between the two surfaces (as shown by the laminated array withstanding pinching and twisting in the left inset of Fig. 1), and reduces discomfort to the user, who eventually will not feel the presence of the device on the skin. The researchers also show that the arrays can be mounted on microperforated elastomeric substrates, enabling perspiration of the tissues and allowing temperature measurements to be made with an accuracy of a few millikelvin, even during intense sweating. Importantly, they take advantage of the dual functionality, as sensors and actuators, of the thin metal films to release known amounts of heat and measure the resulting temperature increase, thus assessing the local thermal conductivity and water content of the skin. These compliant devices could therefore be used as wearable health-monitoring tools, collecting clinically relevant information on blood flow and tissue hydration outside hospital settings.

The various constraints — resistance to mechanical stress, high flexibility, stability of the electronic and sensing performance under repeated bending and flexing, and ageing — imposed by the applications envisaged for these devices pose non-trivial problems that must be addressed by proper design and a careful combination of materials with different mechanical properties. Building on the proof of concepts reported by Javey and Rogers, the implementation of a bendable OLED display that is responsive to temperature for robotic applications, where relatively bulky device configurations can be tolerated, may be straightforward. However, complying with the additional constraints of biomedical applications, such as a conformal contact with the epidermis and minimized discomfort to the user, will definitely need more technological effort. Recent demonstrations of imperceptible electronic devices have shown a high degree of integration between sensors, actuators and transistors; further, these devices are ‘mechanically invisible’ (which means that the elastic properties of the devices match those of the surface onto which they are applied). However, at this stage, the possibility of including ultrathin OLEDs that demonstrate stable performance when put in contact with skin or exposed to air has not yet been proven.

Fully autonomous systems will also require an independent power supply, therefore highly flexible and even mechanically stretchable batteries, supercapacitors or other energy-storage elements will need to be integrated. Furthermore, electronic skin will benefit from energy-efficient and adaptable computation systems on board, which are able to filter, elaborate and react to the received stimuli. In this sense, other biological models, such as bees, which have a body mass of less than a gram and are able to perform extremely complex flying skills with a brain that dissipates less than 10 μW of power (ref. 10), may inspire the next steps in this research field. Although, at present, we are far from achieving this state of the art found in nature, looking at the speed of new developments in electronics there is no doubt that there will be rapid progress towards fully integrated electronic skins in the future.

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Contact with what?

Pristine graphitic surfaces seem to be more hydrophilic than previously assumed because of the unexpected influence of the quick adsorption of hydrocarbons from air.

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One of the simplest and most intuitively useful parameters for characterizing a surface is the angle of contact that it forms with a deposited droplet of water. For instance, a small contact angle such as 30° indicates that water spreads fairly well on the surface, that is, the surface is reasonably hydrophilic. Even a rough estimation of the contact angle can be richly informative. For example, consider how water wets the surface of a car as it goes through a washing-and-waxing cycle. Water droplets will spread out over the initially dirty (and hydrophilic) car, but as soon as the surface is waxed, the hydrophobic coat causes the water droplets to bead up and roll off. One could, in fact, reasonably track the steps involved in cleaning a car simply by monitoring how the contact angle that water makes with the hood of the car changes over the course of the cleaning process. This is similar to the approach — reported in Nature Materials — that Lei Li, Haitao Liu and colleagues used to study the surface of graphene. The researchers began with a clean surface and watched how the water contact-angle evolved as molecular contaminants from the environment adsorbed on it. Surprisingly, they found that the pristine graphene surface seemed to be more hydrophilic than had previously been assumed, whereas the contaminated surface matched the hydrophobic character that had been ascribed to clean graphene. This first effort to experimentally clarify the intrinsic versus apparent wettability of graphene is thus especially illuminating.

Graphene behaves as a semimetal with remarkably good electronic properties, which has led to its emergence as a transparent conductor for a host of electronic device applications. Understanding the wettability of a material is a major step towards understanding its performance, including how the material behaves in different environments and how it should be processed during fabrication. For example, oxidized silicon surfaces are highly hydrophilic, which typically leads to poor photoresist adhesion.
Therefore, organosilicon compounds like hexamethyldisilazane are often used in microfabrication processes to make the surface hydrophobic before photoresists are applied. Also, oxidizing reagents such as hydrogen peroxide are usually used to strip off any adsorbed airborne contaminants, which are known to significantly alter the properties of oxidized silicon surfaces, making the contact angle with water increase noticeably over time.

It is thus clear that a basic understanding of the surface properties of graphene is necessary for the robust and reproducible fabrication of graphene-based circuitry. However, it seems that even the slightly hydrophilic nature of graphene has not been well understood. In fact, because the carbon lattice appears perfectly nonpolar, graphite and graphene surfaces have long been regarded as hydrophobic (contact angle ~90°). The results of Li and collaborators, who used spectroscopy to monitor the accumulation of hydrocarbons on graphene, indicate that graphitic surfaces are intrinsically mildly hydrophilic (contact angle ~50°), and that their apparent hydrophobicity is caused by the adsorption of airborne organic contaminants within just a few minutes of air exposure (Fig. 1a). Interestingly, their results imply that the measurement of the contact angle may be a simple yet telling way to estimate the degree of contamination of graphene surfaces.

The discovery that graphene surfaces are intrinsically hydrophilic, but become hydrophobic as a result of the adsorption of airborne contaminants has ramifications that extend beyond the aforementioned analogy with silicon oxide. Because the electrical properties of graphene are highly sensitive to the type and amount of molecules adsorbed on its surface, the intrinsic hydrophilicity of graphene suggests that the performance of graphene-based devices would be especially susceptible to water vapour (and thus environmental humidity). Similarly, the performance of graphene devices will probably be affected by the quick adsorption of volatile organic compounds from the environment. The work of Li and co-workers may also stimulate discussions on how to efficiently functionalize or coat graphene to ensure that the properties that make graphene-based devices attractive are spatially uniform. Coatings that at least partially adhere through hydrophilic interactions may now be given enhanced consideration when designing methods. From a theoretical standpoint, the observed hydrophilic nature of graphitic surfaces presents new challenges, as it indicates that the water–substrate interactions are quantitatively stronger than assumed in previous models. Although carbon is nonpolar, strong water–substrate interactions may still be explained through enhanced H…π interactions resulting from the extended π system in graphene.

If airborne contaminants can strongly influence graphene’s properties, it is perhaps not surprising that a supporting substrate can also affect them. In fact, recent work, albeit inconsistent,7,8, suggests that the wettability of graphene may be at least partially transparent to the wettability of the underlying surface. Li and colleagues explored this issue by measuring the water contact-angles on single-layer graphene supported by copper (44°), nickel-supported few-layer graphene (59.6°) and bulk highly ordered pyrolytic graphite (HOPG; 64.4°). Although these are only three data points, it is tempting to propose that the fact that the contact angles of the monolayer and few-layer graphene are smaller supports the partial-transparency view of wettability.8,9,10 Still, graphene–substrate interactions can be fairly different for the three systems, and each of the carbon surfaces has different amounts and types of atomic defects and step edges.11,12 To this end, additional insight could be gathered by comparing the wetting behaviour of bulk graphite surfaces in which the graphite itself is characterized by different grain sizes and defect densities. Li and collaborators also show that as graphene surfaces are exposed to airborne contaminants and the water contact-angle increases, a contact-angle hysteresis develops (Fig. 1b). This points to an increased surface inhomogeneity as contaminants accumulate. Again, this is likely to implicate defects and step edges as the adsorption sites. In fact, it has been recently shown using graphene templating13 that surface defects (including step edges) on a variety of surfaces (including HOPG graphite) can provide hotspots for the nucleation of adsorbents.14 Hence, it is almost certain that such local defects play important roles in the surface interactions relevant to wetting. Notably, a recent study on the adsorption of small organic molecules on graphene flakes reported significantly more negative adsorption enthalpies for very low surface coverage (less than ∼2%), indicating that adsorption initially occurs on such high-surface-energy sites.15

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