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Liquid Exfoliation of Layered Materials: New Frontiers Opened by the World's Thinnest Materials

Not all crystals form atomic bonds in three dimensions. Layered crystals, for instance, are those that form strong chemical bonds in-plane but display weak out-of-plane bonding. This allows them to be exfoliated into so-called nanosheets, which can be micrometers wide but less than a nanometer thick. Such exfoliation leads to materials with extraordinary values of crystal surface area, in excess of 1000 square meters per gram. This can result in dramatically enhanced surface activity, leading to important applications in microelectronics, energy storage and harvesting, composites, etc. Another result of exfoliation is quantum confinement of electrons in two dimensions, transforming the electron band structure to yield new types of electronic and magnetic materials. Exfoliated materials also have a range of applications in composites as molecularly thin barriers or as reinforcing or conductive fillers.

Here, we review exfoliation—especially in the liquid phase—as a transformative process in material science, yielding new and exotic materials from their bulk, layered counterparts. Of all 2D materials, graphene has generated huge interest in recent years due to its unique physics properties. We have shown that high-quality monolayer graphene can be produced at significant yields by non-chemical, solution-phase exfoliation of graphite in certain organic solvents.

Until a few years ago the standard procedure used to make graphene was micromechanical cleavage, which is a very low yield production method. In order to fully exploit graphene's outstanding properties, a mass production method was necessary and the development of a method to exfoliate cheap, commercial graphite in organic solvents down to large area single graphene flakes with high yield was one major achievement. Recently this work has been extended to a wide range of two-dimensional inorganic nanomaterials. These are potentially important because they occur in >100 different types with a wide range of electronic properties, varying from metallic to semiconducting. The liquid-phase exfoliation method has now been up-scaled to produce grams of a variety of exfoliated materials per day. This talk will first discuss the galaxy of existent layered materials, with emphasis on synthesis, liquid-phase exfoliation, and characterization, to finish off with some key applications recently developed in our laboratories.

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Band Structure, Spin-orbit Coupling, and Nanostructures in 2D Transition Metal Dichalcogenides

Monolayer transition-metal dichalcogenides (ML-TMDCs) are truly two-dimensional (2D) semiconductors, which hold great appeal for electronics, opto-electronics, and spintronics and have been demonstrated in FETs, logical devices, and optoelectronic structures. We investigate ML-TMDCs using k.p theory aided by density functional theory (DFT), finding trigonal warping and electron-hole asymmetries. Unlike graphene, the ML-TMDCs lack inversion symmetry leading to interesting spin-orbit effects. We use the resulting effective band Hamiltonians to describe electronic properties in nanostructures, e.g., quantum dots.

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with J. Ghosh, D. Osintsev and S. Selberherr

Electron Spin Lifetime Enhancement by Shear Strain in Thin Silicon Films

Silicon, the main material of microelectronics, is attractive for spin-driven applications due its long electron spin lifetime.

The main contribution to spin relaxation due to phonons' scattering between the non-equivalent valleys is eliminated by lifting the valley degeneracy. However, in silicon-on-insulator structures the spin lifetime is reduced due to interface scattering.

Uniaxial stress significantly boosts the spin lifetime in thin films. This is due the complete degeneracy lifting between the unprimed subbands by shear strain. This degeneracy was a long-standing problem in silicon spintronics. Lifting the degeneracy in a controllable way is paramount for future silicon spin-driven applications.