News & views

Materials science

Controllable strain enhances a semiconductor

Jian Shi

Semiconductors known as halide perovskites have remarkable optoelectronic properties, but their structural instability limits practical applications. A solution has been found that involves squeezing the compounds' crystal lattices. **See p.209**

The surprising discovery[1] in 2009 that compounds known as halide perovskites can convert sunlight into electricity triggered a revolution in photovoltaics (solar cells), inspiring new cell designs that will enable solar energy to be harnessed efficiently and at low cost. However, tuning the properties of these crystals to enable practical applications has been a long-standing challenge. On page 209, Chen *et al.*[2] report that a solution to this problem has finally been found.

Discovering new materials and identifying appropriate applications can sometimes be achieved serendipitously, but often takes decades, and has historically required centuries or even millennia. The first halide perovskite was discovered in the 1890s[3], but its potential remained untapped until a decade ago[1], when it took photovoltaics by storm. As its name suggests, halogen atoms in the compound enable the formation of a cubic (or pseudocubic) array known as a perovskite structure.

Harnessing the full potential of halide perovskites for technological applications has been difficult. A major obstacle is the tendency of one of the best-performing perovskite crystals, α-formamidinium lead iodide ($HC(NH_2)_2PbI_3$, known as α-$FAPbI_3$), to assume a hexagonal structure at room temperature (Fig. 1a) – the approximate temperature at which photovoltaic devices operate. This hexagonal structure cannot respond to most of the frequencies of light in solar radiation, and hence is not of interest for technological applications. It would therefore be helpful to stabilize the structure of α-$FAPbI_3$.

Several strategies can be used to engineer a material's properties. Two of the most effective are to alter the material's composition or to use it at high or low temperatures, but the costs involved for commercial applications can be tremendous. Scientists have therefore developed a simple but extremely useful approach known as strain engineering, which has been used to tune the electronic properties of semiconductors.

When a crystal is compressed or stretched, the resulting deformation is called strain. Strain is calculated by dividing the change of length of a deformed object by the object's original length, and is expressed as a percentage of the original length. In semiconductors, strain can alter the mobility of charge carriers – a property that characterizes how fast a charge carrier, such as an electron, can travel in a crystal subjected to an electric field. By changing the charge mobility, the electronic properties of a semiconductor can be altered.

Semiconductors in modern electronic devices are most commonly used as thin films, and the maximum sustainable strain of a film is less than a few per cent[4]. Nevertheless, strain modulation can be a highly effective tool for enhancing electronic properties. One such success story is that of lasers based on layered semiconductor structures known as quantum wells. By straining the quantum-well layers, the electrical current needed to power a laser can be reduced by as much as ten times, thus improving the energy efficiency of the devices[5,6]. Most commercial quantum-well lasers are therefore strained[5].

One of the most interesting but problematic features of halide perovskites is that only a few, including α-$FAPbI_3$, have high charge mobility and absorb light strongly, but the technologically useful crystal structures of these few compounds are unstable – some can spontaneously transform into other phases in less than a second. In photovoltaic devices, fast-moving charge carriers and strong light absorption are both needed to convert solar energy into electricity with high efficiency. Unfortunately, structural stability, high charge mobility and the ability to absorb light strongly don't seem to coexist in perovskite halides.

Chen *et al.* have therefore used strain engineering to tackle this problem. They grew crystalline α-$FAPbI_3$ from a solution so that it formed on another, more stable halide perovskite (the substrate). The $FAPbI_3$ atoms in the growing crystal align with the cubic structure of the atoms in the substrate, thereby forming a pseudocubic structure themselves (Fig. 1b). The alignment of atoms in different materials is called epitaxy. This epitaxy locks α-$FAPbI_3$ into the pseudocubic structure as a result of the strong chemical forces between it and the substrate, preventing its transformation into the

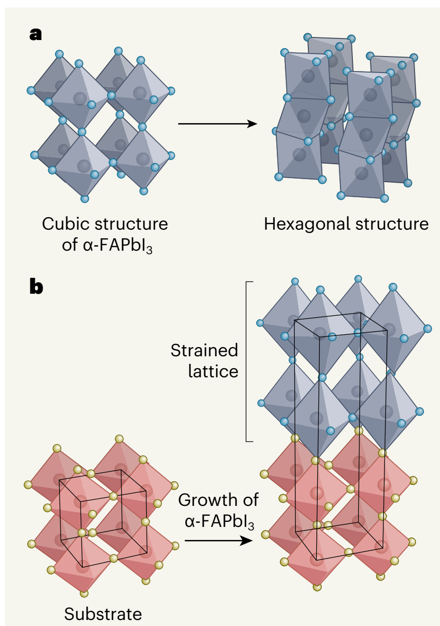

Figure 1 | The stabilization and strain engineering of a semiconductor. a, The semiconductor α-formamidinium lead iodide ($HC(NH_2)_2PbI_3$, known as α-$FAPbI_3$) belongs to the halide perovskite family of compounds, and has potential applications in solar cells. However, its cubic perovskite lattice is unstable, and converts to a hexagonal form that is unsuitable for practical applications. The octahedra represent subunits of the lattices: iodine atoms at the vertices surround a central lead atom; $(HC(NH_2)_2)^+$ ions fill the gaps between octahedra, but are not shown. **b**, Chen *et al.*[2] report that the structure of α-$FAPbI_3$ can be stabilized by growing it on a stable halide perovskite (the substrate) that has an analogous structure, so that the atoms in the two lattices align. Because the lattice dimensions of the substrate are smaller than those of α-$FAPbI_3$, the crystal lattice of the latter is squeezed (put under strain). This strain increases the mobility of electrical charge carriers in the material.

undesirable hexagonal structure. The authors find that the pseudocubic structure remains stable for at least a year at room temperature.

A compressive strain is imposed on the α-$FAPbI_3$ film because the dimensions of the cubic array of the substrate are different from those of the natural atomic array of α-$FAPbI_3$. Chen and colleagues were therefore able to control the strain of α-$FAPbI_3$ from 0 to 2.4% compressive deformation by growing $FAPbI_3$ on substrates that have different lattice dimensions. The authors found that this squeezing of the α-$FAPbI_3$ crystal increases the mobility of positively charged quasiparticles called holes, which correspond to the absence of electrons in the crystal. The authors attribute this increased mobility to the modification of the electronic structure of the crystal under compressive strain: compression leads to faster oscillations of the holes' wavefunctions, speeding up the movement of charge wavepackets (superpositions of wavefunctions) and thus producing higher charge mobility.

Previous work on the strain engineering of halide perovskite films lacked strain control[7] or involved straining methods that are harder to use[8,9]. By contrast, Chen and colleagues' study provides an extremely accessible and practical avenue through which to explore and use the physical properties of strained halide perovskites.

Questions remain about how the authors' findings could be used in solar cells. Currently available halide perovskite photovoltaic devices do not contain a genuinely epitaxial substrate, and so new cell designs will be needed to make use of the reported discovery. But a range of halide perovskite compounds are available that have similar atomic arrays to α-$FAPbI_3$, and which exhibit many different technologically important electronic properties. Chen and co-workers' study therefore suggests that there is plenty of scope for designing and developing epitaxial quantum-well devices using these materials, by mimicking the way in which quantum-well devices were developed using semiconductors from the III–V family of materials. This might bring down the cost of manufacturing these devices.

Finally, it will be interesting to see whether crystals of halide perovskites can be grown with sufficient atomic precision to make superlattices — periodic structures that contain multiple layers of two or more materials. The use of halide perovskites in superlattices could open up otherwise inaccessible electronic band structures, thereby allowing a rich array of physics to be explored, and emerging quantum-well devices to be further developed.

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Population biology

Predator–prey cycles achieved at last

Alan Hastings

A combination of laboratory experiments and mathematical and statistical analysis provides an affirmative answer to a decades-old question — can a predator and its prey coexist indefinitely? **See p.226**

A key question in ecology is what allows species to persist over time — particularly when there are pairs of species in which one is an exploiter and the other its victim. A long-standing theory attempts to answer this question by explaining how relative numbers of predators and their prey can cycle continuously[1]. First, prey numbers would increase, giving the predator more food. The subsequent increase in predators would lead to a decline in prey. Predator numbers would then decline owing to a lack of food, restarting the cycle. However, it has proved unexpectedly challenging to demonstrate this type of persistent predator–prey cycle in simple controlled systems in the laboratory. On page 226, Blasius *et al.*[2] report just such a demonstration, succeeding where almost 90 years of experimental work has failed.

Ecological theories of persistent predator–prey cycles are supported by the apparent existence of such cycles in nature, for instance between the lynx and hare in Canada[3]. However, it is hard to prove that these cycles endure in the wild, because observations over many decades would be needed. But if the theories provide a complete explanation of natural cycles, then it should be possible to demonstrate persistent cyclic behaviour in the laboratory, using species that have much shorter cycle times.

The challenge posed by such a demonstration was exemplified in 1934 by the ecologist Georgii Gause[4], who studied the dynamics of two unicellular organisms — the predator *Didinium nasutum* and its prey, *Paramecium caudatum*. Gause found that, on the one hand, if the predator was efficient, it ate up all the prey and then starved. On the other hand, if part of the environment helped to conceal the prey, the predator was less efficient — and so starved (Fig. 1a). Coexistence and long-term cycles could be achieved only through artificial means — namely, by adding prey at regular intervals.

In 1974, work with the same system showed that, by making the predator less efficient and by providing the prey with less food, the two populations could persist for longer[5]. Even so, coexistence could be maintained for just a few predator–prey cycles. Since then, some models that allow long-term cycle persistence have focused on space, for instance incorporating metapopulation dynamics[6]. In this phenomenon, subpopulations of a species migrate around a larger region. Although a subpopulation might become extinct in one area, the species persists across the region as a whole and can migrate back into that area. However, a better understanding of whether exploiter–victim cycles can persist locally without external input is still sorely needed.

Blasius and colleagues studied the aquatic invertebrate *Brachionus calyciflorus* and its prey, the green algal species *Monoraphidium minutum*. They found that, under simple and constant environmental conditions, the two species could coexist for more than a year — that is, over 50 predator–prey cycles. This result finally demonstrates that the long-standing theory of persistent cycles can be consistent with the reality of simple ecological systems.

Next, the researchers carried out a rigorous statistical analysis of the cycle dynamics in their system. Specifically, they used wavelet analysis, which focuses on dynamics over short periods; the technique has become a standard way to study the presence of periodic behaviour in ecological time series[7]. The analysis revealed interesting dynamic phenomena. The oscillations in the relative numbers of each species showed a characteristic lag in phase, with predator numbers mostly changing in the wake of altered prey numbers.