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InGaN QW in External Electric Field Controlled by Pumping of 2D-Electron Gas

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We present investigations of GaInN/GaN/AlGaN structure containing cavity designed so that the electric field inside it can be changed by illumination. Numerical calculations show that illumination can change carrier distributions and consequently change the field and potential. The electric field influences properties of a quantum well placed in the cavity. We confirmed experimentally that the electric field controlled by external bias or by optical pumping, can change energy and occupation of electronic states in the quantum well. The quantum well energy could be changed of about 80 meV by voltage and 15 meV by illumination.

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1. Introduction

Since nitrides in wurtzite structure exhibit large spontaneous and piezoelectric polarization [1, 2], it is relatively easy to obtain high electric field in nitride structures. In heterojunction devices where strain and heterointerfaces are present, the field is inevitable. The strong electric field can be used to attract electrons which leads to formation of 2-dimensional (2D) electron gas and can be used for polarization doping [3]. Photodetectors that make profit of this effect have been shown [4, 5], including GaN/AlGaN detectors with spectral response tunable by external voltage [6, 7].

In this paper we describe GaN/AlGaN structure with cavity designed so that the electric field inside it can be changed by illumination. The cavity contains a GaInN quantum well. Electric field can be controlled by external bias and optical pumping, so it is possible to investigate properties of quantum well (QW) in significant electric field. It was observed that the photocurrent sign (determined by electric field) changes depending on wavelength and intensity of illumination as well as on external bias. Due to the Stark effect, the field changes also the energy of electronic levels in the QW. These experiments gave as possibility of detailed analysis of high electric field influence on the quantum well.

The structure can be used to build active photodetectors, which change their response for one source when they are switched by illumination from another source.

2. Properties of the structure

The investigated structure was grown by metal organic chemical vapor deposition (MOCVD) on sapphire substrate. On thick, Si-doped GaN layer there were grown several intentionally undoped layers. First 150 nm GaN layer, then AlGaN barrier (with 15% of Al) and InGaN QW (with 10% of In). The InGaN QW was covered by AlGaN layer (with 5% of Al) forming a cavity and finally with AlGaN barrier layer (15% of Al). The whole structure was covered with very thin GaN cap. The width of QW in different parts of the wafer was controlled by transmission electron microscopy. It varied from 2 nm (in the center) to 3 nm (near the edge).

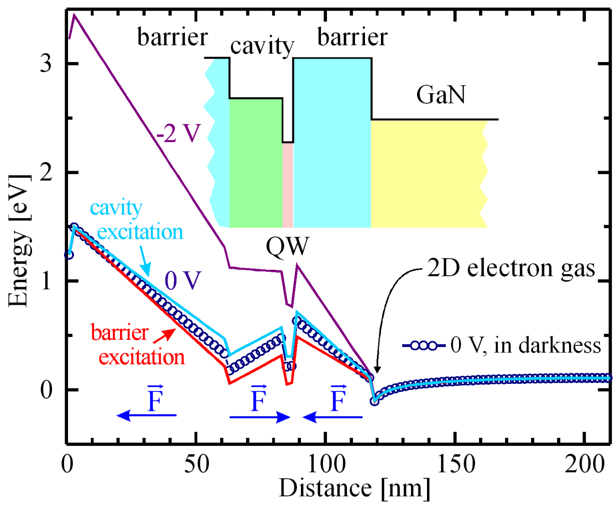

Fig. 1. Calculated distributions of potential and scheme of the structure (in the inset). Equilibrium potential is plotted by circles. Photo-excitation of barriers ($h\nu > 3.7$ eV) leads to decrease in potential in the cavity. Photo-excitation of cavity ($h\nu = 3.6$ eV) leads to increase in potential in the cavity due to accumulation of holes.

Semitransparent Schottky contact made by evaporation of gold gave possibility of external electric field application. Current–voltage characteristics showed good electrical properties of the investigated devices. At $U = -1$ V, dark current density was of the order of 3 nA/cm^2, and photocurrent efficiency was of the order of 0.1 A/W.

Numerical modeling [6, 7] made for this structure shown that illumination can change carrier distributions and consequently change the field and potential. It was obtained that without illumination the $Al_{0.05}Ga_{0.95}N$ cavity is empty. Due to spontaneous polarization, electric field (about 0.2 MV/cm) in the cavity has opposite direction than the field in the barriers. The structure was designed so that photo-injected electrons and holes can form a dipole that changes the field. Moreover, due to different dynamics of electrons and holes, some electric charge can be accumulated. The accumulation of charge changes the potential. Photo-excitation of barriers ($h\nu > 3.7$ eV) leads to accumulation of electrons (holes drift to the surface) causing decrease in potential in the cavity (see Fig. 1). The pumping leads to formation of 2D-gas at the $Al_{0.05}Ga_{0.95}N/Al_{0.15}Ga_{0.85}N$ interface. Photo-excitation of the cavity ($h\nu = 3.6$ eV) leads to increase in potential in the cavity, due to accumulation of holes (electrons are faster than holes so they diffuse out of the cavity).

3. Experiments and discussion

The structure was investigated by electroreflectance (ER), photoluminescence (PL) and photocurrent (PC) measurements at room temperature. PL was measured also at 4 K. Comparison of different experiments is shown in Fig. 2. All three experiments reveal peaks from the GaInN QW at about 3.1 eV, and GaN at about 3.42 eV. The PC and ER showed also features from the $Al_{0.05}Ga_{0.95}N$ cavity and the $Al_{0.15}Ga_{0.85}N$ barriers, at about 3.53 and 3.7 eV, respectively.

Electro-reflectance signal from the InGaN QW was weak but signal from GaN, AlGaN cavity and barriers was very clear (see Fig. 2A). The lines from the cavity shifted slightly to lower energy with decrease in bias and changed their phase (at about –2 V). The effect was probably due to change of direction of electric field in this layer. Signal from the AlGaN barriers showed clear Franz–Keldysh oscillations that were used for calculation of electric field [8]. It was found that field in the barriers was 0.26 MV/cm without bias. It decreased linearly with bias of 0.07 MV/cm per 1 V, in the range –1.5 V to 0.5 V. The InGaN QW was visible in the electroreflectance spectrum at energy about 3.1 eV. The position of the line slightly shifted into lower energies with external bias.

PC measurements shown that current generated by illumination at zero bias had different signs depending on photon energy (see Fig. 2B). For example, it was negative at $h\nu = 3.2$ eV (QW excitation), positive at 3.42 eV (GaN), negative at 3.5 eV (intermediate AlGaN layer) and back positive at 3.7 eV (AlGaN barrier).

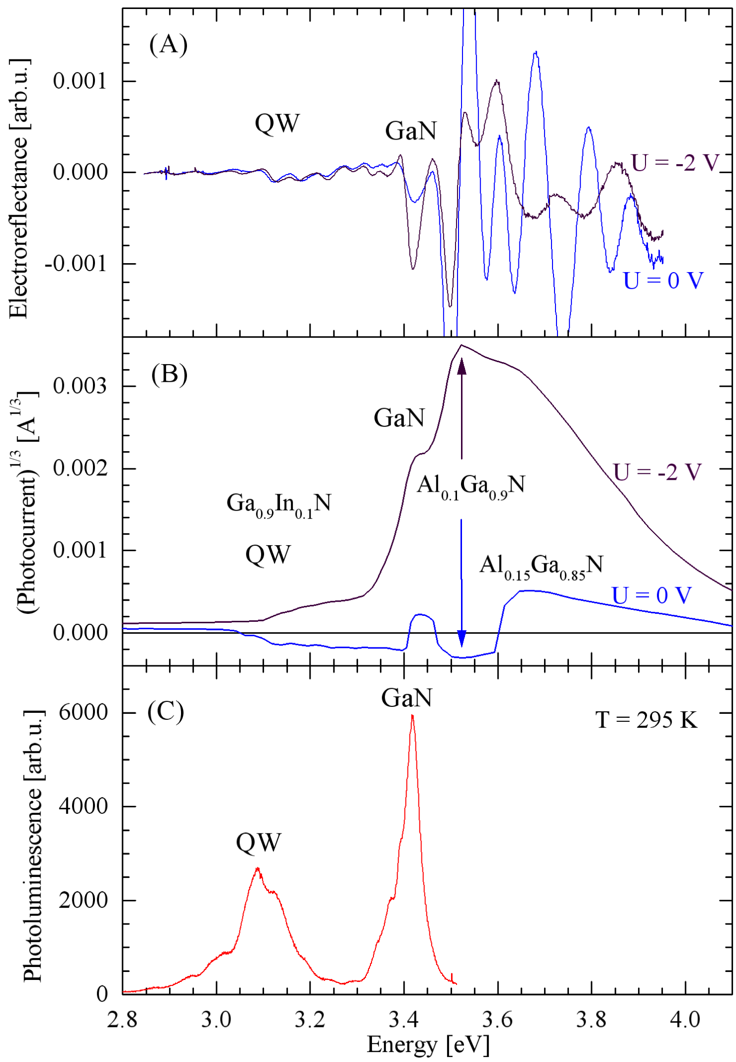

Fig. 2. Comparison of (A) ER, (B) PC, and (C) PL measured on the structure. The ER shows higher amplitude at 0 V than at –2 V, which is due to influence of 2D-electron gas present at 0 V. The QW PC shows change of sign with applied voltage, which is due to change of sign of electric field.

The sign of photocurrent depends on direction of electric field in the place where electron–hole pair was excited. Therefore, we can conclude that direction of electric field in the cavity was opposite to the field in the barriers and undoped GaN.

The sign of photocurrent from the QW and AlGaN cavity could be reversed by external bias (Fig. 2B). The shape of PC spectra changed also with excitation power. The photo-injected electrons and holes were accumulated on the opposite walls of the cavity. Their charges reduced the electric field in the cavity, however could not reverse it.

Photoluminescence was excited with He–Cd laser (3.81 eV), so only GaInN QW and GaN layer were visible (see Fig. 2C). Excitation power density was in the range 10^{-3}–10^{-4} W/cm^2. The GaN line was at 3.418 eV at room temperature and 3.481 eV at 4 K, which is a standard value for GaN grown on sapphire [9].

At room temperature, the energy of the InGaN QW PL increased clearly with increasing excitation power. Its center of mass position changed from 3.06 to 3.11 eV when power increased 20 times. Its amplitude was proportional to the power squared which means that both holes and electrons escaped quickly from the QW. The QW peak was about 80 meV broad.

At low temperature (4 K) the QW peak had width of 40 meV. Its position changed significantly with applied bias and with change of excitation power (see Fig. 3). For example, the PL energy shifted from 2.97 eV ($U = +0.8$ V) to 3.03 eV ($U = -0.5$ V). The changes of QW energy were caused by quantum confined Stark

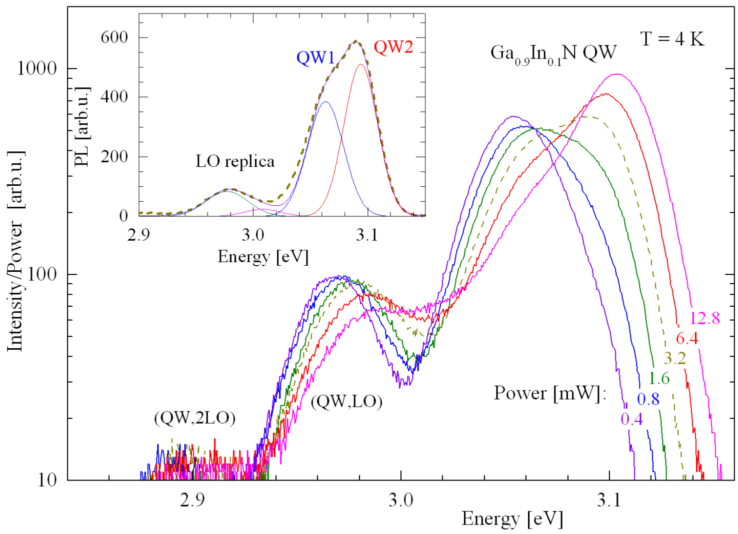

Fig. 3. PL vs. power, at 4 K. PL intensity is normalized by excitation power. It is visible that energy of the QW increases with increase in the power. The QW peak is composed of at least two lines: QW1 and QW2. The Gaussian fits are shown in the inset.

effect [10]. Due to the spontaneous polarization [1, 3], the field in the cavity had positive direction, so positive bias made it stronger. It can be concluded that 0.1 MV/cm increase in electric field caused energy decrease of 60 meV.

The low temperature measurements shown that the QW peak was composed of at least two lines: QW1 and QW2. Two Gaussian curves fitted to the QW spectrum are shown in the inset of Fig. 3. The difference between the two lines was about 0.03 eV which could be attributed to splitting of the valence band. In unstrained GaInN the splitting should be about 0.01 eV, the splitting was higher probably because the GaInN layer was strongly strained by surrounding AlGaN layers. Phonon replicas of the QW luminescence were observed at energy shifted by 84–88 meV. This value was well between energy of LO phonon in GaN (92 meV) and InN (73 meV) [11], so we concluded that these were LO phonon replicas (QW,LO).

Photoluminescence vs. power measurements (at 4 K) showed also that the energy of the QW increased with increase in excitation power. Two effects were involved: fast growth of PL intensity from the higher state (QW2) and increase in energy of both states (QW1 and QW2). Position and intensities of the QW1 and QW2 peaks were determined by fitting of Gaussian curves to the PL band and their phonon replicas. It is interesting to notice that phonon replicas of QW1 were relatively strong. Intensities of (QW1,LO) and (QW1,2LO) were about 15% and 2% of the QW1 intensity, respectively. It gives the Huang–Rhys factor $S = 0.2$, which is in agreement with literature [12]. Intensity of the QW2 replica was only about 5%. Since phonon replicas of the QW2 were much weaker, the (QW1,LO) fits were well determined even for high excitation. In order to obtain stable fits of QW1 and (QW2,LO), a constant shift between zero-phonon lines and their replicas, $\Delta E = 86$ meV, were imposed. The obtained parameters (energies and intensities vs. power) are shown in Fig. 4.

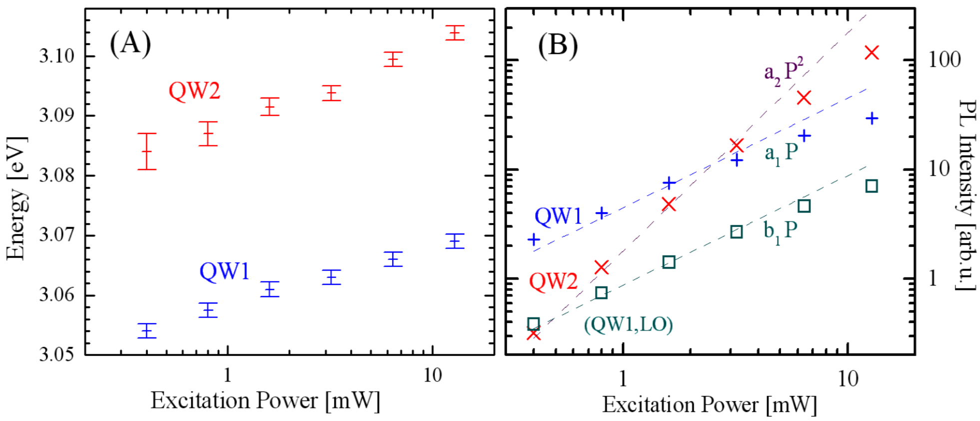

Fig. 4. PL parameters vs. excitation power, at 4 K: (A) energy, (B) intensity of two peaks: QW1 and QW2 and LO phonon replica (QW1,LO). The dashed lines in part (B) show linear and quadratic dependences for comparison with experimental data.

The energy levels of QW1 and QW2 shifted about 15 meV while power increased 30 times (see Fig. 4A). This change of energy can be explained by decrease in electric field and reduction of quantum confined Stark effect with increase in number of photo-injected carriers.

At low temperature, integrated PL intensity vs. power dependence was nearly linear, which suggested that nonradiative recombination was low. However, there was difference between QW1 and QW2 (see Fig. 4B). The dependence of the QW1 peak was slower than linear and the QW2 dependence was nearly quadratic. Since high-energy peak (QW2) grows with the increase in power much faster than the QW1 peak, as the result the center of mass energy shifted 60 meV, that was 4 times bigger than the shift of the QW1 and QW2 energies caused by the Stark effect.

4. Conclusions

An active structure containing QW in controlled electric field was presented. The QW was inside a cavity surrounded by external barriers, so the photo-excitation of the structure caused changes in the electric field and potential distribution.

Numerical calculations showed how photo-excited electrons and holes formed a dipole that changed the field. Moreover, due to different dynamics of electrons and holes, some electric charge could be accumulated which changed the potential.

The changes of electric field were confirmed by electroreflectance, photoluminescence and photocurrent measurements. The field can change sign of photocurrent, as well as energy and occupation of states in the QW. The ground state energy could be changed of about 80 meV by voltage and 15 meV by illumination. LO phonon replicas of the QW peak were observed at $\Delta E = 84$–88 meV.

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