Series - Electronic and optical semiconductor devices

Series 7 - Optical properties of InAs/GaAs quantum dots

1- For deposited thicknesses in excess of 1.7 monolayer (ML), it is more advantageous for the InAs/GaAs system to form small 3D islands called quantum dots (QDs) or sometimes quantum boxes (QBs). In this situation, the deposited InAs layer will minimize its energy compared to the pure 2D case (minimization of the surface energy, elastic relaxation energy and interaction energy between neighboring islands). The sudden energy variation therefore corresponds to the transition from a quantum well type layer to a layer containing dots lying on top of an InAs wetting layer (WL).

2-3- The narrow peak located on the high energy side originates from the WL (as it is thinner than the ensemble dot + WL, confinement energies are larger) and the broad PL peak comes from the QDs.

When moving from position (2) to (5), the dot density progressively increases (transition from the 2D to the 3D region) which explains why the PL intensity associated with dots increases. Note that position (1) corresponds to a deposited InAs thickness less than 1.7ML (it is located ~ 1 mm from the border region) explaining why the corresponding PL peak is located at higher energy than that of the WL.

4- Each dot has a relatively small spatial extent (0D-like structure), $\phi \sim 20$-30 nm, so that it will accommodate a small number of excitons. When decreasing the probe size, the number of dots located below the excitation beam will be smaller. As a result below a certain dot density, the discrete nature of the emitters will be visible. In other words, the emission of single dots will

be reinforced to the detriment of the Gaussian distribution arising from the large density of dots excited when performing standard PL measurements (the Gaussian distribution originates from the size distribution of the dots around a mean value).

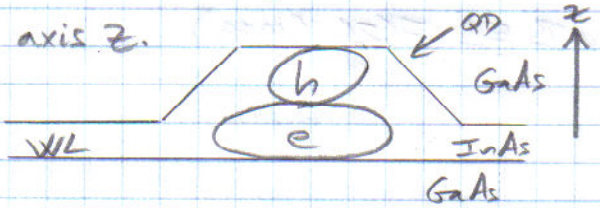
5- The three spectra measured in a $200 \times 200\ nm^2$ area correspond to a single QD emission regime (1 to 3 dots are present). As a result the QD density is $\sigma_{QD} = 1-3 \times [(200 \times 10^{-7})^2]^{-1} \sim 2.5-7.5 \times 10^9\ cm^{-2}$.

6- A single QD can be identified as a first approximation to an atom. The fundamental level of this dot is called "s" level and can accommodate up to $2\ e^-$ of opposite spins ↑↓. The first excited level, the "p" layer can accommodate up to $4\ e^-$/holes (note that it differs from the atomic physic case where the p layer can be six-fold degenerate). The transitions observed in the figure correspond to the progressive filling of excited states of a QD ensemble following the saturation of lower energy levels (due to a trade-off between the filling of the levels (extremely efficient at low temperature for large excitation power densities) and the radiative recombination rate).

7- For arsenide-based compounds, the exciton Bohr radius is typically ~10 nm. This is the direct consequence of the small effective masses of free carriers. Hence, the corresponding wavefunctions will leak into the barriers which can induce an electronic coupling of wavefunctions of adjacent heterostructures provided the electronic levels are sufficiently close to each other in energy. In the present case, the dots are relatively close to each other both on the spatial and morphological levels. The superimposition of dots in successive layers along the growth direction is driven by the strain field generated by the formation of the first QD plane. The strain

field will therefore induce the presence of preferential nucleation sites along the growth direction (vertical axis). When single dots are electronically coupled, we speak of molecular QDs.

8- The change of the transition energy of the dots when an external electric field is applied corresponds to the signature of the quantum confined Stark effect (QCSE). An asymmetric energy shift ΔE is observed with respect to the zero field case. It means that the QCSE exhibits a dependence $\Delta E = aF + bF^2$. The second term corresponds to the direct manifestation of the QCSE whereas the first term results from the presence of a permanent (non-zero) dipole moment p which originated from the asymmetric shape of the QDs. This dipole is oriented along the growth axis z.



The largest transition energy is obtained for an electric field F oriented from the dot apex toward the WL, which corresponds to an attraction of the e^- toward the dot apex and of the hole toward the WL. It implies that in the zero-field case, the electron charge distribution lies below that of the hole with the dipole oriented from the base toward the apex of the dots. The experimental value of p is: $p = 7 \pm 2 \times 10^{-29}$ Cm which corresponds to an e^--hole separation $r =$ Å (deduced from the equation $p = er$). Note that because of their heavier mass, the hole wavefunctions are more laterally confined than those of e^-.

It is important to understand that the orientation of F is dictated by the structure of interest, i.e. the p-i-n and n-i-p structures. As for the p-n junction, a space charge region is present (where the intrinsic layer containing the dots is located). On the n-side of this space

charge region there are no free carriers but positive fixed charges (ionized donors) and inversely on the p-side of the space-charge region, there are negative fixed charges (ionized acceptors). The electric field is oriented from the positive to the negative fixed charges. It is therefore crucial to understand that the direction of F is determined with respect to fixed charges and not vs. free carriers (a risk of error could originate from the name of the junctions: n-i-p, p-i-n...).

Further readings related to this series

① J.Y. Marzin et al., Phys. Rev. Lett. 73, 716 (1994).

② M. Bayer et al., Science 291, 451 (2001).

③ P.W. Fry et al., Phys. Rev. Lett. 84, 733 (2000).

④ S. Raymond et al., Phys. Rev. B 59, 7624 (1999).