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Effects of Quantum Well Recombination Losses on the Internal Differential Efficiency of Multi-Quantum-Well Lasers

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Abstract

Non-uniform carrier distribution in multi-quantum-well (MQW) laser diodes is found to cause QW recombination losses to increase with rising injection current above threshold. These losses can have a larger effect on the internal differential efficiency than carrier leakage.

The external differential efficiency of semiconductor laser diodes is reduced by carrier losses and by photon losses. Carrier losses are described by the internal differential efficiency η_i which is equal to the fraction of current above threshold that results in stimulated emission [1]. The efficiency η_i is affected by spreading current losses (η_s - lateral carrier leakage), by carrier escape from the quantum wells (η_e - vertical carrier leakage), and by recombination losses inside the quantum wells (η_r – Auger recombination, spontaneous emission, and Shockley-Read-Hall (SRH) recombination): $\eta_i = \eta_s \eta_e \eta_r$ [2].

Above threshold, the quantum well carrier density is usually assumed to remain constant with increasing injection current so that QW recombination losses are clamped (η_r=1) [1]. In MQW active regions, the carrier distribution becomes increasingly non-uniform as the number of wells increases and as the bias increases [3]. In InGaAsP/InP long-wavelength MQW lasers, the largest carrier density occurs in the quantum well closest to the p-doped side because electrons travel more easily across the MQW than holes [4]. Since this non-uniformity becomes stronger with larger bias above threshold, the QW recombination losses cannot remain constant in MQW lasers even with constant average MQW carrier density. Especially long-wavelength lasers suffer from strong Auger recombination losses which rise proportional to the cube of the local carrier density.

We have investigated the internal differential efficiency of InGaAsP/InP broad-area (W=50µm) in-plane lasers emitting at 1.5µm wavelength. The active region of the laser structure consists of six 6.5nm wide 1%-compressively strained QW's. The barriers are 5.5 nm thick and are made of lattice matched InGaAsP (1.25µm bandgap wavelength). The MQW is sandwiched between 100nm undoped InGaAsP (1.15µm) separate confinement layers (SCLs). Besides this conventional laser (A) a second structure is fabricated which contains an additional 6nm thick strained $In_{0.81}Ga_{0.19}P$ electron stopper layer (B). The band diagram of structure B near threshold is shown in Fig. 1.

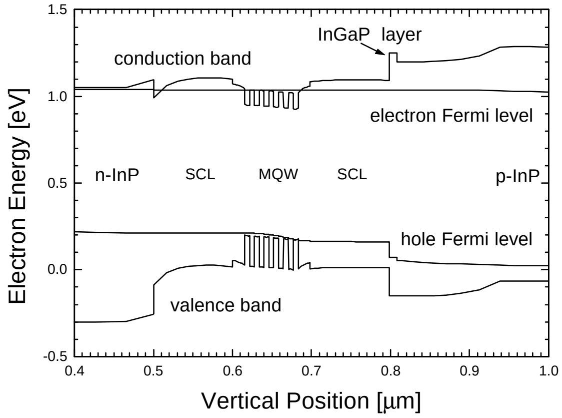

Fig.1: Energy band diagram of laser B.

The InGaP electron stopper layer has a conduction band band offset to InP of about 50meV but it does not hinder hole transport. This stopper layer was expected to reduce electron leakage from the active region but no change in the laser characteristics is measured (Fig. 2). From measurements with different laser length, the internal differential efficiency at room-temperature is found to be slightly less than 80% in both cases. The 20% carrier loss do not seem to be caused by carrier escape ($\eta_e \approx 1$) or by spreading currents ($\eta_s \approx 1$).

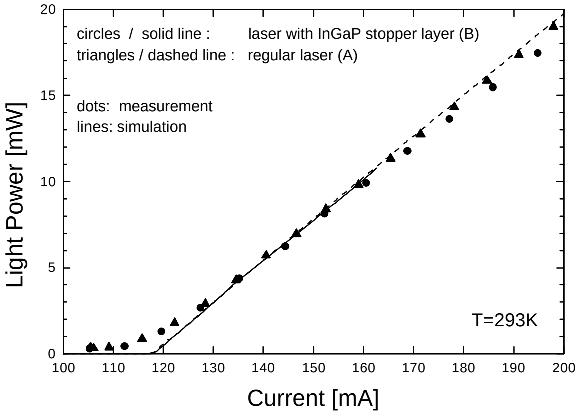

Fig.2: Light-current curves of lasers A and B.

The measurements are analyzed using an advanced laser simulation tool [5]. The software calculates the optical gain in strained quantum wells based on the 4x4 **kp** method including valence band mixing and carrier-carrier interaction. The computed photoluminescence spectrum as well as the emission wavelength agree well with measurements. The current calculation is based on a drift-diffusion model including thermionic emission at heterointerfaces. The simulated light-current characteristics are in perfect agreement with the experimental results for both the device structures (lines in Fig. 2). Electron leakage from the active region can be identified as minority carrier current in the p-InP cladding layer. The leakage related efficiency η_e is calculated to be 98% in both cases, explaining the little effect of the stopper layer at room temperature. Carrier losses due to Auger recombination, spontaneous emission, and SRH recombination are analyzed by integrating the recombination rates at different bias points above threshold. Dividing the increment in recombination current by the increment in total current gives a recombination related efficiency of η_r=80% for both devices. The reason for this impact of recombination losses lies in the increasing non-uniformity of the MQW carrier distribution. The increase of Auger recombination above threshold is shown in Fig.3. The calculated efficiency η_r also includes the rise in SCL recombination losses but their contribution is several orders of magnitude smaller than the QW contribution. In excellent agreement with the measurement, $\eta_i=\eta_e\eta_r$=78% is calculated confirming the validity of our analysis (current spreading effects are negligible

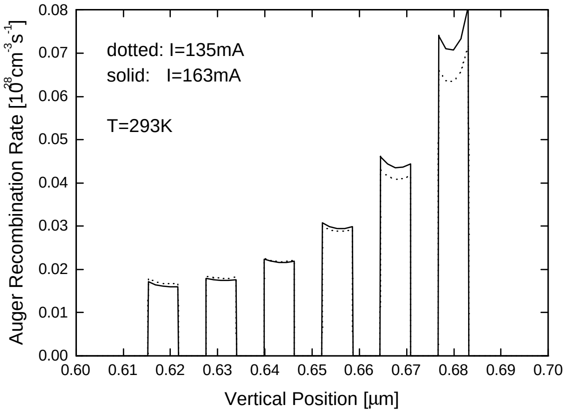

Fig. 3: Quantum well Auger recombination.

In conclusion, quantum well recombination losses can have a major effect on the internal differential efficiency of laser diodes that employ a larger number of quantum wells in the active region.

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[5] PICS3D by Crosslight Software, Inc.