Gallium Nitride: Lighting the Future

Never before has energy efficient lighting been so popular, or so widespread. But we could be doing better. The latest mathematical research is helping to get the most out of the next generation of light bulbs.

Up and down the country our homes and workplaces are filled with over 650 million light bulbs, allowing us to work, rest and play even when the sun has set. Yet for something we rely on so heavily, they are not particularly good at their job. An old fashioned light bulb with a tungsten filament was only five per cent efficient – 95% of the energy you put in wasn't turned into light. Most of it was wasted as heat. During its lifetime it got through as much energy as contained in three tonnes of coal. In this country we currently use about a fifth of our electricity on lighting. More efficient alternatives, then, are good for both the environment and our bank balances.

In recent years there has been a big move towards energy saving light bulbs. They may be better than their tungsten counterparts, but a traditional energy saving lightbulb still only has an efficiency of around 20%. A much better alternative is a bulb that uses light emitting diodes (LEDs). They last much longer than traditional bulbs and are about 30% efficient. They have been used recently to light both Buckingham Palace and the ceiling of the Sistine Chapel. They are constructed from a semiconductor material called gallium nitride (GaN); it is possible to build laboratory GaN LEDs that are up to 60% efficient – a twelve fold improvement on tungsten bulbs. However, they are currently limited by something called "efficiency droop".

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Quantum physics says that electrons can only have certain energies. In different materials, these energies are separated into bands – one called the conduction band, the other the valence band. In insulators there is a big gap between the two and so it is hard for electrons to flow. In conductors, the gap is very small and so current flow is easy. Semiconductors like GaN hold the middle ground. Light is produced in LEDs when electrons drop down from the conduction to the valence band and lose energy.

Unfortunately, this lost energy doesn't always go into light production - sometimes it can be lost to another electron in what's known as the Auger process. That electron is then ejected, removing energy that could have been turned into light. If less energy was lost to this process, LEDs would be more efficient. The trouble is that the amount of Auger loss seen in experiment does not match the level currently predicted by theory. Only when you can confidently carry out calculations that reflect experimental findings can you look at optimising the setup to increase efficiency. This is an active area of mathematical research.

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Modelling the way electrons propagate through pure GaN isn't that challenging because the gallium and nitrogen atoms are arranged in a repetitive lattice pattern. So once you've worked out how the electrons propagate through one part, you can extrapolate it to the rest. But there is an added complication which makes the task more awkward. Indium has to be added to the gallium nitride – in a process called alloying - to make sure that the light emitted is in the visible part of the spectrum (otherwise it would be in the ultraviolet part and useless for lighting). The amount of indium is around 15% and it randomly replaces atoms of gallium and nitrogen in the GaN structure. The symmetry is ruined. Mathematically modelling this more complicated configuration is much more difficult.

The Auger effect is proportional to the current density cubed. So if you double the current density the Auger effect goes up by a factor of eight. The more electrons that gather in a particular part of the material, the more dramatically the efficiency droop rises. If it were possible to model how the electrons propagate it might be possible to make alterations to minimise Auger loss. That modelling involves the mathematics of quantum mechanics.

The rules of quantum physics are notoriously strange and counter-intuitive. For example, it is impossible to predict for certain where a sub-atomic particle like an electron is going to be at any given time. It is not a failure of our mathematics, but just the way nature seems to operate. You're restricted instead to assigning a probability to where it is most likely to be. This probability is given by the square of the wavefunction which is the solution to Schrödinger's equation. Knowing where the electrons are most likely to be allows you to say something about how the current density is likely to vary through the GaN, and therefore the size of the Auger loss. But this current density in turn affects where subsequent electrons are likely to be. So that has to be put back into the Schrödinger equation again. This alters the wavefunction and so also the current density variation, which in turn alters where the next electrons are likely to be. It can be a vicious circle. It is made all the more difficult because of the broken symmetry induced by the necessary indium doping. It means that models have to deal with a lot more atoms, and that requires a lot more computer power to crunch the numbers. Researchers are currently looking for mathematical short cuts that will allow them to reduce the number of computational steps.

If successful, this mathematical trickery could increase the efficiency of LED lighting by 50%, saving consumers money and restricting our impact on the environment.

TECHNICAL SUPPLEMENT

Schrödinger's equation

The Schrödinger equation, named after Austrian physicist Erwin Schrödinger, is a linear partial differential equation that describes how a quantum mechanical system changes over time. The time dependent version of the equation is written as:

$$i\hbar\frac{\partial}{\partial t}\Psi = \hat{H}\Psi$$

where i is the imaginary unit, $\hbar$ is the reduced Planck constant, Ψ is the wavefunction and $\hat{H}$ is the Hamiltonian operator named after Anglo-Irish mathematician Sir William Rowan Hamilton. The wavefunction contains all useful information about the state of a system – all other information can be derived from it by the appropriate mathematical treatment. For example, squaring the wavefunction gives the probability that the system will be in that state.

References

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