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P2_15 Quantum well widths as a function of doping

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Abstract
We iteratively calculate theoretical data within an infinite model, that allows you to determine the required well size given a specific doping, for a laser semiconductor emitting light between the wavelengths $450\ nm \leq \lambda \leq 550\ nm$. This data is useful for the self-assembly of SI lasers.

P2_4 General Physics

Introduction

It is known that the doping in semiconductors is what gives them their unique transport properties. In this paper we look at how the well width of an InGaN quantum well/dot in a GaN/InGaN/GaN wafer varies as a function of the doping.

Theory

In the first instance we look at this problem for a fixed wavelength of the light emitted by the InGaN well. True green semiconductors lasers are currently of interest due to their applications to high-density disc-reading (i.e. the follow-up to Blu-ray). As such we choose $\lambda_{green} = 530\ nm$ [1] and look at how the well size varies w.r.t. the doping.

$$E_{well} = \frac{hc}{\lambda} \quad (1.0)$$

which gives $E_{well}(\lambda_{green}) = 2.34\ eV\ (3\ s.f.)$

In the simplest instance we can treat the InGaN well as an infinite well, of which is sandwiched between layers of GaN as so:

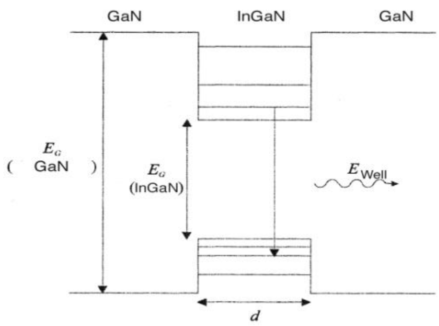

Figure 1.

The corresponding equation relating to the energy of the InGaN well is given as:

$$E_{well} = E_{g,InGaN} + \frac{\hbar^2\pi^2}{2m_0 d^2}\left(\frac{1}{m_e} + \frac{1}{m_h}\right) \quad (2.0)\ [2]$$

where $E_{g,InGaN}$ is the InGaN bulk band gap, *d* is the well width, m_0 is the mass of an electron and m_e, m_h are the effective electron and hole masses in InGaN. As we're interested in the variation in the well width as a function of the doping we rearrange equation (2.0) making *d* the subject.

$$d = \sqrt{\frac{\hbar^2\pi^2}{2md^2}\left(\frac{1}{m_e} + \frac{1}{m_h}\right)\left(\frac{1}{E_{well-}E_{g,InGaN}}\right)} \quad (2.1)$$

The dependence of *d* on the doping *X* is a result of the $E_{g,InGaN}$ term which is a function of the doping. $E_{g,InGaN}(\mathrm{X})$ is given by the expression [3]:

$$E_{g,InGaN}(\mathrm{X}) = XE_{InN} + (1-X)E_{GaN} - bX(1-X) \quad (3.0)$$

where E_{InN} is the band gap energy of InN (dopant), E_{GaN} is the band gap of GaN [4], *X* is the doping factor and *b* is the bowing parameter.

The bowing parameter is a coefficient inferred from the form of the band gap energy of the semiconducting material. Sources vary between ~2 eV and ~4eV [5]. *b* varies w.r.t. the lattice constant [5] and the mismatch between the InN and GaN lattices. So given that we're not accounting for strain in the lattice, it is assumed that an approximate value of *b* will suffice. We set *b* equal to the same value in [3] however, as it's a constant, it won't affect the overall form of the dependence. There is also a dependence from the effective electron mass of InGaN [3]:

$$m_{e,InGaN} = m_{e,GaN} + X(m_{e,InN} - m_{e,GaN}) \quad (4.0)$$

$$m_{h-heavy(In_XGa_{(1-X)}N)} = 0.6m_0 \quad (4.1)$$

where $m_{e,GaN}$ and $m_{e,InN}$ are the effective electron masses of InN and GaN [4].
Substituting (3.0), (4.0) and (4.1) into (2.1) and iterating over the range $0 \leq X \leq 1$ we produce this plot:

Results

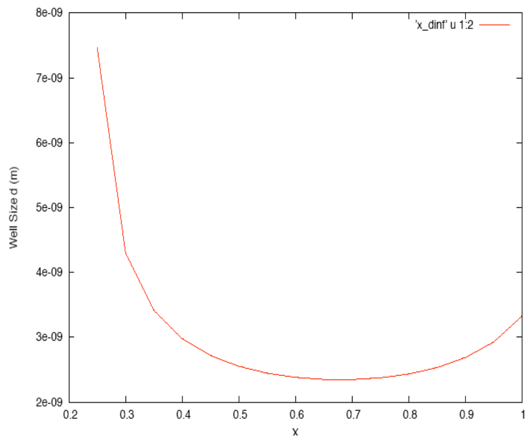

Figure 2. Well Size *d* (m) as a function of doping *X* for $\lambda = 530\ nm$

It can be seen from (2.1) that there is a cut-off doping level $X \leq 0.2$ which corresponds to $E_{well} \leq E_{g,InGaN}$, hence (2.1) goes becomes complex ($d = \sqrt{-ve}$). It is therefore evident that $E_{well} \leq E_{g,InGaN}$ is not energetically possible.

Figure 2 is parabolic as expected from the form of (3.0). So for a true green wavelength laser, we can predict the well sizes of the InGaN based on the amount of doping.

This is for a fixed emission wavelength. It doesn't tell us anything about how to optimise the wavelength of the emitted light as a function of the doping. It simply predicts the well width for given amounts of doping for a true green semiconductor laser, within an infinite model.

In figure 3 we have plotted (2.1) for $450\ nm \leq \lambda \leq 550\ nm$.This allows us to calculate a *d* or *X* given that λ and either *d* or *X* is known. Therefore in context to both experimental and theoretical data we can calculate *d* or *X* w.r.t. λ.
Figure 3 also illustrates that the larger the well size, the larger the emitted wavelength of the semiconductor laser.

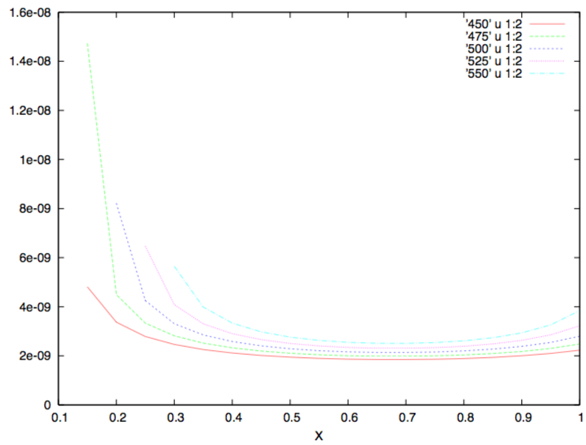

Figure 3. Figure 2 repeated for varying λ.

Conclusion
We have shown that for a given doping ($0 \leq X \leq 1$), you can determine a theoretical well size for a specific emission wavelength, to an approximate degree of accuracy using an infinite well model. Figure 3 displays a series of values which would produce a laser emitting in the range $450\ nm \leq \lambda \leq 550\ nm$.

References
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