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Graphene 2.0

Once the preserve of physicists, graphene is now attracting the attention of growing numbers of chemists, who are discovering new ways to produce this remarkable material.

In January 2008 *Nature Nanotechnology* published a News & Views article entitled "Calling all chemists" by Rod Ruoff[1] about chemical techniques for producing graphene — individual layers of carbon atoms — from graphite. At that time chemists had enjoyed most success with the production of chemically modified graphene, notably graphene oxide, as opposed to pure graphene. "The 'chemistry part' of the graphene story has only just begun," wrote Ruoff, "and because of the extraordinary number of levers that chemistry affords, there will be a growing dialogue between chemists and researchers in other fields (such as physics, materials and processing) who, otherwise, might only have worked with graphene in its pristine form."

Well, chemists have been busy pulling levers ever since, as can be seen in a number of recent papers, including two in this issue (as described by Jun Zhu in the News & Views article on page 528). Hongjie Dai and co-workers report on page 538 that a combination of reintercalation — which basically involves the insertion of other substances, such as nitric acid, between the graphene layers — and sonication produces graphene sheets that exhibit high electrical conductance at room temperature. They also went on to make large transparent Langmuir–Blodgett films. Jonathan Coleman and co-workers, on the other hand, used organic solvents to produce the graphene in solution (page 563), from which they made semi-transparent films and polystyrene–graphene composites with good electrical properties.

As is well known, the experimental rise of graphene[2] started in 2004 with a modern-day string-and-sealing-wax approach that involved the use of 'scotch tape' to peel the graphene from a sample of crystalline graphite, and a more high-tech approach that involved the epitaxial growth of graphene on silicon carbide substrates[3]. A series of breakthroughs in fundamental physics quickly followed[2,4]. (The theory of graphene has a much longer history, dating back to 1947, at least, when Philip Wallace of the Chalk River Laboratory in Canada published a paper entitled "The band theory of graphite"[5]).

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However, both of these approaches had their drawbacks. The epitaxial approach, which has since been demonstrated on other substrates, is expensive, but it may well be suited for electronic applications. The mechanical exfoliation or cleavage approach, on the other hand, is slow and labour-intensive (an optical microscope is needed to find single- or few-layer sheets of graphene among the material peeled off) and is unlikely to ever be able to produce graphene in the volumes needed for applications. However, this method has since been developed to the stage where members of the group at Manchester University that invented this approach have set up a start-up company, Graphene Industries (see page 523).

Fast forward to 2008 and research on graphene is blossoming in a number of different directions. Research into the fundamentals is continuing, such as the observation of various spin-based phenomena, including the Kondo effect: there are also open questions about the stability of true two-dimensional materials[6] (according to Landau[7] and other famous theoretical physicists, two-dimensional structures are not stable), and the parallels between the relativistic charge carriers found in graphene and other areas of physics have still to be explored fully. Theoretical predictions for the minimum conductivity in graphene also differ from experimental measurements by a factor of π. However, this has not stopped research into the nitty gritty details that need to be fully understood before attention turns to the long-term goal of making electronic devices for real-world applications[8]. Beyond electronics, researchers are looking to exploit the properties of graphene in applications as diverse as NEMS[9], advanced capacitors[10] and drug delivery[11].

Back in the lab, meanwhile, chemists are looking for ways to go beyond making samples with good electrical properties and produce graphene that is pristine. Given the rate of recent progress, this might happen sooner rather than later.

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