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P2_12 InGaN quantum-well width w.r.t λ

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Abstract

We derive a value d=3.87 nm (3 s.f.). This is the required InGaN quantum well width to produce a 'true' green laser of ~530 nm, derived using a simple infinite well model. 'True green' semiconductor lasers are the next generation of lasers for use in HD disc-reading devices and as such are of interest.

Introduction

Semiconductor quantum wells lie at the heart of semiconductor lasers for example, current 'Blu-ray' players are based on InGaN quantum wells that generate laser wavelengths in the range of λ =360-480 nm.

True green InGaN lasers in the range λ =515-530 nm have great potential, being more compact, offering greater temperature stability and capable of higher modulation capacity than their current frequency doubling counterparts [1]. A true green laser of λ =530nm has still not been achieved. In this paper we look at the size of the InGaN well required to produce a 530 nm laser.

GaN-InGaN-GaN Hetrostructure

The light emitted by a semiconductor laser is determined by the energy gap of the quantum well within the hetrostucture. This is modified by size quantisation: A layer of semiconductor with a small band gap is sandwiched between layers of a large band gap semiconductor producing a quantum well that can confine both electrons and holes. Blu-ray devices use a GaN-InGaN-GaN structure so we will assume that this structure is most suitable for a true green laser.

GaN
InGaN
GaN

Figure 1. GaN-InGaN-GaN hetrostructure.

The band gap of a quantum well, E_{well} within a simple infinite 1D quantum box approximation is given as,

$$E_{well} = E_{g,InGaN} + \frac{\hbar^2\pi^2}{2m_0 d^2}\left(\frac{1}{m_e} + \frac{1}{m_h}\right) \quad (1.0)\ [4]$$

where $E_{g,InGaN}$ is the bulk band gap in *InGaN*, *d* is the quantum well width, m_0 is the mass of an electron and m_e, m_h are the effective electron and hole masses in *InGaN*.

Rearranging with respect to *d* gives:

$$d = \sqrt{\frac{\hbar^2\pi^2}{2m_0}\left(\frac{1}{m_e} + \frac{1}{m_h}\right)\left(\frac{1}{E_{well-}E_{g,InGaN}}\right)} \quad (1.1)$$

Determining $E_{g,InGaN}$

The energy gap in bulk *InGaN* is both a function of the doping and the temperature.

$E_{g,InGaN}$ w.r.t the doping, *X*, is given by the expression [2]:

$$E_{g,InGaN}(\mathrm{X}) = XE_{InN} + (1-X)E_{GaN} - bX(1-X) \quad (2.0)$$

where E_{InN} is the band gap energy of *InN*, E_{GaN} is the band gap energy of *GaN*, *b* is the bowing parameter of $In_XGa_{(1-X)}N$; set to 2 eV [5] and *X* is the *In* doping relative to *Ga*.

The bowing parameter is a coefficient inferred from the form of the band gap energy of the semiconductor material. Sources vary between ~2 eV and ~4eV [2,5]. *b* varies w.r.t. the lattice constant and the mismatch between the *InN* and *GaN* lattices [5]. Given that we're not accounting for strain in the lattice and *b* is difficult to theoretically calculate, it is assumed that an approximate value will suffice.

Jih-Yuan Chang et al is concerned with blue *InGaN* quantum-well lasers of $\lambda > 435\ nm$. They used *X*=0.2 doping for their *InGaN* wells and found $E_{g,InGaN} = 1.99\ eV$ however, values for E_{GaN} vary between crystal types and values for E_{InN} vary between sources. Here we've used values w.r.t. zincblende *GaN* which is why our values may vary somewhat from Jih-Yuan Chang et al.

Compound	Energy gap (eV) (at 300K)
GaN	3.2
InN	2.0

Table 1. [3]

Considering the doping range $0 < X < 1$ we assume an average doping of *X*=0.5, 50/50 *In/Ga* to achieve $\lambda \sim 500\ nm$.

Using (2.0), $E_{g,InGaN}(0.5) = 2.10\ eV\ (3\ s.f.)$

Calculating the Effective Mass Values [2]

The effective mass of the electrons and holes in *InGaN* are also a function of the doping therefore before we calculate *d* we must calculate the corresponding masses for *X*=0.5.

$$m_{e,InGaN} = m_{e,GaN} + X(m_{e,InN} - m_{e,GaN})$$
(3.0)

$$m_{h-light(In_XGa_{(1-X)}N)} = 0.0583 m_0 \quad (3.1)$$

$$m_{h-heavy(In_XGa_{(1-X)}N)} = 0.6 m_0 \quad (3.2)$$

Compound	Effective mass ($in\ m_0$)
$m_{e,GaN}$	0.13 [3]
$m_{e,InN}$	0.11 [3]
$m_{e,InGaN}$	0.12 (3.0)

Table 2. Effective masses.

The assumption is made here that $N_{h-light} \sim N_{h-heavy}$. Since $m_{h-heavy} \gg m_{h-light}$, we can neglect $m_{h-light}$ in our calculations. This is probably a good approximation as the heavy hole state is the lowest hole energy, located closest to the top of the valence band and the device could be set up in such a way that by filling the light hole state with electrons, only transitions with these heavy hole states will occur. Therefore, substituting values from table 2 into (3.0) and (3.2) give

$$\left(1/m_{e(In_xGa_{x-1}N)} + 1/m_{h(In_xGa_{x-1}N)}\right) = 10 \quad (3.3)$$

Results and Discussion

It is assumed equation (2.0) calculates $E_{g,InGaN}$(X) for T=300 K as it contains no temperature dependence and the values we've used for *GaN* and *InN* energy gaps are both taken at T=300 K.

Therefore, substituting $E_{g,InGaN}(0.5) = 2.10\ eV$ into (1.1) gives d=3.87 nm (3 s.f.)

On comparison to FIG.1 [2] it can be seen that our well size is of the same order of magnitude. The accuracy of the model could be improved further by treating the quantum dot as a finite well and accounting for the strain in the lattice.

Conclusion

Using a simplified model we have shown that the width of an InGaN quantum well in a GaN/InGaN/GaN hetrostructure can be calculated to the correct order of magnitude and that further improvement of the model requires it to be treated as a finite well.

References:

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