

# Magnetic and Magneto-optical Properties of Room Temperature Ferromagnetic Transition Metal Ion Substituted Metal Oxides

L. Bi<sup>1</sup>, J. Hu<sup>2</sup>, P. Jiang<sup>3</sup>, H. S. Kim<sup>3</sup>, D. H. Kim<sup>3</sup>, G. F. Dionne<sup>3</sup>, C. A. Ross<sup>3</sup>, J. L. Xie<sup>1</sup> and L. J. Deng<sup>1</sup>

<sup>1</sup> University of Electronic Science and Technology of China, 16 No. 4 Sec. 2 Jianshe N. Street, Chengdu, 610054, China, Email: bilei@uestc.edu.cn

<sup>2</sup> Department of Materials Science & Engineering, University of Delaware, 305 DuPont Hall, Newark, DE 19716, USA,

<sup>3</sup> Department of Materials Science & Engineering, Massachusetts Institute of Technology, 77 Mass. Ave., Cambridge, MA 02139, USA

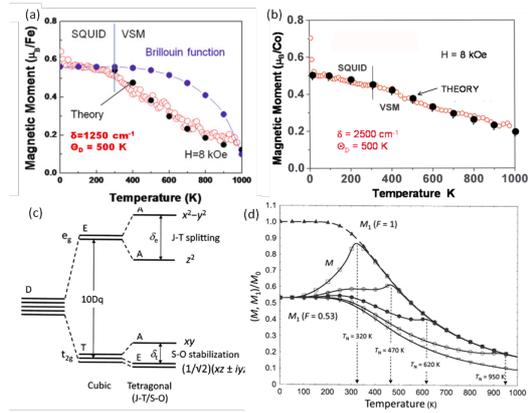
## 1. Introduction

Room temperature ferromagnetism and strong magneto-optical properties in the near infrared range have been observed in transition metal ion (Fe, Co) substituted metal oxides with high ion concentrations. An interesting linear dependence of magnetization versus temperature curve is observed in all oxide systems including Co:CeO<sub>2</sub>, SrTiO<sub>3</sub>:Fe, SrTiO<sub>3</sub>:Co and Fe/Co:SnO<sub>2</sub>, which is significantly different from the Brillouin function description in an exchange coupled ferromagnetic system. The films also showed strong magneto-optical response with high Faraday rotations in the near infrared wavelength range.

## 2. Experimental Approach and Results

Co:CeO<sub>2</sub>, SrTiO<sub>3</sub>:Fe, SrTiO<sub>3</sub>:Co and Fe/Co:SnO<sub>2</sub> films were deposited by pulsed laser deposition, with a transition metal ion concentration is in the range of 2 at.% to 50 at.%. The host lattice remained the oxide phase with no secondary phases as observed by XRD and TEM. To understand the magnetic and magneto-optical properties of the films, we used a generic model considering both magnetoelastic effect and superexchange coupling. The ferromagnetism is believed to originate from magnetoelastic spin ordering.[81] For an ion substituted in octahedral or tetrahedral site, Jahn-Teller or spin-orbital stabilization caused strong magnetic anisotropy and spin ferromagnetic ordering under applied magnetic field; whereas strong antiferromagnetic superexchange lead to decrease of magnetization at high ion concentrations. This effect can be explained by a double tanh equation, which accounts for both Boltzmann distribution between two Jahn-Teller stabilized states and onset of vibronic modes of the oxygen ligand coordination as material approaches the Debye temperature. M-T curve generated by this theory showed a very well match with the experiment data.

In terms of magneto-optical properties, only Fe<sup>4+</sup> and Co<sup>4+</sup> are considered responsible for the magneto-optical properties due to limitation of the selection rule. The saturation Faraday rotation as well as the optical absorption showed significant relation upon donor or acceptor incorporation in the oxide lattices. Strip-loaded waveguides were fabricated using these materials, to determine the absorption loss and magneto-optical figure of merit (FoM). A relatively high FoM of 3~4 deg/dB is observed in Ga and Fe substituted SrTiO<sub>3</sub>.



**Figure 1.**  $M_s$ - $T$  curve of (a) Sr(Ti<sub>0.65</sub>Fe<sub>0.35</sub>)O<sub>3</sub> and (b) Sr(Ti<sub>0.77</sub>Co<sub>0.23</sub>)O<sub>3</sub> films and the theoretical fitting. (c) The crystal-field energy-level diagram of a 3d ion in an oxygen octahedron subject to in-plane biaxial compressive stress producing a tetragonal distortion. (d) Computed M-T curves for a series of Neel temperatures using the generic model.

## 3. Conclusions

In summary, RTFM in transition metal ion substituted metal oxide system is characterized and explained by a magnetoelastic spin ordering model. The tunable magneto-optical property as well as high MO figure of merit make such systems very attractive for on-chip nonreciprocal photonic device applications.

## 4. Open Questions

- Magnetic anisotropy is widely observed in DMS systems. How do we evaluate the magnetoelastic contribution to such anisotropies, and the transport properties.
- In a heavily doped system, interatomic or intervalence electric dipole transitions may also take place, which influence magnetic and magneto-optical properties. How do we quantify and utilize this effect?
- Valence state control is crucial for any DMS system. How to accurately determine and control the valence state of metal ions in a DMS system?

## Acknowledgements

The authors are grateful to the support of the National Science Foundation (Grant No. DMR 0604430, Division of Materials Research, and Grant No. 1231392, Electronic, Photonic, and Magnetic Devices Program).

## References

- [1] Dionne, G. F. Evidence of magnetoelastic spin ordering in dilute magnetic oxides. *J. Appl. Phys.*, 2007, 101, 09C509:1-09C509:3.