2) to the effective lifetime data for the 9 nm QWs as well as the 3 nm QWs using σ_τ as the fitting parameter. The results, plotted in Fig. 2 show that the value for the localization parameter is a

minimum for the unstrained QWs and generally increases if the QW is grown under biaxial compression or tension.

Another effect of carrier localization is reflected in the PL emission line shape. The spontaneous emission spectrum, $R_{\text{sp}}(h\nu)$, for a QW can be approximated by the following expression:⁹

$$R_{\text{sp}}(h\nu) \propto N(h\nu) \exp(-h\nu/kT), \quad (3)$$

where $N(h\nu)$ is the joint DOS related to the convolution integral of the QW step-like DOS and the Gaussian band tail DOS contributed by the localized states. Embedded in $N(h\nu)$ is a broadening parameter, σ_{PL} , related to the degree of localization that strongly effects the PL line shape.⁹ Fitting Eq. (3) to the PL spectra, shown in the Fig. 3 inset, of the 3 nm and 9 nm QWs using σ_{PL} as the fitting parameter, yields the results of Fig. 3. Just as was seen for the peak energy data and the effective lifetime data, the value of the fitted localization parameter is a minimum for the unstrained QWs and increases as strain is increased.

Additional information about the recombination mechanisms in InGaN QWs is gained by analysis of the variation of PL intensity with temperature. The luminescence intensity is governed by the respective rates of radiative and nonradiative recombination, each having a characteristic temperature dependence. For recombination in a QW, the temperature dependence of the emission intensity can be modeled by the following Arrhenius relationship^{10,11}

$$\frac{I(T)}{I(T=0)} = \frac{1}{1 + cT e^{-E_a/kT}} \quad (4)$$

where E_a is the activation energy of the nonradiative recombination process, c is another fitting parameter, and $I(T)$ is the PL emission intensity at temperature T .

A plot of emission intensity versus inverse temperature is presented in the inset of Fig. 4. The reduced emission intensity from the QW with increasing temperature is a thermally activated process. As the temperature increases, more

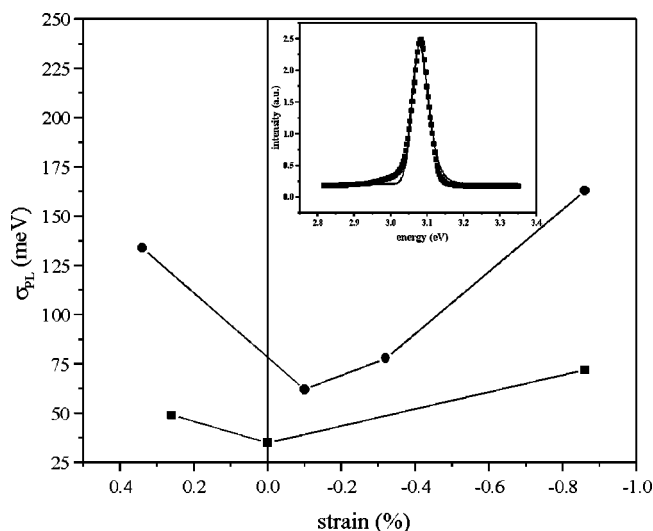


FIG. 3. Localizing parameter from joint DOS PL line shape data plotted versus strain for (squares) 3 nm QWs and (circles) 9 nm QWs. (Inset) Example of modeling the PL spectrum with a joint DOS spontaneous emission equation. The value of σ_{PL} is deduced from curve fitting of the emission spectrum.

carriers are lost to nonradiative recombination and cannot contribute to luminescence. Equation (4) is used to model the PL, intensity data for the 3 and 9 nm QWs using E_a as the fitting parameter. The results of the fitting procedure are plotted in Fig. 4. For the 3 nm unstrained QW, the activation energy is 18 meV. However, for the samples under compression and tension, the activation energy increases to 22 meV and 38 meV, respectively. For the 9 nm QWs the activation energy for nonradiative recombination is smallest for the unstrained well and increases with strain for wells under tension or compression; however, the quantitative variation of activation energy with strain differs between the 3 and 9 nm QWs. In light of the evidence of the preceding models of the strain dependence of localization effects, it is possible that the mechanism behind the strain dependence of activation energy is also related to carrier localization. In essence, localization of carriers within potential minima originating from compositional fluctuations reduces the likelihood of interaction with a nonradiative recombination center such as a crystal defect. The higher the degree of localization, the more thermal energy is required to overcome the potential barrier. A higher thermal energy requirement to encounter a nonradiative recombination center is reflected in a large value for the nonradiative recombination activation energy.

Four experimental techniques were used to study the effects of strain on the optical transitions in InGaN QWs. The analysis of the peak energy dependence on temperature, the effective lifetime dependence on energy, the PL line shape, and the activation energy for nonradiative transitions represent four different approaches to assess the degree of carrier localization due to compositional fluctuations. For each of these approaches, the degree of localization was observed to be a minimum for the unstrained QWs and increase as biaxial strain increases. If the degree of localization is a mini-

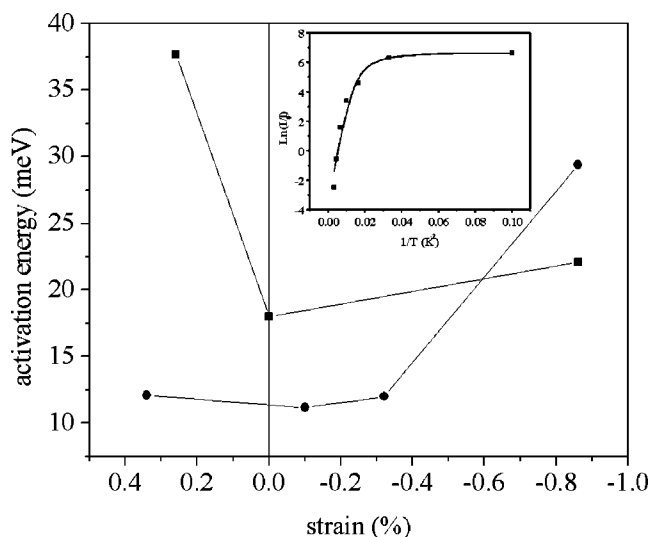


FIG. 4. Activation energy for nonradiative recombination plotted versus strain for (squares) 3 nm QWs and (circles) 9 nm QWs. (Inset) Example of emission intensity versus inverse temperature for 3 nm compressively strained QW to which the Arrhenius model of Eq. (4) is fit.

um for the unstrained QWs, it is to be expected that excess carriers in such a well are more likely to encounter nonradiative recombination centers. However, for the strained QWs, the degree of localization increases, thereby impeding the ability for carriers to nonradiatively recombine.

In conclusion, InGaN QWs under tensile, compressive, and no strain were grown and optical properties analyzed. It was found that the unstrained QW exhibits a smaller degree of carrier localization effects than strained counterparts. Thus, the microstructure of the InGaN QW is a function of the strain experienced during growth.

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