

LASER FABRICATION

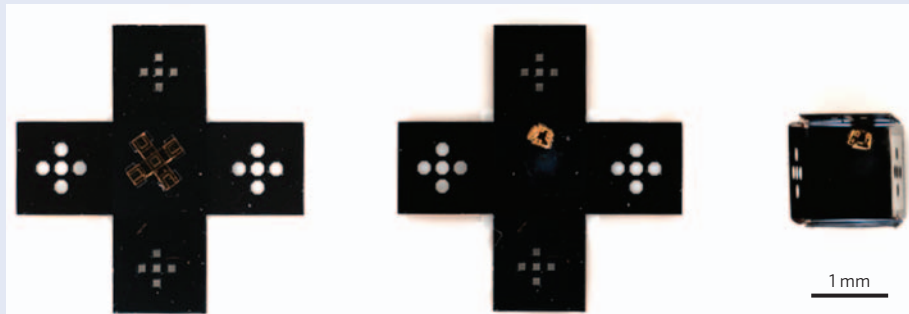
Folding three-dimensional microstructures

The ability to fold microstructures allows the fabrication of complex three-dimensional shapes. Unfortunately, current laser-based folding techniques require the use of extremely intense laser beams reaching thousands of watts per square centimetre.

Now, by exploiting a polymer trigger layer on a pre-stressed metallic bilayer, Kate Laflin and co-workers from John Hopkins University and the US Army Research Laboratory in the USA have developed a laser-triggered sequential folding method that requires a beam intensity of just 680 mW cm^{-2} (*Appl. Phys. Lett.* **101**, 131901; 2012). Their laser-triggered actuation also provides spatial control over the individual hinges, thus allowing three-dimensional patterned cubes to be folded sequentially.

The key to their technique is the hinged actuation, which is based on the intrinsic stress built into metallic thin films. The thin-film hinges contain a layer of chromium, which has high intrinsic stress, and a layer of gold, which has low intrinsic stress. The researchers fabricated their bilayer hinges on copper-coated silicon wafers by vapour deposition and photolithography, and then placed a polymer trigger on top. Bending occurred when the polymer was softened upon heating by laser irradiation.

The team used a commercially available green laser (wavelength of



532 nm, beam power of 40 mW and beam diameter of 1.5 mm) to trigger folding of the smaller cruciform. They then used the same laser to trigger folding of the larger cruciform. This high-precision demonstration of sequential folding across two size scales offers considerable control over the complexity of structures that can be fabricated using laser-triggered actuation.

The researchers also investigated the folding behaviour of various sizes of microstructure, ranging from $300 \mu\text{m}$ to 3 mm, using both the green laser and a near-infrared laser (wavelength of 808 nm, beam power of 100 mW and beam diameter of 3 mm). When the photoresist in each microstructure was heated above $40 \text{ }^\circ\text{C}$, it softened and no longer retained the

stressed bilayer, resulting in spontaneous bending. The time taken for each hinge to close varied between 67 ms and 21 s, depending on the wavelength and intensity of the laser irradiation. By analytically and numerically modelling heat losses from the microstructure, the researchers discovered that the time taken for the hinge to close is determined by thermal conduction into the surrounding air domain, and is therefore proportional to the inverse of the irradiance.

These microdevices could be useful for defence applications such as the remote initiation of energetic materials and for attaching transponder tags or other electronics to various surfaces.

NORIAKI HORIUCHI

OPTICAL MATERIALS

Inspired by strain

Researchers at Peking University and the Massachusetts Institute of Technology propose the use of strain engineering to create a broadband solar 'funnel' in an atomically thin sheet of MoS_2 .

Arend van der Zande and James Hone

Strain engineering is the process of tuning a material's electronic properties by altering its structural or mechanical properties. This technique is widely used throughout the semiconductor industry as a means of enhancing the mobility of electrons in silicon by depositing strained silicon nitride layers on top of transistor channels. The understanding and optimization of strain-engineered materials is also a major

milestone in the international technology roadmap for semiconductors¹. However, the low maximum strains of brittle bulk crystalline materials limit the extent to which their electronic properties can be changed by mechanical means. Bulk silicon, for example, can be strained only 1.2% before breaking, although silicon nanowires with breaking strains of nearly 5% have recently been reported.

The past few years have seen an explosion of interest in two-dimensional (2D) crystals derived from layered materials that possess strong in-plane bonding and weak van der Waals bonding between crystal planes. The most prominent member of this family is graphene; other 2D crystals include hexagonal boron nitride and a number of transition metal dichalcogenides

such as MoS₂, WS₂ and NbSe₂. These materials offer a wide variety of interesting optical and electronic properties. For example, graphene is a highly conductive semimetal, hexagonal boron nitride is a 5.5 eV wide-bandgap semiconductor, and monolayer MoS₂ is a 1.8 eV direct-gap semiconductor². These materials can be fabricated as atomically thin membranes, transferred on to arbitrary substrates and then stacked on top of one another, and can be poked, strained or rippled without breaking. They are also easy to synthesize. Graphene can already be produced in metre lengths using chemical vapour deposition, and rapid progress has been made over the past year in the synthesis of high-quality hexagonal boron nitride, MoS₂ (ref. 3) and WS₂ monolayers.

The 2D sheet geometry of these crystals offers a unique opportunity for studying and utilizing much larger strains than those achievable in bulk (3D) materials. In three dimensions, the ultimate strain is limited by both bulk defects and surface imperfections. 2D crystals can circumvent these limitations for two reasons: first, 2D crystals lack dangling bonds or other imperfections at their surfaces; and second, it is possible to apply highly anisotropic strain to 2D sheets, which limits the strain to a small area inside a single crystalline domain and far from clamping points and edges. These advantages are seen most clearly in graphene, the best-studied 2D material. In experiments, graphene has been seen to withstand elastic strains of up to 25%⁴, which represents the ultimate maximum strain of a perfect carbon lattice. Owing to the large changes in electronic band structure that result under such strain, there is currently great interest in exploiting strain engineering for electronic applications⁵. Moreover, the ability to grow graphene over large areas, combined with its mechanical robustness, has led to a surge of interest in using graphene for flexible electronics. Recent work has demonstrated that other 2D materials share many of the outstanding mechanical properties of graphene: for instance, MoS₂ has a breaking strain of at least 10%⁶. It is likely that the entire family of 2D materials will become a fertile area for exploring and utilizing strain engineering.

Now, writing in *Nature Photonics*, Feng *et al.* consider a new application area of strain engineering in optoelectronic devices⁷. Specifically, they propose a creative new idea in which non-uniform strain applied to an MoS₂ monolayer produces a solar ‘funnel’ that can capture photons with a wide range of energies, thus channelling the resulting electron–hole pairs to a single point for collection. This implementation requires only

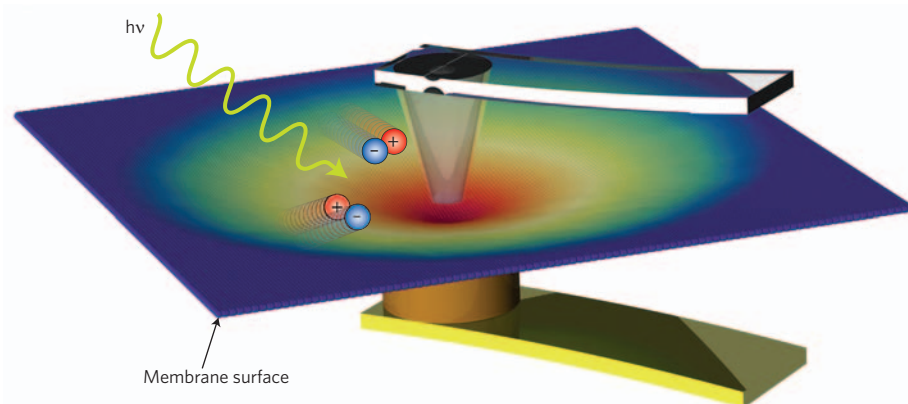


Figure 1 | Solar funnel based on a strained monolayer of MoS₂. Non-uniform strain is induced using an atomic force microscope probe at the centre of the membrane. Light hitting the membrane creates photogenerated electron–hole pairs that drift towards the region of most strain (shown in red) where they are separated and travel to two electrodes, thus generating electricity.

a single sheet of material, whereas previous demonstrations have relied on stacks of graded materials⁸.

By developing theoretical models, Feng *et al.* first show that in-plane tension can be used to tune the bandgap of monolayer MoS₂ continuously from the unstrained value of 1.8 eV all the way down to zero, near a strain of 10%. This result alone, which has also been demonstrated by several other groups⁹, is of significant interest: finding a suitable technique for fixing the strain in the monolayer could allow the bandgap to be set at any arbitrary value. The researchers then propose a new and creative idea of creating spatially varying strain across a single 2D membrane. One of the most unique aspects of a 2D material is the ease at which it can undergo the application of non-uniform strain. In the simplest example, when a suspended circular 2D membrane is indented at its centre, the strain varies almost inversely with radial distance from the centre. For MoS₂ in this geometry, Feng *et al.* show that the bandgap should decrease from the edge to the centre in response to the applied force.

The spatially varying bandgap has two important consequences for the collection of solar energy. First, the bandgap can absorb photons with energies from zero up to the unstrained bandgap of 1.8 eV, which makes the MoS₂ membrane a very wideband absorber. Second, photogenerated excitons (weakly bound electron–hole pairs) created at any point in the membrane will ‘fall’ towards the point of highest strain in the centre of the device, thereby creating a solar energy funnel. In the example studied by Feng *et al.*, these photogenerated electrons and holes are guided to the centre of the membrane

towards an atomic force microscopy tip, which is used as an actuator to apply strain.

The fundamental challenge when making a practical solar funnel is how to separate the electron–hole pairs and transport the charge to electrodes so that electricity can be successfully extracted. In conventional photovoltaics, a built-in electric field at a p–n junction separates the electrons and holes. The positive and negative charges are then collected at different locations by placing electrodes on opposite sides of the exciton-generating material. However, in the MoS₂ solar funnel, both the electrons and holes are funnelled to a single point. To resolve this issue, Feng *et al.* say that two electrodes composed of metals with different work functions placed at the centre point could be used to selectively remove the electrons and holes. Although this approach might work, it introduces several experimental and material challenges. For example, monolayer MoS₂ does not provide a sufficiently large barrier to quantum tunnelling between different electrodes. As a result, parasitic tunnelling will probably prevent generation of a significant open-circuit voltage, which is a key performance metric for an efficient solar cell. One solution to this problem could be to use an applied electric field to break the electron–hole symmetry, thereby allowing the electrons to be collected in the centre of the membrane, while holes could be collected at the edge. Another approach might be to place the MoS₂ on a nanostructured surface (such as a periodic array of steps or holes) rather than suspending it over large holes. The van der Waals adhesion to the substrate would pull down the membrane and induce

spatially varying tension; by carefully placing the electrodes over strained and unstrained regions, the electrons and holes could then be collected separately.

At a fundamental level, the work of Feng *et al.* demonstrates that the strain engineering of 2D materials has many potential applications beyond electronics, and it is likely that these findings will inspire many more investigations into this rich field. For example, it would be interesting to study stacked

heterostructures of these materials. For solar collection, such a heterostructure could allow the vertical separation of electrons and holes, while strain could then be used to guide diffusion to opposite electrodes.

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VIEW FROM... 73RD JSAP AUTUMN MEETING 2012

The search for high efficiency

Tandem solar cells, inverted triple-junction solar cells and photonic-crystal-based solar cells were among the photovoltaic devices discussed at the 73rd Autumn Meeting of the Japan Society of Applied Physics.

Noriaki Horiuchi

The Fukushima nuclear disaster of 2011 has placed increasing pressure on the search for alternative energy sources in Japan, and high-conversion-efficiency solar cells are in high demand. It is unsurprising, therefore, that photovoltaic technology was the highlight of this year's Japan Society of Applied Physics (JSAP) Autumn Meeting, held on 11–14 September in Matsuyama. The meeting gathered 5,700 researchers at the campuses of Ehime and Matsuyama Universities.

In April 2012, the Ministry of Education, Culture, Sports, Science and Technology of Japan assigned Makoto Konagai from the Tokyo Institute of Technology as the Director of Renewable Energy Projects to coordinate research projects ranging from fundamental studies to the commercialization of silicon-based tandem solar cells. These projects are being carried out jointly by academia and industrial collaborators such as Panasonic, Mitsubishi and Kaneka. At the meeting, Konagai, who is also the president of JSAP, announced the launch of Centres of Excellence for solar cells based on silicon nanowires in April 2014 in the Fukushima prefecture. Research performed at these centres will focus on tandem solar cells comprising silicon nanowires on the top layer and conventional silicon solar cells on the bottom layer.

"It is difficult to achieve conversion efficiencies of more than 25% by using conventional silicon-based solar cells because silicon cannot absorb the spectrum of natural sunlight from 1.4 to 1.7 eV, where a fair amount of the energy is distributed," Konagai pointed out. Devices based on silicon



Around 5,700 participants attended the Autumn Meeting of JSAP 2012, which was co-hosted by Ehime and Matsuyama Universities.

nanowires are a different matter altogether. At the meeting, Konagai's research group presented numerical results for tandem solar cells reaching conversion efficiencies of more than 30%.

Atsushi Yoshida from Sharp reported an inverted InGaP/GaAs/InGaAs triple-junction cell with a conversion efficiency of 43.5%. "This conversion efficiency is due to the reduction of current loss by using InGaAs, which has a bandgap of 1 eV, as the bottom cell," Yoshida explained. However, this approach is far from straightforward because the large difference in lattice

constants between InGaAs and InGaP (or GaAs) degrades the crystalline quality and thus increases the current loss. To overcome this problem, Yoshida's group developed an inverted deposition method for growing the disconformable bottom cells at the end of deposition procedure and a technique for printing the InGaP/GaAs/InGaAs triple-junction cells on a supporting substrate. As a result, they succeeded in obtaining a record-breaking solar-cell conversion efficiency of 43.5% under 306-Sun conditions.

The ability to convert broadband thermal emission into a narrowband spectrum with