Dry two-dimensional material integration via adhesive matrix transfer

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Two-dimensional (2D) materials present an emerging platform for engineering devices with functionalities that cannot be achieved through conventional fabrication.[1] Core to these opportunities are van der Waals (vdW) heterostructures formed between 2D and other materials.[2] To fabricate such structures, the 2D layer needs to be transferred from its growth substrate to a target surface. Though universal, vdW interactions are weak and fixed by material properties, and thus cannot facilitate transfer onto arbitrary substrates. To promote transfer, current techniques rely on polymer support layers, solvents and/or high temperatures which can introduce chemical contamination and mechanical degradation.[3] Here, we present an approach that addresses these limitations by decoupling the forces promoting transfer from those present at the functional interface. This approach, adhesive matrix transfer, is dry, low-temperature, aligned and scalable.

The fabrication process is outlined in Figure 1. First, the receiving substrate is fabricated on silicon and embedded in an adhesive matrix (Figure 1a). This substrate is then peeled, revealing an ultrasmooth (<0.5 nm roughness) surface. Concurrently, a 2D material is patterned on a source substrate (Figure 1b). The two substrates are then aligned, brought into conformal contact and separated (Figure 1c-d). The adhesive matrix is chosen to have a strong adhesive interaction to the 2D layer. This interaction promotes the transfer onto the target, forming a pristine heterostructure (Figure 1e) without solvents, heat or a sacrificial layer.

Using graphene as an example, we demonstrate our fabrication technique. To identify an appropriate adhesive matrix, patterned graphene on SiO_2 is brought into contact with candidate adhesive matrices and peeled (Figure 2a). Though no transfer is observed with PDMS, SU-8 and NOA-61 pick-up graphene with near unity yield over mm-scale regions (Figure 2b). Raman analysis indicates negligible defects are introduced during transfer (Figure 2c). We use this adhesive matrix approach to fabricate a heterostructure between graphene and ultrasmooth gold (Figure 3a). Here, the polymer matrix promotes the transfer to allow for the dry, low-temperature fabrication of the graphene-gold vdW heterostructure. Raman mapping (Figure 3b) shows the formation of a continuous graphene-gold interface. This transfer by contact is aligned and scalable (Figure 3b,c) with local fabrication yields as high as 93%.

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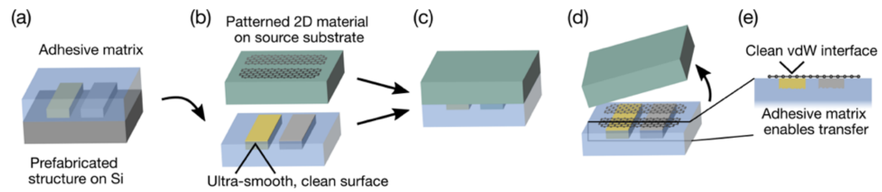

Figure 1: Adhesive matrix transfer. (a) Prefabricated structure on silicon is embedded in adhesive matrix, and (b) peeled revealing ultrasmooth, clean surface. Concomitantly, patterned 2D material is prepared on a source substrate. (c) Substrates are aligned and brought into conformal contact. (d) Substrates are separated, resulting in (e) transfer of 2D material from source to target surface.

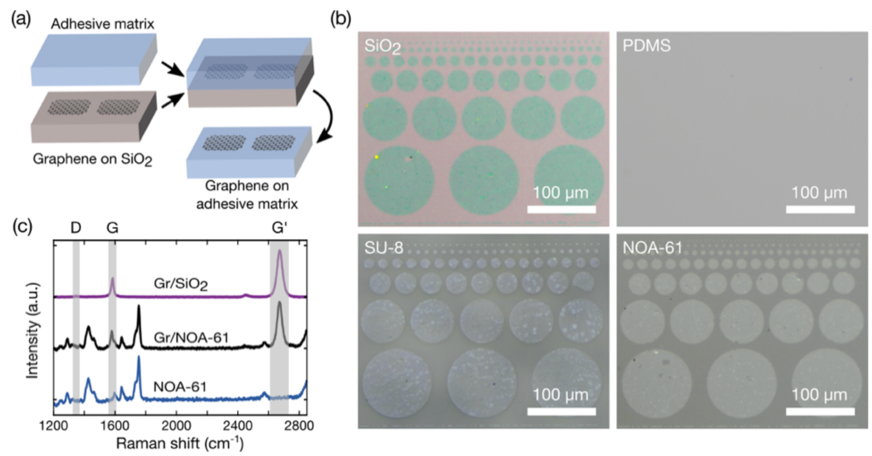

Figure 2: Adhesive matrix selection. (a) Schematic of experiment used to select adhesive matrix. (b) Optical micrograph of graphene monolayer as patterned on SiO_2, and after attempted transfer to various surfaces. Transfer does not occur on PDMS, but occurs with near-unity yield on SU-8 and NOA-61. (c) Raman spectra of graphene (Gr) before and after transfer showing characteristic G and G' peaks in addition to negligible defect-associated D peak both before and after transfer.

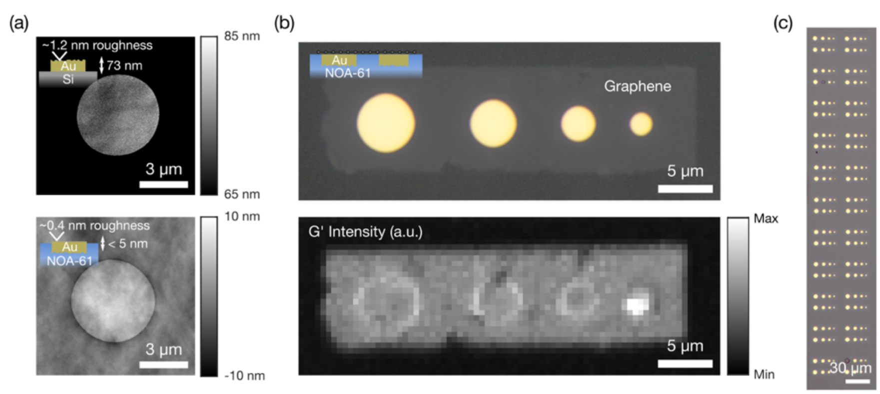

Figure 3: Fabrication of heterostructures. (a) Atomic force micrograph of gold features as patterned on silicon and after peeling, resulting in a reduction in step height from 73 nm to < 5 nm, and sub-0.5 nm surface roughness. (b) Optical micrograph and Raman mapping of aligned graphene/gold heterostructure. (c) Large-area aligned array of heterostructures. Insets in (a,b) show schematic illustrations of fabricated structures.

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