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Investigation of Carrier Recombination Processes and Transport Properties in GaInAsN/GaAs Quantum Wells

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Abstract. It is shown that the dramatic changes in threshold current density with changing active region growth temperature in 1.3 μ m GaInNAs-based lasers can be attributed almost entirely to changes in the defect related monomolecular recombination current in the optically active material. In addition, growth temperature dependent changes in the QW morphology are shown to have a significant influence on the transport properties of the structure.

INTRODUCTION

The dilute III-V alloy GaInAsN is of great interest for its use in optoelectronics. It can be grown lattice-matched on GaAs substrates and due to its unusually strong bowing the band gap can cover the range 0.8 eV < E_g < 1.4 eV, even with N content less than 4%. This makes GaInNAs-based devices ideal for application in the 1.3 μ m-1.55 μ m communication window. However, the detailed band structure of GaInAsN remains relatively unexplored and is the subject of some controversy.

To understand and improve the performance of opto-electronic devices, knowledge of the magnitudes of the various recombination processes is a key factor. In this paper we show that an operating semiconductor laser provides an ideal tool to experimentally determine the required information right up to the carrier density, n_{th} , required for lasing operation.

EXPERIMENTAL

The laser structures used in this study are GaInNAs-based SQW devices grown by molecular beam epitaxy (MBE) on n^+ -GaAs substrates. The GaInNAs QWs have an In content of about 30%, an N

content of about 1.6% and a width of 6.5 nm. Two nominally identical series were grown differing only in the growth temperatures of the active region, T_g , which were set at 422°C and 456°C respectively. The main experimental analysis utilizes a method, successfully applied before [1], which enables the determination of the monomolecular-, radiative- and Auger-related current contributions to the threshold current by studying the integrated spontaneous emission rate from a window milled into the n-contact of the devices.

RESULTS AND DISCUSSION

The structural homogeneity of the QWs in the two laser structures is estimated on the basis of transmission electron microscopy (TEM) images that were acquired from simpler reference structures. These reference structures were grown at the same temperatures, but the respective QWs contained somewhat more In (37%). The measurements suggest for the low T_g laser structure a very even and homogeneous QW, and for the high T_g laser a clear non-uniformity in composition. This has a measurable effect on the transport properties of the devices. In an ideal QW laser the carrier density and hence the integrated spontaneous emission rate becomes pinned at its threshold value, n_{th} , for pump currents larger than

the threshold current. However, in strongly inhomogeneous devices, carriers can localise in potential minima above the lasing energy and cannot take part directly in the lasing process. The transfer rate between the minima is slow compared to the depletion rate by stimulated emission and a quasi Fermi-Dirac electron distribution is not maintained. This leads to an increasing carrier density above threshold and, hence, an increasing spontaneous emission rate. With rising temperature, thermal excitation out of the potential minima provides faster transport and improved pinning of the carrier density. These effects are observed in the low T_g sample, with the more homogeneous QW morphology, where we observe a poor pinning for temperatures lower than 200K. For $T > 200K$ the pinning improves and for $T > 250K$ the carrier density pins perfectly (Fig 1a).

FIGURE 1. Integrated spontaneous emission rate versus current for increasing temperatures (70K – 300K) for QW growth temperatures $T_g = 422^\circ\text{C}$ (a) and $T_g = 456^\circ\text{C}$ (b). A good pinning for $T > 200K$ can be observed for the low T_g samples.

In contrast to this in the high T_g samples (Fig 1b), where significant compositional fluctuations occur, the carrier density does not pin over the whole temperature range measured (70K – 300K), indicating the strong

influence of the QW morphology on the carrier transport properties.

Comparing the threshold current densities, J_{th} , of the two device types around room temperature ($T = 290K$) we observe that $J_{th} \sim 970 \text{ A/cm}^2$ for the low T_g lasers, while $J_{th} \sim 330 \text{ A/cm}^2$ for the higher T_g devices. This is a surprising result, as the structure with the more pronounced structural inhomogeneity exhibits the lower threshold current. To explain the origin of the threefold difference in J_{th} value, the current densities at threshold as a function of temperature for the monomolecular current, J_{mono} , radiative current, J_{rad} , and Auger current, J_{Aug} , were determined experimentally for the two laser structures. For the low T_g devices we find that the monomolecular current contributes $\sim 61\%$ to the total threshold current at 290K and $\sim 48\%$ for the high T_g devices. The total monomolecular current density is reduced by a factor of 3.8 from $J_{mono} \sim 600 \text{ A/cm}^2$ down to 160 A/cm^2 when increasing T_g from 422°C to 456°C . However, the reduction observed for the Auger ($\propto n^3$) and radiative ($\propto n^2$) component is much less significant and can be attributed to a slight variation in the threshold carrier density, n_{th} , between the two structures. However a slightly smaller n_{th} cannot explain the strong reduction in the monomolecular recombination ($\propto n$), which therefore requires a strongly decreased monomolecular recombination coefficient with increasing T_g .

The results suggest that in term of carrier transport homogeneous 2D QWs are desirable. However, these structures do not necessarily show the lowest threshold current densities, as the defect density and hence the threshold current density seems to be more dependent on the growth temperature than on the QW morphology.

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