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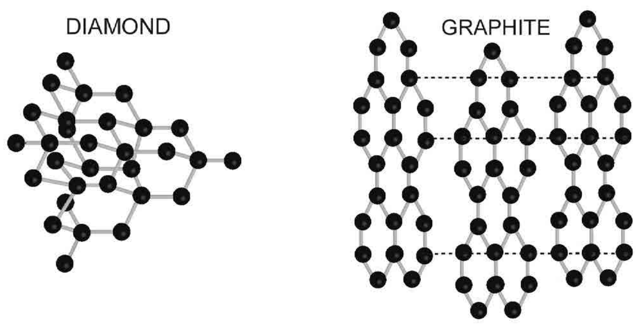
Diamond
More than just a gemstone

Key words
diamond
bonding
hardness
synthetic

When asked to think of diamond, a sparkling, colourless gemstone typically comes to mind, mined from deep within the Earth. Diamond, however, can be grown in the laboratory, with small changes in growth conditions resulting in diamonds with a range of colours and vastly different properties. UK scientists, led by the University of Warwick, are exploiting these extreme properties for a range of exciting new technologies.

Structural differences

Both diamond and graphite (found in pencils) are made of carbon, but they exhibit vastly different properties. For example, graphite is soft, whilst diamond is the hardest material known to man. This is due to that fact that each has a unique arrangement of carbon atoms. In graphite, each carbon atom is bonded to three others, to form flat sheets, with the carbon atoms arranged hexagonally. The sheets can move easily over one another. In contrast, in diamond, each carbon atom bonds to four others creating a rigid three dimensional tetrahedral crystal structure.



Two structures of carbon. (Black dots represent carbon atoms.)
Left: tetrahedrally bound carbon atoms in diamond.
Right: carbon bonding in graphite, where the flat layers are clear to see.

The rigid structure of diamond is not just responsible for its extreme hardness; it also allows heat (and sound) to travel very quickly through the lattice. Diamond is in fact the best thermal conductor of any three dimensional material. For this reason, synthetic diamond is used to dissipate heat in electronic devices and to transmit clear sound in audio systems.

Changing the recipe

By growing diamond in the laboratory, the properties of diamond can be altered to our advantage. For example, we can add different elements into the crystal lattice provided they fit. For this reason only elements either side of carbon in the periodic table are considered. Adding boron during growth turns the diamond from electrically insulating (where all the electrons are tied up in bonds) to electrically conducting. This process is called doping. As the energy levels in the diamond structure are modified during doping, the way the material interacts with light changes too. Adding boron turns the diamond from colourless to blue, and eventually black. Making diamond conductive allows scientists to fabricate superior electrodes to metals. By doping with nitrogen, the diamond is turned yellow.

CVD-grown wafers of diamond (transparent, left) and boron doped diamond (black, middle, right).

Scientific applications

Laboratory grown diamond is finding use in many exciting scientific applications. On an industrial scale, microscopic synthetic diamonds are routinely used for cutting and abrasive applications, taking advantage of the fact that diamond is extremely hard (scoring 10/10 on the Mohs hardness scale). Diamond coated cutting tools, are used for the manufacture of car and aeroplane parts, and to dig through the earth for oil, machining faster and for longer than other non-diamond based tools.

As diamond can withstand high pressures and temperatures and is optically transparent, diamond also finds use as optical windows in pressure cells and high power laser devices.

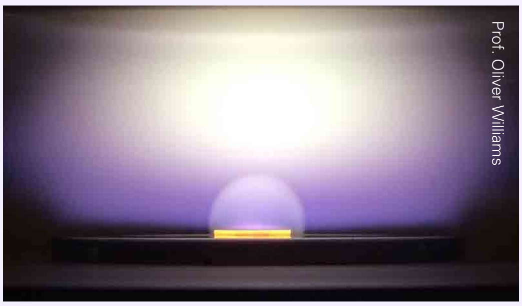
How to grow diamond

Natural diamond is grown over billions of years, in the upper mantle of the Earth, under extremely high temperatures (>1000 °C) and pressures (> 10 GPa). In the laboratory three main methods exist to produce diamond on much shorter time-frames:

Detonation Diamond: Carbon-containing explosives, in a metal chamber, are detonated, producing temperatures and pressures similar to those found within the Earth's mantle. The diamond produced is typically tiny (nanometres in size) and used primarily in abrasives.

High Pressure High Temperature (HPHT): High temperatures (1500 °C) and pressures (55 000 times our atmosphere) are applied to carbon dissolved in a metal solvent using large scale hydraulic presses. Large diamonds are obtained using HPHT.

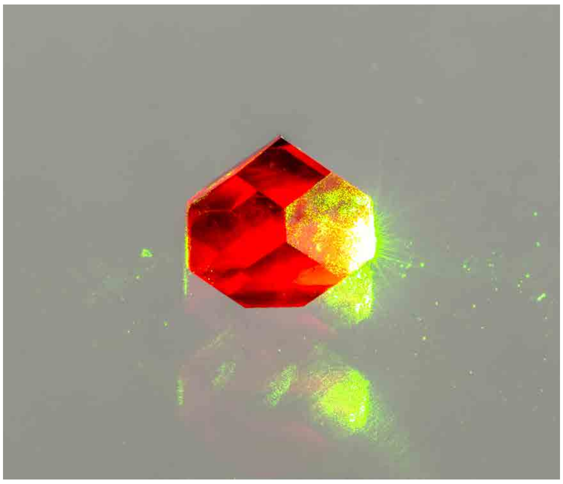
Chemical Vapour Deposition (CVD): Diamond is grown using a plasma, a carbon containing gas, such as methane, and hydrogen. The carbon containing molecules are broken down in the plasma, and deposited onto a substrate to form wafer-like structures. CVD is conducted at much lower pressures than HPHT. CVD can produce diamond wafers over 10 cm in diameter.



Looking inside a CVD diamond growth reactor. The silicon substrate (yellow: 50 mm in diameter) on which the diamond is growing is clearly visible surrounded by a high temperature plasma.

Sensors produced from boron doped diamond (BDD) electrodes can also be used for sensing chemicals in solution environments. For example, monitoring the *p*H of our oceans is extremely important as a means of detecting the effects of climate change. Due to the high-pressure, high salinity (corrosive) environment presented by deep sea monitoring, most materials cannot survive for long periods of time. As BDD electrodes can be made *p*H sensitive, they offer the possibility for continuous *p*H measurement in this challenging environment. Furthermore, as diamond is made of carbon, it is biocompatible and can be placed in the human body without rejection. Research is now underway into using diamond electrodes for a whole host biomedical applications.

Synthetic diamonds are also finding uses in the latest quantum technologies. By introducing defects into diamond during the growth process, such as nitrogen-vacancy (NV) centres (where two neighbouring carbon atoms are replaced by a nitrogen and the other is left vacant) magnetic fields can be detected. The production of a NV defect results in energy levels in the diamond which enable the absorption of high energy green light from a laser but emit lower energy red light (due to energy loss). The intensity of the emitted red light can be strongly influenced by the presence and strength of a magnetic field. Hence NV defects in diamond can be used to sense a wide variety of magnetic fields ranging from small variations in the earth's magnetic field to detecting magnetic fields in the human brain.



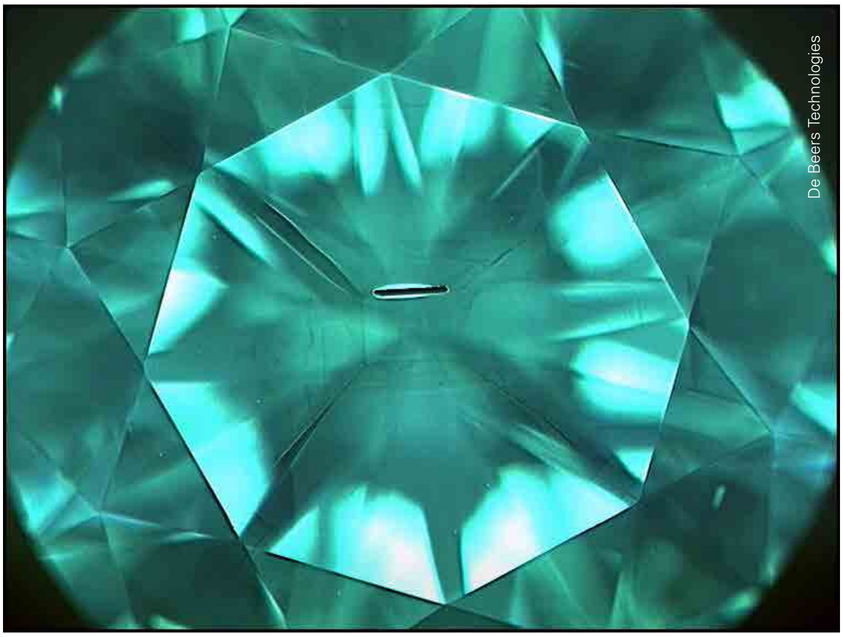
Green light shone onto a diamond crystal containing NV defects. The diamond emits red light. (Photo copyright Dr Jon Newland)

What is the cost?

Natural diamonds can sell for millions of pounds, so how much does it cost to grow synthetic diamond? Equipment can be costly due to the energy required to reach the temperatures necessary to grow diamond. The size and quality of the diamond produced is also a key factor. Microscopic, imperfect synthetic diamonds for cutting and abrasive applications are relatively inexpensive (sold for a few dollars per gram). Making large, perfect crystals is much more difficult, requiring longer growth times (thus more energy) to ensure defects are kept to a minimum. For example, single crystal plates, grown by chemical vapour deposition (CVD) and approximately millimetres in size, can be bought for a few hundred pounds. Synthetic diamonds cut and polished appropriately for gemstone use are also cheaper than those mined naturally. Synthesis offers the ability to grow diamond to order for the application of interest. Finding appropriate diamond for applications requiring large scales would be impossible with natural diamond, mined from the ground, but is now routinely possible through synthesis.

Spot the difference?

Synthetic and natural diamonds are both made of four-bonded carbon, so the question is, can we tell the difference? To the naked eye, the two are indistinguishable, but if we look closely enough using modern scientific equipment, differences can be identified. Natural diamonds are typically over 1 billion years old and require volcanic events to occur before they are moved close enough to the Earth's surface for humans to find. In that time, small impurities and defects can form. These form a fingerprint, allowing the origin of the diamond to be determined. When grown in the laboratory, the defects formed are different, and distinctive growth patterns can be determined. Placing the diamond under ultraviolet light can reveal the hidden patterns presented by the defects in diamond.



Synthetic HPHT grown diamond illuminated using DiamondViewTM UV technology. Cubic and octahehdral growth regions are revealed that are absent in natural diamonds.

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