

stress reflects the existence of an energy barrier needed to overcome the resistance of materials to plastic deformation, which is material-specific and depends strongly on pressure. This conclusion is supported by the fact that in soft metals with isotropic bonding, such as aluminium and copper, the experimental melting temperatures agree with those calculated for the solid–ideal-liquid transition.

The proposed behaviour for tantalum will not resolve all of the questions about its behaviour at extreme  $P$ – $T$  conditions, but could imply significant progress. In particular, it does not necessarily explain why, in experiments performed under different stress conditions (with the sample immersed under soft or stiff pressure media), the same melting temperature is detected in DAC experiments<sup>4</sup>. However, it clearly provides a new framework for studying the  $P$ – $T$  region constrained by 200 GPa and 5,000 K. The work of Wu *et al.* will, without doubt, stimulate further laboratory experiments and computer calculations. In particular, new shock-wave measurements of the sound speed between 100 and 200 GPa might be

beneficial to understanding the structural properties of tantalum beyond 3,250 K. Furthermore, recording of second-scale time-resolved X-ray diffraction patterns during temperature cycling would provide valuable information<sup>9</sup>. These experiments will not only be appropriate to test Wu and colleagues' findings, but also to check other hypotheses on the high-pressure behaviour of transition metals. For example, the creation of local structures in the liquid, owing to Peierls and Jahn–Teller distortions<sup>10</sup>, are expected to lower the melting point of transition metals on compression. In particular, X-ray diffraction experiments can give valuable information on the radial distribution function of tantalum and similar metals. These experiments will be fundamental for distinguishing between the plastic flow of a liquid-like 1D glass and the free motion of a 'true' or a 'clustered' liquid.

The most important implication of the proposed shear-induced melting is that similar 1D-glass formation features are also found in other transition metals such as molybdenum and vanadium, implying that this melting mechanism is expected to

hold generally for other transition metals, probably even for iron. Such conclusions therefore could have important geophysical implications. It is possible that a new era in the study of high-pressure melting of metals has begun. An explanation for different experimental observations and theoretical predictions may finally be within our grasp. □

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## EPITAXIAL GRAPHENE

# How silicon leaves the scene

Large and homogeneous layers of graphene are obtained by annealing silicon carbide in a dense noble gas atmosphere that controls the way in which silicon sublimates. Epitaxial graphene thus gets back on track towards future electronic applications.

Peter Sutter

Since it was first isolated in 2004, graphene, a sheet of pure carbon just one atom thick, has generated a flurry of research activities. Although much of the initial 'gold rush' has focused on the fascinating properties of this two-dimensional crystal<sup>1</sup> — which have as much to do with fundamental quantum electrodynamics and particle physics as with solid state physics and materials science — researchers have recently begun addressing the more mundane question of how some of these characteristics might be harnessed in applications ranging from post-Moore's law electronics over ultra-responsive sensors and actuators to transparent solar cell contacts. Assuming a continuation of 'top-down' processing similar to today's silicon microelectronics, the bottleneck clearly lies in synthesizing the required starting material: structurally

perfect, macroscopically large graphene sheets with uniform thickness, into which active device structures can be carved. On page 203 of this issue, Emtsev *et al.* demonstrate an important step towards this goal for a specific fabrication strategy: graphene epitaxy on silicon carbide (SiC)<sup>2</sup>.

Epitaxial growth on SiC (Fig. 1), a highly resistive material which would not shunt the current flow in graphene and which is already available in the form of large-diameter wafers, is often seen as one of the most likely avenues to graphene-based electronics. The graphitization of SiC by Si sublimation during high-temperature vacuum annealing was demonstrated as early as the 1960s<sup>3</sup>, and has recently been refined<sup>4</sup>. Even so, considerable challenges have remained. Although graphene grows with a well-defined orientation and its lattice fits well

on a reconstructed interfacial layer on Si-face SiC, graphitization in vacuum has so far invariably transformed the ordered substrate surface (Fig. 1a) into a rough, highly corrugated landscape covered by small graphene domains with pronounced thickness variations (Fig. 1c). Such disorder not only hinders further processing, it can also limit device performance by scattering charge carriers flowing in the active graphene layer.

The solution is quite obvious, at least in principle. Roughness, excess surface steps as well as small-grained graphene are generated if a system cannot attain its most favourable morphology because the necessary microscopic processes — the detachment, diffusion and reattachment of surface atoms — are suppressed. Increasing the growth temperature should lift such constraints. However, for graphitization in

vacuum, higher annealing temperatures also drive faster sublimation and higher graphene growth rates, which in turn promote roughening and the nucleation of small graphene flakes. Progress can only be made if mass transport on the surface is effectively decoupled from Si evaporation away from the surface. Emtsev *et al.* accomplished this feat by resurrecting an 80-year-old trick originally developed to extend the lifespan of incandescent lightbulb filaments<sup>5</sup>. Instead of processing their samples in vacuum, they placed them in a furnace with an unreactive argon atmosphere at nearly ambient pressure. The dense cloud of gas molecules hinders the transport of Si atoms away from the SiC surface, reducing the overall sublimation rate and allowing an increase in graphitization temperature by several hundred degrees. Samples produced by this process have smooth surfaces made up of large, flat substrate terraces that reach tens of micrometres in length and several micrometres in width, and are separated by steps several times the height of the original

substrate steps (Fig. 1d). The carbon layer grown on this surface now consists primarily of monolayer graphene, with narrow bilayer (and occasional trilayer) stripes at the terrace edges.

The key question, of course, is whether the improved sample morphology translates to a reduced scattering of charge carriers in the epitaxial graphene. Emtsev *et al.* begin to address this question by comparing the electron mobility — a measure of the charge carrier drift velocity in an applied electric field — for samples prepared in vacuum and in ambient-pressure argon, patterned into simple test structures. Their results are encouraging. Samples produced by the new process show a nearly twofold improvement over the previous record mobility in Si-face epitaxial graphene. But the findings also raise a number of issues. Particularly puzzling is the enormous difference — about a factor of 100 — in electron mobility between epitaxial graphene on SiC and exfoliated graphene. The fact that the highest carrier mobilities were achieved in suspended

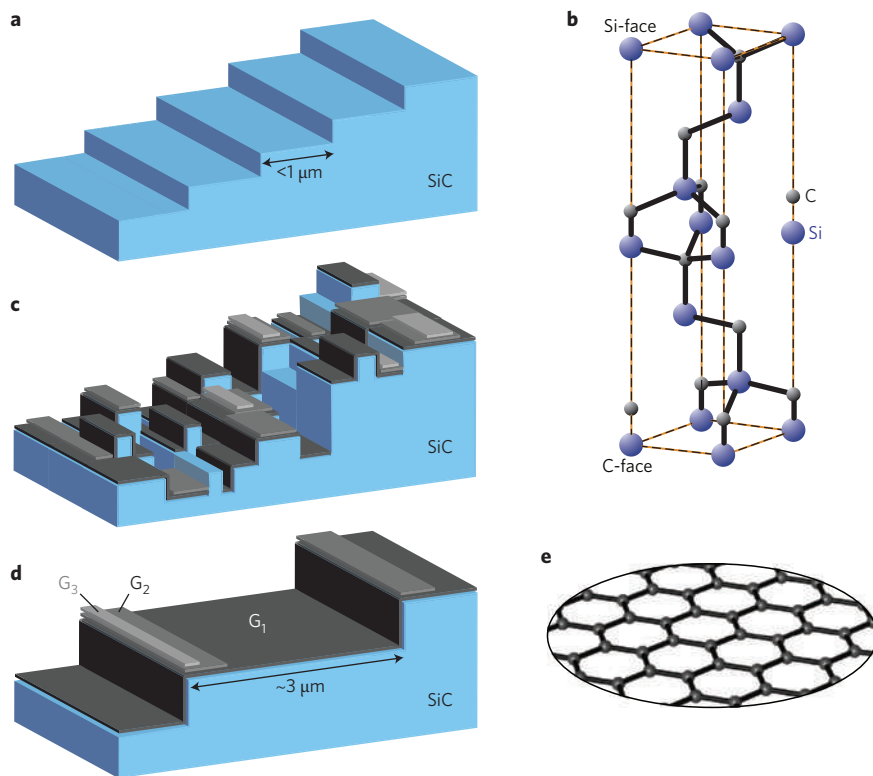
sheets<sup>6</sup>, whereas both epitaxial graphene and supported exfoliated graphene show far lower values, raises questions about fundamental limitations to carrier transport due to long-range scatterers in a substrate or support. The nature of these scattering centres is generally unknown, but the work by Emtsev *et al.* sets the stage for their identification for epitaxial graphene on SiC by reducing roughness and increasing the graphene domain size. A careful comparison of transport parallel and perpendicular to substrate steps, for instance, should reveal whether the steps themselves, or the two- and three-layer domains near the steps, cause electron scattering. The complex buffer layer sandwiched between the graphene and the SiC substrate needs to be considered as another possible scatterer that would be difficult to eliminate.

For some time now, epitaxial graphene on SiC has been considered one of the leading contenders in the race to find ways to mass-produce graphene, particularly for electronics. The improved properties demonstrated by Emtsev *et al.* should provide an additional boost for this technology. But the race is still far from over. Competing approaches have also seen rapid progress recently. Transition-metal-catalysed graphene growth, in particular, has been shown to yield macroscopic single-crystalline graphene domains with very low defect density and outstanding thickness control<sup>7</sup>. Still needed are methods to isolate the carbon layers from a metal substrate. A recent successful demonstration of the transfer of large graphene flakes, using growth on thin polycrystalline nickel films that can be etched away to free the carbon layers, underscores the viability of this approach<sup>8</sup>. A true leap forward, however, would be the development of an atomically precise 'bottom-up' synthesis of graphene nanostructures. If the tools of materials science, chemistry and nanotechnology are combined, such a vision might just become a reality. □

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**Figure 1** | Evolution of the surface during graphitization of Si-face SiC. **a**, SiC starting surface with a staircase of flat terraces and atomic steps. **b**, Unit cell of 6H-SiC. **c**, Schematic morphology of vacuum-graphitized SiC. **d**, Morphology obtained in high-pressure argon. The surface termination is predominantly monolayer graphene, G<sub>1</sub> (**e**), with narrow stripes of bilayer (G<sub>2</sub>) and trilayer (G<sub>3</sub>) graphene near the upper edge of the substrate steps.