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Ferromagnetism in TiO_2-based Diluted Magnetic Semiconductors

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Electronic and magnetic properties of semiconducting 3d transition-metal-doped TiO_2 thin films with rutile and anatase structures have been investigated. Ferromagnetic properties were observed at room temperature for Ni-, Co-, Fe-, and Mn-doped films. Existence of oxygen vacancies ($TiO_{2-\delta}$) was found to be important for the ferromagnetism as well as achieving significant conductivity. The observed ferromagnetic strength varied with dopant species and its density. Analysis on the ionic valences of the substituting transition-metal elements for Ti^{4+} sites was performed. Despite the possibility of extrinsic magnetic cluster formation contributing to the observed ferromagnetic properties, spin coupling among substituting magnetic ions mediated by charge carriers is likely to induce the ferromagnetism. The transition-metal doping was found to induce p-type character but the observed ferromagnetism was not directly dependent on mobile hole density or conductivity. Formation of magnetic polarons around oxygen vacancies can be an acceptable mechanism for the ferromagnetic alignment of the randomly distributed impurity spins in $TiO_{2-\delta}$.