

## Effects of the introduction of a Chromium Oxide monolayer at the $C_{60}/Fe(001)$ interface

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The introduction of a two-dimensional oxide layer at the interface between an organic semiconductor and a ferromagnetic metal (spinterface) can help in tailoring the formation of spin-polarized hybridized interface states. Here we consider the case of a  $Cr_4O_5$  monolayer at the  $C_{60}/Fe(001)$  interface, which is already known to feature the occurrence of spin-polarized states in the fullerene molecules. In this work, we employ scanning tunneling microscopy/spectroscopy and photoemission spectroscopy to show that the  $C_{60}/Cr_4O_5/Fe(001)$  spinterface is characterized by the formation of a well-ordered fullerene monolayer and of strongly hybridized interface states. These experimental results are discussed in terms of state-of-the-art ab initio calculations of the structural, electronic, and magnetic properties at the interface.

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## I. INTRODUCTION

In the last years, several experimental and theoretical investigations have suggested that organic materials can achieve comparable, or even enhanced, performances in spin-based devices with respect to inorganic materials, and that they can also provide new concepts, leading to the new field of Organic (or Molecular) Spintronics.<sup>1</sup> The key role in such systems is played by the so-called spinterfaces,<sup>2-4</sup> i.e. interfaces between ferromagnetic (FM) materials, which provide spin-polarized electrons, and organic semiconductors (OS), which are characterized, in particular, by long lifetimes for spin-polarized electrons. It is now commonly understood that the fundamental processes related to spinterfaces, such as the modifications of the magnetic properties of either the OS or the FM layers and the possibility of injecting spins in the organic layer, are governed also by the chemical interactions occurring at the OS/FM interface.<sup>5</sup> For this reason, a detailed control over the interface characteristics is of paramount importance to define and, eventually, tailor physical systems with capabilities of interest for potential applications.

In inorganic spintronics systems, it is well-known that the intercalation of thin and ultra-thin oxides in proximity to FM metals (for instance, as tunneling barriers in multilayer junctions) directly influences the magnetic properties of the system, very often with favorable effects.<sup>6</sup> This aspect has not been, so far, thoroughly investigated in Organic Spintronics, even if thin oxide films were already exploited in organic spin valves based on standard spintronics concepts.<sup>7</sup> Recently, we started evaluating the influence of introducing an oxidized layer in a spinterface by comparing the early stages of growth of  $C_{60}$  fullerene films onto either the Fe(001) surface or the oxygen-passivated Fe(001)- $p(1 \times 1)$ O surface.<sup>8</sup> We were able to show that the oxygen passivation of the Fe(001) surface, which results in forming an FeO-like monolayer with enhanced spin-dependent properties,<sup>9-11</sup> substantially affects the interface in terms of the growth morphology, by changing the molecular surface diffusivity, and of the electronic properties, with a substantial electronic decoupling in presence of the oxidized layer. We have furthermore studied the magnetic hybridization at such interfaces and at the interface between  $C_{60}$  and a  $Cr_4O_5$  monolayer stabilized onto the Fe(001) surface.<sup>12</sup> Those investigations lead to the observation of spin-polarized fullerene states in all cases.

In this work, we analyze in more detail the  $C_{60}/Cr_4O_5$  spinterface by exploiting com-

bined experimental and theoretical approaches. The interaction of  $C_{60}$  molecules with the  $Cr_4O_5/Fe$  surface is experimentally characterized by a relatively strong electronic coupling and by a low diffusion barrier, resulting in a well-ordered fullerene monolayer with strongly hybridized interface states. The experimental observations, based on scanning tunneling microscopy and spectroscopy and on photoemission spectroscopy, are supported by state-of-the-art ab initio calculations, used to discuss how the local interaction between the  $C_{60}$  molecule and the substrate affects the electronic and magnetic properties of the interface.

## II. METHODS

### A. Experimental Methods

Samples were prepared in ultrahigh vacuum (UHV) (low  $10^{-10}$  mbar range) by growing 400 nm-thick Fe(001) films on MgO(001) single crystal substrates by molecular beam epitaxy (MBE). The Fe surface was first passivated by oxygen to obtain the oxygen-saturated Fe(001)- $p(1 \times 1)O$  surface, as described in previous works.<sup>10,13</sup> A  $Cr_4O_5$  monolayer oxide was then prepared by depositing 0.8 equivalent monolayers (ML) of Cr on top of the Fe(001)- $p(1 \times 1)O$  surface, with the sample held at about 400 °C, as measured by a thermocouple mounted in close proximity to the sample position. Such a two-dimensional Cr oxide has been demonstrated to form a stable wetting layer on Fe(001), characterized by a regular array of Cr vacancies that results in a  $(\sqrt{5} \times \sqrt{5})$ -R26.6° surface lattice.<sup>14</sup> This system is characterized by a long-range FM order with in-plane magnetization, oriented anti-parallel with respect to that of the Fe substrate.<sup>15,16</sup> Fullerene films were grown onto the  $Cr_4O_5/Fe$  substrates by MBE under UHV conditions, with the substrates held at room temperature.

Scanning tunneling microscopy (STM) was performed in situ (Omicron VT-STM) in the constant-current mode with homemade electrochemically etched W tips. Scanning tunneling spectroscopy (STS) was performed at liquid nitrogen temperature (sample temperature about 100 K). Tunneling spectra were obtained by superimposing a modulation voltage (rms amplitude of 20 mV) to the applied sample bias  $V$  and detecting the  $dI/dV$  signal by a lock-in amplifier.

Photoemission spectroscopy (PES) in the UV range was performed with He I radiation ( $h\nu = 21.2$  eV) from a He discharge lamp. Photoelectrons were collected by a 150 mm

hemispherical electron analyzer (SPECS GmbH) operated at a pass energy of 0.5 eV (the estimated instrumental resolution is about 0.05 eV full width at half-maximum).<sup>17</sup>

## B. Computational Methods

The ab initio theoretical calculations were performed in the density functional theory (DFT) formalism. We treat exchange-correlation, accounting for the spin polarization of the system, by exploiting the vdW-DF2-c09x functional. This combines vdW-DF2 functional<sup>18</sup> with the Cooper gradient correction to the exchange,<sup>19</sup> and includes the van der Waals interaction between C<sub>60</sub> molecules and the substrate. We adopted the plane-wave ultrasoft pseudopotential method<sup>20</sup> implemented in the PWSCF code of the Quantum-ESPRESSO distribution.<sup>21</sup> Pseudopotentials were generated starting from scalar-relativistic all-electron calculations and using non-linear core corrections. The *3s3p* semicore states of Cr are included.

The substrate surface geometry is assumed to correspond to the  $(\sqrt{5} \times \sqrt{5})$ -R26.6° reconstruction, as experimentally observed for single Cr<sub>4</sub>O<sub>5</sub> layer on Fe(001).<sup>14</sup> The C<sub>60</sub> molecules are placed in a squared arrangement with a  $(\sqrt{10} \times \sqrt{10})$ -R-18.4° periodicity, with a surface supercell having a double area than the primitive Cr<sub>4</sub>O<sub>5</sub> one. This choice, although not strictly corresponding to the experimentally observed periodicity (see below), allowed us to catch the fundamental aspects of the local molecule-substrate interaction avoiding an excessive increase of the computational cost. A slab with four Fe layers was used to model the Fe(001) substrate, with the Cr<sub>4</sub>O<sub>5</sub> layer and the molecules placed on one side. The periodic replica of the slabs are separated by 25 Å of vacuum along the orthogonal direction *z*.

We considered different orientations of C<sub>60</sub>, namely the ones corresponding to a molecule facing the surface by a hexagonal face, by a C-C bond, and by a pentagonal face, and placing the molecule on top of Cr atoms, Cr vacancies, and O atoms farthest from the vacancies. Once the system was prepared in these local configurations, the *z* coordinate of the carbon atoms was left free to relax until the forces reached the limiting value of 0.001 Ry/Bohr.

The surface Brillouin zone was sampled by a Monkhorst-Pack grid<sup>22</sup> equivalent to a 14×14 mesh in the surface unit cell of Fe(001). The kinetic energy cutoffs are 55 Ry for the wave function and 280 Ry for the effective potential and the charge density.

### III. RESULTS AND DISCUSSION

Figure 1(a) displays a large scale STM image acquired after the deposition of about 1 ML  $C_{60}$  on the  $Cr_4O_5$  surface. The molecules form a compact and homogeneous monolayer, wetting the substrate, with only a small portion of second layer forming upon completion of the first one (brighter areas in the STM image). Panel (b) displays the Fast Fourier Transform of the STM image, in which two hexagonal lattices mutually rotated by  $90^\circ$  are detected. The presence of two rotational domains stems from the fourfold symmetry of the substrate and indicates that there is a well-defined epitaxial relation between the latter and the molecular overlayer. In particular, in each domain one unit vector of the  $C_{60}$  lattice is aligned with either the [100] or the [010] crystallographic direction of the Fe(001) surface. A quantitative evaluation of the peak-peak separation in the reciprocal space, reported in the profile corresponding to the red dashed line drawn in the inset of panel (b), yields a real space lattice parameter of 1.03 nm, a value in good agreement with that characterizing the (111) surface of bulk face-centered-cubic  $C_{60}$ .<sup>23</sup> Panel (c) shows an enlarged view of the  $C_{60}$  overlayer, in which a boundary region between two domains is visible. Two white parallelograms are drawn to highlight the unit cells in the adjacent domains.

The curve in panel (d) has been obtained by averaging several STS spectra acquired on the  $C_{60}$  wetting layer. In the occupied states side of the spectrum (negative bias) a broad feature at about 2 eV below the Fermi level  $E_F$  is detected, which can be assigned to HOMO states. On the unoccupied states side (positive bias), a peak corresponding to the LUMO level can be observed at about 1 eV above  $E_F$ .

The electronic structure of the spinterface was also investigated by means of PES. Selected PES spectra related to 1 molecular layer of  $C_{60}$  on Fe(001), Fe(001)- $p(1 \times 1)$ O and  $Cr_4O_5$ /Fe have already been discussed in previous publications.<sup>8,12</sup> In Fig. 2 we present a set of normal emission PES spectra related to the  $C_{60}/Cr_4O_5/Fe$  system, by reporting them as a function of molecular coverage. The  $Cr_4O_5/Fe$  substrate spectrum, displayed in the bottom row, is characterized by a metallic Fermi edge and by a large peak located at a binding energy of -4.9 eV. The latter, which is related to oxygen states, is reminiscent of a similar peak that characterizes the PES spectrum of the Fe(001)- $p(1 \times 1)$ O substrate (not shown here) as discussed in Ref. 16.

Molecular peaks start to appear already in the submonolayer coverage regime and become

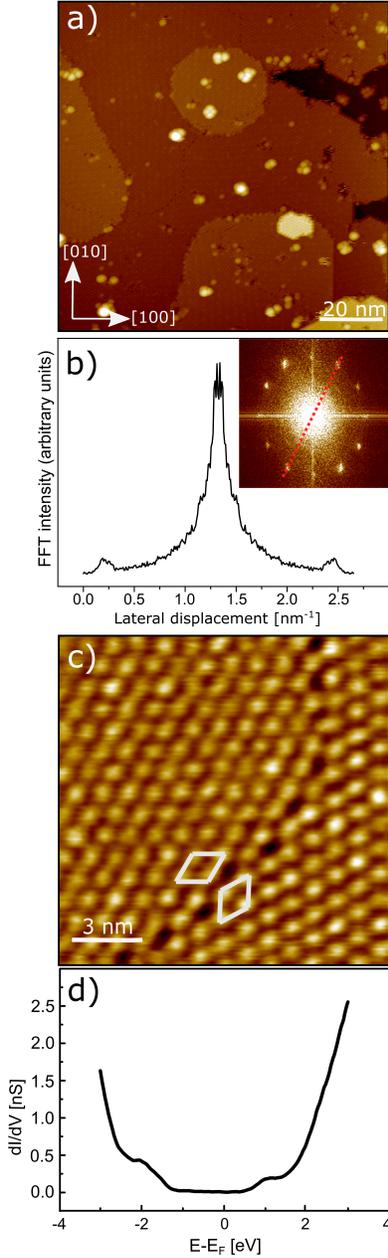


FIG. 1. (a) STM image of 1 ML  $C_{60}$  on  $Cr_4O_5/Fe$ . Image size is  $105 \times 105 \text{ nm}^2$ . Tunneling parameters  $\Delta V = 1.7 \text{ V}$ ,  $I = 400 \text{ pA}$ . (b) Fast Fourier Transform of panel (a), in which two orthogonal hexagonal domains are observed. The side of the reciprocal hexagonal lattice is  $1.12 \text{ nm}^{-1}$ , corresponding to  $1.03 \text{ nm}$  in the real space. (c) Zoom of panel (a) showing the boundary between two hexagonal domains. The white parallelograms indicate the unit cells. Image size is  $14 \times 14 \text{ nm}^2$ . (d) STS curve obtained by averaging 30 spectra acquired on 1 ML  $C_{60}/Cr_4O_5/Fe$ .

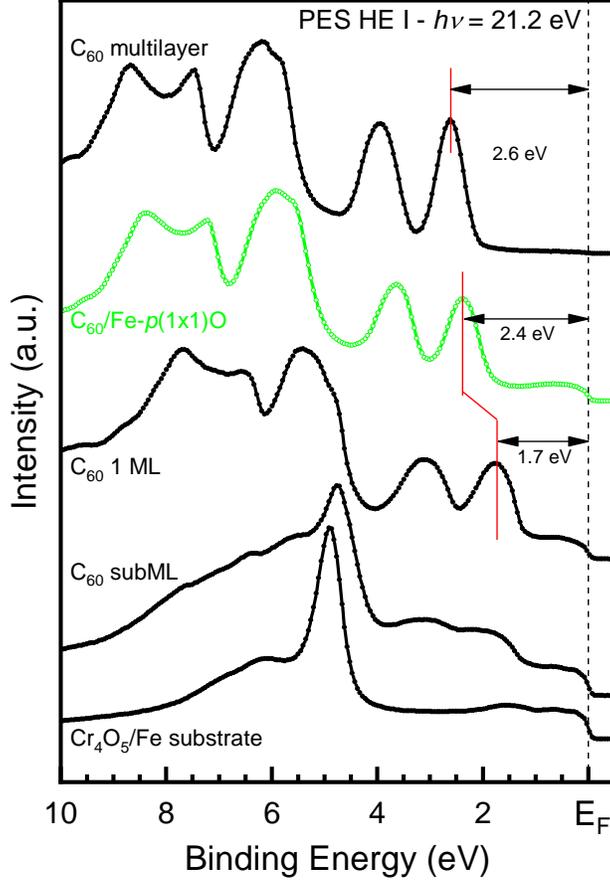


FIG. 2. Photoemission spectra ( $h\nu = 21.2$  eV) acquired at normal emission on the  $\text{Cr}_4\text{O}_5/\text{Fe}(001)$  substrate (bottom spectrum), and after  $\text{C}_{60}$  deposition with increasing coverages (from bottom to top), as indicated. The spectrum related to 1 ML  $\text{C}_{60}/\text{Fe}(001)-p(1 \times 1)\text{O}$  (green dots) is also reported, for reference.

well-defined at the completion of the first molecular layer. At this stage, the HOMO peak is centered at  $-1.7$  eV from  $E_F$ . This HOMO position reveals the occurrence of a significant charge transfer, which is estimated to be about 1.5 electrons per molecule, as discussed below, on account of a relatively strong interaction with the metallic substrate. The strength of the interface coupling also reflects in a small shift of about 0.15 eV of the oxygen related peak (formerly at  $-4.9$  eV) toward lower binding energy, in good agreement with the donor role played by the substrate.

The green spectrum is related to 1 ML of  $\text{C}_{60}$  deposited on  $\text{Fe}(001)-p(1 \times 1)\text{O}$ , which is shown here as a reference. In the latter case, the interface coupling was observed to be weaker, so that the peak positions are close to those observed in multilayer films that,

being characterized by the weak van der Waals interaction between adjacent layers, are representative of a fullerene layer poorly interacting with the substrate. It is worth to notice that in the spectra related to 1 ML of  $C_{60}$ , the substrate DOS close to  $E_F$  is still visible, thus ensuring a correct setting of the binding energy scale.

Finally, a spectrum related to a multilayer  $C_{60}$  film on  $Cr_4O_5/Fe$  is shown in the upper row of Fig. 2. As discussed above, the lineshape and the peak positions here are consistent with those typical of fullerene layers on poorly interacting substrates. Also, features related to the substrate are no longer visible.

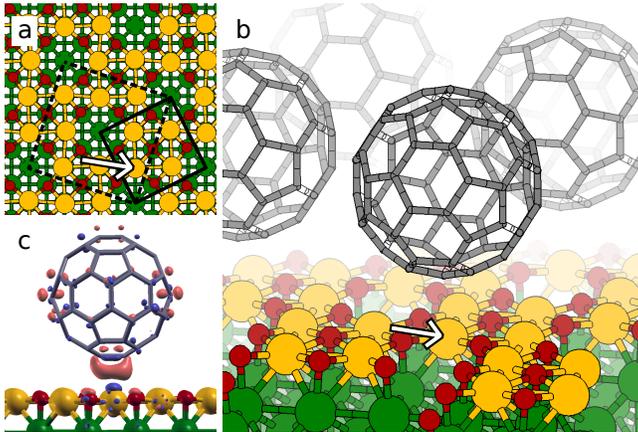


FIG. 3. (a) Ball-stick model of the pristine surface showing the  $(\sqrt{5} \times \sqrt{5})\text{-R}26.6^\circ$  reconstruction (solid line) and the  $(\sqrt{10} \times \sqrt{10})\text{-R}-18.4^\circ$  supercell used in the simulations (dashed line). Small dark (red) spheres are used for showing O atoms, large bright (yellow) spheres for Cr ones, and large dark (green) spheres for Fe atoms. (b)  $C_{60}$  (gray wireframe) adsorbed by a C-C bond on top of a Cr atom (see the arrows in panels a and b), the most stable adsorption configuration identified as optimized by DFT. (c) Electron density displacement upon adsorption,  $\Delta\rho = \rho_{\text{mol/surf}} - \rho_{\text{mol}} - \rho_{\text{surf}}$  showing increase (red) and depletion (blue) of electron density at isovalue  $\Delta\rho = \pm 0.01 \text{\AA}^{-3}$ .

According to our ab initio calculations, the most stable configuration among those analyzed is for  $C_{60}$  adsorbing through a C-C bond on top of a Cr atom (“bond/Cr” in the following). The corresponding geometry is reported in Fig. 3a, in which the squared unit cell is reported (dashed line) in comparison with that of the clean surface (solid line) and the adsorption position is marked by an arrow. The height of the C-C bond over the Cr atoms plane is  $2.74 \text{\AA}$ , corresponding to a C-Cr distance of  $2.80 \text{\AA}$  (see Fig. 3b).

This configuration is stabilized by the interaction between the  $\pi$  orbitals of  $C_{60}$  and the

$d$  states of Cr, as can be evidenced by looking at Fig. 3c. There, the adsorption charge displacement is reported,  $\Delta\rho = \rho_{\text{mol/surf}} - \rho_{\text{mol}} - \rho_{\text{surf}}$ , where  $\rho_{\text{mol/surf}}$ ,  $\rho_{\text{mol}}$  and  $\rho_{\text{surf}}$  are the electron densities of the full system, the  $\text{C}_{60}$  molecules, and the clean surface, respectively, all computed with the same atomic configurations. Electron density accumulates in the region between the C-C bond and the Cr atom.

Some predominant increase of electron density can also be appreciated (red lobes). This can be estimated by the Löwdin charges: we find that upon adsorption the molecule gets negatively charged (by adding  $1.55 e^-$ ), mostly at the expenses of O atoms (with a variation of  $-0.75 e^-$  per unit cell), then Cr atoms ( $-0.44 e^-/\text{unit cell}$ ) and Fe ones ( $-0.34 e^-/\text{unit cell}$ ). It should be noted that the Cr atom below the C-C bond (arrow in Fig. 3a and b) is computed to have a very similar charge state ( $-0.066 e^-/\text{atom}$ ) to the average of the Cr atoms ( $-0.055/\text{atom}$ ). This indicates that the interaction of  $\text{C}_{60}$  with the surface, in addition to the localized covalent bond, involves many atoms surrounding the molecule, each one participating to the charge displacement.

The second most stable adsorption configuration is again by the C-C bond, but at a Cr vacancy, and it is 0.7 eV higher in energy than the bond/Cr configuration discussed so far. The same molecular orientation at an O site is even higher ( $\approx 4$  eV). Looking instead at different molecular orientations at the Cr site, a molecule facing the substrate with a hexagonal face is 2.1 eV more energetically expensive than that facing the substrate by exposing the C-C bond; the energetic cost further increases the energy to 3.2 eV for a  $\text{C}_{60}$  molecule facing the Cr atom with a pentagonal face. Clearly, these adsorption configurations cannot be stabilized by the same mechanism (interaction of one  $\pi$  bond with the Cr states) available for the bond/Cr configuration. Indeed, for a molecule facing the substrate by a hexagon it would be more convenient to adsorb at a vacancy site (that we found to be the third most stable configuration, at +1.1 eV).

Coming back to the electronic properties of the system in its optimized geometry (bond/Cr), in Fig. 4a we report the spin polarization (the difference  $\rho_{\text{up}} - \rho_{\text{dw}}$  where Fe is magnetized “up”). This shows that the magnetization of the Cr layer (negative valued blue isosurfaces) is opposite to the one of iron (positive valued red isosurfaces), as expected for the clean surface. Also, most magnetization in the ground state lies in the substrate whereas the molecule is much less affected. Nevertheless, a mild spin polarization is induced in  $\text{C}_{60}$  by interaction with the substrate, as can be appreciated when a smaller isovalue of

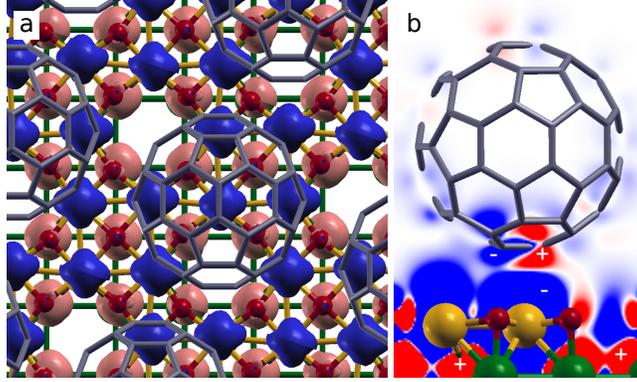


FIG. 4. Spin polarization in the bond/Cr geometry. a) Top view of the system with isosurfaces set to  $\pm 0.1 \text{ \AA}^{-3}$ . b) Side view with isosurfaces set to  $\pm 0.002 \text{ \AA}^{-3}$  to better highlight the contribution on the molecule. Brighter (red) and darker (blue) regions correspond to positive (spin-majority) and negative (spin-minority) polarization, respectively, as further indicated by  $+/-$  signs in panel b.

the spin polarization is considered, especially for those atoms of the molecule that are closer to the surface, as reported in Fig. 4b.

Similar but more quantitative information can be deduced by the density of states projected on different atoms (PDOS), which is reported in Fig. 5. The two lowest panels show the antiferromagnetic alignment of Cr and Fe while in the third one the small spin polarization of oxygen atoms can be appreciated, as discussed in our earlier work.<sup>16</sup> Notably, the binding energy of the oxygen-related features is in good agreement with the peak observed in the PES. The upper panel of Fig. 5 displays the PDOS on the  $C_{60}$  molecule (solid lines) and the contribution to the PDOS summed over the two carbon atoms facing to the surface (dashed lines). The molecular features are compatible with the peaks observed in the PES at  $-1.7 \text{ eV}$ ,  $-3.0 \text{ eV}$  and  $-5.0 \text{ eV}$ . The magnetization on the whole molecule is negligible on this scale. Differently, the two carbon atoms directly involved in the interaction with the substrate show a mild spin dependence of the DOS. Still, they are characterized by a small spin polarization parallel to one of the Cr atoms and amounting to 0.004 for the C atoms pointing towards a Cr, while the C atom closer to the vacancy displays a smaller spin polarization ( $-0.0019$ ), parallel to that of the iron substrate. These results demonstrate that there is a proximity effect of the substrate on the molecule, inducing a magnetic moment on carbon atoms which depends on the local environment.

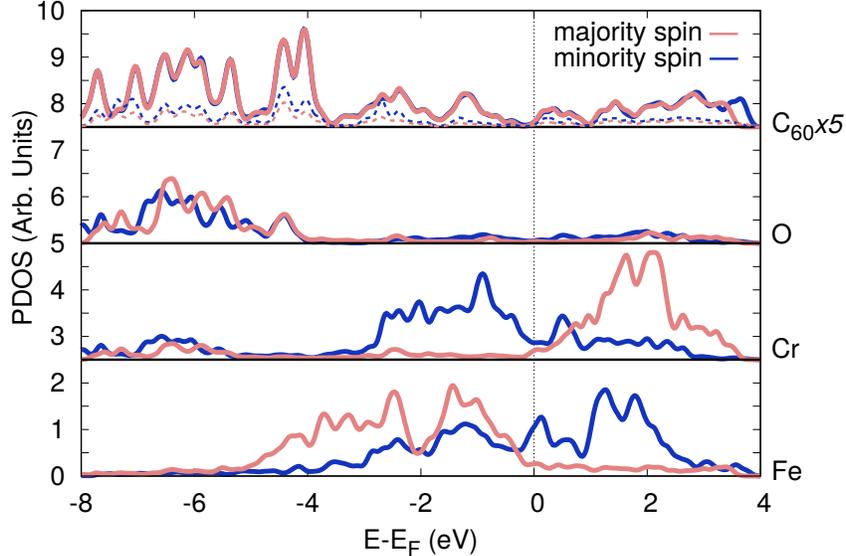


FIG. 5. Density of states projected on different atoms and summed over the Fe substrate, the Cr layer, the O atoms, and the  $C_{60}$  molecule, from bottom to top. Curves are stacked for clarity. The dashed lines shown on top are the spin-dependent PDOS summed over the two carbon atoms of the bond facing the substrate.

#### IV. CONCLUSIONS

In conclusion, we have focused our attention on a specific spinterface, formed by the coupling between  $C_{60}$  fullerene and the two-dimensional magnetic oxide  $Cr_4O_5$ , stabilized onto the Fe(001) substrate.

Such a system appears to be very interesting as it combines a significant electronic interaction, which is necessary in order to generate spin-polarized hybrid interface states, with a growth mode characterized by a high degree of order of the overlayer, which can form a compact fullerene monolayer. Both characteristics are promising in view of applications, where the interface states might play an active role in mechanisms such as spin filtering, while the possibility of growing compact molecular layers would be favorable for the realization of layered structures.

The ab initio calculations have offered further insights into the nature of this spinterface by determining the interaction and charge transfer between fullerene and substrate, and the spin-polarized electronic states. Simulations appeared to substantially agree with the experimental observations, thus crucially supporting them.

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