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VIEWPOINT

Strain engineering of oxides

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Structurally compatible oxides can exhibit the full spectrum of electronic, magnetic and optical behaviour: e.g. insulating, semiconducting, metallic, superconducting, ferroelectric, piezoelectric, ferromagnetic. In addition, these properties can be coupled, e.g. magnetoresistance, coexistent ferromagnetism and superconductivity, and simultaneous ferroelectricity, ferromagnetism and/or ferroelasticity (*multiferroic* properties). Within this field the mixed valence manganites (manganese oxide based perovskites) exhibit a vast array of fascinating magnetic and magneto-transport properties, and offer great potential for new device and memory applications. A review of the structure/property relations, fabrication and applications of these materials has been given by Prellier *et al* [1].

Advances in film deposition capabilities following the discovery of the high-temperature superconducting oxides have contributed to tremendous progress in the development of techniques for the controlled deposition of complex multicomponent oxide thin films such as the manganites. Known or predicted film compositions can now be grown to order with controlled stoichiometry, crystalline structure and orientation. This has led to great advances, not only in the fabrication and characterization of such functional device materials, but also in the understanding of their structure and properties, and the links between them.

The manganites are chemically flexible, with the scope to control the ion substitutions, charge exchange, and hence the electrical, magnetic and transport properties. Distortion of the oxygen octahedra and overlap between the manganese d orbitals and the oxygen p orbitals, which define the Mn–O–Mn bond angle and the Mn–O distance, make them extremely sensitive to strain effects and to substitutions of differently sized cations [2], offering the ability to control film properties through strain and substitutions. The concept of controlled, substrate-mediated strain (*strained layer epitaxy*) in thin film structures, which has been used for some time to control band gaps in semiconductors [3], is now being applied to these materials, illustrating a wide area of opportunity.

The paper of Muduli *et al* [4] reports on the careful measurement of the effects of lattice strain on the physical properties of thin films of $\text{La}_{0.45}\text{Sr}_{0.55}\text{MnO}_3$ (LSMO). What has been demonstrated is that similar changes in magnetic and transport properties can be observed through imposition of a biaxial strain as by cation substitution in the bulk. Strain is imposed through deposition of a thin film onto a substrate with a closely matched, though not exactly matched, lattice parameter. Epitaxial film growth is achieved, but the film's lattice adjusts to

fit the substrate, leading to an in-plane, biaxial strain. Two different substrate types were used, both resulting in a tensile in-plane film strain, but of different magnitude.

Films were deposited by pulsed laser deposition from a stoichiometric oxide target of the required composition. This is a specialized film deposition technique which is now becoming widely available in laboratories around the world, and advanced, complex deposition procedures have been optimized to achieve high-quality, uniform and reproducible film growth. Although this may currently be seen as rather 'routine' growth, the development effort that has gone into such methods should not be underestimated. A strength of this particular work is that the film deposition was performed simultaneously onto the two different substrates, avoiding any issues of possible process variability leading to subtle differences in the films being compared.

The substrates used were SrTiO₃ (STO) and NdGaO₃ (NGO), the former giving a higher lattice misfit, and hence leading to a higher biaxial film strain. The resultant films show some remarkable differences. Films on STO resemble bulk LSMO, whilst those on NGO, with reduced biaxial strain, have properties similar to those of the bulk neodymium-substituted phase, Nd_{0.45}Sr_{0.55}MnO₃. Nd is a smaller cation than La, and hence this result demonstrates an equivalence between lattice contraction due to reduced in-plane tensile strain and substitution of the smaller cation. Measurement of properties as a function of the film thickness is correlated with strain variation (as observed directly through the lattice peak positions in x-ray diffraction). On increasing film thickness, changes in the Néel temperature and the polaron binding energy correspond with the change in *c*-lattice parameter associated with strain relaxation, and linked directly with Mn–O–Mn orbital overlap.

This work illustrates the application of nano-engineering of these oxides, as described by Schlom *et al* [5]: the precise tailoring of material properties through film growth procedures. Structural distortion through ion substitutions, and interfacial strain through heteroepitaxy and lattice mismatch in thin film systems, provide powerful means of such material property control. The family of manganites offers great promise for device applications and for the development of multiferroic materials, combining functional properties either within one nanocomposite material (for example, with separate phases coupled through heteroepitaxy) or within artificially constructed device heterostructures, such as superlattices [6].

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