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Positive and Negative Impact of Drastically Reduced Energy Relaxation on Zero-Dimensional Devices

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0-D systems present a challenge from both physical and technological points of view. Quantum-box lasers (Fig.1) are a typical case where quantization energies larger than thermal energies are predicted to result in very low threshold currents, increased bandwidth, narrower linewidth, easier monomode action[1]. It should be reminded, however, that mechanisms relevant to device action generally involve several steps, of which the last one only, e.g. radiative recombination, gives the actual output signal. One such step, namely the relaxation of excited carriers, has recently been shown to decrease drastically in 0-D on an intrinsic basis[2], whereas it is not the limiting one in 3-D or 2-D. It is the purpose of this communication to discuss the drawbacks and possible advantages of this step as a limiting one in two cases of device action.

Firstly, the very negative effect of drastically reduced energy relaxation on the interband luminescence properties of quantum boxes is presented. We explicit how the requirement of both energy and momentum conservation reduces the relaxation rate within the n=1 subband of a patterned quantum well (Fig.2). Electrons are thus retained in their cascade to the ground state (Fig.3). We point out how the orthogonality relations between hole and electron states in a box prevent radiative recombination in this configuration. To quantify these effects, we present a realistic model of a multilevel box (Fig.4). As shown on Fig.5, the luminescence collapses for lateral quantization narrower than 100-200 nm. This corresponds to energy level spacings larger than about 1 meV. This is far weaker than the quantization energies of the order of kT required to take advantage of specific 0-D properties. Moreover, the predicted onset of decreased luminescence is shown to be independent of any adjustable parameters under broad conditions of validity. This means that we account for the poor experimental luminescence results in 0-D systems[3] on an intrinsic basis. This is in strong contrast with the universal belief that explains these results in terms of extrinsic process-induced surface defects, of which little deep understanding is available. Our approach adds a more sound intrinsic limitation upon extrinsic ones. We eventually discuss experimental support from wire and box luminescence features as well as from quasi 0-D systems obtained from quantum-well lasers in a strong perpendicular magnetic field. Trends of predicted luminescence characteristics are discussed for various materials and geometries.

Next, we consider the very positive implications of reduced relaxation on intersubband devices when going to 0-D. Here intersubband refers to the subbands (n=1,2,..) of the original quantum well before lateral patterning. Differences between the intersubband and intrasubband cases are discussed from the (n=2) to (n=1) example. A strong bottleneck effect sets in again for weak lateral quantization. Its location in the energy cascade depends on details of capture and injection. The emphasis will be therefore on 0-D systems coupled by tunneling, where injection takes place in well-defined conditions. Preliminary results related to changes in the transfer probability will be presented. Starting from a 2-D quantum-well based system and going to weak 0-D quantization, the positive effect of modified transfer probability on other steps of device action will be discussed.

References

1. Y. Arakawa and H. Sakaki, Appl. Phys. Lett. **40**, 939 (1982)
2. U. Bockelmann and G. Bastard, Phys. Rev. B42, 8947 (1990)
3. See e.g., B.E. Maile et al., J. Vac. Sci. Technol. **B7**, 2030 (1989), A. Izrael et al., Appl. Phys. Lett. **56**, 830 (1990), M. Notomi et al., Appl. Phys. Lett. **58**, 720 (1991)

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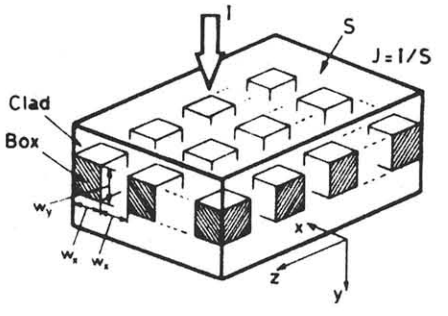


Fig. 1: Schematic view of a quantum-box laser

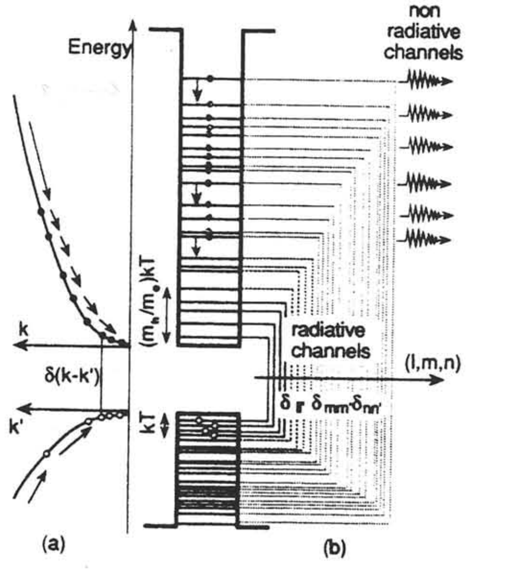
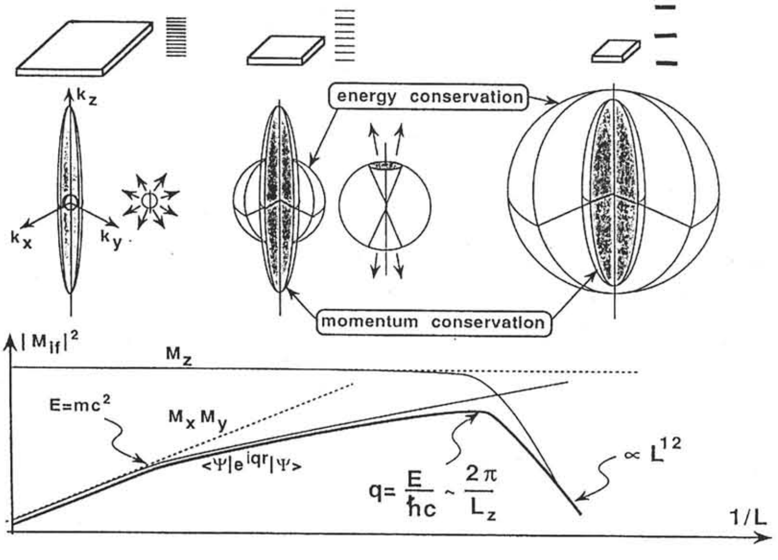


Fig.3: Energy cascade from capture to "luminescent" state, in 3-D or 2-D (a) and in a 0-D box (b). Non radiative recombination is efficent when electrons are retained.

Fig.2: Schematic aspect of the Fourier transform of an n=1 wavefunction and of the sphere of energy conservation in q-space. The matrix element, proportional to the area of the intersect, vanishes above a given lateral size



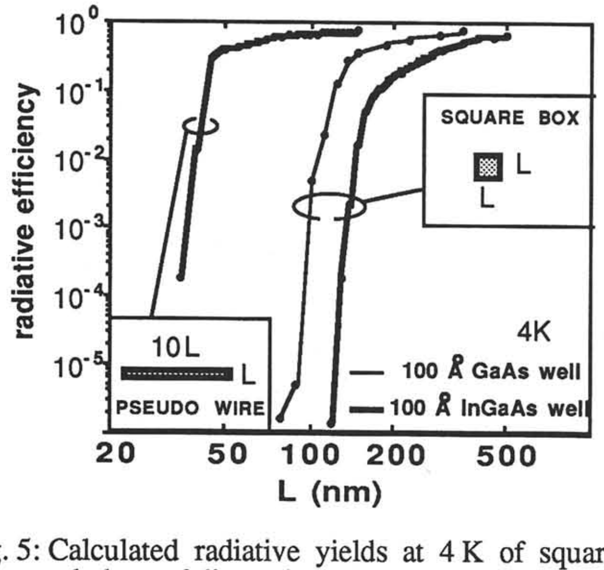


Fig. 5: Calculated radiative yields at 4 K of square and elongated dots of dimensions (L × L) and (L × 10 L) respectively fabricated from 100 Å quantum wells of GaInAs lattice-matched to InP or Ga(Al)As as a function of L.

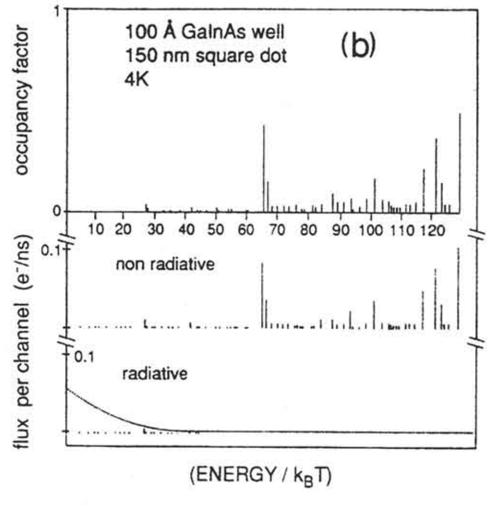


Fig.4: Occupancies and radiative/non radiative fluxes in a model of a capture, relaxation and recombination, far from equilibrium, in a multilevel quantum box