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Voltage controlled magnetism in 3d transitional metals

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Despite having attracted much attention in multiferroic materials and diluted magnetic semiconductors, the impact of an electric field on the magnetic properties remains largely unknown in 3d transitional ferromagnets (FMs) until recent years. A great deal of effort has been focused on the voltage-controlled magnetic anisotropy (VCMA) effect where the modulation of anisotropy field is understood by the change of electron density among different d orbitals of FMs in the presence of an electric field. Here we demonstrate another approach to alter the magnetism by electrically controlling the oxidation state of the 3d FM at the FM/oxide interface. The thin FM film sandwiched between a heavy metal layer and a gate oxide can be reversibly changed from an optimally-oxidized state with a strong perpendicular magnetic anisotropy to a metallic state with an in-plane magnetic anisotropy, or to a fully-oxidized state with nearly zero magnetization, depending on the polarity and time duration of the applied electric fields. This is a voltage controlled magnetism (VCM) effect, where both the saturation magnetization and anisotropy field of the 3d FM layer can be simultaneously controlled by voltage in a non-volatile fashion. We will also discuss the impact of this VCM effect on magnetic tunnel junctions and spin Hall switching experiments. This work, in collaboration with C. Bi, Y.H. Liu, T. Newhouse-Illige, M. Xu, M. Rosales, J.W. Freeland, O. Mryasov, S. Zhang, and S.G.E. te Velthuis, was supported in part by NSF (ECCS-1310338) and by C-SPIN, one of six centers of STARnet, a Semiconductor Research Corporation program, sponsored by MARCO and DARPA.