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Invited

Physics of GaN-Based LED's and Lasers

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1. Introduction

Optoelectronic devices for the visible and ultraviolet regions based on III-nitrides have recently attracted an enormous number of research groups. This is partly due to the strong commercial interest in such devices, but may also in part be attributed to the lack of knowledge concerning many fundamental properties of GaN, AlN, and InN. In particular, the basic emission mechanisms both in GaN-based LED's and laser diodes have long been subject to considerable controversy.

For about two years, it was seriously discussed by many researchers whether phase separation of GaN and InN in the GaInN active layers of nitride LED's and lasers would create nanoscale potential fluctuations [1, 2] acting like natural quantum dots, i.e. creating a three-dimensional confinement of excitons and thus keep them away from the defects present in large numbers, where they could recombine non-radiatively. However, more recently it was recognized that quantum wells from wurtzite GaInN are subject to piezoelectric (and possibly pyroelectric) polarization fields [3, 4, 5], which strongly influence their optical properties.

2. Optical transitions, polarization fields, and LED's

The luminescence for nitride quantum wells under low injection conditions is strongly red-shifted with respect to the bulk band gap [3, 4, 5]. This is a consequence of the quantum confined Stark effect in these structures due to the piezoelectric and pyroelectric polarization. In contrast to the usual quantum confined Stark shift in other III-V semiconductors, where the shift of the band gap amounts to typically about 50 meV, the shift in nitride structures can be as large as 500 meV. In case of GaInN/GaN wells, the polarization field is proportional to the In mole fraction in the wells as shown in Fig. 1, reaching approximately 1.3 MV/cm at 10 % In.

Along with the red-shift of the band gap, there is also a large spatial separation of the electron and hole wavefunctions which leads to a dramatic loss of oscillator strength for wide wells [4, 5]. The decay time of the luminescence in such structures may be well in the microsecond range, depending on well width. Moreover, due to screening of the polarization fields by injected carriers, the decay times are energy-dependent, or, equivalently, there is a temporal shift of the emission towards lower energy.

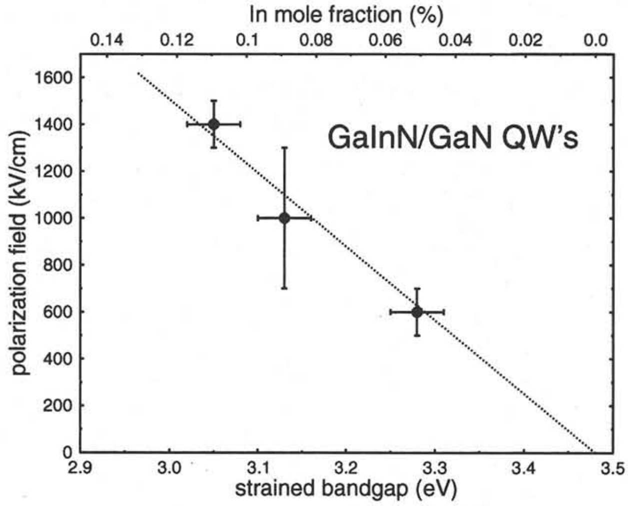

Figure 1: Polarization field vs. low-temperature strained bulk bandgap in GaInN/GaN quantum wells. The field increases linearly with increasing In mole fraction.

Recently, it has been argued that a large "Stokes" shift between emission and absorption in nitride quantum wells could be indicative of carrier localization due to compositional fluctuations. However, this "Stokes-like" shift can be naturally explained by the polarization fields: The emission comes from the ground state, which is red-shifted and has a large electron-hole separation, leading to a small oscillator strength. For the same reason, the ground state essentially has a vanishing absorption coefficient. Only highly excited states, which exhibit less localized electron and hole wavefunctions can effectively absorb light. Consequently there is an energy shift between emission and absorption, which is of the order of the Stark shift.

For LED's it has long been known that the emission wavelength exhibits a blue-shift with increasing injection current. In fact, this is also a natural consequence of the built-in polarization fields. With increasing injection level, the field gets more and more screened by injected carriers, leading to a blue-shift of the emission. Therefore, the emission wavelength of an LED is not only determined by the In content of the active layer but also by its strain state and the well width, as well as by

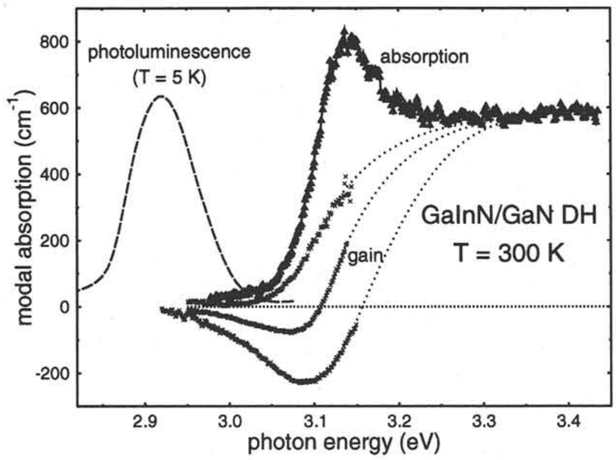

Figure 2: Comparison of optical absorption and gain spectra at different pump levels (0.3, 0.6, and 1 MW/cm^2) for a 15 nm GaInN/GaN SQW structure.

the background carrier density. Since the strain and the polarization effects become larger for larger In content, the blue-shift with injection current may be very difficult to avoid for green, yellow (and red) nitride LED's.

3. Optical gain and lasing

Nitride-based violet laser diodes are now rapidly approaching commercialization [6]. The fundamental lasing mechanism in these devices is still subject to quite some debate. Similar to LED's, the idea of localized states contributing to the lasing has been put forward. However, very recent experiments make it more likely that the optical gain is due to an electron-hole plasma [7, 8]. In fact, the gain amplitude may be somewhat enhanced by excitonic effects [9].

Fig. 2 shows a comparison between the absorption spectrum, gain spectra at several pump power densities, and the photoluminescence of a 15 nm thick GaInN/GaN single quantum well. The photoluminescence is considerably red-shifted with respect to the absorption edge, whereas the optical gain peak appears right at the absorption edge. The continuous transition between absorption and optical gain with increasing pump level is just as expected for an electron-hole plasma, where there is first a increasing degree of screening of excitonic states and finally, under inversion conditions, optical gain with some extent of excitonic enhancement.

The red-shift of the photoluminescence peak is simply due to the built-in piezoelectric field, as discussed earlier. Under the high injection levels needed to obtain optical gain, the piezoelectric fields are almost completely screened. The optical gain spectrum therefore appears at the flatband bandgap with no Stark shift. The absorption spectrum which is measured under low-excitation conditions, does not exhibit a Stark shift due to the fact that the Stark-shifted states have an extremely small oscillator strength and therefore do not contribute to the absorption.

It is interesting to note that the pump power needed to obtain stimulated emission increases strongly with increasing emission wavelength [10]. This indicates that the polarization fields are not completely screened even under lasing conditions, making it increasingly difficult to reach inversion at larger In mole fractions.

4. Conclusions

Piezo- and pyroelectric fields are now identified to be the most essential effect in GaInN/GaN/AlGaN heterostructures. Localization due to compositional fluctuations is certainly present as well, but is not of major importance for device operation.

Acknowledgements

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