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Continuous Wave Spectroscopic Method for Measuring the Carrier Lifetime in Quantum Dot Devices

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1. Introduction

One key fundamental parameter for laser and superluminescent diode design and operation is the carrier lifetime. This is especially true of long wavelength self-assembled QD structures, and dot in a well (DWELL) structures in particular, where the active region is close to the limit of strain relaxation. Currently, a number of techniques are employed to measure carrier lifetimes either in the semiconductor material or processed devices. Small signal modulation of LEDs and sub-threshold lasers allows the differential carrier lifetime to be determined [1]. Carrier lifetimes may also be measured on an unprocessed wafer by time resolved photoluminescence (TPRL). Whilst regularly measured, this last method does not directly correlate to a given drive current.

Here we report a simple optoelectronic technique for measuring the carrier lifetime in QD devices by utilising an inherent property of QDs, namely state saturation due to Pauli exclusion. The relative intensities of the ground and first excited state emission of a QD provides a direct measure of the QD occupancy and hence, by relating this to the applied current, the carrier lifetime.

2. Sample Design and Preparation

Samples are based on DWELL laser structures with ground state emission tailored to 1.3μm. Detailed growth parameters are reported elsewhere [2].

Modulation doping has been found to improve gain, T_0 and modulation speed in QD lasers and is therefore an ideal vehicle to test a carrier lifetime measurement method. As such, wafer A was a control wafer with no doping in the spacer layers whereas wafers B and C were grown with a 6nm wide 'modulation p-doped' layer located 9nm below each DWELL. These doped layers result in nominal concentrations corresponding to 6 and 18 acceptors per QD for wafer B and C respectively.

15μm wide, 500μm cavity length ridge lasers were fabricated with as cleaved facets. This cavity length was chosen in order to suppress lasing and allow for ground state saturation at low current, where thermal effects are minimal. Edge emitting lasers are used here since they are typically processed to enable standard length dependant laser characterization. However, we note that similar results are obtained with optical access mesa diode devices.

3. Theory and Model

One property of a QD is the relationship between the spontaneous emission from the ground and excited states of the QD and the carrier occupancy, n. Namely, the number of carriers in a state is known when the emission it saturated, i.e. it has reached full occupancy. In addition, at the point where the emission from the ground and excited states are equal, there are the same number of carriers in both levels. In this simple model, several assumptions are made: The carrier relaxation time is small relative to the recombination time (τ_r). A degeneracy of 2 carriers in the ground state and 4 in the excited state. The radiative and non-radiative recombination rates are equal in the excited and ground-states. The former assumption is reasonable since reported values for relaxation are of the order of ~pS whereas radiation is found to be ~nS. The second assumption is based on the lens shape of the QD and that the excited states are those in the in-plane direction. The final assumption is based on measuring the ground and excited state SE at large carrier densities where a ratio of 1:2 value is observed in agreement with the state degeneracy ratio.

Since this is the case for the individual QD and in reality we have an ensemble of QDs, a random filling will occur. The carrier density, n, in the QD is replaced with an average carrier density <n> in the sample. Additionally, we account for a thermal population of carriers by modifying these confined state occupancies using a Boltzmann distribution. A final assumption is made that each QD remains charge neutral, i.e. the QD filling is excitonic. This is verified at low carrier densities where the ground state emission is not found to be superlinear. Figure 1 shows the spontaneous emission from the GS and ES of the ensemble of QDs as a function of average electron-hole pair occupancy <n> at 300K. The inset shows the ratio of the GS and ES emission as a function of <n>. This plot can now provide a "look-up chart" for uniquely correlating the EL spectra to the average electron-hole pair occupancy. Once <n> is extracted from the spectra at a given drive current, the carrier lifetime, τ_c, is given by:

$$\tau_c = \frac{< n > qN_{qd}}{J \cdot \eta_i} \qquad (1)$$

Where J is the current density, N_{qd} is the areal dot density and q is the electron charge. Finally, η_i is the internal quantum efficiency which is determined from length dependant laser characterization of the same material.

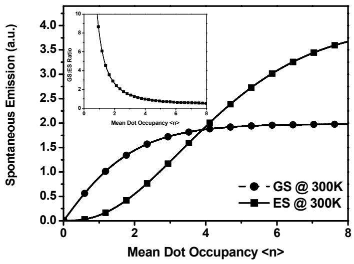

Figure 1. ground, GS, and excited state, ES, spontaneous emission as a function of mean carrier density <n>. Inset is the ratio of the emission of the two states.

3. Results and Discussion

The spontaneous emission spectra of the QD ensemble was extracted from the captured spectra which included amplified spontaneous emission. Figure 2 inset shows the deconvoluted spontaneous emission spectra from wafer C at increasing drive current densities. At each drive current both ground state and excited state components of the spontaneous emission spectrum were then integrated to determine their respective intensities. The ratio of ground to excited state emission for each laser was plotted as a function of drive current in figure 2.

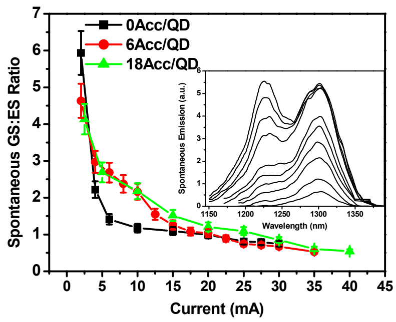

Figure 2. Gs:1ex emission ratio as a function of current for the three samples. The inset shows and example of the spectral emission from sample B (inset)

Figure 3 shows the values of carrier lifetime deduced as a function of current from the three samples.

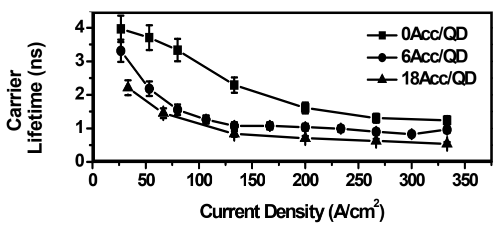

Figure 3. Deduced carrier lifetimes as a function of current density for the three wafers.

One significant result is that increasing p doping in QDs has the beneficial effect for directly modulated lasers of decreasing the carrier lifetime, so enabling higher speed data transmission. We believe that increased p doping enhances the scattering time for electrons into the GS by a hole assisted Auger process.

A TRPL study was carried out on the unprocessed wafers and the results of the carrier lifetime from the two techniques are compared and shown to be in good agreement.

Further investigation of the differential carrier lifetime on these samples is shown in figure 4. It is worth noting that the differential carrier lifetime is a factor of 2 to 3 lower than the carrier lifetimes[3]. This is expected to be the case if the bimolecular or trimolecular recombination dominates. Indeed, further analysis leads to the conclusion that Auger recombination is significant for all samples and also increases with increasing doping. This indicates that whilst increasing the number of holes in the QD benefits the device by increasing the carrier relaxation rate to the ground state it also has the detrimental effect of increasing non-radiative recombination.

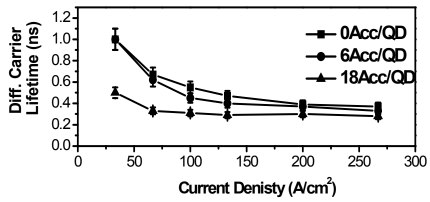

Figure 4. Differential carrier lifetime as a function of current density derived from small signal modulation.

5. Conclusion

We have demonstrated a simple spectroscopic technique for measuring the carrier lifetime of QD lasers that is far simpler to apply than current ultrafast measurement techniques. We have shown that increasing p doping in QDs has the beneficial effect for lasers devices of decreasing the carrier lifetime. Increased doping, we believe, enhances the scattering time for electrons into the GS and also reduces the hole thermal broadening effect.

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