InSb/AlInSb quantum-well light-emitting diodes

G. R. Nash^{a)}

*QinetiQ, Malvern Technology Centre, Malvern WR14 3PS, United Kingdom and Photonics Group,
Department of Electrical and Electronic Engineering, University of Bristol, Bristol BS8 1UB, United Kingdom*

M. K. Haigh, H. R. Hardaway, and L. Buckle

QinetiQ, Malvern Technology Centre, Malvern WR14 3PS, United Kingdom

A. D. Andreev

Department of Physics, Advanced Technology Institute, University of Surrey, Guildford GU2 7XH, United Kingdom

N. T. Gordon

QinetiQ, Malvern Technology Centre, Malvern WR14 3PS, United Kingdom

S. J. Smith

Photonics Group, Department of Electrical and Electronic Engineering, University of Bristol, Bristol BS8 1UB, United Kingdom

M. T. Emeny and T. Ashley

QinetiQ, Malvern Technology Centre, Malvern WR14 3PS, United Kingdom

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We have investigated the room-temperature electroluminescent properties of InSb/Al_xIn_{1-x}Sb quantum-well light-emitting diodes. The maximum emission from diodes containing quantum wells occurred at significantly higher energies than the band gap of InSb. Close agreement between experimental and theoretical data confirms that recombination occurs within the quantum well.

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There is growing interest in the development of InSb/Al_xIn_{1-x}Sb quantum wells (QWs) for both uncooled, low power dissipation high speed transistors,¹ and for quantum devices,² where the small InSb effective electron mass offers the prospect for room temperature operation due to enhanced quantum confinement. The large g factor (~ 51) also makes InSb QWs attractive for spintronics and quantum information processing, and the motivation of the work reported here is the realization of the surface acoustic wave (SAW) single photon source,³ using InSb/Al_xIn_{1-x}Sb QWs to give emission in the 3–5 μm wavelength region.⁴ This would enable long distance free-space secure communication, via quantum cryptography, with low atmospheric scattering and absorption.⁵ In this letter we describe InSb/Al_xIn_{1-x}Sb QW light-emitting-diodes (LEDs) which, combined with a simple technique for the fabrication of lateral diodes,⁶ represent a significant step towards the fabrication of a SAW single photon source emitting in the mid-infrared. Additionally, the LEDs described here might also find application in areas such as gas sensing.⁷

The samples studied were grown by molecular beam epitaxy at QinetiQ Malvern on semi-insulating GaAs substrates.¹ A schematic diagram of the QW LED structure is shown in Fig. 1. The InSb QWs were grown on top of a 3- μm -thick Al_xIn_{1-x}Sb barrier, and were capped with a 120-nm-thick layer of Al_xIn_{1-x}Sb. Tellurium and beryllium were used to dope the layers n type and p type to nominal levels of $2 \times 10^{17} \text{ cm}^{-3}$ and $5 \times 10^{18} \text{ cm}^{-3}$, respectively. Two different QW structures were investigated: QW1 contained a 40-nm-thick undoped InSb QW, with a barrier composition of $x = 0.077$ and QW2 contained a 20-nm-thick undoped InSb

QW with a barrier composition of $x = 0.143$. Measurements from these samples were also compared to LEDs that contained no quantum wells: B1 contained a 2- μm -thick undoped Al_xIn_{1-x}Sb active layer of similar composition to the barrier material in QW1 ($x = 0.0875$), and B2 contained a 2- μm -thick undoped InSb active layer. Further details of similar bulk LEDs can be found in Ref. 7. The composition of the Al_xIn_{1-x}Sb layers was determined by x-ray diffraction. Devices were fabricated using a series connected architecture,⁷ yielding LEDs with a total emitting area of $\sim 1 \text{ mm}^2$. These were mounted substrate side down onto standard TO2 carriers, producing top emitting devices. No antireflection coating was applied, and measurements were performed at room temperature.

Figures 2(a) and 2(b) show typical forward bias emission spectra, measured on a Fourier-transform infrared (FTIR) spectrometer using a calibrated 77 K HgCdTe detector, for samples B1 and QW1, respectively. The diodes were driven

FIG. 1. Schematic cross section showing the structure of the QW LEDs. L is the quantum well thickness.

^{a)}Electronic mail: grnash@qinetiq.com

FIG. 2. Measured room temperature emittance and spectral response of (a) bulk sample B1 and (b) quantum well sample QW1. The dashed line in (b) corresponds to the predicted emittance.

using a square waveform at 20 kHz at a peak injection current of 50 mA. The spectra were calibrated by calculating the total power emitted from the devices (driven as above) using a second calibrated detector, correcting for the collection efficiency of the optics. An identical configuration was used for each sample so that the values obtained can be compared from one sample to another. Minima in both spectra seen at around 292 meV are due to CO₂ absorption, whereas the large minimum seen in the QW1 spectrum at 216 meV is due to water absorption. The measured emittance maximum, M_{peak} , occurs at significantly different energies for the two samples; 325 meV $\pm$ 5 meV for B1 and 228 meV $\pm$ 5 meV for QW1. The latter is also considerably larger than the energy at which M_{peak} occurs for the InSb sample B2 [Fig. 3(a)], sug-

FIG. 3. Measured room temperature emittance and spectral response of (a) bulk sample B2 and (b) quantum well sample QW2. The dashed line in (b) corresponds to the predicted emittance.

gesting that emission in QW1 is due to recombination within the InSb quantum well. The emission from QW1 between approximately 300 and 350 meV is thought to be from the Al_xIn_{1-x}Sb barrier. Also shown in Fig. 2 are the typical spectral responses of B1 and QW1, which were measured at zero applied bias using the FTIR spectrometer, and calibrated by measuring the integrated response of the device to a known 500 K blackbody source. The photodetector quantum efficiency, which is defined as the percentage of photons detected, has a peak of $\sim$ 16% at 440 meV for B1, and $\sim$ 19% at 480 meV for QW1. The spectral responses of the two samples above energies around 300 meV are broadly similar, as expected, with the differences probably due to differences in transmission through the layers above the active layer (B1 and B2 contain a 1 μ m thick, rather than 100 nm, heavily doped *p*-type layer above the active layer). However, although the response from B1 approaches zero at energies below 300 meV, there is a clear response from QW1 between 200 and 300 meV. This overlaps with the emission spectrum from the same sample and suggests that absorption is taking place within the quantum well.

Figures 3(a) and 3(b) show the measured forward bias emission spectra, and spectral response, of samples B2 and QW2, measured as described earlier. M_{peak} occurs at a much greater energy for sample QW2 (236 meV $\pm$ 5 meV) than for sample B2 (194 meV $\pm$ 5 meV), and the response of QW2 [Fig. 3(b)] also extends to much lower energies than would be expected if the sample contained no quantum well (the band gap of the barrier material in this sample is $\sim$ 450 meV at room temperature). The dashed lines shown in Figs. 2(b) and 3(b) are the spontaneous emission spectra of QW1 and QW2 modeled using 8×8 k $\cdot$ p theory with strain taken into account.⁸ Reasonable values of injected carrier densities (4×10^{11} cm⁻² for both samples), and a commonly used value of inhomogeneous broadening (20 meV at room temperature)⁸ were chosen to compare the calculated and measured spectra for both samples. The aim of these calculations was to compare the energy positions of the experimental and modeled emission peaks, to confirm that emission was from confined levels within the quantum well, and to calculate the ratio of emittances from the two samples. Absolute values of emittance were not calculated at this stage. The two modeled spectra were therefore scaled by the identical amount to fit on the same graphs as the measured data. The calculated energies of the emission peak are in good agreement with the experimental data for both samples, confirming that recombination is taking place within the quantum wells. For QW2 (20 nm well) the emission peak corresponds to the optical transition between the ground electron and hole levels, which is not the case for QW1 (40 nm well) for the same injected carrier density. In the calculated emission spectrum for QW2 there is also a shoulder at around 300 meV, which is due to the lowest energy excited transition. This shoulder, although heavily masked by the CO₂ absorption, can be also seen in the experimental data, indicating that the model is able to accurately predict the energies of both the ground and excited state emission peaks. Finally, the calculated ratio of 2.86 between the emittance peaks from QW1 and QW2 is in good agreement with the experimental value of approximately 2.3, with the narrower well giving the larger emittance peak in both cases.

The total integrated emission from samples QW1 and QW2 was calculated as 3.1 and 5.3 mW/cm², respectively

FIG. 4. Measured integrated emittance as a function of forward bias current for all four samples.

(these values have an unknown systematic error estimated to be in the range $\pm 20\%$), corresponding to external quantum efficiencies of 1.4×10^{-4} for QW1 and 2.4×10^{-4} for QW2. The internal quantum efficiencies can be estimated by multiplying the external efficiencies by $n(n+1)^2$, where n is the refractive index of the active layer (3.96 for InSb, 3.88 for $\text{Al}_{0.088}\text{In}_{0.912}\text{Sb}$), yielding values of 0.9% and 1.6% for samples QW1 and QW2, respectively. The higher values of both integrated emission and efficiencies obtained for QW2, which has the thinnest quantum well and highest barriers, might be expected due to better spatial confinement of the injected carriers. The total integrated emission from samples B1 and B2 was calculated to be 4.0 and 7.2 mW/cm^2 , which are comparable to measurements on similar diodes,⁷ with corresponding external/internal efficiencies of $3.2 \times 10^{-4}/2.0\%$ and $3.6 \times 10^{-4}/2.4\%$. These are of the same order of magnitude as the QW devices, although direct comparison between the bulk and QW samples is difficult due to their different structures. In particular, significant absorption of the emitted light within the $1\text{-}\mu\text{m}$ -thick top p -type layer is expected in the bulk samples.⁹ Finally, in Fig. 4 typical integrated emittances are plotted as a function of forward bias current. The output of the bulk InSb LED (B2) has a near linear dependence on current (at these levels) as seen previously in similar devices.¹⁰ The output of sample QW1 turns

over at currents above ~ 30 mA, whereas the outputs of B1 and QW2 show a superlinear dependence on current, with the output of QW2 showing the most dramatic increase with increasing current. Further experiments are underway to investigate the dominant recombination mechanisms in these samples, and also the possible effects of thermal carrier escape from the quantum wells, in order to understand the observed dependence of the emittance on current.

In conclusion, we have observed electroluminescence from single $\text{InSb}/\text{Al}_x\text{In}_{1-x}\text{Sb}$ QW LEDs. This confirms the high-quality of the materials growth and strengthens the prospect that these quantum wells will find application in device concepts such as the SAW single photon source.

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