# Quantum Well Width Dependence of Threshold Current Density in InGaN lasers



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**Abstract**

The quantum confined Stark effect was found to result in a strong quantum well width dependence of threshold current density in strained group-III nitride quantum well lasers. For an $In_{0.2}Ga_{0.8}N/GaN$ structure with quantum well width in the neighborhood of $3.5nm$, our analysis shows that the reduction in spontaneous emission loss by the electron-hole spatial separation outweighs the corresponding reduction in gain to produce a threshold current density minimum.

## DISCLAIMER

For the last several years there has been considerable work directed towards improving and understanding visible wavelength group-III nitride laser behavior. [1,2] One result is the discovery in laser experiments of stronger dependence of threshold properties on quantum well structure than usually found in conventional near-infrared III-V lasers. In particular, a noticeably smaller threshold current was measured in InGaN lasers with quantum well width of $4nm$ than $2.5nm$. [3] This result has useful implication to laser design, especially if the reason is understood. In this paper, we investigate whether the above quantum well width dependence of threshold current can arise from the intrinsic physical properties of group-III nitrides.

In our analysis, we first compute the gain $G(\omega, N, T)$ at temperature $T = 300K$, for different carrier densities $N$ and quantum well widths, where $\omega$ is the laser frequency. The approach we chose involves solving the semiconductor Bloch equations, where collision and screening effects are treated at the level of quantum kinetic equations. The details of the calculations are given in several papers. [4,5] This approach has several advantages over the more familiar gain calculations based on the relaxation rate approximation. [6–8] It eliminates the dephasing rate as a free parameter, and therefore gives more precise predictions of gain properties. Equally important, it includes an important piece of physics involving contributions from nondiagonal Coulomb correlations. These contributions, which are unique to semiconductor systems, are neglected in relaxation rate treatments. They are found to be important in describing the experimental shape and carrier density dependence of gain spectra in conventional III-V lasers. [9] When applied to the nitrides, our approach provides a consistent treatment of optical behaviors from low electron and hole densities, where excitonic absorption is present, to high carrier densities, where gain is produced by an interacting Coulomb correlated electron-hole plasma.

The input to the gain calculations are the bandstructure properties, specifically the electron and hole energy dispersions, as well as the optical dipole matrix elements. These quantities for a wurzite InGaN/GaN strained quantum well are computed using a $6 \times 6$ Luttinger-Kohn Hamiltonian and the envelope approximation [10]. The effects of a screened piezoelectric field [11] are taken into account by the iterative solution of the Luttinger-Kohn Hamiltonian and Poisson equation. Input parameters to the bandstructure calculations are the bulk wurtzite material parameters. For the calculations described in this paper, we use the values listed in Ref. [5].

The next step in the analysis involves the calculation of the corresponding spontaneous emission rates. We performed this calculation using the phenomenological relationship between the spontaneous emission spectrum $S(\omega, N, T)$ and gain spectrum $G(\omega, N, T)$. [13] Integrating the spontaneous emission spectrum gives the spontaneous emission contribution, or the fundamental limit, to the injection current density $J_{sp} = ehw_{sp}(N, T)$, where $e$ is the electron charge, $h$ is the quantum well width, and $w_{sp}(N, T) = \int_0^\infty d\omega \; S(\omega, N, T)$ is the spontaneous emission rate.

The results of our calculations are summarized in Fig. 1, where we plotted the spontaneous emission contribution to the threshold current density versus quantum well width for different threshold gains. We chose an $In_{0.2}Ga_{0.8}N/GaN$ quantum well structure, and assumed operation at temperature $T = 300K$ with a TE (polarization in the plane of the quantum well) polarization. The TM gain is considerably smaller than the TE gain. Each curve is for a fixed threshold gain, $G_{th}$ which we defined to be the material (local) gain in a quantum well. In our calculations, we also assumed operation at the gain peak, i.e., $G_{th} = G(\omega_{pk}, N, T)$ where $\omega_{pk}$ is the peak gain frequency. For an experimental device, the threshold gain is also determined by the optical resonator parameters according to $G_{th} = \Gamma^{-1}\left[\alpha_i - L^{-1}\ln\left(R_1 R_2\right)\right]$ ,where $R_{1(2)}$ is the facet reflectivity, $L$ is the resonator length, $\alpha_i$ accounts for the internal optical losses, and $\Gamma$ is the confinement factor describing the spatial overlap between the optical mode and the quantum wells. The threshold current density plotted on the y-axis is for each quantum well in the active region. For the case of a multiquantum well active region, the total threshold current density is $N_{qw}J_{sp}$, where $N_{qw}$ is the number of quantum wells. Since we considered only the spontaneous emission contribution to the threshold current, Fig. 1 gives the fundamental limit to the threshold current density.

An interesting result shown in Fig. 1 is the lower threshold current density for the wide ($w > 3nm$) quantum wells. The reason may be understood with the help of Fig. 2. In the case of a narrow quantum well, e.g., of width $2nm$, the relative displacement of the electron and hole eigenfunctions is limited by strong quantum confinement, so that the dipole matrix element is not significantly reduced. As a result, gain for the narrow wells occur at relatively low carrier densities of $N > 3 \times 10^{12} cm^{-2}$, as shown by the solid curves in Fig. 2a. One the other hand, the weaker quantum confinement makes a wider well more susceptible to piezoelectric field effects. One consequence is appreciable separation between the confined electron and hole eigenfunctions, resulting in significant decrease in the optical dipole matrix element. [12] The dashed curves in Fig. 2a show that only at much higher carrier densities ($N > 10^{13} cm^{-2}$) is the piezoelectric field sufficiently screened for gain to be present in the wide $4nm$ quantum well. However, the reduction in dipole matrix element also results in lower spontaneous emission rate for the wider well, as shown in Fig. 2b. According to our calculations, the reduction in spontaneous emission loss in the wide quantum well more than compensates the reduction in gain, so that for the same threshold gain, the wide quantum well device has lower threshold current density.

Experiments have shown the presence of alloy fluctuations in InGaN active regions due to localization during growth. Figure 3a shows the effects of In fluctuations in the quantum wells. We assumed that the localized regions are sufficiently large so that the quantum confinement remains essentially in the epitaxial direction. This allows the description of inhomogeneous broadening effects by a statistical average of the homogeneous gain and absorption spectra. [4] The alloy fluctuation is represented by a normal distribution $P(x) = (\sqrt{2\pi}\sigma)^{-1} \exp\{-[(x - x_0)/(\sqrt{2}\sigma)]^2\}$, where $x$ is the indium concentration. The distribution is characterized by an average $x_0$, and a standard deviation $\sigma$. We choose a typical threshold gain of $G_{th} = 10^3 cm^{-1}$. The curves show increasing threshold current density with increasing standard deviation in In concentration. They also show that the narrow wells are more sensitive to alloy fluctuations than the wider ones. This insensitivity of the wide quantum wells to In fluctuation is because they have significantly broader gain bandwidths, since they operate at higher carrier densities (see Fig. 2a). For the $4nm$ quantum well, the gain bandwidth is greater than the inhomogeneous width for the alloy fluctuations considered, wheras the opposite is true for the $2nm$ case. However, operating at high carrier densities also makes the wide quantum wells susceptible to nonradiative carrier losses. This is shown in Fig. 3b, where we have again looked at the $G_{th} = 10^3 cm^{-1}$ case. The nonradiative losses are approximated by an additional contribution to the threshold current density, so that the total threshold current density is $J_{th} = J_{sp} + J_{nr}$, where $J_{nr} = eN\gamma_{nr}$ is the contribution from nonradiative carrier losses, and $\gamma_{nr}$ is an effective nonradiative carrier loss rate.

In summary, this paper investigates the quantum well width dependence of the threshold current density in InGaN quantum well lasers. The analysis is based on a microscopic theory where bandstructure and many-body Coulomb effects are treated consistently. We found a quantum well width dependence of the threshold current density due to the quantum confined Stark effect. Our calculations show that the reduced dipole matrix element in the wide quantum well actually benefits laser operation, because the resulting reduction in spontaneous emission loss outweighs the reduction in gain. For an $In_{0.2}Ga_{0.8}N/GaN$ structure often used in experiments, we predict a theoretical limit to the threshold current density that minimizes at quantum well widths of $w \approx 3.5nm$. Our results may provide explanation to recent experiments, where improvement in threshold current was found in well thicknesses between 3 and $5nm$. [3] The calculations also indicate that gain structures with wide quantum well widths are less sensitive to alloy fluctuations, while those with narrow quantum well widths are less sensitive to nonradiative carrier losses.

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## Figure Captions

Figure 1. Calculated spontaneous emission contribution to the threshold current density versus quantum well width for $In_{0.2}Ga_{0.8}N/GaN$, temperature $T = 300K$, and different threshold gains.

Figure 2. (a) TE gain spectra for $2nm$ (solid curves) and $4nm$ (dashed curves) $In_{0.2}Ga_{0.8}N/GaN$ quantum wells. For the $2nm$ quantum well spectra, the carrier densities are $N = 4\times, 4.5\times$ and $5 \times 10^{12} cm^{-2}$. For the $4nm$ quantum well spectra, we use the higher carrier densities, $N = 1.5\times, 2\times$ and $2.5 \times 10^{13} cm^{-2}$, in order that they show comparable gain. The blue shift of the $4nm$ quantum well spectra with increasing carrier density is due to screening of the piezoelectric field. Also the $4nm$ quantum well spectra have wider gain bandwidth because of the significantly higher carrier densities. (b) Spontaneous emission rate versus carrier density. The dots indicate the values for the carrier densities used in the top figure.

Figure 3 Threshold current density versus quantum well width, showing the effects of (a) alloy fluctuations and (b) nonradiative carrier losses. The results are for $In_{0.2}Ga_{0.8}N/GaN$, temperature $T = 300K$, and threshold gain $G_{th} = 10^3 cm^{-1}$. The curves in (a) are labeled according to the standard deviation in In concentration in the quantum well, and those in (b) are labeled according to the nonradiative carrier loss rate.

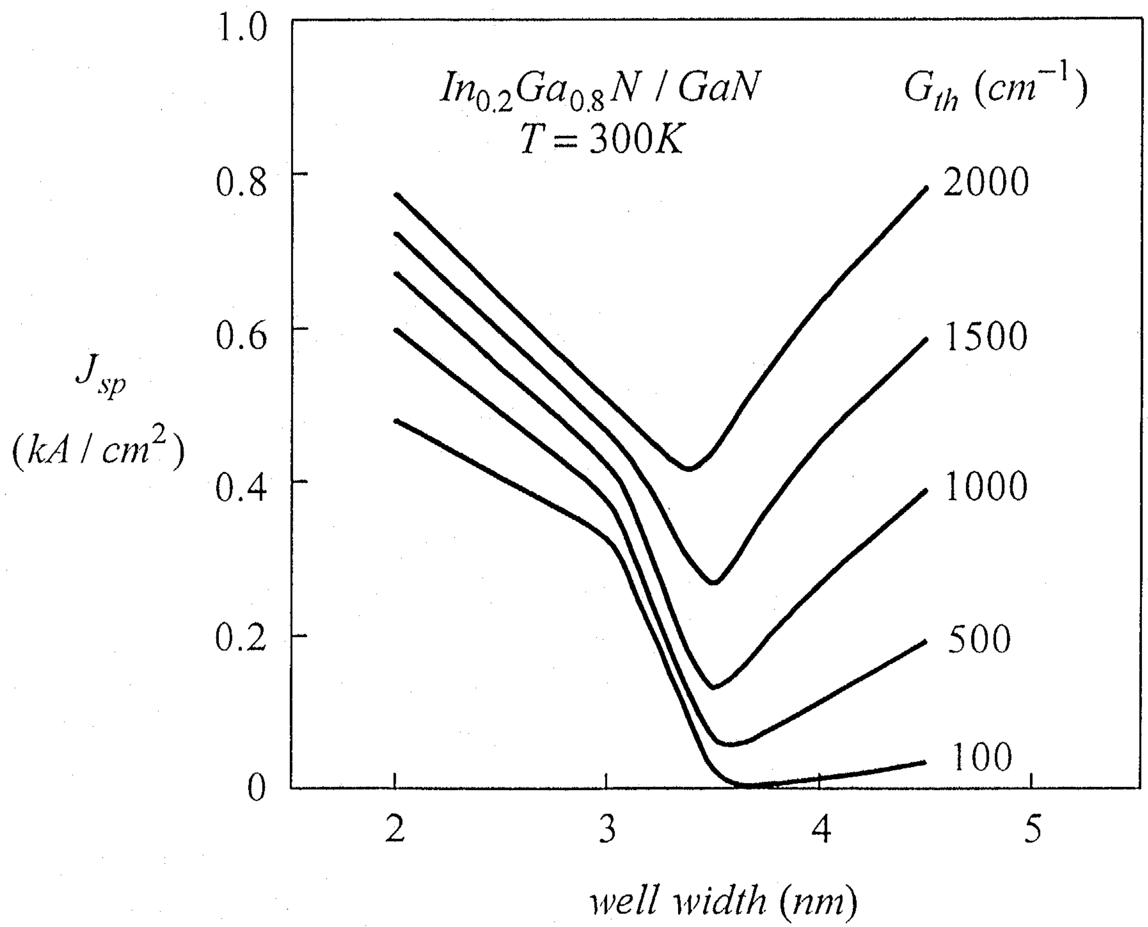


Fig. 1, APL, Chow

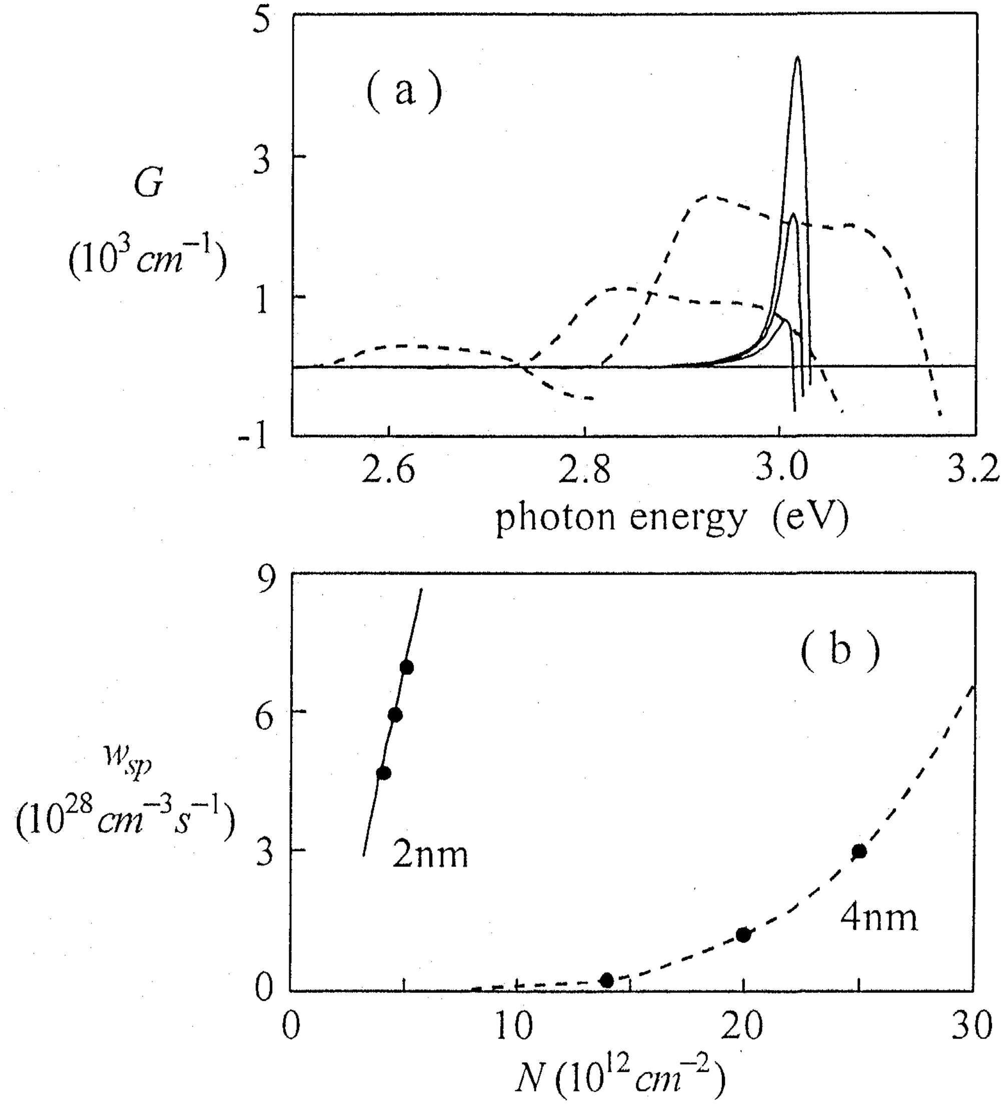


Fig. 2, APL, Chow

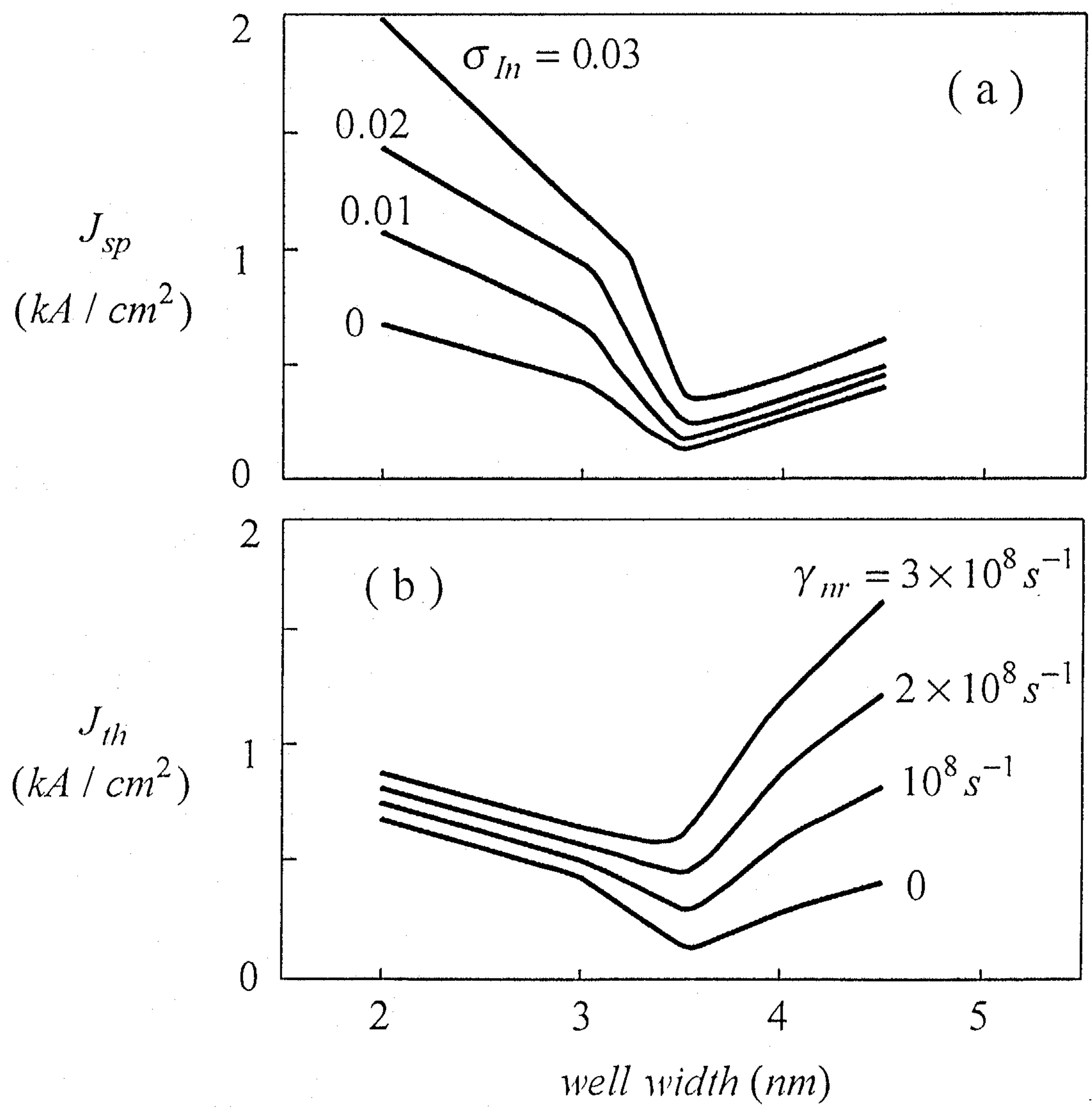


Fig. 3, APL, Chow