Direct Determination of the Built-in Polarization Field in InGaN/GaN Quantum Wells

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Results of absorption and electroabsorption measurements on wurtzite (In)GaN light emitting diodes are reported. Despite the relatively high excitonic binding energy of 25meV in GaN no pronounced excitonic features could be observed in the absorption spectra. Electroabsorption measurements were performed to study the field induced absorption changes both in the InGaN quantum wells and the GaN barriers. This technique allows precise determination of the strong internal field changes at the GaN/InGaN-hetero-interface that originate from strain-induced polarization and differences in spontaneous polarization. We find field-induced absorption changes as large as 7000 cm^{-1} below and almost 20000 cm^{-1} above the band edge. The deduced polarization fields vary between 1.1 and 1.4 MV/cm for indium concentrations in InGaN quantum wells ranging from 7% to 9%.

1. Introduction

The rapid development of GaN-based semiconductor devices has initiated numerous innovative applications in optical data storage, high temperature electronics and semiconductor lighting. Especially in the field of LEDs and lasers, where InGaN/GaN heterostructures allow adjusting the emission wavelength over a spectral range from near UV to the visible, a lot of progress was made. Despite this progress the theoretical and experimental understanding of many fundamental properties in this material system is still relatively incomplete. For example, on the InGaN/GaN hetero-interface large internal fields exist due to the strain-induced piezoelectric effect and the difference in spontaneous polarization. These internal fields have been discussed in many theoretical and experimental publications [1-8], but reliable values are still lacking, although their impact on optoelectronic devices may be quite important. Another interesting issue is the lack of pronounced excitonic features in the optical spectra. As a consequence of the large exciton binding energy of 25 meV clear excitonic effects should be observable at room temperature at least in heterostructures.

2. Experimental

Our absorption and electroabsorption (EA) experiments were performed on wurtzite InGaN/GaN quantum wells embedded in the intrinsic region of GaN p-i-n diodes. Various samples with quantum well thicknesses ranging from 4nm to 20nm were examined. A schematic picture of the sample design is shown in Fig.1 a).

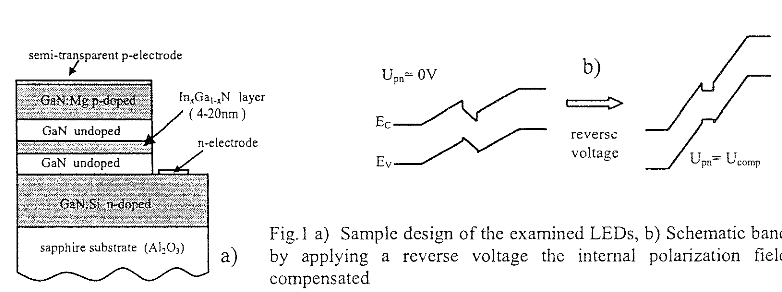

Fig.1 a) Sample design of the examined LEDs, b) Schematic band structure; by applying a reverse voltage the internal polarization fields can be compensated

In all the measured samples the absorption spectra are similar and reflect the behavior expected for a bulk semiconductor, indicating that the carrier-confinement in the InGaN layers is relatively weak. No pronounced excitonic features are observable even if the strong internal polarization fields are compensated by an external bias (as indicated in Fig. 1b). Therefore, the Franz-Keldysh effect is more suitable to describe the absorption behavior of the heterostructures than the quantum-confined Stark effect. In Fig. 2 a typical absorption spectrum obtained for a 4nm thick InGaN layer is compared with a theoretically expected spectrum for bulk InGaN representing the Franz-Keldysh effect. The measured spectra show no sign of the quantum confined Stark effect but do resemble the Franz-Keldysh spectra. We believe that this is caused by field ionization of the excitons due to lateral variation of the strong internal piezoelectric fields and/or due to a relatively weak carrier confinement in the InGaN QWs due to a small valence band offset.

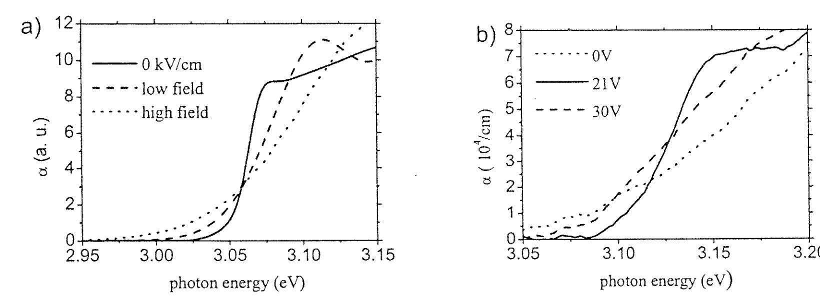

Fig. 2: a) Theoretically expected Franz-Keldysh (FK) absorption spectra for bulk InGaN. b) Measured absorption spectra for a sample with 5 InGaN QWs embedded in GaN, each 4 nm.

Field-induced absorption changes occur for photon energies around the bandgap energy and can be observed for any material within the space charge region of the diode. Since our samples containing InGaN layers embedded within GaN barriers a separated electroabsorption signal can be measured for both materials. In usual hetero-structure diodes containing no polarization fields (e.g. AlGaAs/GaAs) the internal field within the entire space charge region increases with increasing reverse bias. This is different for our InGaN/GaN heterostructures where a strong internal polarization field occurs inside the InGaN layer. The unusual band diagram of these diodes as shown in Fig. 1b is confirmed by our electroabsorption results.

In Fig. 3 the field-induced absorption changes of a GaN p-i-n diode containing a 20 nm thick InGaN layer are shown. Field-induced absorption changes around the InGaN band gap as large as 7000 cm^{-1} below and almost 20.000 cm^{-1} above the band edge have been found. We want to emphasize that the absorption changes are clearly resolvable at room temperature even in diodes containing only one single 4 nm quantum well. The analysis of the electroabsorption data allows a precise determination of the strong internal fields, originating from strain-induced polarization and differences in the spontaneous polarization. The basic idea of this method is to determine the applied reverse voltage necessary to compensate the internal field within the InGaN layer. Together with additional measurements of the space charge layer width (by CV-measurements), we are able to determine the magnitude of the piezoelectric field in our heterojunction diodes.

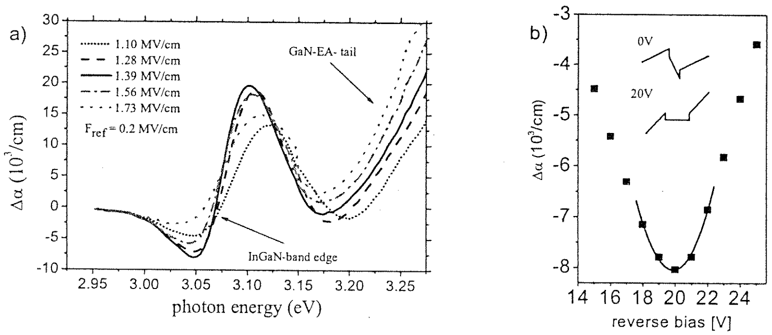

Fig. 3: Absorption changes Δα for a 20 nm thick InGaN layer. The largest absorption signal corresponds to the compensation voltage. The diagram on the right displays the largest absorption change below the InGaN band edge obtained for each voltage.

The measurements in Fig. 3 reveal that the electroabsorption signal of the InGaN layer and the GaN barrier are of opposite sign. With increasing reverse bias the electric field in the GaN barriers increases, but decreases in the InGaN layer (see inset of Fig. 3b). The internal polarization field in the InGaN layer decreases until the applied reverse bias exactly compensates the polarization field. For this compensation voltage U_{comp} the largest electroabsorption signal around the InGaN band edge can be observed. In Fig. 3b the maximum amplitude of electroabsorption below the InGaN band gap is displayed as a function of the applied reverse bias.

The absorption curves for all applied voltages intersect at a photon energy corresponding to the band gap of the semiconductor. This allows a precise determination of the band gap energy E_g. Note that the electroabsorption tail originating from the GaN barriers influences the common intersection point in Fig. 3. This influence has to be taken into account when deducing the compensation voltage and E_g from Fig.3. Knowing the compensation voltage and the thickness d of the space charge region, the internal polarization field can easily be calculated [8]. The space charge region of our devices was determined by CV-measurements.

Measuring diodes with different In content yields a plot of the internal field versus In content as shown in Fig.4. The In content has been calculated from the experimentally determined band gap energy using the formula provided by McCluskey in [9]. The measured fields vary between 1.1 MV/cm and 1.4 MV/cm with the In-content in the InGaN-layer ranging from approximately 7 % to 9 %. With this slope, the internal field is expected to be negative for zero In-content in the InGaN layer. This should not be possible and indicates, that the function of the piezoelectric field vs. In-content shows a bowing as suggested by Bernardini [2]. Unfortunately, the range of In-contents in our samples was not large enough (approx. 2 %) and the error committed by deducing the In content from E_g is to large in order to determine the bowing parameter precisely.

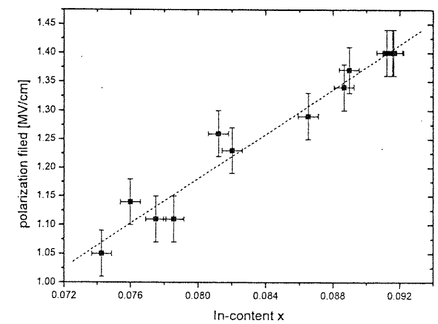

Fig. 4 Polarization fields in $In_xGa_{1-x}N$ layers determined by EA-measurements vs. the In content x. The square symbols represent the experimental data, the solid line shows a linear interpolation of the data points.

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