1.52 μm electroluminescence from GaAs-based quantum dot bilayers


InGaAs strain reducing layers (SRLs) are applied to InAs bilayer quantum dot layers (QDs) grown by molecular beam epitaxy on GaAs substrates. By control of the QD size and density and the composition of the SRLs, peak ground state electroluminescence of up to 1.52 μm is demonstrated from devices incorporating five QD bilayers, without the need for a metamorphic buffer layer.

Introduction: Over recent years, considerable effort has been invested in developing 1.3 μm lasers based on InAs/InGaAs quantum dots (QDs) to the point of their current commercialisation [1–3]. One of the main application areas is in optical communications. For GaAs-based quantum dot heterostructures, many of their features (low cost, zero chirp, temperature insensitivity, and single photon emission) are particularly attractive at 1.55 μm. There is therefore continuing interest in extending the emission wavelength to this region. To date, there have been only isolated reports of photoluminescence emission in excess of 1.5 μm on GaAs substrate, for example by capping InAs/GaAs QDs grown by metal organic chemical vapour deposition with a high In composition InGaAs strain-reducing layer (SRL) [4, 5], capping with SRLs containing N or Sb [6, 7], and growing large QDs on nano-patterned substrates [8]. Room temperature electroluminescence (EL) and lasing at 1.515 μm has been demonstrated by growing InAs QDs on an InGaAs metamorphic buffer [9], however repeatability and reliability are issues for commercialisation of such structures. In this Letter, we demonstrate room temperature EL at 1.52 μm without the need of an InGaAs metamorphic buffer layer, from devices incorporating QD bilayers [10] capped by InGaAs SRLs. Such structures are a promising approach for the realisation of GaAs-based QD devices in the 1.55 μm region.

Experiment: The samples were PIN edge-emitting laser structures grown on n+ GaAs(100) substrates by molecular beam epitaxy. The active region for the structures was located in a 500 nm undoped GaAs layer sandwiched between 1500 nm Al0.33Ga0.67As doped cladding layers, with a 400 nm p-type GaAs:Be contact layer completing the structure. The active region consisted of five GaAs-capped or InGaAs-capped QD bilayers, each separated by 50 nm GaAs, as shown in the transmission electron microscopy (TEM) image in Fig. 1. Each bilayer consists of two closely-spaced InAs/GaAs QD layers: a seed layer and an upper emission layer. Strain fields from the underlying QDs in the seed layer penetrate the thin GaAs spacer layer (10 nm between QD layers), providing preferential nucleation sites for QDs in the second layer. This leads to a high degree of vertical correlation between QDs in the two layers (as observed in the TEM image in Fig. 1) [11], such that the seed layer acts as a template for growth in the second layer, fixing the QD density in this layer over a wide range of growth conditions. By reducing the growth temperature for the second layer to suppress In/Ga intermixing, large, In-rich QDs can be formed with ground state (GS) emission from GaAs-capped bilayers of up to 1400 nm at room temperature, which can be extended to beyond 1500 nm by capping the QDs with an SRL [12]. Samples A and B were grown to investigate the effect of the SRL on laser performance, and for these samples the seed layer was grown at a temperature of 480 °C by the deposition of 2.4 ML of InAs at a growth rate of 0.014 MLs⁻¹, giving a QD density of 2.7 × 10¹⁰ cm⁻². The seed layer QD was capped by 10 nm of GaAs spacer layer, also grown at 480 °C, before the temperature was raised to 580 °C for 10 min to smooth the growth surface and desorb segregated indium. The emission layer was then grown at a reduced temperature of 467 °C by the deposition of 3.3 ML of InAs at the same growth rate as for the seed layer. For sample A, the QDs were then capped with 15 nm of GaAs, whereas the second QD layers in sample B were capped by an SRL of 4 nm In0.18Ga0.82As followed by 11 nm GaAs, also at 467 °C, after which the temperature was ramped to 580 °C for subsequent GaAs growth. The growth conditions for the QD bilayers in sample C were chosen to provide the greatest extension of the emission wavelength: for this sample, the seed layer was grown at a higher temperature of 505 °C, which yields a low density (7 × 10⁹ cm⁻²) of larger QDs, leading to a concomitant increase in the size of the QDs in the second layer [12]. The In composition of the SRL was also increased, so that the second layer QDs were now capped by 4 nm In0.26Ga0.74As. Wafers were processed into broad area lasers (7 to 100 μm width) and characteristics were measured in the pulsed regime (5 μs pulsed duration, 1% duty cycle) to minimise thermal effects. All measurements were performed at a tile temperature of 298 K.

Results and discussion: Fig. 2a shows edge-emission EL spectra with increasing current density (70–350 A/cm²), obtained from a device fabricated from sample A where lasing is inhibited (device length 1 mm). Emission at 1.34 and 1.26 μm for the GaAs-capped samples is attributed to emission from the GS and first excited state (X1) of the second layers. There is an extension of the GS and X1 emission conditions from sample B. There is an extension of the GS and X1 emission from the SE layer QDs grown under these conditions is at ~1.20 μm and a small peak at this wavelength is only observed at high bias for sample A. The suppression of emission from these QDs in all samples indicates that there is efficient electronic coupling between the QD layers in each bilayer. The insets to Figs. 2a and 2b show EL lasing spectra obtained from other devices fabricated from samples A and B, respectively, at bias levels of 1.2 times the laser threshold current (Ith) for each device. Both devices exhibit lasing in the ground state, at a wavelength of 1.34 μm with Ith = 83 A/cm² for sample A (with a device length of 2 mm) and a wavelength of 1.41 μm with Ith = 360 A/cm² for

Fig. 1 Dark field 002 cross-section TEM image of active region of sample A

Fig. 2 EL spectra against current density obtained from sample A (GaAs capped QD bilayer) (Fig. 2a), sample B (In0.18Ga0.82As-capped QD bilayer) (Fig. 2b), and sample C (In0.26Ga0.74As-capped QD bilayer) (Fig. 2c)
sample B (with a device length of 8.7 mm). The increased device length required to achieve GS lasing (and corresponding increase in $J_{th}$) for sample B may be as a result of increased optical losses owing to an increase in the roughness of one of the GaAs/AlGaAs interfaces in this sample, observed by TEM (images not shown). However, the GS lasing wavelength is similar to previous reports of bilayer lasers [13], and in this case growth of the QD layers was carried out using a constant growth rate.

Fig. 2c shows EL spectra obtained from sample C against current density (20–60 A/cm$^2$). The reduction in the bias required to achieve equal intensity of emission from both GS and XI for sample C (60 A/cm$^2$) compared to samples A and B (∼350 A/cm$^2$) is unsurprising since sample C has ∼1/4 the areal density of QDs compared to samples A or B. Devices of lengths up to 8 mm (with as-cleaved facets) were tested but GS lasing was not observed, probably due to an insufficient QD density in this sample. Incorporation of more QD layers or further optimisation of the SRL for bilayers with higher QD density may allow lasing approaching 1.55 μm, offering full coverage in the O – S band, and the current growth technology is immediately applicable to saturable absorption devices such as semiconductor saturable mirror absorbers.

Conclusion: We have shown a method of extending the emission wavelength of QDs on GaAs by using a bilayer growth technique. Ground state electroluminescence at 1.52 μm is demonstrated using optimised growth conditions and using a 4 nm In$_{0.26}$Ga$_{0.74}$As SRL. Significantly, this method does not rely upon a metamorphic buffer layer.

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