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Photoluminescence of Mg-doped *m*-plane GaN grown by MOCVD on bulk GaN substrates

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Photoluminescence (PL) properties are reported for a set of *m*-plane GaN films with Mg doping varied from mid 10^{18} cm^{-3} to above 10^{20} cm^{-3}. The samples were grown with MOCVD at reduced pressure on low defect density bulk GaN templates. The sharp line near bandgap bound exciton (BE) spectra observed below 50 K, as well as the broader donor-acceptor pair (DAP) PL bands at 2.9 eV to 3.3 eV give evidence of several Mg related acceptors, similar to the case of *c*-plane GaN. The dependence of the BE spectra on excitation intensity as well as the transient decay behaviour demonstrate acoustic phonon assisted transfer between the acceptor BE states. The lower energy donor-acceptor pair spectra suggest the presence of deep acceptors, in addition to the two main shallower ones at about 0.23 eV. Similar spectra from Mg-doped GaN nanowires (NWs) grown by MOCVD are also briefly discussed.

1 Introduction Recently the interest of using non-polar crystallographic planes for epitaxial growth of III-nitride based light emitting diode (LED) and laser diode (LD) structures has grown dramatically, since the vertical polarization field in the structures can be avoided for non-polar directions [1]. It is less clear how doping can be controlled for such surfaces. Previous reports on high quality Mg-doped m-plane GaN layers grown on bulk GaN concentrated on electrical properties [2]. We report a photoluminescence (PL) study of Mg doping of *m*-plane GaN layers over a wide range of Mg concentrations. This is also relevant for LEDs based on GaN/InGaN nanowire (NW) arrays, where the main emitting planes are the *m*-planes. PL data for Mg-doped GaN nanowires with *m*-plane side facets are also discussed.

2 Samples and experiments

2.1 Growth conditions The 500 nm thick Mg-doped m-plane GaN films were grown on bulk *m*-plane GaN substrates under 400 Torr chamber pressure at ~1000-1010˚C, using metalorganic chemical vapor deposition (MOCVD). Trimethylgallium (TMGa) and ammonia were used as the Ga and N sources with a flow rate of 54 µmol/min, and 7 SLM (standard liter per min), respectively. The Mg doping concentration ([Mg]) was varied by changing the Cp_2Mg source flow rate from 0.24 µmol/min to 7.2 µmol/min. The samples discussed here have estimated Mg concentrations 8×10^{18} cm^{-3} (A), 2×10^{19} cm^{-3} (B), 5×10^{19} cm^{-3} (C), and 1×10^{20} cm^{-3} (D). The *m*-plane freestanding GaN substrates, provided by Kyma Technologies, have a threading dislocation density < 5×10^6 cm^{-2}. The NW samples are grown with MOCVD at GLO AB, using a Thomas Swan close-coupled showerhead growth chamber.

2.2 Annealing and optical measurements Each of the planar samples was cut in two pieces, and one piece was furnace annealed for about 10 min at 800° C in flowing N_2 gas. Stationary PL spectra were measured with cw UV excitation (photon energy of 4.66 eV or 3.81 eV), from 2 K to 300 K. PL transient measurements were done using femtosecond pulses from a frequency tripled Ti:sapphire laser (76 MHz, 4.66 eV), and detected with a UV sensitive Hamamatsu streak camera with a fast sweep unit.

3 Experimental results and discussion

3.1 PL spectra Fig. 1 shows low temperature stationary PL spectra in the near bandgap region for sample A. The free exciton (FE) and donor bound exciton (DBE) peaks are weak. A dominant peak at 3.466 eV is the Mg-related A1 acceptor BE peak (ABE1) [3]. This peak has a low energy wing due to acoustic phonon coupling, common for ABEs in wide bandgap materials. A broad second ABE peak (ABE2, related to acceptor A2 [3]) is seen at 3.454 eV, this peak increases superlinearly in intensity with increased excitation. This broad feature shows some structure, a peak at 3.458 eV is observed in the figure. A weaker peak (X) at 3.444 eV with a low energy acoustic phonon wing completes the near bandgap spectrum.

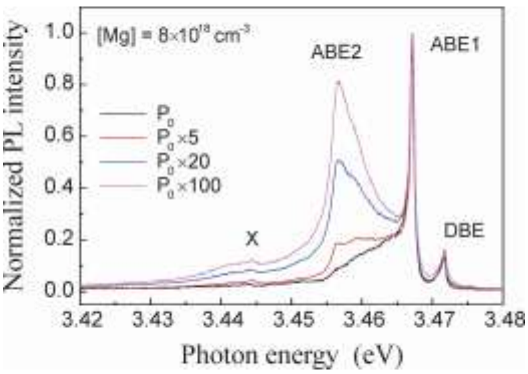

Figure 1 Low-temperature (2 K) PL spectra in the near bandgap region of sample A at different excitation power.

There is no strong difference in PL spectra between virgin samples and annealed samples, presumably due to a significant activation of the acceptors during growth and cool down, i. e. the H passivation is largely removed.

Fig. 2 shows the PL spectra at 2 K at lower photon energies, in the region of the DAP recombination. The dominant 3.27 eV DAP emission with its LO phonon replicas is present in all samples, but broad emission bands at lower energies are dominant for the highest doping.

Fig 3 shows NW array PL spectra as well as micro-PL spectra for two single NWs of about 400 nm diameter with Mg doping density estimated as high 10^{18} cm^{-3} and high 10^{19} cm^{-3}, respectively. In the low doped sample the 3.27 eV DAP emission dominates, while PL in the highly doped sample peaks at lower energy. This is similar to the data for the epi-layers in Fig. 2, and demonstrates the feasibility of controlling Mg-doping in the nanowire growth process.

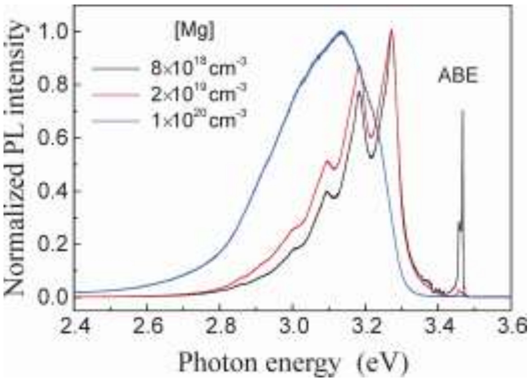

Figure 2 Low-temperature (2 K) PL spectra of three samples A,B and D.

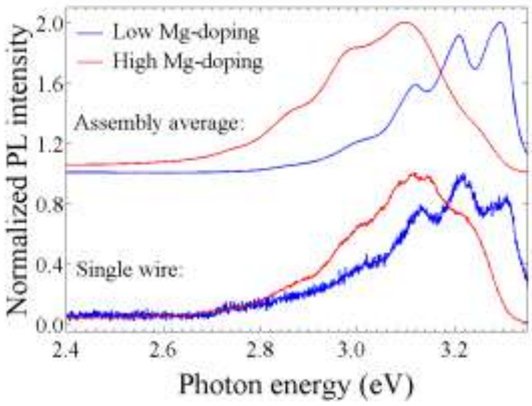

Figure 3 Low-temperature (4 K) NW array spectra (top) and micro-PL spectra in the DAP region (bottom) for two Mg-doped NW samples (see text). The single wire spectra are slightly distorted by whispering gallery modes.

Fig. 4 shows an example of the excitation intensity dependence of the PL spectrum in the DAP region for sample D. This sample shows no PL in the near bandgap region at 2 K. At low excitation the main PL peak occurs around 3.1 eV (presumably related to the acceptor A2 [3]), while at the highest excitation the A1-related 3.27 eV DAP peak is enhanced. This behaviour is explained mainly by saturation of DAP emissions involving deeper acceptor states, which have a lower oscillator strength for the DAP emission [4]. It is assumed that the main donors present are shallow O and Si donors [4]. We suggest that the deeper PL emission peaking around 3.0 eV (Fig. 2) is related to DAPs involving deep acceptors and shallow donors [4].

3.2 Temperature dependence Fig. 5 shows near bandgap PL spectra of the lowest doped sample at some different temperatures. The ABE1 and ABE2 features are largely quenched at 40 K, while the weaker 3.444 eV peak survives up to about 50 K. ABEs in GaN are quenching at these low temperatures, the somewhat higher stability of the 3.444 eV peak is consistent with its stronger binding energy. The origin of this peak (X) is not identified, it could be related to a deeper Mg-related acceptor than A1 and A2, but it may also be related to a structural defect, since it was not observed in *c*-plane Mg-doped samples [3,4].

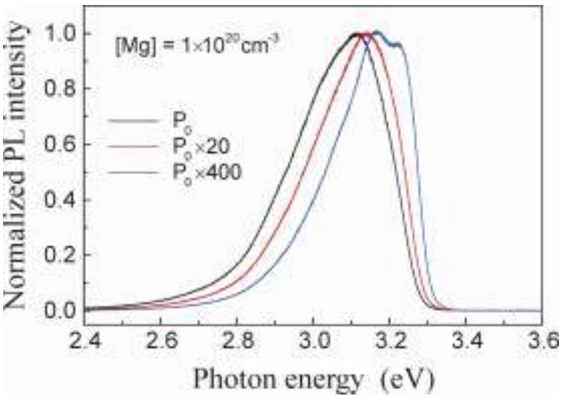

Figure 4 Low-temperature (2 K) PL spectra in the DAP region of sample D at different excitation power.

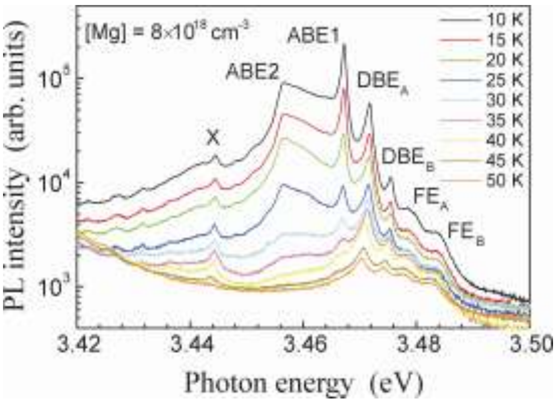

Figure 5 Near bandgap PL spectra for sample A taken at different temperatures.

3.3 Transient PL data, decay times In previous work it was determined that the radiative decay time of ABE1 is about 900 ps [5], as obtained from low doped n-type samples. For high Mg-doping exciton transfer processes affect the decay times substantially. Fig. 6 shows decays for the ABE region for sample B. The ABE1 shows a non-exponential decay with a fast initial part about 400 ps, and a slower later part. This faster decay is interpreted as evidence of exciton transfer from ABE1 to the lower broad ABE2 spectrum and also to the X-line. The X peak at 3.444 eV clearly has a different longer decay time.

3.4 Discussion The PL spectra for *m*-plane Mg-doped samples are very similar to the corresponding ones for *c*-plane growth [3]. This is expected unless specific defect reactions occur on the *m*-plane surface during the growth procedure. Under the growth conditions for these samples acceptor activation seems to be largely completed after cool down from growth. The main new spectral feature in the Mg-doped *m*-plane samples seems to be a weak peak X at 3.444 eV, with an associated acoustic phonon wing. This peak is so far unidentified. The broad spectral features for the 3.454 eV ABE2 PL peak may be understood considering an acoustic phonon assisted transfer of excitons to the ABE2 state, occurring on the same time scale as the ABE recombination. The appearance of the DAP spectra in the range 2.9 eV to 3.3 eV is similar to the corresponding results for the *c*-plane Mg-doped samples studied earlier [3,4]. There seem to be several Mg-related acceptors present, some are considerably deeper than 0.2 eV, and these are expected to influence the position of the Fermi level in case of low residual donor concentrations [4]. The PL spectra for Mg-doped NW samples are consistent with the set of planar epi-layers studied.

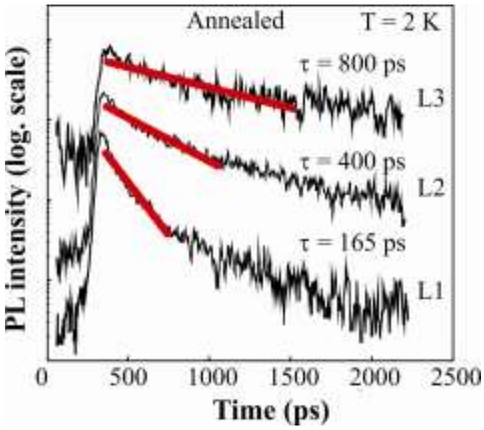

Figure 6 Three decay curves at 2 K corresponding to the spectral positions of ABE1 (L1), ABE2 (L2) and X (L3), respectively. The lines with τ values are just indications of the time scale of the decays, and do not represent evaluated radiative lifetimes.

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