Quantitative analysis of the polarization fields and absorption changes in InGaN/GaN quantum wells with electroabsorption spectroscopy

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Electroabsorption measurements are reported for wurtzite InGaN/GaN quantum wells. The electroabsorption technique allows exact quantitative analysis of absorption and absorption changes in InGaN quantum wells and barrier layers, with recorded field-induced absorption changes as large as 7000 cm^{-1} below and almost 20000 cm^{-1} above the band edge. The technique thus allows precise determination of the strong internal fields that originate from strain-induced polarization and differences in spontaneous polarization. The fields measured on functioning diodes vary between 1.1 and 1.4 MV/cm for indium concentrations in InGaN quantum wells ranging from 7% to 9%. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1493229]

Extensive research has been reported on the (In)GaN materials system in the past few years. This material is very interesting for optoelectronic components like violet laser diodes or blue and green light emitting diodes (LEDs) because the band gap of the InGaN alloy covers a wide spectrum ranging from UV (GaN) to red (InN).[1] To date various GaN-based devices have been developed, such as blue and green LEDs and violet laser diodes (LDs).[2] Despite these developments theoretical and experimental understanding of many fundamental properties in this material system is still relatively incomplete. One example is the strength of the piezoelectric fields in InGaN films grown on GaN. In this letter we will demonstrate that electroabsorption (EA) spectroscopy performed on functioning heterojunction diodes is a powerful method by which to quantitatively measure the absorption changes $\Delta\alpha(\hbar\omega)$ and absorption $\alpha(\hbar\omega)$ and to determine the strong internal polarization fields in these materials.

Wurtzite (In)GaN films exhibit spontaneous polarization along the (0001) direction. At the InGaN/GaN interface, the spontaneous polarization changes. This difference in spontaneous polarization causes an electric field within the InGaN layer. In addition, a thin pseudomorphically strained InGaN layer grown on top of a GaN layer exhibits piezoelectric polarization in the InGaN layer. Both the electric field due to a difference in spontaneous polarization and the field due to the piezoelectric field algebraically total the internal polarization field in the InGaN layer. The spontaneous polarization is almost equal for GaN and InN,[3] and as a consequence the net spontaneous polarization field should be small. However, recent results of Bernardini *et al.*[4] suggested bowing of the spontaneous polarization between GaN and InN, depending on the In content.

Piezoelectric fields were calculated by Takeuchi *et al.*[5] in 1997. The same year, Bernardini *et al.*[3] published their results of the piezoelectric constants of GaN and InN. Takeuchi *et al.*[6] observed a blueshift of the photoluminescence peak of quantum well (QW) $p-i-n$ structures with an increase in applied reverse voltage due to the piezoelectric field. Chichibu *et al.*[7] explained the emission mechanisms of strained InGaN QWs by considering piezoelectric fields. More recent measurements were done by Jho *et al.*[8] and by Lai *et al.*[9] Those authors reported different field strengths, most of which are smaller than those presented in the present work.

The basic idea behind our method for determining polarization fields is to embed an InGaN layer or QW inside the intrinsic layer of a GaN $p-i-n$-diode and to compensate the internal polarization fields by applying reverse bias. The internal polarization field is exactly compensated at a certain field strength which is determined by a minimum of the absorbed light power according to the Franz–Keldysh effect. The internal polarization field strength is then calculated from the compensation voltage with the device parameters.

The sample structure for EA spectroscopy is shown in Fig. 1(a). The samples were grown on *a*-face sapphire substrates by metalorganic chemical vapor deposition (MOCVD). There is no difference in the EA measurements whether the samples are grown on *c*- or *a*-phase sapphire. First, a 5 μm thick Si-doped GaN buffer layer was grown. The active region which followed was comprised of a thin InGaN layer sandwiched between undoped *n*-type GaN barriers. The thickness of the InGaN quantum well was either 4 (sample A) or 20 nm (sample B). A third sample was a multiple quantum-well diode with five 4 nm thick InGaN quantum wells inside the intrinsic region with 6 nm wide GaN barriers. An approximately 250 nm thick Mg-doped GaN layer was grown on top of the active region to form a $p-i-n$ diode.

In the experiments, which were performed at room temperature, we measure the power of the incoming light P_0 and the power $P(U)$ transmitted through the sample as functions of the photon energy $\hbar\omega$ at various applied reverse voltages. This allows determination of the relative transmission spec-

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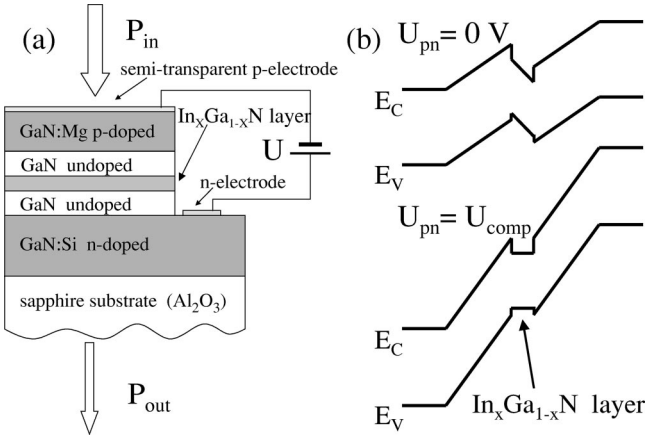

FIG. 1. (a) Schematic of the structure of the sample. For the EA measurements a reverse bias is applied across the $p-i-n$ diode and the transmitted light output P_{out} is measured. (b) Schematic of the band structure of the $p-i-n$ diode with an InGaN QW with (top) and without (bottom) applied reverse bias voltage.

tra $P(U)/P(U=0\,\mathrm{V})$, the absorption changes $\Delta\alpha(\hbar\omega)$ and the absorption spectra $\alpha(\hbar\omega)$. The absorption changes are given by $\Delta\alpha=-1/d\,\ln[P(U)/P(U=0\,\mathrm{V})]$, where d is the thickness of the InGaN layer. Typical absorption spectra are shown in Fig. 2. They resemble the absorption spectra of a bulk semiconductor. A schematic of the EA spectra of bulk InGaN is also displayed in Fig. 2. The EA spectra of a bulk semiconductor displays the Franz–Keldysh effect (FKE). Applying an external electric field to a bulk semiconductor results in tilting of the valence and conduction bands. This alters the envelope electron and hole-wave functions so that they mathematically resemble Airy functions, which have oscillating behavior in the bands and show exponential decay in the band gap. Therefore, an electric field leads to increased absorption below and oscillating absorption above the band gap. The absorption curves for all applied fields intersect at band gap energy E_g. The quantum confined Stark effect (QCSE) can arise when an applied electric field tilts the valence and conduction bands in a QW. This leads to an increase in the redshift of the absorption spectra at increasing applied fields. The measured absorption spectra from a 4 nm InGaN QW imbedded in GaN, shown in Fig. 2, shows no sign of the QCSE but does resemble the FKE of a bulk semiconductor. We performed the measurements on samples with InGaN layer thicknesses of 4 and 20 nm. In both cases the resulting absorption spectra resembled FKE spectra. We believe that this is due to the relatively weak carrier confinement in InGaN QWs relative to the strong polarization fields, maybe due to a small valence band offset.

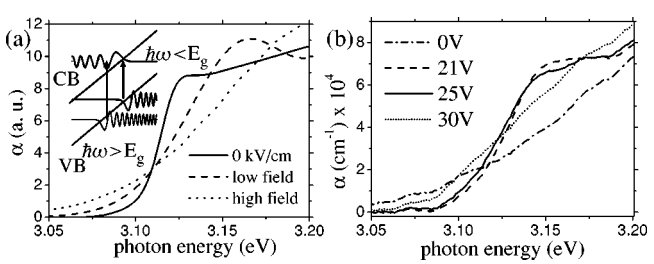

FIG. 2. (a) Schematic of the FKE in bulk InGaN. The inset shows a schematic of the band structure and envelope wave functions in the presence of an electric field. (b) Measured absorption spectra of a sample with five InGaN QWs embedded in GaN, each 4 nm. It resembles the FKE spectra. Note: The GaN EA tail interferes with the InGaN signal at high voltages.

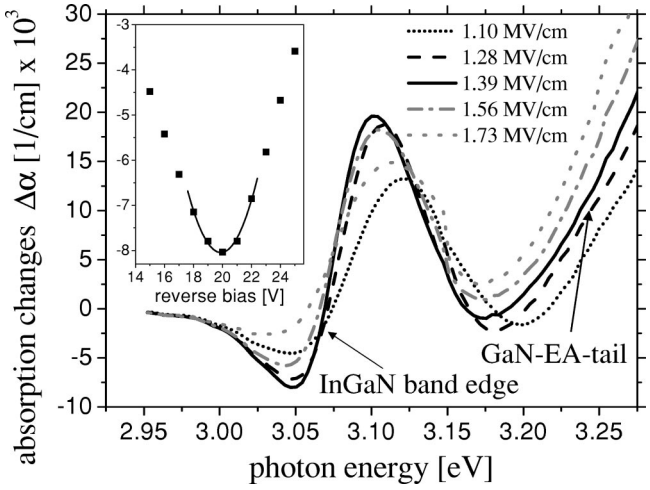

FIG. 3. Measured room-temperature absorption changes in a 20 nm thick InGaN layer. The diagram in the inset shows the maximum of the absorption changes vs the applied reverse bias, extracted from the first minimum of the main plot. The relative absorption curve at the compensation voltage is the lowest curve below E_g, allowing detection of the compensation voltage. The data presented are for a sample with a 20 nm InGaN layer.

The field-induced absorption changes occur for photon energies near the band gap energy of semiconductor materials within the space charge region of the diode. Since the space charge region of the sample consists of an InGaN layer embedded within GaN barriers, the EA signals of both semiconductors can be observed separately. Figure 3 shows the field-induced absorption changes of a GaN/InGaN/GaN double-heterostructure $p-i-n$ diode with a 20 nm thick InGaN layer in the space charge region. In heterostructure diodes with no internal piezoelectric field (e.g., AlGaAs/GaAs), the internal field within the entire space charge region increases with an increase in reverse bias.

In the case of an InGaN/GaN-heterostructure diode there already exists a (piezoelectric) field within the InGaN layer, even when no bias is applied. Therefore the measurement in Fig. 3 reveals that the EA signals of the InGaN layer and of the GaN layer are of opposite sign. Because of this, according to the FKE, there is increased absorption below the band gap. By compensating for the internal field with an applied reverse bias (compensation voltage), the absorption below the band gap decreases and vanishes when the internal polarization field is compensated. At that point, the absorption below E_g is minimized. A further increase in reverse bias results in a field in the InGaN layer and again in increased absorption below the band gap. In a plot of the absorption changes at increasing reverse bias, the absorption changes below the band gap will therefore decrease, reach the lowest value at the compensation voltage and will increase again afterwards. The absorption curves for all applied voltages intersect at a photon energy that corresponds to band gap energy E_g of the semiconductor. This allows precise determination of the band gap energy. Note that the intersection in Fig. 3 is influenced by the GaN EA tail. A typical experimental result of absorption changes is shown in Fig. 3, where one can identify the compensation voltage and band gap energy E_g.

The compensation voltage extracted yields the total internal polarization field, which is composed of spontaneous and piezoelectric fields. In a $p-i-n$ diode, the field in the space charge region is the slope of the potential curve. Since there is no field in the InGaN layer if the internal field is compensated exactly, only the thickness of the GaN layers in the space charge layer needs to be taken into account. Therefore if the internal field is compensated, the field in the space charge layer and subsequently the internal field is given by

$$F_{\mathrm{int}}=\frac{U_{\mathrm{comp}}+V_{\mathrm{bi}}}{d_i-d_{\mathrm{qw}}+d_n^+/2+d_p^-/2}, \tag{1}$$

where d_i is the thickness of the space charge layer and it can be extracted precisely from *CV* measurements. d_{qw} is the thickness of the InGaN layer, measured by x-ray diffraction. U_{comp} is the compensation voltage and V_{bi} the built-in voltage of the $p-i-n$ diode. d_n^+ and d_p^- are the widths of the space charge layers in the *n*-doped and *p*-doped regions, respectively. They depend on the known doping concentrations ($N_A=1.2\times10^{20}\,\mathrm{l/cm^3}$, $N_D=2.9\times10^{18}\,\mathrm{l/cm^3}$) and on internal polarization fields F_{int}. Therefore Eq. (1) has to be solved self-consistently. Then, typical values for d_n^+ and d_p^- are approximately 25 and 1 nm, respectively, with an error range of 10%. F_{int} can be extracted with an error of approximately 5%, which mainly originates in the accuracy of the U_{comp} measured, which has been 0.1–0.5 V, depending on the width of the intrinsic region of the sample.

So, from the results of the relative absorption changes the compensation voltage can be extracted with high accuracy. Measuring diodes with different In contents yields a plot of the internal field strength versus the In content. The In content is calculated from band gap energy E_g according to the formula found by McClusky *et al.*[10] ($E_g=3.42-3.93x, x<0.12$). The band gap energy can be measured with high accuracy at the common intersection of the field-induced absorption changes. The results are shown in Fig. 4. The internal field strength varies between 1.1 and 1.4 MV/cm for an In content of 7%–9%. With that slope, the internal field is expected to be negative for zero In content in the InGaN layer. This should not be possible and would indicate that the function of the piezoelectric field versus In content is not linear, but that there is bowing. The range of In contents in our samples was not large enough ($\Delta x\approx2\%$) to determine that. To verify the bowing, additional measurements of samples with lesser or higher amounts of In are necessary. However, the segregation of In at high In concentrations would have to be considered in the analysis of EA data.

The expected piezoelectric field strength can be calculated by the piezoelectric tensor of the materials system. Using the piezoelectric constants, recently calculated by Bernardini *et al.*,[3] and interpolating GaN and InN values to receive first-order InGaN values results in the piezoelectric field strength plotted in Fig. 4 versus the In content. Both are in reasonably good agreement, although the experimental values for the internal fields are lower than the calculated

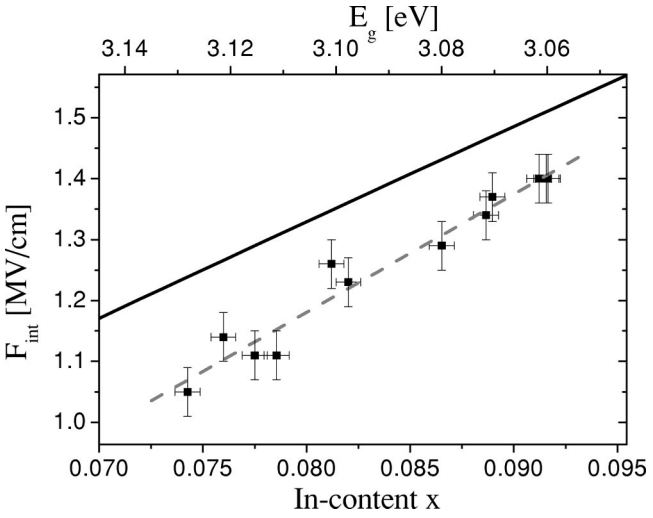

FIG. 4. Polarization fields in $In_xGa_{1-x}N$ layers determined by EA measurements vs the In content *x*. The square symbols represent the experimental data, the dashed line is a fit to the experimental data, and the solid line shows a calculated curve.

piezo fields. This may originate from differences in spontaneous polarization between GaN and InGaN due to bowing.

In summary, the dependence of the piezoelectric field on the In content was determined, and the experimentally derived field strengths are found to be larger than previously assumed. EA measurements were performed on $p-i-n$ diodes with the InGaN layer inside the space charge region. With this technique the piezoelectric/internal fields are not influenced by free carriers. It is also well suited to determining the piezoelectric fields in other materials systems and not restricted to only GaN/InGaN heterostructures. The measurements provided a quantitative analysis of absorption change and absorption spectra around the band gap energy of the InGaN layer at various applied reverse bias voltages. The results showed that the absorption spectra of a 4 nm InGaN QW resembles that of bulk FKE spectra.

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