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New approach to cathodoluminescence studies in application to InGaN/GaN laser diode degradation

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Summary

Cathodoluminescence (CL) studies are widely applied in semi-conductor science and technology. However, for structures with a p-n junction the CL spatial distribution can be strongly affected by internal current flows of the electron beam induced current generated within the structure. This influence is the investigated in application to CL studies of degradation in aged laser diodes with InGaN multiquantum wells.

Introduction

The progress of optoelectronic applications, especially of high-capacity optical data storage systems is connected with the development of nitride laser diodes (LDs) emitting blue, violet, and ultraviolet lights. The market demand for InGaN-based LDs is estimated at hundreds of millions per year. To meet this demand, the further development of the production of more reliable LDs is necessary. Therefore, an investigation of the degradation mechanisms of InGaN-based nitride LDs is now an important research area.

The dislocation density is most frequently indicated as the main factor increasing the degradation rate in aged LDs (e.g. Kuroda *et al.*, 1998; Hansen *et al.*, 2002; Tomiya *et al.*, 2004; Furitsch *et al.*, 2006; Marona *et al.*, 2006). The mechanism responsible for laser degradation is electrothermally activated (Meneghini *et al.*, 2008). The degradation rate is not related to the dislocation multiplication but to the propagation of point defects, supposedly the diffusion of magnesium, along threading dislocations (TDs) existing in the samples prior to the degradation. The number of TDs depends on the lattice mismatch between the substrate and the grown GaN epitaxial layers, where the mismatch for sapphire or SiC substrates is respectively about 13 and 3.5%. Therefore, the use of the crystalline GaN substrates brings new possibilities for the degradation rate decreasing. However, the crystals obtained by the presently dominating method of GaN substrate production have an average density of dislocations in the order of 10^5–10^6 cm^{-2}. Alternative methods, like the high-pressure synthesis method offer advantages, with the TD density lower than 100 cm^{-2} in grown crystals (Perlin *et al.*, 2008). Because TDs density in the initial substrate influences TDs density in the epitaxial layers, the nitride-based LDs with such almost dislocation-free high-pressure grown crystalline bulk GaN substrates are very promising from the reliability point of view. Such LDs are investigated in this paper.

An important research tool for the degradation investigations of nitride LDs is cathodoluminescence (CL) studies (Hansen *et al.*, 2002; Tomiya *et al.*, 2004; Marona *et al.*, 2008; Rossi *et al.*, 2008). Two direct conclusions can be drawn: (1) the appearance of new peaks in the CL spectrum (especially at low-temperature measurements) revealing the existence of new recombination centres in the aged samples and (2) a decrease in the CL intensity of the spontaneous excitation at the designed LD wavelength (i.e. related to the quantum well) in the aged samples in comparison with the non-aged ones. The ageing is often performed on devices mounted *p*-side down towards a heat sink, and CL measurements allow for the non-contact measurement of devices without metallization, dismounted for a structural investigation. CL studies allow also for the separation of direct material-related degradation features of ageing (like creation of non-radiative recombination centres), revealed by CL, from construction-related features (like facet, contact or electron-barrier degradation), undetected by CL. However, it has been demonstrated lately that the results of CL studies are highly dependent on the resistances existing within the measured semi-conductor structures (Czerwinski *et al.*, 2008, 2009). This work shows the impact of this effect on the conclusions obtained from typical studies of CL intensity degradation in InGaN-based LDs.

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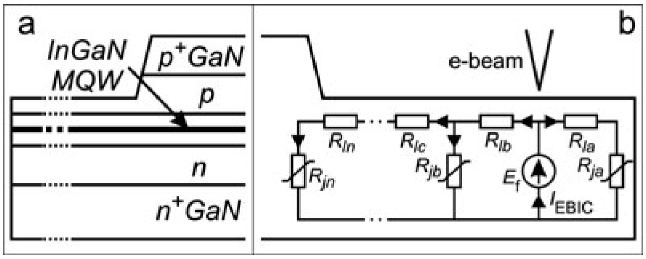

Fig. 1. (a) Simplified diagram of the InGaN laser cross-section. (b) Corresponding electrical diagram of the internal current loop in this structure with schematically drawn the voltage source E_f, lateral (layer) resistances R_l, non-linear junction resistances R_j and outflowing internal I_{EBIC} current (total and its components) marked with arrows. Only lateral resistances of thinned upper p-type cladding (in the lateral confinement region) are marked, because in this structure they are much larger than resistances of the thick n-type layer.

Experimental

The oxide isolated, ridge waveguide LDs manufactured by metal organic chemical vapour deposition (MOCVD) on high-pressure synthesized bulk GaN substrate were investigated. The stripe width was 5–20 μm and the resonator length was 500 μm. The active region of the LDs consisted of five undoped $In_{0.09}Ga_{0.91}N$ quantum wells (QWs) and silicon doped $In_{0.02}Ga_{0.98}N$ barriers. The structures also contained Mg doped and Si doped GaN waveguides and $Al_{0.20}Ga_{0.80}N$ electron blocking layer. The mesa was etched down to the middle of the upper AlGaN cladding layer. Figure 1(a) shows a simplified diagram of a typical structure. After complete processing some LDs (non-aged) were powered for a short period of time in order to check their parameters. The other LDs (aged) were powered for tens or hundreds of hours. Afterwards, the metallization was removed from all of the examined LDs. The CL measurements were performed using the scanning electron microscope (SEM) Philips XL30 equipped with the MonoCL (Oxford Instrument) CL system. In this CL setup the photons emitted towards the parabolic mirror placed above the structure are collected. Two types of CL studies were performed: (i) the standard imaging, when the CL image was registered while scanning the examined structure with the electron beam (Fig. 2) and (ii) the quantitative measurements, when the CL signal was collected while a rectangular area (2×30 μm^2) of the structure was exposed to the electron beam (the diagrams shown in Fig. 3). In the CL measurements the same distance between the specimens and the detector

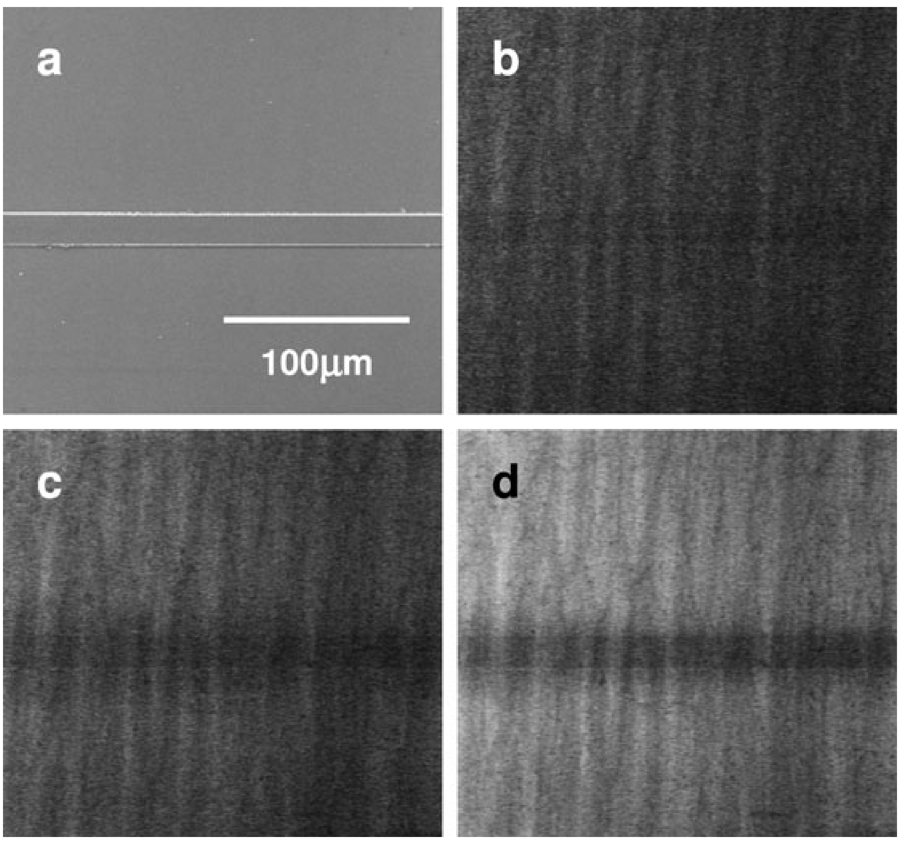

Fig. 2. Secondary electron mode image of a fragment of an aged LD (a) and CL mode monochromatic images of this structure recorded at an E_{beam} of 22 keV, and a wavelength $\lambda = 395$ nm (corresponding to the quantum well) for three different I_{beam} currents: 1.5 nA (b), 4.6 nA (c) and 10.4 nA (d).

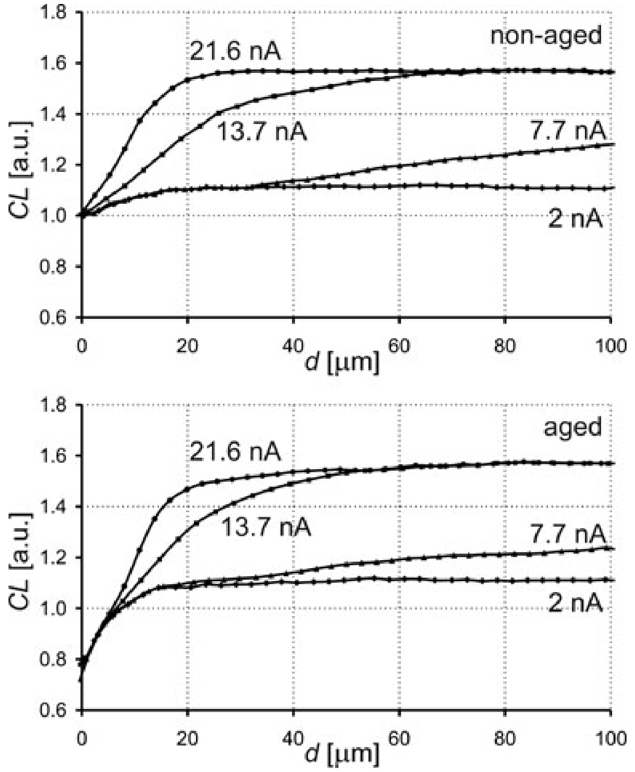

Fig. 3. Dependence of the CL signal versus distance *d* from the mesa for exemplary non-aged and aged structures. The CL signals (normalized to unity at the mesa of non-aged structure) are increasing from lower to higher values with I_{beam} current increase.

was set precisely in order to maintain the same measurement conditions. All the investigations were performed at room temperature.

Method

The electron beam (e-beam) generates electron-hole (e-h) pairs in semi-conductors, which can diffuse randomly and recombine radiatively or non-radiatively. In the former case, photons are emitted, which can be detected by a CL detector in SEM or a scanning transmission electron microscope (STEM). The electrical field associated with the presence of the p-n junction in the examined structures causes the separation of the e-h pairs that were generated within the depletion region or that diffused into it.

If both sides of the junction are connected by an external electric circuit, an electron beam induced current (EBIC, I_{EBIC}) flows and can be measured. In typical EBIC measurements the junction is shortened by a current meter with low resistance and therefore most of separated pairs outflow to the external circuit. In this case the built-in potential of the junction remains approximately unchanged and the CL intensity is low. This is because EBIC and recombination are competing processes, where an e-h pair that recombines does not generate any EBIC and a pair that results in EBIC does not lead to any recombination.

When the external circuit is open, which is typical in CL measurements, an open-circuit voltage of the junction is generated similarly to the photovoltaic effect in a photodiode (Czerwinski *et al.*, 2006, 2007, 2008, 2009, Rossi *et al.*, 2008). The existing e-h pair separation causes a forward bias between both sides of the junction. It reduces the depletion width and electric field strength, increasing the recombination, and therefore also the CL signal.

Changing the resistance within the external circuit by adding for example a serial resistor influences I_{EBIC} (Czerwinski *et al.*, 2006, 2007) and CL intensity (Czerwinski *et al.*, 2008, 2009) measured in semi-conductor structures. The I_{EBIC} value depends on the resistance because the potential drop on this resistance cannot increase above the finite value open-circuit voltage. The number of pairs generated at the fixed e-beam current (I_{beam}) and energy (E_{beam}) is constant, therefore when the I_{EBIC} outflow changes, the CL intensity varies in the opposite direction. Although I_{EBIC} that constitutes the junction current increases with I_{beam}, the I_{EBIC}/I_{beam} ratio is constant only for low I_{beam}. For higher I_{beam} values the I_{EBIC} increases sub-linearly with the increase of I_{beam}. In this case, fewer e-h pairs are dissociated in the electric field and some balance occurs. The recombination (also the radiative recombination) increases, therefore the measured CL is higher.

Even without the presence of any external electrical circuit, i.e. in typical CL measurements, the rest of the structure beside the region excited by the e-beam constitutes a load for the generated voltage (Czerwinski *et al.*, 2008, 2009). As a result an electric current (i.e. I_{EBIC}) flows also in internal current loops within the structure. Therefore, resistances existing within semi-conductor structures also strongly impact the measured CL.

Figure 1(b) shows an electrical diagram of a structure with a p-n junction (Rechid & Reineke-Koch, 2001). The voltage source E_f generated by the e-beam and an internal flow of I_{EBIC} are shown. The I_{EBIC} current may flow all over the structure but the local density of the current depends on the total resistance R_T along a specific current path. R_T consists mainly of lateral resistances of the layers and the local resistances of the junction. The junction resistance non-linearly depends on the forward voltage across the junction. This voltage is caused by the source E_f. It is highest close to the e-beam and is lowered due to a drop of the potential along the current path. Thus, in our case the non-linear resistance of junction depends on I_{beam} and E_{beam} and on lateral resistances in the structure (e.g. layer resistances). These lateral resistances are usually proportional to the length of lateral path. On the contrary, the spatial distribution of local junction resistance may be highly inhomogeneous. The structures contain usually regions with the increased radiative recombination or local shunts, which may cause higher junction-current density in such places.

At a very low I_{beam}, i.e. for a very low junction current, the non-linear resistance across the junction is so high that it is usually much higher than lateral resistances. Therefore, the potential drop due to lateral resistances is low even far from the e-beam position. The current would flow to any place in the whole structure where the local conductivity of the junction is significantly higher than in other places. This outflow of I_{EBIC} decreases the measured CL.

At a higher I_{beam}, i.e. for a higher junction current, the non-linear resistance across the junction decreases in the area close to the e-beam position to a level comparable with lateral resistances. Therefore, due to the significant impact of lateral resistances, the potential drops fast with the distance from the irradiated point. As a result, at higher I_{beam} most of the internal I_{EBIC} flows in the vicinity of generation region. Therefore, radiative recombination measured by CL is less affected by any enhanced conductivity located far away from the e-beam.

Such enhanced junction conductivity appears at the mesa region of aged lasers since most of the current during aging flows through the mesa region. Therefore, the degradation increases the non-radiative recombination and the density of junction current at the mesa in comparison with the rest of the structure (Czerwinski *et al.*, 2008, Marona *et al.*, 2008). As it was explained above, it depends on the I_{beam} level, whether the I_{EBIC} outflow through such a place lowers CL.

Figure 2 shows the secondary electron SEM image of an aged LD (Fig. 2(a)) and its CL images (Fig. 2(b–d)) at three values of I_{beam} (1.5, 4.6 and 10.4 nA). The images were collected without any change of the CL-detector settings (i.e. the photomultiplier voltage, the brightness and the contrast). In each case the CL intensity at the region of the mesa was lower than that at the region of lateral confinements. This difference was caused among the others by thicker layers above the quantum wells at the mesa. The maximum excitation density at E_{beam} equal to 22 keV for the mesa region occurs approximately at the depth where QWs exist and for the lateral confinements just below this depth of QWs (due to thinner layers covering the QWs at lateral confinements). It was experimentally confirmed that at this E_{beam} the CL intensity at the mesa was approximately maximal. The increased density of the junction current at the mesa causes in Fig. 2 an increase in CL contrast (between regions at the mesa and far away from the mesa) when I_{beam} increases. The increased junction current at the mesa lowers CL all over LD structure at low I_{beam}, whereas at larger I_{beam} the density of the current that outflows towards the mesa from regions placed far away from the mesa is low. Therefore, the area of this CL lowering around the mesa shrinks with the increasing I_{beam}. Accordingly, CL image is brighter in places lying further from the mesa if no additional (local) source of increased non-radiative recombination is present nearby. Non-uniformities of CL signal prove the presence of local inhomogeneities in distribution of defects. For example, the increased surface (non-radiative) recombination, obviously present at outer edges of the laser diode structure, is responsible for the shadowing of CL image closely to the edges of structure (best visible at the upper and bottom edges in the bright image of Fig. 2(d)).

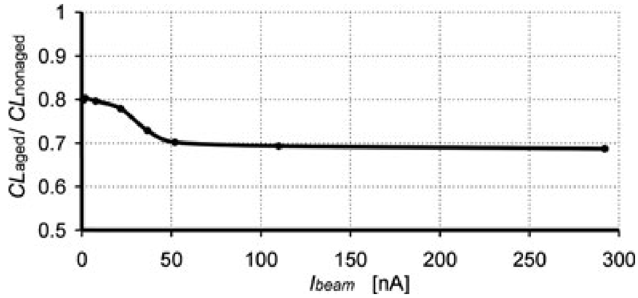

Fig. 4. Dependence of the $CL_{aged}/CL_{non\text{-}aged}$ ratio between aged and non-aged lasers on I_{beam} current.

Our quantitative studies of laser degradation were performed on pairs of aged and non-aged LD structures. Each pair originated from one epitaxial process and from possibly the closest regions of the GaN substrate. It provided almost identical initial parameters of both LDs. During the measurements the e-beam was shifted across the LD structures perpendicularly to the mesa region. The registered monochromatic CL signal corresponded to the peak of quantum well emission (wavelength $\lambda = 395$ nm for the measured samples). The wavelength of this peak in the investigated samples was the same in aged and non-aged LDs, as also confirmed by the luminescence measurements by Marona *et al.* (2006). Such stability was mentioned also by Rossi *et al.* (2006) for the emission related to InGaN multiquantum wells. This measured wavelength of the peak was also independent of I_{beam} values in our investigations.

Results

Figure 3 presents the CL values for non-aged and aged structures versus distance d from the mesa, obtained at I_{beam} equal to 2, 7.7, 13.7 or 21.6 nA and at an E_{beam} of 22 keV. The results was normalized in such a manner that the CL signal from the mesa of non-aged structure corresponds to unity. The CL signal at the mesa is weaker in the aged than in the non-aged LD structure, as expected, and in both structures the normalized CL far away from the mesa is the same at 13.7 and 21.6 nA. However, for low I_{beam} (2 and 7.7 nA) this CL signal is quenched all over the structure for both aged and non-aged LDs and the signal at 13.7 nA is quenched close to the mesa. These drawings illustrate quantitatively the change of the CL contrast between regions at the mesa and far away from the mesa, observed with an increase in I_{beam} in Fig. 2 and related to a higher level of junction-current density at the mesa.

Each LD (even a non-aged one) was powered for short period of time in order to check its parameters. The lower intensity of CL signal at low I_{beam} also for the non-aged LDs proves that the non-aged LDs became in fact less aged ones because of the previous powering. It also shows that the degradation process of these LDs is initially very fast. Such especially high rate of degradation at the initial stages of ageing was already described previously (Furitsch *et al.*, 2006, Marona *et al.*, 2006). Finally, the ratio between the CL measured at the mesa for aged and non-aged LDs, $CL_{aged}/CL_{non\text{-}aged}$, is analysed (Fig. 4). It is visible that although this ratio is expected to be a measure of LD degradation its value depends on I_{beam} used in CL mesurements. In the range of lower I_{beam} the ratio is approximately constant, equal to about 0.8 in Fig. 4 at I_{beam} less than 15 nA. This range of I_{beam} is often applied in typical CL measurements of nitride-laser degradation (Hansen *et al.*, 2002; Rossi *et al.*, 2008). In the range of intermediate I_{beam} values the $CL_{aged}/CL_{non\text{-}aged}$ ratio decreases (to 0.7 in Fig. 4 for I_{beam} between 15 and 50 nA). For higher I_{beam} values (50–400 nA in Fig. 4) the ratio again stabilizes at the lower value.

The output of the LDs was more reduced by ageing than it was visible in CL measurements. Three kinds of degradation: facet and near facet degradation, bulk degradation and quite rarely, contact degradation, were observed (Marona *et al.*, 2008). The component of bulk degradation due to the ageing has been related to an increased non-radiative recombination and an increased p-n junction current.

Each LD structure has sites of enhanced junction conductivity, e.g. laser edges with high surface non-radiative recombination, structural defects, etc. placed all over the structure, also far from the mesa region. These places of enhanced junction conductivity placed far away from the mesa region influence CL, but are not related to the ageing. As already mentioned, when I_{beam} is low, lateral resistances are low in comparison with the junction resistance and all sites of enhanced junction conductivity serve as current paths. The CL values measured at any place in the structure are lowered by a significant outflow of the internal I_{EBIC} current from the pair generation region. Therefore, the differences between CL results for aged and non-aged structures are comparatively low. On the contrary, when I_{beam} current and therefore also the I_{EBIC} current increase, then the junction non-linear resistance decreases and becomes comparable to the lateral resistances. The total resistance becomes strongly dependent on the length of the lateral paths where the current flows. Therefore, the density of the current outflow to sites placed far away from the generation region occurs to be low. Thus, an area around the mesa, in which an enhanced junction conductivity may influence CL measured at the mesa, shrinks as I_{beam} increases. Finally, it includes only the mesa and its closest vicinity. Because the degradation due to ageing occurs just at the mesa, differences between the CL intensity for aged and non-aged structures are stronger for high I_{beam} than for low I_{beam}. Therefore, the lower $CL_{aged}/CL_{non\text{-}aged}$ ratio at higher I_{beam} is a better estimation of the degradation than its value at low I_{beam}. A further shrinkage of this area (as I_{beam} increases) becomes weak, leading to the almost constant $CL_{aged}/CL_{non\text{-}aged}$ ratio, because the sheet resistance (measured in ohms per square) at the mesa region is much lower than outside the mesa. It is worth noting that the $CL_{aged}/CL_{non\text{-}aged}$ ratio depends also on the junction currents flowing through sites existing before ageing and on non-radiative recombination at the e-beam location before ageing. Therefore, the same degradation due to ageing gives higher $CL_{aged}/CL_{non\text{-}aged}$ ratio at the mesa if the junction-current density at the mesa is lower before ageing.

Conclusions

We report that the value of electron-beam current used in measurements has important impact on the results of CL studies of semi-conductor laser degradation, i.e. the revealed degradation depends on I_{beam} current. Significant values of I_{beam} are recommended, higher than these typically used, to suppress the effect of defects located far away from the incident electron beam position. A useful method is given of an assessment whether the applied range of I_{beam} current is optimal, which is based on changes of the degradation. To diminish dependence of results on defects located far away from the e-beam location, e-beam currents higher than typically used may be recommended also for other CL studies.

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