Photoluminescence measurements on GaN/AlGaN modulation doped quantum wells

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Photoluminescence spectra were measured for 100 Å wurtzite GaN AlGaN modulation doped quantum wells. Three well-resolved peaks originate from the quantum well. The theoretically calculated confinement energies have been compared to the experimental energy positions and found to be in good agreement with the data, assuming that the piezoelectric field is largely screened by the electron gas. The highest energy transition may originate from the Fermi edge, consistent with the temperature dependence of the photoluminescence. Decay times for the different transitions indicate that the photoexcited holes are localized.

1 Introduction

There has recently been an increasing interest in III-nitrides, partly due to their promising properties for high power microwave devices; e.g. modulation doped field-effect transistors (MODFETs) [1], [2]. By doping of the barrier layer close to a hetero-interface, i.e. modulation doping, charge transfer across the interface occurs and the electrons form a two-dimensional electron gas (2DEG) in the approximately triangular shaped potential in the active layer close to the interface. Since these electrons are spatially separated from the donor impurities in the barriers, they should have a relatively high mobility. This is an important property utilized in devices such as high electron mobility transistors (HEMTs). Optical and electrical properties in these kind of structures have been extensively investigated, especially in the GaAs/AlGaAs [3], [4], but also in the InGaAs/InP [5], [6] materials system. The interest on the III- nitride side has so far mostly been focused on GaN/AlGaN modulation doped heterostructures [7], [8], [9], [10]. The understanding of the electronic structure and transitions involving the 2DEG is still limited, however. To the best of our knowledge, no detailed optical investigations have been done on modulation doped GaN/AlGaN quantum wells (QWs) [11]. Therefore, further investigations of these structures are necessary to achieve a proper understanding of the physical properties of this system, in order to exploit the full benefits of the high potential this materials system offers.

2 Samples and experimental procedure

We have performed photoluminescence (PL) and time resolved PL (TRPL) on modulation doped GaN/AlGaN QW samples. Two similar structures have been investigated, with nearly identical optical spectra. Detailed results for one of these structures are discussed below. The experimentally observed luminescence from confined states in the well has been compared with simple theoretical predictions. The samples were grown by metal organic vapor phase epitaxy on sapphire substrates. First, a 50 nm thick AlN buffer layer was grown, followed by a 0.7 μm AlGaN layer before a 1 μm layer of GaN. On top of this, a 2 μm thick AlGaN barrier, followed by the 10 nm GaN QW and another AlGaN barrier were grown. The second barrier consists of a 3 nm undoped spacer layer closest to the well, and a 100 nm thick Si-doped layer on top (see Figure 1).

The samples were placed in a liquid helium bath cryostat in which the temperature could be varied between 2 and 300 K. For stationary PL measurements the samples were excited by the 334 nm line of an Ar laser. The luminescence was collected and dispersed by a 0.6 m single monochromator before detection by a photomultiplier tube using standard lock-in techniques. TRPL measurements were performed using pico-second pulsed excitation from a frequency doubled mode locked dye laser. A syncroscan streak camera system with a time resolution of about 20 ps was used for measurements on a short time scale.

3 Modeling of the electronic structure

We have modeled the electronic energy level structure in the studied QWs. Due to the large piezoelectric (PZ) constants in III-nitrides; the strain induced PZ fields present in strained GaN/AlGaN QWs are significant. Incorporating free carriers in the structures, e.g. by doping, will reduce the effects of such PZ fields via screening. If, as a first approximation, we assume that we have a perfect square well without any PZ field present, the recombination energy E_{nm} between the n:th confined electron state and the m:th confined hole state in the QW can be estimated as follows:

$$E_{nm} = E_{gw} + E_s + E_{ne} + E_{mh}$$

where E_{gw} is the bandgap of the well material, E_s is the shift of the bandgap due to strain, E_{ne} and E_{mh} are the confinement energies of the n:th electron and m:th hole states, respectively. From PLE spectra (not shown) for this sample, the barrier bandgap E_{gb} is found to be 3.75 eV. The Al content (x=0.09) and the lattice constant a_b of the AlGaN barrier are then calculated by linear interpolations [7], [12] between values of AlN and GaN. Using the deformation potential given in Ref. [13], and standard theory of elasticity, the strain contribution is E_s =28 meV. The confinement energies are calculated by solving the Schrödinger equation numerically, using a method described in Ref. [14]. This method allows calculations for an arbitrary potential profile and a PZ field across the well can thus be modeled. For the band offset ratio between the conduction band and the valence band the value of 75:25 [15] has been employed and the effective masses ($m_e = 0.22\ m_0$ and $m_h = 1\ m_0$) are taken to have the same value in the barrier as in the GaN well. For a perfect square well, this results in a recombination energy for the ground state $E_{11} = 3.54$ eV. For the transition between the n=2 and n=3 electrons, and the m=1 hole state, the corresponding energies are $E_{21} = 3.58$ eV and $E_{31} = 3.63$ eV, respectively. The standard selection rule forbidding transitions between states with different n and m values is relaxed in our sample due to the asymmetric potential from the PZ field present and also from the modulation doping [16].

The strain-induced PZ field in the case of no screening in this structure can be estimated using equations and numerical values given in Ref. [17]. The resulting electric field is then around 165 kV/cm, corresponding to 165 meV across the 100 Å GaN well. However, the electrons accumulated in the well will effectively screen this field so that the actual field across the well is much smaller.

According to the simple estimation for density of states in the 2D case $\rho_{2D} = \frac{m^*}{\pi \hbar^2}$, where m^* is the effective mass, the sheet density of electrons required to fill the first subband up to the second subband is $\approx 3 \times 10^{12}$/cm^2. To fill the second subband up to the third subband, an additional concentration of $\approx 9.7 \times 10^{12}$/cm^2 is required. Hall measurements at room temperature on a piece from the same wafer as the sample optically characterized show a mobility of 853 cm^2/Vs and an average electron concentration of 9.5×10^{15}/cm^3, corresponding to a sheet density of 3×10^{12}/cm^2 in the 100 Å well if all electrons are accumulated in the channel. According to these estimations, the electron concentration is not sufficient to start filling the second subband, but optical data (see below) suggest that the concentration is enough or nearly enough to start filling the third subband. This discrepancy with the concentrations obtained by Hall measurements is not fully understood. However, some electrons may be trapped in the fluctuating potentials and thus not accounted for in the Hall measurements. Also, a PZ field will narrow the effective well width and thus increase the effective electron concentration in the QW potential.

4 Optical spectra and discussion

Figure 2 shows PL spectra of the sample with different excitation photon energies. The spectra are measured with pulsed excitation and time integrated detection. In the upper spectrum, the excitation is above the AlGaN barrier and in the two lower spectra, the excitation photon energies are indicated by the arrows. The emission on the high energy side at 3.654 eV is related to the AlGaN barrier, and the emission of lower energy, at 3.490 eV, originates from the GaN buffer layer. (This is evident if looking at the same spectra (not shown) for a similar structure, lacking the GaN buffer layer, since the corresponding peak is not present in that sample). Between these two peaks, three other well-defined peaks are observed at 3.535 eV, 3.585 eV and 3.620 eV, respectively. The peak at 3.620 eV is better separated from the barrier related emission when the excitation energy gets closer to this emission energy, as seen in the second spectrum from top. This spectrum, obtained with an excitation energy below the AlGaN barrier bandgap, clearly shows that these peaks do not originate from the barrier, but rather from recombination processes in the QW.

In Figure 3, the suggested model for the recombination transitions observed in the sample is shown. The emission at 3.535 eV is attributed to the ground state recombination between electrons from the lowest n=1 subband and holes in the m=1 hole subband. The energy

position of this peak agrees very well with the theoretical estimate of 3.54 eV. However, the effects on the potential of the PZ field and the modulation doping have not been taken into account in the calculations, and both of these effects will lower the recombination energy. If a PZ field of 35 meV across the well is included (corresponding to a decrease of the PL energy of approximately 5 meV), the match is excellent for this transition, but also for the $nm = 31$ (assuming band-to-band) transition.

The second QW related emission at 3.585 eV is interpreted as recombination between the second $n=2$ electron subband and the same holes as the ground state emission. The theoretical estimate of 3.58 eV is again rather close (but this time somewhat lower in energy) to the experimentally measured position of the peak.

The third QW related emission might then originate from the third electron subband. The energy position of this peak, 3.620 eV is in good agreement with the theoretical prediction of 3.63 eV. However, since it is not clear that the electron concentration is large enough to start filling the third subband, it is also possible that the emission is related to electrons at the Fermi edge. Two mechanisms to conserve the momentum in this type of transition have been suggested. If the separation between the Fermi level and the next highest electron subband is sufficiently small, a scattering path near $k = 0$ is available for electrons at the Fermi energy [18]. Alternatively, there are significant potential fluctuations present in the GaN/AlGaN QWs, and the spatial localization of the photo-induced holes at these potentials may provide the necessary spread in their wave vectors to conserve momentum [19].

The temperature dependence of the PL (continuously excited with the 334 nm line of an Ar-laser) for the sample is shown in Figure 4. An accurate temperature dependence for the peak at 3.62 eV is difficult to determine, since the peak is hardly resolved from the barrier recombination due to limits in the tuneability of the laser available for this experiment. It is clear however, that it disappears quickly as the temperature is increased from 2K, and this is consistent with an interpretation of the 3.620 eV emission as being due to a Fermi edge enhanced recombination, which is known to quench rapidly with temperature.

Decay curves for the different peaks, excited with photons of an energy below the barrier bandgap, are shown in Figure 5. All decays are non-exponential and the decay times are taken as the time required to reduce the intensity to a factor of 1/e during the first hundreds of ps of the decay. The AlGaN barrier decay is around 230 ps and the decay of the GaN buffer layer is about twice as fast, in agreement with earlier data for neutral donor bound exciton decay times in GaN layers. The slowest emission is the QW ground state emission, which has a decay time of ≈840 ps. The other two emissions from the QW are faster with lifetimes around 300 ps.

The decay time is expected to be determined by the availability of photoexcited holes. If the holes in the QW are localized in potential fluctuations [20], all QW-related emission would have a similar decay time (assuming no excitons are present at this electron concentration). The different decay times observed for the QW-related emissions could possibly be due to some spatial distribution in the hole localization potentials, allowing some difference in the corresponding decay times. Clearly the intrinsic decay time for the recombination of the ground state electrons is expected to be much longer than for the higher electron states in the QW. There is also a possibility that the recombination via the higher electron states is excitonic in character. In this case it would be natural to expect different lifetimes for localized excitons involving different electron states.

5 Conclusions and summary

Earlier investigations of the PL properties of the 2DEG in AlGaN/GaN modulation-doped heterojunctions [10], [20] illustrate the difficulties of observing the related spectral features, due to the competition with bulk recombination in the GaN layer. In the case of a simple heterojunction most of the photo-excited holes will suffer recombination in the bulk GaN, rendering the 2DEG-related spectra weak, and often not observable. In a modulation-doped QW structure, on the other hand, the photo-excited holes are confined to the QW. This greatly facilitates the observation of 2DEG-related PL features, as demonstrated for the first time in this work.

In summary we have investigated the optical properties of a modulation doped GaN/AlGaN QW by means of stationary and time-resolved photoluminescence. Three transitions related to the QW have been observed by PL. Dynamical studies provide decay times in the sub-ns regime for all emissions observed. The 2DEG-related emissions are tentatively interpreted as band-to-band transitions involving localized holes and 2DEG electrons from the first subbands. This interpretation is consistent with a simple calculation of the recombination energies in the QW potential.

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FIGURES

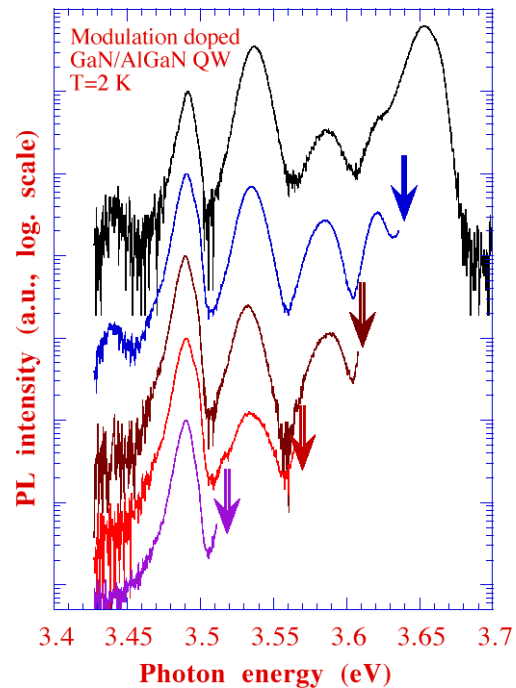Figure 1. Growth structure of the modulation doped quantum well sample.

Figure 2. Photoluminescence spectra of a modulation doped GaN/AlGaN QW with different excitation photon energies, as indicated by the arrows. The topmost spectrum was excited with 3.72 eV photons. The three middle peaks originate from emissions in the QW. The energetically lowest emission is from the GaN buffer layer, and the highest energy emission originates from the AlGaN barrier.
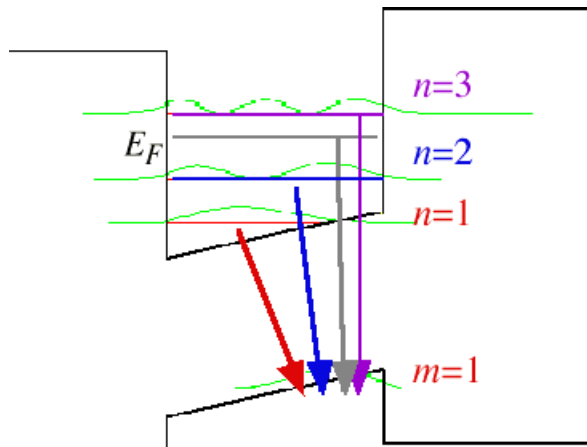
Figure 3. Schematic energy band model of the modulation doped GaN/AlGaN QW with a weak piezoelectric field across the well. Also shown are the confined states, and the suggested transitions involved are indicated by arrows. The Fermi energy is believed to lie close to the third electron subband in the QW. (The wavefunctions and energy positions of the confined states are from a calculation with a 165 keV/cm piezoelectric field across the QW.)
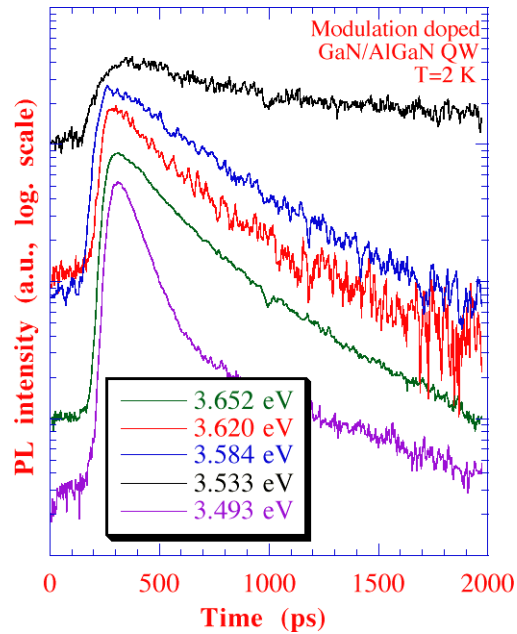

Figure 5. Time resolved decay curves for the five different peaks shown in Figure 1. The curves are measured at (from the top) 3.54, 3.59, 3.62, 3.66, and 3.49 eV, respectively.
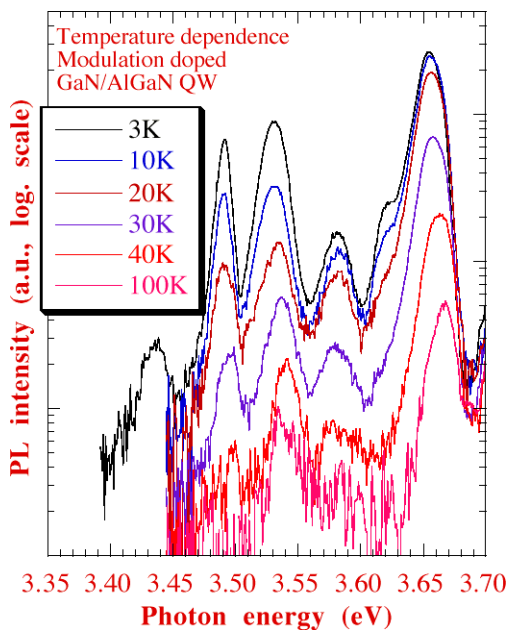

Figure 4. Temperature dependence of the PL spectra for the same GaN/AlGaN QW as in Figure 1. Spectral curves (starting from the top) are measured at 3, 10, 20, 30, 40 and 100 K, respectively.

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