Photoluminescence study of high density InAs/GaAs quantum dots

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The quantum dot (QD) based structures are of great interest in recent years due to their δ-function-like density of states and the spatial confinement of electrons and holes in artificially designed spaces.

In this work, the optical properties of high density self-assembled InAs/GaAs QD samples at low temperatures (20K) were studied. We found that the collective behavior of the high density dots has a strong influence on their photoluminescence spectra. In low density QD samples, each QD can be treated as independent and the carrier recombination time is smaller than the time needed for carriers to migrate from one to another. For high density dot samples, the situation, however, can be very different. If adjacent QDs are close enough, the carriers can tunnel from one to another before they are recombined. In this situation, the QDs can not be regarded as an ensemble of individual ones. The PL emission spectrum becomes dependent on the density of the QDs. In this study, various excitation powers from 50uW to 10mW were used. Unlike the low density samples, the high density samples showed a blue shift in the emission peak as the power is increased. The amount of shift is a strong function of the dot density.

The samples in our study were grown by molecular beam epitaxy on (001) GaAs substrates in a Varian Gen-II reactor. Two high density samples were prepared. Sample #1 was deposited with 2.4ML of InAs at a growth rate of 0.15um/hr under an As4 partial pressure of 2.8×10^{-5} Torr for the dot formation. The QDs in sample #2 was grown in an As2 environment at a partial pressure of 1.6×10^{-5} Torr. 2.6ML of InAs was deposited at a growth rate of 0.05um/hr. Both samples were grown at the same substrate temperature of 480℃. We also grew an additional QD layer with the same condition at the surface of each sample for AFM measurement. The dot density determined by AFM was $3.25\times10^{11}/cm^2$ and $3.63\times10^{11}/cm^2$ for sample #1 and #2, respectively. The average center to center distance between nearby QDs is about 17nm. To compare the results from the high density samples, we also prepared a standard low density sample (sample #3) with a dot density of $4.12\times10^{10}/cm^2$. Table 1 lists the dot density, the measured ground state energy, and the full width at half maximum (FWHM) of the PL emission from the three samples.

Figure 1 shows the position of the emission peak as a function of the pumping power for the three samples mentioned above. A blue shift of 8meV for sample #1, 4meV for sample #2, and 1meV for sample #3 were observed as the excitation power was increased. As expected, the low density sample had a very small blue shift. But a significant blue shift was observed for the high density samples. We noticed that the amount of shift, besides being a function of the dot density, is also dependent on the ground state energy of the QDs. The two high density samples, although had similar dot densities, showed different blue shift. Sample #1, which has a higher ground state energy, has a larger blue shift. For all samples, we noticed that the amount of blue shift saturates when the excitation power exceeds 5mW.

In high density QD samples, the distance between adjacent dots is very small. The excited carriers can be thermalized through the tunneling process. At low excitation power, the carrier in smaller QDs can transfer to the nearby larger ones. In this way, The PL spectrum is mainly contributed by the larger QDs. As the excitation power increases, the larger QDs are filled with carriers, which prevent further transfer of carriers from the smaller QDs to the larger dots. As a result, the PL emission comes from all of the QDs and this results in a blue shift of the PL emission peak. When the QDs are smaller, or the transition energy is higher, the tunneling probability between dots increases. This will further enhance the blue shift as the pumping power is increased.

In figure 2, we observe that FWHM also becomes larger as the excitation power increases. From the PL spectra shown in Fig.3, we notice that increase in the line width is only at the high energy side. So large QDs always contribute to PL emission while the emission from the small dots needs pumping at a higher power level. This effect is stronger for high density dots and dots with small sizes.

In conclusion, the tunneling between QDs plays an important role in the PL emission spectrum. Denser and smaller dots give a clear blue shift in the emission peak as the pumping power is increased as a result of carrier transfer among the QDs through the tunneling process.

Table 1: sample information

Sample #	Dot density (#/cm^2)	Ground state energy (eV)	FWHM (meV)
Sample #1 (200uW)	3.25×10^{11}	1.2679	57.5
Sample #2 (200uW)	3.63×10^{11}	1.1665	66.6
Sample #3 (20uW)	4.12×10^{10}	1.1632	58.3

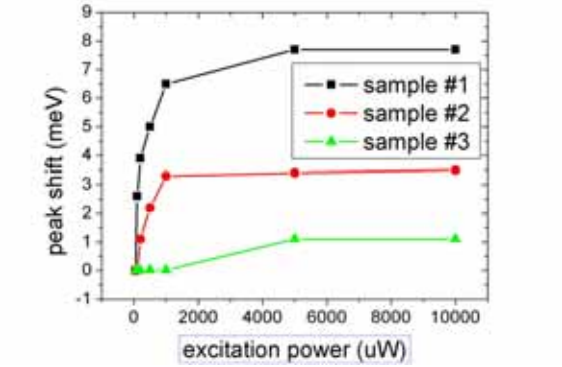

Figure 1: peak shift at different excitation power

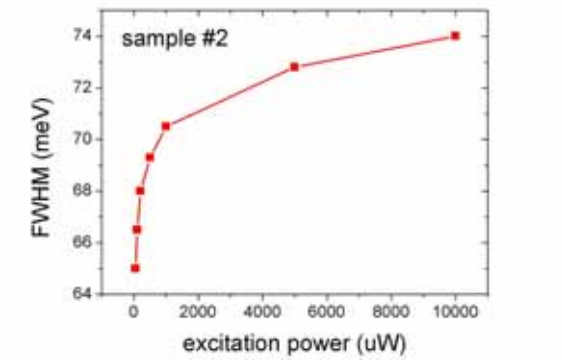

Figure2: FWHM at different excitation power.

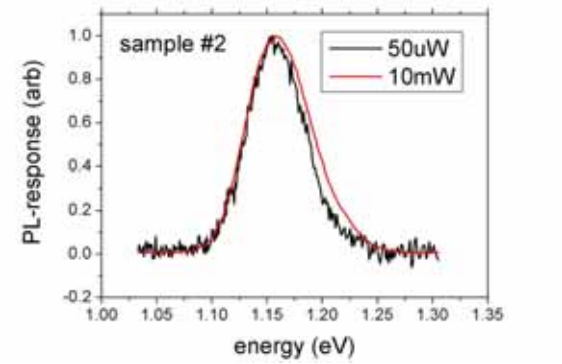

Figure3: PL spectrum at two different excitation powers

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