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Temperature dependence of electroabsorption dynamics in an InAs quantum-dot saturable absorber at 1.3 μm and its impact on mode-locked quantum-dot lasers

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We report temperature-dependent absorption recovery times in an InAs p-i-n ridge waveguide quantum-dot modulator under low reverse bias, investigated via subpicosecond pump-probe measurements. The measured decrease in absorption recovery time with increasing temperature (293–319 K) is in excellent agreement with a thermionic emission model. A similar trend in pulse duration with increasing temperature is also observed from a two-section mode-locked quantum-dot laser fabricated from a similar epitaxial structure. These measurements confirm the key role of the absorber recovery time in the reduction in the pulses generated by two-section mode-locked quantum-dot lasers, both at room and elevated temperatures. © *2010 American Institute of Physics*. [doi:10.1063/1.3489104]

Quantum-dot (QD) structures are currently one of the most promising materials for the design of saturable absorbers that have been employed in a wide range of ultrafast laser systems, turning them into more compact and reliable ultrashort pulse laser sources.[1,2] A QD-based saturable absorber presents several advantages such as ultrabroadband absorption, ultrafast absorption recovery, and lower saturation fluence than its quantum-well based counterpart.[2] Such advantages have been demonstrated in the generation of ultrashort pulses from monolithic mode-locked laser diodes (MLLDs), where the required specifications of a saturable absorber are more stringent—in particular, the absorption recovery time should be fast enough to accommodate the high repetition rate pulses generated by MLLDs. In a previous publication, we investigated the ultrafast absorption recovery time from a QD modulator and its dependence on the applied reverse bias.[3] Absorption recovery times at room temperature ranging from 62 ps (0 V) to 700 fs (10 V) were found, showing a decrease by nearly two orders of magnitude with increasing reverse bias, and indicating two regimes of carrier escape as follows: thermionic escape, which was dominant between 0 and 4 V and tunneling escape, which dominated above 4 V. The results suggested that the dynamic response of the device is limited by one type of carrier only, in contrast to measurements reported in other QD structures with no applied bias.[4] More recently, Piwonski *et al.*[5] have measured the absorption recovery time for both ground and excited state transitions, as a function of reverse bias—which revealed different intradot relaxation dynamics depending on which of the states was populated.

We have also previously shown that mode locking in a QD MLLD also remains stable in a broad temperature range and up to 80 °C.[6] Interestingly, it was also found that ML operation at high temperature could be achieved from lower values of reverse bias applied to the saturable absorber.[6] A subsequent experimental and theoretical investigation showed that the pulse duration decreases significantly as the temperature is increased, for a fixed reverse bias.[7] An assessment of carrier escape from such structures at elevated temperatures would therefore prove valuable for understanding and modeling the processes responsible for pulse formation. The insights from this study are also of significance for the development of QD lasers that can generate ultrashort pulses under uncooled operation.

In this work, we have directly measured the temperature-dependent QD absorption recovery in a waveguide structure utilizing differential transmission spectroscopy (DTS) with a degenerate pump-probe setup, which has been previously described elsewhere.[3] A schematic of the DTS setup is depicted in Fig. 1. The orthogonally polarized pump (TM) and probe (TE) pulses are produced by an 80 MHz optical parametric oscillator with an output pulse duration of 250 fs. The pump

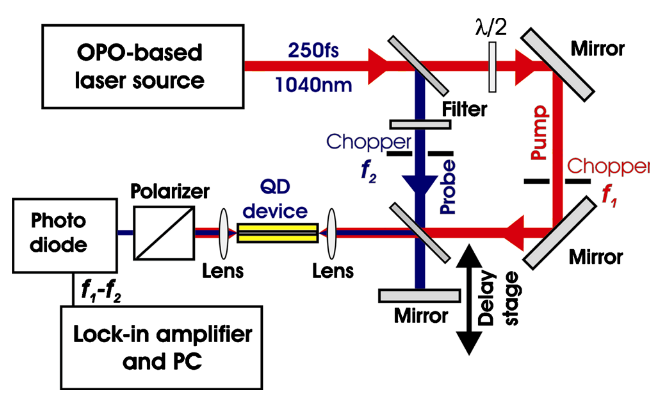

FIG. 1. (Color online) Schematic of the DTS setup.

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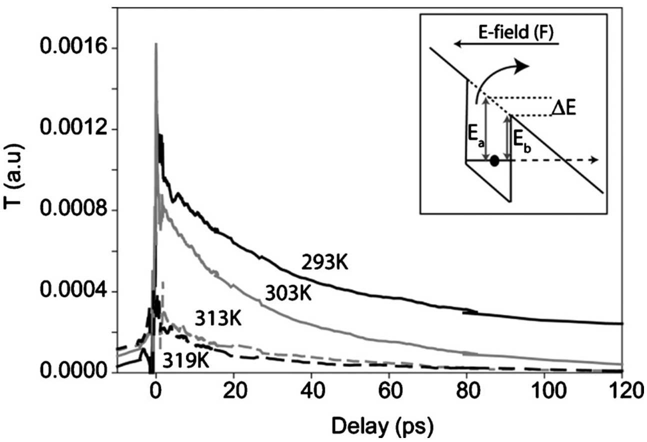

FIG. 2. Absorption recovery in an InAs DWELL QD saturable absorber for a reverse bias of 2 V over an elevated temperature range. Inset illustrates thermionic emission and tunneling.

and probe pulse energies employed were 580 fJ and 58 fJ, respectively. The pump/probe pulses were tuned to the ground state transition of the QD sample (1280 nm) and with a pulse bandwidth of 7.5 meV, direct excitation to the upper state was avoided. The sample was based on a p-i-n InAs dot-in-a-well (DWELL) waveguide structure, grown on a Si-doped GaAs substrate. The waveguide was 1.1 mm long with a 6 μm ridge width. The active region comprised five periods of 2.5 monolayers of InAs, 5 nm $In_{0.15}Ga_{0.85}As$, followed by 33 nm of GaAs buffer material. Including the active layers, the width of the intrinsic region was d=360 nm. The sample was mounted on a copper heatsink and a Peltier-based element was used for control and stabilization of the operating temperature.

We carried out DTS on the above sample with an increasing device temperature, from 293 to 319 K.[8] The measured traces for an applied reverse bias of 2 V are shown in Fig. 2. The pump pulse energy employed was 580 fJ, causing absorption saturation through band-filling and giving rise to the steplike increase in probe transmission.

With increasing probe delay, the transmission decays as photogenerated electrons and holes either escape or recombine. The curves in Fig. 2 show initially high transmission of the probe when delayed relative to the pump pulse, indicating a saturation of the ground state. We found that the measured absorption recovery traces are best fitted to a single exponential of the type $\exp(-t/\tau)$ in a simple rate equation model, where τ is the recovery time, indicating that the dynamic behavior is dominated by one type of carrier, as previously observed in the measurements as a function of applied field.[3] As previously demonstrated in our work, tunneling processes are highly improbable under low reverse bias and thermionic emission is expected to be the dominant carrier escape mechanism.[3] As such, the characteristic times are then fitted to a thermionic emission equation, $\tau = A^{-1}T^{-2}\exp(E_b/kT)$, where τ is the carrier escape time, A is a material dependent constant, E_b is the barrier height, and k and T are the Boltzmann constant and absolute temperature, respectively. A similar approach has been extensively used for the thermionic emission of carriers from quantum wells.[9]

The experimental results and the fit are depicted in Fig. 3(a), indicating a decrease in absorption recovery time from 38 (293 K) to 24 ps (319 K) for a constant reverse bias of 2 V (55 kV/cm). This trend implies that the temperature assists the removal of the photogenerated carriers in the absorber and therefore contributes to the reduction in absorber recovery time. Such observation agrees with previous measurements reported in the literature using time-resolved photoluminescence at reduced temperatures (in the range 10–130 K), which have demonstrated emission back into the wetting layer of QD structures with increasing temperature.[10]

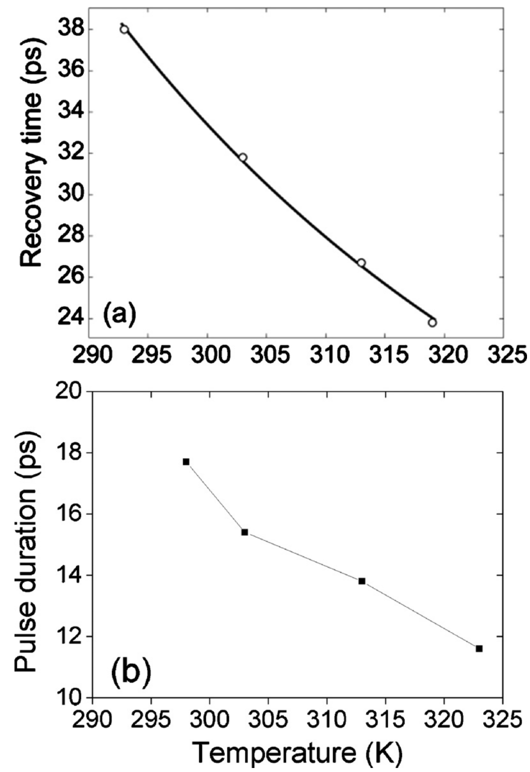

FIG. 3. (a) Absorption recovery time fitted to a thermionic rate equation. (b) Comparison with pulse duration from a monolithic MLL over the same temperature range.

Further to this investigation, we have also characterized the mode-locking performance of a two-section MLLD, fabricated from a QD structure with a similar epitaxial design as the waveguide device investigated. The MLLD had a total length of 8 mm while the saturable absorber was ~900 μm long (corresponding to a pulse repetition frequency of 5 GHz and a round-trip time of ~200 ps). By applying a forward bias in the gain section and a reverse bias in the saturable absorber section, stable ML operation was achieved from 288 K up to 333 K. The variation in pulse duration was measured for a reverse bias of 2 V applied to the saturable absorber while using the same temperature range as described previously. As depicted in Fig. 3(b), a reduction in the pulse duration is observed, exhibiting a strong similarity with the results represented in Fig. 3(a). It is important to stress that the forward bias applied to the gain section was increased for each of the higher temperature points in order to maintain a constant value of average power for the several points (in this case, 11.5 mW). The intention of this approach was to avoid the concurrent effect of the pulse duration reduction due to a decrease in optical power with increasing temperature. As depicted in Fig. 3(b), the rate of pulse duration decrease with temperature in the MLL is slightly slower than what is observed in the QD modulator. Indeed, other effects also play a part in the mechanism of pulse formation in the MLL. One of the most important factors in a MLLD is the interplay between absorption recovery time and gain recovery time—which defines a net gain window that has a direct and proportional influence on the pulse duration. It is well known from the previous literature that the gain recovery time becomes shorter with increasing temperature and increasing bias current.[11] Such effect will then counteract to some degree the pulse-shortening effect of the faster absorber recovery, thus inhibiting a faster reduction in the net gain window with increasing temperature—which would consequently account for the slower rate of pulse duration decrease in the MLL, as compared to the modulator.

The results presented here show that when thermionic emission is the dominant absorption recovery process in a QD-based material: ML operation can still be supported, as long as the absorber recovery time is shorter than the reciprocal of the pulse repetition rate. Furthermore, this investigation also supports previous reports from our group and others, which demonstrated that stable ML operation is possible at higher temperatures, for lower values of reverse bias applied to the absorber section.[6,12] The insights resulting from this investigation not only demonstrate that the absorber recovery time plays a key role on the duration of the pulses generated by QD MLLD lasers, but also provide relevant information for the uncooled operation of these lasers, which is of technological importance for many applications such as optical communications.

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