Materials in the Flatland: Graphene and other 2-dimensional crystals

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Carbon can exist in different forms. Diamond and graphite are the most famous carbon-based materials. They have different atomic structure giving contrasting optical and electronic properties. However, the properties of a material also depend on its dimensionality. When one writes by a pencil, thin flakes of graphite are left on a surface. Some of them are only one angstrom thick and can be viewed as individual atomic planes cleaved away from the three-dimensional (3D) bulk material. This strictly two-dimensional (2D) crystal, called graphene, was presumed not to exist in the free-state and remained undiscovered until a few years ago. Despite looking similar to graphite, graphene shows unique and outstanding properties: graphene is almost transparent, it is extremely hard and its electrons flow through the plane like lights goes through glass, i.e. they move as if they were mass-less through the hexagonal lattice, leading to a giant charge intrinsic mobility. This behavior drastically changes with the number of layers, i.e. the unique properties of graphene are strictly related to its mono-atomic thickness. In addition, graphene can be elastically stretched (up to 20%), it shrinks with increasing temperature, and it is impermeable to gases. The very unusual electronic properties of this material as well as the possibility for its chemical modification make graphene a promising candidate for future electronic applications. In particular, graphene has enormous potential for use in ultra-fast electronic transistors and flexible displays, it can be used in composite materials and in electric batteries due to its large surface-to-volume ratio and high conductivity, for transparent membranes due to its atomic thickness, in micro-mechanical resonators due to its robustness and light weight, and for bio-chemical detectors due to its extremely high sensitivity.

Graphene is not the only 2D crystal available. In fact, there exists a whole class of such materials: micro-mechanical or chemical exfoliation can be successfully applied to other layered materials such as $Bi_2Sr_2CaCu_2O_x$, $NbSe_2$, BN, MoS_2, Bi_2Te_3 and other *Dichalcogenides*. Such crystals are stable, and carry many properties which cannot be found in their 3D counterparts. As with graphene, the crystal quality of the obtained monolayer samples is very high. Many of the 2D materials conduct and even demonstrate field effects (changes of the resistance with gating). As we have full control over the 2D crystals, we can also create stacks of these crystals according to our requirements. Here, we are not merely talking about stacks of the same material: we can combine several different 2D crystals in one stack. Insulating, conducting, probably superconducting and magnetic layers can all be combined in one layered material as we wish. The properties of such heterostructures depend on the stacking order, so they are easily tuneable. This introduces a new concept in material engineering – Materials on Demand.