White light from solid state sources

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Abstract

The human perception of colour is paramount to the production of white light sources. Historical lighting technologies such as incandescence and fluorescence have been shown to have poor luminous efficiency and short lifetimes. Solid state lighting technology including quantum wells and light emitting diodes has been shown to be an efficient method to produce lighting and methods to produce white light discussed. Quantum dot technologies show promise in the field of solid state lighting with emphasis on their tunability and capability to produce white light. Economic considerations of producing a quantum dot generation of solid state devices has been considered and reference made to the United State department of energy studies on cost effectiveness.

1) Introduction to white light

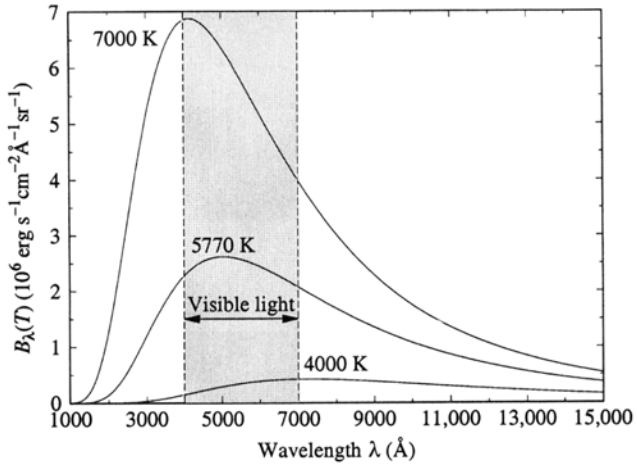
1.1) The Planck distribution function

The spectral radiance emitted by a black body of temperature T is given by

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT}-1} \qquad \textit{Eqn. 1}$$

where B_λ is the spectral radiance and all other symbols have their standard meaning (Carroll & Ostilie,1996). Given that the sun has a surface temperature of 5770 Kelvin, the distribution function peaks in the so called 'visible range' of light. The sensitivity of the human eye effectively matches to the visible part of this distribution resulting in the best vision possible during daylight hours.

Fig. 1



The Planck distribution of radiation for three different black body temperatures. The visible region of the electromagnetic spectrum is indicated and fills covers the peak of 5770K

1.2) The response function of the human eye

The human eye detects colour by the use of three different cones. Each cone detects a portion of the visual spectrum, the ranges over which each cone detects overlap with differing sensitivities. In this manner the human eye sends three different signals to the brain which are built together depending on their strength to generate a colour.

The human eye interprets the black body spectrum of our sun in the visual range to be white light. Replication of a 'white' light source can be achieved in two possible ways, either by reproducing the relative intensities of a blackbody spectrum or finding a combination of three or more wavelengths which trick the human eye into believing it is seeing the spectrum of the sun.

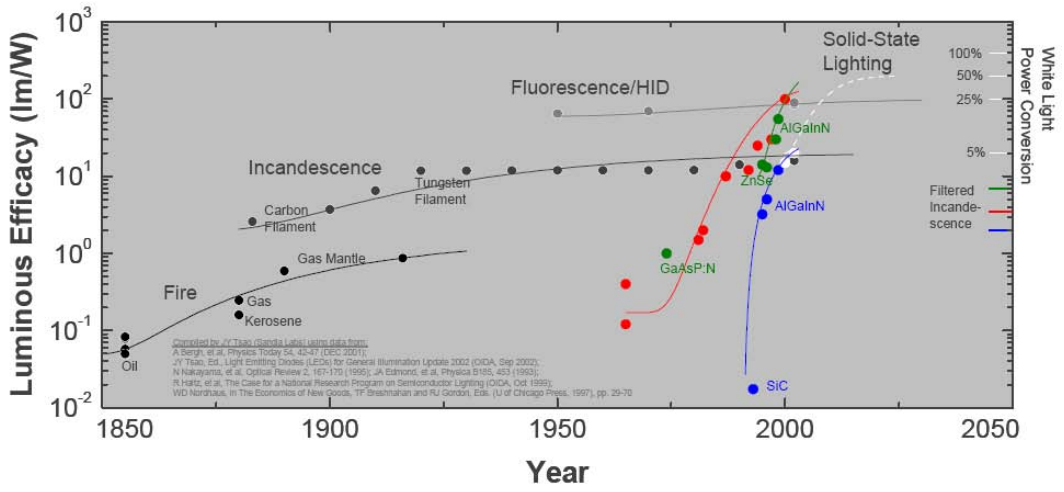
2) History of lighting sources - (Tsao 2004)

Artificial lighting technologies are used to substitute or compliment sunlight. The human eye is sensitive in the 425 to 675 nm spectral range and the goal of artificial lighting is to simulate the solar spectrum as efficiently as possible. As time has passed and technology progressed, the transition to more efficient light sources has occurred (Fig. 2). The obvious goal is to achieve a 100% efficient light source which converts all input energy to light in the visible range and lasts forever.

The three historical techniques for generating light are fire, incandescence and fluorescence. These technologies have progressed since their conception but seem to be fundamentally limited to efficiencies in the range of 1 to 25 %. 25% efficiency refers to only one quarter of the input energy being converted to useful light in the visible spectrum and the remaining 75% will go primarily to heat. A big limitation of all lighting technologies is the lifetime of the source. Incandescent light bulbs have relatively small lifetimes due to evaporation of the filament caused by extreme heating. Typical lifetimes for incandescent sources are of the order of 1000 hours, and 10000 hours for fluorescence.

The latest branch of lighting technology is solid state lighting. The technology is based around injecting electrons into a forward biased semiconductor p-n junction, these electrons recombine with holes in the valence band and photons are emitted. With the goal being to produce white light, these photons are either mixed with different colour photons from other LEDs to make white or down converted into a distribution of colours by using a variety of phosphors or other down conversion materials. At every stage in the process energy is wasted, improving each step of the process will yield efficiency gains.

Fig. 2



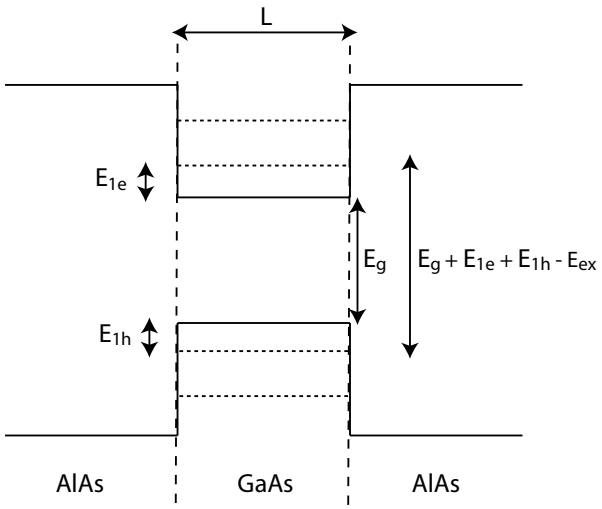
How different lighting technologies have advanced over time and been superseded by more efficient devices.

3.1) Production of light with solid state devices

One of the simplest methods to produce tunable solid state lighting is via quantum wells. A quantum well is semiconductor formation which confines electrons/holes in one dimension forcing them to occupy a planar region. When the confined electron hole pairs recombine, they emit photons at a wavelength which is related to the well width.

Quantum wells are produced by layering semiconductor materials such that a narrow band gap material is sandwiched between two wider bandgap materials. A possible combination of materials is gallium arsenide (GaAs) sandwiched between two layers of aluminium arsenide (AlAs). These layered structures can be grown by molecular beam epitaxy.

Fig. 3



Quantum potential well diagram from a quantum well laser

Figure 3 shows a potential structure for a quantum well. To produce emission, electrons can be injected into the top layer (conduction band) resulting in them falling into the GaAs narrow band gap well, holes will correspondingly pool at the top of the GaAs lower band (valence band). When an electron falls through the GaAs potential and recombines with a hole a photon is released. The energy of the photon and hence its wavelength is determined by

Eqn. 2a + 2b

$$E_{h\nu} = E_g + E_{1e} + E_{1h} - E_{ex}$$

$$E_{h\nu} = E_g + \frac{\hbar^2}{2m_e^*}\left(\frac{\pi}{L}\right)^2 + \frac{\hbar^2}{2m_h^*}\left(\frac{\pi}{L}\right)^2 - E_{ex}$$

where E_{ex} is the exciton binding energy, this correction is due to the coulomb potential between an electron hole pair. From equations 2a and 2b it can be seen that the energy of the emitted photon is dependent on the width of the well. This means that it is possible to alter the wavelength of the emission by altering the well width during the MBE production process. Unfortunately the possible variation in the emission is small compared to the band gap energy E_g.

To allow for further tunability of emission, the energy E_g can be altered by varying the materials from which the well is made from. Indium arsenide (InAs) has a smaller band gap and allows for creation of lower energy photons. It is also possible to mix gallium arsenide (GaAs) with indium arsenide (InAs), essentially alloying the two materials together to form a third material with a band gap with a value between the two materials.

$$GaAs + InAs \rightarrow Ga_{1-x}In_xAs \qquad \textit{Eqn. 3}$$

*3.2) Frequency doubling - (*Boyd 1992)

If the emission from a quantum well is not what you require, it is possible to manipulate the output further to produce a different wavelength. The output of the well is passed through a frequency doubling crystal and this halves the wavelength of the light, unfortunately this is not a very efficient process. Potassium Titanyl Phosphate $KTiOPO_4$ (KTP) is a material which allows for the doubling of wavelengths from around 1064nm to 532nm (green).

KTP is a non linear crystal and frequency doubles via the process of second harmonic generation (SHG). The SHG power grows quadratically with the power at fundamental wavelength, it is therefore important to make the fundamental power as high as possible for efficient conversion. Efficiencies range from 1% to 80% depending on the power of the fundamental for this doubling process with KTP. Blue lighting can also be achieved by frequency doubling a wavelength of 914nm.

3.3) Phosphors

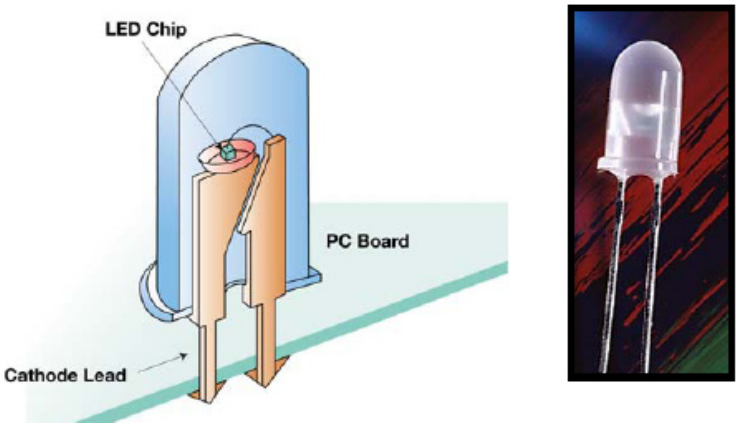
Phosphors are used to down convert high energy photons into lower energy photons. Current phosphor technology produces non tunable emission by the use of doped oxides or rare earth metals coated over the surface of a light emitting source. As the light source emits, these photons impinge on the phosphors which in turn excites electrons across the bandgap of the phosphor.

The electrons in the phosphors conduction band eventually relax causing them to emit light at the band gap energy. This process effectively converts one wavelength to another with a loss of energy due to the relative energies of the different wavelengths. The major problem with current phosphors are their lack of tunability for both absorption and emission, these are both limited by the material choice available. Poor tunability means that it is very difficult to produce the whole array of colours necessary for efficient production of white light.

3.4) Light Emitting Diodes (LEDs)

Current LED technology produces non tunable electroluminescence via emission from a p-n junction. As an electric current is driven through the junction, electrons are excited across the bandgap into the conduction band. Electrons then diffuse away from the junction and decay back across the bandgap to the valence band emitting light at the band gap energy. This produces a narrow distribution of wavelengths dependent on the material choice. This light can then strike phosphors to produce different colours if desired. Blue and white LEDs are typically formed by using a UV emitter and a phosphor which down converts UV light into the desired colours.

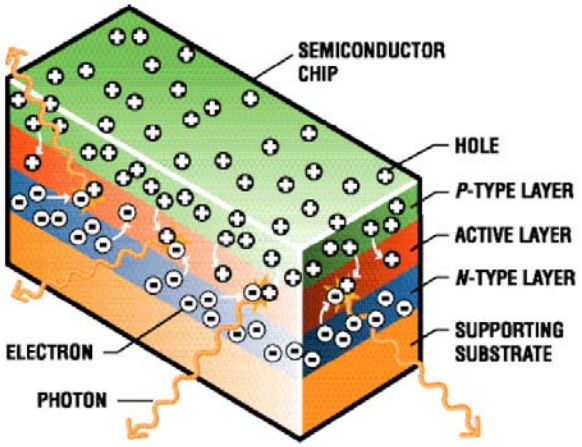
Fig. 4



Cross section view of a 5mm LED

A basic diagram of a p-n junction as found in an LED chip is shown in figure 5. The p-n junction consists of a p-type and n-type semiconductor layer on a substrate base. At the point where the two doped semiconductor layers meet, a depletion layer forms whereby the free electrons due to doping in one layer combine with the holes due to the doping from the other. When a forward bias is applied to the device, high energy electrons in the n-type layer are able to surmount the potential of the depletion layer and radiatively recombine with holes resulting in emission of light.

Fig. 5



Basic structure of an LED solid state chip (p-n junction) with emission shown by arrows

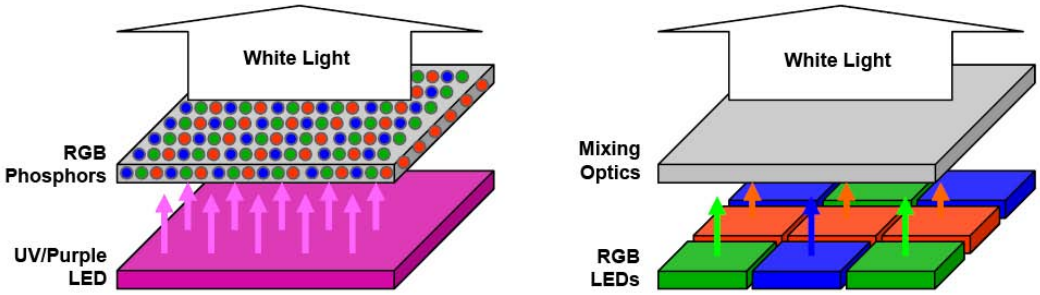
4) Current state of technology - (Tsao 2004)

4.1) Mechanisms to produce white light

There are two main mechanisms to produce white light which are both illustrated in figure 6. Phosphor down conversion uses a UV or purple LED to excite a variety of phosphors which emit at different wavelengths, in this manner RGB white light can be produced. The technology to produce white LEDs in this down conversion manner exists and is currently the mechanism of choice. There are inherent efficiency issues in this design because down conversion of photons incurs significant losses.

Colour mixing technology relies on the production of multiple LEDs which produce red green and blue light which can then be combined together to produce a white light source. Colour mixing has the potential to be more efficient because it doesn't waste energy down converting the photons. At this time the technology exists to produce the blue and red proportions of the RGB scheme but no efficient LEDs exist in the green/yellow/orange range. This is the most important area because it is where the human eye is most sensitive.

Fig. 6



Phosphor Down-conversion **Color Mixing**

Phosphor down conversion and colour mixing approach to produce white light.

4.2) The need for change

With the advent of more efficient light sources, worldwide electricity consumption due to lighting could be decreased by more than 50%, and total consumption of electricity could be decreased by more than 10% (J.Y. Tsao, 2006). This is assuming 100% market penetration of 50% power conversion efficiency optoelectronic devices for lighting. These efficiency savings could help decrease carbon emissions by a corresponding 10% with some unknown impact on global warming.

4.3) Challenges

An improved understanding of the physics of AlGaInP and AlGaInN materials and nanostructures is required if solid state lighting is to advance. Nanostructures hold the key to developing tunable emission sources but material choice is also important for creating sources which emit in the visible range. Improved optoelectronic devices are required to aid efficient photon generation

and extraction, this is especially important for high power light sources where inefficiencies in the generation process will result in excess heating of the device. It will be necessary to design packaging which can resist heat damage to keep the nanostructures stable.

Improved wavelength-conversion technologies are required to aid the phosphor down conversion process, new technologies will be needed which allow for greater tunability of the light source to produce a high quality white. Colour-mixing is an alternative to more advanced phosphors and requires development of tiny sources which can be mixed together to form the white light. Yet all of this is superfluous if high volume low cost techniques for manufacturing are not devised. The cost of a light source is a function of its running costs, breakdown rate and production cost, if these numbers are unable to prove commercially viable then solid state lighting will not properly take off without legislative pressure.

Fig. 7

LAMP TARGETS	**SSL-LED 2020**	**Incandescent**	**Fluorescent**
Luminous Efficacy (lm/W)	200	16	85
Lifetime (hr)	100,000	1,000	10,000
Flux (lm/lamp)	1,500	1,200	3,400
Input Power (W/lamp)	7.5	75	40
Lamp Cost (in $/klm)	2.0	0.4	1.5
Lamp Cost (in $/lamp)	3.0	0.5	5.0
Color Rendering Index (CRI)	80	100	75
DERIVED LAMP COSTS			
Capital Cost [$/Mlmh]	0.13	1.25	0.18
Operating Cost [$/Mlmh]	0.35	4.38	0.82
Ownership Cost [$/Mlmh]	0.48	5.63	1.0

Summary of US DOE statistics for the cost of current and future lighting sources

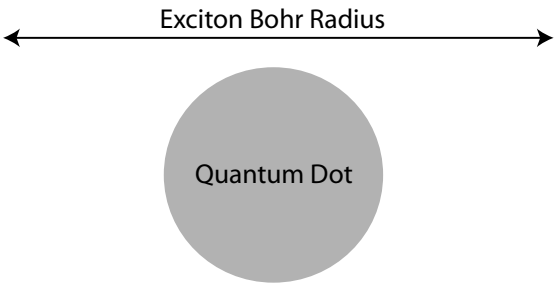
Figure 7 shows a summary of the US Department of Energy expectations for the field of solid state lighting by the year 2020 compared to current technologies. The main desired improvements are luminous efficiency and lifetime which results in an impressive overall cost per lumen. The improvements in luminous efficiency are important because they reduce the running costs of the device for a given light output. The lifetime of the device is also important, it is a measure of how long the device is expected to last before it has to be replaced. Production of the solid state lighting sources is expected to be considerably more costly than for current incandescence and fluorescence, this is due to the specialist nature of producing nanoscale devices, but this is clearly outweighed by the longevity of the device.

Colour rendering index (CRI) is a measure of how accurately the light source illuminates 8 standard pastel colour when compared to the black body spectrum of the sun (100). The CRI expectation for solid state lighting is not as high as current incandescence, this is due to the difficulty in efficiently producing a simulated solar spectrum. Producing high CRI sources is an economic balance between cost, efficiency and human perception.

5.1) The Future - Quantum Dots

The future of solid state lighting lies in quantum dots. Quantum dots are semiconductor formations which range in sizes from 2 to 10 nanometres (10 to 50 atoms) in diameter. At these sizes the quantum confinement of the electron holes pairs (excitons) results in a large spread of discrete energy levels for the system and a band gap which drastically varies with the addition or subtraction of a single atom from the structure.

Fig. 8



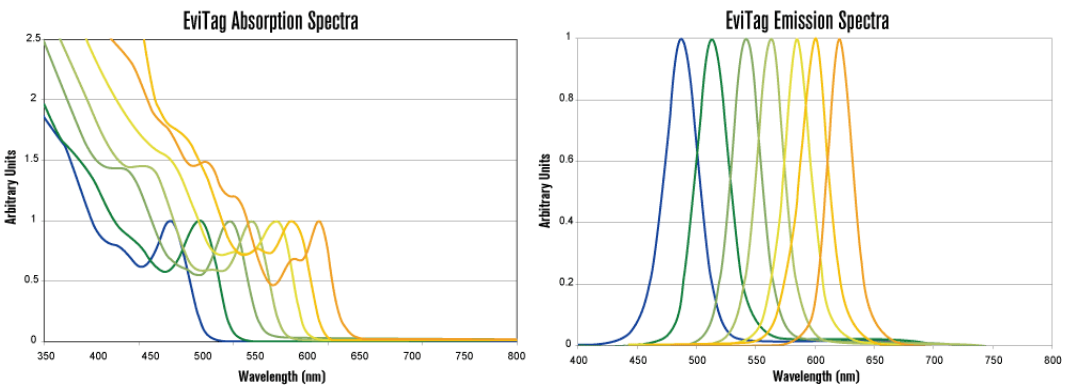
A diagrammatical representation of the relative sizes of a quantum dot and the exciton Bohr radius in a typically zero dimensional system

Quantum dots are often termed zero dimensional structures because the exciton is confined in all three dimensions, such that the exciton Bohr radius is greater than any dimension of the crystal. The exciton Bohr radius is the natural physical separation in a crystal between an electron in the conduction band and the hole it leaves behind in the valence band. The exciton is held together by the coulomb force and can be treated as a hydrogenic system with different masses.

5.2) Tunability of quantum dots

Quantum dots can both emit light at a specific wavelength, and exhibit a tunable absorption peak as well. Quantum dots have a relatively large probability to absorb any wavelength of light with energy greater that or equal to its band gap. This is a clear advantage over phosphors where absorption is material dependent and typically only in a narrow wavelength band. Figure 9 shows how the absorption and emission spectra of some quantum dots of different sizes, the y axis units are arbitrary to allow for simplistic comparison between colours.

Fig. 9



Absorption and emission spectra of quantum dots produced by Evident Technologies. Colours range from blue on the left through to orange on the right

Quantum dots can be tuned by changing the mass and or shape of the dot. The addition of an atom to the structure will move the emission profile, changing the shape of the dot effects the symmetry of the exciton wavefunction and subtly changes the ground state emission. Production of various shaped quantum dots (Fig. 10) is possible in the lab but the goal is to create quantum dots which can be easily mass produced.

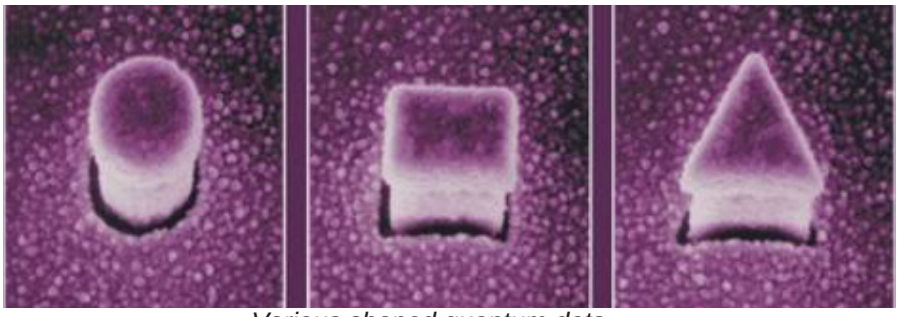


Fig. 10

Various shaped quantum dots

5.3) Quantum yield

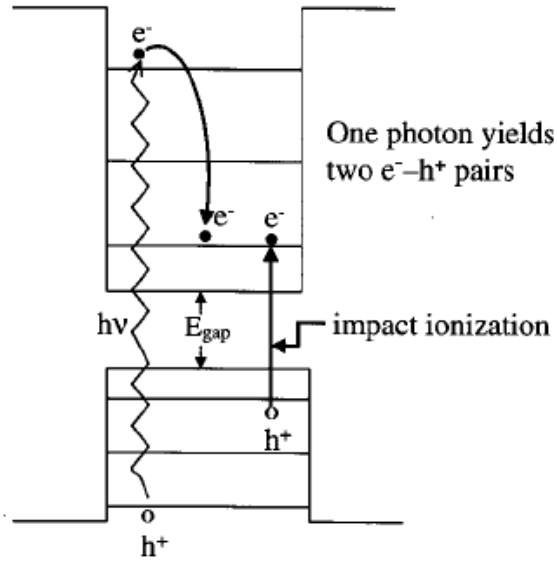
The percentage of absorbed photons that result in an emitted photon is called the Quantum Yield (QY). In a normal semiconductor the expectation is for slightly less than one exciton per incoming photon. This yield is reduced by non-radiative recombination processes which largely occur at the materials surface where the chemistry of the system is different to that of the bulk. It is possible to increase the quantum yield by coating the surface of the dots with an inorganic wide band gap semiconductor, this coating increases the probability of electrons relaxing directly back to the valence band.

It has been demonstrated that the absorption of a single photon by a quantum dot can yield more than one exciton. Multiple excitons per absorbed photon are formed when the energy of the absorbed photon is far greater than the semiconductor band gap (E>2 times band gap). Quantum yields of 300 percent have been achieved for 2.9nm diameter PbSe (lead selenide) quantum dots with a photon energy greater than 4 times the band gap energy.

The impact ionisation process show in figure 11 accounts for how multiple excitons can form. The charge carriers are confined within a minute volume, thereby increasing the probability of interactions and the sharing of energy. When an extremely high energy electron in the conduction band impacts an electron in the valence band, it transfers some energy to the low energy electron allowing it to surmount the band gap, this results in multiple excitons.

In a bulk semiconductor the excess energy of the excited electron is lost to heat in non radiative relaxation processes. Multiple collisions are unlikely because the electron is less confined and free to move in an open space.

Fig. 11



Enhanced photovoltaic efficiency in quantum dot solar cells by impact ionization.

Impact ionisation has applications in solar cells where multiple excitons will increase the current created by the device and therefore raise its efficiency. This process also has applications in quantum dots being used as phosphors, in this manner a high energy source can pump the quantum dots of different sizes. The larger dots with small band gaps may be able to emit two or more photons per source photon, thus raising the brightness of the device.

5.4) Quantum dot LEDs

QLEDs (Quantum Light Emitting Diodes) could be made out of networks of quantum dots and would operate in a similar manner to a traditional LEDs, but with much greater versatility. An electrical current would be driven through a quantum dot network, but instead of traditional semiconductor energy bands, the current would encounter discrete energy bands of the quantum dots which made up the network. The band gaps of the quantum dot network could be varied by producing slighting different sized dots, in this manner any colour LED could be produced.

5.5) Advantages of Quantum Dot Electroluminescence

High quality, low-cost white light can be produced by intermixing red, green and blue light emitting quantum dots to form a composite semiconductor. The proportion of each colour required to produce white light can be controlled by altering the number density of each size dot.

Traditional semiconductors are grown at high cost by producing very pure wafers then cutting them to a specific size. Quantum dots can be grown easily in large batches by colloidal chemistry then manipulated in to many final forms.

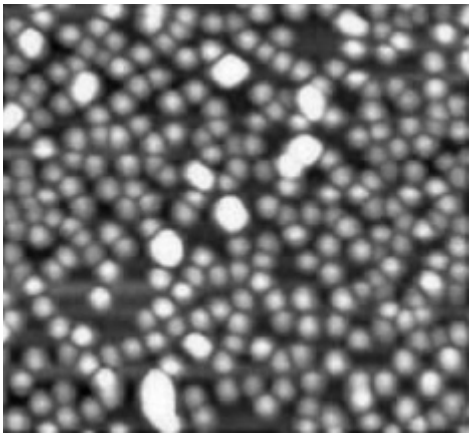
5.6) Production of Quantum dots

Very basic quantum dot formations are possible by Stranski-Krastanov growth. Quantum dots will spontaneously form during molecular beam epitaxy when the substrate and growth material are not lattice matched. The strain which results between the two materials causes islands to form on top of a two dimensional wetting layer. The islands can subsequently buried in a large band gap semiconductor to form quantum dots.

Before burring, the quantum dots can be capped in a different material. In recent years it has been shown that during the capping stage the structural properties of the quantum dot can change. Under the right conditions the buried islands are coherent quantum dots, i.e. the strain is accommodated through elastic relaxation. If the conditions are not correct, plastic relaxation can occur and dislocations form in order to release the strain. Such dislocations are not desirable because they can strongly reduce the luminescence efficiency of the dot.

There are problems with this growth mechanism which are yet to be satisfactorily resolved. The wetting layer can cause interference of incident light onto the quantum dots, this can prevent absorption and distort the energy bands for the dot. It is very difficult to control the size of each dot and the expectation is for a normal distribution of dot sizes focused about some mean value. Finally the placement of the quantum dots is often random. Figure 12 is a image of some self assembled InGaAs quantum dots in an apparently random formation with some variation in sizes.

Fig. 12



1000nm by 1000nm image of self assembled InGaAs quantum dots

The shape of the quantum dots is influenced by how the two layers of materials release strain, this is often a result of the differing lattice constants. Pyramidal, cuboidal and cylindrical dots are some of the possible shapes which can form, each with their slightly different quantum properties. There have been substantial efforts to produce regular arrays of quantum dots for modern solid state lighting devices which are stable at high temperatures. Progress has been made by exploiting regular strain patterns on specific miller index crystal planes (T Mano, 2005).

6) Conclusion

Solid state lighting has the capability to replace both incandescence and fluorescence as the number one lighting source of choice. Solid state devices are already being implemented into many devices and often taking the place of highly inefficient incandescent bulbs. Bicycle lights are a good example of an application where the high efficiency LEDs have become dominant, they offer longer battery life than conventional filament bulbs and a variety of colours.

Current uptake of solid state devices is limited by factors such as the cost of the device and the difficulty in producing high energy output devices. Heat stability is a major problem in current solid state lighting technologies, as the power output is raised, the amount of heat produces raises proportionally. Arrays of LEDs are one option to increase the power output of a system but as the energy output is scaled up, the size increases. Quantum dots have been shown to be more stable in extreme environments and they possess a clear efficiency advantage over quantum well and p-n junction devices, this helps minimise the heating problem further.

The time frame for 100% uptake of solid state devices for lighting is unclear at this point. By 2020 solid state lighting is expected to be far superior to conventional lighting but its uptake will be very dependent on energy prices. As the cost of electricity rises, solid state lighting research will receive more corporate investment with the goal to raise their efficiency and produce them cheaply. The cost of acquisition and energy prices will be the major factors in the speed of uptake of this technology.

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