The effect of environmental contaminants on the interfacial properties of 2D materials

1. Introduction

The application of two-dimensional (2D) materials such as graphene or graphite requires the understanding of their interfacial properties. The exact nature of these various 2D materials cannot be fully characterized without studying the effects of contaminants, particularly environmental, on the properties of these materials [1]. Environmental contaminants can drastically alter the properties of these 2D materials as well as their interactions with other substances [2]. For example, the wettability of graphene changes drastically with variable changes in contact angle causing a varying range of hydrophilicity [3]. The intrinsic properties of 2D materials such as wettability, electrochemical properties, or doping effect are altered through external factors which are in part environmental contaminants that are induced unintentionally during sample preparation such as volatile organic compounds (VOCs) that are present in the air, water from cleansing processes, or oxygen from the air [4]. These contaminants that remain in the 2D material after its synthesis thus alter the interaction of the materials with other substances and by association the interfacial properties of these 2D materials are altered through environmental contaminants.

The interfacial properties of 2D materials predict the effects of applying a 2D material to a different surface. 2D materials can be used to alter surface properties to prevent or facilitate chemical reactions, change or amplify hydrophobicity and hydrophilicity, or affect other properties such as friction and adhesion [2, 3]. Changing these properties of surfaces has a wide variety of applications, including technologies involving microfluidics, heat transfer, and electronics [2]. Graphene was the first 2D material and since its discovery, over 150 different classes of 2D materials have been discovered [5]. These materials are typically classified by structure, including categories such as transition metal dichalcogenides, metal oxides, metal nitrides and carbides, and 2D polymers [5]. Due to the wide application range of these materials, they have been actively sought after; however, measuring different properties can prove to be difficult due to contamination skewing data. Figure 1 illustrates how with the growth of the 2D material field, the increased interest in contaminants' effects on property measurement has also significantly increased.

When analyzing the properties of 2D materials in an experimental setting, one of the most important factors to control is the environmental contaminants. During the preparation of a sample, environmental contamination can be unintentionally introduced to the system, changing the observed properties and skewing measured observations [1]. A particularly prevalent way of environmental contamination is via airborne contaminants which have been shown to drastically increase the hydrophobicity of pyrolytic graphite, a 2D compound, as well as other 2D compounds such as graphene, SiO_2, and Tu. VOCs that are present in the air become absorbed by the 2D compounds and form a surface contamination layer of increasing thickness until 0.55 mm [6]. An increase in contamination characteristically leads to an increase in the required water contact angle thus presenting a perceived intrinsic hydrophobicity of 2D materials [6]. Surface contaminants have the potential to affect any measured properties depending on surface energy, chemical reactivity, or dielectric effects [7]. For highly oriented pyrolytic graphite (HOPG), double layer capacitance was found to decrease after prolonged exposure to air [7]. Hydrocarbon contaminants have also been found to decrease the differential capacitance of HOPG [7]. Recent discoveries present that graphene and other similar 2D materials are mildly hydrophilic as opposed to prior conclusions of hydrophobicity which is actually caused by hydrocarbon contaminants [8]. The surface sensitivity of wettability is thus drastically affected by these contaminants which then simultaneously affect other interfacial properties like adhesion, absorption, carrier mobility, and charge doping [8]. The doping effect is especially troublesome for 2D materials such as graphene as surface contaminants can cause structural deformation and add charges to the usually 'zero-gap' and neutrally charged substance [9]. Chemical vapor deposition (CVD) synthesized graphene also has a high surface energy and surface area, causing it to absorb contaminants more easily [9]. On graphitic surfaces, water contact angles have been found to decrease significantly after putting forward efforts to remove contaminants through methods such as thermal annealing and ultraviolet-O_3 treatment [10].

In addition to graphitic materials, other 2D materials such as hexagonal boron nitride (h-BN), MoS_2, and mica, also are affected by environmental contaminants, which alter their measured properties. h-BN shares a similar structure with graphene and can also be synthesized through CVD [11]. However, when exposed to air for a prolonged period of time, the measured water contact angle was found to increase around 23 degrees [11]. Similarly, discrepancies in values for surface energy as well as hydrophobicity changes of MoS_2 also have been linked to airborne hydrocarbon contamination [12]. On mica surfaces, ambient contaminants can cause a phenomenon known as dewetting, where instead of layering, ionic liquids form droplets on the surface due to a raise in temperature replacing water molecules with hydrocarbons [13].

An effective method to prevent contamination of 2D material surfaces is through water adsorption onto the 2D materials such as graphitic carbon. Specifically, in order to drastically decrease the rate of airborne contamination on 2D surfaces, water adhesion must occur on freshly produced pyrolytic graphite surfaces [14]. Another possible solution for the production of uncontaminated or minimally contaminated graphene is through a stepwise process with first through the use of metallic surfaces for graphene and other 2D material growth [15]. Following the formation of the 2D material, often a transfer to a secondary substrate is required in many cases being PMMA which is then removed through the use of solvents and thermal annealing. However, thermal annealing can leave PMMA residues on graphene and other 2D materials thus modifying its properties. Consequently, H_2 plasma can be used to clean graphene surfaces of PMMA residues thus producing contaminant free 2D materials whose actual properties like wettability can then be characterized [15].

Since the discovery of 2D materials, the field has grown exponentially due to its wide applications. However, environmental contaminants have proved to be a major difficulty for researchers, causing discrepancies between similar studies. These airborne contaminants have the ability to change a wide variety of interfacial property measurements, obscuring the true nature of these 2D materials. This vitalizes steps to prevent contamination and monitoring changes in properties after prolonged exposure to ambient air. Once these obstacles are overcome, studying 2D materials should become more instrumental towards progress in the various fields of their applications.

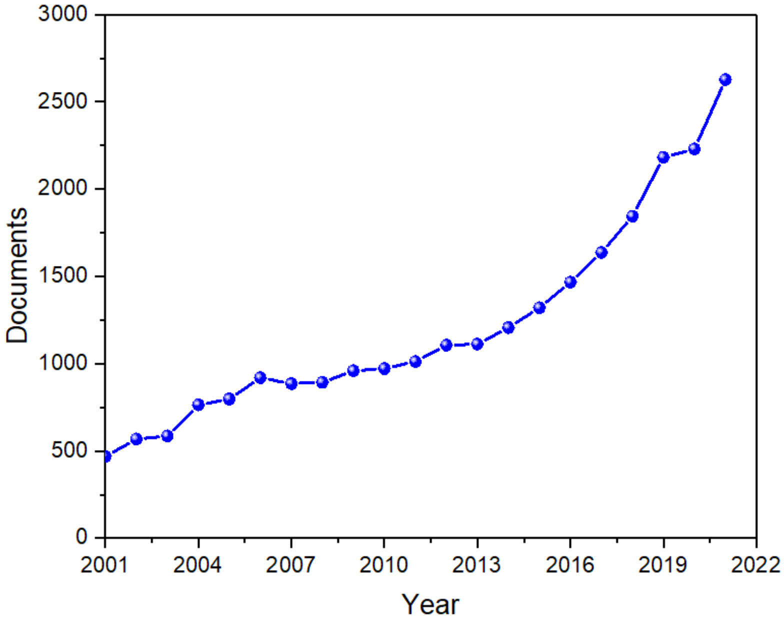

Figure 1. Trend in the research on contaminants for 2D-materials in the past 20 years (from Scopus database). Key words: “contaminants” AND “materials” OR ”2D” OR “graphene” OR “MoS2” OR “mica”.

2. Effect of hydrocarbon contaminants on hexagonal 2D materials

The surface of hexagonal materials like graphene, HOPG, BN, and MoS_2 likely adsorb organic contaminants from the air. The exposition of 2D material on ambient air can create a thin layer of vapor organic compounds on them, which radically changes the surface properties of the 2D materials [16]. This phenomenon was discovered on HOPG and graphene again and popularized by Dr. Li and Dr. Liu groups [11, 12, 17-19]. After this, more and more researchers start working on the effect of hydrocarbons' deposit onto carbon and other 2D materials [1, 11, 18]. Hydrocarbons change the surface character from hydrophilic to hydrophobic [11, 12, 19]**.** Figure 2 presents water contact angle (WCA) evolution in time for HOPG, SLG, $MoS_{2,}$ and BN. Initial all materials are hydrophilic (Table 1): 64° HOPG, 44° graphene, 62° BN, and 69° MoS_2. However, after a short time of exposure to ambient air, we can observe a rapidly increasing WCA value, then the growth is slowing down and the value is stabilized. It was observed that about 30 minutes is necessary for forming the thin monolayer of hydrocarbons (0.55-0.6 nm) onto the graphite surface [6, 10-12, 16]. The final WCA values for exposed samples were: 80° graphene, 91-96° HOPG, 89° $MoS_{2,}$ and 85° BN. These values are much more hydrophobic, which cases present VOCs. What is more the calculated total surface energy (Fowkes model) also decreased: HOPG 54.5 mJ/m^2 → 41.1 mJ/m^2, SLG 57.5 mJ/m^2 → 41.5 $mJ/m^2$and MoS_2 54.5 mJ/m^2 → 46.0 mJ/m^2. Furthermore mainly and radically value of the polar part of surface energy is reduced, which can explain the higher value of WCA (Table 1). However, studying this phenomenon is not an easy task due to the low amount of contaminates needed to change the surface. To understand this phenomenon, it was used many analytical techniques, but only a few can handle it. Typical methods for characterization of surface 2D materials like Raman spectrometry, X-ray photoelectron spectroscopy (XPS), and atomic force microscopy (AFM) cannot be used to monitor such minor changes, because of too high a limit of detection [3, 6, 10, 14, 16, 20]. Although attenuated total reflection Fourier transform infrared spectroscopy (ATR-FTIR), ellipsometry ultraviolet photoelectron spectroscopy (UPS) allow manifesting the presence of -CH_2- group from adsorbed hydrocarbons. All techniques can be Figure 3 presents the results of changing the chemical composition due to the effect of ambient air. UPS spectrum also presents VOCs (Figure 3a) – after about 15 minutes we can observe significant changes. In addition, the UPS spectrum of HOPG exposure for 18 hours in an ultrahigh vacuum does not have any signs of deposition and morphology [6]**.** The ATR-FTIR spectrums (Figure 3b) of fresh samples do not have the characteristic peaks from CH_2 and their intensity is growing over time, which proves hydrocarbon deposition from the air [6, 10, 16, 17]. Ellipsometry as not destructive and sensitive technique is the perfect tool for measuring the thickness of layer deposited compounds onto flat hexagonal materials. Due to comparable results, it can be assumed that the process of VOCs adsorption on the MoS_2 surface is similar to graphene. As was mentioned before thickness of the hydrocarbons layer for graphene is 0.55 – 0.6 nm [16], and for MoS_2 average value is 0.4 – 0.53 nm (Figure 2c). Figure 2c shows spectrums made in different days, months, and years, which suggests that the deposition process depends on many factors such as temperature, humidity, and air pollutions concertation.

The wettability has a massive impact on electrochemical properties, for example, capacity [4, 7, 14, 21] and heterogeneous electron transfer rate constant (k_0) [17] because it defines the degree of integration between solution and surface of the solid phase. In the case of supercapacitors or double-layer capacitors, hydrocarbons can deposit from two sources: air and solution. The exposition HOPG electrode on ambient air for 10 minutes caused a capacity reduction to 70% of the initial value and in the case of 1-octadecene to 30%. What is more, storage of the electrode in a petri dish also decreases the capacity, but there is no trend between the time of storage and capacity [7]**.** Figure 4 presents cyclic voltammetry (CV) analysis of aging HOPG electrodes in ambient air at room temperature. A notable decrease in electrical current was observed and the separation of the peaks (ΔEp) was increased from 59 mV to 177 mV, because of exposition on ambient air at room temperature [14]. In most cases, the reason for electrochemical changes is the limitation of the contact space between carbon surface and solution by hydrocarbons deposit. Although the aging in the solution of inorganic salts and "pure water" with the addition of organic compounds reduce the electrochemical properties (capacitance) too. After 24 h the value of HOPG electrode stored in NaCl aqua solution decreased by 67% [7]**.** Figure 4c presents of results the deposition of VOCs onto supercapacitors from active carbon by saturation. It was observed that impact of chemical structures of polyaromatics hydrocarbons (PAHs) on capacitance. For small VOCs, it was observed that the trend of higher water solubility causes a lower decrease in capacitance. Also, the selected type of storage has a big impact on electrochemical properties. It was observed that the capacitance of the active carbon electrode increased. Tolman et all explained that the cause of this phenomenon is water chemisorption on the surface, but like the authors wrote more results must be done to better understand it. To prove the hypothesis they stored the electrode in a dried (> 1ppm H_2O) nitrogen environment (glovebox has filled the gas) and observed the decreasing capacitance due to hydrocarbons adsorption. The source of them was not defined, but it can be from plastic elements of gloveboxes or storage organic solutions [21]. The results of this research show that higher molecular PAHs: anthracene, pyrene, and coronene decreased the research electrochemical properties by more than 50% compared to the pristine value. However, naphthalene reduced only about 20%.

To sum up, the presence of VOCs has negativity effect on hydrophilicity and electrochemistry properties of 2D materials. Some of the best tools, which scientists can use to understand this phenomenon are UPS, ATR-FTIR, and ellipsometry. Other techniques cannot detect surface changes. The value of decreasing the properties depends on: the kind of VOCs, temperature, and humidity.

Table 1 Value of WCA and surface energy for chosen materials

2D Materials	Water contact angle		Surface energy		References
	Fresh	Aged	Fresh	Aged	
HOPG	64°	91-96°	Dispersive: 46.5 mJ/m^2 Polar: 8.0 mJ/m^2	Dispersive: 41.0 mJ/m^2 Polar: 0.1 mJ/m^2	**[12, 19]**
Single-layer graphene (SLG)	44°	80°	Dispersive: 43.5 mJ/m^2 Polar: 14.0 mJ/m^2	Dispersive: 37.9 mJ/m^2 Polar: 3.6 mJ/m^2	**[19]**
MoS_2	69°	89°	Dispersive: 49 mJ/m^2 Polar: 5.5 mJ/m^2	Dispersive: 45.4 mJ/m^2 Polar: 0.6 mJ/m^2	**[12]**
Hexagonal BN	62°	85°	-	-	**[11]**

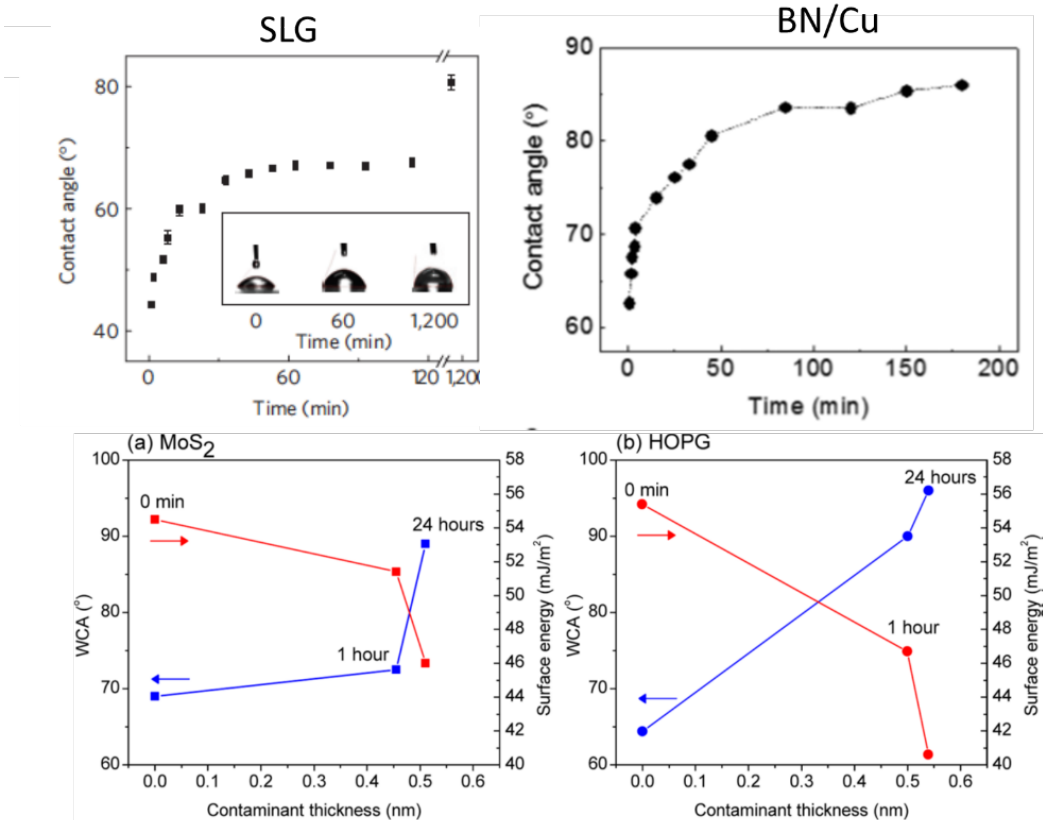

Figure 2. Evolution of WCA in time a) SLG on copper [10] b) BN/Cu [11] c) MoS_2 [12] d) HOPG [12].

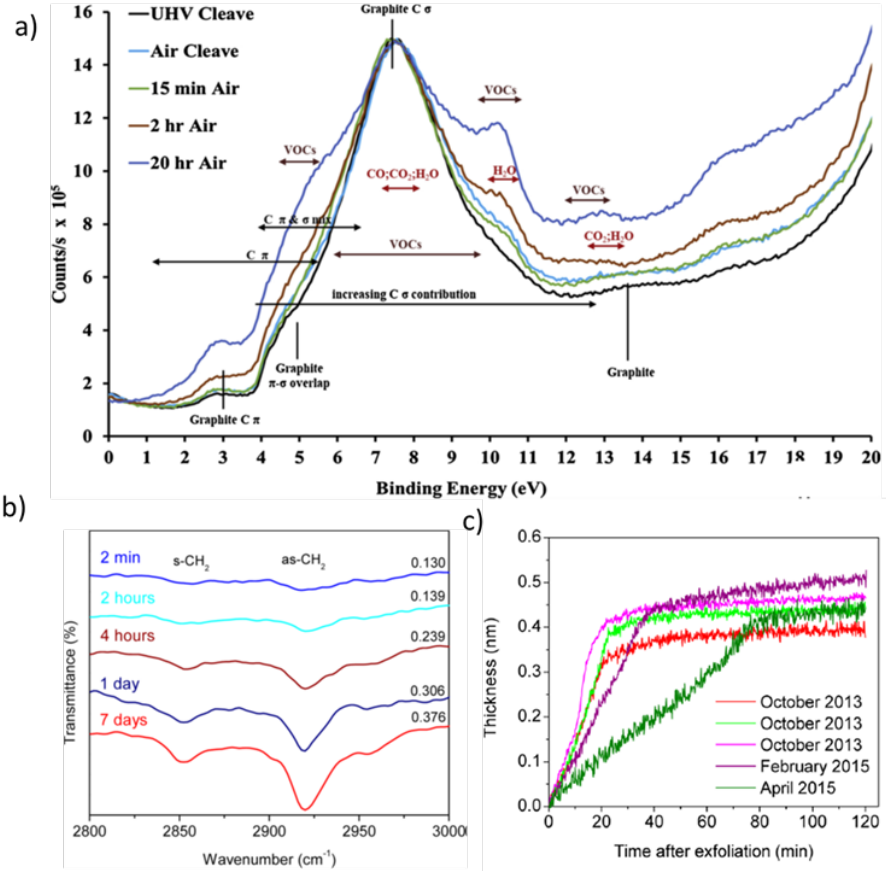

Figure 3. Investigation of surface change due to exposition on ambient air: a) ATR-FTIR of graphite [16] b) UPS of HOPG [6] c) Impact of weather and season on deposit thickness measured by ellipsometry [12].

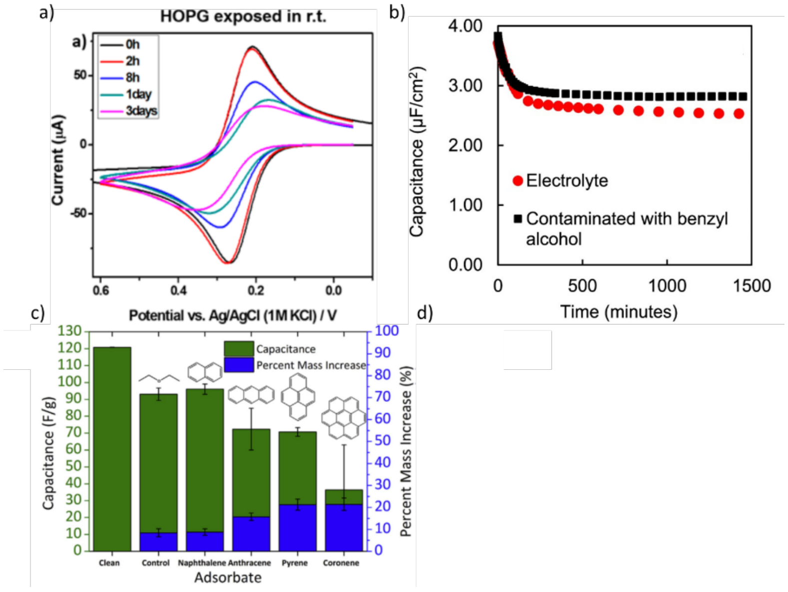

Figure 4. a) Evolution of voltammetry curve in time due to deposition of hydrocarbons [14] b) aging HOPG supercapacitor in 1 M NaCl solution and with addition benzyl alcohol [7] c) capacitance of active carbon with PAH deposit [21].

3. Effect of environmental contaminants on supported IL 2D materials

Over the past decades, unique physicochemical properties of ionic liquids (IL), e.g, thermal stability, nonvolatility, electrochemical stability, etc., received enormous attention allowing numerous applications in the field of lubrication and catalysis. Exploring the molecular-level structure of IL is critical since nanometer-thick films of IL are applied to a solid substrate, e.g, mica, silica, sapphire, etc [22-24]. The role of surface contamination leads the nature of the molecular-level structure of IL was uncovered by Gong et al. on the mica surface [13]. While the mechanisms of why the same IL exhibit different structure reported by different research groups are still under debate [25], understanding the effect of environmental contaminants on IL/solid interface promotes the development of IL for all potential applications. Gong et al. reported the importance of water adsorption on the mica surface to the formation of the extended layering of ionic liquids [13]. This finding challenges the general acceptance of the electrostatic interaction as the major factor towards extended layering [24, 26]. The underlying mechanism resulting in the extended layering effect proposed that water adsorbed on the surface enables ion exchange between potassium ion (K^+) and the cations of IL on the mica surface. Furthermore, ever since the adsorbed water molecules have been replaced by hydrocarbons and covering the mica surface, dissociation of K^+ ions will become impossible. Consequently, hydrocarbon contaminants induce the transformation of the dewetting structure of IL. The transfer from extended layering to the dewetting structure was captured by the ATR-FTIR spectrum, Figure 5 (left), that the water molecules were removed at 120 °C and hydrocarbons were replacing the water molecules after heating indicated by the CH_2 and CH_3 peaks [13, 24]. This result was further confirmed by WCA measurements, Figure 5 (right), that when the mica surface was covered by water, BMIM-FAP showed an extended layering structure [13]. However, if hydrocarbon contaminants were present on the mica surface, BMIM-FAP displayed a droplet (dewetting) structure. Both FTIR and WCA measurements demonstrated the competition between water and hydrocarbons on the IL/solid interface which led to the hypothesis that the K^+ ion exchange event only occurs if a layer of water is present on the mica surface as shown in Figure 6 [13]. The negatively charged surface then will interact with cations from the IL which induces the ordered packing of IL to result in the extended layering structure. This study initiated the research interest to discover the whole picture of the extended layering effect of IL on the mica surface [13].

The significance of water molecules leading to the extended layering effect of IL on the mica surface was further confirmed by another research group [27, 28] indicating adsorbed water as the key parameter for the event. In order to systematically study the effect of adsorbed water on the mica surface, humidity control experiments would provide evidence for the controlled molecular arrangement of IL on the mica surface and other potential solid surfaces. In this direction, Gong et al. further investigated relative humidity (RH) effects on the extended layering structure of IL on mica surfaces [25]. The results illustrated the wetting behavior at the nanoscale level changed dramatically with RH using AFM. At low RH, below 50%, dewetting or droplet structure was observed. As RH gradually increase, more network-like "terraces" representing extended layering structures of BMIM-FAP appeared. The mica surface was completely covered by BMIM-FAP with total wetting of nanoscale IL [25]. The "water-enabled surface charging" mechanism could explain this finding. Due to low dielectric constants, IL cannot dissolve and remove K^+ ions effectively from the mica surface which leads to surface charging. Water molecules, indeed, have a high electric constant that can induce surface charging by detaching K^+ ions from mica to leave empty sites on the surface [29]. Higher RH would increase the chance of K^+ ions being dissociated from the surface. The detachment of K^+ ions converts the mica surface to become negatively charged which can be easily occupied by cations of the IL. The replacement of K^+ ions with IL cations initiates the alternative layering of cation/anion of the IL. Therefore, extended layering structure only occurs in high humidity conditions. Whereas at low humidity, although IL nanodroplets exhibit layered structure, due to weak mica-IL interaction, solid-like IL with very low mobility at the nanoscale level identified as no terrace-like flow was observed [29]. In addition, Cheng et al. reported IL became disordered in relatively low humidity environments on the low-charged surface by AFM force-distance experiments [28]. Not only restricted to mica surfaces, but similar events also emerged on silica surfaces where water promotes surface charging through the dissociation of Si-OH groups induces layering structures, and reduces the coefficient of friction at high RH [23].

Besides the "water-enabled ion exchange" mechanism, another hypothesis is the "water-assisted self-assembling" of IL shown in Figure 7 [24, 26]. Via attachment by hydrogen bonding, water promotes the self-assembling event of IL which enables the segregated polar and non-polar domains to form an extended polar network in a bulk environment [26]. Similarly, the same event could also occur at the IL/mica interface where IL packing initiates on the mica surface (flat template), thereby, leading to extended layering structure on the mica surface [25, 26].

Meanwhile, the principle of extended layering structure of IL on solid surfaces remains elusive. The complexity of functionalized IL with different task-specific functional groups will create dissimilar results. Other research reported humidity or the presence of water disrupts the layering event on the mica surface due to molecular size differences [30]. Water concentration at the IL/solid interface could also be a key factor that causes diversity to show different behaviors [13].

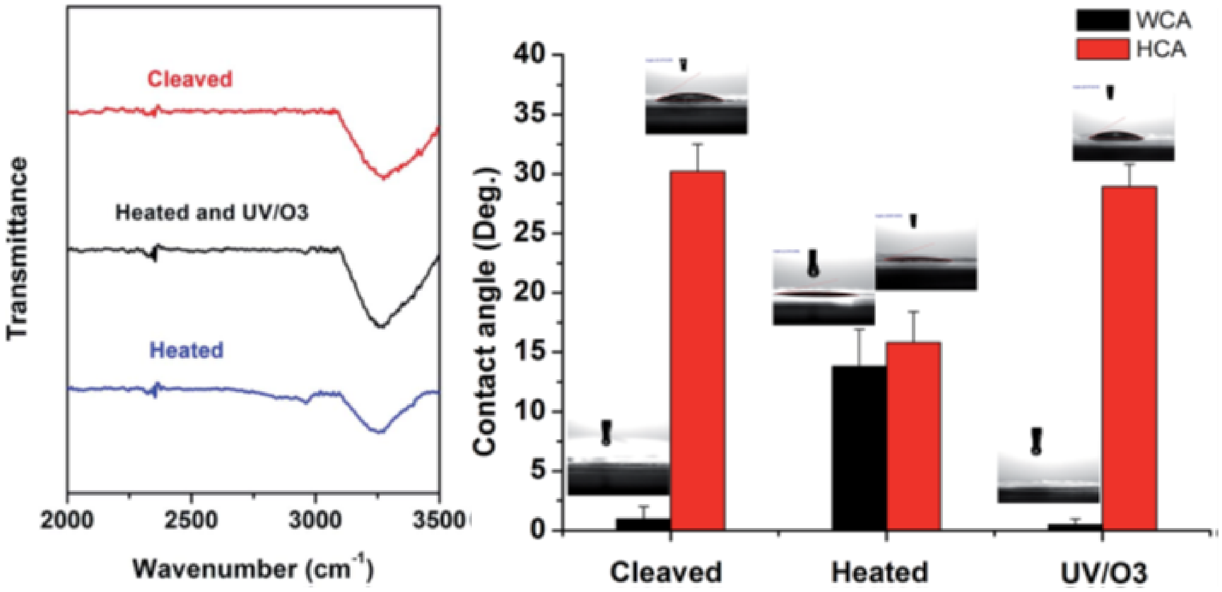

Figure 5. (Left) ATR-FTIR of freshly cleaved mica (red), heat-treated (1 h at 120˚ C) mica (blue), and heat-treated mica with UV/O_3 treatment (black). (Right) WCA and HCA on freshly cleaved mica, heat-treated (1 h at 120˚ C) mica, and heat-treated mica with UV/O_3 treatment [13].

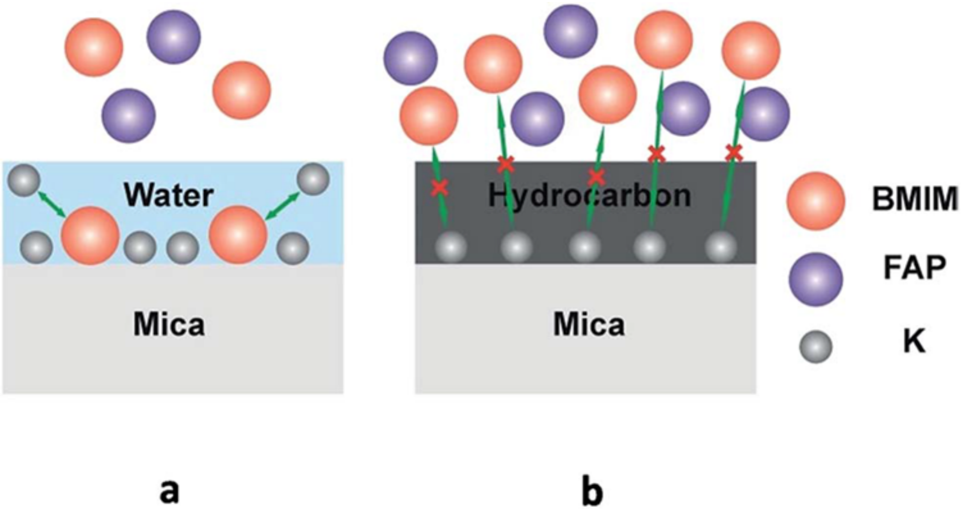

Figure 6. (a) Schematic of ions exchange at the freshly cleaved mica surface (b) schematic of ions exchange blocked at the heated mica surface [13].

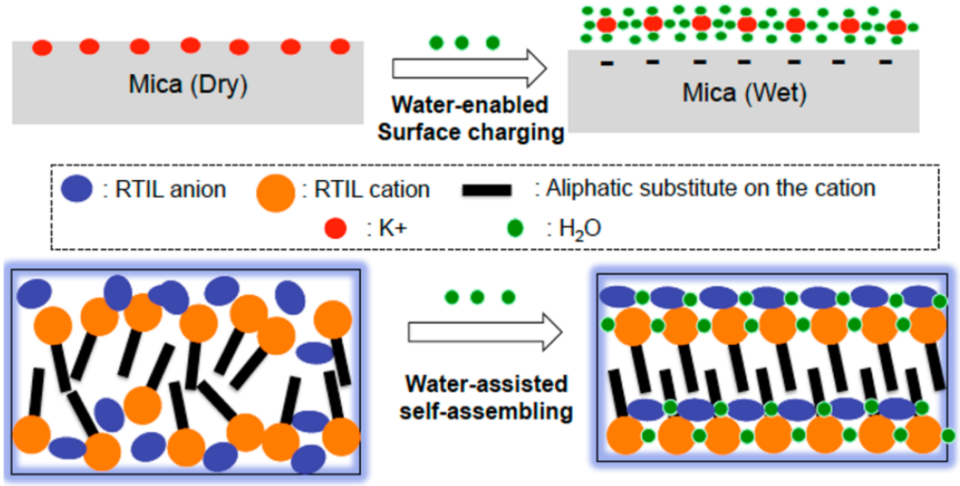

Figure 7. Schematic of the effect of adsorbed water on the layering of room temperature ionic liquid on the mica surface [24].

4. Other environmental effects or impacts

It was mentioned in chapter 2 that humidity is one of the principal factors that have influenced VOCs deposition. The presence of water on the HOPG and graphene surface slows the adsorption process of the hydrocarbons, thus the exposed materials for air contamination are longer hydrophilic. Moreover, the electrical properties of 2D materials are decreasing much slower due to this surface contamination [17, 20]. According to proposed the mechanism water (Figure 8a) created a thin film on the 2D carbon surface, which is next replaced by higher molecular weight hydrocarbons [14, 20, 21]. What is more, this process can be slowed down by storage at low temperatures. Furthermore, electrochemical properties can be preserved. Figures 8b and 8c show that electrodes, which are stored at -15 °C for 1 day, have the same curves and ΔEp as "fresh" [14]. – Moreover, the adsorbed water onto the active carbon surface might be a cause of increasing capacitance of supercapacitor during storage on lab shelf (Figure 8d) [7].

On the other hand, the high humidity causes the creation of hysteresis behavior in field-emission transistors (FETs) made of exfoliated graphene [31] and MoS_2 [32]. This topic was deeply described in our previous publication [4]. In short, to occur this behavior of FETs needs oxygen, which is necessary to create O_2/H_2O redox (one of the possible mechanisms) and doping effect. For samples treated with vapor water, the effect was not observed [4]. This was exclaimed that adsorbed water changed trapping charge and has impact for mobiles ions, thus H_2O is not doping the surface. However, it presents to enhance the effect of doping created by O_2. It was observed that stored in several mouths of MoS_2 and WS_2 in the presents of water and oxygen causes cracking and quenching (corrosion) of these 2D materials [33]. It was also observed that water can diffuse between the graphene layer and SiO_2 (support substance) and causes moves or rolling of graphene onto the surface [34].

Oxygen from the air is a p-type doping agent for 2D materials like graphene [35], MoS_2 [31], and WS_2 [32]. Figure 9a proved that nitrogen and argon don't have an impact on the Fermi level of graphene (lack of change in D peak area and significant Raman shifts of G peak) and the O_2, which is part of dry air, doped carbon nanomaterial [35]. Most of the thin materials like graphene, monolayer MoS_2, or WS_2 are deposited on the base due to their synthesis way and mechanical properties [19, 32]. The effect of the base is well visible for thin materials such as graphene and it causes two main phenomena: doping and wetting transparency. Figure 9b shows the impact of Fermi level (work function) on wettability – change of electron/hole density causes an increase of hydrophilicity. The mechanism is not clear. It has also a high impact on charge mobility and electrical conductivity [36]. Wetting transparency can be observed on CA measurements. Figure 9c presents that WCA for single-layer graphene (SLG) deposited on superhydrophilic hydrogel is ~10° for less hydrophilic copper is 80°. The calculated surface energy for support substances with/without graphene is similar – SLG does not have a significant impact on WCA value. However, bi-/multilayer graphene has bigger values of WCA. Thus in the case of thin materials, CA is directly dependent on base surface character – hydrophilic substances degrease CA for polar liquid and hydrophobic for nonpolar [37]. All of the described phenomena can be used for explaining the surface properties modification and should be considered during creating a research plan or analysis of the experimental results.

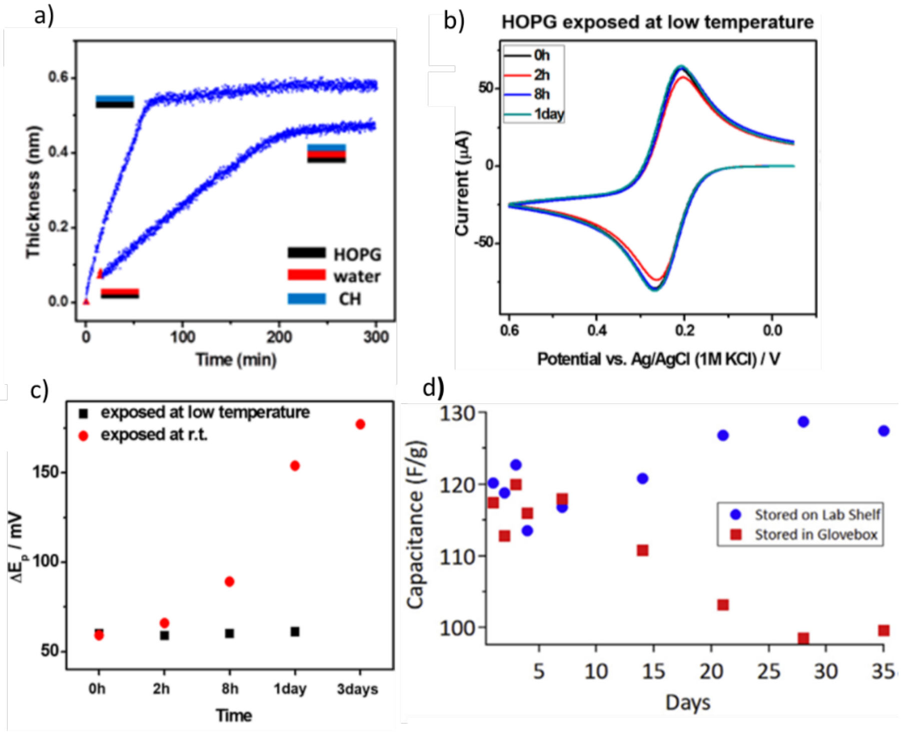

Figure 8. Water impact on properties on 2D materials: a) role of water in mechanism hydrocarbons deposition [7] b) graphs present changing CV curses of samples stored in low-temperature (-15 °C) in time c) effect of temperature on peak separation [14] d) capacitance of samples stored in lab shelf and glovebox [21].

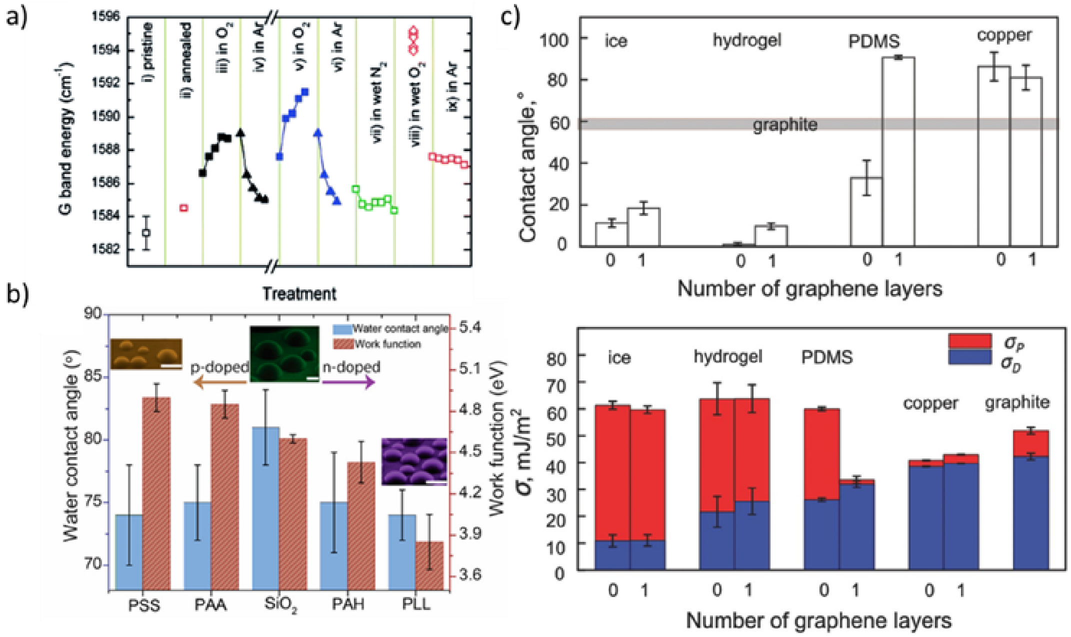

Figure 9. Graphs present a) maximum of G peaks shift caused by air and its parts for graphene [33] b) impact of doping on the wettability of graphene [34] c) effect of base for water contact angle and surface energy on graphene monolayer [35].

5. Remove and avoid environmental contamination

Removal and inhibition of environmental contaminations are crucial when studying high-energy solid surfaces because surface properties are highly impacted by contaminants adsorbed on the substrate. Simple, cost-effective, and scalable methods are preferred to treat particular surfaces allowing the original state to return. For graphitic 2D materials, surface treatments mainly focused on hydrocarbon removals. For instance, HOPG samples were placed inside ultra-high vacuum (UHV) chambers for 15 hours allowing the surface to become hydrophilic rather than hydrophobic if exposed to ambient air, Figure 10a [6, 16]. Simple UV/Ozone treatment for 5 minutes can effectively remove 1-octadecene hydrocarbon adsorption on HOPG and graphene, Figure 10b [16, 38]. Both UHV and UV/Ozone treatment would have a similar impact on the surface which the surface will maintain its hydrophilicity (below 60° WCA) right after the treatment for a short period but will quickly return to hydrophobic (above 80° WCA) after a few minutes of exposure to ambient air. Other methods suchlike thermal annealing at 550 °C in Ar cause contaminated graphene samples to regain their hydrophilicity to 55° WCA and again back to 80° WCA with subsequent air exposure [21, 38]. High-density H_2 & Cl_2 plasma treatment which provides large fluxes of reactive radicals and ions is reported to efficiently clean graphene [15, 39]. A simple and non-invasive method of dry-cleaning treatment developed using activated carbon can produce large-scale atomically clean single-layer graphene [40]. However, the above-mentioned methods are only effective when dealing with graphitic surfaces. Cleaning other surfaces, like mica, simple annealing, and UHV treatments may not be the solution [41, 42]. Despite contamination-free mica sheets can be prepared by hot-wire cutting method, inhibiting airborne contaminants adsorbed on the surface should be considered to retain the nature of the surface [43]. Therefore, developing technologies for inhibiting environmental contaminations on 2D materials should receive equal attention as contamination removal techniques. A currently available inhibition method is to use simple water treatment or exposure to low temperature causing a nanometer-thick water layer to cover the surface which is reported to effectively prevent hydrocarbon contamination on graphitic surfaces [14, 21, 38].

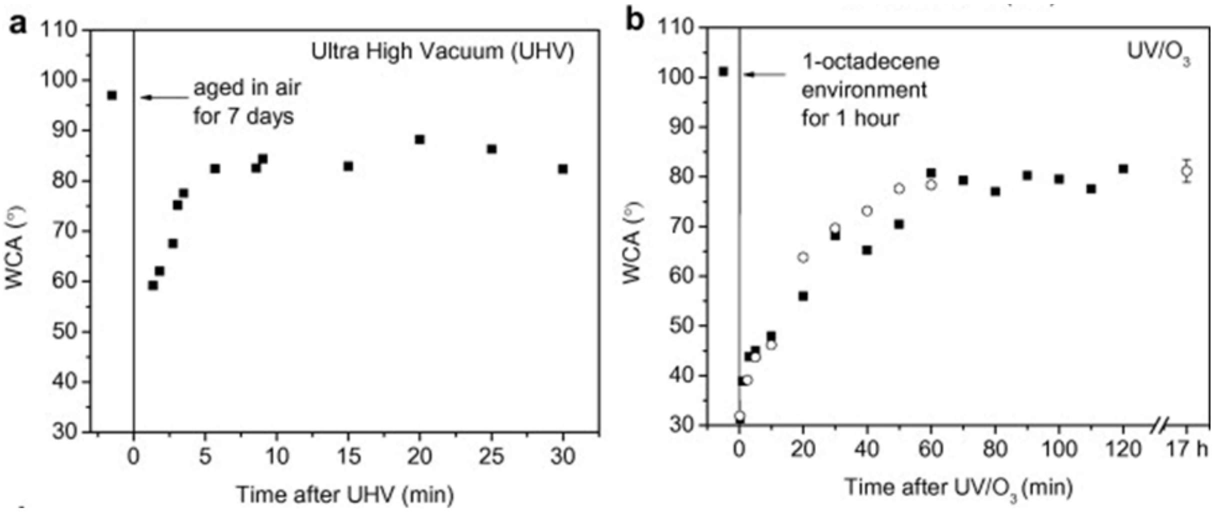

Figure 10. (a) WCA of exfoliated HOPG exposed to ambient air for 2 weeks then ultra high vacuum (UHV) for 15 h. Solid line indicates UHV treatment. (b) WCA of exfoliated HOPG exposed to UV/O3 for 5min. Solid line indicates UV/O3 treatment [16].

6. Conclusion and outlook

- The high impact of environmental contaminants on interfacial properties of above covered 2D materials
- Research gap - lack mechanism of wetting transparency and impact environmental contaminates on its problem with characterization
- Lack of defining the structure of hydrocarbons/VOCs/PAHs
- “Natural mystification” – hiding true character properties of 2D materials
- New potential application of pure 2D materials due to enhance properties after removing contaminations
- Development of new methods for surface characterizations

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