Vertical Cavity Surface — Emitting Lasers using InGaN Quantum Dots

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GaN-based lasers for the UV spectral range are the key devices for optical storage applications in the near future. At the same time, significant difficulties are still to be bypassed for this technology, namely:

- The high density of defects, resulting in necessity of epitaxial lateral overgrowth (ELOG) technique
- The lack of suitable native cleavage planes for mirrors in edge-emitting devices
- Problems related to high series resistance of the relatively thick p-type GaN cladding layer

Further device development also requires cost reduction and improved beam divergence, together with the achievement of a high degree of on-chip integration.

VCSELs to the Rescue

Vertical cavity surface-emitting lasers (VCSELs) can solve most of the above problems. Monolithically integrated multilayer distributed Bragg reflectors (DBRs) can bypass the cleavage plane problem, while the possibility to fabricate VCSELs with ultra-small lateral dimensions ease the problem of high dislocation density in GaN.

The key element of the VCSEL technology is the highly reflecting monolithic DBRs, which ensure that the saturation gain is higher than the external losses, a condition necessary to achieve lasing. To achieve relatively small saturation gain in conventional quantum well (QW) devices, both mirror reflectivities must be of the order of 99.9%. This is difficult to achieve in the case of coherent AlGaN-GaN DBRs, because of the significant lattice mismatch and relatively small refractive index difference in this system. Use of a dielectric DBR for the bottom mirror requires complex lift-off technology and even if this technique is applied only to the top mirror, it results in strongly increased resistivity of the device due to the increased current path in the p-type GaN cladding layer.

To succeed with GaN-based VCSEL one should find a way to work with moderate (about 90%) reflectivity using coherent GaN-AlGaN DBRs and/or non-alloyed p-contact metal layers. This is possible if one can achieve saturation modal gain in excess of 2×10^4 cm^{-1} for the active layer thickness of 0.1 µm while maintaining the excitation density at a moderate level. These high modal gain values can be hardly realized using conventional quantum wells or bulk materials in view of the gain saturation problem and the corresponding strong increase in nonradiative losses at high pumping levels.

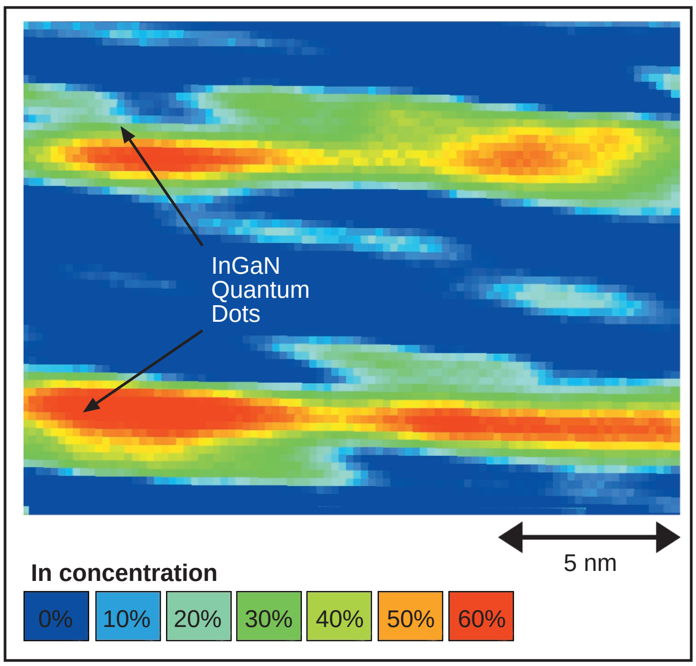

***Figure 1.** Color-coded map of indium distribution in structure with multiple ultra-thin InGaN insertions evaluated using cross-section high-resolution transmission electron microscopy and DALI image-processing (courtesy of Laboratorium für Elektronmikroskopie der Universität Karlsruhe). The active region was formed by temperature cycling during InGaN layer growth (average In content ~10%).*

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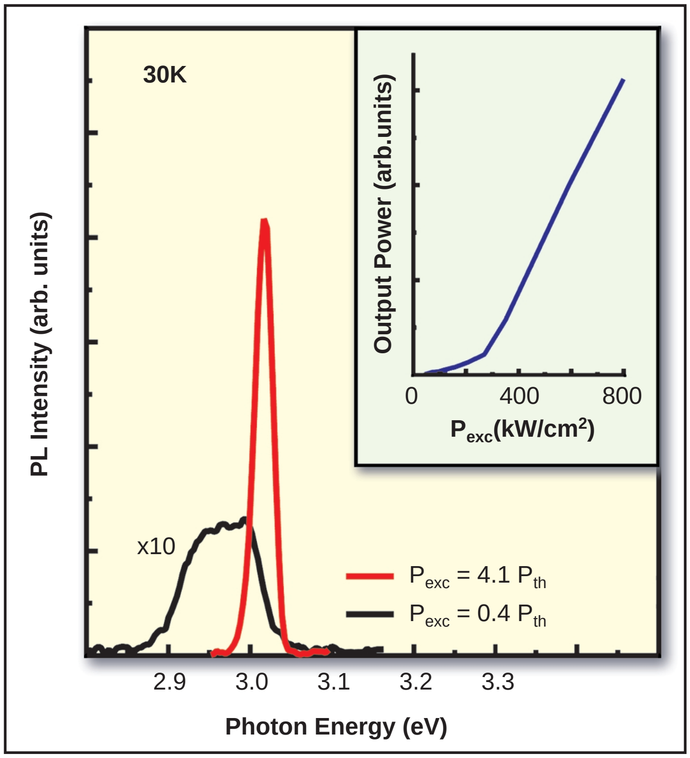

Figure 2. Low temperature photoluminescence spectra below and above threshold for a structure with twelve InGaN insertions in a GaN matrix, grown without both top and bottom DBRs. (P_{exc} = excitation density, P_{th} = threshold density). Inset: Output power versus excitation density for the same structure.

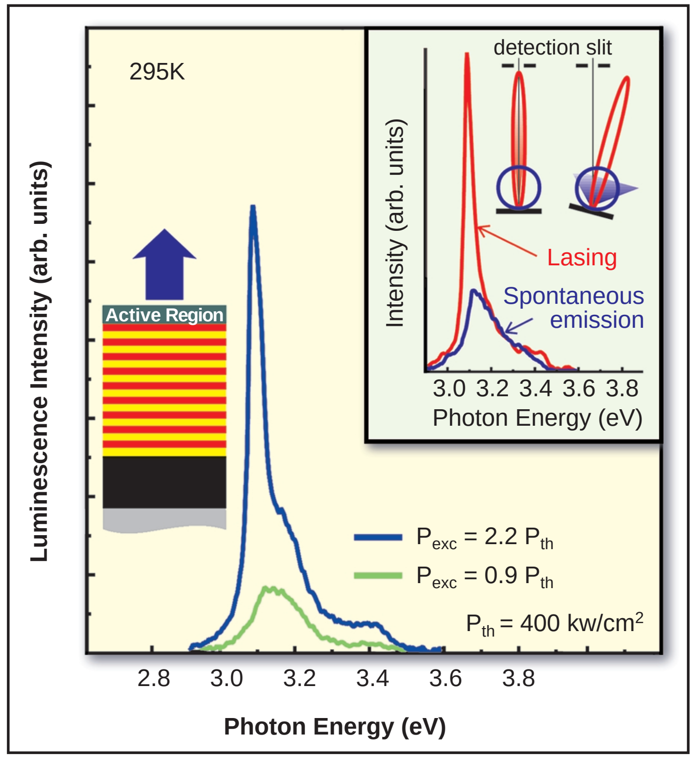

Figure 3. Room temperature PL spectra below and above threshold for the VCSEL structure with a bottom DBR only. Inset: Angular dependence of spontaneous emission and lasing for the same structure. Note that the lasing emission is highly directional and dominates the spectrum when the sample surface is directed perpendicular to the optical axis (red curve). Tilting of the normal to the surface with respect to the optical axis results in a practically complete disappearance of the lasing emission from the spectrum (blue curve) in agreement with narrow far-field pattern of the lasing emission (red dashed line in the inset). As opposite, the spontaneous emission is weakly affected in this case, and the far-field pattern is close to a cosine intensity distribution (blue dashed line in the inset).

Quantum Dots

An alternative idea is to use dense arrays of quantum dots (QDs) as an active medium of the device. In the case of small QDs, the material gain is inversely proportional to the QD volume and can approach giant values [1]. To realize high *modal* gain, very dense arrays of QDs need to be created. For inhomogeneous broadening of the order of ~100 meV, to obtain modal gain of about 10^5 cm^{-1} one must keep the QD density above 10^{18} cm^{-3}. For wide-gap structures, where the exciton Bohr radius is smaller than 10 nm, these densities are potentially feasible. Complete exciton localization in QDs lifts the problem of nonradiative recombination at defects and dislocations, particularly at high excitation densities, and, also, the problem of radiative annihilation of excitons having large k-vectors dominating at high temperatures and observation densities in wide-gap QWs and bulk materials [2].

Arrays of QDs with very high density were realized in our case using closely stacked ultra-thin InGaN insertions with QDs. The QDs were obtained in a self-organized way using spinodal decomposition of an ultra-thin InGaN coverage at appropriate deposition and overgrowth conditions.

The structures were grown by MOCVD on sapphire, commencing with an AlGaN nucleation layer and a 2.5 µm GaN buffer or AlGaN/GaN DBR. The active layer consisted of a 25 nm relaxed InGaN layer with a low In content followed by a strain-compensated multilayer structure composed of 12 periods and having the same average In content (~10%), which was formed by temperature cycling between 730°C and 860°C. As the In incorporation is strongly affected by substrate temperature, the result is a modulated In composition profile.

In Figure 1, we show a color-coded map of indium distribution in a structure with multiple InGaN insertions, evaluated using the DALI image-processing technique [3]. The bimodal distribution of QD lateral sizes peaking at 7–8 nm and 2–3 nm was observed in both plan-view and cross-section images. The sheet density of QDs is around 10^{12} cm^{-2}, and the indium content in the QD region is as high as 60%.

Figure 2 shows photoluminescence spectra above and below threshold for a structure with twelve InGaN insertions in a GaN matrix, grown without both top and bottom DBRs. The inset shows output power versus excitation density dependence for the same structure. The cavity is formed in this case by the

GaN-sapphire interface (bottom) and the GaN surface (top), and is manifested by the weak interference modulation of the luminescence spectrum. At high excitation densities the relative intensity of one of the vertical Fabry-Perot cavity modes increases, and a dramatic narrowing of the emission spectrum occurs. This narrowing is accompanied by a strong increase in the slope efficiency. The lasing starts on the high-energy side of the luminescence spectrum and on the low energy side of the InGaN-related absorption onset [4]. The lasing occurs via smaller QDs and/or exited states of larger QDs, i.e. via relatively weakly confined QD states. Due to thermal escape of carriers from QDs, room temperature operation has not been achieved in this structure.

Effect of a Bottom AlGaN/GaN DBR

Use of moderately reflecting (80–90%) metamorphic bottom DBR composed of 37 AlGaN-GaN pairs allowed us to reduce substantially threshold excitation density and achieve room temperature operation [5] (Figure 3). The threshold excitation density was the lowest in the spot on the sample surface, where the maximum of the DBR reflectivity curve and the low-energy side of the luminescence spectrum were overlapping. Thus, ground states of larger QDs having larger carrier localization energies contribute to lasing in this case, and the threshold excitation density shows relatively weak temperature dependence (increases by 3 times in a range from 77 to 300 K).

Despite the very low finesse of the cavity, the lasing emission demonstrates a highly-directional far-field pattern, much narrower than the far-field pattern of the spontaneous emission of the same cavity, as it is illustrated in the inset of Figure 3. No top dielectric or metal mirrors have been used in this case. One can thus expect that applying of non-alloyed metal contact placed directly on top of the thin p-GaN layer with light output from the sapphire substrate side will result in further strong reduction of the threshold excitation density, sufficient for CW current-driven VCSEL operation.

References

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