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THE GROWTH OF QUANTUM WELL GaAs/GaAlAs LASER STRUCTURES

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Résumé

Dans ce papier nous décrivons la croissance des interfaces abruptes pour l'application des lasers à puits quantiques.

Nous rapportons les caractéristiques d'une structure Laser GRIN-SCH à puits quantique qui a montré la plus petite densité de courant de seuil jamais rapportée (232 A cm² pour une longueur de cavité de 413 μm) tout en conservant de bonnes propriétés thermiques et électriques.

Une comparaison des longueurs d'ondes d'émission obtenues avec celles que la théorie laisse prévoir, nous a permis d'étalonner la vitesse de croissance de la couche active entre 60 Å et 400 Å et d'estimer que la largeur de l'hétérointerface est inférieure à 10 Å.

Abstract

In this paper we describe the growth of abrupt heterojunctions for use in quantum well laser applications.

We give the characteristics of a GRIN-SCH quantum-well laser structure which exhibits the lowest threshold current density ever reported (232 A cm⁻² at a cavity length of 413 μm) while maintaining good thermal and electrical properties.

A comparison of the emission wavelengths with those predicted theoretically has allowed us to calibrate the growth rate in the layer thickness range 60 Å to 400 Å and to estimate a heterointerface abruptness of less than 10 Å.

2. Introduction

The technique of organometallic vapour phase epitaxy (OMVPE) has proven itself to be an attractive alternative to liquid phase epitaxy for the growth of conventional GaAs/GaAlAs DH laser structures. In addition to "state of the art" laser performance (1) the OMVPE technique offers reproducible growth on large areas of substrate with a uniformity of laser characteristics superior to that obtained in LPE grown material (2).

In this paper we show that the OMVPE process can also be used for the growth of quantum well lasers and that these devices offer very low lasing threshold current densities while maintaining good thermal and electrical characteristics.

The term "quantum well" can be applied to the active layer of a DH GaAlAs/GaAs laser when the thickness of that layer is less than approximately 400 Å. In that case the electron gas within the active layer exhibits two dimensional properties and the density of states within
the conduction and valence bands display discrete levels. As the active layer thickness is decreased the energy and separation of these quantised levels increase.

Recently very low threshold current densities have been achieved in graded refractive index (GRIN) separate confinement heterostructure (SCH) single quantum well lasers, the material being grown by MBE (3) (4) and OMVPE (5) (6). In particular (6) we have achieved the lowest ever lasing threshold current density of 232 A cm\(^{-2}\) for a chip size of 413 \(\mu\)m by 140 \(\mu\)m and 121 A cm\(^{2}\) for a chip size of 1788 \(\mu\)m by 140 \(\mu\)m.

In this paper we describe the growth of quantum well structures for laser applications. We discuss the system parameters which can affect the abruptness of heterojunctions and describe some techniques which we have used to measure the interface abruptness.

Finally we describe the characteristics of some broad area quantum well lasers under pulsed operation, which show indirectly that the interface abruptness of these structures is better than 10 \(\AA\).

3. The growth of quantum wells

The quantum size effect (7) is of interest for single potential wells having a thickness (\(L_z\)) within the range (50 \(\AA\) \(<\) \(L_z\) \(<\) 400 \(\AA\)). For a thickness of less than 50 \(\AA\) carrierc capture by a single quantum well is inefficient due to the incomplete thermalisation of the injected hot carriers.

At the upper limit, of approximately 400 \(\AA\), the separation of the quantised levels is negligible.

Thus the growth system must be capable of growing thin layers controlably, with a good reproducibility, also the compositional changes at heterointerfaces must be abrupt, ideally on the order of 1 or 2 monolayers. For a good yield of devices the thickness must also be uniform over the grown slice. The measurement of layer thickness and compositional grading on this scale is difficult and will be discussed later, however there are several reactor design principles (see below) which we have followed and which we believe are important to the growth of abrupt heterointerfaces and thin layers.

In a typical growth sequence for a quantum well laser the flows of trimethyl gallium (TMG) and arsine are continuously injected into the reactor. The trimethyl aluminium (TMA1) flow (and donants) are switched between the waste line and reactor as required, see figure 1.

![Fig.1 Schematic diagram of the gas panel of the system](image-url)
In our low pressure OMSVPE system, shown in figure 1, the source gases are carried by hydrogen at a total flow rate of 18 \( \text{m}^3\text{y} \) (all flow rates are measured at 1 Atm.). The time taken for gas to travel between an organometallic bubbler and the reactor tube is approximately 0.1 sec, which at our typical growth rate of 300 \( \text{min}^{-1} \) represents an interface thickness of less than one monolayer. Thus if this is the limiting process, an interface thickness of one monolayer is theoretically possible. In a real system, however, as described below, the design of the gas handling system and the flow dynamics in the reactor tube can control the abruptness of the interface.

In our gas handling system the OM bubblers are opened into the waste line, to allow the gas flow through the bubbler to stabilise, before directing it to the reactor. The waste line and reactor line impedances are approximately the same so that when the TMAl flow is switched from waste line to reactor, for the growth of a GaAs/GaAlAs heterojunction, there is no transient change in the flow through the TMAl bubbler. Thus the desired step change in composition of the gas is achieved. This method is felt to be superior to that where the output of the OM bubbler is directly connected to the reactor line and heterojunctions are achieved by opening and shutting the bubbler. In this case the transient flow which occurs at the opening of the bottle, even when the flow is controlled by a mass flow controller, will be reflected in an overshoot of composition (e.g. an aluminium "spike") at the start of the GaAlAs layer.

At the end of a GaAlAs layer, when the TMAl flow is switched from the reactor line to the waste line, the TMAl mole fraction in the gas arriving at the reactor tube will fall rapidly providing there are no "dead spaces" or unswept volumes in the reactor line. If a "dead space" exists then during the growth of the GaAlAs layer it will slowly burn TMAl vanour by diffusion. When the main flow of TMAl is switched off at the reactor line at the end of the layer, the TMAl stored in the dead space will slowly diffuse into the reactor line causing a thick heterointerface. For this reason we have minimised the volume of dead space in the construction of the reactor shown in figure 1.

When growing a heterointerface between GaAlAs and GaAs, where \( x \neq y \neq 0 \), the interface width will probably be limited by the response time of the TMAl mass flow controller (MFC) if a continuous growth is used. In our system the MFC response time is typically 5 secs which represents an unacceptably large interface thickness of 25 \( \text{Å} \), therefore, we stop the growth during the time required for the MFC on the TMAl line to stabilise, by switching the TMG and TMAl flows into the waste line.

Attention to the gas panel design therefore allows an effectively instantaneous change of composition in the gas arriving at the reactor tube. Even in this case, however, the interface may be far from abrupt due to grading effects which arise from mixing in the reactor tube.

Let us consider the situation inside the reactor tube during the growth of a GaAs (first layer)/GaAlAs (second layer) heterointerface. The step change of TMAl mole fraction can be considered as a wavefront of TMAl, which on entering the reactor tube will either remain intact, in the case of a perfectly laminar flow in the reactor, or will be diluted by mixing with the gas ahead of the wavefront, by diffusion, convection or turbulence.

Therefore, in the case of a perfectly laminar flow we would predict that the interface width will be of the order of 1 monolayer while in the case of non-laminar flow the interface width will depend on the extent of mixing. In figure 2 we have computed the change in TMAl mole fraction in the gas phase as a function of time, for various cases of mixing. At 100 % mixing the total reactor volume of 12 litres dilutes the incoming gas, while for lower values of mixing the flow tends towards a laminar gas flow and an abrupt interface.
In our horizontal low pressure system the gas flow is fast but laminar in the vicinity of the susceptor (2). There is, however, probably some turbulence near the reactor entrance due to the higher gas speed in this region.

The laser structures which we have studied are shown in figure 3. Figure 3a shows the separate confinement heterostructure (SCH) laser in which we have varied the quantum well active layer thickness between 60 Å and 400 Å. Figure 3b shows the GRIN-SCH laser structure which has been grown with a range of active layer thicknesses and outer confinement layer compositions. As described previously (5) we approximated the linear change of aluminium fraction by a series of small steps grown without stopping the growth. The whole of the optical cavity, i.e. the SCH region and quantum well active layer, was undoped to reduce free carrier absorption, which is otherwise significant in these devices as the optical confinement factor (\( T_0 \)) is generally low.

4. Results

The laser slices were characterised by fabricating conventional cleaved and sawn broad-area lasers on an area of 0.5 cm² of the growth slice (total area 8 cm² to 12 cm²).

To date the lowest threshold current densities have been obtained in a GRIN-SCH structure, see figure 3b, in which the aluminium fraction in the outer confinement layers was 0.6. The characteristics of this structure are shown in figure 4. Despite the high aluminium fraction (Ga0.4 Al0.6 As) the forward voltage is only slightly higher (1.9 V compared to 1.2 to 1.5 V) than that of devices with outer confinement layers of Ga0.65 Al0.35 As. The structure displays a very low threshold current density, of 232 A cm⁻² for a cavity length of 413 µm, which reduces to 121 A cm⁻² at a length of 1788 µm.

Furthermore the carrier confinement is efficient as reflected by the good \( T_0 \) value of 150 K, and a high internal efficiency which was calculated to be between 80% and 100% (6).
The emission wavelength of this and other structures with thicker active layers, is shown in figure 5, where we have plotted the emission wavelength at below the lasing threshold in order to avoid the wavelength shifts due to bandfilling. The curves shown in figure 5 are the calculated emission wavelengths \((\lambda)\) for recombination between electrons in the quantised conduction band and either light holes (Lh) or heavy holes (hh), in a GaAs potential well bounded by barriers of 250 meV. The agreement between the experimentally measured and predicted wavelengths is reasonable, considering that the growth time of a 60 Å layer is only 12 secs, and it would appear that the quantum well thickness is within 10% of the value estimated from the growth rate of thicker layers. Further this suggests that the interface abruptness at the heterojunction between Ga\(_{0.82}\)Al\(_{0.18}\)As and GaAs, see figure 3, is less than 10 Å.

The use of the spectral characteristics to calibrate the well thickness (and grading) has so far given more reliable results than the direct technique of composition measurement by Auger spectroscopy. Several Auger profiling techniques were tried but the best resolution of 40 Å, obtained by tracking a small Auger soot down a chemically etched bevel \((q)\) with an angle of only 0.057°, was too high to be useful in the assessment of quantum well structures.

At higher levels of current drive the emission wavelengths shown in figure 5 decreased but in all cases we were unable to detect emission corresponding to recombination involving electrons from the second level \((n = 2)\) of the quantum well conduction band.

Conclusions

We have described the reactor design principles which we believe are important for the growth of abrupt heterojunctions in quantum well lasers.

It is shown that in spite of the very thin active region a very low
FIG. 4: CHARACTERISTICS OF BEST GRIN-SCH

FIG. 5: EMISSION WAVELENGTH (JUST BELOW THRESHOLD) AS A FUNCTION OF ACTIVE LAYER THICKNESS
threshold current density can be achieved (232 A cm$^{-2}$ for a chip length of 413 µm) while maintaining good thermal and electrical characteristics.

The spectral emission from these lasers has been used to calibrate the thickness of the quantum wells and it can be inferred that the interface abruptness in these lasers is less than 10 Å.

References