

GRAPHENE

Surfing ripples towards new devices

The electronic properties of graphene can be changed by exploiting its unusual thermal properties to introduce periodic ripples with given wavelengths and amplitudes.

Rodolfo Miranda and Amadeo L. Vázquez de Parga

Hopes for a new generation of strain-based electronic devices made from graphene will rest on our ability to control the electromechanical properties of these two-dimensional sheets of carbon atoms. These hopes have now moved a step closer to reality following demonstrations by Chun Ning Lau and colleagues at the University of California at Riverside that periodic ripples can be introduced in a controlled way to suspended samples of few-layer graphene¹. This new approach takes advantage of the thermal strains produced by the negative thermal expansion coefficient of graphene.

Ripples are difficult to avoid in two-dimensional materials and have been seen in graphene before. The first ripples to be observed were randomly distributed across the surface², but periodic ripples were subsequently created by depositing single-layer graphene on single-crystal metal surfaces^{3,4}. The ripples resulted from the surface and the graphene having different lattice parameters. For example, when graphene was deposited on iridium or ruthenium surfaces, ripples with a wavelength of 2.4–3.0 nm and an amplitude of 0.02–0.05 nm were observed. These ripples have also been shown to be associated with periodic variations in the electronic properties of the graphene^{1,3} [AU: Ok?].

In general, ripples in graphene (Fig. 1) [AU: figure insertion ok here?] are expected to strongly influence its electronic properties by introducing spatially varying potentials⁵ or effective magnetic fields (also known as gauge fields)⁶. And if the ripples are periodic, one can, in principle, open up a bandgap between the valence and conduction bands occupied by the electrons. Graphene does not have an intrinsic bandgap, which is why it is known as a zero-gap semiconductor or a semi-metal. Moreover, one could arrange for the bandgap and the energy of the Fermi surface (which separates occupied and unoccupied electron energy levels at absolute zero temperature) to coincide by doping or applying a suitable bias voltage. Having a gap at the Fermi level is vital for

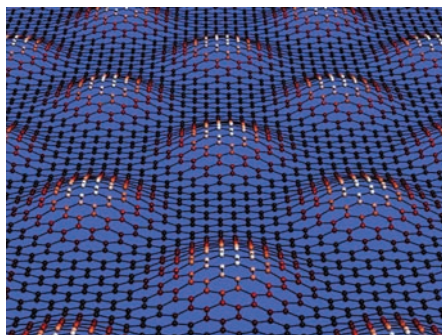


Figure 1 | Artistic impression of periodic ripples in single-layer graphene. The ripples lead to a small distortion of the carbon-carbon bonds, which leads to changes in the amplitude of the electron hopping between atoms and to the simultaneous appearance of inhomogeneities in the electronic structure. The whiter atoms indicate that the density of occupied electronic states at the Fermi level is higher at the peaks of the ripples.

applications in digital electronics because it is essential that transistors should not permit any current to flow in the off state – this cannot be achieved with zero-gap semiconductors.

Lau and co-workers placed their graphene samples across pre-defined trenches on a silicon/silicon dioxide substrate and observe the ripples with a scanning electron microscope and an atomic force microscope. The crests of the ripples are usually perpendicular to the edges of the trench, with amplitudes between 0.7 and 30 nm, and wavelengths in the range 370–5,000 nm. The ripples disappear when the samples are annealed or heated to 700 K, but new ripples with larger amplitudes and longer wavelengths appear when the graphene is cooled again, although the graphene sometime buckles on cooling instead.

The Riverside team explains this behaviour in terms of the unusual thermal properties of graphene. Unlike most materials, apart from water in a small range of temperatures, graphene has a negative thermal expansion coefficient: this

means that graphene shrinks when it is heated and expands when it is cooled. This happens because the out-of-plane atomic vibrations are energetically favoured over in-plane vibrations in two-dimensional crystals. Ripples are formed when the system is cooled because the graphene expands while the silicon (which has a positive thermal expansion coefficient) contracts, resulting in compressive stress in the graphene.

This cycle of ripples disappearing and reappearing — which repeats itself as the temperature is cycled back and forth between room temperature and the annealing temperature — can be observed quite easily with an electron microscope. Moreover, the amplitude and wavelength of the newly formed ripples depends on the annealing temperature, which gives researchers experimental control over the most basic properties of the ripples. Surprisingly, most of the observed behaviours can simply be explained with classical thin-film elasticity theory.

We already know that the mechanical properties of graphene are truly amazing: it is the strongest material ever measured⁷, with an extremely high Young's modulus (1 TPa) and a breaking strength (40 N m⁻¹) that is close to the theoretical limit; it can also be stretched more than any other crystal (20%). To these properties we can add that it has a very low thermal expansion coefficient: this means that the performance of graphene-based devices will not be adversely affected by small changes in the working temperature. Even more importantly, the periodic rippling [AU: Ok?] of graphene produced on heating to 700 K could be used to control the electronic properties of graphene. Thus, a crucial next step is the experimental verification of the predicted influence of ripples on the transport properties of graphene. This could open the way to all-graphene strain-based electronic devices, because all the necessary features (electron confinement and collimation, one-dimensional channels and a suitable energy gap) could be engineered by suitable tailoring of the strain.

Rodolfo Miranda^{1,2} and Amadeo L. Vázquez de Parga² are in the ¹Departamento de Física de la Materia Condensada, Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain, and the ²Instituto Madrileño de Estudios Avanzados en Nanociencia (IMDEA Nanociencia), Cantoblanco, 28049 Madrid, Spain.
e-mail: rodolfo.miranda@uam.es

References

1. Bao, W. *et al.* *Nature Nanotech.* **4**, XXX–XXX (2009).
2. Fasolino, A., Los, J. H. & Katsnelson, M. I. *Nature Mater.* **6**, 858–861 (2007).
3. Vázquez de Parga, A. L. *et al.* *Phys. Rev. Lett.* **100**, 056807 (2008).
4. N'Diaye, A. T., Bliedkamp, S., Feibelman, P. J. & Michely, T. *Phys. Rev. Lett.* **97**, 215501 (2006).
5. Park, C. H., Yang, L., Son, Y.-W., Cohen, M. L. & Louie, S. G. *Nature Phys.* **4**, 213–217 (2008).
6. Castro Neto, A. H., Guinea, F., Peres, N. M. R., Novoselvo, K. & Geim, A. K. *Rev. Mod. Phys.* **81**, 109–162 (2009).
7. Lee, C., Wei, X., Kysar, J. W. & Hone, J. *Science.* **321**, 385–388 (2008).