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Theory and optimisation of 1.3 and 1.55 μm (Al)InGaAs metamorphic quantum well lasers

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***Abstract*—The use of InGaAs metamorphic buffer layers (MBLs) to facilitate the growth of lattice-mismatched heterostructures constitutes an attractive approach to developing long-wavelength semiconductor lasers on GaAs substrates, since they offer the improved carrier and optical confinement associated with GaAs-based materials. We present a theoretical study of GaAs-based 1.3 and 1.55 μm (Al)InGaAs quantum well (QW) lasers grown on InGaAs MBLs. We demonstrate that optimised 1.3 μm metamorphic devices offer low threshold current densities and high differential gain, which compare favourably with InP-based devices. Overall, our analysis highlights and quantifies the potential of metamorphic QWs for the development of GaAs-based long-wavelength semiconductor lasers, and also provides guidelines for the design of optimised devices.**

I. INTRODUCTION

Metamorphic growth of semiconductor heterostructures – in which a "virtual" substrate with a desired lattice constant is obtained by growing a lattice-mismatched MBL on a conventional substrate such as GaAs – is attracting increasing interest due to its potential to facilitate the development of improved optoelectronic and photovoltaic technologies. Of particular interest is the use of metamorphic growth techniques to develop GaAs-based semiconductor lasers operating at the technologically important 1.3 and 1.55 μm wavelengths [1]. By growing a relaxed InGaAs MBL on a GaAs substrate heterostructures can be grown with a lattice constant intermediate between those of GaAs and InP, providing enhanced scope for device design and optimisation.

1.3 and 1.55 μm QW lasers are typically grown on InP substrates and are based on the InGaAsP or AlInGaAs quaternary alloys. While AlInGaAs/InP devices demonstrate improved temperature stability compared to their InGaAsP counterparts, uncooled operation has yet to be realised in practical applications and there remains a drive to improve the performance of semiconductor lasers at these technologically important wavelengths. The development of long-wavelength lasers on GaAs enables exploitation of the improved carrier and optical confinement offered by AlInGaAs heterostructures. GaAs substrates are also attractive due to their flexibility – e.g. the potential to monolithically integrate photonic devices with GaAs-based microelectronics – and are of lower cost than InP substrates, making the development of GaAs-based devices appealing from a commercial perspective. Recently, significant progress has been made in the development of GaAs-based metamorphic QW lasers. Wu et al. [2] have demonstrated room temperature operation of a 1.3 μm AlInGaAs device having a low threshold current density $J_{\text{th}} = 205$ A cm^{-2}, while Arai et al. have demonstrated uncooled operation at 10 Gb s^{-1} up to 85°C [3], and operation at 200°C with a high characteristic temperature $T_0 = 220$ K [4].

Despite significant progress in materials growth and device engineering, there has, until now, been no detailed theoretical investigation of metamorphic QW lasers. We present a comprehensive analysis of the properties and performance of GaAs-based 1.3 and 1.55 μm (Al)InGaAs QW lasers grown on InGaAs MBLs. Firstly, we identify (i) the ranges of strain and wavelength accessible to pseudomorphically strained AlInGaAs alloys on InGaAs MBLs, and (ii) alloy compositions of interest for the design of the laser active region. Secondly, we perform a detailed analysis and optimisation of a series of 1.3 and 1.55 μm metamorphic QW laser structures. We focus primarily on laser structures containing compressively strained ternary InGaAs QWs with unstrained (Al)InGaAs barriers, and study these novel heterostructures by varying the alloy composition, strain and QW thickness in order to optimise the device performance. This enables us to quantify the properties of GaAs-based metamorphic QW lasers, to identify general trends in their gain and threshold characteristics, and to recommend optimised laser structures for improved performance. Full details of this analysis can be found in Ref. [5].

II. THEORETICAL MODEL

Our theoretical model for metamorphic QW lasers is based on an 8-band $\mathbf{k}\cdot\mathbf{p}$ Hamiltonian, which explicitly includes the effects of strain, spin-orbit coupling and band mixing on the electronic structure of AlInGaAs alloys grown on InGaAs MBLs. Our calculations of the QW band structure and eigenstates employ a numerically efficient plane wave approach, and our calculations of the QW optical spectra use the QW eigenstates directly in the computation of the optical transition matrix elements, so that all key band structure effects are incorporated explicitly in our analysis of the laser properties.

Using the calculated variation of the peak material gain with carrier density, and by evaluating the optical confinement and temperature-dependent radiative and Auger currents directly for each laser structure, we compute the threshold current density (J_{th}) and differential gain at threshold ($\frac{\text{d}g}{\text{d}n}$). We then identify optimised laser structures by varying the alloy composition, strain and QW thickness in order to optimise the device performance by respectively minimising and maximising J_{th} and $\frac{\text{d}g}{\text{d}n}$, thereby identifying efficient devices that offer high-speed performance at low injection currents [5].

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III. RESULTS

Firstly, we have used our theoretical model to identify the ranges of strain and wavelength accessible to pseudomorphically strained (Al)InGaAs alloys grown on InGaAs MBLs. Fig. 1 summarises part of this analysis, and demonstrates that the use of an InGaAs MBL considerably reduces the strain required to obtain 1.3 and 1.55 μm emission compared to using compressively strained InGaAs QWs grown on GaAs substrates. We note that InGaAs MBLs having In compositions $\gtrsim 20\%$ allow for 1.3 and 1.55 μm emission in InGaAs QWs having strains $\lesssim 2\%$, so that it should be possible to obtain high-quality strained QWs using this growth platform. Further analysis of the band structure of strained AlInGaAs quaternary alloys suggests that the permissible growth combinations for 1.3 and 1.55 μm metamorphic laser structures are compressively strained ternary InGaAs QWs, having unstrained or tensile strained ternary or quaternary (Al)InGaAs barriers [5].

Secondly, we have (i) calculated the properties of a series of 1.3 and 1.55 μm metamorphic laser structures, and (ii) identified optimised laser structures having low J_{th} and high $\frac{\mathrm{d}g}{\mathrm{d}n}$. Our calculations indicate that optimised metamorphic laser structures have the potential to offer (i) threshold current densities (differential gains) which are lower (higher) than those than can be obtained in InP-based devices at the same wavelengths, and (ii) high differential gains equivalent to those that one would expect to obtain in InGaAs QWs grown on GaAs substrates [5]. Further analysis has indicated that the performance of these laser structures is, in part, governed by a trade-off between the carrier and optical confinement, which can be engineered in order to optimise the threshold characteristics through incorporation of Al in the barrier layers to form structures consisting of compressively strained InGaAs QWs and quaternary AlInGaAs barriers.

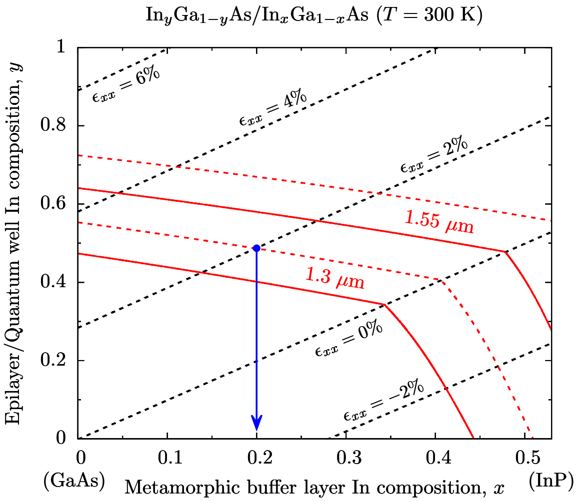

Fig. 1. Composition space map showing the calculated variation of the in-plane strain (ϵ_{xx}) and strained bulk and QW band gaps for $\text{In}_y\text{Ga}_{1-y}\text{As}$ grown pseudomorphically on an $\text{In}_x\text{Ga}_{1-x}\text{As}$ MBL. Dashed black and solid red lines denote, respectively, alloy compositions for which ϵ_{xx} and the $\text{In}_y\text{Ga}_{1-y}\text{As}$ strained bulk band gap are constant. The dashed red line above each solid red line denotes alloy compositions for which the bulk band gap of the $\text{In}_y\text{Ga}_{1-y}\text{As}/\text{In}_x\text{Ga}_{1-x}\text{As}$ QW material is constant, so that the QW emission wavelength is the same as that denoted by the solid red line below. The closed blue circle and vertical arrow show that an $\text{In}_y\text{Ga}_{1-y}\text{As}$ QW with an emission wavelength of 1.3 μm can be grown with 2% compressive strain on an $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ MBL. (See Ref. [5] for details.)

Our analysis has also enabled us to draw conclusions regarding the impact on the performance of existing devices of defect-related recombination, a known issue in metamorphic heterostructures due in large part to the prevalence of threading dislocations [1]. Our calculations of J_{th} as a function of temperature suggest that the temperature dependence of radiative and Auger recombination in GaAs-based metamorphic laser structures is broadly comparable to that in conventional InP-based devices. This suggests that the large values of T_0 measured for some devices are likely to be attributable to defect-related recombination, which is relatively insensitive to temperature and will, when it accounts for a large portion of J_{th}, tend to artificially enhance T_0 for the device. This suggests that significant reductions in J_{th} can be expected to result from refinements in the growth of metamorphic heterostructures, but at the cost of also reducing T_0. Our analysis also indicates that optimised 1.3 and 1.55 μm lasers grown on InGaAs MBLs require a small number of QWs, typically $\lesssim 3$, which is lower by approximately a factor of two than the number required in InP-based devices operating at the same wavelengths [5].

IV. CONCLUSION

We have presented a theoretical investigation and optimisation of the properties and performance of GaAs-based 1.3 and 1.55 μm metamorphic QW lasers grown on InGaAs MBLs. Beginning with a consideration of the strained AlInGaAs band structure we demonstrated that there is large scope for the design of 1.3 and 1.55 μm metamorphic QW lasers, using compressively strained ternary (InGaAs) or quaternary (AlInGaAs) QWs with unstrained or tensile strained ternary or quaternary barriers. Through a detailed analysis of a series of ideal laser structures, we have demonstrated that the use of InGaAs MBLs has the potential to deliver GaAs-based 1.3 and 1.55 μm semiconductor lasers whose calculated performance is competitive with, and in some cases exceeds, that of optimised InP-based devices at the same wavelengths.

Overall, our theoretical analysis has identified important trends in the performance of GaAs-based metamorphic QW lasers, has provided design parameters for optimised laser structures, and has confirmed the promise of these novel heterostructures for the development of high performance GaAs-based 1.3 and 1.55 μm semiconductor lasers.

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