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Ultrafast gain dynamics in 1.3 μm InAs/GaAs quantum-dot optical amplifiers: The effect of *p* doping

Valentina Cesari, Wolfgang Langbein, and Paola Borri[a)]
School of Physics and Astronomy, Cardiff University, The Parade, Cardiff CF24 3AA, United Kingdom and School of Biosciences, Cardiff University, Museum Avenue, Cardiff CF10 3US, United Kingdom

Marco Rossetti and Andrea Fiore
Institute of Photonics and Quantum Electronics, Ecole Polytechnique Fédérale de Lausanne, Station 3, CH-1015 Lausanne, Switzerland

S. Mikhrin, I. Krestnikov, and A. Kovsh
Innolume GmbH, 44263 Dortmund, Germany

Ultrafast gain dynamics of the ground-state transition are measured in electrically pumped InAs/GaAs quantum-dot amplifiers emitting near 1.3 μm at room temperature. Gain recovery on a subpicosecond time scale occurs at high electrical injection. However, when comparing *p*-doped and undoped devices fabricated under identical conditions and operating at the same gain, faster absorption recovery but *slower* gain dynamics are observed in *p*-doped amplifiers. The slower gain dynamics is attributed to a reduced reservoir of excited-state electrons in *p*-doped quantum-dot devices, which limits the recovery of the electron ground-state occupation mediated by intradot carrier-carrier scattering. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2739079]

Semiconductor quantum-dot (QD) lasers and amplifiers are promising devices for optoelectronics with a number of predicted superior performances related to zero-dimensional systems. Epitaxially grown self-assembled In(Ga)As/GaAs QDs are among the most widely investigated and most advanced systems owing to continuous improvements in their fabrication and room-temperature emission in the optical telecommunication 1.3–1.55 μm wavelength range.[1–3] Recently, In(Ga)As QD lasers incorporating *p*-type modulation doping have generated much interest due to reports of temperature insensitive threshold current,[4] increased peak modal gain,[1,5,6] and high modulation bandwidth.[3]

The role of *p* doping in improving the maximum modulation speed in QD lasers has been particularly debated in literature. Recent predictions attributed considerable improvements to an increase in the differential gain,[7–9] while, on the other hand, carrier-capture and relaxation processes play a crucial role for achieving high-frequency operations and are likely to be influenced by *p* doping. Time-resolved photoluminescence experiments have shown faster carrier capture and relaxation from the GaAs barrier to the QD ground state in doped (*p*- and *n*-type) QDs as compared to undoped ones, both at low and room temperatures.[10,11] These findings would support the development of high-speed QD lasers with faster carrier dynamics in modulation-doped QDs. Recent reports on *p*-doped InGaAs QD semiconductor optical amplifiers (SOAs) have shown nearly distortion-free amplification of up to 80 GHz pulse trains[12] and ultrafast gain recovery after amplification of double pulses,[13] further supporting the idea that high-speed operation is possible in *p*-doped QD devices due to faster gain dynamics.

However, a direct comparison of the gain dynamics between undoped and *p*-doped QD amplifiers under working conditions (i.e., under electrical injection and at room tem-

perature) has not been performed so far; thus direct evidence of improved gain dynamic due to *p* doping is still missing. In this work, we measured the ultrafast gain dynamics of the QD ground-state (GS) transition in three electrically pumped InGaAs QD amplifiers emitting near 1.3 μm at room temperature, grown by molecular beam epitaxy under identical conditions except from different levels of *p* doping in the active region.

All investigated samples are *p*-type–intrinsic–*n*-type ridge waveguide diode structures of 4 μm in width and 0.5 mm in length containing ten InGaAs dot-in-well layers separated by 33 nm GaAs spacers and embedded between 1.5-μm-thick AlGaAs cladding layers (see sketch in Fig. 1).
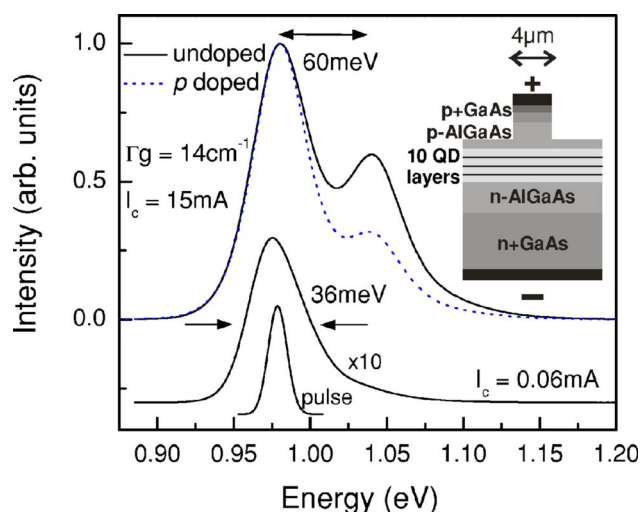

FIG. 1. (Color online) Room-temperature amplified spontaneous emission spectra at low and high injection currents (I_C) as indicated. The two spectra for undoped and *p*-doped devices correspond to the same modal gain and have been normalized to the GS emission for comparison. Curves are shifted vertically for clarity. The spectrum of the laser pulse used in the experiment is also shown.

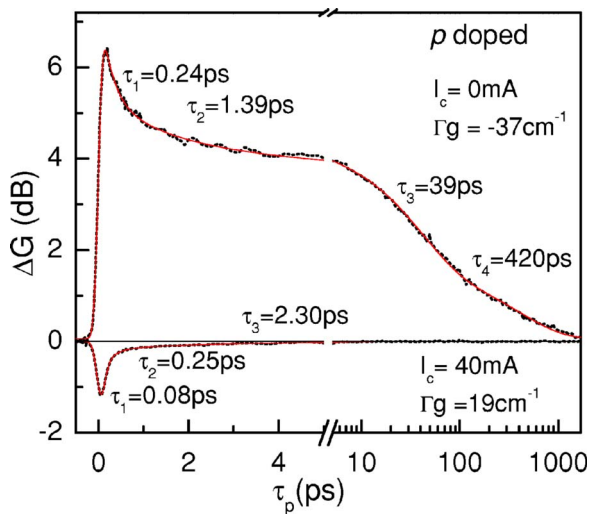a)Electronic mail: borrip@cardiff.ac.uk

FIG. 2. (Color online) Pump-induced transmission change of the ground-state transition at 300 K in the *p*-doped QD amplifier. Data (dotted lines) together with fits (solid lines) are shown in the absorption and gain regimes as indicated. The time constants deduced from a multiexponential fit are also indicated.
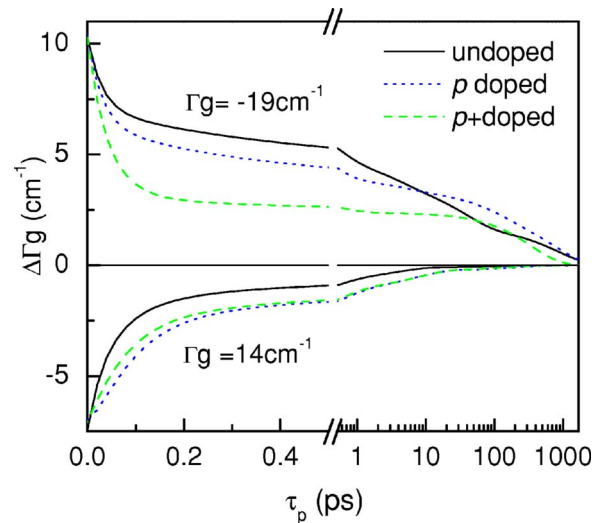

FIG. 3. (Color online) Pump-induced modal gain change after deconvolution with the pulse intensity autocorrelation. A comparison between the samples for the same pump intensity and the same small-signal modal gain is shown in the absorption and gain regimes.

p doping near the QDs is achieved by incorporating a 10-nm-thick layer of carbon-doped GaAs in the spacing 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 ($\sim 7°$) to avoid back reflections into the waveguide mode and lasing.[6] Gain dynamics is measured using a pump-probe differential transmission technique in heterodyne detection, as described in our previous works,[14,15] with ~ 100 fs Fourier-limited pump and probe pulses at 76 MHz repetition rate in resonance with the QD GS transition (see Fig. 1).

Amplified spontaneous emission spectra at different injection currents (I_C) are shown in Fig. 1. At small current, the spectrum of the undoped device is dominated by the GS emission with an inhomogeneous broadening of ~ 36 meV due to fluctuations in dot size and alloy composition (similar spectra were measured for all samples[6]). With increasing I_C, emission from the first optically active excited-state (ES) transition is visible 60 meV above the GS. In Fig. 1, two spectra are compared for the undoped and *p*-doped devices at an injection current corresponding to the same GS modal gain $\Gamma g = 14$ cm⁻¹ (modal gain versus I_C was measured via the transmission of the weak probe[14,15]). The comparison clearly shows a suppression of the ES emission in the *p*-doped sample, similar to what was reported in Ref. 1.

The pump-induced change of the gain in decibels (ΔG) deduced from the probe transmission change is shown in Fig. 2 versus pump-probe delay time τ_P (positive when the pump pulse is leading) for the *p*-doped sample in the absorption and gain regimes as indicated. Data taken for the same input pump intensity are normalized to the pump intensity averaged along the device length L by dividing through the factor $(1/L)\int_0^L \exp((\Gamma g + \Delta\Gamma g)z)dz$. Fits of the dynamics (solid lines) are obtained by convoluting the pulse intensity autocorrelation with a multiexponential response function (time constants are given in Fig. 2), also including instantaneous contributions from two photon absorption and coherent artifact.[14] While the absorption bleaching rises following the integral over the pulse duration and eventually recovers over

several hundreds of picoseconds by interband recombination processes, the gain dynamics is much faster, dominated by subpicosecond time constants with complete gain compression recovery after only a few picoseconds.

In order to compare directly the gain dynamics in undoped and *p*-doped QD amplifiers, we measured the dynamics at the same modal gain in all devices. The good quality of our fits allowed us to extract the material response function deconvoluted from the pulse autocorrelation. Response functions deduced from the data after the normalization discussed above for the same input pump intensity in all devices are shown in Fig. 3. In the absorption regime, a speeding up of the initial dynamics is systematically observed with increasing doping. On the other hand, gain recovery dynamics is clearly slower in the doped samples. Another way of comparing gain dynamics between samples is shown in Fig. 4
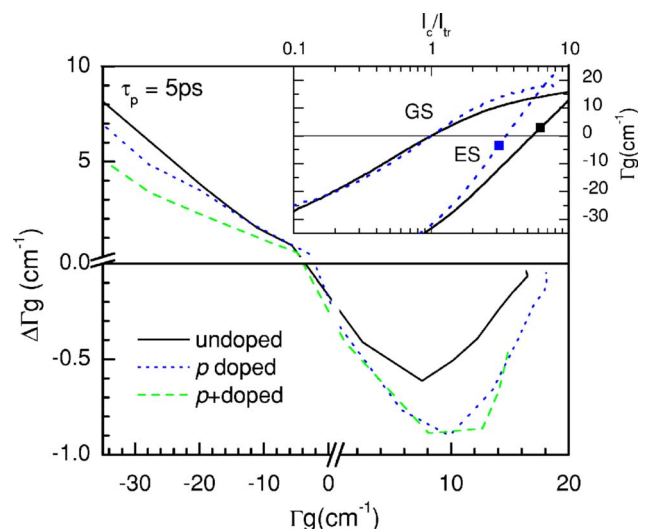

FIG. 4. (Color online) Pump-induced modal gain change after 5 ps pump-probe delay as a function of the small-signal gain. In the inset, the ES and GS small-signal gains are shown vs injection current in units of GS transparency current I_{tr}, this latter being 2.4 and 4.8 mA for the undoped and *p*-doped samples, respectively. Symbols highlight the ES gain at 14 cm⁻¹ GS gain.

where the modal gain change $\Delta\Gamma g$ left after the pump pulse [deduced from $\Delta G = (10 \log e)\Delta\Gamma gL$] at 5 ps delay time is plotted as a function of the small-signal modal gain Γg. In absorption, the change 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, the undoped device exhibits the smallest gain change (in absolute value), i.e., the fastest recovery dynamics.

Our findings in the absorption regime are consistent with the expectation that large built-in excess number of holes within the dot due to p doping might accelerate carrier-carrier scattering mediated dynamics, as suggested in recent time-resolved experiments.[10] Since our optical excitation is in resonance with the GS transition, we are not monitoring carrier relaxation dynamics but carrier escape away from the GS transition. Therefore, the carrier-carrier scattering events being accelerated by the built-in holes might be quite different from the electron-hole scattering mechanism discussed in Ref. 10. At room temperature, we observe only $\sim 20\%$ reduction of the GS absorption in the p-doped device, indicating an occupation of excited and wetting layer states by the built-in holes due to thermal spreading and hole Coulomb repulsion. This allows hole-hole scattering once GS holes are optically injected.

On the contrary, slower gain dynamics in p-doped QDs appears surprising. In Fig. 4, $|\Delta\Gamma g|$ shows a maximum with increasing electrical injection and consequently modal gain, which can be understood as follows. Initially, $|\Delta\Gamma g|$ increases since with increasing GS modal gain, a higher population inversion is available for pump-stimulated transitions. This effects saturates like the modal gain Γg, which is displayed versus injection current in the inset of Fig. 4. A further increase of the electrical injection no more results in an efficient increase of the GS gain but in a population of the ES and higher energy transitions.[6] At this stage, $|\Delta\Gamma g|$ decreases implying faster gain recovery dynamics consistent with several other reports underlining the importance of a carrier reservoir in the ES and wetting layer for an ultrafast GS gain recovery mediated by Auger-like relaxation processes.[15–18] In p-doped devices, the maximum of $|\Delta\Gamma g|$ is bigger in amplitude and shifted to higher Γg. Recent reports have shown that the modal gain spectra of InGaAs QDs are quite different between p-doped and undoped devices.[5] For the same GS modal gain, p-doped QDs show an ES distribution of carriers spectrally crossing transparency at significantly lower energies than undoped devices. These findings are consistent with our observation of suppressed ES emission in p-doped QDs for the same GS gain compared to undoped dots (see Fig. 1). Indeed, we also measured a reduced ES small-signal gain for the same GS gain in the p-doped devices (see inset of Fig. 4). The slower gain dynamics in p-doped QD SOAs as observed in Figs. 3 and 4 is thus consistent with a reduced carrier reservoir in the ES and wetting layer states and thus less ultrafast relaxation dynamics mediated by Auger-like processes. We believe that electrons, rather than holes, have a reduced ES occupation for the same GS gain in p-doped QDs. In fact, the large built-in hole concentration is thought to ensure that the same GS gain is achieved with less total number of injected electrons in p-doped compared to undoped dots.[8] Moreover, given the larger energy level separation for electrons than holes in InGaAs QDs, the ES/GS emission ratio at room temperature, which we measure to be reduced in p-doped QDs, mainly reflects the ratio in the electron occupation.

In conclusion, although complete gain recovery can be achieved after only a few picoseconds at high levels of electrical injection in InGaAs QD amplifiers, the gain recovery is *slower* in p-doped SOAs compared to identically fabricated undoped devices when directly comparing the dynamics at the same modal gain. We believe that these results provide a significant step forward to a clearer understanding of the benefit of p doping for the development of high-speed QD-based lasers and amplifiers and might stimulate improved modeling of the carrier distributions in these systems.

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