Analysis of the Quantum-Confined Stark Effect in InGaN Single Quantum Wells

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Motivation—The InGaN/GaN quantum well (QW) system has recently attracted much attention due to its central role in the development of green, blue, and ultraviolet optoelectronics. Based on the wurtzite crystal structure, large (MV/cm) polarization-induced electric fields are known to exist in strained InGaN quantum wells grown on the basal plane of GaN; these fields influence optical-device performance by altering the electron and hole wave-function overlap. A number of authors have confirmed the existence of such fields, but reported measurements of the field differ, even for structures of similar indium composition. In general, measured Stark shifts are much smaller than expected from theory, and since InGaN/GaN QW polarization fields have typically been inferred from the measured Stark shifts via band-structure theory, polarization fields are usually underestimated as well.

Accomplishment—The present research resolves these discrepancies using a new approach where QW polarization fields are directly measured by capacitance-voltage (CV) techniques. By combining these direct measurements of the field with standard optical measurements of the QW emission energy, we can compare the dependence of Stark shift on the polarization field to fully independent band-structure theory. These unique comparisons yield new insights into carrier-recombination efficiency in InGaN/GaN QWs.

Here, we examine $In_xGa_{1-x}N$ (x=0.11-0.14) single quantum wells (SQWs) embedded in the *n*-side of GaN p^+n junctions. Electron density profiles obtained from CV measurements reveal sharp peaks associated with charge storage in the SQWs, with total QW charge consistent with calculated values (Fig. 1). Photocurrent and electroreflectance spectra were separately measured as a function of applied field, and we observe a blue shift due to the quantum-confined Stark effect (Fig. 2). Unlike many prior results where the inferred polarization fields are too small, our direct measurements of the SQW polarization fields show good agreement with Schrödinger-Poisson calculations performed using *ab-initio* values for the polarization. Nonetheless, the presently observed Stark shifts remain much less than predicted, as in the previous studies (Fig. 3 – see ideal model vs experimental data).

By comparing further band-structure calculations to the measured Stark shift versus electric field, we show that *without decreasing the SQW polarization field* a simple model incorporating hole localization in the SQW removes much of the observed Stark-shift discrepancy (Fig. 3 – see localized-hole model vs. experimental data). The operative hole-localization mechanism could arise from indium-rich domains, defect states, or intrinsic hole-wavefunction localization produced by the ionic character of the bonding in wurtzite-structure III-V nitrides.

Significance—If holes are in fact localized, the electron-hole wave-function overlap in InGaN/GaN QWs is larger than currently believed. Thus, improvements in brightness expected from InGaN-QW emitters grown on non-polar GaN may be less than presently anticipated, while emitters grown on the polar basal-plane of GaN may ultimately become more efficient than now thought possible. These new scientific findings alter the pathway forward to energy-efficient solid-state lighting.

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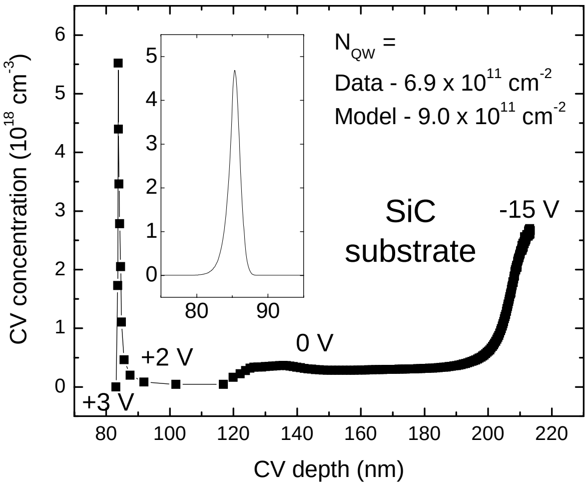

Figure 1. Differential CV measurements of the electron density depth profile and the total integrated QW charge (N_{QW}). The QW is 2.5 nm thick and consists of $In_{0.14}Ga_{0.86}N$. Inset: Calculated electron density profile over the SQW region at +3 V bias. The inset axes have the same units as the main axes.

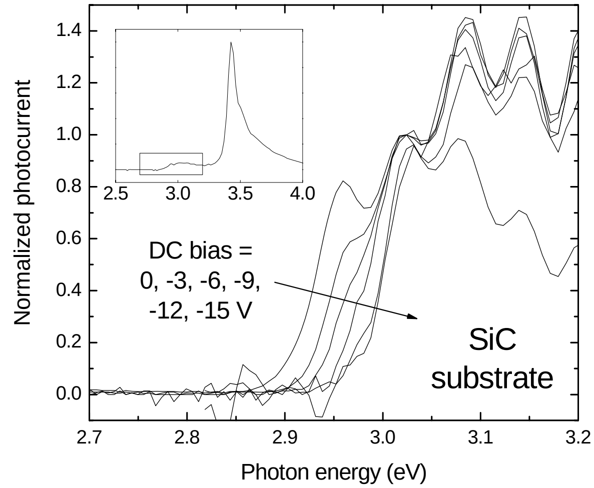

Figure 2. Normalized photocurrent spectra in the vicinity of the SQW absorption edge, measured at 77K using the bias values indicated. The same $In_{0.14}Ga_{0.86}N$ QW as in Fig. 1 is examined. Inset: Zero-bias photocurrent measured over a wide spectral range. The inset axes have the same units as the main axes.

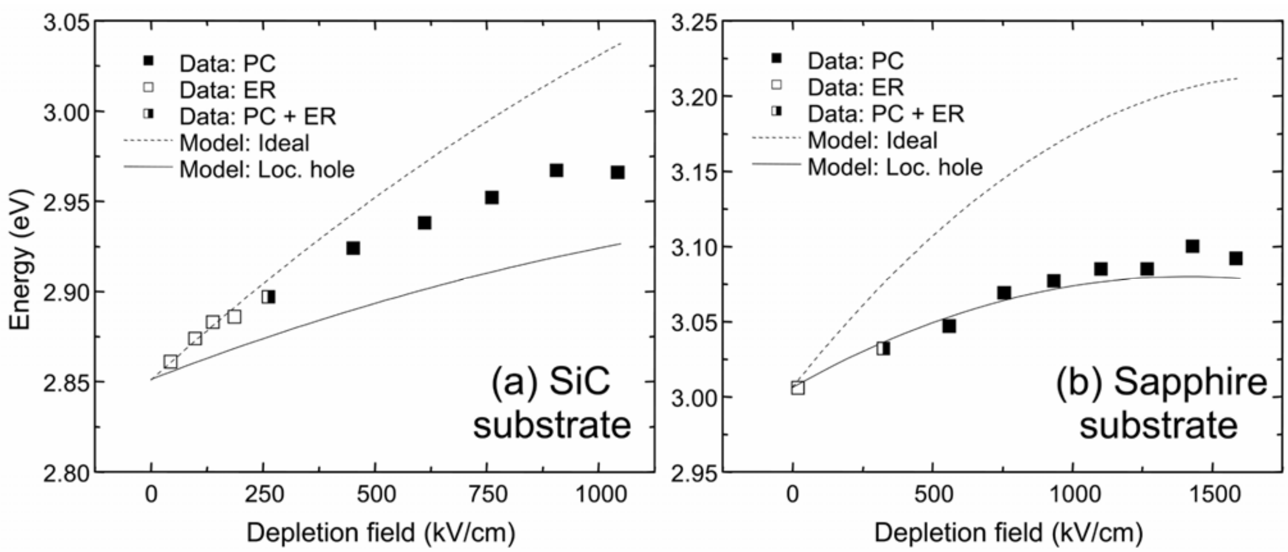

Figure 3. Energy of the SQW absorption edge versus the diode depletion field in the SQW. Solid and open squares indicate experimental points obtained from photocurrent (PC) and electroreflectance (ER), respectively. Smooth curves show the theoretical Stark shift vs. field calculated using ideal and localized-hole Schrödinger-Poisson models. Models are offset to the experimental energy at zero field to facilitate direct comparisons of the experimental and theoretical *energy shifts* produced by the quantum-confined Stark effect. These small offsets remove field-independent differences in energy arising from experimental uncertainties in the SQW composition and thickness, imprecise knowledge of the exact energy level of the localizing state, and similar effects. Note that the localized-hole model substantially improves the overall agreement between theory and experiment.