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<th><strong>Title</strong></th>
<th>Anisotropic magnetoresistance and weak spin-orbital coupling in doped ZnO thin films</th>
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<td><strong>Citation</strong></td>
<td>Tian, Y., Lin, W., &amp; Wu, T. (2012). Anisotropic magnetoresistance and weak spin-orbital coupling in doped ZnO thin films. Applied Physics Letters, 100(5), 052408-</td>
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<tr>
<td><strong>Date</strong></td>
<td>2012</td>
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<tr>
<td><strong>URL</strong></td>
<td><a href="http://hdl.handle.net/10220/9163">http://hdl.handle.net/10220/9163</a></td>
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Anisotropic magnetoresistance (AMR) is a defining property of magnetic materials in which the resistivity depends on the magnetization orientation with respect to either the electrical current and/or the crystalline axis. AMR in thin films has important applications in technologies such as magnetic field detection and data storage, and the related research often yields important insights on the intricate coupling between charge, spin, and orbital in the materials. In the “ordinary” situation, the dependence of resistance on the relative orientation between the magnetic field and the electrical current is known as the Lorentzian magnetoresistance (MR), which is a result of the Lorentz force acting on the conducting carriers. In some more profound cases, the dependence on the crystalline axis can provide valuable information regarding spin-orbit and magneto-elastic couplings in some materials.

Large AMR has been extensively reported in perovskite manganite and III-V magnetic semiconductors. Recently, there has been interest in exploring the magnetic orders in transition metal (TM) doped wide band gap oxides like ZnO, but little work has focused on the anisotropic magneto-transport properties of TM-doped ZnO. Furthermore, previous results from different groups contradict each other. For example, some researchers found that MR is independent on the orientation of the applied field with respect to the current and/or the crystalline axis, while others claimed that MR is sensitively dependent on the field direction and/or the ZnO c-axis.

In this work, we focus on the angular-dependent MR effect in Cu-doped ZnO films. Cu doping does not introduce magnetic impurities or clusters, thus helping to eliminate experimental artifacts. So far, however, there has been no report on the AMR effect in Cu-doped ZnO thin films. We carried out a systematic comparative study by growing films on sapphire substrate with different orientations. The electrical current and/or the crystalline axis can provide valuable information regarding spin-orbit and magneto-elastic couplings in some materials.

 Both out-of-plane and in-plane anisotropic magnetoresistance (AMR) of Cu-doped ZnO thin films with different crystal orientations are studied. Comparative data of angular dependent AMR suggest that the out-of-plane AMR comes from the geometric effect, while the in-plane AMR can be attributed to the field-dependent path-length effect. Moreover, the small magnitude of AMR and the negligible magneto-crystalline anisotropy suggest that the spin-orbit coupling in Cu-doped ZnO is relatively weak. © 2012 American Institute of Physics. [doi:10.1063/1.3681795]
Al₂O₃ into a cross structure using lithography, which enables the current flow either along or perpendicular to the c-axis of ZnO. The orientation was confirmed by XRD in-plane phi scan in prior to the patterning. We did not observe any notable difference (Fig. 2(a)), which further confirms that the magneto-transport has no dependence on the current flow direction with respect to the ZnO c-axis.

In the scenario of geometric effect, the resistance is higher (lower) when the applied field is parallel (perpendicular) to the film surface. The angular dependence can be well explained by a phenomenological uniaxial anisotropic model,²⁷ which gives \( \rho(\theta)/\rho(0) = \alpha(\sin^2 \theta + \cos^2 \theta)^{-1/2} \). Here, \( \alpha \equiv \rho^\perp/\rho^\parallel \) represents the uniaxial resistivity ratio, where \( \rho^\perp \equiv \rho(\theta = 0) \) (\( \rho^\parallel \equiv \rho(\theta = 90) \)) denotes the resistivity for field parallel (perpendicular) to the substrate normal direction. In line with the previous works, we believe that the observed AMR between \( \rho^\perp \) and \( \rho^\parallel \) mainly reflects the difference in current path through the sample, which leads to variations in the effective localization and scattering of free carriers.¹⁹,²⁸ In particular, when the applied field is in plane, the Lorentz force is out of plane, thus there is more surface and interface scattering, which results into a higher resistance state. On the other hand, when the applied field is out of plane, the force is in plane, thus the surface and interface scattering is less pronounced, which leads to a lower resistance state. A larger magnetic field increases the local magnetization, boosting the AMR (Fig. 3(a)), while a higher temperature makes the film more uniform, leading to a decrease of spin-dependent scattering and AMR (Fig. 3(b)).

The good agreement between the theoretical fitting and the experimental results indicates that the underling physics has been adequately captured: the geometric effect can explain the AMR in doped ZnO films without invoking the magneto-crystalline effect.

In the measurements of in-plane AMR, a magnetic field of 7 T was applied to ensure the orientation of magnetization is identical with that of the applied field. In this measurement configuration, both Lorentz force and spin-orbital coupling could contribute to the observed AMR. Experimentally, both Cu-doped ZnO films with different growth orientations show the same \( \sin^2 \phi \) dependence, indicating that the in-plane AMR only depends on the angle between magnetization and current with \( \rho^\parallel > \rho^\perp \). This is consistent with the Lorentz force induced path-length effects. For field perpendicular to
spin-down resistivities. The positive AMR is generally for the negative AMR. However, the conduction band in electrons, while the minority-spin electrons are responsible regarded as a consequence of scattering of the majority-spin alloys. According to the microscopic theory, the sign and dependence in the in-plane MR, which has been invoked to small, indicating that the spin-orbital coupling in ZnO is very weak and not capable to cause any notable anisotropy in magneto-transport.

We acknowledge the support from the Singapore National Research Foundation.