Temperature-dependent Radiative Lifetimes of Excitons in Non-Polar GaN/AlGaN Quantum Wells

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Abstract. We report theoretical and experimental studies of radiative recombination of carriers in GaN quantum wells grown on low defect *a*-plane GaN templates fabricated by lateral epitaxial overgrowth. The radiative rates are presented as functions of temperature and well width.

Non-polar GaN/AlGaN multiple quantum wells (MQW) have shown an improved quantum efficiency due to better wave function overlap in the absence of the large polarization fields normally found in their *c*-plane counterparts. The zone-center effective mass model is used to obtain hole energies and valence to conduction band dipole matrix elements. The bulk energies and matrix elements are obtained using **k·p** Hamiltonian for the valence band of GaN [1]. The quantum well exciton effects are treated here in parabolic approximation in single GaN well with $Al_xGa_{1-x}N$ barriers, with x = 0.16. In the bulk exciton case neglecting spin-orbit splitting in the valence band one can use spherical approximation near the zone center with band parameters $m_c/m_0 = 0.2$ for electrons and $m_v/m_0 = 1.1$ for heavy holes. Then the bulk exciton radius is a_0 =28 Å and binding energy is 26 meV. For the quantum well (QW) exciton we use variational wave function. Radiative decay of excitons in QW neglecting other scatterings can be obtained as an imaginary part of polariton self-energy [2,3,4]: an exciton with in-plane 2D wave-vector q couples to an electromagnetic continuum of photon states with 3D wave-vectors with arbitrary values of the wave-vector component in the growth direction z'. Exciton-photon coupling strength

$$A(\mathbf{q},\mathrm{k}) = \mathrm{i}\sqrt{\frac{2\pi}{\hbar \mathrm{ckAL_R}}}\,\omega_{\mathbf{q}} D_{\mathrm{vc}}(\mathbf{q})$$

where the exciton dipole moment is related to the zone center band transition dipole moment d_{vc}

$$D_{vc}(q) = NI_{vc}A^{1/2}\left|\mathbf{d}_{vc}\cdot\hat{\mathbf{e}}(\mathbf{q},k\hat{z}')\right|$$

where **e** is photon polarization vector. N is the normalization coefficient of the electron-hole in-plane relative motion and I_{vc} is the overlap integral of the electron and hole QW envelope functions.

Radiative decay rates are obtained as functions of in-plane wave-vector q and exciton polarization , denoted T and L for $\mathbf{d}_{vc}$ in the QW plane, perpendicular and parallel to **q** , and Z' for $\mathbf{d}_{vc}$ in the growth direction z':

$$\Gamma_T(q) = \Gamma_0 \eta \theta(q_0 - q)\frac{q_0}{\sqrt{{q_0}^2 - q^2}}$$

$$\Gamma_L(q) = \Gamma_0 \eta \theta(q_0 - q)\frac{\sqrt{{q_0}^2 - q^2}}{q_0}$$

$$\Gamma_{Z'}(q) = \Gamma_0 \eta \theta(q_0 - q)\frac{q^2}{q_0\sqrt{{q_0}^2 - q^2}}$$

$$q_0 = \omega_{exc}/c \approx E_g/\hbar c$$

where speed of light $c = c_0/n$ (for GaN n = 2.2 at the band edge, Eg ≈ 3.4 eV), $\eta \sim O(1)$ is a function of the orientation of the dipole moment with respect to c-axis z, and can be 0 (oscillator strength selection rules). From Kane's model we estimated zone center dipole moment $d_{vc}/e \approx 2$ Å and using a value of exciton transition dipole moment we evaluated for 10 nm QW, we obtain for a 10 nm QW $\tau_0 \equiv 1/\Gamma_0 = 5.9$ ps.

Effects of exciton scattering on radiative times of free excitons: only the excitons within the homogeneous linewidth Δ(T) contribute to recombination[5]. Assuming an equilibrium thermal distribution of free

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excitons near the bottom of the band, one obtains

$$\frac{1}{\tau_{fr}} = \frac{8E_0\Gamma_0}{3\hbar\Delta(T)}\left[1-\exp(-\hbar\Delta(T)/k_BT)\right]$$

and we assumed that the homogeneous part of the zero temperature linewidth is about 10 meV.

In accounting for effect of exciton localization by interface defects due to well width fluctuations[4] the function for lateral confinement was chosen to be of the Gaussian form exp($-R^2\beta^2/2$)$\varphi(r)$ and the decay time can be found from

$$\frac{1}{\tau_{loc}} = (1/\pi\beta^2)\int d^2q \exp(-q^2/\beta^2)\Gamma(q)$$

We estimated, for a 10 nm GaN QW, τ_{loc} ~ 100 ps. Assuming n_D faction of excitons are localized, we obtain

$$\frac{1}{\tau(T)} = \left[1-\exp(-E_{loc}/k_BT)\right]n_D\frac{1}{\tau_{loc}}$$
$$+\left[(1-n_D)+n_D\exp(-E_{loc}/k_BT)\right]\frac{1}{\tau_{fr}}$$

where we estimated E_{loc} ~ Δ_0 ~ 5 to 10 meV. We assumed 10% of the excitons are localized (n_D = 0.1) and evaluated radiative decay time as a function of temperature for two different GaN QW widths, L = 5nm and L = 10 nm, Fig. 1.

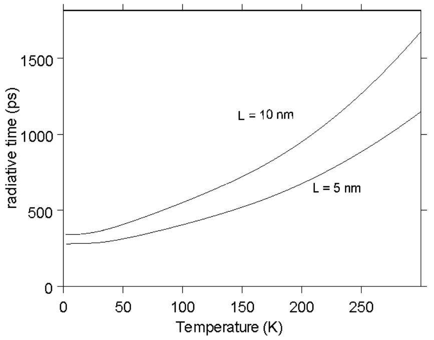

Fig. 1. Calculated temperature dependence of radiative times for non-polar GaN quantum wells of two different widths L, at low excitation power.

In the experimental work we performed time-resolved photoluminescence studies at high pump intensity and in the temperature range from room temperature down to 11 K and in a larger range of carrier densities. The samples studied consist of a LEO *a*-GaN template grown by hydride vapor-phase epitaxy on which a set of MQW, each consisting of 10 periods of GaN/AlGaN MQW were grown with well thicknesses of 5, 10 and 20 nm and a fixed barrier of 10 nm. Also some single well samples with 3 and 10 nm well thickness were studied. Temperature dependent time-resolved photoluminescence (TRPL) [6] and time-integrated PL data were taken with a pump laser that produced femtosecond pulses at 325 nm and powers giving estimated carrier densities in the 10^{17} to 10^{19} cm^{-3} range. With rising temperature, the TRPL lifetime is observed to increase, faster at high carrier density than at low carrier density, and with longer lifetimes seen in the thicker MQWs, Fig. 2. The variations of PL intensity as a function of well width at variable carrier densities are associated more with the excitonic properties in the well than with increased non-radiative lifetimes.

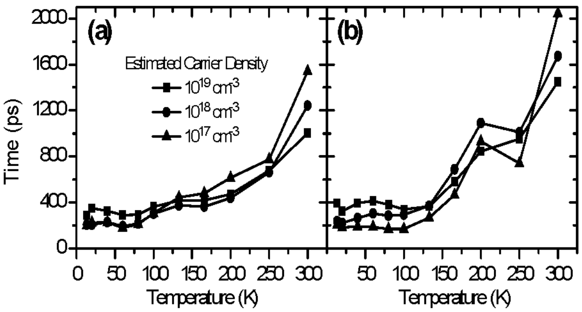

Fig. 2. Experimentally determined radiative times for a-LEO quantum wells of width L= 5 nm (**a**) and L=10 nm (**b**), for three different values of density of photo-generated carriers.

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