Evidence of correlated electron hole pairs in dots in asymmetric quantum well structures

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Abstract. We introduce the study of InAs quantum dots embedded in an InGaAs quantum well. The quantum dot potential strongly modifies the energy states of the quantum well structure. Hence, the carrier thermodynamics is also influenced. The dependence of the integrated photoluminescence on the excitation power density shows linear dependence with very little deviation from linearity at a high temperature. That result contributes to the strong correlation between the electron and hole pairs, which is attributed to the enhanced confinement provided by the asymmetric quantum well structure.

1. Introduction

It was shown earlier that the InAs quantum dot (QD) density can be increased essentially if the dot is grown inside the InGaAs/GaAs quantum well (QW) (dot in a well, DWELL) structure [1]. The most important aspect for light emitting device based on InAs QD and operated at room temperature is the understanding of excitation power and temperature dependence photoluminescence emission (PL)[3]. The problem of how to reach the 1.3 μm emission at room temperature has been discussed before [4], however the problem is that the total InAs amount in active region is relatively high which leads to high probability of dislocation formation, which in return affects the PL emission [6]. DWELL structure based on InAs QD has been effective in improving the performance of emitting device in the long wavelengths regime since it helps decrease the thermal escape rate of the carriers from QDs at high temperature [7, 8]. Among the proposed mechanisms of long wavelength emission from InAs QDs, it is believed that residual strain plays a key role. The asymmetric DWELL was reported to have enhanced uniformity in dot morphology, narrower line width of emission from ground state transition [9]. The fundamental problem is to understand the temperature dependence of QD PL. Two main ways: (a) thermal escape (capture) of carriers (electron and hole) in/from QDs takes place as an exciton or correlated electron hole pair [10]; or (b) the excitons dissociate and single electrons (holes) thermally escape or capture independently [11]. In Asymmetric DWELL structure the introduction of surrounding QW changes the potential barrier height for exciton thermal escape from QDs and can increase the density of nonradiative (NR) centers. In this work, the parameters of the QW alters the thermal quenching of the PL intensity, the study of PL, its temperature and power dependence in InAs QDs embedded in asymmetric InGaAs/GaAs DWELL structures are presented.
2. Experimental details

| Layer   | Thickness |
|---------|-----------|
| InAs    | MEE QD 3ML|
| InGaAs  | 0.7 nm    |
| GaAs    | 35 nm     |
| InGaAs  | 5 nm      |
| InAs    | MEE QD 3ML|
| InGaAs  | 0.7 nm    |
| GaAs    | 35 nm     |
| GaAs buffer | ~100 nm |
| GaAs sub|           |

The schematic diagram of the sample structure, InAs QD embedded in asymmetric InGaAs/GaAs QW, is shown in figure 1. Details of the growth procedure are described elsewhere [8]. The sample is excited with 532 nm from solid state laser. The PL spectra were collected using a grating monochromator with Peltier cooled detector. The monochromator is ACTON-SPECTRA PRO-23001. The sample was mounted in a closed-cycle He cryostat where the temperature is varied from 16 to 300K. The power dependence of the PL is measured in the range 1 to 30 mW—measured using power meter directed to the laser beam. Laser power is changed using neutral density filter. Spot size of laser on the sample is ~ 1 mm².

3. Results and discussion

The PL spectra of InAs QD in asymmetric InGaAs/GaAs QW at 16K are shown in figure 2(a) for different exciting laser power, namely 1mW to 30 mW. The graph shows that PL intensity increase with increasing laser power. Four peaks are found, the low energy peak around 850 nm is assigned to GaAs emission, 940 nm assigned to emission from wetting layer (WL), while the other two peaks at 1100, 1200 nm are assigned to QW and QD emission, respectively. The PL spectrum represents recombination of excitons localized at the QD ground state as well as InGaAs QW.

The PL spectra of the asymmetric DWELL structure in Figure 2(b) shows that the long wavelength emission near 1.3 µm could be achieved at room temperature. The PL intensity is found to decrease as the temperature increase, due to thermal quenching. In general thermal quenching of the PL intensity can be explained by thermal escape of excitons from QDs into the GaAs barrier or WL with subsequent nonradiative recombination as well as by thermal activation of exciton capture by nonradiative (NR) centers. Our data enhance the picture of the two stage process of exciton capture (thermal escape) from GaAs barrier to QW (I stage) and from QW to QD (II stage) as shown before [12].

The power dependence of the integrated intensity over the entire PL spectra for QD peak is shown in figure 3 (b). The fitted value of the integrated intensity of the ground state QD with the power law

\[ I_{PL} = \xi P_{exc}^\alpha \]

where \( I_{PL} \) is the integrated intensity, \( \xi \) is the proportionality constant and the exponent \( \alpha \) determines the linearity or the super-linearity. The plot for the exponent \( \alpha \) is shown in figure 3 (a). The
Figure 3. (a) Temperature dependence of the exponent $\alpha$ for the QD PL Peak emission. (b) Dependence of the integrated PL intensity of the QD peak emission on the excitation power ratio measured at different temperature. The exponent $\alpha$ is found to be directly proportional to excitation power up to 210K and then switch to super linear, it has been shown [13, 14] that the power dependence show linear behavior in a temperature region where carrier dynamics are controlled by correlated electron hole pair and then switches to super linear in a region where electrons and holes behaves independently, with some degree of correlation.

The temperature dependence of peak position for QD peak emission is fitted with Varshni relation $E(T)=E_o-aT^2/(T+b)$, (graph is not shown here). The fitted parameters $E_o$, $a$ and $b$ estimated from the peak position of the PL are presented in Table 1. Comparison of the corresponding parameters for the variation of the energy band gap versus temperature in the bulk of InAs, GaAs are presented as well. The parameters of QD are found to be bigger than the corresponding value in the InAs bulk crystals that permit the assumption that the studied asymmetric DWELL has a material composition that partially changed due to Ga/In interdiffusion [15].

| Table 1: Comparison of Varshni Parameters with bulk values |
|-------------------------------------------------------------|
|               | $E_o$ (eV) | $a$ (meV/K) | $b$ (K) | References |
| QD-Peak        | 1.05394    | 0.5409      | 202.7   | This work  |
| InAs Bulk      | 0.418      | 0.308       | 65      | 15         |
| GaAs Bulk      | 1.519      | 0.540       | 204     | 16, 17     |

4. Conclusion
We investigated PL temperature dependence of QD embedded in InGaAs asymmetric DWELL structure. The sample showed 1.3 $\mu$m PL emission at room temperature Analysis of power dependence shows linear dependence in the temperature region 16K up to 210K enhancing the idea that carrier dynamics are controlled by correlated electron-hole pairs. The temperature dependence of the peak position for QD is measured and fitted with Varshni relation, and the bigger values of Varshni parameters are attributed to In/Ga inter diffusion during growth.

5. Acknowledgement
This work is supported by MEST by GRL Program.

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