



Magneto-Electroluminescence Studies of a Coupled Quantum Dot – Quantum Well Structure in the InAs/InSb/GaSb System

Petchsingh C.* [a], Shields P. A. [b], Bumby C. W. [b], Li L. J. [b], and Nicholas R. J. [b]

[a] Department of Physics, Thammasat University, Klongluang, Patumtani, 12121, Thailand

[b] Department of Physics, Oxford University, Clarendon Laboratory, Parks Rd., Oxford, OX1 3PU, U.K.

*Author for corresponding, e-mail : cattleya@tu.ac.th

ABSTRACT

Low temperature electroluminescence is performed on InAs/InSb/GaSb structures under varying magnetic field. The samples studied consist of a single narrow InAs quantum well (QW) grown below a layer of InSb quantum dots (QDs) separated by an undoped GaSb spacer layer whose thickness is varied. Electroluminescence in the region of 1.7-2.6 μm is observed in this system and is believed to be associated with electronic coupling of wavefunctions through the intervening spacer layer between the dots and the well. Magneto-electroluminescence measurements are performed at 2 K in a 21-Tesla VTI cryostat with pumping currents of 5-100 mA and continuous magnetic field perpendicular to the sample plane. The experimental results show apparent shifts of the emission energy with a dependence on magnetic field, providing evidence that the emission energy can be ascribed to strain-mediated correlation of the localised states in the system.

Keywords: InAs Quantum well, InSb Quantum dot, magneto-electroluminescence, Mid-infrared emission.

1. INTRODUCTION

InSb QDs in GaSb matrix have been shown to efficiently emit in the mid-infrared with energies around 0.70-0.74 eV [1,2]. Magneto-luminescence studies of such a system have further revealed that there is substantial penetration of the electron wave function into the barrier and the system properties are dominated by the barrier material [3]. This allows for inter-dot communication, both laterally and in growth direction, and allows the opportunity to explore coupling between different nanostructures even with different dimensionality. Our scheme here includes a layer of InAs QW in order to add more emission wavelength tuning flexibility to the previous QD system. The InAs QW

neighbouring the QDs results in a strongly confined electron state and a localized hole in the QDs. In the recent studies on a variety of samples with different separations of QW and QDs [4], it was shown that electroluminescence was possible at room temperature and the emission energies could be influenced by the thickness of the intervening layer. In particular the QD growth was strongly dependent on the nature of the surface on which the dots were grown, with it being sensitive to single monolayer of a different material. This work extends the above studies to include the effects of perpendicular magnetic field in order to trace transitions pairs that could be the cause of the mid-infrared emission.

2. EXPERIMENTAL DETAILS

The samples were grown onto nominally undoped and n-doped (100) GaSb substrates in a horizontal MOVPE growth reactor at atmospheric pressure using trimethylallium (TMGa), trimethylindium (TMIIn), trimethylantimony (TMSb) and tertiarybutylarsine (tbAs) as chemical precursors. Table I lists the samples used in this paper and Figure 1 shows schematic drawing of the device and band structure. In the series of samples, a thin buffer layer was grown at 555 °C before the temperature was ramped down to the 505 °C QW and QD grown temperature. Once the temperature was stabilized the coupled

structure was grown; 2.6 s of InAs and 3.0 s of InSb, separated by a GaSb spacer layer whose thickness was varied. Before increasing the temperature back up to 555 °C, where the growth of GaSb is more efficient (3.5 Å/s as opposed to 0.53 Å/s at 505 °C), the quantum dot were capped in order to prevent significant changes to their size due to thermal annealing. An additional InAs layer of 100nm thick was grown on all the samples in order to aid electrical contacting. Standard photolithography and wet etch techniques were used to process the structures grown on the n-doped substrates into 400 μm mesas. A gold ball-bonder was used to directly contact to

Table I: Details of the GaSb spacer thickness for the samples used [5].

Sample Number	Spacer growth time (s)	Thickness (Å)
4436	600	320
4437	60	32
4438	15	8.0
4439	4	2.1
4441	0	0
4442	QW only	-
4443	QD only	-

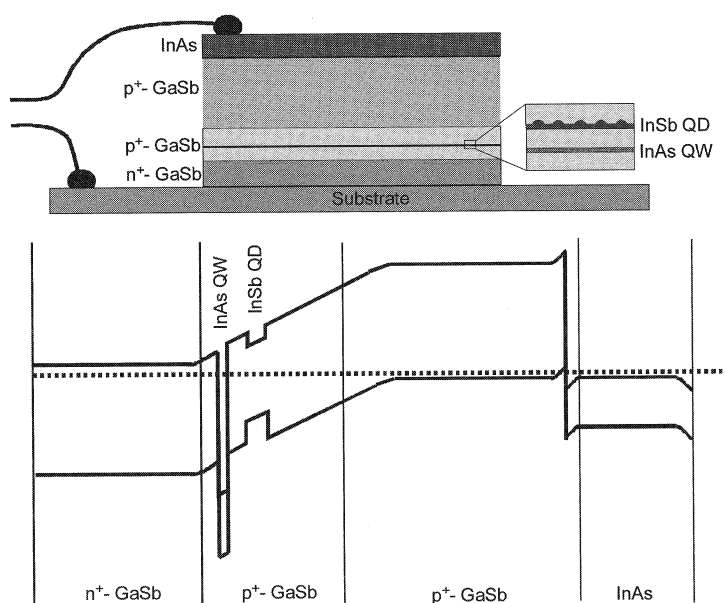


Figure 1. Schematic drawing of the device and the sample band structure.

the InAs front layer and also to an Indium dot that had been annealed into the n-GaSb substrate. Quasi-continuous electroluminescence (50% duty cycle) of all samples was measured at 4 K in a VTI cryostat with pumping current varying between 5-100 mA. A magnetic field up to 19 T was applied perpendicular to the sample plane in the Faraday geometry. The luminescence was delivered by chalcogenide optical fibres to be analysed with a 300 l/mm grating spectrometer in conjunction with a cooled InSb detector.

3. RESULTS AND DISCUSSION

A comparison of the zero-field EL at 100 mA for the different samples is shown in Figure 2 both at room temperature and at low temperature (25 K). We note that the typical threshold current of the samples in this series is around 10 mA depending on the mesas. Current densities of 360 Acm^{-2} (450

mA) could be achieved before the device failed, thus a 100 mA excitation is above the driving range but still much below this failure cut-off current. The absolute values of the emission roughly show the relative intensities for the different samples. Small changes in the intensity are due to the difficulty in reproducing the optics after changing the sample. At room temperature several of the samples show broad emission between 1700-2600 nm. The strong high-energy luminescence peak at $\sim 1750 \text{ nm}$ that can be seen in all samples and all temperatures has been identified as being due to recombination in the n-doped substrate [4]. With an exception of the above peak, the shape of the EL spectrum changes significantly at different temperatures. At low temperature there is an absence of a peak centred at 1930 nm which is observed at room temperature for all samples. Reduction in amplitude of the peaks above 2000 nm is also noticeable. For the QW-only sample, two

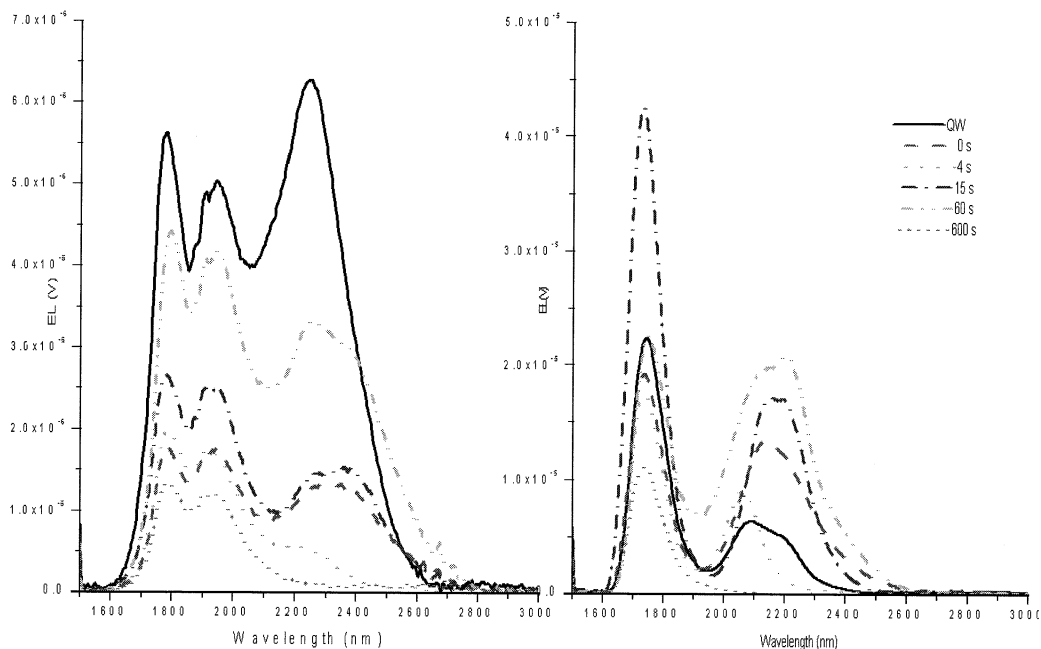


Figure 2. Comparison of room temperature (Left) and low temperature EL spectra for the series with 100 mA excitation. The curves have been ratioed with the spectral response of the system to eliminate the strong atmospheric absorption feature at 2600-2800 nm.

peaks are observed at 2200 and at ~ 2100 nm and previous EL measurements for variable excitation currents have revealed that the high-energy peak out of these two peaks emerges as the current increases [5]. An explanation for the origin of the two peaks has also been offered based on the temperature dependent results: the lower energy peak corresponds to localized states in the QW; and the upper peak to the true 2D QW wave function. To justify the cause, $\mathbf{k} \times \mathbf{p}$ calculations have been used to indicate that no higher confined subband states were expected for such a thin QW [6]. Figure 3 shows the spectra at high magnetic fields of strongly coupled structure 4437. In this sample, 60 s of GaSb spacer layer is grown between the dots and the well, and broadening and increasing of EL spectrum are observed compared to other samples. At low excitation (no greater than

10 mA), an emission peak at approximately 2400 nm is observed which is believed to have the same origin as the 2200 nm (or lower) peak observed in other samples. This peak appears at approximately 2300 nm at a 100 mA excitation as seen in the left hand panel of Figure 3. Essentially, as the excitation current increases from 10 to 100 mA (current densities of 8-80 Acm⁻²) the high energy peak appears and the amplitudes of both peaks grow as illustrated in the left panel of Figure 3 for EL results at 19 Tesla. The above results could be explained by the filling up of higher energy state as current density increases. A general effect of the magnetic field is also present as a slight increase of the overall emission energy. The magneto-EL spectra shown on the right-hand side of Figure 3 shows an apparent shift of the low energy peak (2400 nm) as the magnetic field is raised

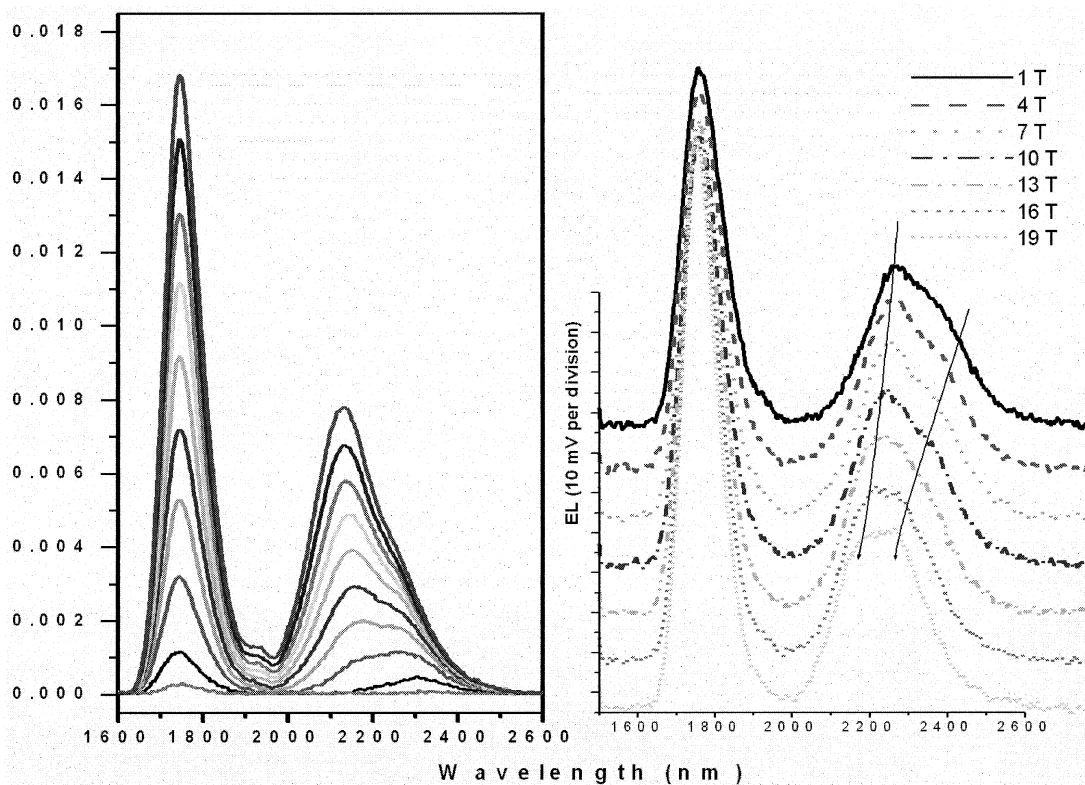


Figure 3. Left - low temperature EL spectra of 4437 at 19 Tesla for 5-100 mA in steps of 10mA. Right - EL spectra at various magnetic fields for the same sample with an excitation current of 10mA. The dotted arrows are guides for the eye.

to 19 T. We note that the observed decrease is much more rapidly when compared with the shift of the high energy peak as guided by the arrows. For the difference of 18 T in field, the emission energy has shifted approximately by about 50 meV. This 2400 nm peak is believed to be associated with the electronic coupling of the carriers' wavefunctions through the spacer layer between the dot and the well.

In previous QD growth studies it has been found that the substrate temperature strongly effects the QD growth as a result of the change in surface mobility of the dot species [3]. Since the InSb QDs are formed through a process of strain relaxation, the siting of the quantum dots will be highly sensitive to the strain fields in the previous material. InAs has a 0.6% smaller lattice constant than GaSb, which gives a critical thickness of ~ 200 Å. Therefore, the QW will grow with the same lattice constant as the GaSb substrate followed similarly by the spacer layer which will grow unstrained. Despite having the same lattice constant, the strained in the InAs will influence the QD growth with a strength that is diminished by a thicker GaSb spacer layer. The structural difference in the QDs and the effect of well shrinkage due to atomic segregation during growth [7,8] could explain the sharp transition in the emission energy for small spacer thicknesses. For large spacer thickness as in sample 4437, we would expect the electronic coupling effects to be dominant with reduction in the coupling as the thickness is increased. In such a case, it has been found that vertical organization of the dot positions can occur and is mediated through the QD strain over spacer thicknesses of up to ~ 100 monolayers [9]. Although the strain associated with the InAs QW is much smaller than that associated with a layer of QDs, correlation might still occur albeit over much smaller distances. Hole states in QDs can reside on preferential location above or between QW localized states. Localised states could be identified by strong broadening of lumines-

cence peak with increasing excitation current. This is because filling of higher energy states could be forced once any local states are saturated. Thus from Figure 2 localised states could be identified in all but the 4 s sample (4439). The siting of the QDs can also be in a random location as is believed to be the case of sample 4437 with some holes preferring to confine next to lower energy QW state. The energy shift of 50 meV of this low energy emission peak at high magnetic field as shown in Figure 3 does not disagree with this model.

4. CONCLUSION

We have reported the first magneto-optical results in the novel InAs/InSb/GaSb coupled quantum dot – quantum well system. Electrically-pumped mid-infrared emission can be obtained from such a system in which the emission energy can be influenced through the thickness of the intervening spacer layer. All samples emit broadly over the 1700-2600 nm wavelength range and could be useful as an infrared light source. The magneto-EL results presented here confirm that the GaSb spacer layer has a complex effect on the emission wavelength of the dot-well structure. The thickness of the spacer layer seems to have lowered the energy from that of a quantum well with a dependence that can not be described solely through electronic coupling of the wavefunctions. In order to explain the phenomenon more conclusively, we anticipate that in-plane magneto-optical measurements will be necessary.

ACKNOWLEDGEMENT

Much of this work is funded by the Thailand Toray Science Foundation (TTSF) and their support is gratefully acknowledged.

REFERENCES

- [1] Alphandéry E., Nicholas R.J., Mason N.J., Lyapin S.G., and Klipstein P.C., *Phys. Rev.*, 2002; **B 65**: 115322
- [2] Tsatsul'nikov A.F., Ivanov S.V., and Kop'ev P.S., *et al.*, *Microelectronic Eng.*, 1998; **85** : 43-44.

- [3] Alphandéry E., Nicholas R.J., Mason N.J., Zhang B., Mock P., and Booker G.R., *Appl. Phys. Lett.*, 1998; **74(14)**: 2041.
- [4] Shields P.A., Bumby C.W., Li L.J., and Nicholas R.J., *Applied Phys. Lett.*, 2004, In press.
- [5] Shields P.A., Li L.J., and Nicholas R.J., *Physica*, 2004; **E 20**: 204.
- [6] Child R.A., Nicholas R.J., Mason N.J., and Alphandéry E., *Physica*, 2002; **E 13**: 241-245
- [7] Magri R., and Zunger A., *Phys. Rev.*, 2002; **B 65**: 165302
- [8] Steinshnider J., Harper J., Weimer M., Lin C.-H., Pei S.S., and Chow D.H., *Phys. Rev. Lett.*, 2000; **85**: 4562
- [9] Xie Q., Madhukar A., Chen P., and Kobayashi N.P., *Phys. Rev. Lett.*, 1995; **75**: 2542.