

clusters into smaller ones occurs, in a tug of war with molecular motors. Therefore, in contrast with passive nucleation and growth in (near) equilibrium systems, the result here is a steady-state distribution of cluster sizes. Bausch and co-authors show that this steady-state regime requires a finely tuned system at the edge of stability, between fluidization and permanent network stability. They also show results from a simple computer-simulation model that seems to be able to reproduce the observed structural patterns and dynamics, including the need for marginal stability of the networks. Still, attaining a quantitative and predictive theoretical understanding for the observed phenomena remains a challenge for the future.

The steady-state formation and dissolution of network clusters observed by Bausch and co-workers (Fig. 1c) is reminiscent of actin–myosin cluster formation in developing embryos⁹ (Fig. 1b). In both cases, transient structures are observed, which appear to be rather disordered in contrast to the more regular spindle-like asters³ (Fig. 1a). Similarly, Martin *et al.* observed myosin cluster formation and coalescence in *Drosophila* embryos that appeared to depend on actin filaments¹⁰. Such cellular processes may be examples of the kind of nucleation and growth proposed by Bausch and co-authors. It is also interesting to note that the coalescence of the clusters observed by Martin *et al.* depended on the presence of polymerized actin. Perhaps the structures they observed were also marginally stable, as in the reconstituted

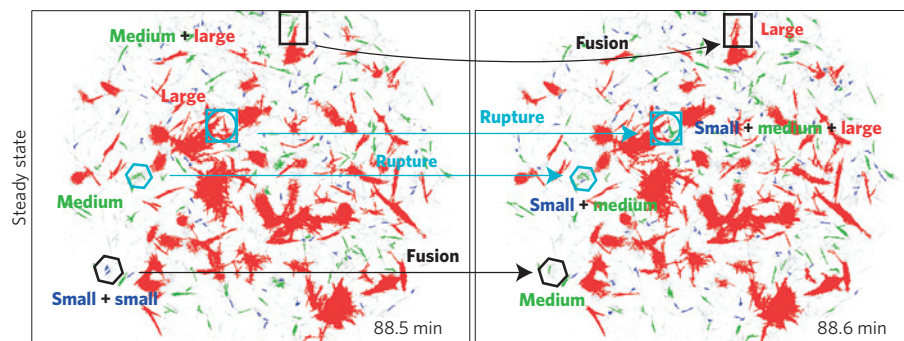


Figure 2 | Fusion and rupture of network clusters in a minimal cytoskeletal network model. When the effects of the static crosslinkers (fascin) and the active motors (myosin II) are balanced, a steady-state, but highly dynamic regime ensues. In this state, small (blue), medium-sized (green) and large (red) clusters of filaments continuously interchange material via fusion and rupture events whilst the distribution of cluster sizes remains stable. Figure reproduced from ref. 1, © 2011 NPG.

networks discussed here. However, more work will be needed to establish whether the nucleation-and-growth mechanism suggested plays a role, or is even present, in living cells. An even longer-range, yet possibly equally interesting avenue of research is to explore the possibility of fabricating synthetic materials: the ability of the cytoskeleton to maintain mechanical integrity while constantly remodelling holds out the prospect of adaptive or self-healing materials that can yield or flow under stress, and yet re-establish a mechanically coherent steady state. In this regard, in addition to providing insight into intracellular dynamics, minimal models such as that of Bausch and co-authors may point to new design principles for biomimetic materials.

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GRAPHENE

Pushing the boundaries

Grain boundaries in polycrystalline graphene are an obstacle to electron transport. However, cunning refinements in growth techniques push the limits to obtain super-sized single-crystal domains.

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Practical materials are almost always polycrystalline. This is the direct result of nucleation, growth and coalescence of grains resulting in broken periodicity in materials. In three-dimensional structures, the sizes of grains and the boundaries between them strongly influence the physical properties. For example, in metals, grain boundaries impede dislocation motion and hence induce mechanical strengthening, but on the other hand increase electron scattering and decrease

electrical conductivity. Recent advances in the growth of two-dimensional (2D) structures, most notably graphene¹, give no reasons to believe in exceptions. Several reports^{2,3} have clearly shown the presence of grain boundaries in graphene layers prepared through the exfoliation of graphite or grown on metal surfaces by the chemical vapour deposition of hydrocarbons. In fact, it is no secret that the best electronic properties of graphene ever demonstrated have come from layers of graphene peeled

off from rare natural graphite formed under extreme geological conditions.

The great challenge for graphene researchers is how to control the early stages of nucleation and growth of the material on preferred metal surfaces, such as copper, and eventually create large grains that would essentially present single-crystal graphene domains. The trick is to create nucleation sites located far enough from each other and to grow the single crystalline domains fast enough so that

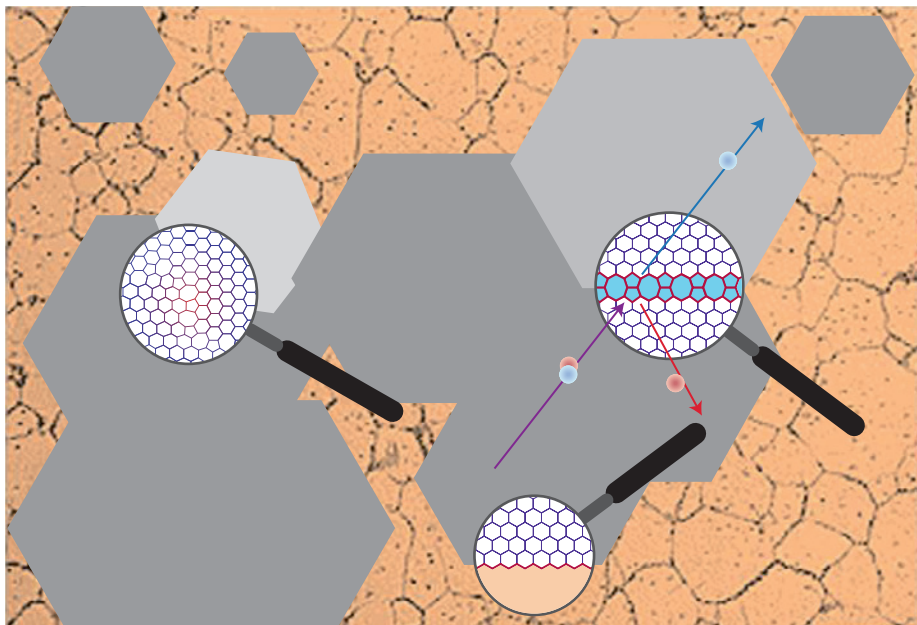


Figure 1 | Hexagons beget hexagons. At specific conditions, graphene domains grow robustly, transcending the trenches and grains of the underlying copper substrate, while preserving their inherent hexagonal shapes. Slight misorientations or shifts may enable avoidance of grain boundaries, as well as controllably creating interfaces that could serve as conducting wires or filter electrons according to the valley they occupy near the Fermi level.

no additional nucleation sites can emerge. However, the growth should also be slow enough to occur isotropically in two dimensions to minimize defects. Writing in *Nature Materials*, Yu *et al.*⁴ report considerable advance in understanding the growth mechanism of single crystalline graphene films on polycrystalline copper substrates, and suggest an approach by which the quality can be improved. The paper also addresses the deleterious effects of grain boundaries in graphene, which limit electron mobility. In another recently published paper⁵, Li *et al.* propose a new recipe that allows the growth of large single-crystal domains of monolayer graphene reaching lateral sizes of a fraction of a millimetre.

The substrate used in both reports is polycrystalline Cu, with grain sizes of few microns. The growth of graphene on Cu occurs via a surface nucleation and 2D grain expansion. The paper by Yu *et al.* shows fascinating evidence that as the graphene grains grow, they have very little interaction with the underlying substrate (no epitaxy) and cross the Cu grain boundaries without losing their crystallographic orientation. The underlying reason for this is the very rigid — in two dimensions — make-up of the graphene lattice relative to the much softer Cu template. Driven by the strong affinity of carbon atoms to self-assemble

and expand the sp^2 lattice, the graphene ‘bulldozes’ its way through the humps and bumps on the supporting metal. Seeing it experimentally is a surprise, but it could be a positive note in graphene growth as the grain size of graphene may not be locked in by the substrate microstructure and has the possibility to grow into larger domains. Even more curious is that the large grains keep nearly perfect hexagonal shapes with the boundaries dominated by the zigzag edges of the graphene lattice (Fig. 1). This morphology cannot result from the thermodynamics-based Wulff construction — a mathematical recipe to determine the shape of a crystal based on its surface energy minimization — as the zigzag edge is higher in energy than any other direction⁶. Instead, it must be a result of the kinetic selection of the slowest-growing facets⁷ — known to be zigzag for carbon lattices of nanotubes or graphene. In the work of Li *et al.*⁵, the use of low partial pressures of the hydrocarbon (methane) allows a very low density of nuclei and slow growth, both criteria for obtaining large grains in the fully grown layer. The technique allows them to grow exceptionally large grains, nearly half a millimetre in size. An approach for making large single crystals in bulk is the well-known seeded-growth technique, practiced commonly in the semiconductor industry. The same could work in two-dimensions,

as Yu *et al.* point out, seeding well-defined graphene nuclei on Cu using patterning, and re-growing continuous layers of graphene from these nuclei. This could ultimately turn out to be a powerful technique in the growth of 2D crystals, where the crystallographic orientation of the lattice, as well as the grain size, can be controlled by growth from planted seeds that have the right orientation, shape and separation.

Recently, it has emerged that the electronic properties of graphene are severely affected by the presence of grain boundaries. Indeed, the measurements of electrical resistance across grains and within individual grains show that grain boundaries contribute significantly to the resistance across grains⁴, instead of possible perfect reflection or transmission⁸. The measured electron mobilities in graphene are also significantly higher in devices with grains larger than few hundred microns. Grain boundaries (separating the perfect domains that are either misoriented or shifted) seem to be of a few types (Fig. 1). These include meandering grain boundaries^{2,3}, which are rather disordered sequences of pentagons and heptagons, and emerge perhaps from coalescence of rough-edge domains; relatively ordered, low-angle grain boundaries, which appear between slightly misoriented grains; and a special kind of translational grain boundary between the grains of identical orientation, yet slightly shifted in transverse direction. Notably, the zigzag-edge hexagonal domains observed by Yu *et al.* may systematically yield exactly this type of translational grain boundary and serve as metallic wire⁹. Recent theoretical analysis of such zigzag-zigzag grain boundaries¹⁰ further shows interesting ‘semi-transparency’ in quantum transport and the ability to filter electrons according to the valley they occupy near the Fermi level (Fig. 1).

Graphene seems to be only a small part of the research on 2D materials. As new layered compositions such as boron nitride, dichalcogenides and topological insulators^{11,12} become part of the diverse set of materials selection in future, the importance of controlled growth of their atomic layers becomes paramount. The lessons we learn from graphene and the techniques we develop for its controlled growth will be useful in the development of these other 2D structures. Among the several challenges that graphene electronics will face in the future, growing large grains seems to be at the top, as the promises of graphene don’t seem to hold up when the grain boundaries become a

nuisance to the transport of charge carriers through an otherwise perfect graphene honeycomb lattice. □

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