Gases containing electrically charged particles offer an excellent way of manipulating and transforming materials in a controlled way.
Plasmas are the most common form of matter in the visible Universe. They are gases containing charged particles – usually electrons and atoms that have lost electrons (ions). All the stars we see are essentially plasma, as is much of tenuous matter found between the stars. Interactions between charged particles, and with any neutral atoms or molecules, produces light. We can see the effect in the beautiful aurora – as plasma from the Sun (the solar wind) interacts with molecules in the Earth’s atmosphere – and, closer to home, in fire, lightning and in brightly coloured neon signs.

Plasmas behave rather differently from electrically neutral gases, solids and liquids (for this reason they have been called the fourth state of matter). Because they are charged, plasmas created on Earth can be manipulated with electric and magnetic fields, and can be used to effect technologically useful physical and chemical transformations in controllable ways. Over recent decades, there has been an explosion of activity in exploiting plasmas industrially. Today, the world market for plasma technologies is worth well over £100 billion. Industrial plasmas are employed to manufacture a huge variety of products from computer chips to medical implants. They are also used in environmental clean-ups and to purify drinking water.

Plasmas come in many forms, existing over a wide range of temperatures and pressures. In the dense core of the Sun, the temperature is 100 million degrees – hot enough for nuclear fusion reactions to occur. Fusion reactors on Earth try to emulate these plasma conditions to create energy. ‘Thermal’ plasmas at about 10,000 degrees and at atmospheric pressure, generated by arc discharges, are used in welding and in furnaces to anneal materials, and to vitrify or destroy toxic or biological waste.

**Low pressure plasmas**

However, industry is mostly interested in much cooler, very low pressure plasmas, which contain neutral atoms and molecules as well as ions and electrons. They have the unusual but useful characteristic that the electrons are extremely energetic, or ‘hot’, while the remaining gas constituents remain cold. Such low pressure plasmas are generated by applying a radiofrequency voltage in an evacuated chamber through which the rarefied gas flows. Any electrons present are accelerated and they release more electrons from atoms until there are sufficient to produce the familiar steady glow associated with a plasma. In these low pressure plasmas, the lightweight electrons move much faster than the atoms or molecules. In effect, they can provide enough energy to transform the other, colder gas constituents into chemically active species, which then react at surfaces. Plasmas thus offer a uniquely sensitive environment which allows otherwise fragile molecules to undergo ‘hot’ chemistry.

Such plasma processing has been crucial to the development and growth of the electronics industry. The circuits on semiconductor chips are created by depositing or removing...
various materials, and plasmas are an ideal conduit. The plasma set-up can be subtly tailored to regulate the chemistry. A good example is the use of carbon tetrafluoride gas to etch silicon chips. It first breaks up into carbon and fluorine fragments in the plasma reactor, and the highly reactive fluorine atoms attack and remove the insulating silicon dioxide layer on the chip. When all the exposed silicon dioxide has been removed, the carbon then deposits as a protective layer which prevents further attack by the fluorine on the silicon underneath. Clever plasma chemistry based on hydrocarbons and hydrogen is also used to deposit coatings of diamond.

Another hugely important area for plasma technology is lighting. Every fluorescent tube contains a plasma. This emits UV light which interacts with the phosphor coating on the tube wall causing it to fluoresce and emit white light. One of the challenges today is to make strip lighting more efficient and replace the mercury which is the major light-emitter in the phosphor. Scientists are also working on modulating the plasma physics to alter the colour of the light. High-intensity arc lamps used in outside public areas rely directly on the plasma to produce the light and their colours depend directly on the chemical elements in the plasma, not on a phosphor coating.

A recent development to hit the high-street, that exploits plasma light-emission, are the plasma displays used in large screen TVs. They operate at half an atmosphere pressure but rely on the same principle as fluorescent tubes. The pixels in the screen contain phosphors which can glow red, green or blue as the result of a UV-emitting plasma discharge.

**Surface engineering**

Plasma technology still has enormous potential in many areas of manufacturing: surface engineering using plasmas is now big business. Aero-engine parts are surface-hardened by laying down just a few atomic layers of a ceramic using plasma processing. Anti-reflective and anti-scratch coatings, similarly prepared, are an option when you go to buy new glasses at the opticians.

The non-thermal nature of low pressure plasmas is being increasingly exploited to deposit coatings that render a soft polymer surface water-attracting or repelling, or improve the uptake of dyes. Jas Pal Badyal at Durham University has a company called Surface Innovations which markets plasma technologies for making surfaces highly water and oil-repellent, and also for manufacturing protein chips for gene-sequencing. Robert Short and colleagues at the University of Sheffield has developed pioneering techniques to deposit polymer coatings using low power plasmas, which are used for culturing skin cells and delivering them to wounds that won’t heal. The research is now being marketed through a spin-out company CellTran.

Increasingly, plasma researchers are trying to devise such systems that operate at atmospheric pressure, thus avoiding the need for vacuum pumps, so that they can be used to deposit, for example, polymer coatings over large areas of fabric or packaging materials.

Another application at atmospheric pressure is in environmental clean-up. Christopher Whitehead at Manchester University is working on an ‘end-of-pipe’ plasma system to treat diesel exhaust and remove volatile organics from waste solvents. The process, which relies on creating highly reactive chemical species called radicals, can also be applied to kill airborne microbes, say, in hospitals where infection with antibiotic-resistant bacteria is becoming an increasing risk.

There are a huge range of plasma techniques available and the process used has to be carefully tailored to the application. Much of the development in industry has been based on trial and error, but physicists are trying to understand and model the complex behaviour in technological plasmas so as to predict optimum operating conditions. The UK has a network of academic research groups working in this field to take forward this commercially important and growing technology.
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