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The Physics of the Quantum Well Laser

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Abstract

This paper reviews some of the properties of quantum well lasers (QWLs), with emphasis on the two-dimensional origins of these. It is shown that two main effects determine the lowering of threshold current, namely the diminished density of states (DOS) (favourable factor) and the diminished optical confinement (unfavorable factor). The good operation of GaAs–GaAlAs QWLs also relies on more subtle effects such as the square 2D DOS, the enhanced optical matrix element, the high quantum efficiency . . . The poor operation of GaInAs based quantum well lasers is due to the detrimental Auger effect which is larger than in 3D lasers because of the higher carrier densities at which QWLs operate. Several other useful properties of QWLs in the performance (high-frequency, narrow-line) and manufacturing fields are discussed. Problems and advantages of 1 and 0D quantum-wire and quantum-box lasers are briefly evaluated.

1. Introduction

The quantum-well laser (QWL) has by now a few well established properties [1–3] at variance with those of the now well-understood double heterostructure (DH) laser [4, 5]: it has extremely low threshold currents, well below those predicted by the simple extensions of DH laser theory, temperature coefficients of the lasing threshold current T_0 sometimes better (but also sometimes worse!) than DH lasers, high-frequency modulation capabilities, low degradation rates etc . . . . It is therefore interesting to understand the physical basis leading to these operational characteristics, as they are intimately related to the two-dimensional nature of the electron states in the structure. The purpose of this short review is to demonstrate that *the operation of the QWL is strongly connected to its bidimensional character, and that actually it is a good laboratory to understand the pros and cons of low-dimensional devices.* The extension of the QWL concept towards lower dimensionality will be briefly addressed at the end of this paper.

2. Preliminary: The two main opposite effects in quantum well lasers (QWLs)

The QWLs have two main differences with DH lasers, acting in opposite directions:

(i) The number of available quantum states in the active region is strongly diminished: in the z-growth direction, i.e., perpendicular to the active layer plane, the thickness of the order of 200 Å or less reduces the allowed values of momentum in that direction to one or a few quantized values within occupied states at threshold (i.e., $\approx$ a few kT above the ground state) whereas the number of occupied k_z-states in a 1000 Å DH laser would amount to a few tens.

(ii) The efficiency of emitted photons to interact with an electron-hole pair to induce another stimulated recombination process is strongly reduced because of the poor optical confinement and has two origins:

– Firstly, at small confining material thickness, the waveguiding properties of a DH are poor, and the usually confined optical wave tends to a "natural" extension of $\approx$ one wavelength, the more so as the confining layer thickness diminishes.

– Secondly, the rather wide optical wave has an overlap with the active layer which diminishes as d.

Therefore, both effects tends to diminish the optical confinement factor Γ as d^2, with a good approximation expression as [4]:

$$\Gamma \approx \left(\frac{d}{\lambda_0}\right)^2 (2\pi)^2 n \Delta n \tag{1}$$

where λ_0 is the wavelength in vacuum, n and Δn are the average and differences in indices of refraction of the materials of the DH. In order to improve on that factor, Tsang has used the separate-confinement heterostructure schemes shown on Fig. 1, where one can show that the approximate value of Γ is then given by [6]:

$$\Gamma_{\mathrm{SCH}} \approx 3 \times 10^{-4} d(\text{Å}) \tag{2}$$

for a $GaAs/Ga_{0.82}Al_{0.18}As/Ga_{0.6}Al_{0.4}As$ SCH structure. In eq. (1) for the common $GaAs/Ga_{0.7}Al_{0.3}As$ structure, one calculates $\Gamma \approx 0.004$ for $d = 100$ Å and $\Gamma \approx 0.28$ for a DH laser with $d = 1000$ Å. In the SCH case, with $d = 100$ Å, one finds $\Gamma \approx 0.03$.

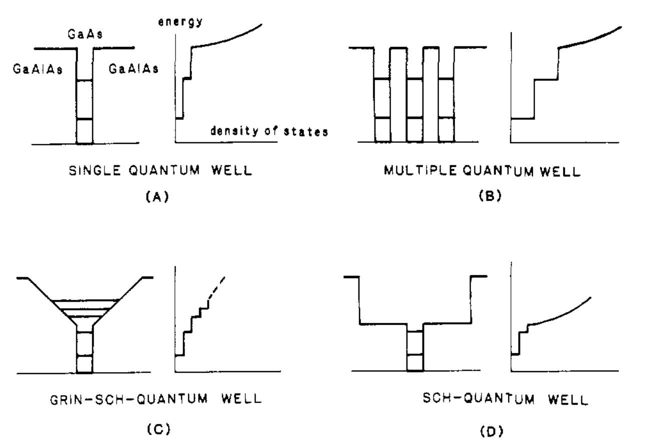

Fig. 1. Various quantum well laser structure schematically depicted by their conduction band edge space variation (left-side of each figure) and their 2D density-of-states (DOS) (right side). (a) Single Quantum Well. Each quantized well state introduces a 2D DOS equal to $m^*/\pi\hbar^2$, while the onset of 3D states at the top of the well introduces a much larger DOS. (b) Multiple Quantum Well (MQW): Each quantized state introduces a 2D DOS equal to $Nm^*/\pi\hbar^2$, N being the number of wells. (c) Graded-Index Separate Confinement Heterostructure (GRIN-SCH laser). Note the ladder of quantum states in the graded region. (d) Separate-Confinement Heterostructure (SCH) laser: The intermediate-composition layers introduce a large DOS, not as far apart from the ground state as in the DH, SQW or MQW cases.

From the preceeding discussion, it is clear that in single quantum well lasers (SQWLs), the diminution in Γ is unacceptable unless a SCH scheme is used (the other alternative, i.e., the use of *multiple* QWs (MQWs) will be discussed later). Overall, one calculates that the decrease in number of states tends to just balance the decrease of available quantum states to be inverted at threshold [6].

3. The more subtle effects in 2D-QW lasers

In order to analyze in more details the operation of QWL's, one has to consider the following effects:

(i) *The square 2D-DOS* lead to several specific effects:

– gain remains finite even for low handfilling, in opposition with DH lasers where the DOS, and therefore the gain, tend to zero. This implies that the gain vs current curve is steeper than in 3D, and also that low-temperature operation of QWL's will be excellent, with threshold currents reaching to very small values at extremely low-temperature [7].

– the carrier density required to achieve a given gain is smaller in 2D than in 3D, as is self-explained [1] in Fig. 2.

– the maximum of the gain value increases with injected carrier concentration until complete state filling is achieved. Then, the gain saturates, at variance with the ever-increasing gain curve of 3D lasers. In order to reach higher values of the gain coefficient, one then needs to increase the density in energy space of 2D-quantum states. This is best achieved by reaching upper-quantized levels, where one then doubles, triples ... the allowed quantum states, or by using multiple quantum wells, where one develops parallel lasing channels, and where therefore the saturated value of the gain is multiplied by N, number of quantum wells (Figs. 2, 3).

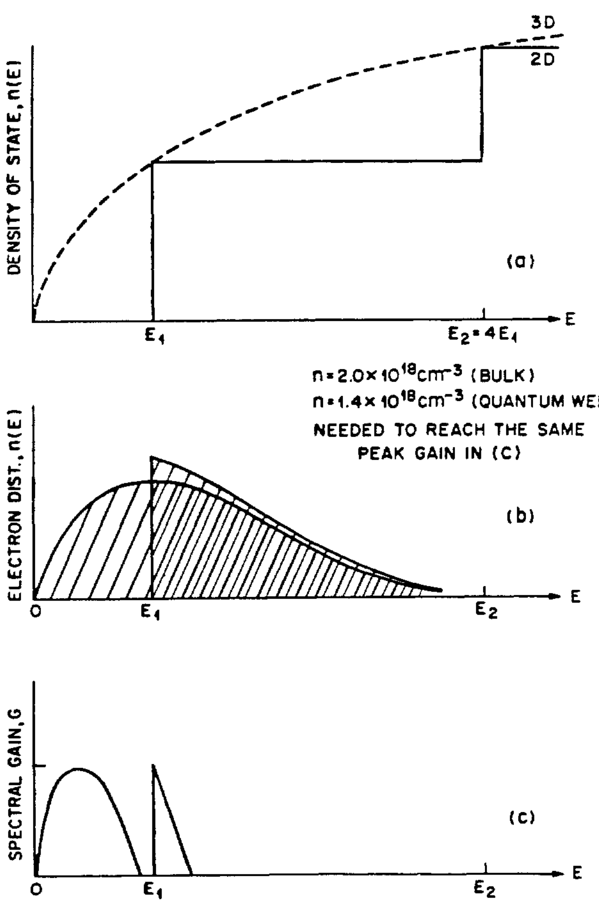

Fig. 2. Comparison of the injected carrier densities required to achieve a given gain in 2 or 3D systems. (a) Densities of states in 2D or 3D systems with equal thicknesses. (b) Occupied states in 2 and 3D systems in order to achieve the gain curves shown in (c) which have the same maximum gain (from Tsang [1]).

(ii) *The optical matrix element* is somewhat larger in 2D than in 3D. Whereas in DH one has to average transition probabilities over all carrier-momentum directions, the quantization of hole states in 2D selects the heavy-hole state with angular momentum mainly $\pm 3/2$ as the hole ground state. For such states, the electron-hole matrix element is 1.5 times larger than in the bulk. The detailed calculation of matrix elements and their variation with carrier energy has been carried out by several teams [9–11].

(iii) *Electron-hole correlation effects* might play a larger role in 2D than in 3D lasers, thanks to the increased electron-hole interaction as evidenced by the strong excitonic effects of quantum wells. Correlation effects tend to be weakened at high carrier densities, but the strength of the 2D electron–hole interaction in quantum wells tends to induce some increase in the optical transition probability even at the carrier densities encountered in quantum-well lasers [12].

(iv) Quantum wells exhibit a *very large improvement in quantum efficiency* of spontaneous light emission. *This has been reported for every materials pair studied up to now* and should be the result of one or several of the following effects:

– inactivity of dislocations as non-radiative recombination centers [13],

– impurity gettering at interfaces, outside the active layer region [14],

– increase of radiative electron-hole recombination probability through enhanced electron-hole correlation and/or relaxation of the k-selection rule [12, 15],

– more basic effects (not yet evaluated) pertaining to 2D such as reduced carrier capture.

Although these effects have not been *quantitatively* analysed, they all point to a diminished threshold current due to the only presence of the radiative recombination path of injected carriers.

4. The GaAs/GaAlAs case

Numerous laboratories have reported excellent results on GaAs/GaAlAs single quantum lasers [1–3]. Besides their low threshold current, which is understood in terms of the above-mentioned improvement factors, several hitherto unexplained results only recently received complete explanation [16]:

(i) The advantage of the GRIN-SCH structure over the SCH (Fig. 1(c) and (d)) is due to their smaller DOS in the light-confining layer: in normal conditions, the detailed calculation of carrier densities at threshold yields a quasi-Fermi level which is quite high in the quantized layer, typically 60 meV. Therefore, the Fermi-Dirac distribution function has a significant tail in the light-confining layer which has a large DOS. One therefore expects an important population of carriers in the cavity states, the more so for the SCH structure which has a large 3D-like DOS (Figure 1(d)). This population is actually calculated to be of the same order of magnitude as that of the quantum-well states. Therefore, a large fraction of injected electrons are not in the useful quantum-well states.

(ii) On the other hand, *optimal T_0 is not always associated with low-threshold QWs*: standard MQW laser have better T_0

than DH, GRIN-SCH and SCH lasers, in decreasing order of merit. MQW's are the most two-dimensional lasers, as the potential barrier of the confining material is the highest and therefore limits carrier leakage. In that case the Fermi-Dirac tail (unuseful electrons because uninverted) is smaller (constant DOS) than in 3D (square-root increase). The GRIN-SCH is not as good as the MQW laser because with increased temperature some states can be populated in the barrier material in addition ot the QW states. The worse of the lasers is the SCH laser where a large DOS at rather low energies above the bottom of the QW conduction band gets populated with increased temperature.

(iii) In the early days of QW lasers it was argued that due to the 2D-DOS and its finite gain at low band-filling, gain curves would be narrow. This is actually not the case (Fig. 4) and is explained in terms of the large quasi Fermi energy and higher-lying quantum-states population.

(iv) Quantum-well lasers were predicted [19] to possibly lase on $n = 2$ transitions. This was actually recently independently observed by several groups [16–18] when increasing losses, thus requiring higher gain. This might prove useful to achieve multiwavelength lasers [20] by actively-controlled loss.

5. SQW versus MQW laser operation

As seen from Fig. 3, gain appears at lower injected current in

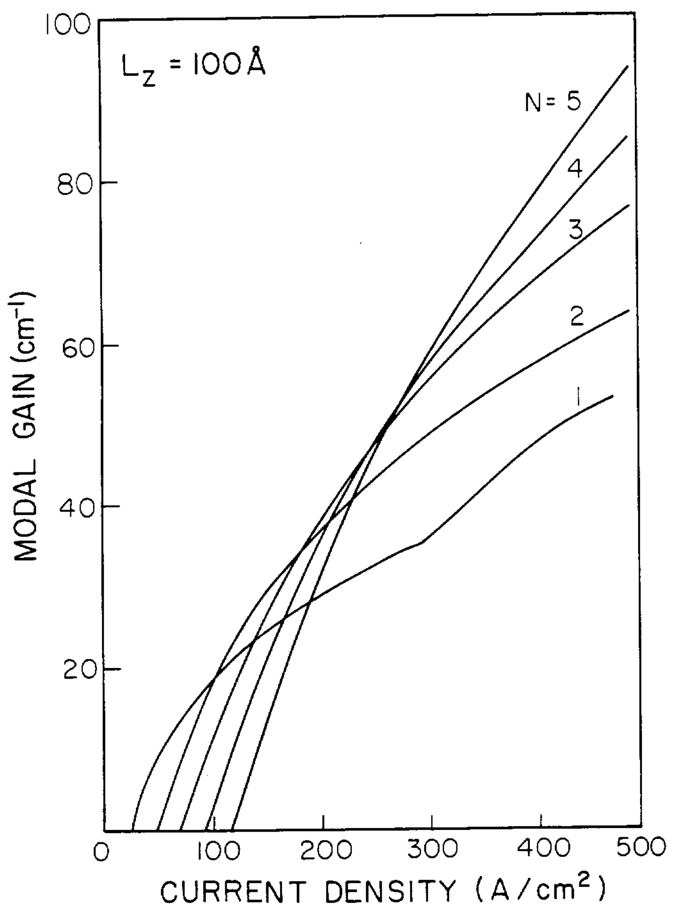

Fig. 3. The modal gain (Γg) variation as a function of injected current density for various numbers of quantum wells. Note the saturation of the $n = 1$ quantum state for the single QW laser above $\approx 100\,\mathrm{A/cm^2}$ and the onset of $n = 2$ quantum state transitions leading to higher gain at $300\,\mathrm{A/cm^2}$. Net gain starts at higher currents for increasing number of wells because of the increasing number of states to be inverted. Well thickness is 100 Å (from Arakawa and Yariv [8]).

SQW than in MQW, due to the smaller DOS to be inverted in the former case. However, the gain tends to saturate with band filling, and it is then more advantageous to use the MQW increased DOS and saturated gain value. For a given loss, one always find an optimum number of QW's. The optimum number of required QW's is usually small. This is true only when no non-linear effect sets in. As will be discussed below in the GaInAs/InP case, *quantum-well lasers have to operate at high volume-gain*, therefore at high-carrier densities, because of the bad confinement factor (recall that it is the modal gain, product of the volume gain times the optical confinement factor which must equate losses at threshold; losses are roughly the same at 2D and 3D and mainly due to proton escaping the cavity). The Auger effect is therefore increased in SQW lasers, whereas MQW lasers, while operating at low carrier densities in each well, can retain some of the advantages of 2D QW lasers while not increasing non-radiative recombination mechanisms like the Auger effect.

6. The GaInAs–InP and GaInAs–InAlAs QW laser

In strong contrast with the GaAs/GaAlAs materials system, no laser emission could be obtained in SQW lasers in the GaInAs materials case. The situation arising is clearly shown in Fig. 5 and in measured gain curves [21]. As carrier injection increases, heating of carrier occurs, presumably by Auger effect. It decreases the carrier inversion, i.e., the gain, and increases dramatically the confining layer population. The structure shown in Fig. 5 actually lases at $1.3\,\mu$ for $I = 450$ ma. It was shown by reducing the lattice temperature that carrier heating is indeed responsible for this poor performance and not intrinsic poor properties of the 2D system: this laser emits with excellent milliamp current threshold below 100 K, which shows that the saturated value of the gain is enough to balance losses. Multi-quantum well lasers in the In materials system have been successfully operated, but with threshold characteristics which are not significantly better than 3D DH lasers.

7. Additional properties of QW lasers

Besides their good current threshold and T_0, QW lasers possess a number of additional important features which make them highly useful.

7.1. *Modulation limits*

Due to the high-differential gain $\mathrm{d}g/\mathrm{d}I$ of QWLs where I is the injected current, Arakawa and Yariv [8, 22] have shown that an increase in speed response of a factor ≈ 2 could be expected from QW lasers over DH lasers. This was confirmed by Uomi *et al.* [23].

7.2. *Spectral linewidth*

From the same high-differential gain in QW lasers, Arakawa and Yariv [8, 22] have predicted narrower linewidths than in 3D DH lasers. Although this improvement has not yet been directly measured, the related linewidth enhancement factor α is diminished by 50% in QW lasers as compared to DH lasers [24].

7.3. *Reliability isssues*

Although relatively few degradation studies have been reported

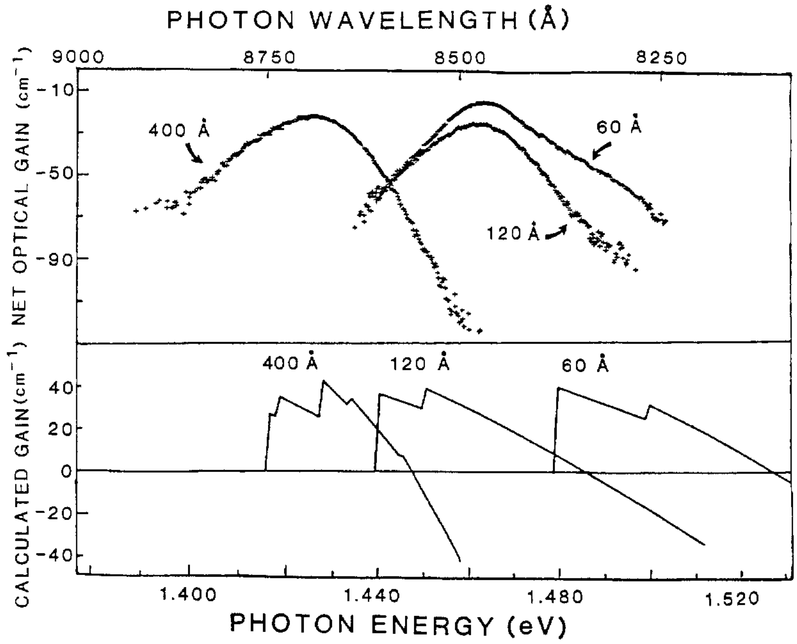

Fig. 4. Measured net optical gain curves (top) and corresponding calculated curves for modal gain (Γg). The low-energy side of the gain curve is not treated in the theory as no band tailing is included. The high-energy slope of the gain curve is well represented by the calculations. The peak positions are shifted relatively to the calculated ones because of the presence of some Al in the active region due to memory effects in the MOCVD reaction (from Nagle *et al.* [16]).

on QW lasers, they all point to very good performance [25]. This might be due to several factors, including inactivity of dislocations, stabilization of defects by interfaces, smallness of the carrier-induced facet degradation as the active layer is much thinner than the optical cavity.

7.4. *Impurity-induced interdiffusion (IID)*

Impurity-induced interdiffusion of quantum wells has been evidenced in many materials systems with various n and p-type implanted species [3]. It allows to transform an implanted region with thin wells and barriers into an alloy with the average composition. Such an alloy has the usual properties of light and carrier confinement. Therefore, one can use such an effect to construct a variety of stripe-geometry lasers, window lasers (i.e., lasers where the active region does not extend to the external facets) etc. . . Excellent results have been obtained by such techniques which permits to manufacture complex devices with simple planar-type operations while one would otherwise require multiple-step etch and deposition processes. In particular, a three-fold increase in catastrophic-damage threshold was demonstrated in window lasers [26].

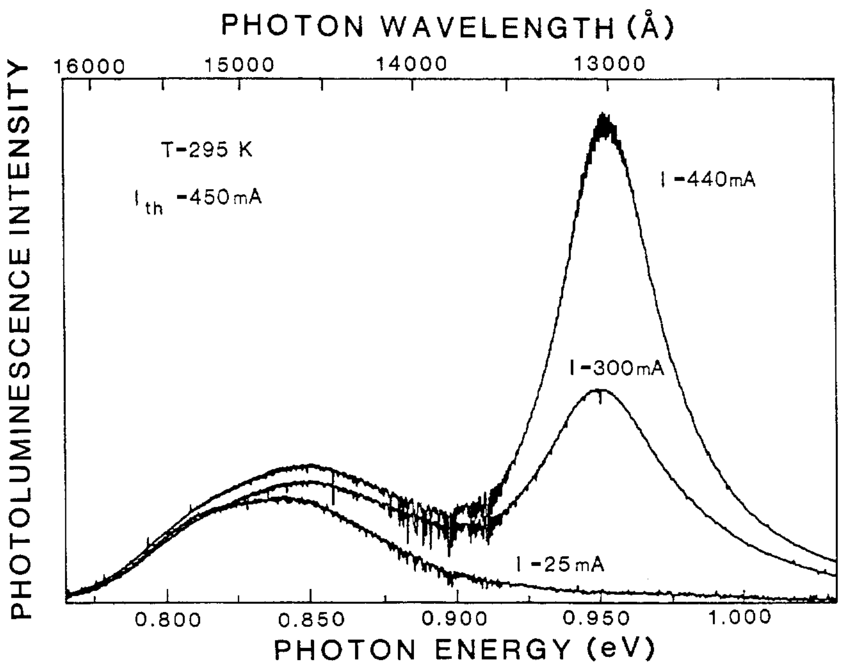

Fig. 5. Spontaneous emission of a GaInAs–GaInAsP–InP SQW laser. Quantum well thickness is 50 Å; Confining layer material has a gap at 1.3 μ and a thickness of 2000 Å. Note the heating of carriers with increased current as revealed by the increasing slope of the 1.5 μ emission and the increased confining material emission (from Nagle *et al.* [21]).

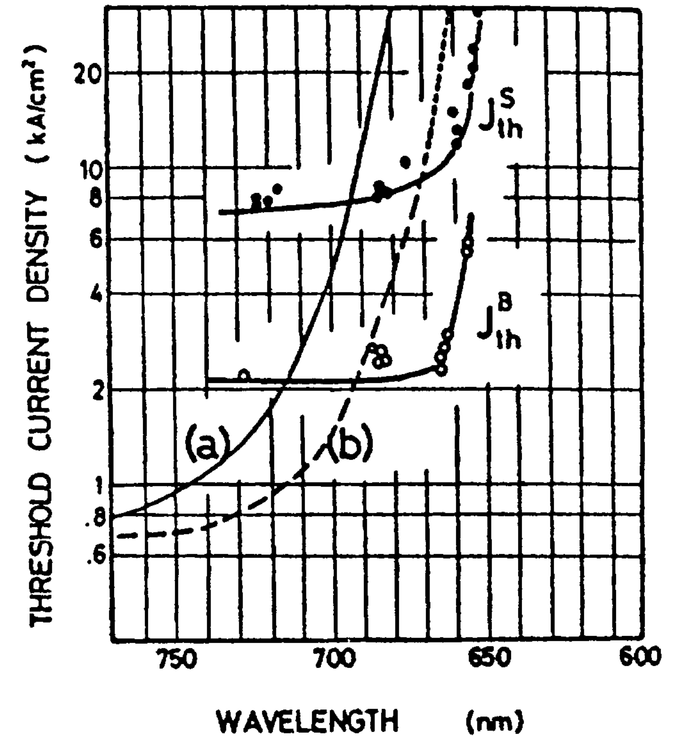

Fig. 6. Threshold current density at 300 K as a function of lasing wavelength for AlGaAs laser diode. Curve (a) is the lowest j_{th} realized so far by conventional DH laser diodes with $Al_xGa_{1-x}As$ active layer. Curve (b) is the result of MOCVD grown SQW laser with 40–60 nm QW layer. GaAlAs SCH-MQW results with well Al content from 0.15 to 0.35 are indicated by open and closed circles. Open circles: broad area diodes. Closed circles: stripe geometry diodes (from Saku *et al.* [33]).

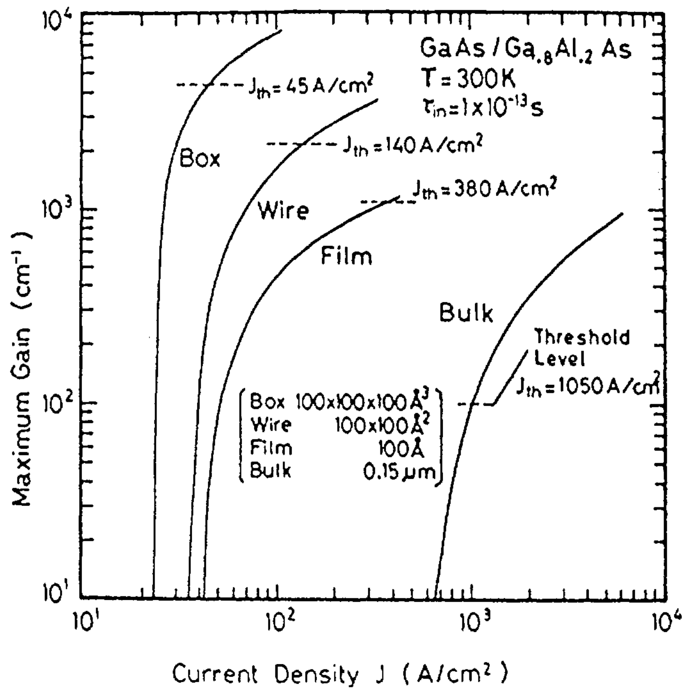

Fig. 7. Calculated maximum gain curves for 0D, 1D, 2D, 3D GaAs/GaAlAs systems as a function of injected current. A confinement factor of 0.4 in bulk and 2D, 0.1 in 1D and 0.05 in 0D is assumed. Dashed lines on each curve indicates the level of modal gain ($= \Gamma g$) required for laser threshold for each system (from Asada *et al.* [29]).

8. Evolution towards 1 and 0D

Several papers have theoretically shown that 1 and 0D physical systems should in principle have even better performance than the 2D QW laser systems thanks to their advantageous DOS [27–29]. Although this is in principle true, we would like to emphasize two important drawbacks of such systems.

8.1. *The importance of fluctuations*

It is by now quite well established that interface disorder is limiting recombination line sharpness in quantum wells [30], although some recent interrupted-growth experiments evidence excellent improvement [31] (however at the expense of high-impurity incorporation). In a series of very demonstrating experiments, Okamoto and his group [32, 33] have shown that in order to reach short wavelengths with quantum wells, the use of ultra-narrow quantum wells led to unacceptable linewidth increase, leading in turn to inhomogeneously-broadened gain curves. It is only by an optimization of quantum well thickness and alloying that a short red wavelength was obtained with a reasonable threshold (Fig. 6). From this example, one sees the importance of size fluctuations in 2D. It is at the moment difficult to imagine 1 and 0D systems which would not exhibit significantly broadened linewidths, as a large number of 1 and 0D systems have to be operated together.

8.2. *The required high density of states, i.e., high number of 1 and 0D systems*

As is evident from the above discussion of the 2D QW laser, one cannot diminish too much the active material volume for two reasons:

(i) Required carrier densities per 1 or 0D well are so high that total band filling would occur before enough gain would be obtained.

(ii) The confinement factor would be vanishingly small.

Therefore, if one would work with constant confinement factor and total number of states when going from 3 to 2 to 1 to 0D, one certainly obtains the results predicted theoretically (Fig. 7). One has however to remember that this then represents thousands of 0D quantum boxes to be fabricated for each laser and with no fluctuation!

The full 0D quantization occurring for 2D systems when placed in a strong, perpendicular, magnetic field is unique [22, 32]; The magnetic field creates at once thousands of quantum boxes with sizes equal to the cyclotron orbit radius: one retains *all* the 2D quantum states, as it is well-known that the degeneracy of a Landau level is exactly equal to the number of states which were previously situated in the energy range between two adjacent Landau levels. Therefore, the number of states and the confinement factor are the same in the 0D system created in a strong magnetic field as in the original 2D system. The experiments performed up to now have however never evidenced huge effects, just an anisotropy of the spontaneous emission spectrum, which shows the creation of 0D quantum states [34].

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