Hydrogel platforms for strain-free and homogeneous 2D materials and devices

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Applying mechanical strain in two-dimensional (2D) materials alters the interactions between photons, electrons and phonons and, consequently, the electronic, magnetic and optical properties of the 2D materials. Examples of phenomena induced or affected by extrinsic strain in 2D materials include modification of the charge carrier and exciton properties in graphene, alternation of vibrational properties and optical characteristics of quantum emitters in hexagonal boron nitride (h-BN), modification of magnetic properties, moiré potentials, excitons and phase transitions in van der Waals heterostructures of 2D materials. Both tensile and compressive strain in graphene cause degradation of graphene field effect transistor (GFET) performances by reducing the charge carrier mobilities in comparison to unstrained graphene. Moreover, even when no strain is applied intentionally, random strain fluctuations are still ubiquitously present across the surface of a 2D material, originating from the inhomogeneities and imperfections of the 2D material-substrate interface, particularly from the inherent substrate roughness, lattice mismatch and fabrication-induced impurities and corrugations. These inhomogeneous strains introduce variations of electrostatic potential, centers for charge carrier scattering and exciton recombination, local modifications of the band structure and random effective magnetic fields in the sheets of 2D materials, and ultimately – degraded performances and large device-to-device variations in 2D materials-based devices. Although strain fluctuations have been successfully reduced in graphene and MoS2 by encapsulating them between atomically flat h-BN layers, their presence is still substantial even in the most state-of-the-art samples. This indicates a fundamental limit in strain reduction that can be achieved with flattening of the substrate. On the other hand, suspending graphene over the surface of water at water/air or water/nonpolar liquid interfaces was shown to reduce strain in CVD (chemical vapor deposition) graphene to nearly zero, achieving the uniformity level superior to that observed with graphene on solid substrates. As opposed to solid surfaces, in liquids fast diffusion is constantly compensating occurring inhomogeneities and gradients, making the surface of a liquid a superiorly uniform, adaptable and molecularly smooth support for 2D materials. However, a free-floating graphene sheet cannot be immobilized on the liquid surface and integrated into devices, hence this phenomena has not been practically incorporated, despite its potential promise. In this work we propose hydrogels as substrates for 2D materials and devices, which harness the strain relaxation and unification effects of liquids for practical applications. Hydrogels are water-infused polymeric matrices, in which liquid content typically exceeds 90%, but on which nonetheless monolayer materials can be immobilized and probed. We demonstrate that graphene sheets deposited on hydrogel slabs show the lowest mean value (zero) and the most uniform distribution of strain, compared to graphene on other state-of-the-art substrates, including h-BN and liquid water. The strain relaxation and unification effect was observed with both tested types of hydrogels - agarose- and acryl amide(AAm)-based hydrogels. Furthermore, this strategy was also proven to work on monolayer h-BN, and can, in principle, be used as a general approach for achieving uniform untrained sheets of any 2D material grown on metals. Finally, we propose how such graphene/hydrogel platforms can be integrated into devices by demonstrating a graphene/hydrogel-based field effect transistor (FET) with superior charge carrier mobilities.