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Mixed state effects in waveguide electro-absorbers based on quantum dots

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Multi-pulse heterodyne pump-probe measurements are used to investigate the reverse bias dynamics of InAs/GaAs quantum dots in a waveguide structure. Using a femtosecond pulse, we simultaneously populate high energy ground states and low energy excited states and measure the resulting gain and phase dynamics over the bandwidth of the pulse. We identify a ~5 ps timescale in the phase dynamics which can be associated with low energy ground states outside the pulse bandwidth and may provide an explanation for the deterioration of monolithic mode locked laser performance at high reverse voltages. © *2011 American Institute of Physics*. [doi:10.1063/1.3653287]

Semiconductor quantum dot (QD) based optical materials have been studied intensively in recent years due to their unique blend of atomic and solid state physics.[1] Notable applications include monolithic mode-locked lasers (MMLLs),[2] electro-absorption modulators,[3] saturable absorber mirrors,[4] and broad band emitters.[5] In investigations of the carrier dynamics of such materials, time-resolved pump-probe spectroscopy has proved a useful tool, an early example being the impact of different carrier types for quantum well absorbers.[6] Recently, multi-pulse variations of the technique were applied to QD structures to investigate the nature of the semiconductor optical amplifier (SOA) dynamics.[7]

Carrier interaction between various states within a dot (intradot dynamics) is of particular importance in two promising application areas where multiple optical transitions within each dot may be involved, namely broad band emitters[5] and MMLLs.[2] In both of these applications, simultaneous operation at ground state (GS) and excited state (ES) wavelengths can occur. In the case of broad band emitters, large emission bandwidths are achieved by engineering a large inhomogeneous broadening which spectrally flattens the total emission from the (usually spectrally distinct) GS and first ES transitions. In the case of MMLLs, as the reverse bias (RB) of the absorbing section is increased, the absorption exhibits a red-shift due to the quantum confined Stark effect and so the lasing emission from the main section GS transitions can interact with both GS and ES transitions in the absorber. In this letter, such a situation is investigated by performing pump probe measurements of an absorber when both GS and ES wavelengths are contained in the pulse bandwidth, which we term "mixed state" dynamics.

To illustrate the situation further, the absorption spectrum of a typical absorber structure is shown on Figure 1 as a function of RB and exhibits the usual Stark red-shift and reduction in absorption due to spatial separation of electron and hole wavefunctions (see Ref. 8 for explanation of a similar structure). In a MMLL structure, where the lasing wavelength remain at 1320 nm as RB increases, simultaneous interaction with GS and ES absorbing transitions would become important at ~8 V. It is important to note that, while QD MMLLs have demonstrated significant advantages such as reduced timing jitter and locking range, the experimentally observed locking range is usually restricted to reverse voltages less that 8 V. The performance deterioration at higher RB levels is accompanied by a strong hysteresis loop and an output power jump in the light-current characteristics,[9] increased pulsewidth,[10] increased pulse-to-pulse timing jitter,[11] decreased locking range and increased pulsewidth of the hybrid ML regime.[12] Previous studies on the dynamics of QD absorber transitions have focused attention on studying the GS and ES dynamics separately[13] or using two color techniques to examine their interplay.[14]

The QD waveguide absorber device studied was 1 mm long, had 4 μm width ridges together with tilted, anti-reflection coated facets. Its active region included six stacks of InAs/GaAs QDs in a dots-in-a-well structure, grown by Zia, Inc. (see Ref. 15 for details of material). In forward bias, inhomogeneously broadened transitions (due to QD size dispersion) are apparent at 1320 nm (GS) and 1250 nm (ES). The heterodyne pump probe technique[14] for tracing the transmission and phase dynamics was extended to a double pump pulse

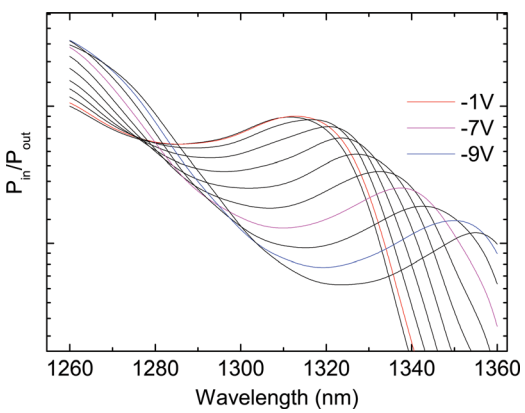

FIG. 1. (Color online) Absorption spectra at various RB voltages measured using a CW tunable source.

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configuration to more closely resemble the operating conditions in an actual 125 GHz MMLL, where both pump pulses have the same energy (see Ref. 7 for a very similar approach).

Figure 2 displays the transmission and phase dynamics at a RB voltage of 1 V when the pump/probe wavelengths are centred on the GS absorption peak at 1320 nm. At this RB level, the level of absorption bleaching by the second pulse is very similar to that of the first pulse even though the absorption has not recovered to its steady state value between pulses. Thus, since both pump pulses have equal energy, we can conclude that we have almost a full bleaching of the absorption for both pulses whereby most of the states involved in the transmission must be completely populated by both pump pulses. There will still be partially populated states at the edges of the pulse's bandwidth but these have a very small effect on the transmission of the pulse. The dynamics may be fitted by a bi-exponential with associated fast (~1 ps) and slow (~20 ps) timescales, these low voltage timescales have been investigated previously in Ref. 13.

Interestingly, the phase dynamics (Figure 2) reveals a much slower phase recovery due to cancelling contributions from either side of the absorption maximum.[16] However, a larger offset occurs at the second pulse when compared to the first pulse, in contrast to the absorption where the maximum transmission is the same for both pulses. We attribute this difference between absorption and phase as an effect of partially populated states on the edge of the pulses bandwidth which can be populated to a higher level after the second pump pulse. The effect of this increased population would be minimal on the transmission but, as the phase response in reverse bias is very similar to that of an atomic transition,[16] these non-resonant states can play a much larger role in the overall phase behaviour.

To investigate the impact of moving to the mixed state regime, where the propagating pulses at 1320 nm interact with both high energy GS and low energy ES in the imhomogeneously broadened ensemble, the transmission and phase dynamics in high RB regime (7 V, 9 V) were recorded (Figure 3). The transmission is similar to the lower voltage case although as shown previously, the dynamics can now be fitted to a single exponential with ~1–2 ps timescale[13] and commonly attributed to tunnelling into the wetting or barrier layers.[17] The tunnelling timescale primarily depends on the

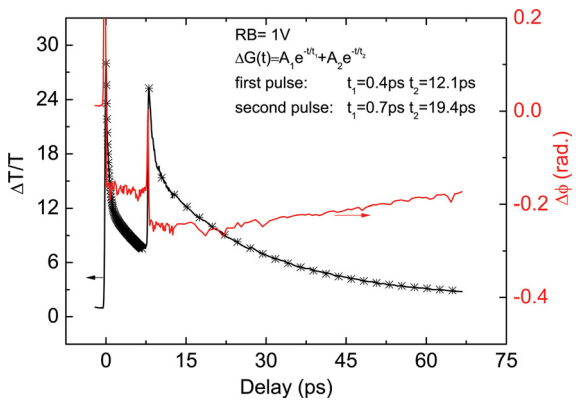

FIG. 2. (Color online) Transmission and phase dynamics at 1V RB, together with bi-exponential fits to the transmission (stars). The discrepency between fitted times for the first and second pulse can be attributed to the limited range of data for the first pulse.

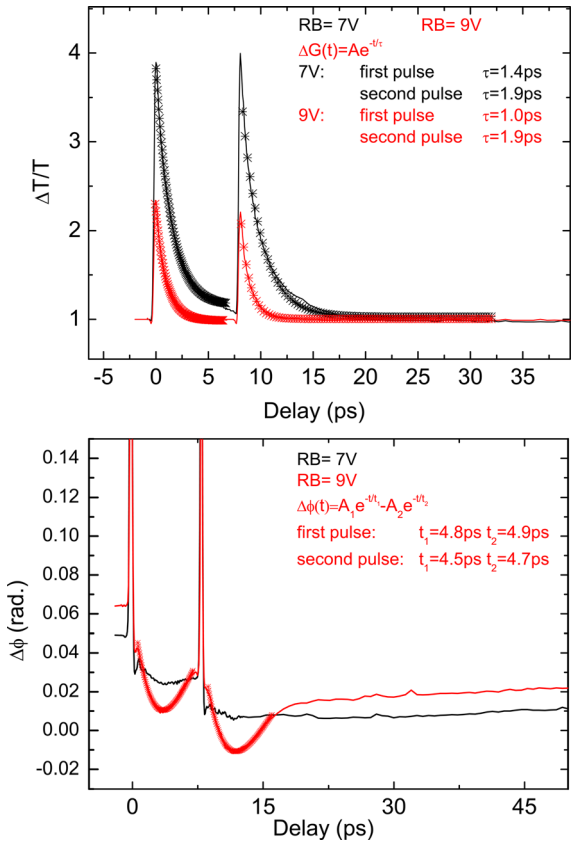

FIG. 3. (Color online) Transmission (top) and phase (bottom) dynamics at 7V and 9V RB, together with single exponential fitting to the transmission (stars) and bi-exponential fitting to the phase at 9V (stars). Note that the bi-exponential components in the phase fitting are of opposite sign.

effective barrier thickness which greatly reduces at high reverse bias due to the large tilting of the band edge and so depends on the energy offset between the QD state and wetting layer. This offset is similar for both the high energy GS states and low energy ES states that are contained within the pulse bandwidth and so a similar tunnelling timescale should occur for both. Such a picture is consistent with the simple single exponential timescale that is apparent after each of the pump pulses (see Figure 3).

The phase dynamics in the mixed state regime (7 V, 9 V) is shown in Figure 3 (bottom). At 7 V, the behaviour is similar to that at lower voltages, where the phase timescale is elongated due to cancelling contributions from various spectral components as occurs in the low voltage case. However, increasing the RB to 9 V results in an unusual phase oscillation whose amplitude is greater than the amplitude of the 7 V phase signal even though the level of absorption bleaching has decreased. Neglecting the spiking in the signal (which follows the autocorrelation of the pulse and is attributed to nonlinear effects such as four wave mixing and two photon absorption), a single oscillation can be fitted by a bi-exponential where each component has opposite sign and slightly different timescale, in Figure 3, it is 4.8 ps and 4.9 ps after the first pump pulse, after the second pulse it is 4.5 ps and 4.7 ps.

This ~5 ps timescale does not appear in the absorption dynamics at high RB which mainly involves high energy GS and low energy ES. However, due to inhomogeneous broadening, these states belong to different sized dots and so states

that are not involved in the transmission dynamics such as low energy GS states may be important for the phase dynamics through the Kramers-Kronig relations.

To explore the possibility of low energy GS states contributing a ~5 ps timescale to the phase dynamics, we consider a simple model of those QDs whose ES interacts with the pump/probe pulses. Following Ref. 13, Auger type carrier exchange between ES and GS should dominate and so we have the following equations for the occupation probabilities of the GS (ρ_g) and the ES (ρ_e), respectively:

$$\frac{d\rho_g}{dt} = -\tau^{-1}\rho_g + 2\tau_{cap}^{-1}\rho_e^2(1-\rho_g) - 2\tau_{esc}^{-1}\rho_g(1-\rho_e), \quad (1)$$

$$\frac{d\rho_e}{dt} = -\tau_w^{-1}\rho_e - \tau_{cap}^{-1}\rho_e^2(1-\rho_g) + \tau_{esc}^{-1}\rho_g(1-\rho_e), \quad (2)$$

where $1-\rho_{g,e}$ is the Pauli blocking factor, τ_{cap}^{-1} (τ_{ecs}^{-1}) are the carrier capture (escape) rates, and $\tau \approx 1$ ns is the carrier recombination time in the dots. The term $\tau_{cap}^{-1}\rho_e^2(1-\rho_g)$ describes recapture by the GS. The factor 2 in Eq. (1) accounts for the ES degeneracy and the parameter τ_w^{-1} is the carrier tunnelling rate from the ES to the wetting layer (WL) or barrier and strongly depends on the reverse bias. The initial conditions corresponding to ES pumping are $\rho_g(0)=0$, $\rho_e(0)=\rho_0\leq 1$.

We are interested in the solution for high voltages which implies $\tau_w^{-1} \approx \tau_{cap}^{-1} \gg \tau_{esc}^{-1}$, where $\tau_w = 1-2$ ps, $\tau_{cap} = 1-2$ ps, and $\tau_{esc} = 10$ ps, following the parameters used in Ref. 13. It can be proved that after the fast layer, we may approximate the solutions by two exponentials,

$$\rho_g(t) \sim \exp(-2t/\tau_{esc}), \rho_e(t) \sim \exp(-t/\tau_w).$$

So, the recovery of the ES will be completely determined by the direct escape to the barrier, and the recovery of the GS will have a timescale $\tau_{esc}/2$. Recalling that $\tau_{esc} = 10$ ps, this analysis results in a 5 ps timescale for the GS recovery.

Note that this treatment, while predicting a ~5 ps timescale for low energy GS populations outside the bandwidth of the pump/probe pulses, does not consider the possibility for tunnelling directly from the GS to the WL or barrier. It is very difficult to estimate this time without detailed knowledge of the structure's band edge and its deformation under high RB. Nonetheless, it is sensible that the timescale would be somewhat longer than the ES tunnelling time (~1 ps) and could also provide some correction to the dynamics in the ~5 ps range. The existence of these timescales in the low energy GS carrier populations could provide an oscillatory contribution to the phase dynamics at higher energies through the Kramers-Kronig relations while leaving the transmission at higher energies unaffected.

To provide an unambiguous mechanism for the phase oscillation, detailed calculations over the full absorption spectrum must be carried out. However, having demonstrated the existence of such an oscillation, it is useful to consider its impact on the performance of MMLLs. Such a phase variation would result in small optical cavity length fluctuations, which would directly result in an increase in the pulse to pulse jitter as well as impacting other important performance characteristics such as pulse-width, locking range, etc. Existing models[18] could be extended to incorporate such a phase oscillation in the absorber section to investigate this point further.

In conclusion, the reverse bias dynamics of InAs/GaAs quantum dots in a waveguide structure were investigated using multi-pulse heterodyne pump-probe measurements. The resulting transmission and phase dynamics over the bandwidth of the pulse were measured in the low RB single state case and the high RB mixed state case, where we simultaneously populate high energy GS and low energy ES. We identified a ~5 ps oscillation in the phase dynamics which we associated with low energy GS states and linked this oscillation to a possible role in the deterioration of monolithic mode locked laser performance at high reverse voltages.

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