ESTIMATION OF EXCITATION DENSTITY OF REPORTED TWO-PHOTON PHOTOLUMINESCENCE INTENSITY DISTRIBUTIONS AT A DISLOCATION IN AN n-GaN LAYER ON A M-3D SUBSTRATE

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We estimated the excitation density of the reported two-photon photoluminescence from an n-GaN layer on an M-3D substrate by fitting the intensity distributions at a dislocation. We found that all the data points of the intensity distributions were reproduced with the effective dislocation radius of 8 nm. Considering the range of the excess hole concentration ($\varDelta p$) within which almost all data points fell, we estimated $\varDelta p$ to be $10^{16\pm1}$ cm^{-3}.

I. Introduction

Development of high-quality GaN substrates has made it possible to easily fabricate vertical $\mathrm{p^+n}$ diodes on free-standing substrates. A record high breakdown voltage of 5 kV has been achieved in combination with a low on-resistance R_{on} of 1.25 $\mathrm{m\Omega\ cm^2}$ at a forward voltage of 5 V.[1)] The quality of substrates has also been improved. For example, low-dislocation-density ($N_{\mathrm{dis}} \leq 4\times10^5$ cm^{-2}) GaN substrates became available via hydride vapor phase epitaxy (HVPE) and a maskless 3D (M-3D) method.[2)] To suppress propagation of dislocations from the seed crystal, the M-3D method avoids *c*-plane growth; namely, the initial three-dimensional growth is followed by two-dimensional growth in which growth temperature and partial pressures of gallium chloride and ammonia are changed.[2)]

On M-3D substrates, as well as on conventional substrates by the void-assisted separation (VAS) method,[3)] Ohta et al. fabricated GaN $\mathrm{p^+n}$ diodes and observed a positive correlation between R_{on} and N_{dis}.[4)] They also observed two-photon photoluminescence (2PPL) from an 8-μm-thick n-GaN (donor density N_{D}: 1×10^{16} cm^{-3}) layer on an M-3D substrate and identified dislocations as dark spots.[4-7)] The ambipolar lifetime τ_{a} determined by 2PPL, however, depends on the excitation density, which was not clear with respect to their 2PPL measurement. Accordingly, in this paper, we estimate τ_{a} and the excess hole concentration ($\varDelta p$) in the 2PPL measurement reported in Ref. 4.

II. Analysis

The diffusion and recombination of electrons and holes generated by the source $Q(\boldsymbol{r})$ are described by the following three-dimensional equation

$$D_{\mathrm{a}}\,\varDelta n(\boldsymbol{r}) - n(\boldsymbol{r})\,/\,\tau_{\mathrm{a}} + Q(\boldsymbol{r}) = 0, \qquad (1)$$

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where D_a is the ambipolar diffusivity. τ_a is expressed from charge neutrality as

$$\tau_a = \tau_{po}\,[1 + \{\Delta p\,/\,(N_D + \Delta p)\}], \tag{2}$$

where τ_{po} is the hole lifetime under low-injection conditions. Based on anode-radius-dependent forward current/voltage characteristics of GaN p^+n diodes on an M-3D substrate, Mochizuki et al. extracted Shockley−Read−Hall lifetime τ_{SRH} of 11 ns.[8] τ_{SRH} is expressed as

$$\tau_{SRH} = (\tau_{no}\,\tau_{po})^{0.5}, \tag{3}$$

where τ_{no} is the electron lifetime under low-injection conditions. Here τ_{po} and τ_{no} are given as

$$\tau_{po} = (N_t\,v_{thp}\,\sigma_p)^{-1}, \tag{4}$$
$$\tau_{no} = (N_t\,v_{thn}\,\sigma_n)^{-1}, \tag{5}$$

where N_t is the concentration of a non-radiative recombination center, v_{thp} and σ_p are, respectively, the thermal velocity and capture cross section of holes, and v_{thn} and σ_n are, respectively, the thermal velocity and capture cross section of electrons. At 300 K, σ_p, σ_n, v_{thp}, and v_{thn}, were reported, by Chichibu et al.,[9] Maeda et al.,[10] and Saini et al.,[11] to be 7×10^{-14} cm^2, 3×10^{-13} cm^2, 2.38×10^7 cm s^{-1}, and 2.43×10^7 cm s^{-1}, respectively. Putting these values into Eqs. (3)−(5) results in the following relation:

$$\tau_{SRH} = 0.48\,\tau_{po}. \tag{6}$$

The influence of surface recombination can be ignored because the excitation energy in 2PPL is smaller than the bandgap of n-GaN.[12] The flux to the cylindrical surface of a dislocation can thus be simply calculated. When the carrier-recombination velocity at a dislocation with the effective radius R is S, the normalized photoluminescence intensity at a distance r from a dislocation, $I(r)$, is expressed as[13]

$$I(r) = 1 - K_0(r/(D_a\tau_a)^{0.5})/[K_0(R/(D_a\tau_a)^{0.5} + (D_a/RS)], \tag{7}$$
$$D_a = [N_D + \Delta p + (n_i^2/N_D) + \Delta p]\,D_e D_h\,/\,\{D_e(N_D + \Delta p) + D_h\,[(n_i^2/N_D) + \Delta p]\}, \tag{8}$$

where K_0 is the zeroth order modified Bessel function of second kind, n_i is the intrinsic carrier concentration, D_e is the electron diffusivity, and D_h is the hole diffusivity. D_h was reported to be anisotropic; namely, a ratio of 1.17 for diffusivity perpendicular and parallel to the c-axis.[14] Hall measurement of a *c*-plane GaN layer is thus suited for determining diffusivity perpendicular to the *c*-axis. We carried out Hall measurement of a 1×10^{18} cm^{-3} doped p-GaN layer on an M-3D (0001) substrate and found that the majority hole mobility μ_h was 29 cm^{2}V^{-1}s^{-1}. Since μ_h is typically constant at [Mg] < 1×10^{18} cm^{-3} [15] and the minority hole mobility was reported to agree with μ_h,[16] D_h was calculated from the Einstein relation to be 0.75 cm^{2}s^{-1} at 300 K. With respect to S, a constant value was assumed by Conolato in their dislocation model of semiconductors.[17] Although this is the case under low excitation conditions, modeling S is complex under high excitation conditions. Here we simply assume S to be as large as the thermal velocities of carriers.[11]

τ_a and D_a saturate when Δp is less than 10^{13} cm^{-3} or larger than 10^{19} cm^{-3}. As shown in Figs. 1(a) and 1(c), some data points are not within $\Delta p = 10^{16\pm3}$ cm^{-3} under the assumption of R = 6 or 10 nm. In contrast, all data points fall within $\Delta p = 10^{16\pm3}$ cm^{-3} when we assume R of 8 nm [Fig. 1(b)]. Considering the Δp range within which almost all data points fall, we estimated Δp being $10^{16\pm1}$ cm^{-3}.

III. Conclusions

By fitting the intensity distributions at a dislocation in an n-GaN layer on an M-3D substrate, we estimated the excess hole concentration during the reported two-photon photoluminescence measurement to be $10^{16\pm1}$ cm^{-3}.

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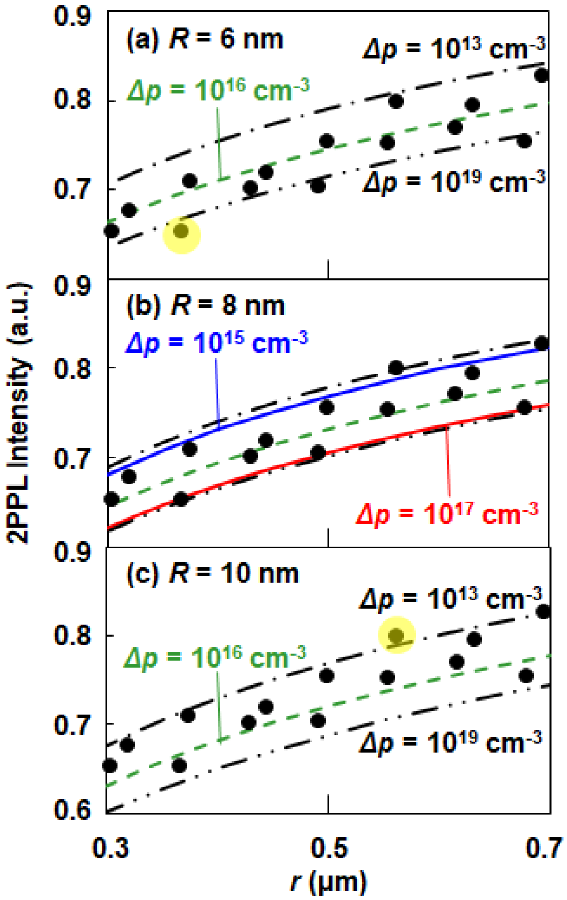

Fig. 1. Measured (symbols)$^{4)}$ and fitted (lines) distributions of 2PPL intensity at a dislocation in an n-GaN layer on an M-3D substrate. R: effective dislocation radius; Δp: excess hole concentration.

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