

## **Coupling of ferromagnetism and structural phase transition in V<sub>2</sub>O<sub>3</sub>/Co bilayers**

Wang, C.; Xu, C.; Wang, M.; Yuan, Y.; Liu, H.; Dillemans, L.; Homm, P.; Menghini, M.;  
Locquet, J.-P.; Haesendonck, C. V.; Zhou, S.; Ruan, S.; Zeng, Y.-J.;

Originally published:

November 2017

**Journal of Physics D: Applied Physics 50(2017), 495002**

DOI: <https://doi.org/10.1088/1361-6463/aa9607>

Perma-Link to Publication Repository of HZDR:

<https://www.hzdr.de/publications/Publ-26371>

Release of the secondary publication  
on the basis of the German Copyright Law § 38 Section 4.

Manuscript submitted to *Journal of Physics D: Applied Physics*

## Coupling of ferromagnetism and structural phase transition in $V_2O_3/Co$ bilayers

Changan Wang,<sup>1,2</sup> Chi Xu,<sup>2</sup> Mao Wang,<sup>2</sup> Ye Yuan,<sup>2</sup> Haoliang Liu,<sup>3a)</sup> Leander Dillemans,<sup>3</sup> Pia Himm,<sup>3</sup> Mariela Menghini,<sup>3</sup> Jean-Pierre Locquet,<sup>3</sup> Chris Van Haesendonck,<sup>3</sup> Shengqiang Zhou,<sup>2</sup> Shuangchen Ruan,<sup>1</sup> and Yu-Jia Zeng<sup>1b)</sup>

1) Shenzhen Key Laboratory of Laser Engineering, College of Optoelectronic Engineering, Shenzhen University, 518060 Shenzhen, China

2) Helmholtz-Zentrum Dresden-Rossendorf, Institute of Ion Beam Physics and Materials Research, Bautzner Landstr. 400, 01328 Dresden, Germany

3) Laboratory of Solid-State Physics and Magnetism, KU Leuven, Celestijnenlaan 200 D, BE-3001 Leuven, Belgium

<sup>a)</sup> E-mail: [liuhaoliang03@gmail.com](mailto:liuhaoliang03@gmail.com) (H.-L. Liu)

<sup>b)</sup> E-mail: [yjzeng@szu.edu.cn](mailto:yjzeng@szu.edu.cn) (Y.-J. Zeng)

**ABSTRACT**

Interfacial coupling in hybrid magnetic heterostructures is being considered as a unique opportunity for functional material design. Here, we present the temperature dependence of magnetic properties of  $V_2O_3/Co$  bilayers influenced by the structural phase transition that is accompanied by a metal-insulator transition in  $V_2O_3$ . Both the coercivity and the magnetization of Co layer are strongly affected by the interfacial stress due to the magnetostrictive effect in the ferromagnetic film. The observed change in coercivity is as large as 59% in a narrow temperature range. The changes in the magnetic properties are reproducible and reversible, which are of importance for potential applications.

Keywords: Magnetostrictive coupling, Metal-insulator transition, Structural phase transition, Heterostructure

## I. Introduction

Manipulating magnetic properties of ferromagnetic (FM) layers through stimuli other than a magnetic field has attracted a lot of research attention in recent years due to its potential for device applications [1-3]. Examples of external stimuli include electric field, electric current, pressure and light, which open new routes to tune the properties of magnetic materials in a controlled way [3-8]. Thin-film hybrid structures are particularly sensitive to external stimuli and they are ideal platforms to investigate the underlying physical mechanisms dominating the properties of magnetoelectric heterostructures, such as ferromagnetic/multiferroic, piezoelectric/ferromagnetic and ferroelectric/ferromagnetic heterostructures [9-11]. One promising approach that can exploit the manipulation of the magnetic properties is provided by placing a ferromagnet in proximity to materials that undergo a structural phase transition (SPT) accompanied by a metal-insulator transition (MIT) [5, 12-15]. In this case, the MIT and SPT can be induced not only by changing temperature, but also can be driven by pressure, light or electric current [5]. Therefore, these materials offer the possibility to tune the magnetic properties of the ferromagnetic layer by multiple stimuli.

Among all the materials that show a MIT and SPT, vanadium sesquioxide ( $V_2O_3$ ) is one of the most fascinating systems due to its rich phase diagram [16, 17].  $V_2O_3$  shows a first-order phase transition (at  $\sim 160$  K) from a high temperature metallic state to a low-temperature insulating state [18]. The change in resistance can be as large as 7 orders of magnitude across the MIT [5]. These remarkable features are associated with a SPT from a rhombohedral crystal structure in the metallic phase to a monoclinic crystal structure in the insulating phase that occurs simultaneously with the electronic phase transition [13]. The crystallographic change occurring in  $V_2O_3$  provides the possibility to achieve reversible manipulation of the magnetic properties of the FM layer in hybrid thin-film through the magnetoelastic anisotropy that is induced by phase coexistence at the nanoscale in the MIT

1  
2  
3 material and the interfacial stress within the transition temperature range. As already  
4 reported in literature [12, 13, 15], the proximity of FM layers, such as Fe, Co or Ni, to  $V_2O_3$   
5 and  $VO_2$  affects the magnetic and electronic properties at the interface between FM and SPT  
6 materials. Hence, combining  $V_2O_3$  film with a ferromagnetic Co film in a bilayer  
7 configuration provides a unique way to investigate the coupling effect when the oxide  
8 undergoes a SPT accompanied by a MIT. However, the coupling effect between  $V_2O_3$  and  
9 Co has not been studied in detail.

10  
11 In this paper, we describe the fabrication of  $V_2O_3/Co$  bilayers grown by molecular  
12 beam epitaxy (MBE) and investigate their temperature-dependent magnetic properties. We  
13 find that the ferromagnetic properties of the Co thin film in the bilayers are strongly affected  
14 by interfacial stress associated with the SPT accompanied by a MIT in  $V_2O_3$ . Reversible  
15 changes are observed for the coercivity and magnetization across the SPT in the  $V_2O_3$  film.  
16 This effect results in a reproducible modification of magnetic properties, which is of direct  
17 relevance for technological applications.

## 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 **II. Experimental details**

38  
39 The  $V_2O_3/Co$  bilayers are grown by MBE in a chamber with a base pressure of  $1 \times 10^{-9}$   
40 mbar. 30-nm-thick  $V_2O_3$  films are deposited on (0001)- $Al_2O_3$  substrates at a temperature of  
41 742 °C and in an oxygen partial pressure of  $8.3 \times 10^{-7}$  mbar. 5-nm-thick Co films are then ex-  
42 situ deposited on the  $V_2O_3$  thin films as well as on bare  $Al_2O_3$  substrates at room temperature  
43 and at a base pressure of  $5 \times 10^{-9}$  mbar [19]. To prevent oxidization, 3 nm of Au is deposited in-  
44 situ as capping layer on top of the Co layer. The thin-film samples are characterized by means  
45 of high resolution X-ray diffraction (XRD) using Cu  $K\alpha$  radiation. The surface morphology of  
46 the Co film on  $V_2O_3$  is characterized by *in-situ* scanning tunneling microscopy (STM) before  
47 capping with Au. The temperature-dependence of the resistance of the  $V_2O_3$  film is measured  
48 using a four-probe geometry and a constant current source. Temperature is swept at a slow  
49 rate of 1-2 K/min with a Lakeshore 332 temperature controller. Magnetic properties are  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

measured with a superconducting quantum interference device magnetic property measurement system (SQUID-MPMS, Quantum Design).

### III Results and discussion

In Fig. 1(a) we present the XRD scan for a 30 nm-thick  $V_2O_3$  film grown on an (0001) oriented  $Al_2O_3$  substrate. It is obvious that the sample shows good crystalline quality and the absence of any secondary phase. In this case, only the peak corresponding to the (0006) plane of  $V_2O_3$  is observed, indicating that the  $V_2O_3$  film grows epitaxially on the substrate along the (0001) orientation. To determine the microscopic structure of the Co film, we present in Fig.1(b) the STM image of a 5-nm-thick Co layer on  $V_2O_3$ . Nearly circular, coalescing Co grains are observed with typical size smaller than 8 nm and with a RMS roughness of 0.52nm. The inset of Fig. 1(b) shows the height profile across the line indicated in the 2D map. The RSM roughness and height profile confirm the successful preparation of the  $V_2O_3$ /Co bilayers, which allows performing a reliable investigation of the heterostructural magnetic properties.

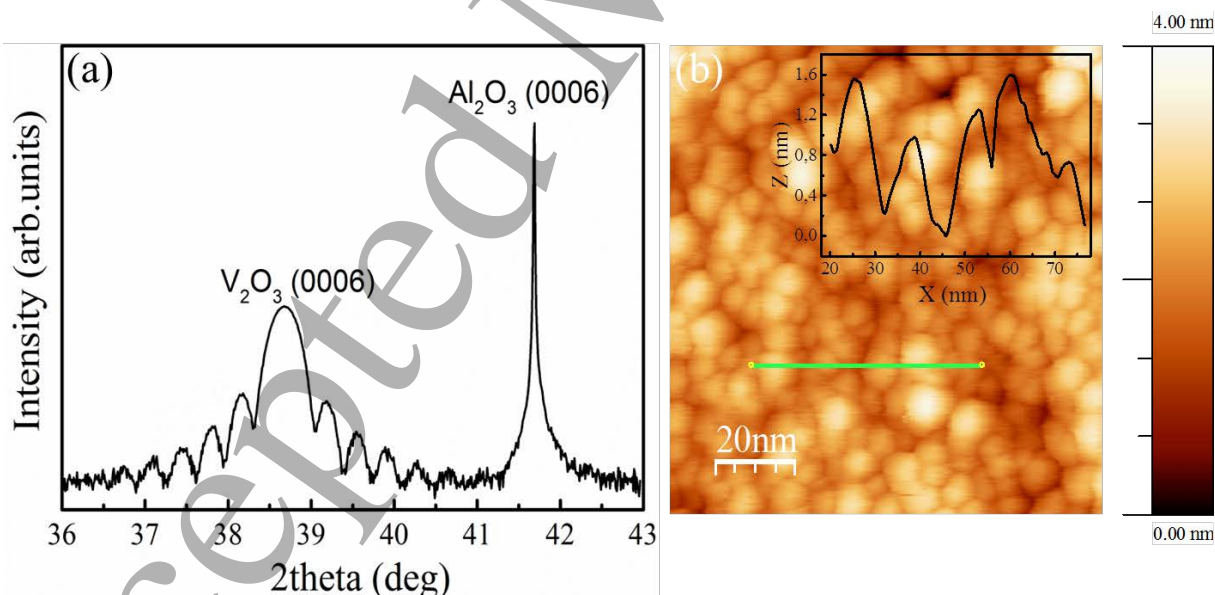


Fig. 1. (a) XRD  $\theta/2\theta$  scans for a 30 nm-thick  $V_2O_3$  film grown on an  $Al_2O_3$  substrate. (b) Surface morphology of a 5-nm-thick Co film on top of a 30-nm-thick  $V_2O_3$  film as measured by STM. Inset shows the height profile along the line in (b) and the extracted RSM roughness is 0.52 nm.

To investigate the coupling between  $V_2O_3$  and Co, the magnetization curves of the  $V_2O_3$

1  
2  
3 /Co bilayers are measured at different temperatures near the SPT in the  $V_2O_3$ . The results are  
4 plotted in Fig. 2(a). All curves show a ferromagnetic behavior with varying coercivity,  
5 originating from the top Co layer. Fig. 2(b) summarizes the dependence of the coercive field  
6  $H_c$  on temperature for the  $V_2O_3$ /Co bilayer compared to a reference Co film grown directly on  
7  $Al_2O_3$ . For the Co reference film, we observe the standard (almost) linear dependence of the  
8 coercivity on temperature. For the bilayers, however, a strong deviation from the linear  
9 behavior of  $H_c$  occurs within a narrow temperature range (160 K - 185 K). For temperatures  
10 higher than 185 K,  $H_c$  of the bilayer is almost the same as of the Co layer. However, an  
11 increase in  $H_c$  of ~59% (from 92 Oe at 185 K to 146 Oe at 160 K) is observed in the bilayer  
12 while the change in the same temperature range for the Co film is of only ~15%. Interestingly,  
13 the deviation in  $H_c$  is observed within a temperature range where the  $V_2O_3$  structural phase  
14 transition occurs (in this temperature range the  $V_2O_3$  layer exhibits a MIT, see Fig. 3(a)) [13,  
15 20]. On the other hand, the coercive field in the  $V_2O_3$ /Co bilayers is slightly larger for  
16 increasing than for decreasing temperature (see inset in Fig. 2(b)), which can be attributed to  
17 the typical thermal hysteresis observed for the structural phase transition in  $V_2O_3$  [12].  
18 However, when the temperature is below 160 K and above 185 K, i.e. outside of the phase  
19 transition region, the coercivity shows a quasi-linear dependence on temperature and it is  
20 independent of the temperature sweep direction. We therefore can conclude that the observed  
21 anomalous ferromagnetism in the thin Co films is associated with the SPT in the adjacent  
22  $V_2O_3$  thin film.  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

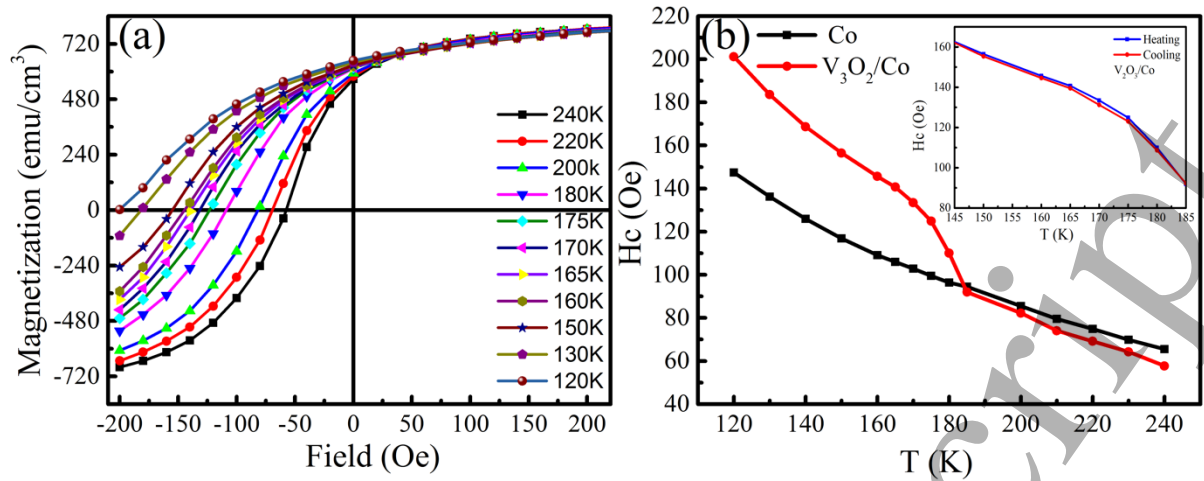


Fig. 2. (a) In-plane M-H curves of a V<sub>2</sub>O<sub>3</sub>/Co bilayer at different temperatures near the structural phase transition in the V<sub>2</sub>O<sub>3</sub> film. (b) Coercivity versus temperature for a V<sub>2</sub>O<sub>3</sub>/Co bilayer compared to a reference Co film. The inset in (b) shows the coercivity dependence on temperature between 145 K and 185 K.



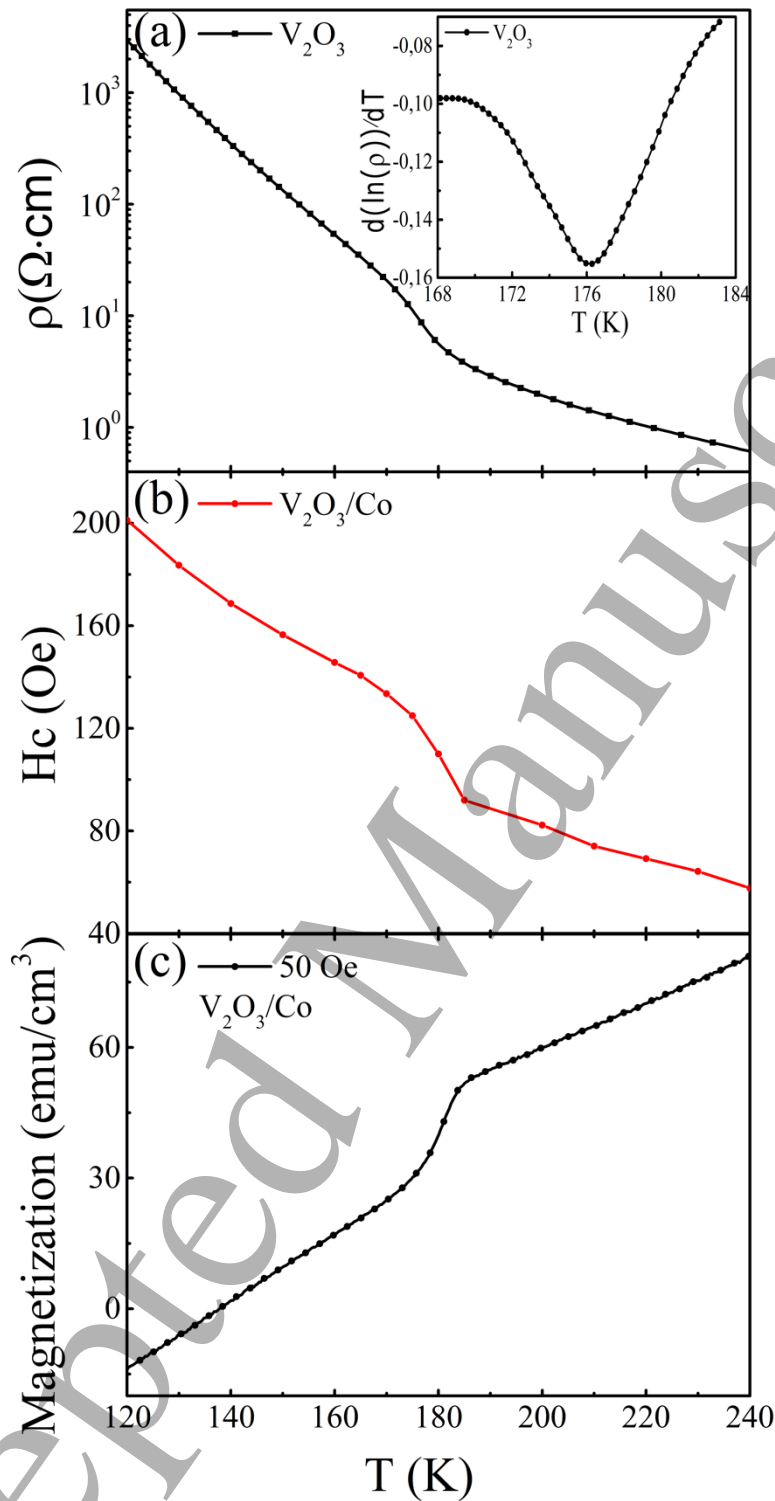


Fig. 3. (a) Resistivity as a function of temperature for the  $\text{V}_2\text{O}_3$  film. Inset shows the differential curves of resistivity vs temperature to indicate the transition temperature of 176 K. (b) Coercivity versus temperature and (c) ZFC magnetization measured at 50 Oe as a function of temperature for a  $\text{V}_2\text{O}_3/\text{Co}$  bilayer.

In Fig. 3(a) we present the resistivity as a function of temperature for a  $\text{V}_2\text{O}_3$  film. One can

1  
2  
3 see that a typical MIT is observed for our  $V_2O_3$  films, which is similar to previous reports for  
4  
5  $V_2O_3$  [20, 21]. The transition temperature ( $T_{MIT}$ ) is determined from the derivative of  $\ln(\rho)$   
6  
7 and plotted with respect to temperature, as shown in the inset of Fig. 3(a). The plot shows a  
8  
9 clear peak, indicating  $T_{MIT}$  in resistivity at 176 K. Fig. 3(b) summarizes the dependence of the  
10  
11 coercive field on temperature for the  $V_2O_3$  /Co bilayer. It indicates the deviation from the  
12  
13 linear behavior in the temperature range where the  $V_2O_3$  SPT occurs. In Fig. 3(c) we present  
14  
15 the behavior of the zero-field-cooled (ZFC) magnetization as a function of temperature in the  
16  
17 presence of a 50 Oe magnetic field. It is evident that an anomaly in the magnetization occurs  
18  
19 within the same temperature range where the deviation from the linear behavior of the  
20  
21 coercivity is observed. Hence, the MIT and SPT are centered approximately at the same  
22  
23 temperature at which the behavior of the coercivity and magnetization with temperature  
24  
25 deviate from the Co reference film. Thus, the magnetic properties of the Co layer can be  
26  
27 modified by relying on the SPT and MIT in the adjacent  $V_2O_3$  layer. Note that the transition in  
28  
29 resistivity typically spans a broad region in Fig. 3(a). This is because the transition in  
30  
31 resistivity with decreasing temperature goes through four successive stages: a homogenous  
32  
33 metallic state, a striped nanotexture of percolating electronic phase coexistence, an  
34  
35 inhomogeneous correlated insulator state and a homogeneous insulator state [18]. As  
36  
37 described in Ref. [18], in the region of coexistence of insulating and metallic domains below  
38  
39 the bulk  $T_{MIT}$ , the transport is influenced by percolation.  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

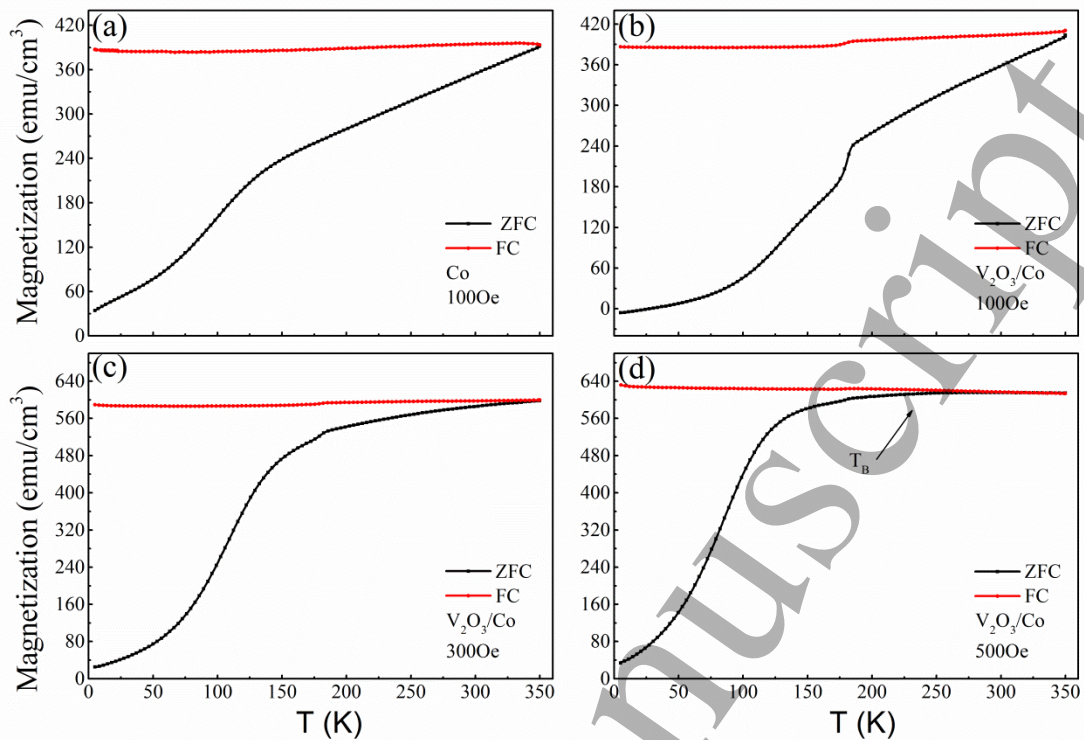


Fig. 4. The ZFC and FC magnetization measured for (a) a Co film at 100 Oe and (b) a V<sub>2</sub>O<sub>3</sub>/Co bilayer at 100 Oe, (c) 300 Oe and (d) 500 Oe. Note that the blocking temperature  $T_B$  is indicated only for a field of 500 Oe. For other fields  $T_B$  is above 350 K.

In Fig. 4 the zero-field-cooled (ZFC) and field-cooled (FC) magnetization curves of a Co thin film at 100 Oe and of the V<sub>2</sub>O<sub>3</sub>/Co bilayer at different magnetic fields are shown. Since the contribution of the V<sub>2</sub>O<sub>3</sub> to magnetization is negligible, all curves have been normalized with respect to the Co volume. From Fig. 4(a) it is clear that the Co thin film shows splitting of the ZFC and FC, which is likely due to the small size of Co grains contained in the film. The magnetization reveals a superparamagnetic behavior with “blocking” occurring at a temperature higher than 350 K [22]. On the other hand, it is noticeable that there is a different behavior in the magnetization of the bilayers as already shown in Fig. 3(c) (see Fig. 4(b)). The magnetization (both in the ZFC and FC curves) shows a small kink in the same temperature range where the deviations from the linear behavior in the coercivity are observed, as shown in Fig. 3(b). This further indicates that both effects are closely related to the SPT in the V<sub>2</sub>O<sub>3</sub>

1  
2  
3 thin film. In Fig. 4 (b) and (c) the splitting between the ZFC and FC magnetization at different  
4  
5 magnetic fields disappears at higher temperatures, which can be attributed to a  
6  
7 superparamagnetic behavior resulting from the presence of small Co grains (see Fig. 1(b)).  
8  
9 We note that the ZFC magnetization gradually increases (grains become unblocked) until  
10  
11 reaching the average blocking temperature  $T_B$ , while the FC curves slowly decrease with  
12  
13 increasing temperature. Moreover, it is evident that  $T_B$  tends to shift to lower temperatures  
14  
15 when the applied magnetic field increases. This is expected and can be accounted for the fact  
16  
17 that a larger magnetic field tends to reduce the energy barriers that hinder the fluctuation of  
18  
19 magnetic moment, resulting in a transition to a thermally unfrozen state at lower temperatures.  
20  
21  
22  
23  
24

25 As indicated above, another interesting finding is that the kink in magnetization, which is  
26  
27 observed within the temperature interval where the SPT in the  $V_2O_3$  thin film occurs,  
28  
29 gradually vanishes when increasing the applied magnetic field, as illustrated in Fig. 4 and Fig.  
30  
31 3(c). Moreover, when the applied magnetic field is relatively low, these striking changes in the  
32  
33 magnetization as function of temperature indicate that the Co magnetization may be not fully  
34  
35 saturated. On the other hand, the SPT in  $V_2O_3$  appears to play a crucial role to induce these  
36  
37 changes in the magnetic behavior of the  $V_2O_3$  /Co bilayers. It is well known that the  
38  
39 magnetism of magnetic metal atoms is susceptible to an environment with fewer nearest  
40  
41 neighbor atoms [23]. For example, surface atoms can reveal a strong magnetic polarization,  
42  
43 while the bulk atoms have a smaller magnetic moment. Hence, the weaker interatomic  
44  
45 hybridization at the  $V_2O_3$  /Co interface is likely to influence the magnetization of Co atoms at  
46  
47 the interface. The symmetry and coordination number at the interface of the bilayers can be  
48  
49 changed due to the SPT in the  $V_2O_3$  film, which induces a narrowed  $d$ -band and therefore  
50  
51 localizes surface states or surface resonance states in the Co atoms. This then results in a  
52  
53 significantly stronger magnetic polarization in the interface region and can induce an anomaly  
54  
55 in the magnetization for small applied magnetic fields [23, 24]. When the applied magnetic  
56  
57 field is, however, increased to 500 Oe, the results in Fig. 4 (d) illustrate that the coupling  
58  
59  
60

effect at the interface is suppressed and the magnetization of the Co layer is not affected by the SPT in the  $V_2O_3$  layer. This indicates that the effect of weakened interatomic hybridization near the  $V_2O_3$ /Co interface becomes suppressed by the external magnetic field at which the Co may also be fully saturated.

As we mentioned above, the remarkably reproducible modification of the coercivity is also a result of the SPT in the  $V_2O_3$  layer, which is accompanied by a MIT. The  $V_2O_3$  SPT gives rise to a 1.4 % volume increase when undergoing a transition from a rhombohedral phase at higher temperature to a monoclinic phase at lower temperature [21]. The volume expansion leads to epitaxial stress in the adjacent FM Co layer, thus changing the magnetic properties by an inverse magnetostrictive effect. The magnitude of the stress that produces the variations in coercivity shown in Fig. 2(b) can be estimated from the stress anisotropy field  $H_{K\sigma}$ , which is given by: [25]

$$H_{K\sigma} = \frac{3\lambda_{si}\sigma}{M_S} \quad (1)$$

where  $\lambda_{si}$  is the saturation magnetostriction,  $\sigma$  is the stress in MPa, and  $M_S$  is the saturation magnetization in G or emu/cm<sup>3</sup>. The observed value of coercivity at 120 K, at which the SPT is expected to be completed, is 147 Oe and 201 Oe in the single Co film and the bilayer, respectively [see Fig. 2(b)]. The additional anisotropy coercivity produced by the coupling effect is then 54 Oe. We calculate  $M_S$  to be 632 emu/cm<sup>3</sup> according to the results presented in Fig. 2(a). However, there are large variations of reported  $\lambda_{si}$  values for Co, ranging from  $\sim -11 \times 10^{-6}$  to  $-95 \times 10^{-6}$  [25-28]. Also, the Co layer is likely to be a collection of coalesced nanoparticles forming a continuous film. We therefore cannot make a good estimate of the stress produced by the  $V_2O_3$  layer according to the Equation (1), nor can we make a comparison with the coupling of a  $VO_2$ /Ni layer, which produces a  $\sigma = 589$  MPa across the SPT [12]. However, we expect a stronger coupling effect when the Co films are grown in-situ on top of the  $V_2O_3$  films.

#### IV. Conclusion

We observe magnetostrictive coupling across the interfaces of hybrid magnetic heterostructures. The coupling is caused by the interfacial stress induced by the structural phase transition accompanied by the metal-insulator transition in the  $V_2O_3$  film, which causes pronounced changes in the magnetic properties of  $V_2O_3/Co$  bilayers due to the magnetostrictive effect. The change in coercivity is as large as 59% within a narrow temperature range across the transition. The reversible modification of the magnetic properties of ferromagnets opens up new possibilities for technological applications in which relevant ferromagnetic properties, such as magnetization and coercivity, can be tailored for desired applications.

#### Acknowledgments

This work was supported by the National Natural Science Foundation of China under Grant No. 51502178, the Shenzhen Science and Technology Project under Grant No. JCYJ20150324141711644 and the Natural Science Foundation of SZU. C. A. Wang, C. Xu, M. Wang and Y. Yuan thank China Scholarship Council for financial supports. P. Homm acknowledges support from Becas Chile-CONICYT. We are thankful to Dr. Jörg Grenzer for discussions.

## References

- [1] Cherifi R, Ivanovskaya V, Phillips L, Zobelli A, Infante I, Jacquet E, Garcia V, Fusil S, Briddon P, and Guiblin N 2014 *Nat. Mater.* **13** 345-51.
- [2] Chernyshov A, Overby M, Liu X, Furdyna J K, Lyanda-Geller Y, and Rokhinson L P 2009 *Nat. Phys.* **5** 656-9.
- [3] Kirilyuk A, Kimel A V, and Rasing T 2010 *Rev. Mod. Phys.* **82** 2731.
- [4] Vaz C A 2012 *J. Phys.: Condens. Matter.* **24** 333201.
- [5] Yang Z, Ko C, and Ramanathan S 2011 *Annu. Rev. Mater. Res.* **41** 337-67.
- [6] Kim J, Sinha J, Hayashi M, Yamanouchi M, Fukami S, Suzuki T, Mitani S, and Ohno H 2013 *Nat. Mater.* **12** 240-5.
- [7] Rokhinson L P, Overby M, Chernyshov A, Lyanda-Geller Y, Liu X, and Furdyna J K 2012 *J. Magn. Magn. Mater.* **324** 3379-84.
- [8] Saranu S, Selve S, Kaiser U, Han L, Wiedwald U, Ziemann P, and Herr U 2011 *Beilstein. J. Nanotech.* **2** 268-75.
- [9] Heron J, Trassin M, Ashraf K, Gajek M, He Q, Yang S, Nikonov D, Chu Y, Salahuddin S, and Ramesh R 2011 *Phys. Rev. Lett.* **107** 217202.
- [10] Geprägs S, Brandlmaier A, Opel M, Gross R, and Goennenwein S 2010 *Appl. Phys. Lett.* **96** 142509.
- [11] Mardana A, Ducharme S, and Adenwalla S 2011 *Nano. Lett.* **11** 3862-7.
- [12] De La Venta J, Wang S, Ramirez J, and Schuller I K 2013 *Appl. Phys. Lett.* **102** 122404.
- [13] De La Venta J, Wang S, Saerbeck T, Ramírez J, Valmianski I, and Schuller I K 2014 *Appl. Phys. Lett.* **104** 062410.
- [14] Saerbeck T, de la Venta J, Wang S, Ramírez J G, Erekhinsky M, Valmianski I, and Schuller I K 2014 *J. Mater. Res.* **29** 2353-65.
- [15] Sass B, Tusche C, Felsch W, Bertran F, Fortuna F, Ohresser P, and Krill G 2005 *Phys. Rev. B.* **71** 014415.

- 1  
2  
3 [16] Sakai J, Limelette P, and Funakubo H 2015 *Appl. Phys. Lett.* **107** 241901.  
4  
5  
6 [17] Hansmann P, Toschi A, Sangiovanni G, Saha - Dasgupta T, Lupi S, Marsi M, and Held K  
7  
8 2013 *Phys. Status. Solidi. B.* **250** 1251-64.  
9  
10 [18] McLeod A, van Heumen E, Ramirez J, Wang S, Saerbeck T, Guenon S, Goldflam M,  
11  
12 Anderegg L, Kelly P, and Mueller A 2017 *Nat. Phys.* **13** 80-86.  
13  
14 [19] Liu H-L, Brems S, Zeng Y-J, Temst K, Vantomme A, and Van Haesendonck C 2016 *J.*  
15  
16 *Phys.: Condens. Matter* **28** 196002.  
17  
18 [20] Dillemans L, Smets T, Lieten R, Menghini M, Su C-Y, and Locquet J-P 2014 *Appl. Phys.*  
19  
20 *Lett.* **104** 071902.  
21  
22 [21] McWhan D and Remeika J 1970 *Phys. Rev. B.* **2** 3734.  
23  
24 [22] Li D, Zeng Y, Pereira L, Batuk D, Hadermann J, Zhang Y, Ye Z, Temst K, Vantomme A,  
25  
26 and Van Bael M 2013 *J. Appl. Phys.* **114** 033909.  
27  
28 [23] Freeman A and Wu R-q 1991 *J. Magn. Magn. Mater.* **100** 497-514.  
29  
30 [24] Hattox T M, Conklin J, Slater J, and Trickey S 1973 *J. Phys. Chem. Solids* **34** 1627-38.  
31  
32 [25] Cullity B and Graham C D. Introduction to Magnetic Materials: *John Wiley & Sons*  
33  
34 2009.  
35  
36 [26] Klokholm E, and Aboaf J 1982 *J. Appl. Phys.* **53** 2661.  
37  
38 [27] Lee E W 1955 *Rep. Prog. Phys.* **18** 184.  
39  
40 [28] Bozorth R M 1954 *Phys. Rev.* **96** 311.  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60