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Optical gain characteristics of a-plane GaN/AlGaN quantum well lasers grown on strain-engineered MgZnO layer

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ABSTRACT

Optical gain characteristics of a-plane (11 $\bar{2}$ 0) AlGaN/GaN quantum well (QW) lasers grown on a GaN buffer with strain anisotropy using a strain-engineered MgZnO layer were investigated using the multiband effective mass theory. The calculated transition energies for QW structures grown on MgZnO layer are in good agreement with experimental results. The optical gain of the QW structure grown on the MgZnO substrate is dominated by the z'-polarization because the dominant states constituting the topmost valence subband for the QW structure changes from $|Y'>-$ to $|Z'>$-like and carriers occupy higher states above $k_{\|}=0$ at a higher carrier density. On the other hand, the optical gain of the QW structure grown on conventional GaN buffer is dominated by both y'- and z'-polarizations. Thus, the optical polarization characteristics of a-plane AlGaN/GaN QW lasers can be engineered by using MgZnO substrate.

1. Introduction

Quantum-wells (QWs) based on wurtzite (WZ) gallium nitride (GaN) and related nitrides are of considerable current interest because of their use as the active region in short-wavelength light-emitting diodes and laser diodes [1]. GaN-based QW lasers with the (0001) crystal orientation require higher carrier densities to generate optical gain, in comparison with zinc-blende (ZB) GaAs- or InP-based QW lasers. This is attributed to the fact that the GaN-based QW structures have a large internal field due to piezoelectric (PZ) and spontaneous (SP) polarizations [2,3]. The internal field in the QW structures causes the intrinsic quantum confined Stark effect, resulting in a red shift of the transition energy and the decrease of the transition probability. Thus, the control of the internal field is very important for the realization of high performance short wavelength devices.

The crystal orientation effects on electronic and optical properties in WZ GaN-based QW structures has been extensively studied as one of band structure engineering, in order to decrease the internal field effect [4–6]. In particular, non-polar GaN-based QW structures are interesting because the internal field is expected to be zero at this orientation. So far, most studies for the crystal orientation effect on non-polar QW structures have been focused on those grown on GaN templates [7–10]. On the other hand, nonpolar GaN-based QW structures grown on several different substrates such as ZnO, SiC, MgZnO, and so on have been proposed to improve light emission characteristics of these devices [11–14]. Among them, Xia et al. [15] recently demonstrated that non-polar a-plane (11 $\bar{2}$ 0) AlGaN/GaN QW structures grown on the GaN buffer layer on (11 $\bar{2}$ 0) MgZnO templates show an in-plane (x'-y' plane) anisotropic light emission with a strong in-plane anisotropic strain in the GaN buffer layer. With these results, we expect that z'-polarized light emission along the a-axis will be also affected by this in-plane anisotropic strain. In the case of laser diodes (LDs), the light emission polarized along a-axis is important because LD stripes oriented along the c-axis exhibit a lower threshold current [16–18]. On the theoretical side, however, there has been a very little work on the light emission characteristics of QW lasers grown on MgZnO substrates.

In this paper, we investigate electronic and optical properties of a-plane (11 $\bar{2}$ 0) AlGaN/GaN QW lasers grown on a GaN buffer with strain anisotropy using a strain-engineered MgZnO substrate. These results are compared with those of conventional AlGaN/GaN QW structures grown on a unstrained GaN buffer. The band structures and wave functions are obtained by solving the Schrödinger equation for electrons and the 6×6 Hamiltonian for holes [19,20]. We take into account the many-body effects on the optical gain spectrum, which were taken from Refs. [21] and [22].

2. Results and discussion

Fig. 1 shows the calculated PL transition wavelengths as a function of the well width for a-plane GaN/$Al_{0.2}Ga_{0.8}$ N QW structures grown on a GaN buffer with strain anisotropy and comparison with experimental data at $T = 14$ K. The interband transition energy corresponds to the energy difference between the first conduction subband (C1) and the first valence

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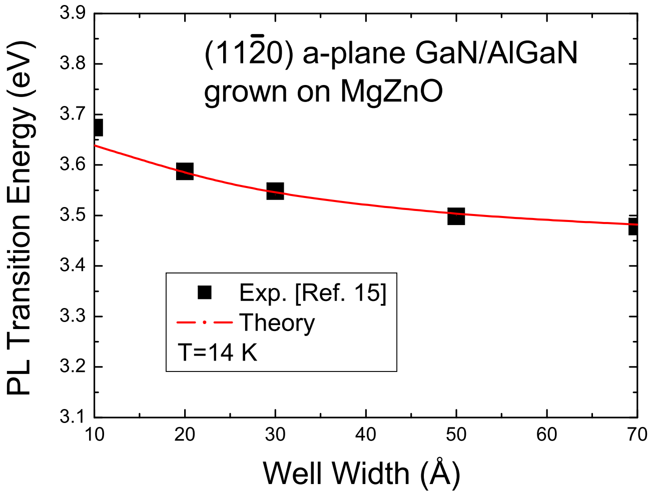

Fig. 1. Calculated PL transition wavelengths as a function of the well width for a-plane $GaN/Al_{0.2}Ga_{0.8}N$ QW structures grown on a GaN buffer with strain anisotropy and comparison with experimental data at $T = 14$ K.

subband (HH1). The experimental data for the $GaN/Al_{0.2}Ga_{0.8}$ N QW structure grown on a GaN buffer with strain anisotropy on (11 $\bar{2}$ 0) MgZnO templates were taken from Ref. [15]. The lattice constants of the GaN buffer layer used in the calculation are 3.1946, 3.1873, and 5.1801 Å along [1 $\bar{1}$ 00], [11 $\bar{2}$ 0], and [0001] directions, respectively. The material parameters for GaN and AlN used in the calculation were taken from Ref. [23] and references in there, except for band-gap. The parameters for $Al_xGa_{1-x}N$ were obtained from the linear combination between the parameters of AlN and GaN and the band-gap expression was obtained from Ref. [24]. The band gaps of GaN and AlN used for fitting with the experiment are $E_g(GaN) = 3.510 - (0.909 \times 10^{-3}T^2/(T + 830.0)$ and $E_g(AlN) = 6.25 - (1.799 \times 10^{-3}T^2/(T + 1462.0)$, respectively [25]. To compare with the measured PL energies, the C1-HH1 band edge transition energies are redshifted by 35 meV for the excitonic binding energy and the PL Stokes shift [26]. We know that the theoretical wavelength shows a reasonable agreement with the experimental result.

Fig. 2 shows optical gain spectra for x'-, y'-, and z'-polarizations of a-plane $GaN/Al_{0.2}Ga_{0.8}N$ QW structures grown on (a) unstained and (b) anisotropically strained GaN buffers and (c) peak intensities as a function of the sheet carrier density for both QW structures. The carrier density used to self-consistent solutions is $N_{2D} = 20 \times 10^{12}\text{cm}^{-2}$. Here, z'-polarization means that the optical gain is polarized along the growth direction, i.e., along a-axis. On the other hand, x'- and y'-polarizations mean that they are polarized along an in-plane direction. In a case of the QW structure grown on unstrained GaN substrate, the y'-polarized optical gain is shown to be much greater than the x'-polarized optical gain. Also, the y'-polarized optical gain is comparable to the z'-polarized optical gain and their difference is gradually reduced with increasing carrier density. This is mainly due to the fact that the $|Y'\rangle$-wave function composition gradually decreases while the $|Z'\rangle$-wave function composition increases with increasing the in-plane wave vector. On the other hand, the difference of the peak intensity for x'- and the y'-polarizations is reduced for the QW structure grown on strained GaN buffer. In particular, the QW structure grown on strained GaN buffer shows that the z'-polarized optical gain is dominant because the optical matrix element for z'-polarization rapidly increases with increasing in-plane wave vector, as discussed below. As a result, the in-plane optical anisotropy ρ for y'- and z'-polarizations is greatly enhanced. For example, the absolute values of the in-plane optical anisotropy at the carrier density of $N_{2D} = 20 \times 10^{12}\text{cm}^{-2}$ are 0.05 and 0.81 for QW structures grown on unstrained and strained GaN buffers, respectively. Here, the in-plane optical anisotropy ρ is given by $(I_{z'} - I_{y'})/(I_{z'} + I_{y'})$ where I is the peak intensity for z'- or y'-polarization.

Fig. 3 shows the valence-band structures of a-plane $GaN/Al_{0.2}Ga_{0.8}N$ QW structures grown on (a) unstained and (b) anisotropically strained GaN buffers and (c) wave function components as a function of an in-plane wave vector. Here, the in-plane wave vector is defined as $k'_{\|} = \sqrt{k'^2_x + k'^2_y}$. The naming of the subbands followed the dominant composition of the wave function at the Γ point in terms of the $|X'\rangle$, $|Y'\rangle$, and $|Z'\rangle$ bases [5]. The components $P_m^{i(=X',Y',Z')}$ of each wave function are given by $P_m^{X'} = \langle g'^{(3)}_m | g'^{(3)}_m \rangle + \langle g'^{(6)}_m | g'^{(6)}_m \rangle$, $P_m^{Y'} = (\langle g'^{(1)}_m + g'^{(2)}_m | g'^{(1)}_m + g'^{(2)}_m \rangle + \langle g'^{(4)}_m + g'^{(5)}_m | g'^{(4)}_m + g'^{(5)}_m \rangle)/2$, and $P_m^{Z'} = (\langle g'^{(2)}_m - g'^{(1)}_m | g'^{(2)}_m - g'^{(1)}_m \rangle + \langle g'^{(4)}_m - g'^{(5)}_m | g'^{(4)}_m - g'^{(5)}_m \rangle)/2$, where g'_m are the envelope functions [4]. Both QW

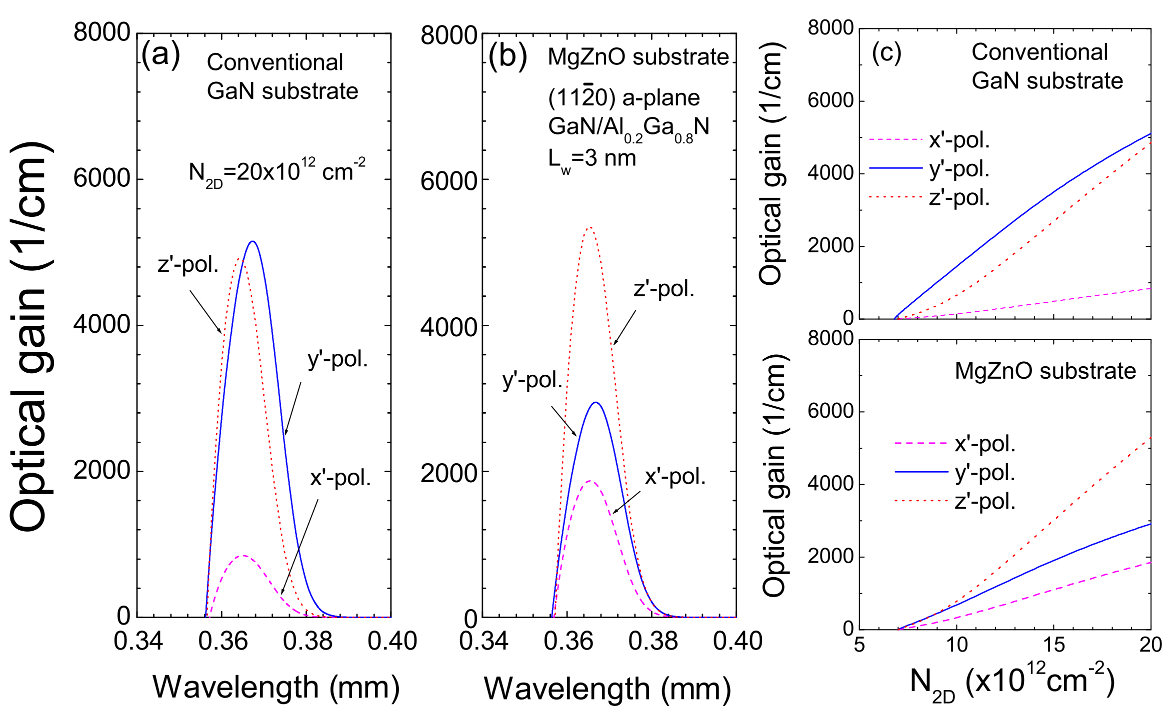

Fig. 2. Optical gain spectra for x'-, y'-, and z'-polarizations of a-plane $GaN/Al_{0.2}Ga_{0.8}N$ QW structures grown on (a) unstained and (b) anisotropically strained GaN buffers and (c) peak intensities as a function of the sheet carrier density for both QW structures. The self-consistent solutions are obtained at the carrier density of $N_{2D} = 20 \times 10^{12}\text{cm}^{-2}$.