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Electron and hole dynamics of InAs/GaAs quantum dot semiconductor optical amplifiers

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Single-color and two-color pump-probe measurements are used to analyze carrier dynamics in InAs/GaAs quantum dot amplifiers. The study reveals that hole recovery and intradot electron relaxation occur on a picosecond time scale, while the electron capture time is on the order of 10 ps. A longer time scale of hundreds of picoseconds is associated with carrier recovery in the wetting layer, similar to that observed in quantum well semiconductor amplifiers. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2771374]

Ultrafast spectroscopy of quantum dot (QD) semiconductor optical amplifiers (SOAs) provides valuable information about the potential of these devices for emerging applications such as multiwavelength regeneration while giving insight on their unique carrier dynamics.[1] Unlike bulk and quantum well materials, QDs have discrete energy levels; it is the carrier capture and relaxation dynamics between these levels that will constitute the intrinsic limiting device bandwidth. For this reason, initial SOA studies have concentrated on the gain and refractive index recovery of the QD ground state (GS), following a pump pulse at the same wavelength. These single-color studies have revealed the presence of several recovery time scales, related to electron capture and relaxation within a dot.[2] Similar SOA studies have been performed on the first excited state (ES) and revealed the presence of similar time scales.[3]

To further investigate carrier transition times, two-color differential transmission spectroscopy has been applied to both quantum well[4] and QD (Ref. 5) structures. Time scales reported include dot capture and relaxation times of a few picoseconds and less than a picosecond respectively for InGaAs QDs,[5] dot to dot carrier scattering times of ~35 ps for InAs QDs,[6] and a <1 ps time scale for thermalization of holes together with a 15 ps time scale for electron GS to ES escape, also in InAs QDs.[7] Previously, we demonstrated that the carrier capture process for InAs QD structures was Auger mediated.[8] However, our analysis did not include the asymmetry that exists between QD electron and hole effective masses, which in turn leads to more closely spaced hole levels. This hole spacing is less than the thermal energy at room temperature, which in turn is less than the electron spacing, and consequently, the dots' hole states can be reduced to a single shared hole population. This has been shown to lead to GS gain compression in QD lasers[9] and subpicosecond hole capture time scales.[7,10] In this letter, we present two-color differential transmission measurements to confirm the presence of these fast hole redistribution processes and deduce the time scales of the remaining electron capture/escape processes. In addition, we develop a rate equation model of the electron and hole occupancies and demonstrate its agreement with the experimental results.

Our experiment is based on the scheme presented in (Ref. 11) where pump and probe pulses of different wavelengths are filtered from a femtosecond pulse spectrum that has been broadened and compressed by propagation in various lengths of specialty fibers. Our setup is modified for 1.3 μm operation by using a 1 m length of single mode fiber (SMF-28) to generate the broadened spectrum. This arrangement allows us to pump/probe independently at either GS or ES wavelengths. The pump/probe pulse width was ~600 fs on entering the SOA, and no correction was performed in the experiment for nonlinearities such as four wave mixing or two photon absorption (occurring near zero pump-probe delay), other than to remove the first picosecond of data before performing any curve fitting. The QD SOAs were 3 mm long, 4 μm wide ridge waveguide devices with tilted, antireflection coated facets fabricated from material consisting of six stacks of InAs/GaAs QDs dots in a well structure, grown by Zia Inc. and operating at 1.32 μm (for further details see Ref. 12). Figure 1 (inset) displays typical amplified spontaneous emission (ASE) together with normalized pump and probe pulse spectra. The dynamics that occurs when the

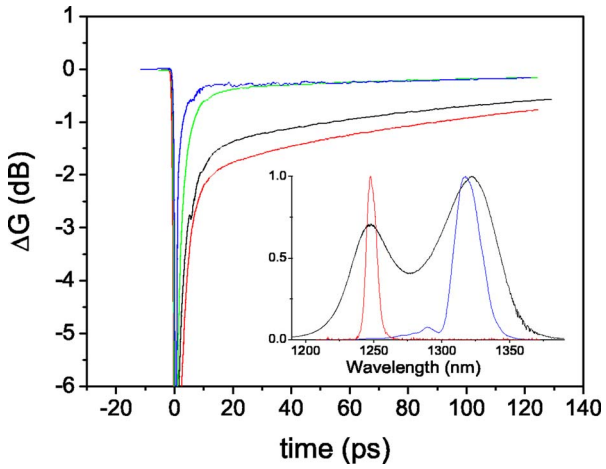

FIG. 1. (Color online) (Main) Recovery dynamics observed at 200 mA: (blue) ES pump GS probe, (green) GS pump GS probe, (black) ES pump ES probe, and (red) GS pump ES probe. (Inset) ASE of QD SOA at 175 mA with normalized pump/probe pulse spectra. GS transparency occurs at 15 mA; ES transparency occurs at 55 mA.

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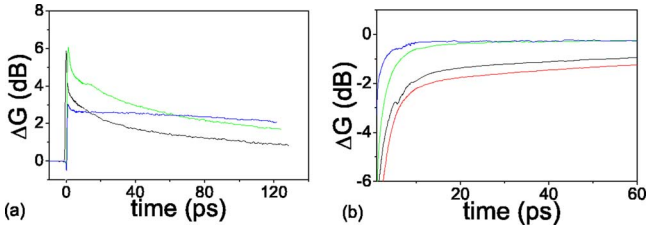

FIG. 2. (Color online) Recovery dynamics of the absorption [(a), 10 mA] and of the gain [(b), 200 mA first picosecond removed]: (blue) ES pump GS probe, (green) GS pump GS probe, (black) ES pump ES probe, and (red) GS pump ES probe.

ground state gain saturates (i.e., far above transparency) is also presented in the main panel of this figure. Each of the gain recoveries (after 1 ps) can be described with a triexponential function that results in three typical time scales for all four cases: an ultrafast time scale (<1 ps), a fast time scale (1–10 ps), and a slow time scale (>100 ps).Since the shape of the GS and ES recovery does not exhibit major changes when going from single-color to two-color configurations (see Fig. 1), we will examine the dynamics in the absorption regime. Finally, it is important to mention that tuning of the pump/probe wavelength away from ES/GS gain peak results in the appearance of an additional ~35 ps time scale related to dot-to-dot transport and similar to that observed in Ref. 6. These processes will not be analyzed here.

The case of absorption dynamics (shown on Fig. 2 (left)) is somewhat simpler to analyze and establishes fundamental lifetimes relevant to the use of a highly inverted system. In this scenario, where instantaneous nonlinearities are reduced due to the lower optical intensity in the device, the pump pulse creates electron-hole pairs in the dots, and the recovery of the resulting GS and ES absorption is measured. The possible decay processes are redistribution of holes, escape of electrons from the dot, and escape/ capture of electrons between the GS and ES. In general, we observe a triexponential behavior with times of the order of 1, 30, and 200 ps. We attribute the longest time to interband recombination between electrons and holes, the intermediate time to a combination of electron thermalization from GS to ES and ES to wetting layer (WL) (similar to Refs. 6 and 7), and the short time to a combination of electron decay from ES to GS and hole redistribution (similar to Ref. 7). These times are also consistent with Ref. 9 where a detailed balance argument was employed in the low carrier density limit to deduce that the escape time of electrons from the GS to ES should be approximately a factor of 10 slower that the corresponding capture process. Here, the high speed of hole dynamics can be deduced by comparing the single-color transients with the two-color ES-pump–GS-probe transient. In the single-color ES transient, a strong ultrafast component is present due to the combined effects of hole redistribution and decay of electrons into the ground state. In the single-color GS transients, hole redistribution alone results in a significant, though reduced, ultrafast component. However, in the ES-pump–GS-probe case, redistribution of holes reduces the GS gain, while the decay of electrons from ES to GS increases the GS gain. The net effect is a further reduced ultrafast component with both effects almost canceling. The GS-pump–ES-probe case is not presented as the measured signal was quite noisy due to the large absorption of the ES. Thus, we conclude that hole redistribution dynamics are in the subpicosecond range, an important factor in considering the high bias dynamics of the device.

TABLE I. Summary of times from three exponential fits of single-color (SC) and two-color (TC) measurements in the 100–200 mA range

	t_1 (ps)	t_2 (ps)	t_3 (ps)
SC GS	0.7–1.2	3.1–9.0	104–151
SC ES	0.9–2.1	4.1–6.3	126–166
TC GS pump	0.2–2.5	2.8–13	122–186
TC GS probe	0.5–0.7	3.0–3.5	162–204

Figure 2 (right) contains the gain transients for single-color and two-color SOA measurements (first picosecond removed), biased well above GS and ES transparency where the pump pulse will remove electron-hole pairs from the dots' carrier populations. We attribute the longest time (hundreds of picoseconds) to WL recovery[8] and the intermediate time (1–10 ps) to a combination of electron capture to the ES from WL and GS to ES electron thermalization (approximately ten times slower that ES-GS relaxation). The shortest time represents a combination of hole redistribution and electron relaxation from ES to GS. In the single-color ES transient, the large ultrafast component in the recovery is due to fast hole redistribution and, as a result, is of a very similar shape to the GS transient. These times are summarized in Table I for currents in the 100–200 mA range.

This ultrafast initial depletion of the GS, when pumped at the ES, is additional evidence that ES and GS gains are connected through a shared hole population. In common with single-color transients, this GS recovery also exhibits an ultrafast recovery through hole capture, an intermediate recovery related to interaction with the ES, and a long time related to subsequent recovery of the WL. Similarly, the ES transient, when pumped at GS, exhibits an ultrafast initial depletion due to shared hole depletion and depletion of electrons into the GS, an ultrafast recovery due to hole capture, an intermediate recovery due to electron capture from the WL, and a long time component related to the recovery of the WL.

To further illustrate these processes, rate equations based on Ref. 13 are examined. This model considers electron and hole dynamics of a single dot in the QD SOA. Electrons are directly pumped into the barrier N_b, from where they refill the WL, N_{wl}, before being captured into the ES and GS of the dots, N_e, N_g. The situation for the holes is simpler, as we assume that they occupy a single hole level, N_h, with a single (subpicosecond) relaxation time. The equations read

$$\dot{N}_b = J - \gamma_0 N_b^{\mu},$$

$$\dot{N}_{wl} = \gamma_0 N_b^{\mu} - \gamma_1 N_{wl}^{\mu}(2 - N_e) + \epsilon_1 \gamma_1 N_e^{\mu} - \gamma_s N_{wl},$$

$$\dot{N}_e = \gamma_1 N_{wl}^{\mu}(2 - N_e) - \gamma_2 N_e^{\mu}(1 - N_g)$$

$$- \epsilon_1 \gamma_1 N_e^{\mu} + \epsilon_2 \gamma_2 N_g^{\mu}(2 - N_e) - \gamma_s N_e,$$

$$\dot{N}_g = \gamma_2 N_e^{\mu}(1 - N_g) - \epsilon_2 \gamma_2 N_g^{\mu}(2 - N_e) - \gamma_s N_g,$$

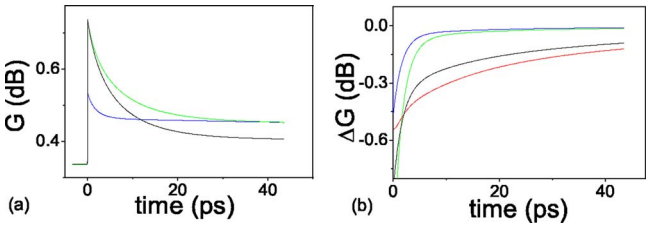

FIG. 3. (Color online) Simulated recovery of absorption (a) and gain (b). (Blue) ES pump GS probe, (green) GS pump GS probe, (black) ES pump ES probe, and (red) GS pump ES probe. Parameters were $J=0.01$ (absorption), 1 (gain), $\gamma_0=1$, $\gamma_1=1$, $\gamma_2=10$, $\gamma_h=2$, $\gamma_s=0.01$, $\epsilon_1=0.01$, and $\epsilon_2=0.1$.

$$\dot{N}_h = J - \gamma_h N_h,$$

where J is the pump and γ_0, γ_1, and γ_2 each determine the strength of the electron capture of the WL from the barrier, the ES from the WL, and the GS from the ES, respectively. ϵ_1 and ϵ_2 are the fractions of electrons which escape from the GS to ES and ES to WL states, respectively. For capture/escape into the GS/ES, we include Pauli blocking factors $1-N_g$ for the GS (one state per dot) and $2-N_e$ for the ES (two states per dot). The capture and escape terms also feature the parameter μ, which describes the nature of the capture/escape process with $\mu=1$ describing a phonon assisted process while $\mu=2$ or higher describing an Auger process. γ_s determines the strength of interband recombination in the dot, and γ_h describes the recovery time of the single hole level. For the remainder of the letter, we will assume that all capture/escape processes are Auger mediated and set $\mu=2$.

The results of the simulation are displayed on Fig. 3 for both absorption and high carrier density regime. This situation is in extremely good agreement with Fig. 2 and demonstrates the validity of our description. An alternative scheme which has been proposed consists of subpicosecond capture to the dot with relaxation to GS taking up to 10 ps. We have considered this case, which can also reproduce the high carrier density behavior observed. However, significant disagreement with experiment occurs in the case of the GS absorption recovery dynamics when pumped at the ES. In this case, the observed cancellation between hole redistribution and electron relaxation from ES to GS does not occur, and a much larger ultrafast component is present as a result. Thus, this alternative model is incompatible with our experimental results.

In conclusion, we have presented two-color pump-probe measurements of ultrafast gain transients in QD SOA structures. By examining the absorption recovery dynamics, we demonstrated that the hole redistribution processes are extremely fast (<1 ps) due to the effective mass asymmetry in InAs QDs. In addition, we have analyzed the gain dynamics far above transparency and found that the ES-GS relaxation is also a fast process, while Auger mediated electron capture to the QD constitutes the main limiting time scale in these devices. We have developed a rate equation model which is in good agreement with experiment. Such results are extremely relevant for the engineering of the next generation of high speed optical components such as regenerators and logic gates as QDs may offer opportunities due to their unique carrier dynamics.

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