How Electron Microscopy and Atom Probe Tomography Can Help to Solve Some of the World's Energy Problems

C.J. Humphreys

Department of Materials Science and Metallurgy, University of Cambridge, Pembroke Street, Cambridge CB2 3QZ, United Kingdom

One of the key problems facing our world today is energy. The world's energy needs are growing more steeply now than at any time in the last two hundred years, partly driven by the increase in the world's population. At the same time, oil wells are slowly drying up. Electron microscopy and atom probe tomography have a key role to play in developing the new materials and devices required to help solve the world's energy problems. For example, in developing more efficient solar cells and more efficient lighting. In this paper I will concentrate on the role of electron microscopy in developing more efficient lighting. In my talk I will refer to other energy areas as well.

Lighting accounts for around one-fifth of electricity consumption globally, and demand is growing rapidly. According to the US Department of Energy: "No other consumer of electricity has such a large energy-savings potential." Solid-state lighting, based on gallium nitride (GaN) light emitting diodes (LEDs) has the potential to reduce the global amount of electricity used for lighting by 75%, thus saving 15% of total electricity usage worldwide and also reducing carbon dioxide emissions by about 15% [1]. White LEDs are semiconductors in which the light emission comes from a very thin crystalline layer called a quantum well composed of indium gallium nitride (InGaN). The blue light emitted by the InGaN is converted into white light using a phosphor.

A major puzzle has been why InGaN quantum wells emit brilliant light even though the dislocation density is very high (typically about 10^9 cm^{-2}). It was widely believed that this was due to nanometer-scale In-rich clusters in the wells which localized the carriers (electrons and holes), thus preventing these from diffusing to dislocations, which would quench the light emission. However, high resolution electron microscopy then showed that the In-rich clusters observed in the electron microscope were due to electron beam damage [2] (fig. 1). So the question remained: why do InGaN quantum wells emit brilliant light even though the dislocation density is high? The problem was solved using atom probe tomography (APT), which showed that InGaN was a random alloy (fig. 2) and that it had monolayer and bilayer steps on the InGaN/GaN quantum well upper interface (fig. 3). Random alloy fluctuations localise the holes on a nanometer-scale and the interface steps localise the electrons on a nanometer scale [3, 4]. With this knowledge gained from electron microscopy and APT we are trying to increase the efficiency of LEDs still further by maximizing the localisation.

The major barrier to the widespread adoption of LED lighting in our homes and offices is cost. GaN-based LEDs are currently grown on expensive sapphire or SiC substrates. If we could grow them on larger silicon substrates this would result in significant cost reductions. However in order to grow GaN-based LEDs on Si, an AlN buffer layer must first be grown. The quality of the AlN buffer is very important, and on studying the AlN/Si interface using aberration-corrected electron microscopy we were surprised to find an amorphous layer about 2 nm thick separating the Si and the AlN [5]. Yet the AlN has grown epitaxially on the Si (fig. 4). We are currently investigating how this is possible with a 2 nm thick amorphous layer in between. In conclusion, we have found that electron microscopy and APT are essential techniques for helping to solve the world’s energy problems.

References
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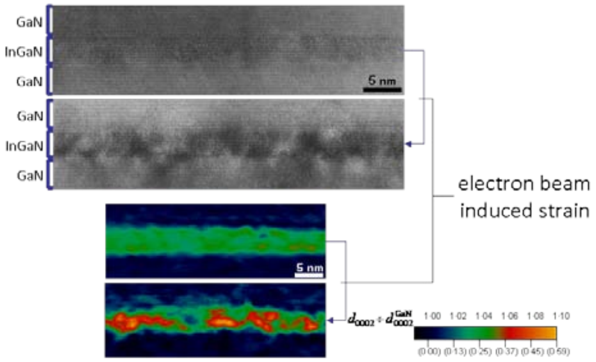

FIG. 1. HREM images and lattice parameter maps for low electron dose and higher dose showing In-rich clusters forming due to electron beam damage.

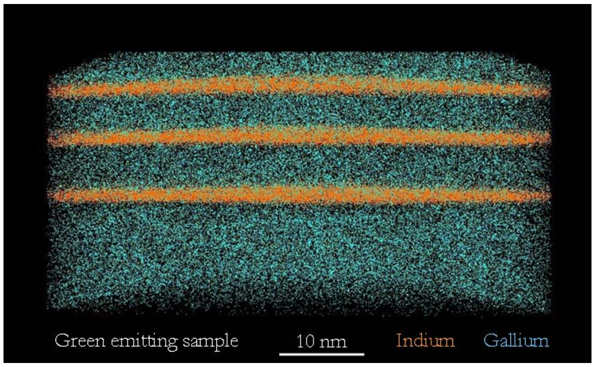

FIG. 2. Atom probe tomography image of InGaN quantum wells with GaN barriers.

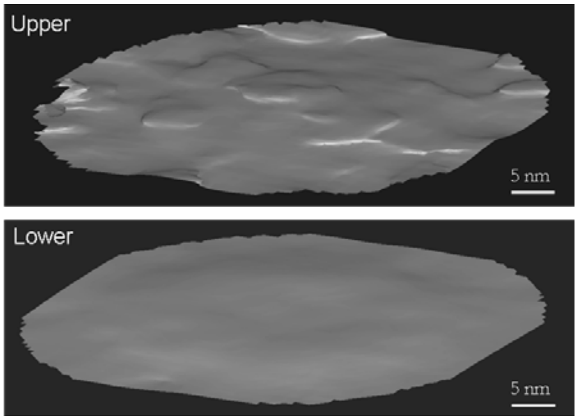

FIG. 3. InGaN/GaN quantum well upper and lower interfaces for a green-emitting sample. The upper interface shows monolayer high interface steps. APT isosurfaces.

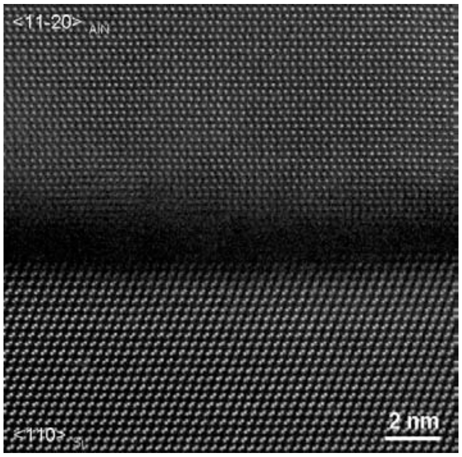

FIG. 4. HAADF image of an AlN/Si interface using a Cs corrected Titan 80-300. There is a 2 nm thick amorphous layer, probably Si_xN_y, at the interface. Titan courtesy G.A. Botton [5].