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Refractive Index Dynamics and Linewidth Enhancement Factor in *p*-Doped InAs–GaAs Quantum-Dot Amplifiers

Valentina Cesari, Paola Borri, Marco Rossetti, Andrea Fiore, and Wolfgang Langbein

Abstract—Using a pump-probe differential transmission experiment in heterodyne detection, we measured the refractive index dynamics at the ground-state excitonic transition in electrically pumped InAs/GaAs quantum-dot amplifiers emitting near 1.3 μm at room temperature. We compare three samples differing only in the level of *p*-doping, and interpret the measured index changes taking into account the gain dynamics in these devices. We find that in absorption, the excess hole density due to *p*-doping accelerates the recovery and reduces the refractive index change, since filling of the hole states by *p*-doping shifts the induced changes in the hole population toward high energy states. Conversely, in gain, the reduced electron reservoir in the excited states in *p*-doped devices results in slower gain recovery dynamics and in larger refractive index changes compared to undoped devices operating at the same modal gain. The linewidth enhancement factor inferred from these measurements shows that *p*-doping is effective in reducing this parameter mainly due to the larger differential gain in *p*-doped devices in the gain regime.

Index Terms—Quantum dots (QDs), semiconductor devices, ultrafast spectroscopy.

I. INTRODUCTION

THE application of semiconductor quantum dots (QDs) in optoelectronics has progressed significantly in recent years, driven by the expectation of superior device performances in systems with reduced dimensionality. Epitaxially grown In(Ga)As–GaAs QDs are among the most widely investigated systems owing to continuous improvements in their fabrication and room-temperature emission in the telecommunication wavelength region. A number of devices embedding

these QDs have been already demonstrated, including electrically pumped diode lasers and semiconductor optical amplifiers (SOAs).

As well as providing gain, SOAs are exploited in optical networks as active nonlinear elements for all-optical signal processing at high speed. Such applications require knowledge of the ultrafast gain and refractive index dynamics to assess speed limits, and recent findings of ultrafast gain recovery dynamics in InGaAs QD-SOAs have attracted much attention. It has been shown experimentally that InGaAs QD SOAs can perform cross-gain modulation without pattern effects at bit rates of 10–40 Gb/s [1], and theoretical predictions of speeds up to 160 Gb/s have been made [2].

In addition to gain nonlinearities, all-optical logic operations using interferometers exploit refractive index nonlinearities. One of the advantages of interferometric schemes is that they can work successfully even at bit periods shorter than the recovery time of the carrier density when using delayed-interference loops [3]. It was recently speculated that interferometers containing QD SOAs are effective for ultrafast cross-phase modulation with low data pattern dependence [4]. This is due to a decoupling of gain and refractive index modulation mechanisms occurring under high electrical injection which would allow a phase change experienced by the probe being dominated by intraband transitions in the wetting layer without a change in the SOA gain by the control pulse. Due to the wetting layer acting as carrier reservoir in QD-SOAs, it was also speculated recently that all-optical XOR operation at 250 Gb/s is feasible using QD-based Mach–Zehnder interferometers [5]. However, only few experiments have been reported so far quantifying the refractive index nonlinearities and their dynamics in QD SOAs.

Ultrafast gain and refractive index dynamics can be directly measured in SOAs using a pump-probe technique in heterodyne detection as demonstrated for bulk and quantum well SOAs by Hall *et al.* [6]. Using an improved version of this technique we measured the gain recovery dynamics of both the ground-state (GS) and first-excited state (ES) transition in different types of InGaAs–GaAs QD SOAs [7]–[9]. We recently performed a direct comparison of the ultrafast gain recovery dynamics in undoped and *p*-doped InGaAs QD SOAs emitting near 1.3 μm at room temperature. The influence of *p*-doping on the gain properties of QD lasers has been attracting much interest as a way to increase the characteristic temperature for lasing threshold [10] and the maximum modulation bandwidth [11], [12]. It was suggested that faster carrier dynamics occur in *p*-doped QDs due to carrier–carrier scattering with the built-in hole reservoir [13],

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Fig. 1. Top: heterodyne detection scheme. AOM: acousto-optic modulators. Bottom: sketch of sample structure.

[14]. On the contrary, our comparison showed that the GS gain recovery dynamics is slower in p-doped amplifiers compared with undoped ones operating at the same modal gain [15]. This finding was attributed to a reduced filling of the electron ES and wetting layer states in p-doped QD devices, thus reducing the GS gain recovery mediated by electron relaxation.

In this study, we report a detailed analysis of the refractive index dynamics in the same undoped and p-doped QD SOAs discussed in our previous work [15]. Refractive index dynamics provides a tool to monitor changes in the population of states involved in optical transitions nonresonant to the exciting optical pulses. In fact, p-doped and undoped devices operating at the same modal gain in the GS transition did show different refractive index changes when excited in the GS, which we could attribute to different ES occupations, consistent with the observed gain dynamics. Moreover, by comparing the measured gain and refractive index changes, we have deduced a linewidth enhancement factor (or α -factor), which resulted to be lower in the p-doped compared to the undoped devices.

II. SAMPLES AND EXPERIMENT

All investigated samples are p-type-intrinsic-n-type (p-i-n) ridge waveguide diode structures of 4- μm width and 0.5-mm length containing 10 InGaAs dot-in-well layers, with a dot ground-state transition around 1300 nm, separated by 33-nm GaAs spacers and embedded between 1.5- μm -thick AlGaAs cladding layers (see the diagram in Fig. 1). p-doping near the QDs is achieved by incorporating a 10-nm-thick region of carbon-doped GaAs in the spacer layer, ending 9 nm below each dot-in-well layer. We estimate a doping level of ~ 8 (p sample) and ~ 15 (p+ sample) acceptors per dot, while a third sample had undoped GaAs spacers. All samples were processed with tilted facets ($\sim 7^\circ$) to avoid back-reflections into the waveguide mode and lasing [16]. Amplified spontaneous emission (ASE) spectra showed on all samples an inhomogeneous broadening of the GS transition of ~ 36 meV due to fluctuations in dot size and alloy composition [15], [16] and an emission from the first optically active ES transition at about 60 meV above the GS transition.

Gain and refractive index dynamics in resonance with the GS transition were measured at room temperature using a pump-probe differential transmission technique in heterodyne

Fig. 2. Gain and refractive index dynamics for the undoped (solid lines), p-doped (dotted lines), and p+-doped (dashed lines) devices as a function of the pump-probe delay time.

detection which is described in detail in [9], [17]. Briefly (see the diagram in Fig. 1), ~ 100 fs Fourier-limited laser pulses at 76-MHz repetition rate are divided into pump, probe and reference beams. Pump and probe pulses are coupled into the transverse electric waveguide mode with a relative delay time τ_p (positive for pump leading) and the transmitted probe is detected using a heterodyne technique. For this technique, probe and pump beams are shifted by a RF amount using acousto-optical modulators. The probe transmitted through the device interferes with the unshifted reference pulse and is detected at the corresponding RF by two balanced photodiodes and a lock-in amplifier [7], [8]. Due to the interferometric detection, we are sensitive to both amplitude and phase changes of the transmitted probe field induced by the pump pulse.

III. GAIN AND INDEX DYNAMICS

Gain and refractive index dynamics of the undoped and p-doped QD SOAs measured for pump and probe pulses in resonance with the QD GS transition are shown in Fig. 2. The pump-induced change of the gain in decibels (ΔG) deduced from the probe transmission change is shown versus pump-probe delay time τ_p for injection currents in the absorption and gain regime, corresponding to the same modal gain (Γg) in all samples. Data are taken for the same input pump intensity and are normalized to the average pump intensity propagating through the waveguide, for comparison [15], [18]. Refractive index changes Δn are deduced from the probe phase changes $\Delta \phi$ via $\Delta n = \Delta \phi(\lambda/2\pi L)$ where L is the device length and λ is the probe wavelength in vacuum.

Fig. 3. Contribution to the refractive index ($n(E)$) probed at the ground state transition E_{GS} if an excited state transition described by the spectral gain $g(E)$ centered at E_{ES} is in the gain ($g(E) > 0$, solid lines) or absorption ($g(E) < 0$, dashed lines) regime.

As discussed in our previous work [15], in the absorption case, a faster recovery of the pump-induced absorption bleaching occurs in the *p*-doped devices compared to the undoped one. Since a significant part of this recovery dynamics occurs within the 100 fs pulse duration, a faster absorption recovery manifests as reduced gain change (ΔG) which is left in the *p*-doped devices after the pump pulse. We showed that, when resolving the initial dynamics from the data, by extracting a material response function deconvoluted from the pulse autocorrelation, a speeding up of the initial dynamics was systematically observed with increasing *p*-doping [15]. When comparing the refractive index dynamics, smaller refractive index changes are measured in the *p*-doped devices compared to the undoped one. In the gain case, the situation is opposite with faster gain recovery dynamics (ie smaller leftover gain change after the pump pulse) and smaller refractive index changes in the undoped device.

To understand these findings, we represent in Fig. 3 the role of an excited state transition, being in the absorption or gain regime, to the refractive index probed at the GS transition. The ES absorption transition contributes with a positive refractive index at the GS, and thus a bleaching of the ES absorption due to carrier occupation into the ES gives rise to a decrease of the refractive index at the GS. Vice versa, the ES gain transition contributes with a negative refractive index at the GS, and thus a compression of the ES gain due to removal of carriers from the ES gives rise to an increase of the refractive index at the GS.

In the GS absorption regime shown in Fig. 2, carriers are optically excited into the GS by the pump pulse. As they thermalize into the ES, a build-up of a negative refractive index change is probed at the GS (i.e., the refractive index decreases). We suggest (see the diagram in Fig. 4) that the reduced refractive index change observed in the *p*-doped samples is due to the built-in hole reservoir which via hole–hole scattering accelerates the removal of the optically injected hole from the GS on a time scale comparable to the pump-pulse duration. This results into a change of the hole occupation probed after the pump pulse which is mainly at energy states higher than the

Absorption:

Gain:

Fig. 4. Schemes of the processes proposed to explain the gain and refractive index dynamics. *p*-doping results in a built-in hole reservoir, as depicted. Absorption: carriers are optically excited into the GS by the pump photons (curly arrow). In the *p*-doped device fast hole-hole scattering occurs within the pump-pulse duration, such that the changes in hole occupation probed after the pump involve high energy states less contributing to refractive index changes. In addition, electron thermalization into the ES might be reduced due to the Coulomb attraction potential (dashed line) induced by the built-in hole reservoir from *p*-doping. Gain: A pump-photon (curly arrow) stimulates the recombination of a GS electron–hole pair. The ES electron reservoir in the undoped sample mediates ultrafast relaxation, such that the change in electron occupation probed after the pump involves high energy states less contributing to refractive index changes.

ES (most probably in the wetting layer) and thus much less affecting changes in the GS refractive index. This picture is consistent with the measured recovery of the absorption bleaching which in the *p*-doped samples occurs on a time scale comparable to the pump-pulse duration and thus manifests as a lower maximum absorption bleaching measured in these samples for the same pump intensity and at the same modal gain. In addition, due to the positively charged built-in holes, one can expect a Coulomb attractive potential experienced by the optically injected electron in the *p*-doped samples (depicted as dashed line in the sketch in Fig. 4). This effect would reduce the electron thermalization into the ES and thus also the probed GS refractive index change.

In the gain case, the opposite occurs. A pump-photon stimulates the recombination of a GS electron–hole pair. As carriers relax from the ES back into the GS, a build-up of a positive refractive index change is probed at the GS (i.e., the refractive index increases). We have attributed the slower gain recovery dynamics in the *p*-doped samples as due to a reduced electron reservoir in the higher energy states thus reducing the GS gain recovery mediated by electron relaxation into the GS [15], [18]. When such carrier reservoir is present, as in the undoped sample (see sketch in Fig. 4), ultrafast recovery of the gain compression mediated by carrier–carrier scattering occurs on a time scale

Fig. 5. Pump-induced gain (in decibels) and refractive index changes versus modal gain Γg at 1-ps and 10-ps pump-probe delay times.

comparable to the pump-pulse duration, as observed in the measurements. Therefore, also in this case, the change of the carrier occupation probed after the pump pulse is mainly at energy states higher than the ES (e.g., wetting layer states) and thus affects the refractive index less.

A complementary way of comparing gain and index dynamics between samples is shown in Fig. 5, where the change left after the pump pulse at a give delay time is plotted as a function of the small-signal modal gain Γg . In absorption ($\Gamma g < 0$), the gain change (ΔG) is smaller in the doped samples than in the undoped one i.e., the recovery of the absorption bleaching is faster. On the contrary, in the gain regime ($\Gamma g > 0$), the undoped device exhibits the smallest gain change (in absolute value), i.e., the fastest recovery dynamics. When comparing the refractive index changes (Δn) we find that as long as negative changes are observed in the absorption regime they are smaller (in absolute value) in the p-doped devices compared to the undoped one. *vice versa* in the gain regime index changes are always larger in the p-doped devices.

In the gain case, $|\Delta G|$ exhibits a maximum with increasing modal gain. As pointed out in our previous works [15], [18], this is explained by considering that $|\Delta G|$ increases since, with increasing GS modal gain, a higher population inversion is available for pump-stimulated transitions, but this effect saturates with the GS modal gain. A further increase of the electrical injection mainly populates the ES and wetting layer states and leads to a decrease $|\Delta G|$, i.e., faster gain recovery dynamics, consistent with the importance of a carrier reservoir in the ES and wetting layer for an ultrafast GS gain recovery [8], [19]–[21]. In the p-doped devices, the maximum of $|\Delta G|$ is bigger in amplitude and shifted to higher Γg , due to a reduced carrier reservoir in the electron ES and wetting layer states and thus less electron-mediated relaxation dynamics. The built-in hole density in the p-doped devices is not significant in accelerating the gain dynamics here, since at gain also the undoped

Fig. 6. Pump-induced gain (in decibels) and refractive index dynamics at GS transparency current (I_{tr}).

sample has a significant hole reservoir in the high energy states due to the smaller hole level spacing, less than the thermal energy at room temperature.

In the regime of gain saturation and ultrafast gain recovery mediated by a carrier reservoir in the ES and wetting layer states, also saturation of the refractive index change toward essentially the same value (for a given pump intensity) is observed in all devices. In this regime a decoupling of the pump-induced changes occurs, with a saturated phase change and a vanishing amplitude change. This can be understood by the large difference between the carrier-carrier scattering time ($\tau_c \sim 10$ fs), and the carrier lifetime $\tau_1 \sim$ ns. The phase change builds with τ_c and decays with τ_1 , while the gain change builds with the pulse duration and decays with τ_c . Thus, in the large time span from τ_c to τ_1 , only the phase change remains. This situation is peculiar to QD SOAs, essentially because higher dimensional devices with larger density of states cannot be driven into complete inversion due to heat dissipation problems. Such decoupling effect can be exploited for ultrafast cross-phase modulation without pattern effects, as suggested in [4].

Near transparency ($\Gamma g \sim 0$), a positive refractive index change is noticeable in the p-doped devices. This is highlighted in Fig. 6 where gain and index dynamics are compared at transparency current for all devices. Transparency of the active medium is reached when the net number of stimulated transitions is zero, and thus no pump-induced changes associated with these transitions are present after intraband thermalization. However, a pump-induced two-photon absorption (TPA) of probe photons (mainly via transitions in the wetting layer and barrier continuum) as well as a pump-induced free carrier absorption (FCA) [22] are still present at transparency and give rise to the observed transients. In particular the significantly different phase dynamics in the p-doped devices show the

importance of hole FCA. The pump-induced FCA is heating the carrier distribution, thus increasing the refractive index experienced by the probe by shifting the ES hole occupation into higher energy states. The resulting phase change recovers on a 100-ps timescale, as expected for a heating effect. Furthermore, since in the *p*-doped devices transparency is reached mainly due to hole occupation, the removal of GS holes by FCA is dominating the gain dynamics. By virtue of the larger density of states, FCA by holes is much larger than for electrons, and therefore the gain change by FCA is larger in *p*-doped devices.

IV. LINEWIDTH ENHANCEMENT FACTOR

An important parameter for the performance of semiconductor optical lasers/amplifiers is the linewidth enhancement factor (LEF), also called α -parameter, which is defined as the ratio between the change induced by carrier density (N) of the real and imaginary part of the susceptibility, i.e., of the refractive index n and gain g , via the expression [23]

$$\alpha = -\frac{4\pi}{\lambda} \frac{\frac{dn}{dN}}{\frac{dg}{dN}} \simeq -\frac{4\pi}{\lambda} \frac{\Delta n_e}{\Delta \Gamma g} \quad (1)$$

where Δn_e and $\Delta \Gamma g$ are the density-induced variations of the effective refractive and of the modal gain, respectively. In a semiconductor laser, the LEF can be used to describe quantitatively the linewidth under continuous-wave (CW) operation but also the frequency chirp under high-speed current modulation. Furthermore, a high value of α leads to self-focusing and, therefore, to filamentation, which limits the performance of high-power semiconductor lasers. In SOAs, the LEF has become a powerful tool for predicting the nonlinear phase shift observed in connection with gain nonlinearities.

QD-based devices in principle offer the possibility to achieve zero LEF due to their atom-like density of states giving rise to a symmetric gain spectrum. Recent measurements of the LEF in InGaAs–GaAs QD lasers and amplifiers indeed indicated values of α below 1, however only at low injection currents near/below transparency or at low temperatures [24], [25]. A smaller LEF at photon energies above the GS, eventually reaching even negative values above the ES, was also observed [24]. On the contrary, close to GS saturation, very large LEF values and even pure phase modulation have been observed [26], [27].

The role of *p*-doping on the α -parameter of QD-lasers was investigated recently [28]. It was predicted that *p*-doping would result in a lower LEF near threshold, however no experimental comparison between undoped and *p*-doped devices was reported. Our measurements of the pump-induced gain and index dynamics, such as those in Fig. 2, allow us to derive a dynamic α -parameter according to the expression [24]

$$\alpha(\tau_p) = -10 \log e \frac{4\pi L}{\lambda} \frac{\Delta n(\tau_p)}{\Delta G(\tau_p)(\text{dB})}. \quad (2)$$

A comparison of the LEF between undoped and *p*-doped devices at the same modal gain is shown in Fig. 7. Similar to our previous results on InGaAs QD SOAs emitting near

Fig. 7. Transient LEF versus pump-probe delay time in the absorption ($\Gamma g = -19 \text{ cm}^{-1}$) and gain regimes ($\Gamma g = 14 \text{ cm}^{-1}$), as indicated.

$1.1 \mu\text{m}$ at room temperature, the LEF is below 1 only in the absorption case and shows a transient dynamics due to the intra- and inter-dot redistribution of the optically pumped carriers. A nearly constant value is approached when both gain and phase dynamics are governed by the same overall carrier density decay at thermal equilibrium ($> 100 \text{ ps}$). It is interesting to observe that the *p*-doped samples indeed exhibit a smaller LEF, which is not *a priori* obvious since both phase and gain changes were found to be larger (smaller) in the *p*-doped samples compared to the undoped one in the gain (absorption) case (see Fig. 2). In fact, the results in Fig. 7 give evidence that is the larger gain change to play a key role in reducing the LEF in *p*-doped devices in the gain regime. Such finding is consistent with the general observation that the LEF is decreased under operating conditions which increase the differential gain, such as low injection current, low device temperature or ES emission [24].

To infer a value of the LEF solely due to carrier-density changes, we have time-integrated the pump-induced gain and refractive index changes for $\tau_p > 100 \text{ ps}$ and defined a time-integrated α -parameter according to the expression

$$\alpha = -10 \log e \frac{4\pi L}{\lambda} \frac{\int_{100 \text{ ps}}^{\infty} \Delta n(\tau_p) d\tau_p}{\int_{100 \text{ ps}}^{\infty} \Delta G(\tau_p)(\text{dB}) d\tau_p}. \quad (3)$$

The results are shown in Fig. 8 for all investigated samples. The region near transparency current is hatched since the error in dividing through small gain changes is large and FCA is also affecting the phase dynamics in the doped devices (see Fig. 6). The LEF increases with increasing injection current (modal gain) and is above 1 in the gain region, however, it increases less

Fig. 8. Time-integrated LEF versus modal gain for the undoped (squares), p-doped (dots), and +doped (triangles) device. The region near transparency which is influenced by FCA is hatched.

rapidly and is lower in the p-doped devices compared with the undoped one operating at the same modal gain. These results thus show that p-doping is indeed effective in reducing the LEF. In the gain saturation regime, the LEF eventually diverges, indicating the possibility of pure phase modulation as discussed earlier [27].

V. CONCLUSION

We have measured and compared the refractive index dynamics in p-doped and undoped InAs–GaAs QD amplifiers operating at the same modal gain. The measured gain and index changes indicate that the built-in hole reservoir due to p-doping facilitates the ultrafast absorption recovery via hole–hole scattering but also results in lower refractive index changes probed after the pump due to hole population changes mainly occurring at energies higher than the first excited state. This in turn corresponds to a lower α -parameter in p-doped devices. *Vice versa*, since in the gain case p-doping allows to achieve the same GS modal gain with a reduced excited-state electron reservoir, the GS gain compression recovery is slower and the refractive index change probed after the pump is higher in p-doped samples compared with the undoped one. The larger gain change left after the pump eventually results in a smaller α -parameter in p-doped devices, even when only the overall density changes are taken into account in the dynamics at long delays. In addition, we find that under very high electrical injection the condition of saturating the refractive index change can be reached while the gain change are negligible in these QD amplifiers, which is promising for ultrafast cross-phase modulation without pattern effects.

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