

2D MATERIALS

Silicene transistors

Artificially synthesized silicene — an atomically thin layer of silicon — is set to rival natural layered materials in the development of field-effect transistors.

Guy Le Lay

Since the creation of the first integrated circuit in 1958, the electronics industry has pursued smaller, faster and cheaper devices. Moore's law, which predicts that the number of transistors in a semiconductor chip roughly doubles every 18 months, will break as the dimensions of the key electronic device, the field-effect transistor (FET), reaches the low nanometre range. At present, approaches that use materials such as strained Si–Ge films and dielectrics with a high dielectric constant are being investigated to fabricate FETs with gate lengths smaller than 10 nm. New device concepts such as FETs based on nanowires are also envisaged. However, more disruptive routes must be explored to push the downscaling towards transistors with gate lengths of 5 nm. To this end, the use of 2D structures in the active channel of the transistor could be essential¹.

Despite its outstanding electronic properties, graphene, the archetypal 2D material, cannot be used in conventional transistor technology because of the inherent difficulty of opening an electronic bandgap in this material. The silicon-based analogue of graphene — silicene — could in principle offer an alternative because its buckled structure (Fig. 1a) favours the existence of a bandgap. A layered

parent silicon crystal, like graphite is for graphene, does not exist in nature, but silicene has recently been synthesized² on a silver substrate using a bottom-up and scalable epitaxy method under ultrahigh-vacuum conditions. However, silicene was not expected to withstand isolation from its metallic template or exposure to ambient air³. Indeed, Harold Zandvliet recently posed the question “Can a silicene transistor be realized?”⁴. Now, writing in *Nature Nanotechnology*, Deji Akinwande, Alessandro Molle and co-workers at the University of Texas at Austin, the IMM-CNR in Milan and US Army Research Laboratory in Maryland, report the fabrication of a single-layer silicene FET that operates at room temperature⁵.

Akinwande and colleagues managed to prevent the degradation of monolayer silicene on removal from its parent silver substrate or on exposure to air by devising a clever process for growing, transferring and fabricating the silicene devices. First, they synthesized epitaxial silicene at low temperature (~250 °C) on a thin film of silver(111) deposited on mica, instead of using single-crystal silver substrates. Atomic-scale scanning tunnelling microscopy images revealed that the resulting silicene monolayer locally exhibits

a 4×4 ‘flower pattern’² (Fig. 1b). Next, the researchers capped *in situ* the silicene monolayer with a protective, non-reactive alumina film, and monitored the integrity of the silicene film by Raman spectroscopy. The capping step allowed the *ex situ* delamination of the silver–silicene–alumina sandwich and the upside-down transfer onto a device substrate (SiO₂ on highly doped silicon). Finally, the team patterned the silicene channel and the source/drain electrodes, defined in the native silver film, using a specially devised etchant to avoid the rapid degradation/oxidation of silicene. The complete process led to the fabrication of back-gate transistor devices (Fig. 2).

The silicene devices, which can be electrically measured in ambient conditions for a few minutes, show Dirac-like ambipolar charge transport similar to graphene FETs, with a typical V-shape drain current (I_d) versus back-gate voltage (V_g) curve. The transfer characteristics reveal low residual carrier density and a high current modulation by the gate voltage (on/off ratio ~10) compared with graphene, and hint at the existence of a bandgap of about ~210 meV. The measured mobility for both electrons and holes is about $100 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, which is quite low compared with that in graphene and also with respect to estimated intrinsic values for free-standing silicene⁶ ($\sim 10^5 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$). However, it is of the same order of magnitude as the carrier mobility in single-layer MoS₂ (ref. 7), which suggests that the devices are promising candidates for 2D transistors. The low mobility is attributed to strong scattering from acoustic phonons and to grain boundary scattering.

Plenty of room remains to achieve higher mobility and better device performance. This can be done by optimizing the silicene growth, engineering and characterizing the interfaces, and tuning and enlarging the bandgap by, for example, surface adsorption⁸, fabricating tunnelling FETs⁸ and protecting the silicene gate (which is exposed to air in the present devices). Multilayer silicene, which is robust in air⁹, could be used to solve this last problem.

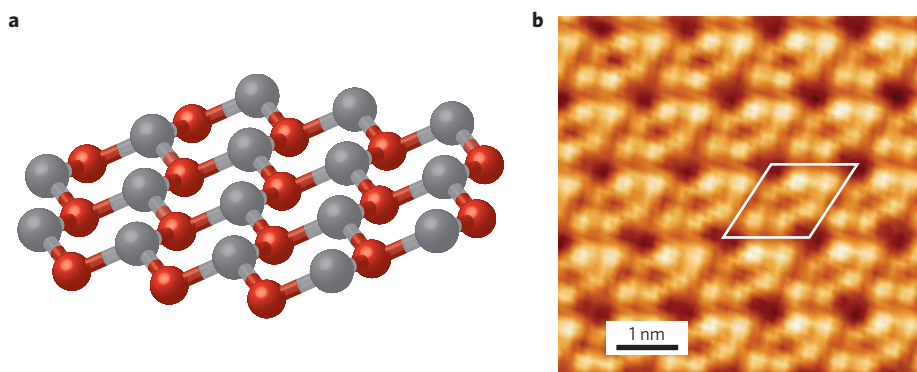


Figure 1 | Atomic structure of silicene. **a**, Ball-and-stick model of the buckled standalone silicene honeycomb lattice composed of two slightly vertically displaced hexagonal sublattices (colour 1 and colour 2). **b**, Scanning tunnelling microscopy image of the prototypical silicene overlayer structure on the silver(111) substrate; the 4×4 unit cell (with respect to Ag(111)) is indicated. Figure adapted from ref. 5, Nature Publishing Group.

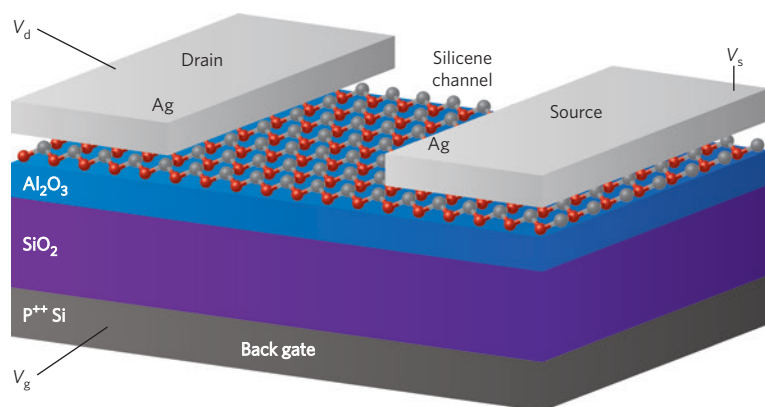


Figure 2 | Schematic of a back-gated FET with a silicene channel and with source/drain contacts defined in the native silver film. V_s , V_d and V_g are the source, drain and gate voltages, respectively. Figure adapted from ref. 5, Nature Publishing Group.

The ingenious approach used by Akinwande and colleagues for the fabrication of silicene FETs is applicable to other air-sensitive 2D materials such as phosphorene¹⁰, and to the Ge- and Sn-based analogues of graphene, namely, germanene (recently synthesized on a gold substrate¹¹) and stanene (not yet realized¹²). Germanene and stanene offer, like silicene, the prospects of direct

compatibility with silicon technology, and devices could potentially be created with these materials using a similar synthetic approach to that developed by Akinwande and colleagues. Furthermore, germanene and stanene are predicted to be 2D quantum spin Hall insulators at near room temperature and above room temperature, respectively¹³, and could therefore lead to spintronic

applications. The demonstration of the silicene FET by Akinwande and colleagues shows that the material to replace silicon in the electronics industry could, in fact, be silicon itself in the form of silicene, or its sister materials, germanene and stanene. □

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UPCONVERSION NANOCRYSTALS

Bright colours ahead

Full-colour displays with high spatial resolution can be produced with properly designed upconversion nanocrystals that emit light at different wavelengths, depending on the properties of the excitation pulses.

Marco Bettinelli

Upconversion is the nonlinear light-emitting process in which a low-energy light beam is converted into a higher-energy one when it hits a specific material. Often these materials include trivalent lanthanide ions Ln^{3+} (ref. 1). Upconversion in Ln^{3+} -doped nanocrystalline materials was first demonstrated almost 15 years ago², and it has found use in a wealth of applications in the areas of bioimaging and labelling, phosphors, scintillators, information storage and displays^{3,4}. One of the main goals in the field of optical displays is to be able to emit light of any desired colour in a broad spectrum through the application of an external stimulus. Many research efforts have been made in this direction, mainly using traditional organic dyes or quantum dots, but this approach is made difficult by the necessity of tuning multiple excitation sources. Further attempts have employed

lanthanide-doped nanoparticles using steady-state excitation and tailoring the intensity ratios of the various emission bands, but progress has been hampered by the difficult process of obtaining optimized concentrations of the various dopants⁵. Writing in *Nature Nanotechnology*, Xiaogang Liu and colleagues — from the National University of Singapore, Nanjing University of Posts & Telecommunications, Nanjing Tech University and the Institute of Materials Research and Engineering in Singapore — now report⁶ a promising approach that exploits non-steady-state upconversion in core-shell NaYF_4 nanoparticles co-doped with several lanthanide ions.

Non-steady-state upconversion is a phenomenon that is normally not observed in studies on upconversion materials (especially nanoparticles) as they are usually carried out with continuous-wave (CW) excitation,

that is, in steady-state conditions⁷. Non-steady-state upconversion is based on pulsed excitation, and, in particular, on the use of excitation pulses of various widths. Liu and colleagues have clearly shown that by using time modulation of the excitation pulse width (ranging between 200 μs and 6 ms) it is possible to vary the intensity ratios of the various transitions of an upconverting ion. This is caused by the fact that the dynamics of the populations of the levels producing anti-Stokes emission (that is, light emission at lower wavelengths than the excitation) is affected by relaxation and/or energy transfer probabilities of various excited states. In the presence of a long excitation pulse, the system has time to reach a condition that is similar to one present with CW excitation, that is, equilibrium. In this case, emission can occur from energy levels that are populated slowly. On the other hand if the pulse width is short,