Quantum Dot Lasers

Lecture in Modern Optics by Björn Agnarsson

Most of this text is taken from the book “Quantum Dot Heterostructures” by Dieter Bimberg, Marius Grundmann and Nikolai N. Ledentsov.

Fabrication of quantum dots

Quantum dots (QD) can be made using a variety of methods but for real applications mainly three methods are used:

1. *Epitaxy growth (MBE, MOVPE).* Stransky-Krastanov growth is a three dimensional growth of nano island (quantum dots). Stransky-Krastanov growth is usually established by strain formation between the substrate and the epilayer due to lattice mismatch between the two ($a_{sub}>a_{epi}$). The epilayer reacts to this strain by forming three-dimensional islands instead of two-dimensional flat surface. These dots are self-assembled and can have very small dimensions (<10nm^3). They either form pretty randomly, on atomically flat substrates, or rather ordered at step edges on substrates with step edges. QD made using this method can be difficult to control both regarding size (volume), and density.

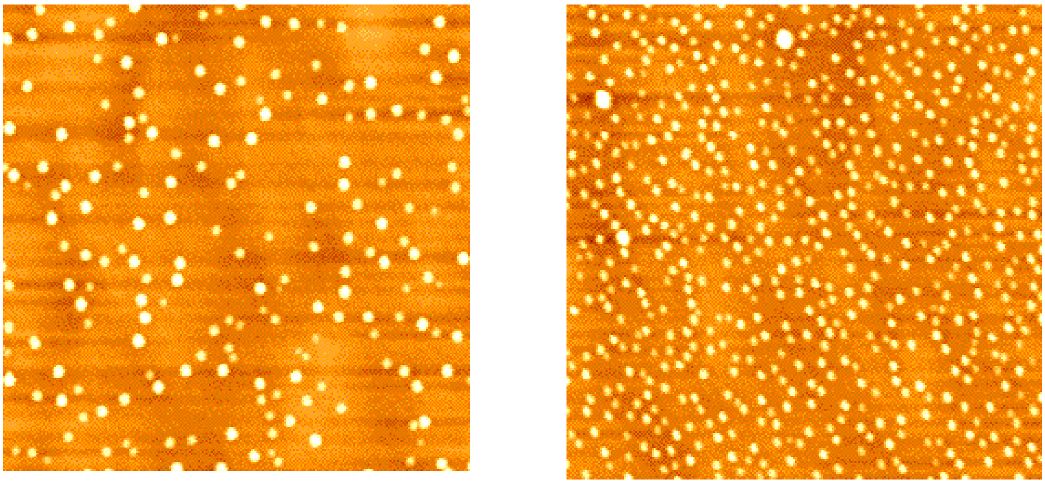


Figure 1 InAs nano-islands. The two AFM figures are from the same sample, taken 3 cm apart. Reason for different QD concentrations is the different growth flux at the two positions (Measurements carried out by Björn Agnarsson).

2. *Microcrystallites in glass or polymers.* Another way of making QD is by poring nano-particles into a molten glass or polymer and cooling it down so that the particles freeze in place (see figure 2).
3. *Artificially patterned dots by electron-beam lithography.* In this way the size and placement of the QD can be controlled in a very precise manner but the huge number of dots needed in a QD laser causes problems for this technique. Also, surface states can cause problems in etched dots.

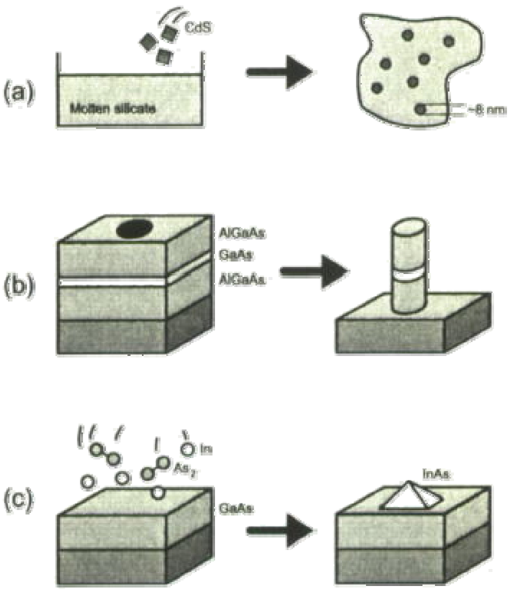


Figure 2 Schematic representation of different approaches to fabrication of nanostructures: (a) microcrystallites in glass, (b) artificial patterning of thin film structures, (c) self-organized growth of nanostructures (Betul Arda, Huizi Diwu. Department of Electrical and Computer Engineering University of Rochester)

Key-issues in fabrication:

1. The QD needs to be small in order for the carriers to be as three dimensionally confined as possible in space (so we get energy delta functions). The three-dimensional confinement potential needs to be significantly high in order for the carriers (electrons/holes) not to be thermally excited out of the QD. QDs need to be operational at and above room, meaning that this potential needs to be substantially larger than kT_{room}=25meV.
2. We need many QDs.
3. QDs need to be as homogeneous as possible; otherwise we will get a spread in our discrete energy levels (see figure below).

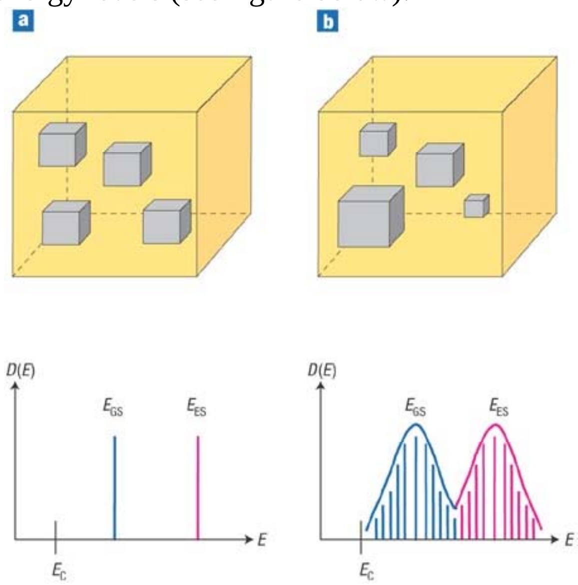


Figure 3

Physics

Electrons/holes can be confined in all three dimensions in a dot or a quantum box. The situation is analogues to that of a hydrogen atom meaning that only discrete energy levels are possible. The density of states if given by.

$$\rho_{0D} = 2\delta(E)$$

So we end up with discrete energy levels:

$$E - E_C = E_{n,m,p} = \frac{\pi^2 h^2}{2m^*}\left(\frac{n^2}{L_x^2} + \frac{m^2}{L_y^2} + \frac{p^2}{L_z^2}\right)$$

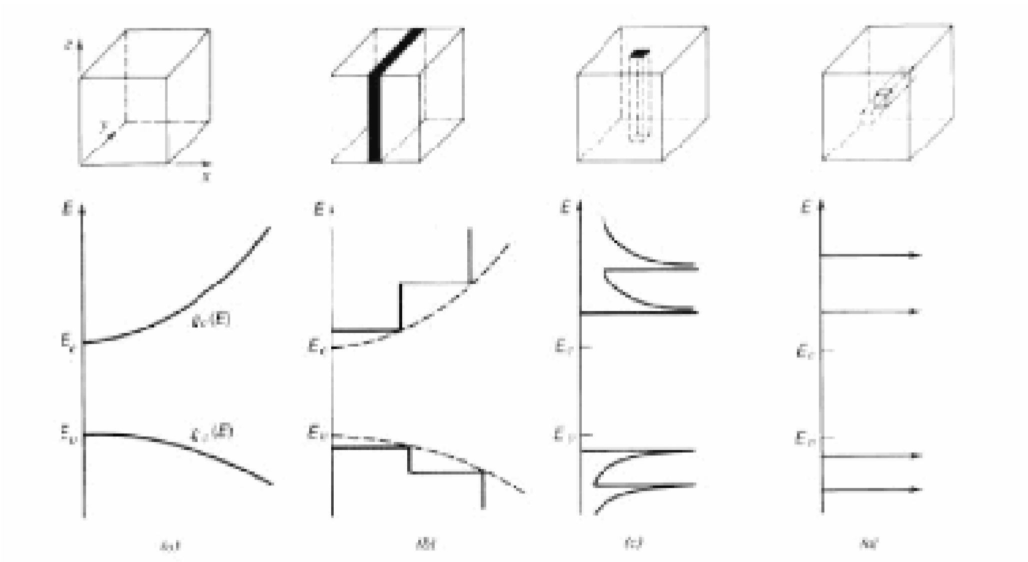


Figure 4 Quantization of density of states: (a) bulk (b) quantum well (c) quantum wire (d) QD (Betul Arda, Huizi Diwu. Department of Electrical and Computer Engineering University of Rochester)

QD-lasers

In principle, QD lasers can be treated in a similar way as quantum well (QW) lasers and the laser structure is fabricated in a similar way, the only difference being that the optically active medium consists of QDs instead of QWs. The figure below shows a simple laser structure, consisting of an active layer embedded in a waveguide, surrounded by layers of lower refractive index to ensure light confinement. The active material consists of quantum wells or quantum dots where the bandgap is lower than that of the waveguide material.

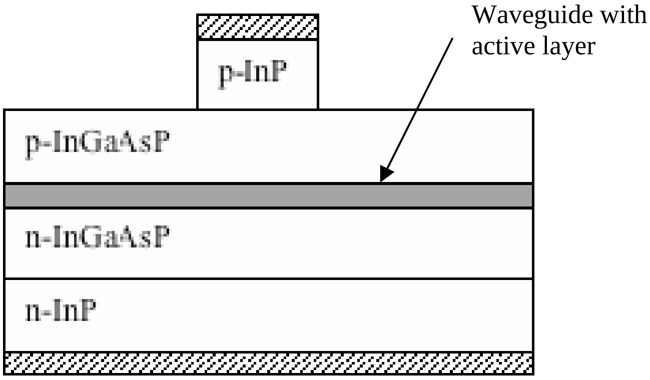


Figure 5

The active layer (QD or QW) is embedded in an optical waveguide (material with refractive index smaller than that of the active layer).

Wavelength of the emitted light is determined by the energy levels of the QD rather than the band-gap energy of the dot material. Therefore, the emission wavelength can be tuned by changing the average size of the dots.

Because the band-gap of the QD material is lower than the band gap of the surrounding medium we ensure carrier confinement. A structure like this, were carrier confinement is realized separately from the confinement of the optical wave, is called a separate-confinement heterostructure (SCH).

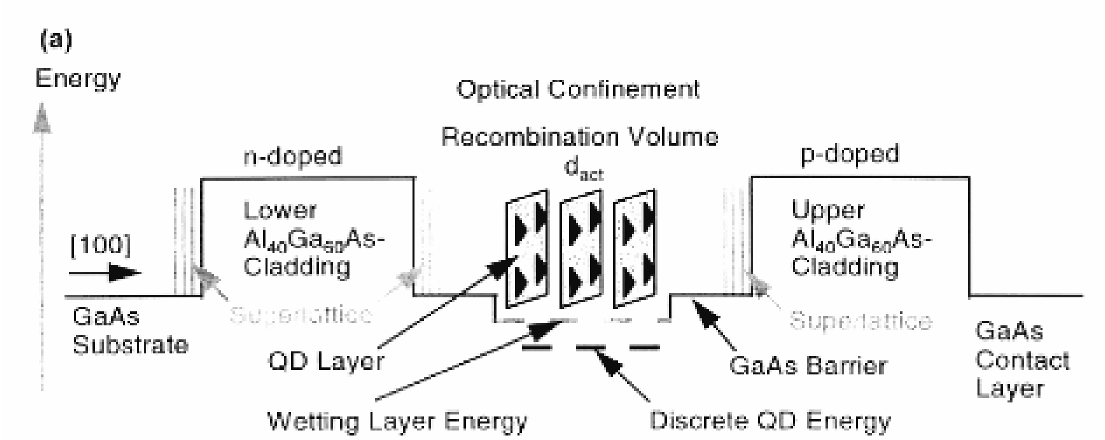


Figure 6 An ideal QD laser consists of a 3D-array of dots with equal size and shape, ssurrounded by a higher band-gap material (confines the injected carriers). The barrier material forms an optical waveguide with lower and upper cladding layers (n-doped and p-doped AlGaAs in this case). (Betul Arda, Huizi Diwu. Department of Electrical and Computer Engineering University of Rochester)

Optical Confinement factor

For a QD array, the optical confinement factor, G, is on the order of total dot volume to total waveguide volume. It can be split into in-plane and vertical components. For consistency with a similar treatment for QW lasers, it should be pointed out that this notation is most appropriate for vertical-cavity quantum dot lasers where the light propagation is perpendicular to the active layer:

$$\Gamma = \Gamma_{xy}\Gamma_z$$

Where

$$\Gamma_{xy} = \frac{N_D A_D}{A} = \xi$$

Where N_D is the number of QD, A_D is the average in-plane size of the QD and A is the xy-area of the waveguide. The factor ξ is called the area coverage of QD.

The vertical component of the confinement factor is given by the ratio of the light intensity in the active layer (QD), averaged over area A, to the total light intensity in the whole heterostructure. This ratio characterizes the overlap between the QD and the optical mode.

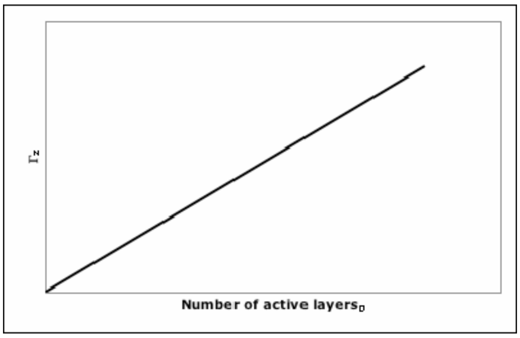
$$\Gamma_z = \frac{1}{A}\int_{QD}|E(z)|^2 dz \Big/ \int_{whole}|E(z)|^2 dz$$

Example:
For N_D/A=4 x 10^{10} QD/cm^2 and volume of QD equal to 7*7*2 nm^3. We get ξ= 0.02. For a 150nm thick cavity a typical vertical optical confinement factor is 0.007. Hence the total optical confinement factor is 1.4e-4

It is worth noticing that since:

$$\Gamma_{xy} \propto N_D$$

by increasing the number of dots (or more precisely by increasing the area coverage of QD, ξ) we get an increase in the total optical confinement factor. In a similar way since G_z is proportional to the thickness of the active layer, by increasing the number of QD layers in the active layer (increasing the number of active layers) an increase in the vertical optical confinement factor is achieved. Both these cases are illustrated in the figures below and both contribute to the total optical confinement factor.



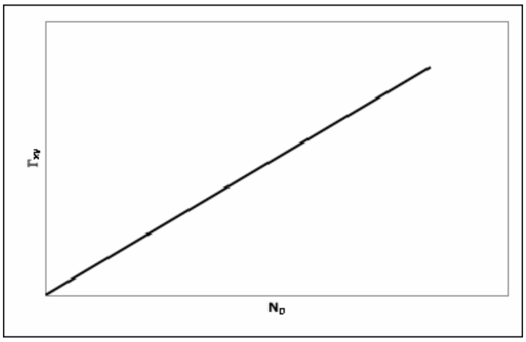


Figure 7

Gain and threshold

As always, in order to achieve lasing we need population inversion and stimulated emission together with some sort of feedback provided usually by reflection by mirrors. The population inversion is obtained by electrically pumping the system with carriers (holes and electrons). In a simple 2-fold degenerate energy level system, this is achieved when enough current is pumped into the system in order to invert the ground-state population level. That is to say, on average there is more than one electron-hole residing in the QD conduction-band state and more than one hole residing in the QD valence-band state.

At a certain threshold current density (j_{th}), the lasing starts and by increasing the current above that threshold we increase the output power linearly with increasing current. The condition for lasing can be written as:

$$g_{\text{mod}}(j_{th}) = \Gamma g_{material}(j_{th}) = \alpha_{tot}$$

Where g_{mod} is the modal gain of the system and a_{tot} is the total loss in the system consisting of internal losses in the active layer (a_i), losses in the waveguide (a_c) and losses at the reflectors ($a_{mirrors}$).

$$\alpha_{tot} = \Gamma \alpha_i + (1-\Gamma)\alpha_c + \frac{1}{2L}\ln(\frac{1}{R_1 R_2})$$

So modal gain is given by:

$$g_{\text{mod}}(j) = \Gamma g_{material}(j) - \alpha_{tot}$$

Assuming that the we have a Gaussian distribution in QD volume size (P_g), and that spectral width of this distribution is much bigger than the width of the Lorentzian describing the intra-band relaxation times, the material gain g_{mat} of a QD ensemble can be calculated using the following formula:

$$g_{mat}(E) = C_g P(E)\left[f_c(E, E_{Fc}) - f_v(E, E_{Fv})\right]$$

Where C is a constant and P_g is the Gaussian distribution and f is the Fermi distribution of the carriers. If one further assumes that the all the injected carriers are captured by QD and that overall charge neutrality exists (i.e $f_v=1-f_c$ and $f_c-f_v=2f_c-1$), the total number (N) of carriers (electrons and holes) is:

$$N = 2 f_c N_D$$

and these carriers are assumed to be equally distributed amongst all the QD. So we end up with a material gain:

$$g_{mat}(E) = \frac{N - N_D}{N_D} C_g P(E)$$

If we take a closer look at this expression for the material gain we see that it increases linearly with increasing number of carriers, N, from $-C_g P(E)$ (when the QD excited state has no carriers) to $C_g P(E)$ (when all QD excited states are filled with 2 electrons, $N^{max}=2N_D$).

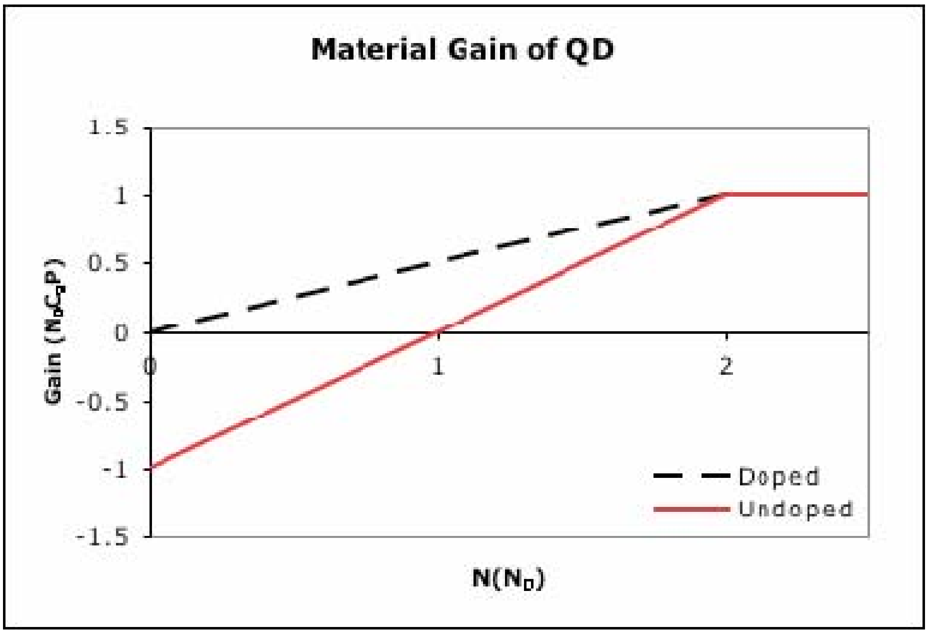


Figure 8

For typical values of C and $P(E)$ we obtain a maximum saturation value in the material gain in the order of 1e5 cm^{-1}, which is huge! However, due to the optical confinement factor one ends up with a much smaller modal gain ($g_{mod}=\Gamma g_{mat}$).

We also see that the shape of the gain function depends on the Gaussian distribution function $P(E)$. This means that the shape of the gain function depends strongly on the uniformity of the QD volume size and shape. The more homogenous the system is, the sharper and higher the gain function is.

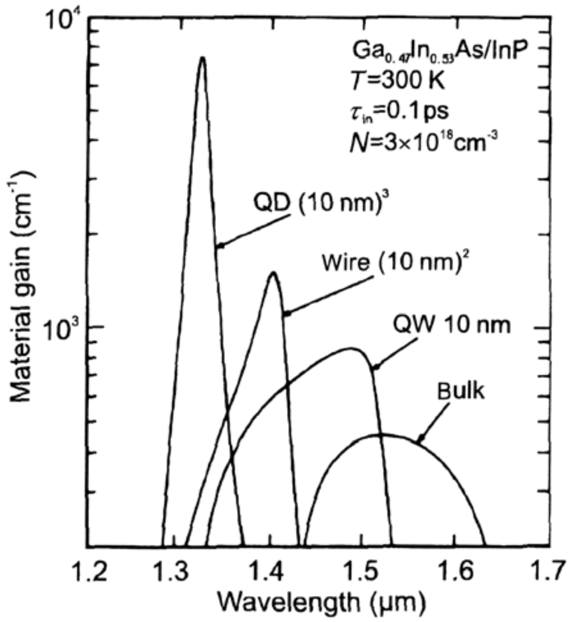


Figure 9 Calculated material gain spectra for $In_{0.53}Ga_{0.47}As/InP$ quantum box, wire, well and bulk at T=300 K. Electron density at $3x10^{18}$ cm^{-3} (After Asada el al., 1986). Notice the height of the QD peak and its width. (Quantum Dot Heterostructures by Dieter Bimberg, Marius Grundmann and Nikolai N. Ledentso)

Example:
For 7*7*2 nm^3 QD with ζ=0.02 (corresponding to $4x10^{-10}$ QD/cm^2), $\Gamma_z=7x10^{-3}$ for 150nm waveguide and saturation material gain g_{mat}=1e5, we only get:

$$\begin{aligned} g_{\mathrm{mod}}^{sat} &= \Gamma g_{mat}^{sat} \\ &= \Gamma_{xy}\Gamma_z g_{mat}^{sat} \\ &= \xi\Gamma_z g_{mat}^{sat} \\ &= 14 \text{ cm}^{-1} \end{aligned}$$

To prevent gain saturation

In order to increase the gain saturation limit of given QD ensemble, the following steps could be used:

1. Increase the modal gain by stacking layers of QD within the active layer
2. Increase the number of QD (N_D) in each sheet of QD in the active layer
3. Decrease the mirror loss by high reflection coatings or many mirrors. In VCSEL we usually have small cavity length *L*. According to the expression for losses in mirrors this would mean larger loss the smaller the cavity. This could be compensated by having R_1 and R_2 high, either by using high reflective coatings or by using many sets of mirrors (20 mirrors in VCSEL give about 99% reflection).

In order to have lasing, the carrier density at threshold, N_{th}, has to be at least:

$$N_{th} = N_D \left(1 + \frac{1}{\xi} \frac{\sqrt{2\pi}\sigma_E \alpha_{tot}}{\Gamma_z C_g} \right)$$

The maximum threshold current density is:

$$N_{th}^{\max} = 2N_D$$

So the minimum area dot coverage has to be:

$$\xi_{\min} = \frac{\sqrt{2\pi}\sigma_E \alpha_{tot}}{\Gamma_z C_g}$$

The relationship between carrier density, N, and injection current, j, is non-trivial but a simplified version, obtained using conventional rate equation models, gives:

$$j = \frac{5}{8} \frac{e}{A_D \tau_D} \xi \left(\frac{N}{N_D} \right)^2$$

Using the above relation for threshold density of states, N_{th}, we obtain the following relation for the threshold current, j_{th}:

$$j_{th} = \frac{5}{8} \frac{e}{A_D \tau_D} \xi \left(1 + \frac{\xi_{\min}}{\xi} \right)^2$$

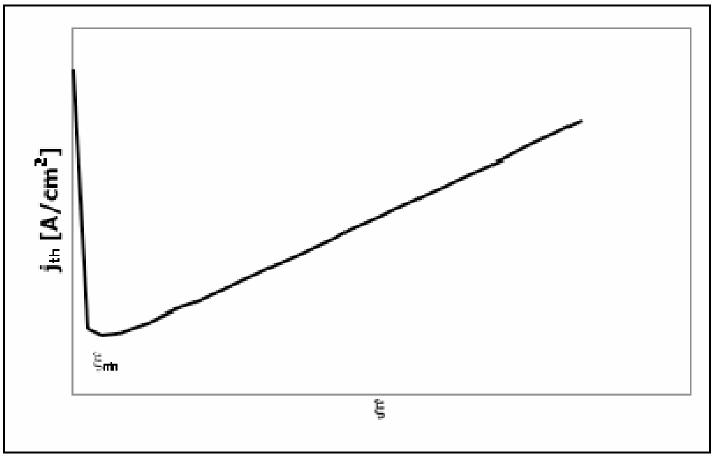


Figure 10 Threshold current density as a function of dot area coverage

For $\xi < \xi_{\min}$ the current density goes to infinity and we will not get any lasing.

Example:
For a_{tot} equal to 10 cm^{-1} and ξ_{min} equal to 0.013 we get a threshold current of 10A/cm^2

By increasing the number of active layers we obtain a decrease in threshold current:
J_{th}= 90 A/cm^2 for 10 layers of $In_{0.5}Ga_{0.5}As/GaAs$
J_{th}= 62 A/cm^2 for 3 layers of $In_{0.5}Ga_{0.5}As/Al_{0.15}Ga_{0.75}As$
J_{th}= 40 A/cm^2 for 3 layers of InAs/GaAs

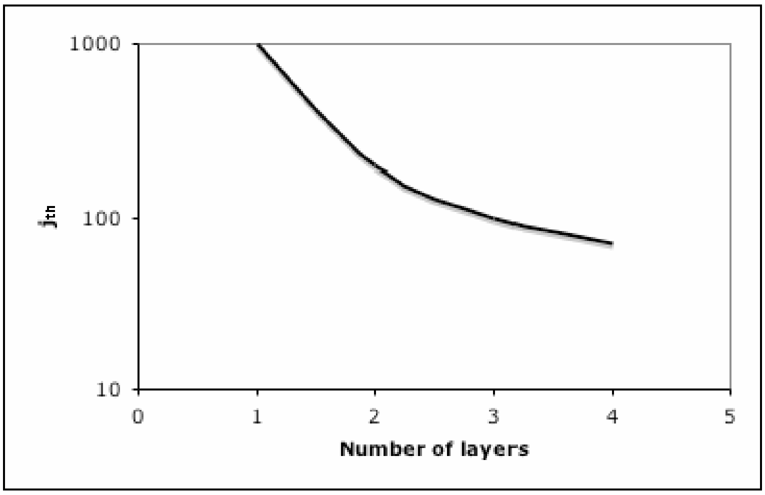


Figure 11

Advantages and complications with QD lasers

Problems:

- Wavefunction is not zero at potential barriers and hence penetrate into it
- m* can be discontinuous, meaning that masses in wells and barriers differ
- Non-parabolicity of *E-k* which means that the mass changes with energy
- Multiple band in valance band (heavy and light holes)
- Fabrication process can be complicated leading to non-homogenous in size and shape leading to the broadening of the gain spectrum (see figure 3).
- High material gain <u>but</u> low optical confinement factor leads to low modal gain
- Barriers are finite, not infinite, meaning that there is a carrier leakage out of the QD
- Strained wells might lead to shift in wavelength due to the existence of light and heavy holes in the valance band.

Advantages:

- Adjustable wavelengths since energy levels rather than band-gap determine the wavelength
- Higher material gain for QD than for QW and quantum wires (QD gain is 10x more than QW gain)
- Material gain curve is narrower than for QW and quantum wires.
- Small volume
    - Low power needed
    - High frequency operation possible
    - Small linewidth of emission peak
    - Low threshold current need compared to QW and quantum wires.
- Superior temperature stability compared to QW
- Suppressed diffusion of carriers compared to QW

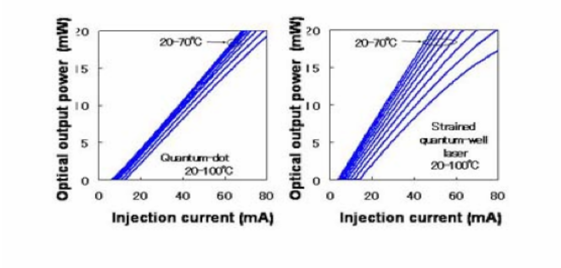


Figure 12 Temperature dependence of light-current characteristics (Fujitsu Temperature Independent QD laser 2004)

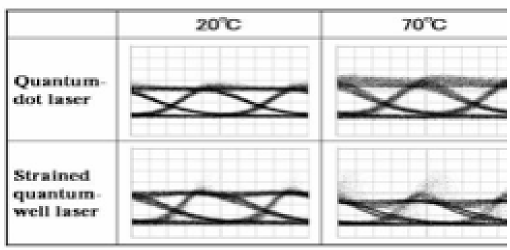


Figure 13 Modulation waveform at 10Bbps at 20°C and 70 °C with no current characteristics (Fujitsu Temperature Independent QD laser 2004).

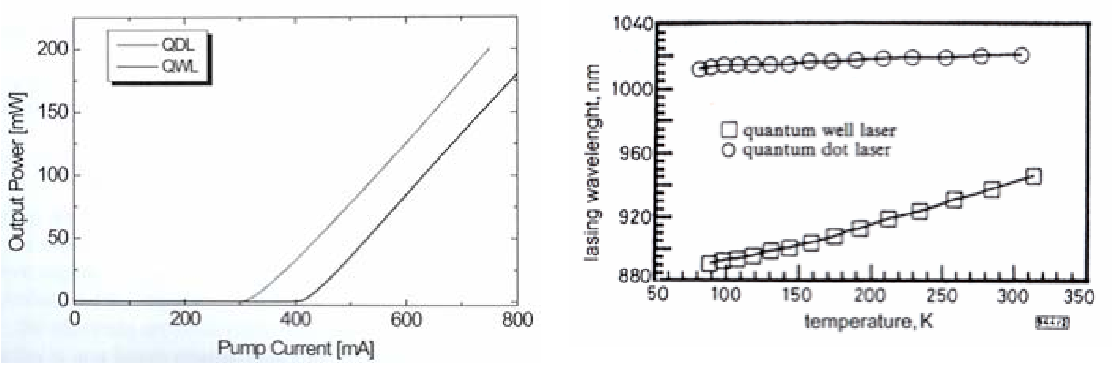


Figure 14 Comparison betweeen QD and QW laser. (Betul Arda, Huizi Diwu. Department of Electrical and Computer Engineering University of Rochester)