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# The Wonder Material Graphene

## Graphene: A Quantum of Current

**Graphene is a two-dimensional honeycomb lattice of carbon atoms (fig. 1a) – only one monolayer of graphite. Yet this single layer has caused quite a stir due to its extraordinary properties: graphene conducts better than copper, shows exceptional mechanical strength and elasticity, and exhibits quantum effects already at room temperature.**

Manufacturing graphene is meanwhile quite streamlined: first experiments used scotch tape to exfoliate single layers from graphite. Nowadays, chemical vapor deposition using methane gas on copper foils allows for growing large scale sheets at high quality in a scalable way – which can then be used, for example, to create touch screens. Graphene is both an excellent conductor and optically transparent because of its extremely small thickness – or rather thinness. This combination makes it ideally suited to replace brittle indium tin oxide (ITO) as material for flexible displays.

### Band Structure

Where do the extraordinary properties of graphene come from? Mostly from its unusual band structure.  The band structure of a material connects the energy of an electron wave inside the material with its wave number. According to quantum theory, electrons travel through materials as waves. Such an electron wave is characterized by its wave length, and its direction of movement. In the space of one wave length $\lambda$ the electron wave performs exactly one oscillation. Conversely, the wave number $k = 2\pi/\lambda$ is the number of oscillations per unit length. An electron wave may move through a crystal lattice in certain directions only with certain wave numbers, as determined by the crystal structure. This relation, called band structure, tells us a lot about the properties of the material: if, for example, no k-values are allowed in a certain energy window, then no current may flow at that energy, meaning the material is insulating. Graphene has no such band gap. Instead, it features a linear relation between energy and wave number: for increasing energy, the wave number increases and the wave length decreases accordingly (fig. 1b).

## A Quantum of Current

Is it possible to directly proof the wave nature of electrons in a material like graphene?

One possibility is to show the quantization of current through a constriction, as shown in figure 2. If one applies a voltage between both sides of the constriction, a current of electrons flows. However, not all electron waves will fit through such a bottleneck of width W. According to the band structure, a larger applied voltage, and hence a larger energy, yields a larger wave number, and thus a smaller wavelength. The electron wave may pass the constriction if and only if the constriction width is an integer multiple of the electron wave length, $W/\lambda = n$, with integer n. Insofar, a small wave length means larger n, and thus more electrons have the chance to pass the constriction, i.e., the current increases. However, this does not happen in a continuous way: each time another integer multiple of the wavelength fits through the constriction, the current jumps up one flux quantum. This sudden increase in current as function of applied Voltage has now been measured for graphene constrictions.

## Experiment

To show the theoretical predictions of a quantized current experimentally is quite challenging: any defect in the graphene membrane will act as scattering center for the electron wave. Electrons are scattered in all directions, and the resulting noise covers any signatures of current quantization. Therefore exceptionally clean graphene samples are used (fig. 2), that are assembled by sandwiching graphene between insulating layers of hexagonal boron nitride, just as a thin slice of cheese in a toast. This device setup avoids any scattering from dirt or adsorbed water molecules. The entire graphene sandwich is then cut to the desired constriction geometry, and cooled to extremely low temperatures: down to about -270 degrees

Celsius (-450 F), where even the rare gas helium becomes a liquid. At such low temperatures, thermal noise is suppressed and the experimental energy resolution is good enough to resolve quantization steps. However, the measured current shows no perfect steps, but regular, reproducible kinks (fig. 3a). Why is that? Computer simulations of the constriction geometry reveal the answer. Even for the ideal conditions of a computer simulation the current shows the same kink pattern: its origin is scattering of the electron wave on the atomic roughness of the constriction (fig. 3b). As the graphene sandwich has to be cut to obtain a constriction, the edge of the graphene lattice is not smooth on an atomic scale. Nevertheless, size quantization signatures can be identified in the spacing between the kinks. This spacing is given by the increase in energy needed to fit one additional wave length in the constriction width. Due to the linear band structure of graphene, the experimental measurement (and the simulation) show equally spaced kinks. Moreover, calculating back from the spacing to an associated width yields exactly the width of the graphene constriction. The combination of experiment and theory thus proofs that the kink signatures are indeed caused by quantization of the conducting electrons at the finite constriction width.

## Outlook

Considering the ever decreasing size in electronic devices as described by Moore’s law, further miniaturization of electronic circuits makes quantum effects more and more important. Instead of considering them a nuisance, we should think about exploiting these effects. Materials like graphene open a pathway towards ultrafast, low power electronics based on quantum effects. The experimental verification of quantum effects in graphene is an important step towards getting them fit for applications.

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