Exchange Splitting of a Hybrid Surface State and Ferromagnetic Order in a 2D Surface Alloy

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Surface alloys are highly flexible materials for tailoring the spin-dependent properties of surfaces. Here, we study the spin-dependent band structure of a DyAg₂ surface alloy formed on an Ag(111) crystal. We find a significant spin-splitting of the localized Dy 4f states and the formation of a parabolic hole-like Dy-Ag hybrid surface state with two exchange split spin branches. Our experimental findings are identified by density functional theory as clear spectroscopic fingerprints for a long-range ferromagnetic order of the localized Dy moments which is mediated by an indirect exchange coupling via electrons of the hybrid surface state.

The growing demand for next generation information technology with higher data processing speed and data storage capacity has triggered the quest to design novel materials with exotic spin structures. A particular effort has been devoted to reduce the size of the spintronic assemblies, which allows one to generate and manipulate spin-polarized charge carriers on ever smaller length scales ultimately down to the single layer limit. In this context, a highly tunable class of materials are surface alloys consisting of heavy metal and noble metal atoms. These 2D binary systems can be fabricated in long-range ordered superstructures on noble metal surfaces in which every third surface atom of the noble metal host material is replaced by a heavy metal atom (Pb, Bi and Sb) of the alloy species.

For spintronic applications, these binary systems are highly intriguing materials due to their spin-dependent band structure. The direct hybridization between both atomic species of the surface layer and underlying substrate results in the formation of a new hole-like hybrid surface state showing a Rashba-type spin splitting therein depends on the atomic spin-orbit coupling strength as well as on the vertical relaxation of the surface atoms. Both material parameters can be manipulated either by replacing the atomic species of the alloy or the host material or by the formation of tailored bonds between the alloy atoms and molecular adsorbates. These different external control mechanisms hence provide a clear route to functionalize 2D Rashba-type surface alloys according to the desired field of application.

So far, however, the concept of band structure engineering by surface alloying has mainly been limited to non-magnetic systems and has not been explored for ferromagnetic surface alloys. This is mainly due to the fact that the existence of long-range magnetic order was only recently demonstrated for 2D surface alloys consisting of the rare-earth material gadolinium (Gd) and the noble metals Ag and Au. While Ormaza et al. were able to reveal the Curie temperature as well as the direction of the magnetic anisotropy axis in both systems, the spin-dependent electronic band structure in the ferromagnetic phase of 2D surface alloys is still elusive.

In this Letter, we provide a comprehensive view onto the spin-dependent electronic properties of a 2D surface alloy consisting of the rare-earth dysprosium (Dy) and the noble metal silver grown on an Ag(111) single crystal surface. We have selected Dy instead of Gd since the non-vanishing orbital moment of Dy in contrast to Gd can lead to a more pronounced correlation between the vertical relaxation of the alloy atoms with respect to the surface plane and the spin-dependent electronic surface band structure, in analogy to the non-magnetic Rashba-type surface alloy. To study the band structure of the 2D surface alloy, we employ spin- and momentum-resolved photoemission using the combination of state-of-the-art time-of-flight momentum microscopy with an imaging spin filter. This novel experimental approach allows us to access the spin-dependent band structure of the 2D surface alloy throughout the entire Brilouin zone in a fixed experimental geometry and hence to disentangle the spectroscopic fingerprints of localized Dy 4f states and novel Dy-Ag hybrid surface states from the manifold of back-folded substrate bands. The latter appear due to the formation of a long-range ordered superstructure. Our experimental findings are discussed in the light of density functional theory (DFT) calculations allowing us to predict the magnetic properties of the 2D surface alloy.

We start our discussion with the growth and the structural characterization of the Dy-Ag surface alloy on the Ag(111) substrate. The adsorption of 1/3 monolayer (ML) of Dy on the clean Ag(111) surface at elevated sample temperature (575 K) results in the formation of the 2D surface alloy with high structural quality as shown
metal surface alloys as well as rare-earth atoms and fcc(111) noble metal surface. Consequently, we propose that the unit cell of the Dy-Ag surface alloy consists of one Dy atom and two Ag atoms forming a long-range ordered DyAg₂ surface alloy on the Ag(111) substrate.

A closer inspection of different local areas of the DyAg₂ surface alloy on a single Ag terrace reveals a non-uniformity of the Moiré superstructure leading to a non-equidistant distribution between the dark and bright areas in Figs. 1(a),(b). Interestingly, these local non-uniformities do not lift the long-range crystalline order of the Dy-Ag surface alloy. This is clearly visible in the low energy electron diffraction (LEED) pattern of the Dy-Ag surface alloy in Fig. 1(c), which exhibits intense diffraction spots with narrow spot profiles even for high diffraction order. For a more detailed analysis, we superimposed the left half of the LEED pattern with simulated diffraction spots of the $(\sqrt{3} \times \sqrt{3})R30^\circ$ superstructure. The red arrows mark the reciprocal unit cell of Ag(111), the green arrows the one of the DyAg₂ surface alloy. (d): Enlarged momentum space region around the first order diffraction spots of the $(\sqrt{3} \times \sqrt{3})R30^\circ$ superstructure. The blue circles correspond to a selected number of diffraction spots simulated for a $16 \times 16$ superstructure.

in the large scale scanning tunneling microscopy (STM) image in Fig. 1(a). We find a homogeneous growth of the surface alloy on the Ag terraces with a very low defect density. The hexagonal pattern of the Dy-Ag film – visible as dark spots in Fig. 1(a) – is not due to the atomic unit cell of the Dy-Ag surface alloy but can rather be attributed to a long range ordered Moiré structure, similar to the one reported recently for other rare-earth noble metal surface alloys. A more detailed view onto the local atomic structure of the Dy-Ag surface alloy can be obtained in the high resolution STM image in Fig. 1(b). Besides the Moiré superstructure which appears as bright and dark areas, the STM image is dominated by a hexagonal lattice of bright protrusions with a periodicity of $(5.1 \pm 0.15) \, \text{Å}$. The unit cell of this superstructure is marked as green hexagon in the inset of Fig. 1(b). The structural parameters of the Dy-Ag superstructure are fully in line with those of a $(\sqrt{3} \times \sqrt{3})R30^\circ$ superstructure, i.e., with the superstructure commonly observed for surface alloys between heavy metals as well as rare-earth

FIG. 1: (a),(b): STM images of a DyAg₂/Ag(111) film recorded with $U_{\text{bias}} = 30 \, \text{mV}$ ($I = 0.07 \, \text{nA}$). The inset in (b) was extracted from the region marked by a black dotted square and shows the local arrangement of the Dy atoms, the dark areas in (b) arise due to the Moiré pattern. (c): LEED pattern of the DyAg₂ structure recorded at $E=55 \, \text{eV}$ and room temperature. The left half of the diffraction data is superimposed with the simulated LEED pattern of a $(\sqrt{3} \times \sqrt{3})R30^\circ$ superstructure. The red arrows mark the reciprocal unit cell of Ag(111), the green arrows the one of the DyAg₂ surface alloy. (d): Enlarged momentum space region around the first order diffraction spots of the $(\sqrt{3} \times \sqrt{3})R30^\circ$ superstructure. The blue circles correspond to a selected number of diffraction spots simulated for a $16 \times 16$ superstructure.

We now turn to the electronic properties of the DyAg₂ surface alloy and start with the spin-integrated photoemission results. These data were obtained using synchrotron radiation from the BESSY II light source (Helmholtz Center Berlin) with horizontal light polarization (s-polarization) and a photon energy of $\hbar \omega = 25 \, \text{eV}$ at a sample temperature of $\approx 40 \, \text{K}$. The momentum resolved photoemission yield was recorded using a time-offlight momentum microscopy detector system which allows us to access the entire momentum space distribution of the valence band electrons above the sample surface in a fixed experimental geometry. Exemplary symmetrized constant energy (CE) maps of the momentum microscopy data set are shown in Figs. 2(a) and (b) for two characteristic binding energies of the Dy-Ag surface band structure. The surface Brillouin zone (SBZ) of the
simulate the expected momentum resolved photoemission yield of the Ag(111) surface due to photoelectron diffraction from Ag bulk states at the periodic Dy-Ag superstructure. This so called surface umklapp process is frequently observed for 2D superstructures on metallic substrates and can severely influence the interpretation of photoemission results of complex hybrid interfaces.\cite{21,23,24} Our simulation of the surface umklapp process at the DyAg$_2$/Ag(111) interface is based on experimental data of the bare Ag(111) surface recorded under identical experimental conditions. For simplicity, we simulated the surface umklapp process only for the ($\sqrt{3} \times \sqrt{3}) R 30^\circ$ superstructure without considering the Moiré pattern observed in our LEED and STM data. The simulated CE map is shown in the left half of the CE map in Fig. 2(c). For comparison, the right half shows the experimental CE map of the DyAg$_2$ surface alloy which we recorded at the same energy ($E_B = 0.8$ eV). The red hexagon marks the SBZ of the Ag(111) surface, the green hexagons illustrate the smaller SBZs of the DyAg$_2$ surface alloy. Most importantly, no photoemission intensity can be observed at the $\bar{K}_{Ag}$-point in the surface umklapp simulations (left half of CE map in Fig. 2c), which unambiguously proves that the ring-like emission features at the $\bar{K}_{Ag}$-point are an intrinsic spectroscopic signal of the Dy-Ag surface alloy. Crucially, the $K_{Ag}$-point of the Ag SBZ is equivalent to the $\bar{\Gamma}_Dy$ of the second SBZ of the DyAg$_2$ surface alloy, i.e., the new hybrid surface state is centered at the $\bar{\Gamma}_Dy$ point of the SBZ.

We conclude that the formation of a DyAg$_2$ surface alloy gives rise to a new Dy-Ag hybrid state at the $\bar{\Gamma}$-point of the SBZ of the 2D superstructure. The band dispersion of this hybrid surface state extracted at the $\bar{\Gamma}_Dy$-(1)-point is shown in Fig. 2(d). The shape of the hybrid band is indicated by a green curve as a guide to the eye. It clearly reveals the dispersion of a hole-like state, in analogy to all hybrid surface states reported for surface alloys on fcc(111) noble metal surfaces.\cite{21,24,41} In addition, we observe the appearance of a second band at larger binding energies indicated by a red curve as well as a non dispersive state close to E$_F$. While the latter can be attributed to the localized 4f states of Dy, the former band is due to a backfolded sp-substrate band.

The complex spin structure of the Dy-Ag hybrid valence band structure can be revealed by using the spin filter branch of the momentum microscope.\cite{21} Spin selectivity is obtained by the spin-dependent scattering of the photoelectrons at the Ir(001) scattering target for two characteristic scattering energies with distinct spin asymmetry at 12.5 eV and a negligible spin asymmetry at 19.0 eV. In this way, we can obtain spin resolved CE maps of the entire valence band structure of the Dy-Ag surface alloy. Five selected spin-resolved CE maps in the energy and momentum space region of the Dy-Ag hybrid surface state are shown in Fig. 3(a). The red and blue colored regions in these CE maps indicate bands of positive and negative spin polarization, while grey color corresponds to unpolarized spectral intensity.

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**FIG. 2:** Constant energy maps of the DyAg$_2$ band structure at $E_B = 0.2$ eV (a) and $E_B = 0.8$ eV (b). The surface Brillouin zone of the Ag(111) surface is sketched in red, the high symmetry directions are marked by dashed red lines. (c) Simulation of the surface umklapp processes of the Ag(111) sp-bands due to the formation of a ($\sqrt{3} \times \sqrt{3}) R 30^\circ$ superstructure. The left half of the CE map shows the surface umklapp simulation of the Ag bands at $E_B = 0.8$ eV, the right half the emission pattern of the DyAg$_2$ surface alloy recorded at $E_B = 0.8$ eV. (d) Band structure cut through the momentum microscopy data cube of DyAg$_2$ surface alloy along the $\bar{\Gamma} M$ direction of the Dy-Ag superstructure. The green curve is included as a guide to the eye to illustrate the band dispersion of the Dy-Ag hybrid surface state, the red curve marks the one of a backfolded Ag band.
All CE maps reveal a distinct spin contrast in momentum space which changes with binding energy. The CE maps at $E_B = 1.8 \text{ eV}$ and $E_B = 0.2 \text{ eV}$ exhibit an almost homogeneous spin contrast of opposite sign in the entire momentum space region. Interestingly, this non-vanishing spin-polarization is not only visible at the momentum space regions of the distinct spectroscopic features but also in the photoemission background pointing to the existence of two weakly dispersing states in this energy range with opposite spin polarization. These characteristic spectroscopic signatures can hence be assigned to the localized Dy 4f states. This conclusion is further supported by the corresponding energy vs. momentum cut in Fig. 3(b) which was extracted in this momentum space region along the $\Gamma M$ direction. It reveals two non-dispersing states of different spin polarization in narrow energy ranges centered around $E_B = 1.8 \text{ eV}$ and $E_B = 0.2 \text{ eV}$, respectively. Based on the energy sequence of the spin split Dy 4f states, we assign the spectroscopic feature with positive spin polarization to the localized Dy 4f states with majority spin character and the feature with negative spin polarization to the localized Dy 4f states with minority spin character. Accordingly, all spectroscopic features with positive spin polarization are attributed to majority states and features with negative spin polarization to minority states.

The spin contrast of the Dy-Ag hybrid surface state can be extracted from the CE maps in Fig. 3(a) recorded at $E_B = 1.2 \text{ eV}$, $E_B = 0.8 \text{ eV}$, and $E_B = -0.1 \text{ eV}$. Below $E_F$, we find a ring-like emission feature with marginal majority spin character (red) which is surrounded by a hexagonal emission pattern with negative (blue) spin contrast. In the energy vs. momentum cut in Fig. 3(b), the negative spin polarization coincides perfectly with the dispersion of the backfolded sp-bands of the Ag(111) surface indicating a spin selectivity of the surface umklapp process at the Dy layer. On the other hand, the small positive spin polarization does not follow the band dispersion of the Dy-Ag hybrid surface state, but is located in the photoemission background. Interestingly, the Dy-Ag hybrid state itself exhibits only a negligible spin contrast in this binding energy range. However, we find a ring-like emission with clear majority spin character in the high-energy cutoff of the Fermi distribution, i.e., at $E_B \approx -0.1 \text{ eV}$, which becomes only visible when enhancing the intensity contrast of this CE map. This spin-polarized band does not appear in the band structure in Fig. 3(b) due to the very small intensity of spectroscopic signatures above $E_F$ and the intensity scale of the energy vs. momentum cut which was optimized for the occupied part of the valence band structure. We propose that this band with majority spin character can be assigned to one spin branch of the hole-like Dy-Ag hybrid surface state.

To gain further insight into the origin of the spin polarized band structure of the Dy-Ag surface alloy, we performed density functional theory (DFT) calculations using the FLEUR ab initio package with the full potential linearized augmented plane wave basis (FLAPW). For the calculations, we selected the LDA-VWN exchange and correlation functional and considered the Coulomb correlation by a Hubbard parameter $U = 1.0 \text{ eV}$ and an exchange interaction parameter $J = 0.7 \text{ eV}$. The plane wave cutoff was set to $K_{\text{max}} = 4.3 \text{ Bohr}^{-1}$ and 733 k-points were considered in the full Brillouin zone. The Dy-Ag surface alloy was modeled by a supercell composed of 1 Dy atom and 8 Ag atoms resulting in one layer of the DyAg$_2$ surface alloy and 2 layers of the Ag(111) substrate. The vertical relaxation of the Dy atom and 1 Ag layer was optimized for the occupied part of the valence states.

The calculated spin-resolved band structure along the
We find an overall excellent agreement between the experimental band structure and the DFT+U calculations. Our band structure calculation predicts the existence of two non-dispersing states of opposite spin character in the Dy-Ag valence band as well as the formation of a hole-like Dy-Ag hybrid state centered at the $\bar{\Gamma}$-point of the SBZ in agreement with our experiment. The non-dispersing bands can be attributed to the localized Dy 4f states. The orbital projected density of states in this energy range is dominated by contributions of Dy 4f states as shown in the right half of Fig. 3(c). The calculations further reveal a vanishing exchange splitting of the Dy-Ag hybrid state for binding energies larger than $E_B = 0.2$ eV, i.e., for energies below the position of the minority Dy 4f band (negative spin polarization). Only for binding energies around the Fermi energy, the Dy-Ag surface state reveals an exchange split of $\Delta E_{\text{ex}} = 120$ meV. One spin branch with a hole-like dispersion and majority spin character is located right at the Fermi energy, the second branch with minority spin character is shifted by 120 meV towards the vacuum level. Hence, the exchange splitting of the Dy-Ag hybrid surface state as well as of the localized Dy 4f states both in theory and experiment are clear spectroscopic fingerprints for the formation of a long range ordered ferromagnetic phase in the DyAg$_2$ surface alloy on Ag(111). Our DFT+U simulation moreover predicts a magnetic spin moment of $\mu_{\text{Dy}} = 4.3 \mu_B$ per Dy atom and a marginal magnetic moment on the Ag sites of the order of $\mu_{\text{Ag}} = 0.003 \mu_B$.

Interestingly, the best agreement between experiment and theory was obtained for a Coulomb interaction constant (Hubbard parameter) $U = 1.0$ eV. This value is surprisingly small compared to previous DFT+U calculations of bulk materials containing Dy$_2$O$_3$ and hence points to a highly efficient screening of the electron correlations of the Dy 4f electrons by the host material Ag. This underlines the important role of the Dy-Ag interaction for the overall spin-dependent and magnetic properties of the surface alloy.

In conclusion, the present experimental and theoretical investigation of the spin-dependent electronic structure of a Dy-Ag surface alloy reveals clear spectroscopic indications for the formation of a low-dimensional ferromagnetic phase at low sample temperature of 40 K. Using spin-resolved momentum microscopy, we found a significant spin-split of the localized Dy 4f states as well as an exchange split hole-like Dy-Ag hybrid surface state in the center of the SBZ. We propose that the long range order of the localized Dy moment is mediated by this Dy-Ag hybrid surface state. As a consequence, the magnitude of exchange splitting of the hybrid surface state crucially depends on the strength of the indirect, RKKY-like exchange coupling in the alloy layer as well as on the localized magnetic moments of the rare earth atoms. Considering the high tunability of binary surface alloys, our findings lay the foundation for tailoring and controlling the spin order and the spin-dependent charge carrier properties in low dimensional structures by surface alloying.

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1. L. Wang, I. Meric, P. Y. Huang, Q. Gao, Y. Gao, H. Tran, T. Taniguchi, K. Watanabe, L. M. Campos, D. A. Muller, et al., Science 342, 614 (2013).
2. B. Dhubash, M.-B. Martin, C. Deranlot, B. Servet, S. Xavier, R. Mattana, C. Berger, W. de Heer, F. Petroff, et al., Nat. Phys. 8, 557 (2012).
3. A. Dankert and S. P. Dash, Nat. Commun. 8, 16093 (2017).
4. C. R. Ast, J. Henk, A. Ernst, L. Moreschini, M. C. Falub, D. Pucilé, P. Bruno, K. Kern, and M. Grioni, Phys. Rev. Lett. 98, 186807 (2007).
5. H. Bentmann, F. Forster, G. Bihlmayer, E. V. Chulkov, L. Moreschini, M. Grioni, and F. Reinert, Europhys. Lett. 87, 37003 (2009).
6. L. Moreschini, A. Bendouman, H. Bentmann, M. Assig, K. Kern, F. Reinert, J. Henk, C. R. Ast, and M. Grioni, Phys. Rev. B 80 (2009).
7. F. Meier, V. Petrov, H. Mirhosseini, L. Patthey, J. Henk, J. Osterwalder, and J. H. Dil, J. Phys.: Condens. Matter 23, 072207 (2011).
8. G. Bihlmayer, S. Blügel, and E. V. Chulkov, Phys. Rev. B 75, 195414 (2007).
9. M. Maniraj, D. Jungkenn, W. Shi, S. Emmerich, L. Lyu, J. Kollamana, Z. Wei, B. Yan, M. Cinchetti, S. Mathias, et al., Phys. Rev. B 98, 205419 (2018).
10. L. Petersen and P. Hedégard, Surf. Sci. 459, 49 (2000).
11. I. Gierz, F. Meier, J. H. Dil, K. Kern, and C. R. Ast, Phys. Rev. B 83, 195122 (2011).
12. I. Gierz, B. Stadtmüller, J. Vuorinen, M. Lindroos, F. Meier, J. H. Dil, K. Kern, and C. R. Ast, Phys. Rev. B 81 (2010).
13. B. Stadtmüller, J. Seidel, N. Haag, L. Grad, C. Tusche, J. Osterwalder, and J. H. Dil, Phys. Rev. B 83, 195122 (2011).
14. R. Friedrich, V. Caciuc, G. Bihlmayer, N. Atodiresei, and S. Blügel, New J. Phys. 19, 043017 (2017).
15. M. Ormaza, L. Fernandez, M. Ilyn, A. Magana, B. Xu, and P. Bruno, K. Kern, and M. Grioni, Phys. Rev. B 83, 205419 (2018).
M. J. Verstraete, M. Gastaldo, M. A. Valbuena, P. Gargiani, A. Mugarza, et al., Nano Lett. p. 4230 (2016).

A. Correa, B. Xu, M. J. Verstraete, and L. Vitali, Nanoscale 8, 19148 (2016).

K. Medjanik, O. Fedchenko, S. Chernov, D. Kutnyakhov, M. Ellguth, A. Oelsner, B. Schonhense, T. R. F. Peixoto, P. Lutz, C.-H. Min, et al., Nat. Mater. pp. pages 615–621 (2017).

G. Schönhense, K. Medjanik, S. Chernov, D. Kutnyakhov, O. Fedchenko, M. Ellguth, D. Vasilyev, A. Zaporozhchenko-Zymaková, D. Panzer, A. Oelsner, et al., Ultramicroscopy 183, 19 (2017).

M. Kolbe, P. Lushchyk, B. Peteroit, H. J. Elmers, G. Schönhense, A. Oelsner, C. Tusche, and J. Kirschner, Phys. Rev. Lett. 107, 207601 (2011).

D. Kutnyakhov, P. Lushchyk, A. Fognini, D. Perriard, M. Kolbe, K. Medjanik, E. Fedchenko, S. A. Nepijko, H. J. Elmers, G. Salvatella, et al., Ultramicroscopy 130, 63 (2013).

J. Anderson and G. J. Lapeyre, Phys. Rev. Lett. 36, 376 (1976).

A. A. Ünal, A. Winkelmann, C. Tusche, F. Bisio, M. Ellguth, C.-T. Chiang, J. Henk, and J. Kirschner, Phys. Rev. B 86, 125447 (2012).

J. Stöckl, A. Jurenkow, N. Großmann, M. Cinchetti, B. Stadtmüller, and M. Aeschlimann, J. Phys. Chem. C 122, 6585 (2018).

Simon Moser, J. Electron Spectrosc. Relat. Phenom. 214, 29 (2017).

L. Giovanelli, F. C. Bocquet, P. Amsalem, H.-L. Lee, M. Abel, S. Clair, M. Koudia, T. Faury, L. Petaccia, D. Topwal, et al., Phys. Rev. B 87, 035413 (2013).

http://www.flapw.de

S. H. Vosko, L. Wilk, and M. Nusair, Can. J. Phys. 58, 1200 (1980).

V. I. Anisimov, F. Aryasetiawan, and A. I. Lichtenstein, J. Phys. Condens. Matter 9, 767 (1997).

A. B. Shick, A. I. Liechtenstein, and W. E. Pickett, Phys. Rev. B 60, 10763 (1999).

K. Rahmanizadeh, G. Bihlmayer, M. Luysberg, and S. Blügel, Phys. Rev. B 85, 075314 (2012).

M. Raekers, K. Kuepper, S. Bartkowski, M. Prinz, A. V. Postnikov, K. Potzger, S. Zhou, A. Arulraj, N. Stüßer, R. Uecker, et al., Phys. Rev. B 79, 125114 (2009).