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Examining the screening limit of field effect devices via the metal-insulator transition

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The electronic screening length, the distance over which an electric field is attenuated in a material, imposes a lower physical bound on the lateral size scaling of semiconductor field effect devices. Alternatives will be needed to achieve devices whose characteristic dimensions approach a nanometer. In this work, we demonstrate the atomic-scale nature of screening at high electron densities, using the polarization field of a ferroelectric oxide, $\text{Pb}(\text{Zr,Ti})\text{O}_3$, to electrostatically modulate the metallicity of ultrathin manganite $\text{La}_{1-x}\text{Sr}_x\text{MnO}_3$ (LSMO) films near the metal-insulator transition. Within the screening length, the transport characteristics of LSMO vary sharply at the scale of a single atomic layer. © 2005 American Institute of Physics. [DOI: 10.1063/1.1897076]

As the computer industry demands ever greater performance from logic and memory devices, various scaling limits are rapidly being approached.^{1,2} Alternatives are being explored to extend these limits, such as replacing the SiO_2 gate dielectric in Si metal-oxide semiconductor (MOS) devices with a higher dielectric constant insulator.³ Eventually, Si itself will reach its scaling limits, as drive currents saturate and electronic effects, such as dopant fluctuations, start to dominate and degrade device characteristics. In terms of size scaling, the electronic screening length sets a lower physical bound on how compact MOS field effect devices can be made. The drain and source in a field effect device must be separated by at least twice the screening length (depletion width) to avoid leakage currents due to overlapping tails of the depletion regions. Even for heavily doped Si ($\sim 10^{18}$ carriers/ cm^3), this length is relatively large, on the order of 10 nm. In the case of metallic materials, which possess much larger carrier densities (10^{21} – 10^{22} carriers/ cm^3), the electronic screening length is concomitantly smaller, on the scale of single atoms. Recently, Newns and co-workers^{4–7} have proposed using metallic materials to transcend this scaling limitation of Si-based MOS devices. In this work, we demonstrate the atomic-scale nature of screening at metallic densities, using the polarization field of a ferroelectric oxide, $\text{Pb}(\text{Zr,Ti})\text{O}_3$, to induce an electrostatic field effect and reversibly modulate the metallicity of ultrathin $\text{La}_{1-x}\text{Sr}_x\text{MnO}_3$ (LSMO) films near the metal-insulator transition. Removing a single plane of atoms from the structure substantially alters the transport characteristics.

LSMO is a colossal magnetoresistive (CMR) oxide whose electronic properties are strongly influenced by changes in the carrier concentration.⁸ In its undoped state ($x=0$), LaMnO_3 is an antiferromagnetic insulator. When hole-doped with Sr, LSMO undergoes a metal-insulator transition (MIT) to a ferromagnetic, metallic state at low temperatures. In its metallic phase, LSMO has a carrier concentration on the order of 10^{21} – $10^{22}/\text{cm}^3$, yielding a screening length of less than 1 nm.

The way in which we characterize the effect of the depletion width is to examine how an externally applied

electric field is attenuated in the material. In this approach, one takes an ultrathin LSMO film and applies an external electric field, inducing an electrostatic field effect that changes the carrier concentration and electrical conductivity of the film. We observe how the field-induced charge modulation evolves as a function of film thickness. When the thickness of the film is comparable to the screening length, modulation of the carrier concentration can be achieved throughout the entire film, and for sufficiently large fields, a MIT can be induced. This approach allows the quantification of the screening length with monolayer accuracy.

This study engenders two challenges: the fabrication of atomically smooth films with thicknesses comparable to the screening length, and the application of electric fields that can modulate large numbers of carriers at metallic densities. The growth of ultrathin complex oxide films with monolayer control can now be achieved using physical vapor deposition techniques, as described below.^{9–12} For the charge modulation, we use the nonvolatile reversible polarization field of the ferroelectric oxide $\text{Pb}(\text{Zr,Ti})\text{O}_3$ (PZT), which has a remnant polarization field of $\sim 3 \times 10^{14}$ charges/ cm^2 . This polarization is an order of magnitude larger than the breakdown field of SiO_2 , and is capable of depleting carriers from a 1 nm thick metallic film with a carrier concentration of 10^{21} charges/ cm^3 . PZT has been used recently in ferroelectric field effect structures to tune correlated electron behavior at metallic densities, such as high-temperature superconductivity and colossal magnetoresistance.^{13–17}

For these experiments, we combine PZT and LSMO in thin-film heterostructure form. The film quality of the heterostructure and the thickness of the LSMO layer are critical factors, since the electric field effect occurs exclusively in the interfacial region between the PZT and LSMO layers. We first investigate the physical properties of single layer ultrathin LSMO films grown on single crystal (100) SrTiO_3 substrates using off-axis magnetron sputtering.¹⁸ The details of the growth process are described elsewhere.¹⁹ X-ray diffraction reveals epitaxial growth of (001)-oriented LSMO (using the pseudo-cubic unit cell); low-angle x-ray reflectivity measurements along with finite size oscillations around the 001 reflection are used to calibrate the deposition rate. The cited thicknesses are nominal values based upon this calibration.

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FIG. 1. (Color) Atomic force microscopy image of the surface of a 4 nm LSMO film. The measured rms surface roughness is 0.1 to 0.2 nm. The image shows a series of terraces spaced a few hundred nanometers apart with a terrace height of 0.2 nm.

Rocking curves taken around the 001 reflection have a typical full width at half maximum of 0.06° . Atomic force microscopy images taken on these films reveal smooth surfaces with atomic steps. Figure 1 shows a $5\ \mu\text{m}$ by $5\ \mu\text{m}$ scan of a 4 nm thick LSMO film; the measured root-mean-square (rms) roughness is 0.1–0.2 nm.²⁰

Transport measurements taken on a series of ultrathin LSMO films ranging in thickness from 3.7 nm to 40 nm are shown in Fig. 2. Films thicker than 4 nm are insulating at high temperatures and metallic at low temperatures, with a peak in the resistance occurring around 250 K, the ferromagnetic Curie temperature.²¹ For the 4 nm sample, the peak temperature decreases to around 180 K, while for films thinner than 3.7 nm, the samples are insulating throughout the entire temperature range investigated. This change in transport characteristics is commonly observed in ultrathin LSMO films, where the material becomes insulating, or electrically “dead,” below a critical thickness on the order of 3–5 nm, which has been attributed to a modified structure at the interface.^{22,23} Here, 3.8 nm is the minimum thickness where metallic behavior is observed. Using this information, we grow epitaxial heterostructures of PZT and LSMO, with a PZT thickness of ~ 300 nm and an LSMO thickness of 4 nm, just above the dead layer thickness.²⁴ The samples are patterned into four-point resistivity paths, and gold electrodes are deposited for transport measurements.

Figure 3(a) shows the temperature dependence of the resistivity of the LSMO layer in a PZT/4 nm LSMO hetero-

FIG. 2. Sheet resistance as a function of temperature for unpatterned LSMO films of various thicknesses (from top to bottom: 3.7 nm, 4 nm, 5 nm, 10 nm, and 40 nm).

FIG. 3. Resistivity as a function of temperature for: (a) A PZT/4 nm LSMO heterostructure and (b) a PZT/3.8 nm LSMO heterostructure for the two polarization states of PZT. In each graph, the upper curve corresponds to depletion of holes and is termed the off state; the lower curve corresponds to accumulation of holes and is termed the on state. The inset in (b) is a semilog plot of the data.

structure as a function of the polarization state of the PZT layer. For the lower curve, which corresponds to the polarization state that attracts carriers into the LSMO layer (the “on” state), the temperature dependence of the resistivity is similar to what is observed in single layer 4 nm LSMO films; the film is insulating at high temperatures, followed by metallic behavior below 200 K.

We then apply a 10 V pulse across the PZT layer to switch the polarization direction, driving carriers out of the LSMO layer and increasing the resistivity (upper curve, the “off” state). As with the on state, the film is insulating at high temperatures, followed by metallic behavior at low temperatures. The temperature at which the transition from insulating to metallic behavior occurs, however, decreases by 50 K. This shift in the transition temperature reflects a decrease in the Curie temperature driven by changes in the carrier concentration.^{15,25} This process is reversible; applying voltage pulses of alternating polarity allows one to switch back and forth between the two resistivity curves.

We then study a heterostructure where the LSMO layer is one atomic layer thinner (3.8 nm), as shown in Fig. 3(b). For the on state (lower curve), where the polarization adds carriers to the system, the material shows a similar temperature dependence to the 4 nm LSMO heterostructure, with a slightly lower peak temperature of 190 K [Fig. 3(b) inset, lower curve]. Applying a 10 V pulse across the heterostructure reverses the polarization, driving carriers out of the sample, resulting in the upper curve in Fig. 3(b). In depletion, the film now exhibits insulating behavior over the entire temperature range, in sharp contrast with the metallic behavior of the 4 nm LSMO heterostructure of Fig. 3(a) (in both

the on and off states). The insulating temperature dependence observed here resembles that of the insulating 3.7 nm single layer LSMO film. Removing carriers from the 3.8 nm film using the field effect has depleted the electrically active layer of carriers so that the entire film becomes insulating. As with the 4 nm LSMO heterostructure, the switching is reversible. We note that when the LSMO layer thickness in the heterostructure is smaller (3.5 nm), the heterostructure is insulating, regardless of the polarization state of the PZT layer.

The changes in the field effect as a function of LSMO film thickness reveal the short-range metallic character of the screening length in LSMO. Both heterostructures in their on states exhibit very similar transport properties, including resistivity, T_C , and magnetoresistance ratio.²⁶ For the off state behavior, when carriers are depleted from the 4 nm LSMO heterostructure, the material retains its low-temperature metallicity, similar to the metallic 3.8 nm single layer film, because the thickness of the electrically active layer is larger than the screening length. However, when carriers are depleted from the 3.8 nm LSMO heterostructure, the material becomes insulating, or electrically dead, as observed in the 3.7 nm single layer film. This transition occurs when the thickness of the electrically active layer is smaller than the screening length. This difference in behavior between the two heterostructures thus reveals a screening length on the order of 0.2 nm, or a single atomic layer, reflecting the atomic-scale nature of the screening length at metallic densities. For an electric field that varies slowly in space, one can estimate the screening length in LSMO using the Thomas–Fermi model, where the electric field is attenuated over a distance that is inversely proportional to the Thomas–Fermi wave vector $k_{TF}=[4\pi e^2 g(\epsilon_F)]^{1/2}$. Here, $g(\epsilon_F)$ is the density of states at the Fermi level of LSMO. Using band structure calculations of LaMnO_3 for $g(\epsilon_F)$ and assuming rigid band filling, we determine a screening length of 0.3 nm for LSMO, in agreement with the experimentally observed screening length of 0.2 nm.²⁷

In conclusion, working at the electric field-induced MIT, we have demonstrated the atomic-scale nature of screening at metallic charge densities. This approach allows one to examine the size scaling limitation of field effect devices and investigate logic devices with atomic level feature sizes.⁴ One can also use these field effect structures to electrostatically tune magnetism and probe the MIT in correlated electron systems.

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