C5.7 Role of defects in GaN-based lasers

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Much has been learned in the thirty-five years since the demonstration of the first GaAs injection lasers [1,2]. The main lesson from that period is that defect-free material is needed. In the 1970s MITI set up a successful five year crash programme to make zero-defect GaAs. The reason behind the zero defect goal for diode lasers is that defects cause emission line broadening, and the threshold current for an injection laser is directly proportional to the emission linewidth. Excitons in semiconductors are very fragile. They can be easily destroyed, or have their linewidth broadened by crystal lattice disruptions of any sort.

Today, the most advanced GaN-based injection laser by far is produced at Nichia Chemical by Shuji Nakamura's group [3]. Their GaN material, from which the first lasers were fabricated, had 10^{10} defects/cm^2 [4]. Nevertheless, CW operation at 20°C has been demonstrated for many thousands of hours. The performance of these lasers flies in the face of conventional wisdom.

This brief Datareview reviews different types of defect that influence diode laser performance and speculates on how GaN diode lasers have seemingly avoided their detrimental influences.

The most prevalent defects in GaN are threading dislocations arising from an extra plane generated to reduce stress resulting from the lattice mismatch between GaN and the basal plane of sapphire. Threading dislocations propagate normal to the substrate surface. Their density in some regions of the epilayer can be greatly reduced by epitaxial lateral overgrowth ELOG [5]. ELOG uses thin narrow stripes of SiO_2 patterned onto an initial GaN epilayer to block the propagation of a majority of threading dislocations. ELOG material nevertheless has 10^6 - 10^8 dislocations/cm^2, i.e. the average dislocation separation is 1 mm at best. If potential fluctuations on the order of 1 eV occur at the dislocation (a reasonable number for GaN) a local field of 10^4 V/cm is created. Such a field strength is well within the Franz-Keldysh effect range [6], and is sufficiently intense to dissociate excitons into unpaired electrons and holes.

Another negative effect attributable to dislocations is the presence of dangling bonds which act as non-radiative recombination centres, and also exciton killers, creating an optical loss mechanism. Dangling bonds are also channels for impurity diffusion and often lead to reduced device lifetimes. Finally, dislocations and their dangling bonds and electrostatically trapped impurities induce localised stresses that perturb the local refractive index, causing light scattering which reduces the coherence of the laser beam.

Local non-uniformities present the danger of hot spot formation where the current forms filaments. Two adverse scenarios can develop: (1) local thermal run away that engenders regions of high defect density which gradually grow in size, and (2) spectral hole burning in which certain spectral modes are locally depleted. For all of these reasons, uniform material properties have always been a mandatory virtue.

Then, why do Nichia's GaN lasers work at all? The answer lies with two other serious non-uniformities present in the laser: (1) an accidental non-uniformity within the quantum well due to spinodal decomposition [7], and (2) the intentional use of quantum wells and heterostructures to define sheets of high population inversion and photon confinement. The former effect creates a granulated, random array of InN-rich quantum boxes within the intended quantum well volume, which confine the population inversion within these nanoscopic regions of high optical quality. While the random location and size of the InN-rich regions broaden the emission spectrum, this effect is far preferable to the excitons freely roaming about the entire intended quantum well volume where they might encounter any of the numerous defects present. Meanwhile, the overall quantum well and active area heterostructure still performs the conventional waveguiding and carrier confinement roles needed for good laser operation since the InN composition fluctuations are small compared to the wavelength of the laser light [8].

Consideration must be given to processing damage. Reactive ion etching (RIE) can leave behind bombardment-induced damage in the form of non-radiative recombination centres [9]. Also the by-products of RIE may deposit on various surfaces causing roughness or contamination that inhibits good electrical contacts or scatters light if present on the exit facet of the laser.

There are so many difficulties facing injection lasers that it is almost a miracle that successful GaN lasers are being made. Success depends on attention to many details and on luck (e.g. spinodal decomposition). Motivated researchers always find solutions to problems and clever ways to exploit luck.

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