Combined Effect of Carrier Localization and Polarity in In$_x$Ga$_{1-x}$N/GaN Quantum Wells

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The influence of carrier localization and polarization-induced electric fields on the spectral variation of photoluminescence was comparatively studied in polar and semipolar In$_x$Ga$_{1-x}$N/GaN strained quantum wells embedded in p-i-n diodes. Two representative structures with $x = 0.16$ for polar (0001) diodes and potential fluctuations for semipolar diodes grown along (1122) direction have been investigated with a reverse bias up to $-4$ V. From the $s$-shaped spectral shift as a function of temperature, the existence of single and triple localization traps was confirmed in polar and semipolar diodes. Within our bias range, we observed the monotonic blueshift with reverse bias in the polar sample, indicating that the carriers are laterally localized and thus influenced by the vertical piezoelectric fields. In clear contrast, the semipolar sample showed the blueshift of localized states only at low temperatures, while the deepest localization features were found at the highest available temperatures, overriding the influence of thermal activation and polarization fields.

Keywords: Localization, Piezoelectric Fields, Quantum-Confined Stark Effect.

1. INTRODUCTION

The identification of strong polarization-induced electric fields in strained In$_x$Ga$_{1-x}$N/GaN structures has inspired various alternative approaches to control the quantum-confined Stark effect (QCSE)\cite{1,2} in light-emitting diodes (LEDs) and laser diodes.\cite{3,4} Significant advances have recently been made toward high-performance, enhanced reliability, and high-power applications. In general, In$_x$Ga$_{1-x}$N/GaN quantum wells (QWs) grown along the (0001) $c$-plane manifest strong QCSE with an inherent piezoelectric field (PEF) larger than 1 MeV/cm\cite{4} possibly represented by the decreased radiative recombination rate via spatial separation of the electron and hole wavefunctions.

In order to reduce or eliminate the PEF, growth of GaN-based LEDs on semipolar or nonpolar planes has been introduced and progressed. For instance, the semipolar structures have a PEF that is at least two times smaller than that of polar structures with similar In compositions.\cite{5}

However, In$_x$Ga$_{1-x}$N/GaN QWs grown in semipolar (1122) directions generally exhibit large fluctuations in the In composition homogeneity as well as misalignment on the surface morphology via the basal-plane stacking faults such as thread dislocation, reduced crystallite scale, and crystal crack.\cite{6,7} The scale of In composition fluctuations has been known to reduce down to few nanometers, resulting in the zero-dimensional carrier confinements in In-rich nanoislands.\cite{5,9}

In this regard, the effects of localization on the active layer of InGaN could be simultaneously considered with bias-dependent spectral shifts via PEF. In this study, we have investigated the lineshapes of PL spectra as a function of temperature and reverse bias in order to explicate the polarity-dependent localization characteristics.

2. EXPERIMENTAL DETAILS

Polar (0001) and semipolar (1122) In$_x$Ga$_{1-x}$N/GaN QW structures were grown on a $c$-plane sapphire substrate and an $m$-plane sapphire substrate, respectively, by metal organic chemical vapor deposition. The In composition for the polar sample was rather homogeneously distributed with 16%, whereas the semipolar sample has inhomogeneous distribution because of basal-plane stacking faults. Figure 1 shows a clear difference in surface...
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Figure 1. Optical microscopic images of (a) polar and (b) semipolar GaN-based diodes.

roughness between the samples. The anisotropic cracking and hillocks are observed only in semipolar samples grown on m-plane sapphire. Two samples have the same structure with layers sequentially grown on different substrates as follows: an undoped thick GaN layer, Si-doped n-GaN, five pairs of In$_x$Ga$_{1-x}$N/GaN QWs (3 nm/10 nm), Mg-doped p-GaN, and a 150 nm indium tin oxide layer for a transparent p-contact layer. Finally, 50 nm/300 nm thick Cr/Au electrodes were deposited by an e-beam evaporator for ohmic contact.

The photoluminescence (PL) spectra were measured using a He–Cd laser at an excitation wavelength of 325 nm or second-harmonic generation of a Ti:sapphire laser at 370 nm (to avoid absorption by p-GaN layer in the case of the semipolar sample with weak PL signals). The excited laser power was around 5 mW, focused onto a spot size of 200 μm. The external reverse bias was varied from 0 to −4 V at either 9 K or 293 K, whereas the temperature was varied from 9 to 293 K at 0 V.

3. RESULTS AND DISCUSSION

In order to clarify the thermally activated localized states in samples with different polarities, PL measurements were performed as a function of increasing temperature from 9 to 293 K (Fig. 2). In Figure 2(a), the PL spectrum of the polar sample near 9 K exhibits the asymmetric spectral profile, which is often observed in samples with localized hole states and ascribed to the broken momentum conservation between photons and electron–hole (e–h) pairs, sometimes revealing the Fermi-energy edge singularity (FES). In addition, the multiple low-energy side replicas observed via optical-phonon emission were simultaneously attained, also indicating that the momentum conservations among e–h pairs, phonons, and emitted photons are not fully satisfied by localization features at low temperatures. The asymmetric FES with a stronger enhancement on the high-energy side gradually evolved to a symmetric shape, possibly because holes are delocalized by thermal activation. In clear contrast, the PL lineshape in the semipolar sample showed persistent FES features throughout the temperature range, as seen in Figure 2(b). In order to relate the localization energies with thermal activation energies in the samples with different polarities, we traced the PL peak energies (scatter lines) as a function of temperature, as shown in Figure 2(c). The fitting based on Varshni’s formula (black solid line) in polar samples with temperatures above 150 K. The deviation from Varshni’s formula at lower temperature regions in polar samples indicates the existence of localization energy of approximately 30 meV.

We note that the PL peak energy variation in polar and semipolar samples was distinguished in several viewpoints. The semipolar sample shows a much larger energy decrement with at least two local minima. The s-shaped PL energy variations are generally associated with thermal broadening of localized states. Considering the continuous features of FES even after the two local minima were overridden at 293 K in the semipolar sample, the various thermionic carriers escape over shallow bound states, and retrapping down to quantum-dot-like deep level is present with severe potential fluctuations. The s-shaped PL energy curve, included in Varshni’s formula for the polar sample, is a characteristic showing the delocalization of carriers from the potential minima with increased temperature. On the other hand, linear PL energy change as a function of temperature was often found in InGaAs-based quantum dots, but is not fully understood for inhomogeneous compositions of InGaN. In this regard, we schematically suggest the simplified energy band diagram under the effect of carrier localization in a lateral plane of an active layer, as shown in Figure 3. In the polar sample with a single-hole localization state, the localized carriers seen in Figure 3(a) become thermally delocalized above $3/2k_BT^*\sim \Delta E^*$ in Figure 3(b). In Figures 3(c), (d) for the semipolar sample, there could be at least two shallower electronic localization states ($\Delta E^*$ and $\Delta E^*_2$ associated with doubly s-shaped PL energy shift, cf. Fig. 2(c)).

Figure 2. PL spectra with temperatures varying from 9 to 293 K in (a) polar and (b) semipolar samples. (c) PL peak energy as a function of temperature. The black solid line was fitting based on Varshni’s formula.
and one deep localization state for an electron and a hole ($\Delta E_z$) associated with FES throughout the range, cf. Fig. 2(b). The linear PL energy shift as a function of temperature could possibly further imply that the $\Delta E_z$ originates from zero-dimensional carrier confinements. The shallow energies ($\Delta E_x$ and $\Delta E_y$) could be overridden by thermal activation, leading to the transition into the deepest $\Delta E_z$ as shown in Figures 3(c), (d) which was experimentally revealed via a PL energy shift that was three times larger in the semipolar sample than in the polar sample.

Such anomalous quantum-dot-like states in the semipolar sample at high temperature were further manifested through bias dependence, as seen in Figure 4. In the polar sample in Figures 4(a), (b), PL spectra showed monotonic blueshift regardless of temperature change, implying that the relevant carrier localization could not alter the influence of the reverse bias and PEF along the $z$-direction. In the semipolar sample, on the other hand, the influence of reverse bias (and corresponding blueshift) was only observed at low temperature, as shown in Figure 4(c).

As displayed in Figure 3(c), the carriers at low temperature are mostly localized into rather shallow energy levels within lateral traps, thus influenced by the $z$-directional reverse bias. The spectral shift was absent in Figure 4(d) in the semipolar sample at 293 K, and this was realized on the basis of the zero-dimensional carrier confinement overriding the $z$-directional potential gradient. Figure 4(e) summarizes the peak energy variations in Figures 4(a)–(d).

4. CONCLUSION

The effects of the carrier localization and polarity on the spectral variation of PL have been studied using polar and semipolar InGaN/GaN QWs. From the PL spectral shift as a function of temperature, the existence of localization traps was confirmed in polar and semipolar samples. The carriers with thermal activation energy could possibly be considered with the potential fluctuation. We have observed the zero-dimensional carrier confinement at the deepest potential minima.3

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References and Notes


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