AlGaInP quantum well based 610 nm metamorphic LEDs as efficient red light emitters

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***Abstract*—In order to maximise white light LED efficiency a phosphor-free RGB design is required with a red light-emitting diode (LED) emitting at 614 nm. The external quantum efficiency (EQE) of conventional red emitters grown on GaAs decreases rapidly at shorter wavelengths. This is primarily due to an increase in electron thermal leakage into the barrier with increasing emission energy, with the reduced electron confinement in the active region also contributing to the decreasing EQE. We propose that growing an AlGaInP quantum well LED structure on a lattice-mismatched $\mathrm{In}_z\mathrm{Ga}_{1-z}\mathrm{As}$ metamorphic buffer layer (MBL) on GaAs offers enhanced scope for bandstructure engineering. Our calculations show that the barrier band gap energy can initially be increased with increasing In composition z, reducing current leakage, while electron confinement at a fixed wavelength may also be increased, leading to an increase in the radiative recombination rate at a given carrier density.**

I. INTRODUCTION

Light-Emitting Diodes (LEDs) that produce white light for solid state light applications conventionally include a blue LED capped with green and red phosphors in the $\mathrm{R_BG_BB}$ design. In order to reduce package losses and energy losses associated with the Stokes shift in the deep red wavelength range, a phosphor-free RGB design, based only on semiconductor emitters, has been proposed to maximize LED spectral efficiency [1]. As part of this design a narrow linewidth red emitter with 614 nm emission wavelength is required.

Red semiconductor emitters can be grown using III-N and III-P (on GaAs) based heterostructures. Although III-N alloys are mostly deployed for green and blue light sources, the best performing InGaN-based red LED was recently demonstrated with 1.1 mW light output power at 20 mA input current [2]. Because high In content is required to produce a III-N based red emitter, the resulting built-in and strain-induced piezoelectric fields strongly suppress the radiative recombination rate, with the device ultimately having a very small external quantum efficiency (EQE) (2.9 %). Unlike with III-N materials, the piezoelectric field can be completely avoided in III-P heterostructures, due to their zinc-blende crystal structure. AlGaInP-based heterostructure are, therefore, a more attractive alternative for shorter wavelength red emitters, enabling a much higher EQE at high power operation [3].

The strong blueshift of the 614 nm emission compared to that in conventional 630 - 650 nm emitters brings a decreased EQE, mainly associated with the increased thermal leakage of electrons from the active region due to the reduced electronic confinement. Photoluminescence measurements we performed on a series of devices support that the electrons are weakly confined in the quantum well (QW). The fundamental limitation for the electron confinement and the threshold for current leakage is associated with the direct-to-indirect band gap crossover in III-P alloys which occurs at around 2.3 eV at 300 K. One approach that was used to addresses this issue includes the incorporation of numerous QWs in the active region [4].

In this work we investigate the electronic and optical properties of AlGaInP QW-based shorter wavelength red LEDs grown on a lattice-mismatched InGaAs metamorphic buffer layer (MBL) on GaAs, focusing on device optimisation for 610 nm emission. Our previous work has shown that the incorporation of a lattice-mismatched MBL can strongly facilitate bandstructure engineering for improved device performance in 1.3 μm semiconductor lasers [5]. Here we start by identifying the range of compositions accessible for direct band gap AlGaInP grown on InGaAs MBLs, showing that growth on a MBL can allow an increase in barrier band gap energy. We then turn our attention to the electronic and optical properties where we focus primarily on AlInP QW structures surrounded by Al(Ga)InP barriers lattice-matched to the InGaAs MBL. We show that the increased barrier band gap allows reduced leakage current at a fixed emission wavelength, and discuss how band offset changes with MBL composition may also be beneficial for LED operation.

II. THEORETICAL MODEL

Our theoretical model is based upon the 8-band $\mathbf{k}\cdot\mathbf{p}$ model that explicitly includes the effects of strain, spin-orbit coupling and band mixing on the electronic structure of the AlGaInP alloys grown on the InGaAs MBLs. Our calculations of the QW band structure and eigenstates employ a numerically efficient plane wave approach [6]. We use the QW eigenstates directly in the computation of the optical transition matrix elements and the QW optical spectra. Additionally we use the one-band effective mass model, including the effects of strain, to investigate the electronic structure of the X states in the active region. We use a Schrödinger-Poisson solver to compute the self-consistent electrostatic potential generated by the spatial separation of the electron and hole charge densities due to the thermal distribution of electrons in the barrier X states. The self-consistent carrier distribution and potential is then used to compute the spontaneous emission spectrum as a function of injected carrier density.

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III. RESULTS

Firstly, we use our theoretical model to identify the range of compositions accessible for a direct band gap AlGaInP grown on InGaAs MBLs. We assume the indirect energy gap in AlP at 300 K to be 2.433 eV [7], and lies 156 meV and 210 meV above that of GaP and InP respectively [7], [8]. It can be expected that the maximum direct gap of Al(Ga)InP grown on InGaAs will be achieved for a ternary AlInP alloy, where Γ and X band gaps are degenerate. The Γ - X crossover occurs in $(\mathrm{Al}_x\mathrm{Ga}_{1-x})_{0.52}\mathrm{In}_{0.48}\mathrm{P}$ lattice-matched to GaAs at an energy of 2.26 eV [9] at 300 K. We calculate in Fig. 1 that this crossover occurs at 2.315 eV for a ternary AlInP alloy grown on an $\mathrm{In}_z\mathrm{Ga}_{1-z}\mathrm{As}$ MBL with $z = 11\%$.

Secondly, we perform a detailed analysis of the electronic and optical properties of a series of Al(Ga)InP-based devices grown with various MBL lattice constants and focus on the factors that limit the EQE of III-P-based red LEDs. We find that the barrier and cladding direct energy gap can be increased on an InGaAs substrate, which will reduce the thermal leakage current in an ideal red LED structure. The electron confinement in a given QW structure depends both on the band gap difference between the well and barrier material, and on the band offset ratio. The calculated variation of band offsets with quaternary alloy composition and strain as a function of substrate composition is sensitive to a range of parameters which are not well known, including the band gap bowing of III-P alloys. We estimate, using model solid theory, that the electrons can be more strongly confined by growing the device on an InGaAs MBL, leading also to an increased electron-hole overlap compared to growth on GaAs. At the same time, the fraction of electrons thermally distributed in the X valley, with a reduced mobility, is strongly reduced due to an increased energy separation between the Γ and X density of states. Consequently we calculate an up to 40% increase in the spontaneous emission intensity at fixed carrier density when growing the device on an InGaAs MBL instead of GaAs.

Although the use of an InGaAs MBL can strongly enhance the emission of blue shifted red LEDs, we note that the magnitude of these improvements is sensitive to the chosen set of material parameters. After analysing the data available in the literature there remain uncertainties when choosing a set of parameters which will be consistent with both theoretical and experimental reports. Thus our calculations provide an estimate of the potential improvements, and also provide motivation to investigate the electronic structure of AlGaInP in more detail.

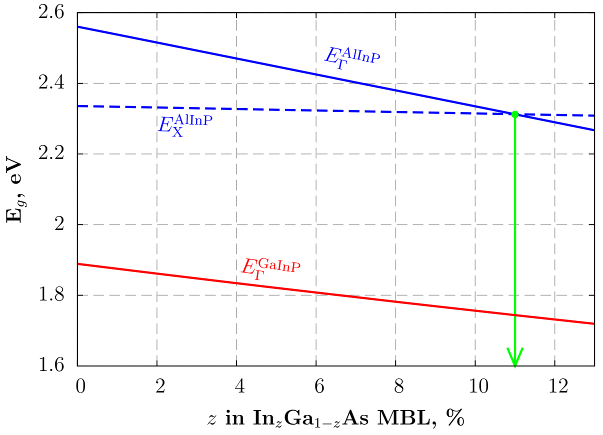

Fig. 1. Calculated variation of the bulk band gap in AlInP and GaInP at 300 K grown pseudomorphically on an $\mathrm{In}_z\mathrm{Ga}_{1-z}\mathrm{As}$ MBL. Solid and dashed lines denote the band gap of the Γ and X conduction states respectively, while the blue lines correspond to AlInP, and the red line corresponds to GaInP. The closed green circle and the vertical arrow show that AlInP can be grown with a direct band gap up to $z = 11\%$ on an $\mathrm{In}_z\mathrm{Ga}_{1-z}\mathrm{As}$ MBL at 300 K.

Finally, we describe how micro-photoluminescence (μPL) measurements performed on comparable AlGaInP QW-based structures show an improvement in photoluminescence quantum yield by growing the structure on an InGaAs MBL.

IV. CONCLUSIONS

We present a theoretical investigation of 610 nm Al(Ga)InP based emitters grown on $\mathrm{In}_z\mathrm{Ga}_{1-z}\mathrm{As}$ MBLs on GaAs. We show that it is possible to increase the barrier energy gap with increasing z, up to $z \sim 10\%$, by growing a ternary AlInP barrier layer with a direct energy gap, which is larger compared to AlGaInP alloys grown on GaAs. This is expected to reduce both electron thermal leakage from the active region and may also reduce the radiative lifetime, consistent with μPL measurements we have performed on comparable devices. The calculated reduction in radiative lifetime is associated with an increased direct gap conduction band offset, but we note that there remains uncertainty in the calculated variation of band offsets as the MBL composition is varied. Overall our analysis highlights the benefits of short wavelength Al(Ga)InP-based emitters grown on an InGaAs MBL, while also indicating that further analysis is required to reduce the uncertainty in some of the material parameters used to describe AlGaInP quaternary alloys grown on InGaAs.

REFERENCES

[1] J. Y. Tsao, M. E. Coltrin, M. H. Crawford, and J. A. Simmons, "Solid-state lighting: An integrated human factors, technology, and economic perspective," *Proceedings of the IEEE*, vol. 98, pp. 1162–1179, 2010.

[2] J.-I. Hwang, R. Hashimoto, S. Saito, and S. Nunoue, "Development of InGaN-based red led grown on (0001) polar surface," *Applied Physics Express*, vol. 7, no. 7, p. 071003, 2014.

[3] M. R. Krames, O. B. Shchekin, R. Mueller-Mach, G. O. Mueller, L. Zhou, G. Harbers, and M. G. Craford, "Status and future of high-power light-emitting diodes for solid-state lighting," *Journal of Display Technology*, vol. 3, no. 2, pp. 160–175, 2007.

[4] J.-I. Shim, D.-P. Han, H. Kim, D.-S. Shin, G.-B. Lin, D. S. Meyaard, Q. Shan, J. Cho, E. F. Schubert, H. Shim, and C. Sone, "Efficiency droop in AlGaInP and GaInN light-emitting diodes," *Applied Physics Letters*, vol. 100, no. 11, p. 111106, 2012.

[5] S. Bogusevschi, C. A. Broderick, and E. P. O'Reilly, "Theory and optimization of 1.3-μm metamorphic quantum well lasers," *IEEE Journal of Quantum Electronics*, vol. 52, no. 3, pp. 1–11, March 2016.

[6] E. P. O'Reilly, O. Marquardt, S. Schulz, and A. D. Andreev, *Plane-Wave Approaches to the Electronic Structure of Semiconductor Nanostructures*. Springer International Publishing, 2014, pp. 155–189.

[7] A. Onton and R. J. Chicotka, "Conduction bands in $\mathrm{In}_{1-x}\mathrm{Al}_x\mathrm{P}$," *Journal of Applied Physics*, vol. 41, no. 10, pp. 4205–4207, 1970.

[8] P. J. Dean, G. Kaminsky, and R. B. Zetterstrom, "Intrinsic optical absorption of gallium phosphide between 2.33 and 3.12 ev," *Journal of Applied Physics*, vol. 38, no. 9, pp. 3551–3556, 1967.

[9] A. T. Meney, D. Prins, A. F. Phillips, J. L. Sly, E. P. O'Reilly, D. J. Dunstan, A. R. Adams, and A. Valster, "Determination of the band structure of disordered algainp and its influence on visible-laser characteristics," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 1, no. 2, pp. 697–706, 1995.