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# Interconnection between ground state and excited state gain in InAs/GaAs quantum dot semiconductor optical amplifiers

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Different energy levels are generally assumed to be associated with ground state (GS) and excited state (ES) gain in semiconductor quantum dot lasers and amplifiers. We present calculations based on an 8 band $\boldsymbol{k}\cdot\boldsymbol{P}$ Hamiltonian which show that this is not the case. Two distinct absorption bands are calculated due to transitions between the GS electrons and all dot hole states. In addition to the peak due to transitions between GS electron and GS hole levels, a higher energy band is also calculated due to transitions between GS electrons and highly excited dot hole states. We demonstrate that the removal of electron–hole pairs through stimulated emission at the ES gain maximum can result in an amplitude reduction for a probe pulse tuned to the GS gain maximum, due to the existence of these higher energy transitions, and also due to the effects of two photon absorption. We also find that the instantaneous phase change at the ES gain maximum due to dot to dot interband transitions is small compared to the measured value.

**1 Introduction** Semiconductor optical amplifiers (SOAs) with active regions composed of quantum dots (QDs) have been the subject of intensive research in recent years, with particular emphasis on potential device applications for all optical signal processing [1]. A clear understanding of the gain and refractive index dynamics in these devices is essential for such applications. Pump–probe spectroscopy based on the heterodyne technique has proved fruitful in providing this knowledge, and has been used to successfully characterise the gain and phase dynamics in bulk, quantum well (QW), quantum dash and QD active regions [2–4]. The method incorporates the injection of a strong optical pump pulse into the waveguide, accompanied by a much weaker, variably time delayed probe pulse, whose purpose is to scan in time the amplitude and phase changes induced by the stronger pump pulse. Single and two colour pump–probe measurements have been reported recently of the gain and phase dynamics in InAs/GaAs QD SOAs [5, 6]. In the case where the pump pulse is tuned to the maximum of the ES gain, an instantaneous reduction in probe amplitude was measured at both the ES and GS gain peak, and was attributed to fast scattering between the closely spaced hole levels [5].

In this paper, we investigate the cause of this ultrafast reduction in GS gain in further detail. The reduction was initially unexpected, because it is generally assumed that independent energy levels contribute to the ground and excited state gain. An 8-band $\boldsymbol{k}\cdot\boldsymbol{P}$ method is used to calculate the QD energy levels and corresponding optical matrix elements for an exemplar 1.3 µm InAs/GaAs QD structure. In addition to fast scattering between hole levels, two additional mechanisms are identified that cause such an instantaneous amplitude reduction of a GS probe pulse by an ES pump pulse. Firstly, we show that transitions between GS electrons and highly excited hole states can contribute to the ES gain, thereby directly depleting the GS gain. This type of coupling is usually neglected in studies of optical gain in semiconductor QDs. In addition, two photon absorption (TPA) involving an ES pump and GS probe photon also contributes to the observed instantaneous probe amplitude reduction. Turning to the instantaneous phase change, we find that the phase change, at the ES gain maximum, associated with population changes among dot states is small in comparison to the overall measured phase change in the pump–probe measurements, highlighting the importance of the free carrier plasma (Drude) and contributions arising from delocalised states to the overall measured phase change [7].

**2 Results and discussion** We present calculations for an InAs quantum dot in the form of a truncated square pyramid with a base length of 15 nm, top length of 11.25 nm and a height of 5 nm. The single particle QD electron and hole energy levels and their related transition strengths are computed using an 8 band $\boldsymbol{k}\cdot\boldsymbol{P}$ Hamiltonian with strain and piezoelectric fields taken into account through Green's function and Fourier transform techniques [8, 9]. The calculated distribution of energy levels for electrons and holes is shown in Fig. 1(a). The calculated squared transition matrix elements for TE polarised light are presented in Fig. 1(b), where it can be seen that the largest matrix element is associated with transitions between GS electrons and GS holes. We use the energy levels and matrix elements in Fig. 1 to calculate the gain as a function of carrier density, assuming overall charge neutrality and that the injected electrons and holes are distributed thermally between the dot states, wetting layer (WL) states, and bulk (barrier) states. The effective mass of electrons (holes) is taken as $0.06m_0$ ($0.12m_0$) in the WL and $0.067m_0$ ($0.4m_0$) in the barrier layer, where $m_0$ is the free electron mass.

The small signal gain calculated for a single layer of QDs is shown in Fig. 2 for increasing values of the total injected carrier density. The total carrier density, $x$, is normalised to the areal dot density ($N_D = 3 \times 10^{10}$ cm$^{-2}$) in one QD layer. A homogeneous linewidth (FWHM) of 13 meV (dephasing time of ~100 fs) and an inhomogeneous linewidth (FWHM) of 40 meV are assumed for all bound to bound transitions at $T = 300$ K. We show separately the calculated contributions to the total gain due to GS electrons recombining with all bound hole states (solid blue lines), and due to first ES electrons recombining with all bound hole states (dashed red lines). A notable feature in the gain spectra of Fig. 2 is the appearance in the GS electron gain curves of a higher energy gain peak, due to transitions between GS electrons and highly excited holes (transition 3 (dashed blue arrow) in Fig. 1(a)). This higher energy peak overlaps with the gain peak due to transitions involving first excited state electrons, indicated as transition 2 (red arrow) in Fig. 1(a).

A pulse centred on the ES gain maximum (1.04 eV) couples to the electron–hole populations involved both in transitions 2 and 3. The transition strengths associated with transition 3 are individually much smaller than those pertaining to transition 2 (see Fig. 1(b)). However, since many different hole states contribute to transition 3, the total gain due to these transitions can be significant. The dashed-double-dotted lines in Fig. 2 show that for the dot considered here transitions involving GS electrons can contribute as much as 20% of the total gain at the ES transition energy in a fully inverted dot.

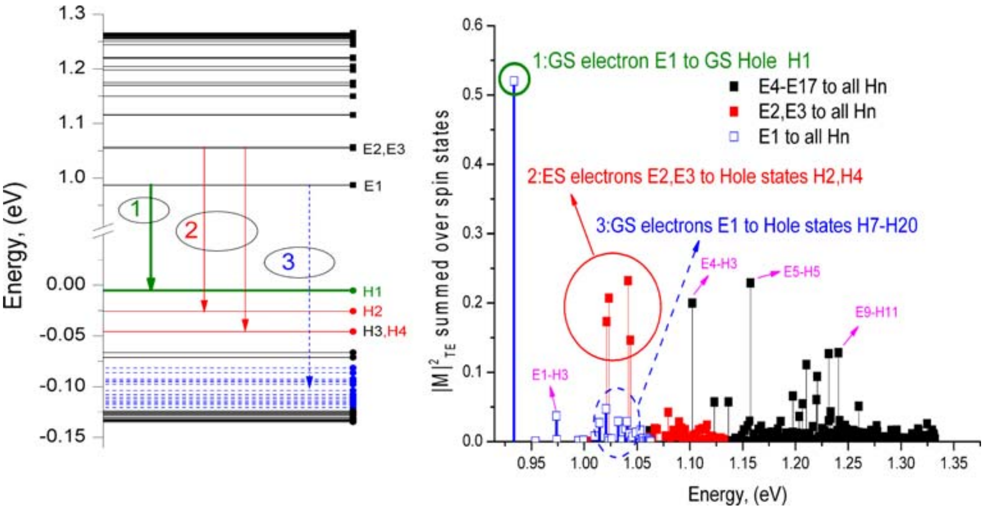

**Figure 1** (online colour at: www.pss-b.com) Calculated (a) doubly degenerate electron (squares) and hole (circles) energy levels for the given quantum dot and (b) matrix elements connecting them for TE polarised light. Transition 1 (thick green arrow) represents GS electrons (E1) recombining with GS holes (H1); transition 2 (red arrows) depicts transitions between ES electrons (E2, E3) and ES holes (H2, H4). Transition 3 (dashed blue arrow) illustrates transitions involving GS electrons (E1) and highly excited hole states (H7–H20).

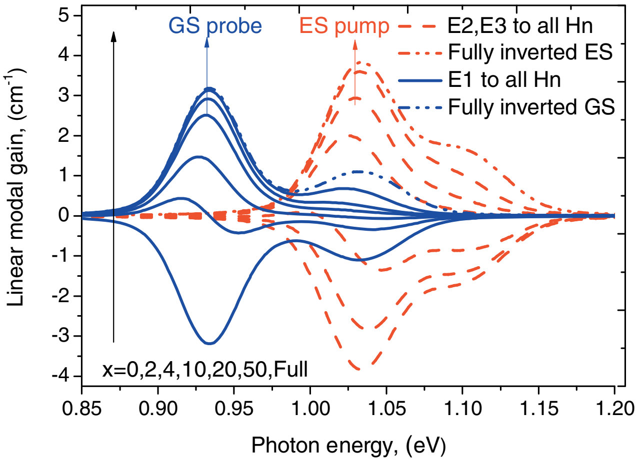

**Figure 2** (online colour at: www.pss-b.com) Single layer linear modal gain spectra for increasing values of the total injected carrier density, $x$, normalised to the areal dot density per QD layer. Blue solid lines: gain due to transitions between GS electrons (E1) and all dot hole states. Dashed red lines: gain due to transitions between ES electrons (E2, E3) and all dot hole states. The blue (red) dashed-double-dotted lines show the calculated gain when all dot states are occupied for transitions involving GS (ES) electrons.

To compare with the pump–probe experimental results, we now examine the level of gain reduction expected at the GS transition (0.93 eV) due to a strong pulse tuned to the ES resonance (1.04 eV). We assume an effective waveguide thickness (width) of 0.2 μm (2 μm), 6 dot layers, a constant waveguide loss of 5 $\text{cm}^{-1}$ and a total pump (probe) pulse input energy of 1 pJ (7 fJ). The holes, due to their large effective mass and consequent closer level separation are assumed to thermalise on a much faster timescale than the pulse duration (~1 ps), while electron re-distribution is considered to be slower [6, 10, 11]. The propagation of the pulses is described by a standard propagation equation including TPA in which a TPA coefficient of 21 cm/GW is included [12].

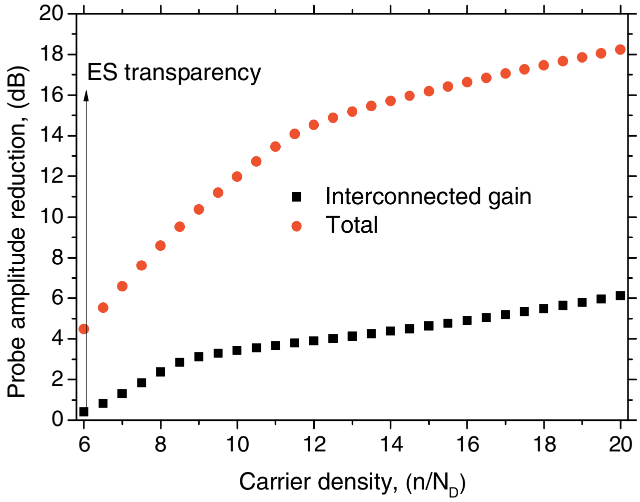

**Figure 3** (online colour at: www.pss-b.com) Amplitude reduction experienced by a probe pulse at the GS energy due to a strong pump pulse at the ES energy, versus normalised carrier density $x$. Black squares: calculated amplitude reduction due to stimulated transitions involving GS electrons. Red circles: amplitude reduction when two photon absorption is included.

The effect of the ES pump pulse on the GS probe pulse is modelled by comparing the amplitude change experienced by the GS probe when it propagates through the SOA waveguide with and without the pump pulse. The calculated probe pulse amplitude reduction, with and without TPA, is shown in Fig. 3. The amplitude reduction due to stimulated emission involving GS electron states (black

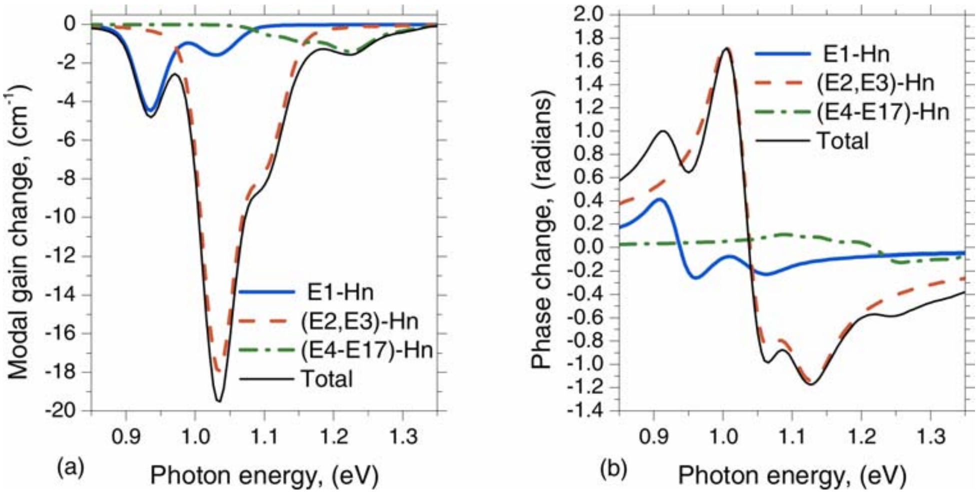

**Figure 4** (online colour at: www.pss-b.com) (a) Instantaneous gain change spectrum averaged over the device length and (b) corresponding phase change spectrum at a carrier injection level of $x = 20$ per QD layer. Solid blue lines: changes due to transitions involving GS (E1) electron states; dashed red lines: changes due to transitions involving excited electron states (E2, E3); dash-dotted green lines: contributions from all other higher energy dot electron states.

squares) including the effects of fast hole redistribution is seen to increase linearly with carrier injection as the highly excited hole population increases. However, when TPA is included, a much larger amplitude reduction results (red circles). At the ES transparency point, the inclusion of TPA is calculated to give a 4.49 dB instantaneous amplitude reduction. In comparison, an amplitude reduction of 2.35 dB is measured at the ES transparency current point [10]. The effects of TPA then increase rapidly with increasing carrier density, driven by the increasing pump pulse intensity in the ES gain regime.

Figure 4 shows in more detail how the gain and phase spectra are modified due to the propagation of the pump pulse. We consider an initial normalised carrier density per QD layer of $x = 20$. Figure 4(a) shows the changes in the QD gain spectrum due to the propagation of the pump pulse. The GS gain is reduced by about 28% compared to its unperturbed value while the ES gain is reduced almost completely, due to the different relative contributions of the GS and ES electrons to the ES gain spectrum. Figure 4(b) shows the calculated phase change for a probe pulse propagating through the SOA due to the carrier depletion in the dots. The calculated phase shift at the ES gain maximum is small compared to the experimentally determined value [6], suggesting that the experimentally measured value is determined primarily by a Drude contribution [7] and by population changes in the higher energy continuum states comprising the WL and barrier layers. It is intended to analyse these different contributions in further detail in a future paper.

## 3 Conclusions

In summary, we have presented a theoretical analysis to investigate the interconnected GS and ES gain in 1.3 μm QD lasers and amplifiers by considering realistic QD energy levels and optical matrix elements. Although the amplitude reduction experienced by the probe has a strong TPA component, an amplitude reduction due to stimulated emission mediated by the interconnected ground and excited state gain was shown to make a significant contribution to the overall amplitude reduction at moderate carrier injection levels. Finally, we have calculated a small phase change, at the excited state gain maximum, originating from interband transitions between bound electron and hole states, indicating that the contribution from the continuum states provides the bulk of the experimentally measured phase magnitude. Overall, we conclude that GS electrons will in general contribute to the ES gain in a QD structure, the consequences of which need more careful consideration in future modelling and analysis of QD lasers and amplifiers.

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