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A tunnel injection structure for speeding up carrier dynamics in InAs/GaAs quantum dots using a GaNAs quantum-well injector

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1. Introduction

Self-assembled quantum dot (QD) materials have received remarkable attention for the application in optoelectronic and photonic devices. One of the attractive features for QD-based devices is that they usually require low-energy operation. For example, QD lasers have demonstrated with ultralow threshold current density [1], whilst ultra-low power consumption has been recently achieved in QD switches.[2] However, one of the major problems which still remaining is how to speed up the modulation speed for practical QD devices.

As one of the solutions, a tunnel injection (TI) structure which employs an additional quantum well (QW) as a carrier reservoir/injector for QDs was proposed to overcome the non-ideal carrier relaxation induced by "hot carriers". A laser device based on the TI structure has realized a modulation bandwidth larger than 10 GHz [3], which is strategically important for the application in optical fibre-communication systems. The tunnelling mechanism in this QW/QD combined structure has been described as due to phonon-assisted processes. However, the density of state of phonons is naturally temperature sensitive. Although a very-short phonon-assisted tunnelling time of a few picosecond has been experimentally observed in some of the TI structures at room temperature (RT), the temperature dependent carrier tunnelling has not yet been discussed in the literature.

In this work, we have employed a low-strain GaAsN QW as the carrier injector.[4] The effect of using different spacer layers between the QW and dot layer has been examined. Both the temperature dependent PL and the time resolved PL reveal that efficient carrier tunnelling occurs at temperatures above 150 K.

2. Sample preparation

(001) GaAs substrates were used to grow QD samples with $GaAs_{0.99}N_{0.01}$ QWs by an Oxford Instruments V90 MBE system. We chose a nitrogen composition around 1%, which results in ~130 meV conduction band discontinuity. InAs QDs were grown within an 8 nm $In_{0.15}Ga_{0.85}As$ quantum well to give a dot-in-a-well (DWELL) structure. 50 nm GaAs spacer layers were inserted between QD layers and three stacks of the DWELL structure were grown. A 4 nm $GaAs_{0.99}N_{0.01}$ quantum well was inserted into the GaAs space layer, separated from the QD layer by a thin GaAs barrier with varied thickness of 3.0, 2.5, 2.0, and 1.4 nm. A growth temperature of 510 °C was selected for both the growth of GaAsN QWs and QDs. A QD-only sample was prepared for reference. In the upper picture of Figure 1, a TEM photography is shown for a TI structure, with only QDs observable in the image. This is due to the low contrast between the GaAs layer and the $GaAs_{0.99}N_{0.01}$ layer. However, this image reveals there is no dislocation or morphological issues caused by the presence of the nitride QW. QDs can be grown with excellent structural quality even with dilute nitride QWs. The lower picture of Figure 1 depicts a diagram for the TI structure. The ground state (GS) of GaAsN QW is separated from the QD excited states (ES) with an energy distance ideally equal to the energy of one longitudinal optical phonon.

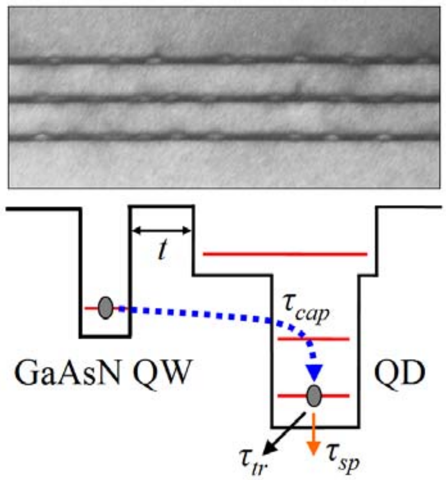

Figure 1. A TEM photography and a schematic diagram for the TI structure. An additional GaAsN QW is separated from the InAs QD layer over a thin GaAs barrier.

3. Characterization

RT and 15K PLs are measured for the characterization of the TI structure. There are two emission peaks presenting in the PL spectra. The longer wavelength peak is around 1.3 μm at RT, which corresponds to the QD GS transition. The shorter wavelength peak keeps the same intensity at 15 K with different thickness of the thin barrier. Although, the QD ES transition normally exists at a wavelength 70-80 nm shorter than the GS transition, the ES emission intensity is supposed to decrease when the thin

GaAs barrier decreases. Hence, assigning the shorter wavelength peak at 15 K to be the transition in the GaAsN QW is more reasonable.

To study the carrier dynamics between the QW and QDs, temperature-dependent PL has been employed. The QD emission intensity in the reference sample keeps almost constant below 160 K. The PL intensity rapidly decreases above 160 K, since the non-raditive recombination occurs at high temperatures. The temperature-dependent PL intensity in the TI structure is rather different, which exhibit an increase of the QD emission intensity below 160 K. This enhancement of the QD emission results from the extra carrier compensation due to the carrier tunnelling from GaNAs QWs. The sample with 2.5 nm barrier thickness exhibits the best tunnelling efficiency, which gives ~100% enhancement of the QD emission around 160 K.

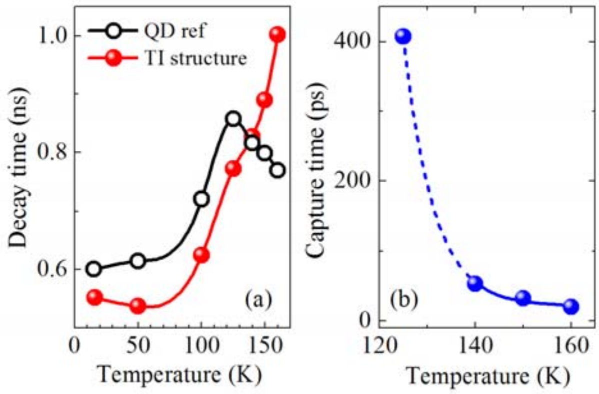

Figure 2. (a) Decay times obtained from time-resolved PLs for the TI structure and the QD reference sample. (b) Evaluated carrier capture time as a function of temperature.

We have further examined the carrier lifetime by time-resolved PL to study the carrier dynamics. A mode-locked Ti: sapphire laser was utilized generate ultrafast optical pulses, which excite the sample at 800 nm with a typical pulse width of 110 fs and a repetition rate of 4 MHz. By using a time-correlated single photon counting method, with a liquid-nitrogen-cooled InP/InGaAsP photomultiplier tube, the PL decay time was determined. The measured carrier lifetimes (decay times for the time-resolved PL signal) are shown in Figure 2 (a) for both of the QD reference sample and the TI structure from 15 to 160 K. Because of the contribution from the non-raditive recombination above 125 K, the reduction of carrier lifetime is observed in the QD reference sample. Very similar behaviours were reported previously for the non-radiative recombination part. However, the TI sample shows continuous increase of the carrier lifetime. We explain this phenomenon by the extra carrier injection from the QW to QDs. Those extra carriers compensated from the QW equivalently prolong the carrier lifetime inside QDs. The nearly constant difference in the carrier lifetime between two samples from 15 to 125 K can be simply attributed to the existence of another carrier recombination channel. One of the possibilities for this carrier channel is due to deep-energy-level carrier traps induced by N-atom diffusion. Based on the above consideration, the carrier dynamics in the QD GS can be described by a rate equation,

$$\frac{dn_{qd}}{dt} = \frac{V_{qw}}{V_{qd}}\frac{n_{qw}}{\tau_{cap}} - \frac{n_{qd}}{\tau_{ref}} - \frac{n_{qd}}{\tau_{tr}}, \qquad (1)$$

Analytically solving the equation (1) generates a solution,

$$\tau_{cap} = \kappa(\tau_{ref}^{-1} + \tau_{tr}^{-1} - \tau_{tun}^{-1})^{-1} \qquad (2)$$

where τ_{tun} and τ_{ref} are obtained from the measured carrier lifetimes for the TI structure and QD reference sample, respectively.

The equation (2) is used to give the carrier capture time from the QW to QD GS. As shown in Figure 2 (b), capture times of 407, 53, 32, and 20 ps have been evaluated for temperatures of 125, 140, 150, and 160 K, respectively. The carrier capture time above 150 K is very close to the carrier relaxation time inside QDs, which is normally at 10 ps order from the excited states to the GS. Hence, efficient carrier tunnelling has been observed in the tunnelling structure at temperatures above 150 K using a GaNAs injector. The temperature dependence of the carrier tunnelling process is simply because enough phonon states start to be occurring in the TI structure.

4. Discussion

As shown in our calculation, the nitrogen-induced shrinking in the band structure mainly exists in the conduction band. This may result in some difficulties for the laser device, especially the hole injection. By combining the TI structure with a *p*-type modulation doing technique, this problem can be possibly solved for QD lasers based on the TI structures. In addition, a pathway from efficient carrier tunnelling process in the TI structure is potentially useful for ultrafast QD switches and saturable absorbers. Introducing in dilute nitrides enhances the non-radiative recombination, which would be helpful for passive-type ultrafast QD devices.[2]

5. Conclusion

In summary, a GaAsN QW injector has been employed in a QD TI structure. The barrier thickness between the GaAsN QW and QDs has been studied by the temperature-dependent PL. The temperature dependent nature of the phonon-assisted tunnelling process has been revealed in the TI structure, which shows effective tunnelling at temperatures beyond 150K**.**

References

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