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Defect related issues in the "current roll-off" in InGaN based light emitting diodes

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Defect related contributions to the reduction of the internal quantum efficiency of InGaN-based multiple quantum well light emitting diodes under high forward bias conditions are discussed. Screening of localization potentials for electrons is an important process to reduce the localization at high injection. The possible role of threading dislocations in inducing a parasitic tunneling current in the device is discussed. Phonon-assisted transport of holes via tunneling at defect sites along dislocations is suggested to be involved, leading to a nonradiative parasitic process enhanced by a local temperature rise at high injection. © *2007 American Institute of Physics*.

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The recent development of III-nitride based light emitting diodes (LEDs) has been remarkable, particularly in the violet-blue spectral range, where internal quantum efficiencies (IQEs) close to 80% at moderate injection have been reported.[1] The active light emitting region in these devices consists of narrow (about 3 nm wide) $In_xGa_{1-x}N$ quantum wells (QWs) with $x<0.2$. The surprisingly high efficiency for these LEDs has commonly been ascribed to localization effects; i.e., the carriers (or excitons) localize in potential fluctuations in the QWs, whereupon they recombine radiatively.[2] The carriers then escape to a large extent the nonradiative defect recombination, expected due to the high density of threading dislocations in these structures ($\geqslant 10^9$ cm^{-2}), related to the growth on foreign substrates such as sapphire, SiC, or silicon.

A problem that has been discussed as a severe obstacle to future applications of such devices for LED based solid state lighting, where high drive currents and a very high light output are generally needed, is the observed lowering of the IQE with increasing drive current.[1,3] Several reasons for this behavior have been discussed recently, such as a high device temperature,[4] restricted hole injection,[5] or carrier overflow problems.[3] The role of defects as being responsible for the drop in IQE has not been seriously discussed, despite the very high threading dislocation density in the present LEDs. A much improved behavior is observed for growth on bulk GaN substrates, where the dislocation density is very much reduced.[3,6] In recent simulations based on the conventional Shockley-Read-Hall defect recombination scheme for the nonradiative part, it is found that such recombination is insufficient to explain the decrease observed in the IQE at high bias.[4,5]

In this paper, we will concentrate on two problems of relevance for a modeling of this decrease of the IQE in InGaN based LEDs. A description of the influence of the screening by injected carriers on the localization potentials,[7] which has been largely ignored in the literature, is discussed. The action of carriers on the localization potentials is typically described in terms of "state filling,"[8] a physically incomplete picture. The screening of localization potentials is important for the IQE in LEDs, since the carriers are gradually released from the diminished localization potentials at increasing injection, whereupon they are free to move to nonradiative defects and recombine there. A second problem is how to describe the major nonradiative process beyond the Shockley-Read-Hall (SRH) model. It is tempting to correlate this non-SRH recombination at high current with the strong tunneling current observed in these LEDs.[9] Carrier injection along dislocations may be described as a tunneling process that does not require participation of free charge carriers. Provided that this process has a local temperature dependence, and that the dislocations are sources of nonradiative recombination, this will reduce the IQE at high injection conditions.

In the InGaN QWs discussed here, the interface roughness is regarded as the dominant source of localization potentials, considerably enhanced by the presence of the polarization induced internal electric fields perpendicular to the interfaces.[10] Another problem frequently discussed for InGaN QWs is the large composition fluctuations in the InGaN alloy,[8] which can, however, be largely avoided for low In compositions ($x<0.2$).[11] The random alloy potential fluctuations are always present.[12] The length scale of the interface fluctuations appears to be a few nanometers.[13] These potential contributions in QWs are of the order of 50 meV, sufficient for the localization of electrons at room temperature.

A separate source has been suggested for hole localization in InGaN QWs. From theoretical calculations, it has been suggested that short In–N chains in the InGaN alloy create localized potentials that localize holes at energies that are close to or resonant with the valence band top, a unique property of this material system.[14] Since the density of such localization centers may be quite high, the injected holes will be localized to a large extent, consistent with a short diffusion length for positrons observed in InGaN.[15] This very short range hole potential will be superimposed on the broader electron localization potential as discussed above. This model conveniently explains that the localization energy observed for excitons at low temperatures is only of the order of <50 meV.[12]

In a three-dimensional (3D) system, the screening increases with the carrier concentration—the Thomas-Fermi (TF) screening length decreases. In a two-dimensional (2D) system, the TF screening length is unaffected by a change in

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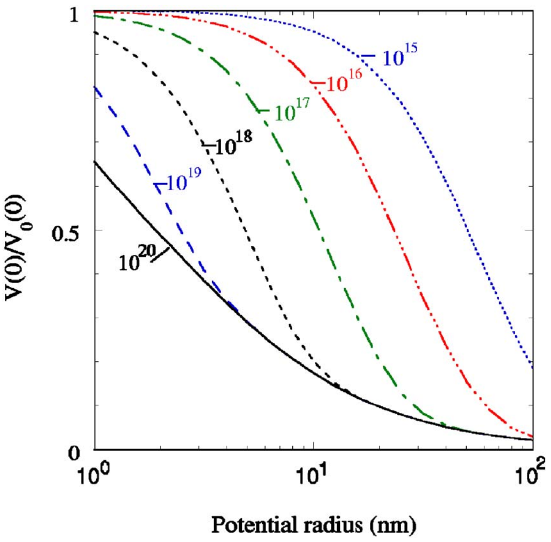

FIG. 1. (Color online) Plot of the relative value of the screened central part of a Gaussian localization potential vs radius of the potential, for different injected electron densities.

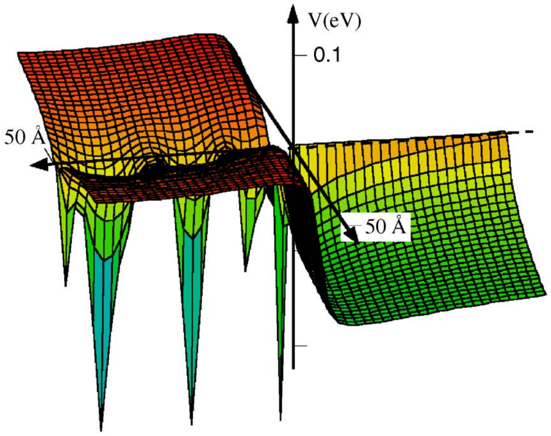

FIG. 2. (Color online) Schematic view of the potential along a dislocation line (the abscissa in the figure), threading the *pn* junction. On the *n* side (right in the figure), the electrons trapped to the dislocation are assumed to form a one-dimensional band. The MQW structure is omitted for clarity. On the *p* side (left in the figure), the trapped holes are more scarce, and the surrounding defects create strong potential fluctuations.

carrier concentration. However, this TF screening length only describes the screening of a slowly varying potential or the resulting potential far away from the center of the potential. The higher the carrier concentration the better the system screens a rapidly varying potential or the core of the potential.[7] This means that the depth of a potential well caused by interface roughness can still vary with carrier concentration. To illustrate this, we have modeled the screening effect of a Gaussian potential, $V_0(r)=V_0(0)e^{-(r/r_0)^2}$, centered at the origin. We have used 2D screening in the Random Phase Approximation.[16] The results are presented in Fig. 1 in the form of the relative value of the screened potential at the origin. The curves are given as functions of the potential radius r_0. Each curve is for a given 3D carrier concentration. Potential shapes other than Gaussian give similar results, but cannot be treated analytically. From Fig. 1, it is clear that screening at a typical LED carrier density of 10^{18} cm^{-3} will decrease the depth of the localization potentials by 15% for a length scale of 2 nm, and 30% for a length scale of 3 nm. This is at least of the same order of magnitude as the effect on the localization by the screening of the polarization fields, and may be critical in causing delocalization of the electrons in the InGaN QWs. At increasing injection above 10^{18} cm^{-3}, the screening effect becomes even larger.

The nonradiative process via deep levels in the active region of a LED will saturate at a rather limited injection current, if described via the conventional SRH mechanism.[4] Available data on the current-voltage characteristics indicate, however, that at high injection, a leakage current (here identified as a tunneling current) is strong in these LEDs, which cannot be modeled within the SRH framework. This tunneling current appears to correlate with a high dislocation density.[9] We will discuss here a possible model involving dislocations threading through the structure perpendicular to the layers. In previous ballistic electron emission microscopy (BEEM) work,[17] it has been shown that the recombination current is indeed crowding at dislocations with a screw component, i.e., such dislocations are a preferred current path in the device for both types a carrier.[17] This process could be the cause of a parasitic nonradiative current mechanism, provided that the carriers can transport by tunneling between spatially close defect levels associated with such dislocations, a process not involving free carriers. This process is unlikely to occur for isolated deep levels (related to point defects), unless these are associated with a shallow defect level with an extended wave function.[18]

For dislocations in GaN, it has been shown that a high density of deep levels exist for screw dislocations at the dislocation core, associated with the dislocation itself.[19] In addition, aggregation of large concentrations of point defects (e.g., vacancy related) is suggested to be typical for threading dislocations (TDs) in these structures.[20] The active multiple quantum well (MQW) region of the device typically has a considerable electron density, in which case the dislocations are negatively charged via the capture of electrons.[21] Concentrating on the hole injection from the *p* GaN, it is known that the dislocations may be positively charged when the Fermi level is low,[20,21] but the situation is less clear from the literature. The dislocation related electronic levels on the *p* side may be described as a dense array of deep levels in the band gap partly occupied with holes. Since the distance between the defect sites along the dislocation are assumed to be of the order of a few lattice parameters, tunneling between such sites may easily occur at room temperature.[22] These transported holes may easily recombine with electrons captured to the dislocation sites in the MQW area, without leaving the vicinity of the dislocation line. This would support the tunneling current in the device and constitute a nonradiative recombination process at the dislocations. In Fig. 2, we show a very rough sketch of how the potential may look along a dislocation threading the *pn* junction; on the left side (*p* side), localized potentials of different signs occur; on the right side (*n* side), we assume that trapped electrons form a one-dimensional continuous band along the dislocation, producing a repulsive potential. The current along the dislocation is limited by the hole transport, which is facilitated by an increased local temperature.

There are two processes that might enhance this tunneling mechanism at high injection current. The screening of the electron localization potentials in the MQW region will gradually release the electrons into the conduction band so that they can easily move to the dislocation sites close to the *pn* junction and recombine with the holes injected there. On the other hand, the current transport along the dislocations will cause local heating, increasing with the injection.[23] A higher local temperature may facilitate the tunneling process, which is typically assisted by acoustic phonons, since there is some disordered potential introduced by the high defect density around the dislocations.[24] This process shows a monotonic increase with rising temperature, a T^n dependence where $n \approx 1-2$.[24] The shunt current flow along dislocations will maintain a higher local temperature there, increasing with increasing drive current. Detailed experimental data for a proper numerical modeling of these effects do not exist at present, unfortunately. The observed drastic improvement with a reduced dislocation density[6] indicates, however, that this process may be a dominant factor in explaining the reduced IQE with higher injection in these LEDs.

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