Summary of pannel discussion on gauge fields and ripples in graphene - Moderation by M. Vozmediano

GENERAL REMARKS

On the experimental side, Jeanie Lau (JL) summarized the main results concerning ripples on their experimental samples. Graphene is exfoliated in a trench. They observe that around 70% of the samples have ripples, presumably coming from the deposition process. Stretching the samples, ripples are formed over a critical value of the stretching. Ripples have been seen for strain values as low as 0.02%. Increasing temperature, ripples are suppressed due to the negative thermal expansion coefficient of graphene (see below).

On the theoretical side, Paco Guinea (PG) explained the theoretical approach used to model the effect of curvature induced by ripples on the electronic properties. Essentially, the idea is that distortions of the lattice give rise to gauge fields, that couple to the electrons through minimal coupling. For a given valley, the effective Hamiltonian is:

$$\begin{pmatrix} 0 & i\partial_z + A \\ i\partial_{\bar{z}} + A & 0 \end{pmatrix} \begin{pmatrix} \psi_A \\ \psi_B \end{pmatrix} = E \begin{pmatrix} \psi_A \\ \psi_B \end{pmatrix} \tag{1}$$

In linear elasticity, the gauge field A is related to the so-called strain tensor

$$\begin{aligned} A_x &\propto u_{xx} - u_{yy} \\ A_y &\propto 2u_{xy} \end{aligned} \tag{2}$$

The latter is related to the in-plane distortions $\vec{u}(x, y)$ [Ref Guinea, leDoussal, Horowitz] and the out-of plane distortion $h(x, y)$ in the following manner:

$$\begin{aligned} u_{xy} &= \partial_x u_x + \frac{(\partial_x h)^2}{2} \\ u_{yy} &= \partial_y u_y + \frac{(\partial_y h)^2}{2} \\ u_{xy} &= \frac{\partial_y u_x + \partial_x u_y}{2} + \frac{(\partial_x h)(\partial_y h)}{2} \end{aligned} \tag{3}$$

As pointed out by T. Ando, there is also a scalar potential generated by distortions that could be important.

PG replied that this potential is proportional to the relative area change $u_{xx} + u_{yy}$ and that in the mesoscopic samples used in the experiment, it is screened and only the gauge fields are relevant (in relative terms, the potential is small by a factor of $1/k_F L$, where L is size of the ripple). Note that gauge fields can also be generated by dislocations (the pseudo flux around a dislocation will be zero). Furthermore, the treatment of elasticity in terms of gauge fields and a scalar potential is only valid near the Dirac point.

Do these gauge fields break time-reversal symmetry?

Maria Vozmediano (MVM): No. Time-reversal symmetry is preserved when the two valleys are considered, since the gauge field has opposite signs in each valley.

Will the alternating curvature of ripples give rise to an alternating pseudo magnetic field? (question by E. Andrei)

MVM: The sign of the field is independent of the sign of the curvature and it will be positive for one Dirac cone, negative for the other.

How is the magnetic field related to the strain field?

PG: The stress and strain field are related by Hooke's law, as usual. In the case of simple stresses, which can be written in terms of a biharmonic function that is dependent on the complex coordinate $z = x + iy$ only (where x and y are the in-plane spatial coordinates), the magnetic field is proportional to the third derivative of this function. The biharmonic function is itself dependent on the boundary conditions.

The out-of-plane distorsion field will also contribute to the correlator of the gauge field (comment by D. Khveshchenko)

Since the gauge field actually contains a quadratic contribution from the out-of-plane distortion (see equations 2 and 3) and $\langle h_q h_{-q} \rangle \propto \frac{1}{q^4}$, one has:

$$\langle A_q A_{-q} \rangle \propto const + \frac{1}{q^2} \,, \tag{4}$$

where the first contribution comes from the terms in $\partial_i u_j$.

O. Vafek: Can one determine the correlator experimentally? M. Fuhrer's group (Nanoletters 7, 1643) measured the height-height correlation function at large distances.

How does one reconciled the fact that, on the one hand, rising temperature suppress ripples, but at the same time, the stretching of graphene due to the temperature increase should create them? (question by H. Schomerus)

JL: This is a result of competing processes: stretching and bending. Being true that at low temperatures graphene is compressed because of its negative thermal expansion coefficient (that would suppress rippling), the dominant effect comes from bending, which is energetically more favourable as graphene is a thin film. In the end, at low T, it is the second effect that dominates.

On what does morphology of the ripples depend?

JL: The morphology depends on many factors, but temperature and pinning of the sample can also be used to control it.

Is the formation of ripples repeatable? (question by D. Haldane)

JL: Yes, up to a certain temperature, after which the sample stacks to the bottom of the trench.

What are the effects of the gauge fields on Landau levels? Can they have measurable consequences?

In order to observe Landau Levels (LL) in graphene due to the gauge fields induced by rippling, you need a sufficiently constant effective magnetic field generated by the gauge fields. So if the modulation of ripples is small enough, it could induce an experimentally observable zero energy LL. There could also be experimental consequences in transport measurements.

Do the gauge fields couple to the spin of electrons? Could this have experimental measurable consequences, like changing spin life-times?

No. The spin degree of freedom is decoupled from the effective magnetic field generated by the distortions.