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Journal:	*ACS Nano*
Manuscript ID:	Draft
Manuscript Type:	Article
Date Submitted by the Author:	n/a
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Towards the Microscopic Identification of Anions and Cations at the Ionic Liquid | Ag(111) Interface: A Combined Experimental and Theoretical Investigation

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ABSTRACT

The interaction between an adsorbed 1-butyl-1-methylpyrrolidinium bis(trifluoromethylsulfonyl)imide [BMP][TFSA] ionic liquid (IL) layer and a Ag(111) substrate, under ultrahigh vacuum (UHV) conditions, was investigated in a combined experimental and theoretical approach, by high-resolution scanning tunneling microscopy (STM) and dispersion corrected density functional theory calculations (DFT-D). Most important, we succeeded in unambiguously identifying cations and anions in the adlayer by comparing experimental images with submolecular resolution and simulated STM images based on DFT calculations. Different adlayer phases include a mobile 2D liquid phase at room temperature and two 2D solid phases at around 100 K, i.e., a 2D glass phase with short-range order and some residual, but very limited mobility and a long-range ordered 2D crystalline phase. The mobility in the different adlayer phases, including melting of the 2D crystalline phase, was evaluated by dynamic STM imaging. The DFT-D calculations show that the interaction with the substrate is composed of mainly van der Waals and weak electrostatic (dipole-induced dipole) interactions, and that upon adsorption most of the charge remains at the IL, leading to attractive electrostatic interactions between the adsorbed species.

KEYWORDS: Ionic liquids, scanning tunneling microscopy, density functional theory, surface chemistry, self-assembly, molecule-molecule and molecule-substrate interactions

Submitted to ACS Nano, **.RECEIVED DATE (…)**

TITLE RUNNING HEAD: Identification of anions and cations of an ionic liquid adlayer on Ag(111)

1. Introduction

Ionic liquids (ILs), which are molten salts usually consisting of organic ions with a melting point below 100°C,[1,2] have attracted considerable interest in recent years because of their unusual physicochemical properties such as high ionic conductivity and electrochemical stability, very low vapor pressure, or low flammability. Due to the large variety of combinations of different anion-cation pairs, the properties of the ILs can be adjusted over a wide range, making them highly interesting molecular building blocks for both fundamental research and specific applications.[1-4] One very interesting application is their use as solvent in electrochemical energy storage, where ionic liquids could replace standard solvents in lithium ion and lithium air batteries.[5-8] They are also discussed as support-modifying functional layers in heterogeneous catalysis.[9,10] For the successful transfer into application, it would be highly desirable to understand the processes at the IL | solid and IL | vacuum interface on a fundamental level, at the molecular scale. As one important point, this includes the various aspects of structure formation of ILs on flat surfaces, as a model for the IL | solid interface.

In this paper we report results of a combined experimental and theoretical study on the adsorption and structure formation behavior of the anion-cation pair 1-butyl-1-methyl-pyrrolidinium bis(trifluoromethylsulfonyl)imide [BMP][TFSA] on Ag(111) under ultrahigh vacuum (UHV) conditions in the sub-monolayer to monolayer range, applying high resolution scanning tunneling microscopy (STM) and dispersion corrected density functional theory (DFT-D) calculations.[11] Despite numerous investigations, conducted both *in situ*, in an electrochemical environment [12-16] and *ex situ* under UHV conditions,[9,10,17-27] studies on the interaction of IL monolayers with single crystalline surfaces are rare. Cremer et al. studied the adsorption of 1,3-dimethylimidazolium bis(trifluoromethylsulfonyl)imide [MMIM][TFSA] and 1-methyl-3-octylimidazolium bis(trifluoromethylsulfonyl)imide [OMIM][TFSA] ionic liquid on Au(111) by angle-resolved X-ray photoelectron spectroscopy (ARXPS) and concluded that at a coverage of up to 1.0 ML both anions and cations are in direct contact with

the surface, presumably in an alternating arrangement.[28] (Note that the authors of that study defined a coverage of 1 ML as a saturated layer of anions and cations on top of each other, while in the present study we define the coverage by using the number of adsorbed ions at saturation of that layer as reference. This requires to multiply the coverages from the above group by a factor of 2, which is done in the following.) In contrast to the findings for Au(111), they found for [MMIM][TFSA] adsorption on Ni(111) that up to coverages of ~0.80 ML the ions are vertically aligned, with the imidazolium cation directly on the Ni surface and the corresponding anion on top of it.[26] By analysing infrared reflection absorption spectroscopy (IRAS) measurements with the help of density functional theory (DFT) calculations, Sobota et al. concluded that at sub-monolayer coverages the adsorption geometry of an imidazolium based IL on Al_2O_3/NiAl(110) is likely to be a *cis*-conformation for $[TFSA]^-$ anions, with the SO_2 groups attached to the substrate.[29]

In a very first molecular resolution STM investigation, a short-range ordered structure was resolved for the 1-butyl-1-methylpyrrolidinium tris(pentafluoroethyl)trifluorophosphate [BMP][FAP] ionic liquid on Au(111) under UHV conditions at 200 K.[30] Molecular objects in form of dots could be identified, which could be either ion pairs in a double layer arrangement or individual ions, with both ions in contact to the surface. More recently, STM measurements by Foulston et al. [31] on 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide [EMIM][TFSA] adsorbed on Au(110) resolved molecular entities, which they assumed to consist of closely associated ion pairs . However, in neither of these cases was it possible to distinguish and to molecularly identify anions and cations by STM imaging. For a detailed molecular scale understanding of the processes at the IL | solid interface, this would be highly desirable, together with a similar understanding of the nature of the substrate – adsorbate and adsorbate – adsorbate interactions. This is topic of the present work, where the combination of high resolution STM imaging with sub-molecular resolution and density functional theory based calculations allows for an unambiguous identification of the different adsorbed species

and gives detailed insight into the bonding situation of the adlayer, including both substrate – adsorbate and adsorbate – adsorbate interactions. To the best of our knowledge, this is the first time that individual ions could be resolved and identified in an IL adlayer.

2. Methods

2.1 Experimental Methods

The STM experiments were performed in a two chamber UHV system, at a background pressure in the low 10^{-10} mbar regime. The microscope is an Aarhus type STM (SPECS Aarhus STM 150), which allows to measure at variable temperatures between 100 K and 400 K by cooling with liquid nitrogen and resistive heating. The tunneling current was between 20 pA and 150 pA and the applied bias voltage between -0.1 V and -1.5 V referred to the sample. The images were recorded in constant current mode. Variable temperature STM experiments were conducted with a heating rate of ~0.5 K/min. The Ag(111) single crystal was purchased from MaTecK, the ionic liquid [BMP][TFSA] from Merck in ultrapure quality. Clean Ag(111) surfaces were prepared by Ar^+-ion sputtering (500 eV) and annealing to 770 K. Prior to deposition on Ag(111), [BMP][TFSA] was degassed in UHV for at least 24 hours in a previously baked out crucible. The ionic liquid was evaporated onto the Ag substrate held at room temperature (RT) with a commercial Knudsen effusion cell for organic molecules (Ventiotec, OVD-3), which was heated to 373 K. The evaporation rates were previously checked by a quartz micro balance. The sample was cooled down to a temperature of roughly 100 K in the time span of 2-3 hours before the STM measurements.

2.2 Calculational Methods

Periodic DFT-calculations were performed using the exchange-correlation functional of Perdew, Burke and Ernerhof (PBE) [32] as implemented in the Vienna *ab initio* simulation package (VASP).[33,34] In order to account for dispersive interactions missing in the exchange-

correlation functionals of the generalized gradient approximation (GGA), we employed Grimme's correction scheme of 2010 (DFT-D3).[11] It has recently been shown that this approach yields reliable adsorption energies and structures for organic molecules and hydrogen-bonded networks on metal surfaces.[35-37] Ion cores are represented by means of the projector augmented wave (PAW) method.[38,39] The electronic one-particle wave functions were expanded in a plane wave basis set up to an energy cut-off of 400 eV.

The Ag(111) surface was represented by a slab consisting of 3 metal layers, separated by a vacuum region of about 25 Å. To model the adsorption of one cation-anion pair at the surface, we chose a Ag(111)-(5x5) overlayer structure with one adsorbed cation-anion pair per unit cell. For the integration over the first Brillouin zone a 2x2x1 Monkhorst-Pack k-point mesh [40] with a Methfessel-Paxton smearing of 0.1 eV was employed. The geometry of the adsorption complex was optimized by relaxing all atoms of the IL pair and the atoms of the uppermost layer of the metal surface. Only these atoms were taken into account for the evaluation of dispersive interactions.

STM simulations are based on the Tersoff-Hamann approximation.[41] Within that model the tunneling current is proportional to the local density of states (LDOS) at the surface close to the Fermi energy at the position of the tip. Constant-current images are simulated by an isosurface of the LDOS integrated between the Fermi energy of the system and the sample bias.

Isolated molecules have also been calculated using the GAUSSIAN09 code [42] in connection with the atom centered basis set aug-cc-pVTZ.[43-45] For isolated molecules no dispersion corrections have been employed.

3. Results and Discussion

To begin with, we discuss the adsorption behavior of [BMP][TFSA] on Ag(111) based on large-scale STM images at sub-monolayer and monolayer coverages. STM images recorded at 300 K do not allow us to resolve single IL entities. Instead, stripy features appear, which are not observed on the clean Ag(111) surface (SI I). Therefore these features are related to adsorbed IL entities in a 2D gas / 2D liquid adlayer that diffuse rapidly on the time scale of the STM experiment and can therefore not be resolved.[46-48] Similar observations were reported by Waldmann et al. for room temperature imaging of [BMP][FAP] ionic liquid adlayer on Au(111) [30] and by Foulston et al. for [EMIM][TFSA] on Au(110).[31]

In Figure 1 we present constant current STM images recorded at sub-monolayer (Figure 1a) and monolayer coverage (Figure 1b) at around 100 K, where a monolayer is defined as the coverage required to completely cover the surface. Figure 1a shows four silver terraces (depicted as *I, II, III, IV*), which are covered with the adsorbed IL species in different ways. On terrace *I*, we find a large, long-range ordered and homogeneous adsorbate phase without any internal domain boundaries. These large ordered domains are solely observed on large silver terraces; small domains or islands of that phase, separated by domain boundaries or other phases, have not been observed. These domains are referred to as an ordered 2D crystalline phase. Note that at large terraces, at least close to the steps, we also observed regions where the IL adsorbates are arranged in a disordered way, which will henceforth be referred to as 2D glass phase. Terrace *II* (Figure 1a), which is only ~10 nm wide, shows an apparently uncovered, adsorbate free region, at least there is no adlayer structure visible, neither ordered nor disordered. Noisy features in the fast scanning direction are again attributed to highly mobile adsorbed species, i.e., also this area is not free of adsorbates. At the left side of terrace *II*, two islands with arbitrary shapes grow from the step. At the present resolution, these islands consist of single dots, which are arranged in a disordered way (see below). Terrace *III* (Figure 1a) shows a larger region covered with a disordered 2D phase,

which extends from the left to the right step. Finally, terrace *IV* (Figure 1 a) is nearly completely filled with the disordered 2D phase.

Successively increasing the coverage (Figure 1b), the 2D crystalline phase is exclusively found on the large terraces; in addition, also disordered regions are found on large terraces close to the steps. Narrow terraces (~10 nm width) in Figure 1b are now completely filled up with the disordered 2D phase. As the influence of the steps is much larger at narrow terraces, it is likely that the interaction with these defects is responsible for the formation of the disordered 2D phase, inhibiting the ordering process. In large-scale STM images, three orientations of the 2D crystalline phase are found (only one orientation per terrace (SI II)), whose orientation differs by multiplies of 120°. Hence, these domains are rotationally aligned with the underlying Ag(111) surface lattice. The observation that large terraces are largely occupied by large and homogeneous ordered domains points towards (weakly) attractive adsorbate-adsorbate interactions.

Next we concentrate on the dynamic behavior of [BMP][TFSA] on Ag(111) at 100 K. Figure 2 shows the boundary between an ordered 2D crystalline phase and an adjacent 2D liquid phase, which typically appears frizzy (Figure 2a). Such frizzy features are generally due to surface mobility at the phase boundary. Even though we used a high tunneling resistance ($R_t \sim 2 – 44$ GΩ), we can not totally exclude tip induced effects. Time sequences of STM images were acquired and selected images from two series are shown in Figs. 2b and 2c. The time interval from image to image was ~ 25 s in Figure 2a and ~6 s in Figure 2b. The main finding is that the interior of the domain remains stable over time, while the location of the phase boundary changes gradually. This behavior can be explained by a 2D adsorption-desorption equilibrium at the phase boundary. The IL entities in the 2D liquid phase are highly mobile and can not be resolved.[46-48]

Dynamic STM measurements were also performed at regions of the surface where both the ordered 2D crystalline phase and the disordered 2D phase coexisted. Selected images extracted from the time lapse movie (see SI III) are shown in Figure 3. On the right terrace, the features in the ordered 2D crystalline phase remain highly stable over time. As in Figure 1a, disordered regions are found close to the step. On the left terrace, the STM time sequence shows that an apparently uncovered region successively fills up with IL species in the disordered 2D phase, i.e., the phase boundary changes with time. As discussed before, the stripy features in the fast scan direction are presumably due to highly mobile adsorbed IL species in a 2D liquid phase.[46-48] Thus, there is exchange of adspecies at the boundary between disordered 2D phase and 2D liquid. In contrast to the 2D crystalline phase, the adsorbed species in the disordered 2D phase are not fully immobile; infrequent molecular jumps are observed. We assume that both the interaction with the steps and the absence of strongly attractive adsorbate-adsorbate interactions prevent the adlayer from ordering on small terraces. As described before, even at low temperatures of around 100 K we did not observe small islands of the ordered [BMP][TFSA] adlayer phase on Ag(111), but just larger ordered areas.

In similar time-resolved measurements we could resolve the 2D melting of the 2D crystalline phase. The results were acquired by applying “slow” linear heating ramps (~0.5 K/min), starting from an initial temperature of around 100 K. This way, we could reproducibly determine a 2D melting temperature of the ordered 2D crystalline phase of 180 ± 10 K. Above 180 K, we observed stripy features, which are attributed to a 2D liquid adlayer (SI IV). The ‘melting’ temperature of the 2D glass phase is presumably slightly lower than that of the 2D crystalline phase; an accurate value can not be given. However, extrapolating the intrinsic motion in this phase at 100 K to higher temperatures, a lower melting point compared to the ordered 2D crystalline phase seems plausible. In a more general sense, the presence of long-range ordered islands with a low melting point and their equilibrium with a surrounding 2D

liquid phase point to weakly attractive adsorbate – adsorbate interactions and a low barrier for surface diffusion.

We now focus on the structure of the stable, ordered 2D crystalline phase. The high resolution STM image of this phase in Figure 4a resolves an alternating sequence of pairs of longish protrusions and round dots, where the latter are indicated by symbols in the STM image. The dimensions of the unit cell are $|a| = 2.3 \pm 0.1$ nm and $|b| = 1.1 \pm 0.1$ nm and $\alpha = 95 \pm 3°$, with two dots and four longish protrusions per unit cell. Hence, the ratio of dots to longish protrusions is 1 : 2 (Figure 4b). The pairs of longish protrusions as well as the dots are aligned along one of the lattice vectors, with always one line of dots followed by one line of longish protrusions. Between successive lines of longish protrusion their orientation changes by ~120°. This together with the observation of three rotational domains indicate that the adlayer is symmetrically aligned with the Ag(111) surface, with the lines oriented along the close packed directions of the Ag(111) surface.

Despite of the detailed structural information gained from the STM data, it is not possible to identify the origin of the different features from these images alone. Further insight comes from DFT-D calculations, which provide a detailed understanding of the anion-cation adsorption complex and can explain the appearance in STM images for the given tunneling conditions. However, both the cation and the anion have many possible conformations at the surface due to rotation around C-C, N-C or S-C single bonds. In order to reduce the number of possible starting conformations of the adsorption structure of the IL pair, we will first analyze the most stable conformations of the isolated cation and the isolated anion. Especially for the cation, the orientation of the alkyl chain may have a strong impact on the appearance in the STM image and/or the packing density of the molecules at the surface. In the gas phase, the 5-membered ring of $[BMP]^+$ adopts an envelope conformation in which the butyl group either occupies the axial position (as shown in Figure 5a) or the equatorial position, i.e., the butyl group is either perpendicular or parallel to the cyclopentane ring. For the isolated cation, the

equatorial position is about 18 meV more stable. As this energetic difference is rather small and the actual conformation at the surface may depend on the coverage, the conformer with the butyl group in the axial position was considered as well. On the other hand, it should also be considered that the axial position, with the butyl group sticking up when the imidazol ring is parallel to the surface, would allow a higher packing density.

To identify the most probable locations for the attachment of an anion, we evaluated the electrostatic potential at an isosurface of the total charge density of the $[BMP]^+$ cation (see Figure 5a). The blue regions reveal the most positive electrostatic potential experienced by a positive test charge, i.e., they indicate the regions where a negative (partial) charge would attach preferentially. In contrast, the red regions reveal the least positive electrostatic potential a positive test charge would experience. Accordingly, the anion most probably attaches in the middle of the triangle formed by the hydrogen atoms of the α-C-atoms.

For the isolated $[TFSA]^-$ anion, two stable conformations are obtained. In the first one, the CF_3 groups are both located above (or below) the S-N-S plane, which is subsequently denoted as *cis*-conformation. In the second conformation, which is accordingly termed as *trans*-conformation, one CF_3 groups is above and the other one below the S-N-S plane. The *trans*-conformer is about 40 meV more stable than the *cis*-conformer. Additionally, the rotational barrier that needs to be overcome for transferring from the one into the other conformer is rather small, in the range of 50-100 meV. Sobota et al. reported for an imidazolium based ionic liquid that in the multilayer both the *cis*- and the *trans*-conformers of $[TFSA]^-$ coexist, whereas in the monolayer the *cis*-conformer is found on a Al_2O_3/NiAl(110) support.[29] Considering the adsorbed ionic liquid rather than an individual anion, two additional factors may affect the relative stability of the respective conformers: the interaction with the counter ion, here the cation, and the interaction with the surface. Due to these interactions, even quite different conformers might be involved in the most stable complexes. Similar to the procedure for the $[BMP]^+$ cation, the electrostatic potential is calculated at and mapped onto an

isosurface of the total charge density of the $[TFSA]^-$ anion (see Figure 5b) to estimate possible positions of attached cations. For both the *cis*- and the *trans*-conformation (not shown), the most attractive regions for positive charges (red regions) are within the S-N-S plane. In order to probe the possible changes in the stability induced by an attached cation, we choose the alkali metal ion Li^+ as a simple model. Both the *cis*- and the *trans*-conformers of $[TFSA]^-$ lead to stable complex structures with the alkali metal cation. Due to the similar stabilization of both $[TFSA]^-$ conformers upon interaction with the cation, the *trans*-conformer is more stable than the *cis*-conformer also in a cation-anion complex.

To elucidate effects resulting from the interaction with the substrate, we first explore the adsorption of $[TFSA]^-$ on Ag(111). In that case, the *trans* conformer leads to the most stable adsorption structure, being about 0.2 eV more stable than the metastable *cis*-conformer. Both the *cis*- and the *trans*-conformer adsorb with their respective dipole moment aligned normal to the surface, with the negatively charged end of the molecule oriented towards the surface. The adsorption distances of both conformers are comparable as well. The distance between the average z-position of the O-atoms (only 2 atoms are taken into account in the case of the *trans*-conformer) and the Ag-atoms of the topmost surface layer is 2.472 Å and 2.717 Å for the *trans*- and *cis*-conformer, respectively.

Although we have worked out stable anion and cation conformations in the gas phase and at the surface, there are still many possibilities for the structure at the surface. In the following we restrict the discussion to only one possibility that has been found to be theoretically stable and that is compatible with our experimental results. A valuable experimental input is that the appearance and the size of the unit cell of [BMP][TFSA] on Ag(111) and others which we observed for related ILs with different alkyl groups ([EMIM][TFSA], [OMIM][TFSA]) are nearly identical, which is a strong indication that the alkyl chain of the cation adopts the axial position, pointing towards the vacuum. Furthermore, there is also some information about the adsorption structure of similar ionic liquids on Au(111) by angle resolved x-ray photoelectron

spectroscopy (ARXPS).[28] According to the ARXPS measurements for [MMIM][TFSA] adsorbed on Au(111), both the cation and the anion are in contact with the surface.[28] The authors of the above study also proposed that the oxygen atoms of adsorbed $[TFSA]^-$ are pointing towards the surface, whereas the fluoromethyl groups are directed towards the vacuum. These experimental findings suggest that the butyl group of adsorbed $[BMP]^+$ adopts the axial position and the *cis*-conformer of adsorbed $[TFSA]^-$ is present in the monolayer of [BMP][TFSA] on Ag(111). Albeit, as shown above, both this conformation itself and its adsorption are less stable than that of the *trans*-conformer, it might still lead to a more stable structure of the total adsorption complex due to more favorable adsorbate – adsorbate interactions, as the electrostatic potential of $[TFSA]^-$ is most negative in the S-N-S plane, which in turn is parallel to the surface in case of the *cis*-conformer. Thus, the interactions with neighboring cations are expected to be stronger than in the case of the *trans*-conformer where the S-N-S-plane (and thus the most negative electrostatic potential) is normal to the surface.

When looking at the structure of the adsorption complex (see Figure 5c) and comparing it to that of pure adsorbed $[TFSA]^-$ (in the *cis*-conformation), there are barely any differences: the anion is only slightly further away from the surface (about 0.10 Å) than for the pure adsorbed [TFSA]. The adsorption energy with respect to the ionic liquid pair in the gas phase is 1.30 eV. However, 95% of the adsorption energy is due to dispersion interactions, i.e., all other interactions (electrostatic interactions, covalent bonding) only lead to an adsorption energy of 0.06 eV. The charge density difference map (Figure 5d) provides an insight into the electronic changes occurring upon adsorption. Upon adsorption, electrons are shifted from the blue regions to the red regions. As expected, there is a depletion of electron charge in the region between the anion and the surface, whereas it is enhanced in the region between the surface and the cation. Thus, the ion pair induces a lateral dipole at the surface which is opposite in sign to the dipole generated by the two adsorbed ions. For the understanding of the adsorption bond it would be interesting to know whether the enhanced/depleted electron density is due to

a charge transfer from the surface to the ionic liquid (and vice versa) or whether it is due to polarization effects within the individual components. This could tell us whether the charge remains at the ionic liquid or whether there is a significant charge transfer to / from the adsorbed species. In the first case, there will be considerable electrostatic adsorbate-adsorbate interactions, which lead to the formation of an ordered structure, in the second case ordering has to occur via different mechanisms, e.g., weaker dipolar interactions or van der Waals interactions between adsorbates, and indirect (surface mediated) adsorbate-adsorbate interactions. However, it is hard to distinguish between charge transfer and polarization effects as the assignment of charges to individual components mainly depends on the position of the border between them. Therefore, different methods for charge analysis that are based on different dividing schemes can lead to very diverse results. In order to get at least a rough estimate of the charge distribution within the system, we used the Bader charge analysis. We found that the charges of the cation and the anion hardly change upon adsorption on Ag(111). This is in agreement with the rather small interaction energy of 0.06 eV if dispersive interactions are excluded, i.e., with the absence of any significant covalent bond formation.

In Figure 6 we show simulated STM images of two possible adsorption structures with comparable adsorption energy. These simulations suggest that the experimentally observed dots in the high-resolution STM images correspond to the cations. This seems to be the only way to explain the large corrugation of the isosurface of the partial electronic density contributing to the STM image. The longish protrusions could be related to the adsorbed anion. It seems that each anion leads to two longish protrusions, each of them stemming from 2 F-atoms of the fluoromethyl groups. This could explain the ratio of 1:2 of dots to longish protrusions. Furthermore, different voltages in between -0.3 V and -1.5 V have been studied; however no voltage dependency could be observed.

According to the STM simulations, the anion-cation pairs in the ordered 2D crystalline phase are depicted in the high-resolution STM image in Figure 6b on the right hand side by

superimposed dots and longish protrusions. Apparently, the IL structure is formed by an alternating sequence of rows in which the anion-cation pairs exhibit the same azimuthal orientation. In this herringbone-type arrangement, the azimuthal orientation of the ion pairs changes by 120° between subsequent rows. The unit cell is included as well; it contains two dots and four longish protrusions, which are now identified as two "anion-cation pairs" with different orientations. It should be noted that the term adsorbed ion pair is in so far misleading as we have no indication for a structure dominated by strongly attractive interactions between intact ion pairs and weak interactions between neighbored ion pairs. Instead, Figure 6b clearly demonstrates that the spacing between anions and cations is rather similar, resembling a 2D ion crystal. Furthermore, the layer is rotationally aligned with the substrate, possibly due to the interaction of the oxygen atoms of the anion with the surface.

4. Conclusions

Having investigated the interaction of [BMP][TFSA] with Ag(111) and the structure formation in the adlayer by variable temperature STM measurements and DFT based calculations, we arrive at the following results and conclusions:

1. Following deposition of [BMP][TFSA] on Ag(111) at room temperature and cool-down to around 100 K, we observed the coexistence of an ordered 2D crystalline phase, a disordered 2D glass phase and a 2D liquid phase. The 2D glass phase was solely observed on small Ag(111) terraces (d ≈ 10 nm), and is probably induced by the interaction with the steps and the lateral confinement. On large Ag(111) terraces, long-range ordered and homogenous domains are formed without any internal domain boundaries.
2. Variable temperature STM measurements reveal melting of the ordered 2D crystalline phase at 180±10 K.

3. Dynamic STM measurements at around 100 K resolve exchange of adspecies at the phase boundaries 2D crystalline phase | 2D liquid and disordered 2D glass | 2D liquid. While the interior of the ordered 2D crystalline phase is stable over time, infrequent molecular jumps are observed in the 2D glass phase.
4. The fact that we observe long-range ordered domains with a low 2D melting point and an equilibrium between the 2D crystalline phase and the 2D liquid phase points to weakly attractive adsorbate-adsorbate interactions and a low surface diffusion barrier.
5. DFT-D calculations reveal a stable adsorption complex for one IL pair with the anion and the cation laterally placed side by side. The butyl group of the cation points towards the vacuum and the anion exhibits a *cis*-conformation of the S-N-S plane, with the SO_2 groups binding to the surface and the trifluoromethyl groups pointing towards the interface IL | vacuum. STM simulations agree with the molecular features in high-resolution STM images, allowing us to identify anions and cations. In addition, the calculations show that the charge remains at the ionic liquid and the interaction with the substrate mainly occurs almost exclusively via dispersion interactions and weak electrostatic (dipole-induced dipole) interactions. The ordered 2D crystalline phase is stabilized by weakly attractive electrostatic interactions between the positive and negative charges of the adsorbed ions. Finally, the layer is rotationally aligned with the substrate surface, probably due to the interaction of the oxygen atoms of the anion with the surface.

5. Figures

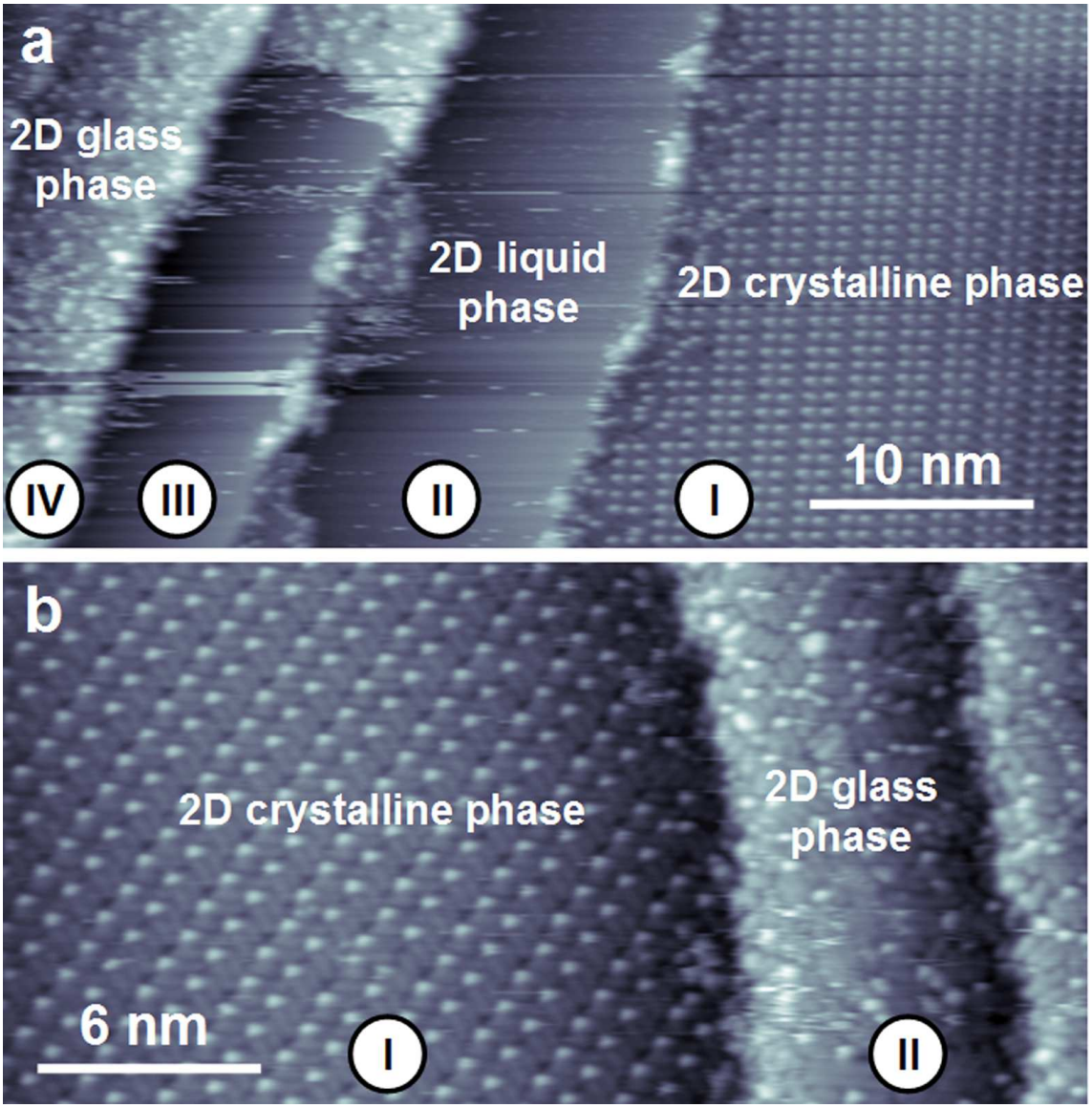

Figure 1. Constant current STM images of [BMP][TFSA] on Ag(111) recorded at ~100 K. (a) The STM image at sub-monolayer coverage shows four silver terraces (indicated by numbers). Both an ordered 2D crystalline phase on the large Ag terrace and a disordered 2D glass phase on small Ag terraces (width ~ 10 nm) could be resolved. (b) At monolayer coverage, the large terrace is occupied by the ordered 2D crystalline, while small terraces are covered by the disordered 2D glass phase ((a) U_t=-0.42 V, I_t=110 pA, (b) U_t=-0.37 V, I_t=130 pA).

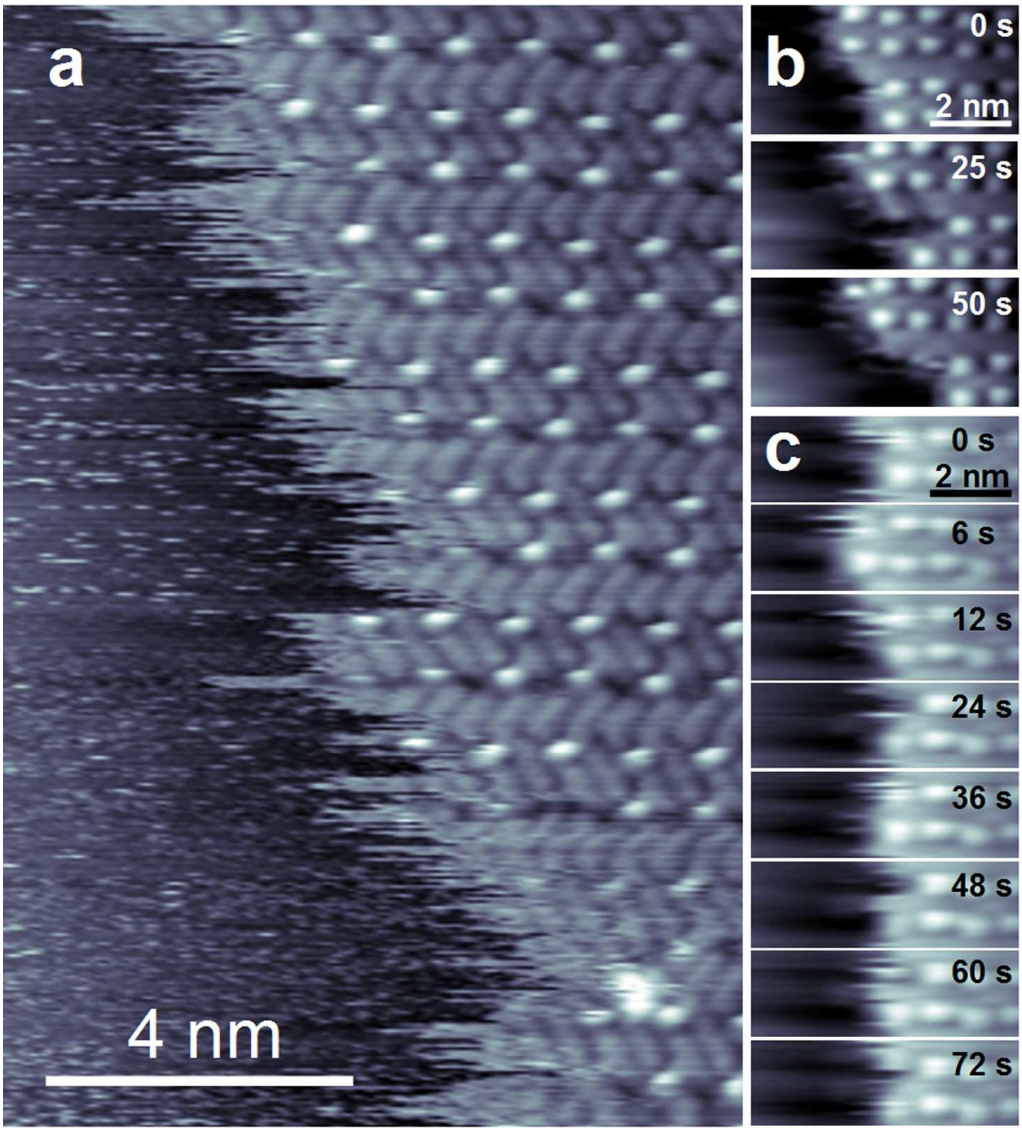

Figure 2. Constant current STM images of [BMP][TFSA] on Ag(111) recorded at ~100 K. (a) STM image of the ordered 2D crystalline phase exhibiting frizzy features at the phase boundary to the 2D liquid phase, which are presumably due to exchange of adsorbed IL species at the phase boundary between 2D solid and 2D liquid. Time sequences of STM images with an image to image time of ~ 25 s in (b) and of ~ 6 s in (c) illustrate the dynamic changes at the phase boundary ((a) U_t=-0.33 V, I_t=150 pA), (b) U_t=-1.2 V, I_t=90 pA, (c) U_t=-1.2 V, I_t=100 pA).

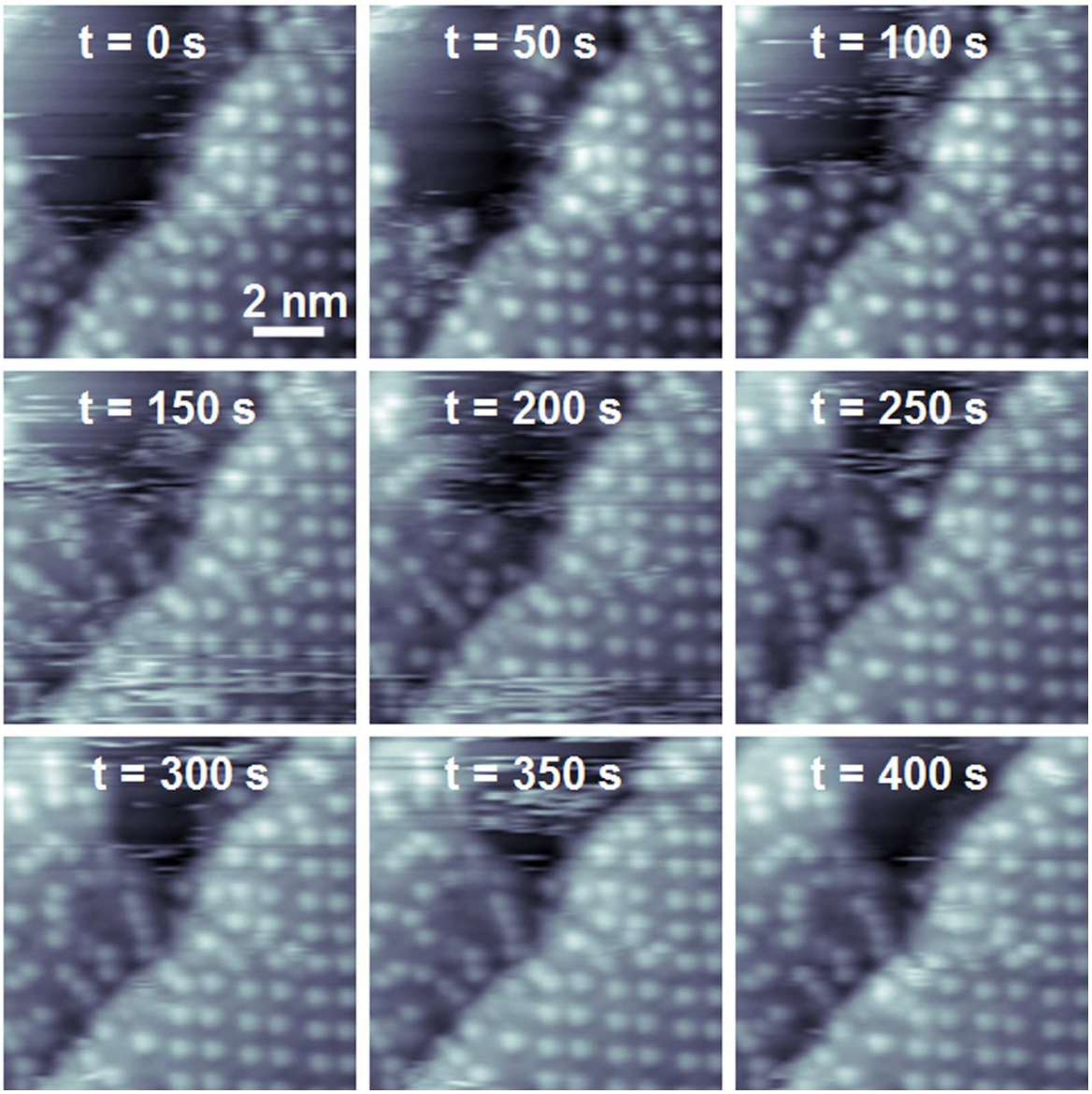

Figure 3. STM time sequence of [BMP][TFSA] on Ag(111) recorded at ~100 K. On the left Ag terrace, the phase boundary between disordered 2D glass and 2D liquid is monitored with a time interval from image to image of ~ 12 s (every fourth image is shown). Both the stripy features close to the phase boundary and the gradually changing phase boundary illustrate the exchange of adsorbed IL species between the phases. The right terrace is partly covered by a stable 2D crystalline phase (U_t=-0.86 V, I_t=50 pA).

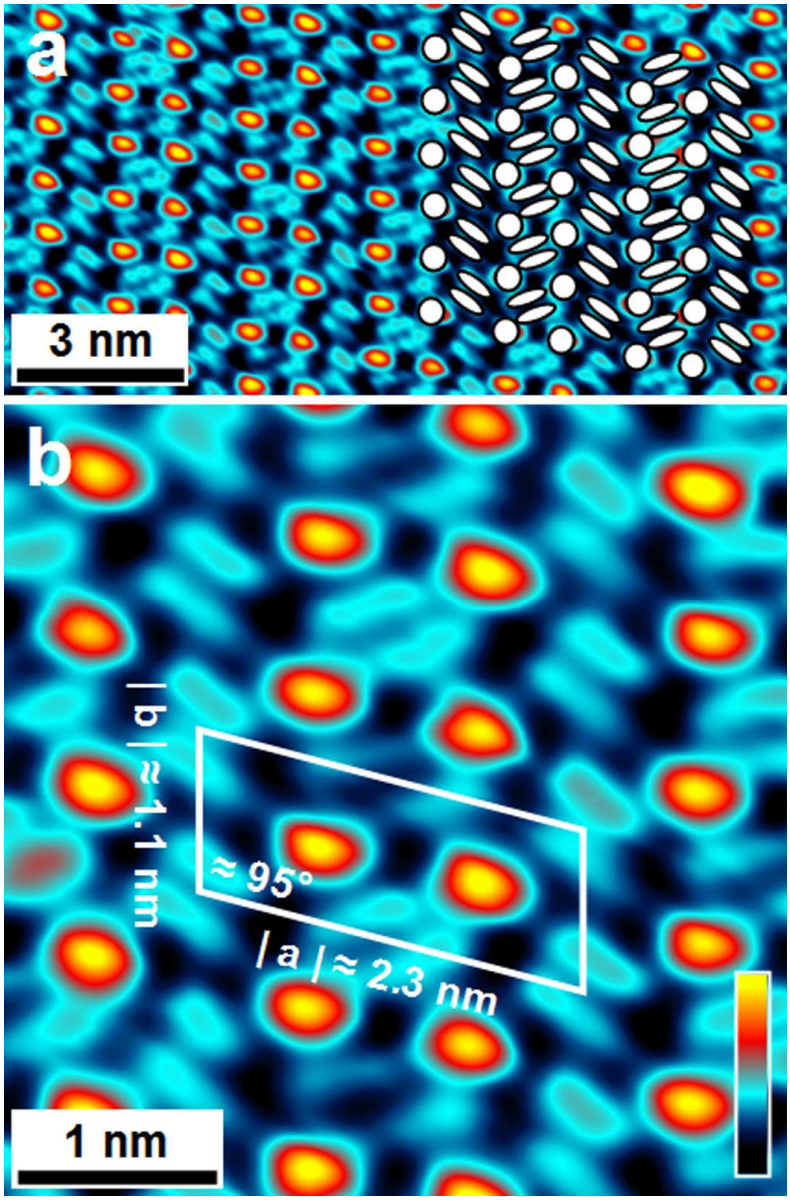

Figure 4. High resolution STM images of [BMP][TFSA] on Ag(111) recorded at ~100 K. (a) High-resolution STM image of the ordered 2D crystalline phase; on the right hand side dots and longish protrusions are superimposed on the image. (b) Enlarged STM image highlighting the structure of the ordered 2D crystalline phase. The unit cell is included, which contains two dots and four longish protrusions (U_t=-1.32 V, I_t=110 pA).

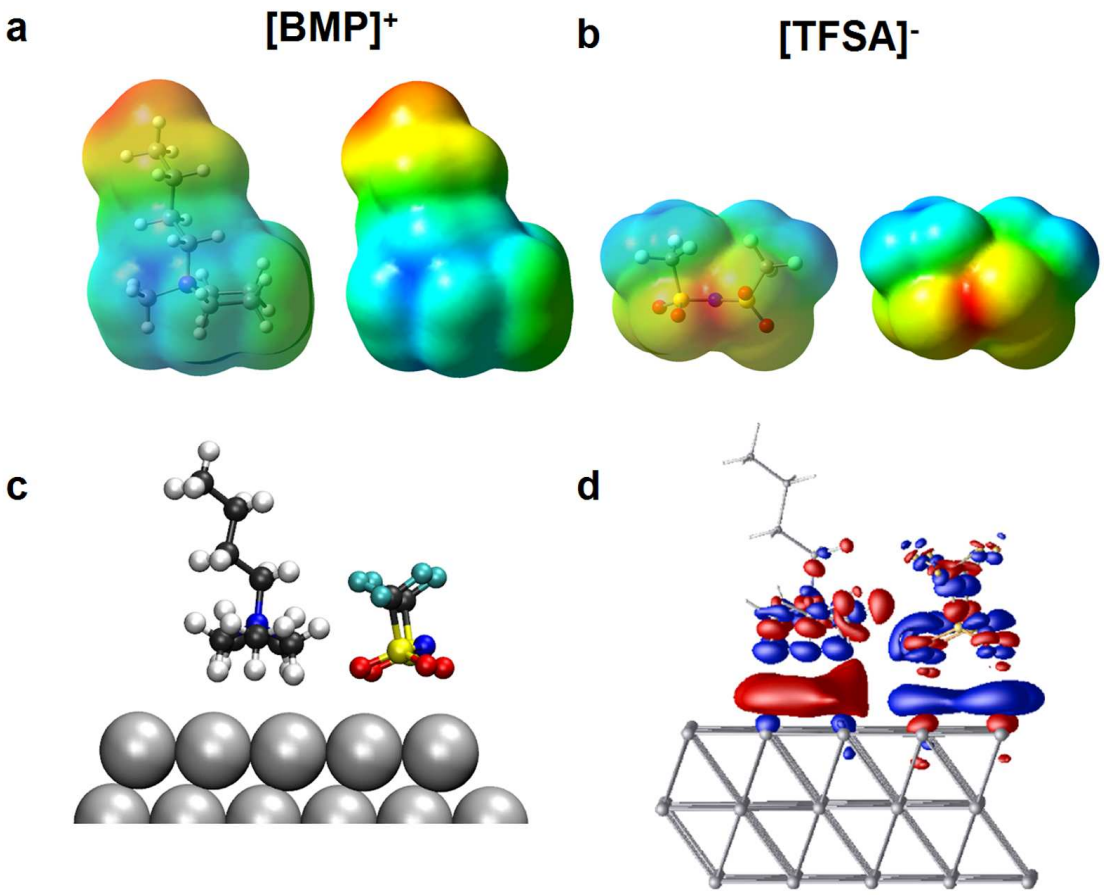

Figure 5. Electrostatic potential at an electron charge isosurface (isosurface charge density $4x10^{-4}$ *e*/bohr^3) of (a) $[BMP]^+$ (view onto the C_{butyl}-N-C_{methyl} plane) and (b) $[TFSA]^-$ (view along the S-N-S plane). Red regions refer to the least positive / most negative electrostatic potential a positive test charge experiences. Blue regions reveal the most positive / least negative electrostatic potential a positive test charge experiences. (c) Side view of the adsorption complex of the ionic liquid ion pair on Ag(111). (d) Isosurfaces (-0.0058 *e*/Å^3 (blue) and +0.0049 *e*/Å^3 (red)) of the adsorption induced changes in the charge density of [BMP][TFSA] adsorbed on Ag(111). The chosen values for the isosurfaces depict a total electron shift of 0.205 *e* from the blue regions into the red regions.

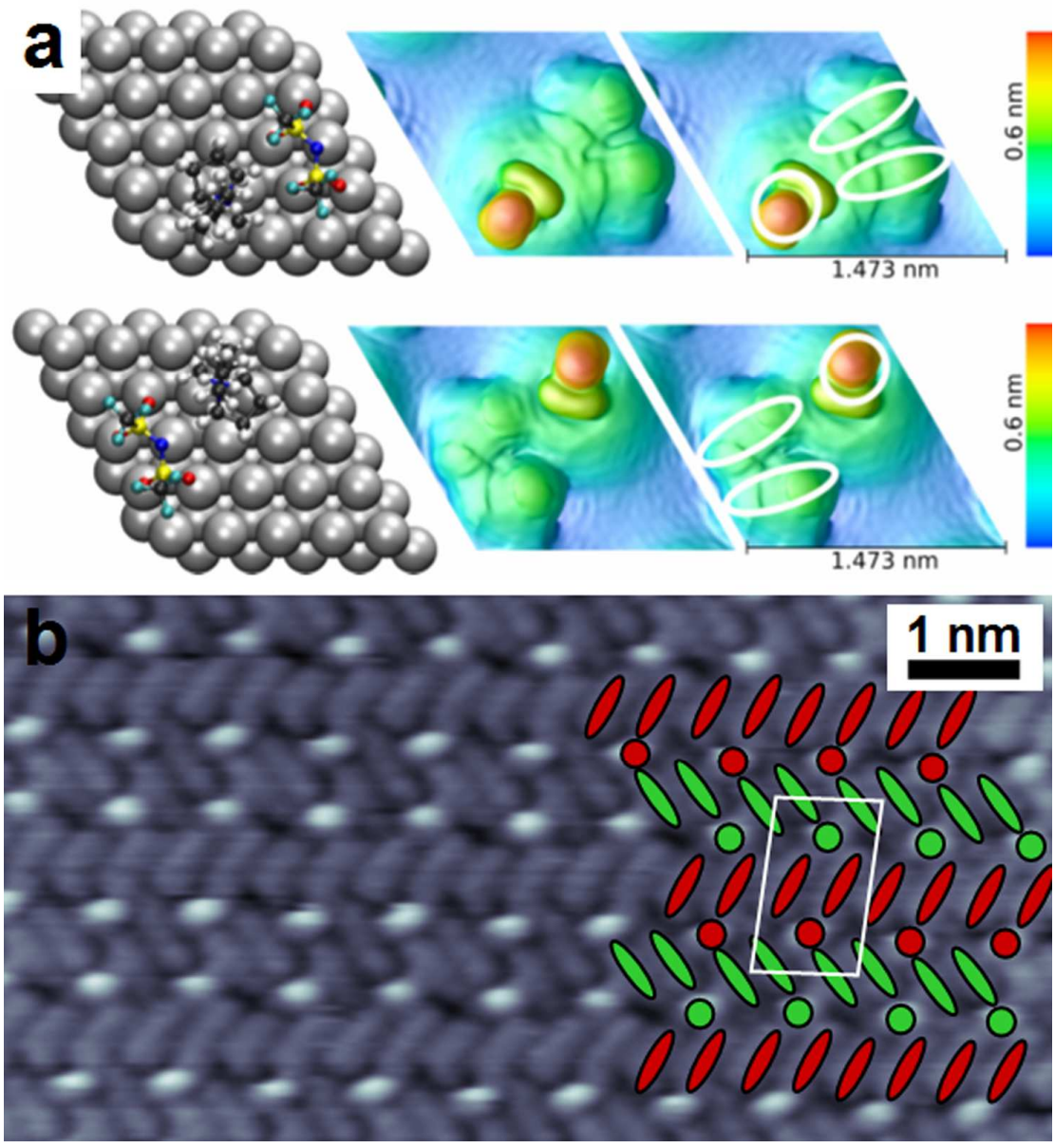

Figure 6. (a) Ball and stick presentation of two mirror symmetric configurations of the adsorbed IL ions together with the corresponding simulated STM images (U_t=-1.35 V, isosurface value=3E-7 e/Å^3) of the adsorption structures of [BMP][TFSA] on Ag(111). The dots and longish protrusions seen in the experimental STM images are indicated on the right. (b) High resolution STM image of the ordered 2D solid phase. On the right hand side, the anion and cations are labeled by schematic drawings, and the unit cell is marked (U_t=-0.33 V, I_t=150 pA).

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENT

B.U. gratefully acknowledges a fellowship by the Fonds der Chemischen Industrie.

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BRIEFS

A pseudo-three-dimensional presentation of a sub-molecularly resolved STM image and the configuration resulting from DFT-D based calculations of the adsorbed ionic liquid [BMP][TFSA] on Ag(111).

SYNOPSIS

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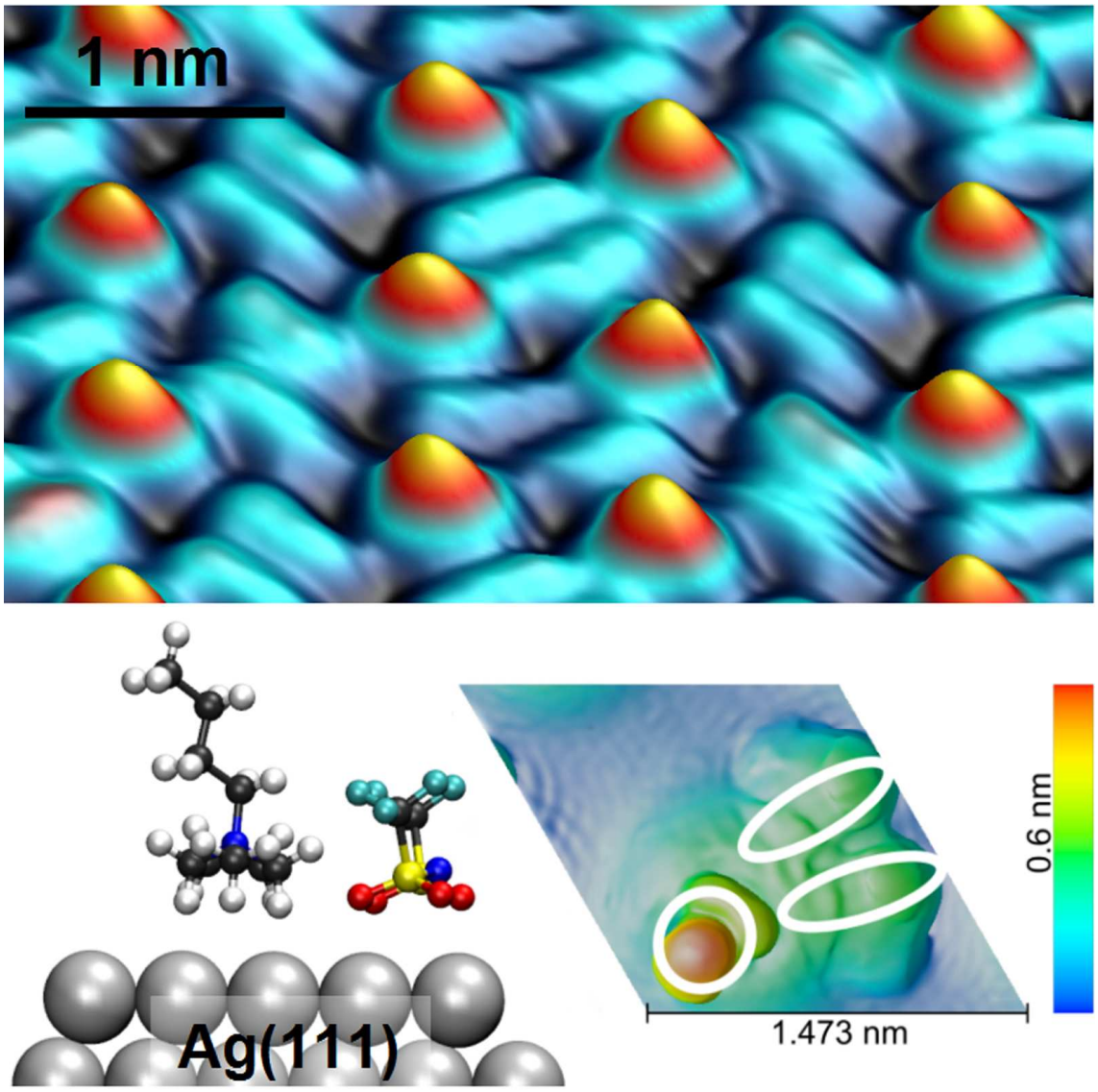

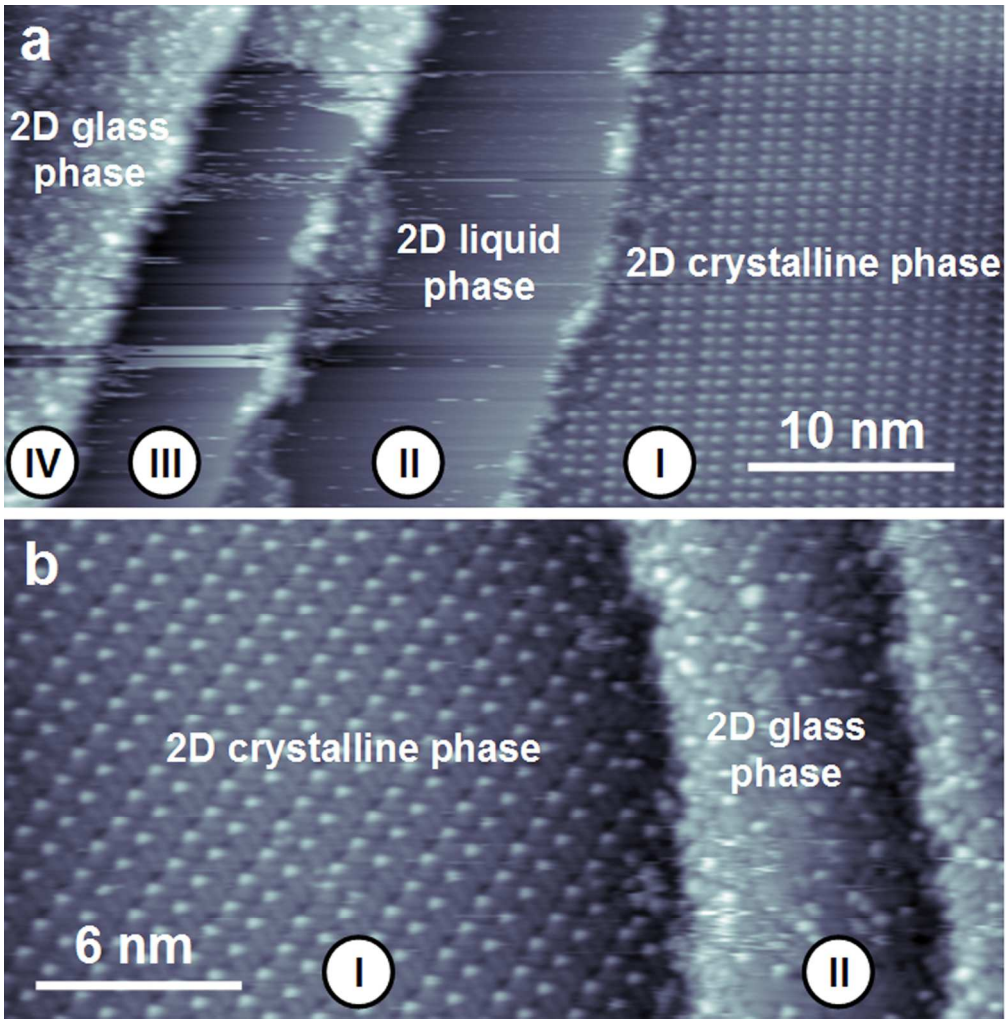

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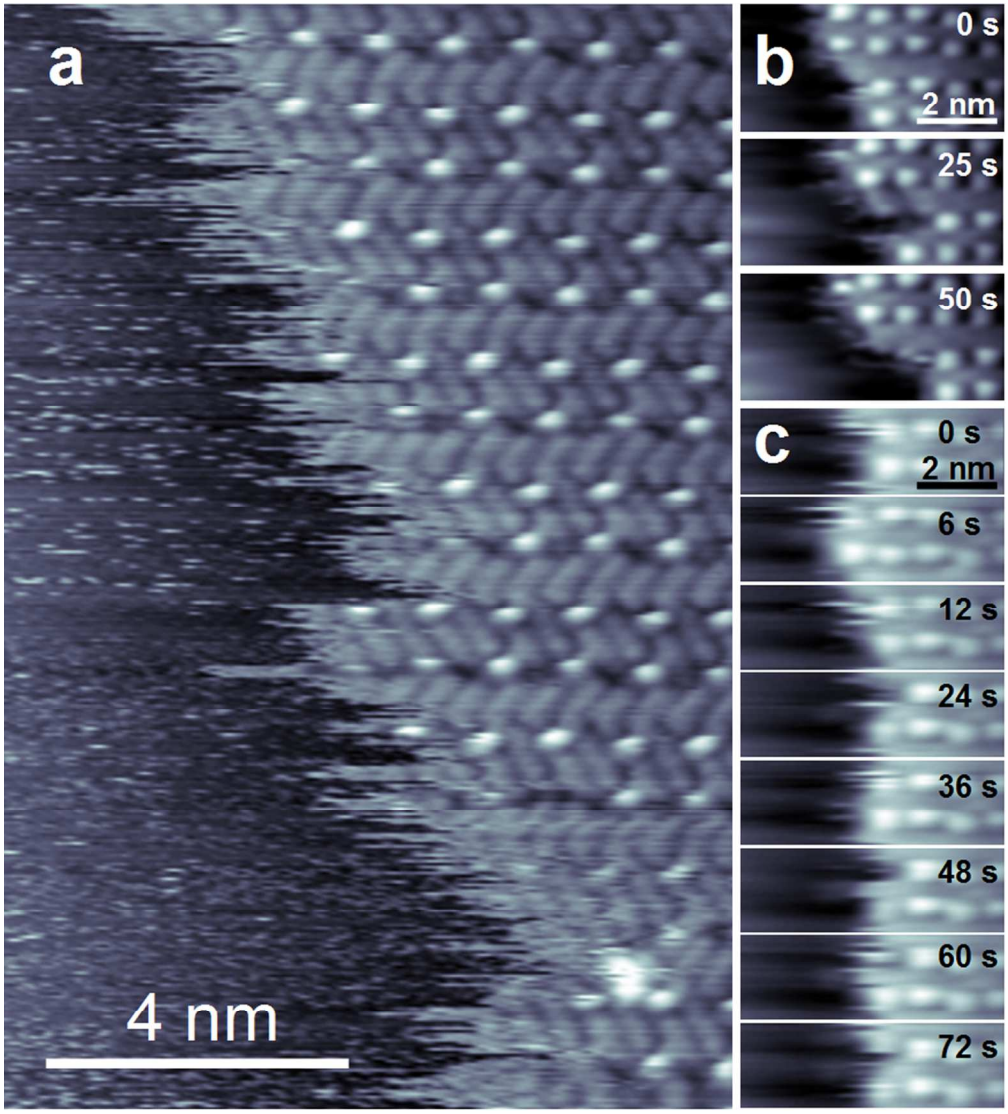

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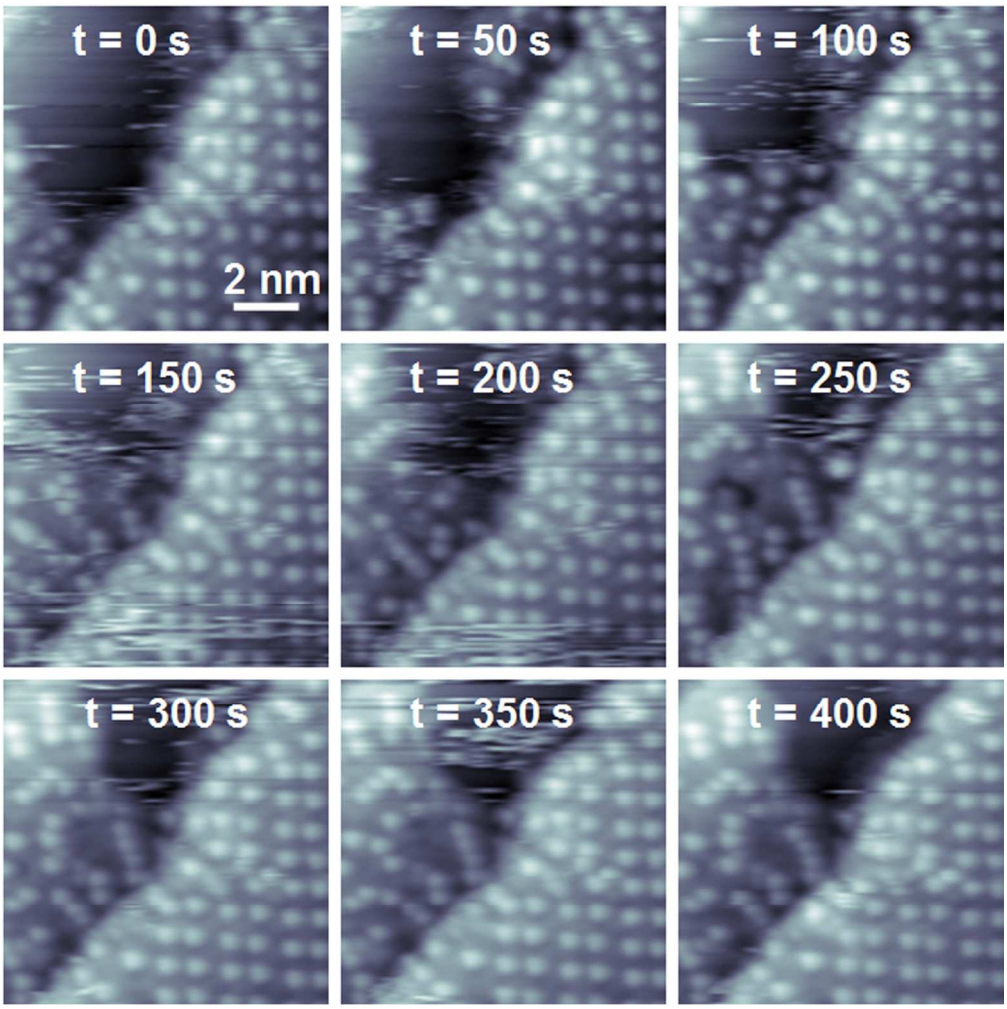

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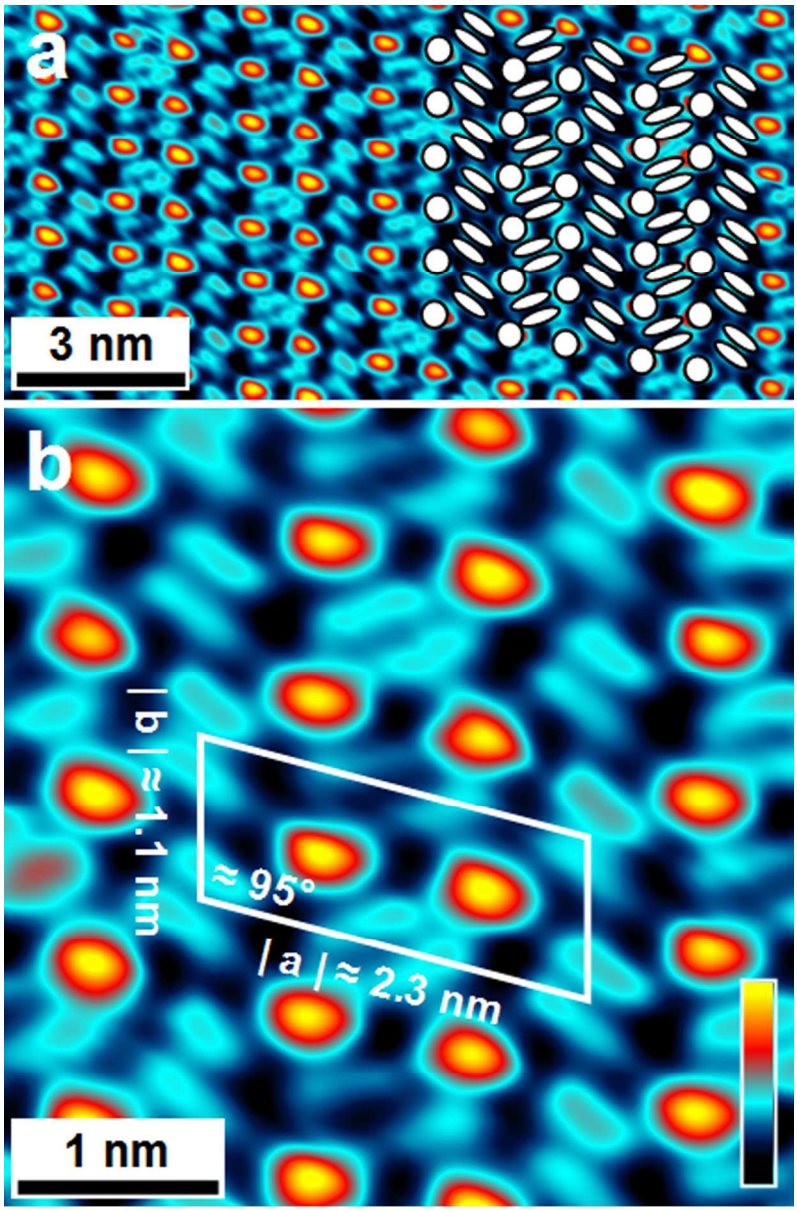

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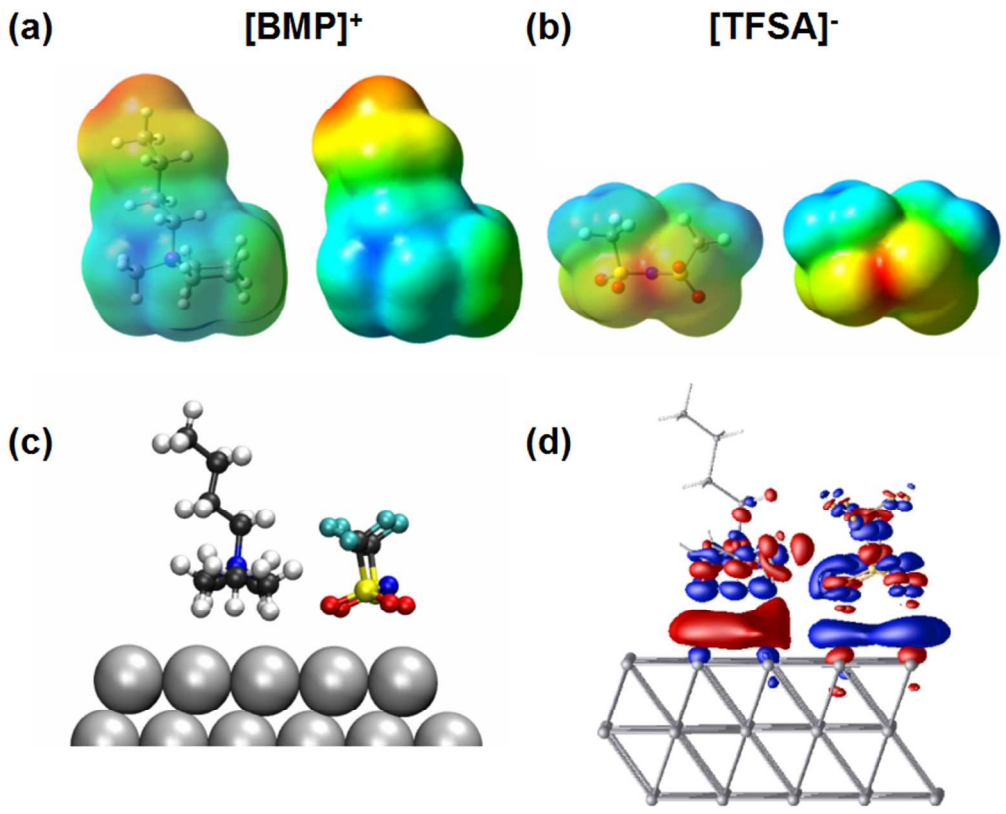

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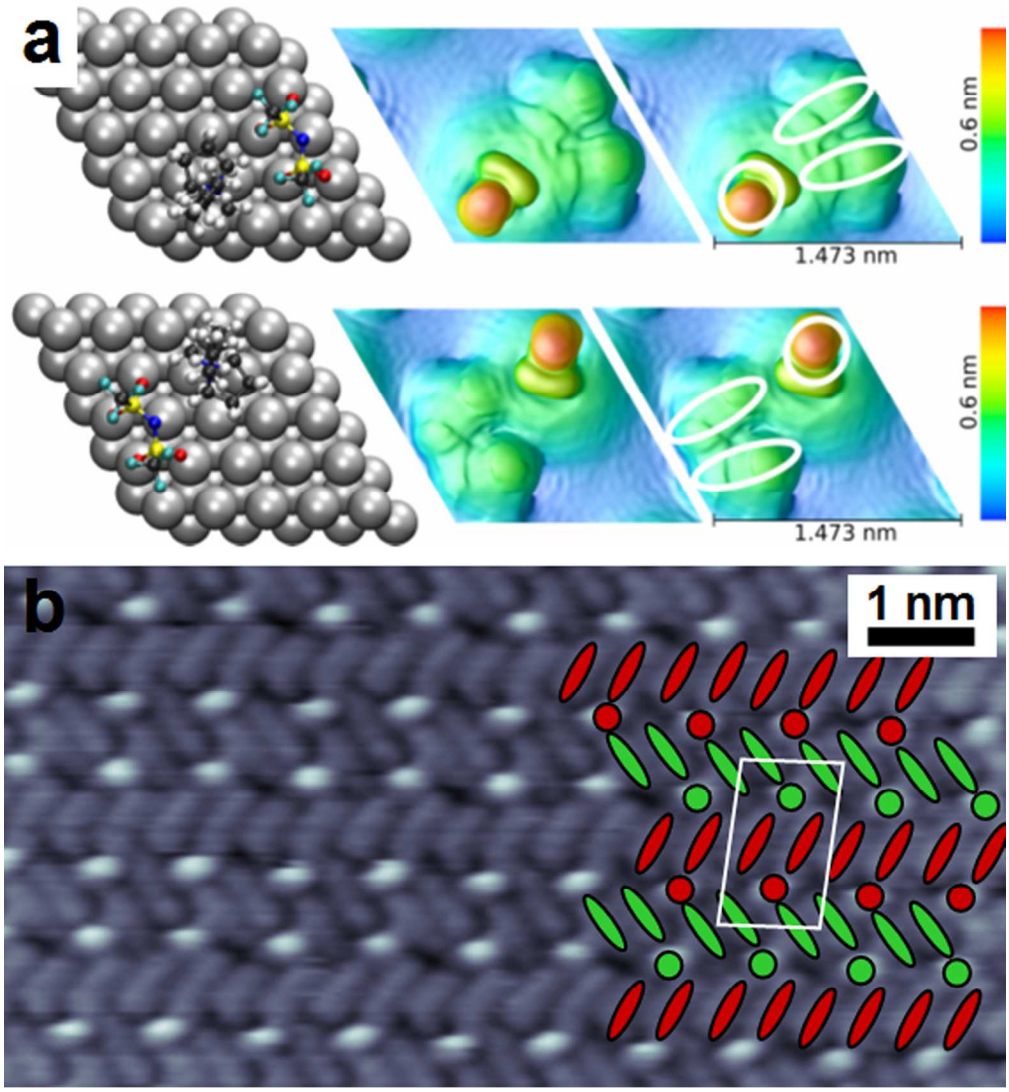

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