APPLIED PHYSICS LETTERS **87**, 041109 (2005)

Fully-screened polarization-induced electric fields in blue/violet InGaN/GaN light-emitting devices grown on bulk GaN

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(Received 12 April 2005; accepted 8 June 2005; published online 22 July 2005)

Photocurrent spectroscopy and hydrostatic-pressure-dependent electroluminescence are used to show that heavy 1×10^{19} cm^{-3} Si doping of quantum barriers is sufficient to achieve full screening of polarization-induced electric fields (PIEFs) in nitride light emitting diodes (LEDs) and laser diodes (LDs) with InGaN quantum wells. Furthermore, it is shown that at currents close to lasing threshold in nitride LDs injected charge alone is sufficient to achieve full screening of PIEFs. In contrast, full screening at low currents can only be accomplished via Si doping of quantum barriers. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2000331]

Blue/violet light emitting devices, such as light emitting diodes (LEDs) and laser diodes (LDs), based on the (Al,Ga,In)N material system have been the subject of extensive study in recent years.[1,2] An important problem to be dealt with in the case of wurtzite group III-nitride heterostructures is the occurrence of large polarization-induced electric fields (PIEFs) of up to a few MW/cm along the *c*-axis of the wurtzite crystal.[3] These PIEFs originate from large spontaneous and piezoelectric polarization effects in wurtzite III-nitride heterostructures.[3,4] The main drawback of the presence of large PIEFs in the quantum wells (QWs) of nitride light emitting devices is the fact that injected electrons and holes are pulled to opposite sides of the QWs, which significantly reduces radiative efficiency.

In the case of blue/violet nitride heterostructures with InGaN active layers, the most widely investigated method for counteracting PIEFs is the use of Si doping in the quantum barriers (QBs) of the active region.[4–6] This method relies on the ionization of shallow Si dopants and the consecutive screening of PIEFs. Most reports pertaining to the effects of Si doping of the QBs on the properties of QW luminescence concern simple InGaN QW samples, whereas information on its effects on nitride light emitting device properties is more scarce. Indeed, the more complex structure of light emitting devices can give rise to significantly different behavior, induced by factors such as different growth conditions or the presence of *p-n* junction electric fields. Also, in light emitting devices densities of electrically injected carriers are typically quite high, which can (partly) account for observed screening phenomena.

The goal of the present work is the investigation of screening of PIEFs in nitride light emitting devices with InGaN QWs via Si doping of QBs. In Ref. 7, we already showed that under conditions of high injection PIEFs are absent in blue/violet nitride LDs with InGaN QWs and 1×10^{19} cm^{-3} Si doped QBs. However, since experiments were performed under conditions of high injection, screening could not unambiguously be attributed to Si doping. In the present work, we will discuss experiments that enable distinguishing between screening effects related to injected charge on one hand, and doping on the other hand.

Two distinct experimental methods will be discussed. First, we used photocurrent (PC) spectroscopy to show that full screening of PIEFs can be achieved, even at low injection conditions, in nitride LED structures with InGaN QWs and Si doped QBs. Second, in order to investigate the influence of an increasing amount of injected charge on screening phenomena, we performed hydrostatic-pressure-dependent electroluminescence (EL) measurements of nitride LD structures. It is worthwhile to remark at this point that bulk GaN substrates were employed in order to obtain high-quality samples.[8]

PC spectroscopy constitutes a sensitive experimental tool for the assessment of the magnitude of the electric field in the active layers of nitride LED structures. It was demonstrated in Ref. 9 that, as is also seen in the Franz-Keldysh effect,[10] the semilogarithmic slope of the absorption edge of nitride LED PC spectra is sensitive to the magnitude of the

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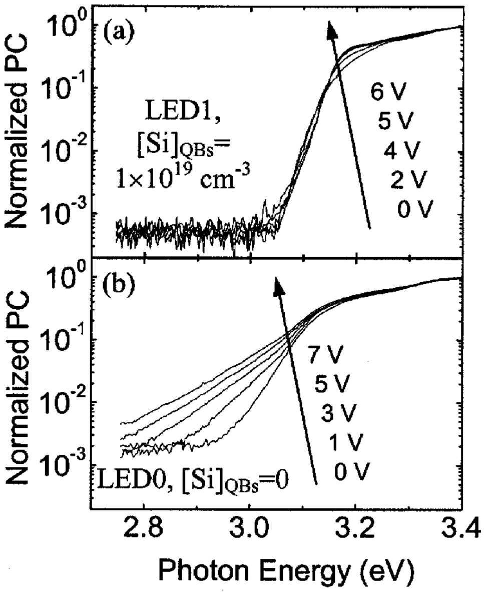

FIG. 1. External bias dependent PC spectra of (a) LED1 and (b) LED0 for a range of reverse biases. Sample LED1 contains 1×10^{19} cm^{-3} Si doping in the QBs, whereas sample LED0 has undoped QBs.

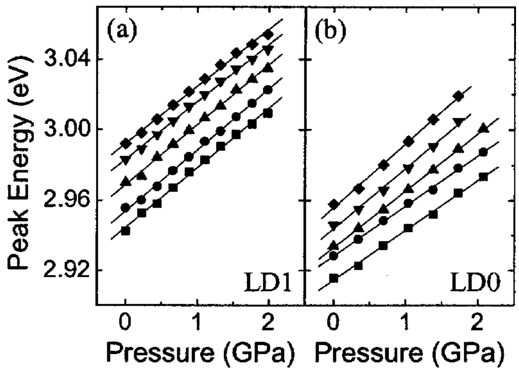

FIG. 2. Pressure dependence of the EL peak energies E_E of (a) LD1 and (b) LD0 for selected currents. Starting from the curves with lowest peak energies, applied currents are: 10 μA, 10 mA, 100 mA, 400 mA, 1 A for LD1; 10 μA, 300 μA, 20 mA, 100 mA, 400 mA for LD0. Solid lines indicate fits of the slope dE_E/dp.

electric field. Indeed, a larger electric field leads to a less steep absorption edge. In the present work, we use PC spectroscopy to investigate screening of PIEFs by Si doping of the QBs. The idea of the experiment is to compare external bias dependent PC spectra of a LED sample with *Si doped QBs* to external bias dependent PC spectra of a LED sample with *undoped QBs*. If indeed PIEFs are fully screened in the sample with Si doped QBs, a change of the external bias should not induce a change of the total electric field in the QWs (provided the modified electric field remains fully screened), and hence no change of the slope of the absorption edge should be observed. In contrast, in the case of undoped or insufficiently doped QBs, we should observe a change of slope of the absorption edge as the external bias varies.

The two investigated samples are designated LED1 and LED0. They are identical, except for the fact that sample LED1 contains 1×10^{19} cm^{-3} Si doped QBs, whereas sample LED0 contains undoped QBs. Metal-Organic Vapor Phase Epitaxy (MOVPE) grown samples consist of, consecutively, 60 μm bulk GaN, 0.5 μm n-type GaN with 1×10^{19} cm^{-3} Si, $5\times[4.0$ nm $In_{0.09}Ga_{0.91}N/8.0$ nm $In_{0.02}Ga_{0.98}N]$ QWs/QBs, and 0.2 μm p-type GaN with 1×10^{19} cm^{-3} Mg. Sample areas were 300×300 μm^2. A description of the PC spectroscopy setup can be found elsewhere.[9] Excitation powers in the PC experiment are of the order of 10 mW/cm^2, which is insufficient to induce significant screening by injected carriers.

Figure 1 shows external bias dependent PC spectra of LED1 and LED0 for reverse biases between 0 V and 6 V for sample LED1, and between 0 V and 7 V for sample LED0. It can clearly be observed that a change of the external bias induces a change of the semilogarithmic slope of the absorption edge in the case of LED0, but not in the case of LED1. According to the argumentation presented above, this can be interpreted as evidence that PIEFs in LED1 are fully screened. Since the carrier densities excited in the PC experiment are too low to screen the PIEFs, the observed screening in sample LED1 can be fully attributed to the presence of 1×10^{19} cm^{-3} Si doping in the QBs.

Having demonstrated the possibility of electric field screening by means of Si doping of the QBs in a nitride LED, we now proceed by investigating the influence of injected charge on electric field screening. For this purpose, we will focus our attention on two nitride LDs, designated LD1 and LD0. The use of LDs instead of LEDs is motivated by the fact that we are mainly interested in the optimization of nitride LD design. For the application of PC spectroscopy the use of LED samples was required because of their larger spatial dimensions and better optical accessibility of the active layers.

The experimental method used to evaluate PIEF screening in nitride LDs relies on hydrostatic-pressure-dependent measurements of the band gap related EL peak energy E_E for a range of current densities. As in Ref. 7, we use the fact that in the case of fully screened electric fields in InGaN QWs dE_E/dp equals dE_G/dp (in which E_G is the band gap energy), whereas in the case of partly screened or unscreened electric fields dE_E/dp is reduced with respect to dE_G/dp because of the pressure-induced increase of PIEFs.[11]

The active region of LD1 consists of $5\times[4.1$ nm $In_{0.09}Ga_{0.91}N/10.5$ nm $In_{0.02}Ga_{0.98}N]$ QWs/QBs, and the active region of LD0 consists of $5\times[5.4$ nm $In_{0.09}Ga_{0.91}N/6.0$ nm $In_{0.02}Ga_{0.98}N]$ QWs/QBs. QBs of LD1 contain 1×10^{19} cm^{-3} Si doping, whereas QBs of LD0 are undoped. Stripe areas are 5×500 μm^2. A description of the experimental high-pressure setup can be found elsewhere.[7] For currents up to 10 mA we applied dc currents, whereas for currents higher than 10 mA pulsed measurements with a 1% duty cycle were performed. All spectra were recorded below lasing threshold, which was about 1 A for both LDs.

In Fig. 2, pressure dependent EL peak positions are shown for selected currents, together with linear fits which were performed to determine dE_E/dp. The current-induced blueshifts of about 50 meV do not provide unambiguous information, since the observed blueshifts are the combined result of blueshift mechanisms such as electric field screening and band tail filling, and redshift mechanisms such as band gap renormalization. However, the sensitivity of dE_E/dp to the presence of electric fields provides us with a tool to evaluate the screening efficiency of the injected

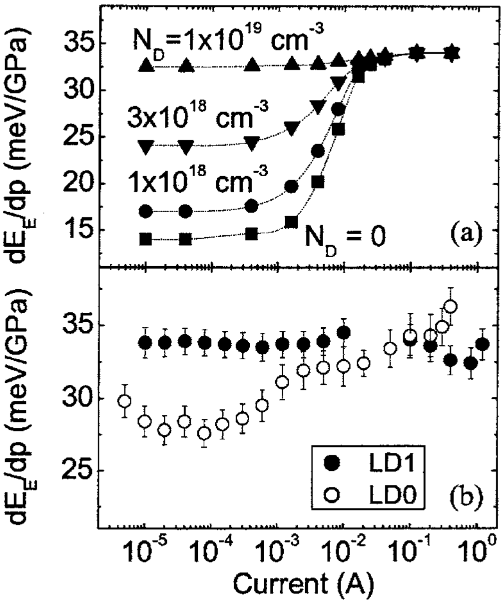

FIG. 3. (a) Simulated dependencies of dE_E/dp on current for different background doping concentrations N_D. Parameters of LD0 were used for the simulation. (b) Measured dependences of dE_E/dp on current for LD1 (1×10^{19} cm^{-3} Si doped QBs) and LD0 (undoped QBs).

charge. Upon close examination, from Fig. 2 it can be observed that dE_E/dp is practically constant in the whole range of currents for LD1, whereas for LD0 dE_E/dp is larger for larger currents.

Before presenting measured values of dE_E/dp in the full current range, it is useful to inspect the quantitive estimations presented in Fig. 3(a). The basis of this simulation was a simple model, in which the electric field in the InGaN QWs was assumed to be constant, and the screening efficiency of a certain amount of charge was inferred from the electron and hole wavefunction overlap. Parameters of LD0 were used for the simulation. Charge sheet densities σ were converted to current densities J via $J=q\sigma/\tau$, assuming an injection efficiency of 100% and a carrier lifetime τ of 1 ns.[2] The used linear relation between σ and J implies the assumption that nonradiative processes are the main source of carrier recombination, which is realistic for blue/violet nitride LDs at room temperature.[2] Taking into account partial compensation of the PIEF by the *p-n* junction electric field, an estimated unscreened electric field value of 0.5 MV/cm was used. For dE_E/dp of fully screened InGaN QWs we took the value of 34 meV/GPa, as is suggested by the experimental data in Fig. 3(b). The pressure derivative of the PIEF was taken from calculation results (concerning structures with similar parameters) presented in Ref. 11. In order to show the effect of additional screening by fixed charges, calculations were performed for a range of background ionized donor concentrations N_D. We see that steplike behavior of dE_E/dp as a function of current can be expected. The saturation of dE_E/dp at high currents corresponds to full screening. In case of sufficiently high QB doping, full screening is achieved for all currents.

In Fig. 3(b), where the measured dependences of dE_E/dp on current for LD1 and LD0 are explicitly shown, steplike behavior is observed for LD0, but not for LD1. Bearing in mind the discussion above, we see that electric fields are screened in the full range of currents for LD1, whereas for full screening in LD0 a current higher than about 10 mA is required. We can therefore conclude that in the investigated samples electric field screening by 1×10^{19} cm^{-3} Si doping of QBs plays an important role at small currents, but that at larger currents (close to lasing threshold) injected charge alone suffices to provide full screening. This suggests that, as far as counteracting PIEFs is concerned, heavy Si doping of QBs is not crucial in operating InGaN based LDs. Because of the approximate character of model and assumptions, a too rigid comparison of the simulations of Fig. 3(a) with the results of Fig. 3(b) cannot be justified. In particular, more advanced modeling should take into consideration the dependence of the carrier lifetime on injected carrier density. Nonetheless, the relatively high value of dE_E/dp for LD0 at low currents as compared to the curve with $N_D=0$ in Fig. 3(a) suggests that even in LD0, which has nominally undoped QBs, some unintentional background doping is present.

In summary, we showed by means of PC spectroscopy that heavy 1×10^{19} cm^{-3} Si doping of QBs is sufficient to achieve full screening of PIEFs in the nitride LEDs with InGaN QWs investigated here. Hydrostatic-pressure-dependent EL experiments on nitride LDS with InGaN QWs confirmed the screening capability of heavy Si doping. Furthermore, also via hydrostatic-pressure-dependent EL measurements, injected charge alone was observed to suffice for the achievement of full screening of PIEFs in nitride LDs close to lasing threshold, but not at low injection currents.

This work was partially supported by the European Commission within Projects No. STREP 5056441-1 “GaNano,” by the Polish Government program “The development of blue optoelectronics,” Project No. 2700/C.T11-8/2000, by EU Integrated Project WWW.BRIGHT.EU (Contract No. 511722), and by the EU Projects DENIS (G5RD-CT-2001-00566) and PRENABIO (G1MA-CT-2002-04055).

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