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Luminescence Efficiency of InGaN/GaN Quantum Wells on Bulk GaN Substrate

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ABSTRACT

Time-integrated and time-resolved photoluminescence measurements on InGaN quantum wells grown by MOCVD on two different substrates (sapphire and GaN) show that the luminescence efficiency in these structures strongly depends on the intensity of carrier excitation. While at low excitation densities the recombination of excited carriers is governed by localization effects the behavior drastically changes at higher densities. At room temperature a suppression of nonradiative recombination could be observed that leads to an super linear increase of the luminescence.

INTRODUCTION

Due to their outstanding optical properties InGaN/GaN heterostructures are the basis of manifold optoelectronic applications. [1] Nevertheless their application potential is not utilized for a long time yet, and the knowledge of the fundamental processes is far away from a deep understanding. Despite of dislocation densities $>10^8$ cm^{-2} light emitting devices (LED) and laser diodes (LD) based on InGaN show excellent performance in the blue spectral range. For LEDs with low excitation densities this can be attributed to the localization of excitons in indium fluctuations up to room temperature [2] that prevents carrier diffusion towards nonradiative recombination centers. The processes at high excitation densities in LDs are still unclear. Recently the homoepitacticial growth on GaN substrates was studied by several groups in order to reduce the dislocation densities in their structure and to improve the performance of InGaN based laser structures, but it is not sufficiently understood how these defects influence the efficiency of these structures.

We present time-integrated and time-resolved photoluminescence (PL) measurements on single InGaN quantum wells (QW) with a well thickness of 9.5 nm and an average indium content of about 10%. The results show that at high optical excitation densities defects are saturated and thus nonradiative recombination channels are suppressed.

EXPERIMENTAL DETAILS

The structures were grown by metal organic chemical vapor deposition on sapphire and high pressure bulk GaN substrates [3]. The samples were grown in the same run. This allows us to compare directly the population and recombination mechanisms in QW's on both substrate materials. Si-doped buffer/barrier layers were used to screen built-in electric fields [4]. The PL measurements were performed in a helium-flow cryostat. The time-resolved PL (TRPL) were excited at 353 nm by the second harmonic wave of a mode-locked Ti:sapphire laser. The temporal width of the laser pulses was 2 ps at a repetition rate of 80 MHz. The detection system consisted of two 0.35 m McPherson monochromators in subtractive mode and an ultra-fast photo detector (micro-channel plate) providing a spectral resolution of about 1 meV and a time resolution of better than 30 ps. As excitation source for the time-integrated PL at low excitation density the 325 nm line of a HeCd laser was used and the luminescence light was collected by a bialkali photo detector.

DISCUSSION

To study the localization effects PL at temperatures from 5 K up to room temperature were performed. Figure 1 shows the energetic position of the PL maximum as a function of the temperature. At cw laser excitation the data of both structures (squares) shows a well pronounced s-shape behavior due to thermally activated redistribution of localized excitons. The data was fitted with a model from Refs. 5 and 6 and the standard deviation of the potential fluctuations σ_E was determined. At pulsed laser excitation (10^5 W/cm^2) the ensemble of localized states is completely filled with carriers. QW states above the mobility edge are populated. this leads to a broadening and a slight blue-shift of the PL (inset in fig. 2). Since the redistribution channels are suppressed now, no s-shape appears anymore.

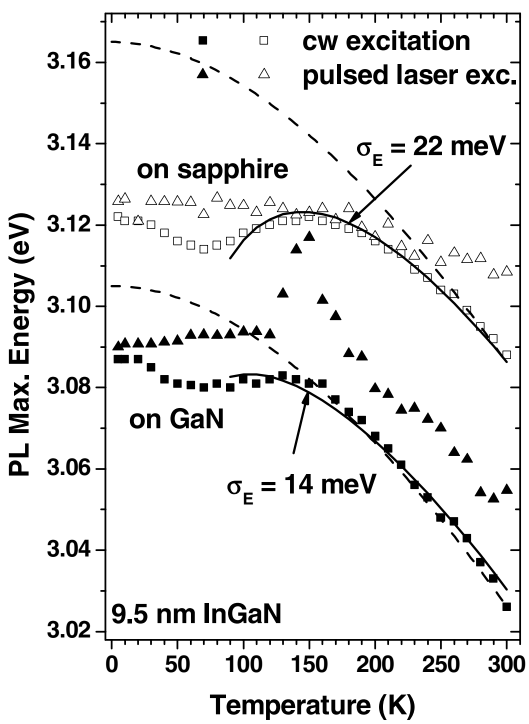

Figure 1. Energetic position of the PL maximum vs. temperature at low excitation density (squares) and at high excitation density (triangles). Fit after Refs. 5 and 6 (solid line), band gap behavior of GaN (dashed line).

The excitation of more and more carriers changes their recombination dynamics. There a completely different behavior appears at low temperatures and at room temperature, respectively. Figure 2 shows the PL intensity of the QW structure grown on GaN as a function of the time. Its decay is single exponential. The decay time of about 700 ps does hardly change with increasing excitation density. For the structure grown on sapphire (not shown here) the decay time decreases from 660 ps (10^2 W/cm^2) to 470 ps (10^5 W/cm^2). This is due to carriers populating states above the mobility edge where they can reach nonradiative recombination centers.

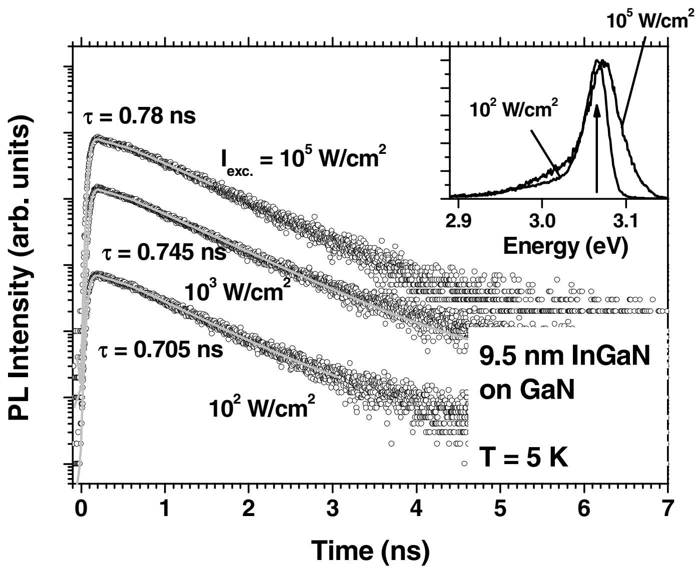

Figure 2. Time-resolved PL at 5 K and different excitation densities. Inset: time-integrated PL.

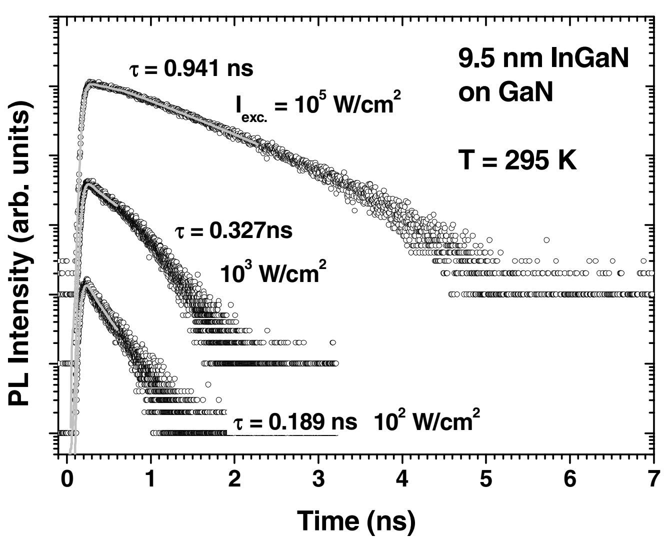

Figure 3. Time-resolved PL at room temperature.

At room temperature we observe at low excitation density a single exponential PL decay with a decay time of 189 ps. The time constant is dominated by the nonradiative recombination of thermally activated carriers. With increasing excitation density the PL decay becomes longer (941 ps at 10^5W/cm^2) and its shape is nonexponential. This is not the well-known nonexponential PL decay of InGaN due to a screening of electric fields or localization effects, where the decay starts with a short time constant and becomes slower [7]. In our case the transient PL starts with a slow decay and becomes faster. This effect could be observed on both samples. We explain this unusual behavior with a suppression of nonradiative recombination channels by a saturation of defects with carriers. The smaller probability of nonradiative processes leads to a longer carrier lifetime and slower PL decay. While the charges are recombining and the saturation of defects diminishes the PL decay fastens. Using the integral PL intensities and the measured decay times the nonradiative lifetimes could be extracted [8]. The results are listed in Table I. The nonradiative lifetime increases from 130 ps to 330 ps and even 990 ps for the QW structures grown on sapphire and on GaN, respectively. Our explanation is supported by the fact that the integral PL intensity at room temperature increases super linear with increasing excitation density, compared to a linear growth at 10 K (see fig. 4). The slope is larger for the QW grown on GaN substrate. This could be attributed to the smaller defect density in this structure.

Table I: Nonradiative lifetimes at room temperature for low and high excitation densities.

	9.5 nm InGaN on sapphire	9.5 nm InGaN on GaN
$I_{exc.} = 10^2$ W/cm^2	0.131 ns	0.129 ns
$I_{exc.} = 10^5$ W/cm^2	0.332 ns	0.994 ns

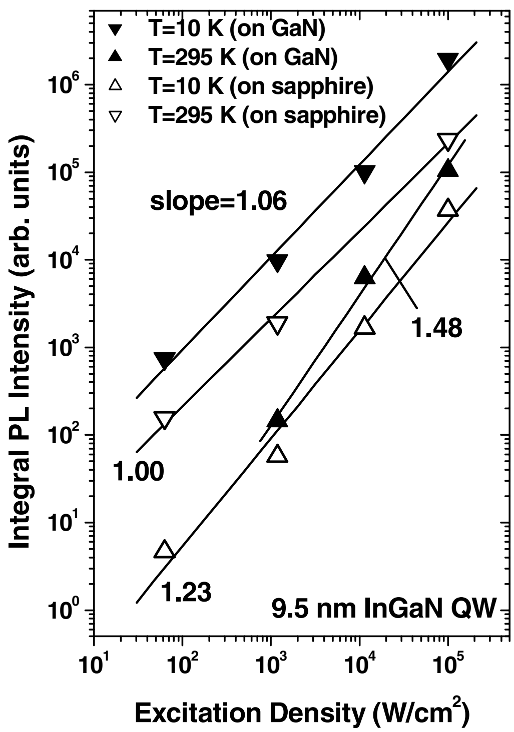

Figure 4. Integral PL intensity vs. excitation density at 10 K and room temperature.

CONCLUSIONS

We found completely different recombination mechanisms at low and at high optical excitation of carriers in InGaN QW structures. While at low excitation densities the luminescence properties are dominated by the localization and redistribution of excitons, at higher excitation densities the saturation of defects leads to less nonradiative processes, thus to longer exciton lifetimes and an increase of the radiative recombination. This explains the excellent performance of laser devices based on InGaN/GaN structures with dislocation densities $>10^8$ cm^{-2} and it could lead to the conclusion that the homo-epitactical growth on bulk GaN substrate with lower dislocation densities could still improve their performance. Since we found the recombination mechanisms to be independent from the substrate type, this last point needs further investigation to be sufficiently clarified.

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