PCSI
Room Ballroom South - Session PCSI-3MoA
Magnetism in 2D Materials and Interfaces

Moderator: Anders Mikkelsen, Lund University, Sweden

4:30pm **PCSI-3MoA-31 Magnetism in Monolayer Transition Metal Dichalcogenides*, Matthias Batzill,*** University of South Florida **INVITED**

Van der Waals heterostructures hold the promise of combining materials with only weak interlayer interaction. This could allow integration of materials with diverse properties and minimize the influences of chemical interface interactions on materials and device properties. Of particular interest is the integration of magnetic materials in such van der Waals heterostructures. Although it has been recently demonstrated that ferromagnetism may be preserved down to the monolayer limit, there exists no known layered van der Waals material with Curie temperatures close to room temperature-- which is a pre-requisite for most applications. Thus there has been excitement by theoretical (DFT) predictions of high Curie temperature ferromagnetism in monolayer materials such as VSe_2, a material that is known to be paramagnetic in bulk-form. In addition, there exist increasing evidence of dilute magnetic semiconductors (DMS) in van der Waals materials. In this presentation, we illustrate direct growth of VSe_2 monolayers on van der Waals substrates (Fig. 1) and demonstrate that these (sub)monolayers indeed exhibit ferromagnetic properties to above room temperature [1], while multilayers exhibit strongly suppressed magnetization (Fig. 2). Recent angle resolved photoemission spectroscopy (ARPES) characterization, however, indicate that VSe_2 monolayers do not exhibit spin-split bands as predicted by DFT. In this talk we discuss possible alternative explanations for the observed magnetism. Moreover, we show evidence for magnetic coupling between monolayer VSe_2 and a van der Waals substrate, which gives rise to an exchange bias that can be measured by magnetometry. Finally, we discuss an alternative approach to induce magnetism in 2D materials. Specifically, we show the formation of DMS by incorporation of magnetic impurities (Fig. 3) by a novel doping mechanism [2] in $MoTe_2$.

[1] M. Bonilla et al. 'Strong room-temperature ferromagnetism in VSe_2 monolayers on van der Waals substrates' Nat. Nanotechnol. **13**, 289-203 (2018).

[2] P.M. Coelho et al. 'Post-Synthesis Modifications of Two-Dimensional $MoSe_2$ or $MoTe_2$ by Incorporation of Excess Metal Atoms into the Crystal Structure' ACS Nano **12**, 3975-3984 (2018).

5:00pm **PCSI-3MoA-37 Epitaxial Growth and STM Characterization of 2D Magnet $MnSe_2$ and VSe_2*, Tiancong Zhu,*** The Ohio State University*; D O'Hara,* University of California, Riverside*; J Repicky, J Cobbert, J Gupta,* The Ohio State University*; R Kawakami,* Ohio State University-Columbus

Magnetism in 2D materials is a fascinating topic. Although extensively studied theoretically, the experimental realization of 2D magnets was not achieved until 2017 [1, 2]. Being only a few atoms thick, the high surface to volume ratio makes 2D magnets extremely sensitive to the surface environment, thus their magnetic properties can be strongly manipulated through proximity with other materials. Recently, the demonstration of epitaxial growth of 2D magnets [3,4] further brings more potential to the material. By directly synthesizing 2D magnet on different substrates, one could manipulate the electrical and magnetic properties of 2D magnet, explore new phenomena at their interface, as well as novel device structures for spintronic applications.

In this talk, we will present the epitaxial growth of 2D magnet $MnSe_2$ and Vse_2 on various substrate materials and characterize some of them with scanning tunneling microscopy (STM). First, we will present our recent discovery of $MnSe_2$ [3], one of the first 2D magnets with intrinsic ferromagnetic ordering at room temperature (Fig. 1). The magnetic properties of $MnSe_2$ grown on GaSe and $SnSe_2$ is compared. Furthermore, we will also show our exploration of the epitaxial growth of 2D magnet Vse_2 on different substrates, including HOPG, GaAs(111) and Bi_2Se_3. Despite of the large lattice mismatch between Vse_2 and the substrates, all the growths show epitaxial registry, as demonstrated by low energy electron diffraction (LEED) and STM (Fig. 2). The epitaxial alignment and clean interface between Vse_2 and the substrate material make it possible to host proximity interaction between them. Finally, some preliminary result of characterizing the 2D magnet materials with spin-polarized STM will be discussed.

[1] Huang, Bevin, et al., *Nature* **546**, 265 (2017).

[2] Gong, Cheng, et al., *Nature***546**, 270 (2017).

[3] O'Hara, Dante J., et al., *Nano letters***18**, 3125 (2018).

[4] Bonilla, Manuel, et al., *Nature nanotechnology***13**, 289 (2018).

5:05pm **PCSI-3MoA-38 Investigation of Low-Energy Ion-Implanted Multilayer Epitaxial Graphene***, P Miceli, **Alessandro Mazza,*** University of Missouri

There is considerable interest in integrating magnetism with graphene in the hope of creating a new class of spintronic materials. With the recent discovery of a large band-gap semiconducting form of graphene on SiC substrates [1], there are new possibilities for epitaxial graphene-based electronics and integrating magnetism could introduce a new technological dimension. One potential avenue is to make graphene magnetic using defects to generate p-orbital magnetism. Indeed, atomic hydrogen [2] attached to the graphene surface as well as vacancies [3] in graphene have been shown to induce magnetism, while high energy (MeV) proton irradiation can produce ferromagnetism at room-temperature in graphite [4]. However, detailed investigations of these systems are absent so that little is known about the density and configuration of defects, the role of interfaces, or how these relate to magnetism. Moreover, the p-orbital magnetism in these materials is unusual and of scientific interest.

In this talk, we will discuss our investigation [5] of atomic hydrogen implanted at low energies into multilayer epitaxial graphene grown on C-face SiC. The flat interface of this epitaxial system is conducive to x-ray and neutron reflectivity studies where the latter is sensitive to both the H density and magnetism. X-ray diffraction, measured *in situ* during 500 eV implantation, shows that the spacing between the graphene layers increases significantly with the ion dose. Most of the H ions remain within the sample after dosing as revealed by unpolarized neutron reflectivity. It is found from SQUID magnetometry that low-energy H implantation induces a ferromagnetic moment at room temperature. The implications of these results and others, such as ARPES and electron microscopy, will be discussed.

[1] M. Conrad, F. Wang, M. Nevius, K. Jinkins, A. Celis, M. Narayanan Nair, A. Taleb-Ibrahimi, A. Tejeda, Y. Garreau, A. Vlad, A. Coati, P. F. Miceli, and E. H. Conrad, Nano Lett. **17**, 341 (2017). M. S. Nevius, M. Conrad, F. Wang, A. Celis, M. N. Nair, A. Taleb-Ibrahimi, A. Tejeda, and E. H. Conrad, Phys. Rev. Lett. **115**, 136802 (2015).

[2] H. González-Herrero, J. M. Gómez-Rodríguez, P. Mallet, M. Moaied, J. J. Palacios, C. Salgado, M.M. Ugeda, J.-Y. Veuillen, F. Yndurain, I. Brihuega, Science **352**, 437 (2016).

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[4] P. Esquinazi, D. Spemann, R. Höhne, A. Setzer, K.-H. Han, T. Butz, Phys. Rev. Lett. **91**, 227201 (2003).

[5] Acknowledge: NSF DGE-1069091, DMR -1401193; Spallation Neutron Source–DOE Office of Science

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5:10pm **PCSI-3MoA-39 Large Positive Linear Magnetoresistance in the Two-dimensional t_{2g} Electron Gas at the EuO/$SrTiO_3$ Interface*, Alexander Demkov,*** The University of Texas

The high mobility two-dimensional t_{2g} electron gas (2DEG) present at oxide/oxide interfaces is currently under intense investigation [1-2]. In this talk, we will discuss the integration of highly spin-split ferromagnetic semiconductor EuO onto perovskite $SrTiO_3$ (001). A careful deposition of Eu metal by molecular beam epitaxy results in crystalline EuO growth via oxygen out-diffusion from $SrTiO_3$ [3]. This in turn leaves behind a highly conductive interfacial layer through generation of oxygen vacancies. Below the Curie temperature of 70 K of EuO, this spin-polarized two-dimensional t_{2g} electron gas at the EuO/$SrTiO_3$ interface displays very large positive linear magnetoresistance (MR). Soft x-ray angle-resolved photoemission spectroscopy (SX-ARPES) reveals the t_{2g} nature of the carriers. First principles calculations strongly suggest that Zeeman splitting, caused by proximity magnetism and oxygen vacancies in $SrTiO_3$, is responsible for the MR [4]. This system offers an as-yet-unexplored route to pursue proximity-induced effects in the oxide two-dimensional t_{2g} electron gas [5].

[1] J. K Lee, N. Sai, and A. A. Demkov, Phys. Rev. B **82**, 235305 (2010).

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[4] L. Gao and A. A. Demkov, Phys. Rev. B **97**, 125305 (2018).

[5] K. J. Kormondy, L. Gao, X. Li, S. Lu, A. B. Posadas, S. Shen, M. Tsoi, M. R. McCartney, D. J. Smith, J. Zhou,L. L. Lev, M. Husanu, V. N. Strocov,and A. A. Demkov, *Scientific Reports* **8**, 7721 (2018).

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