Anisotropic magnetoresistance: A 170-year-old puzzle solved

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Received August 18, 2020; accepted September 8, 2020; published online November 17, 2020

Citation: G. E. W. Bauer. Anisotropic magnetoresistance: A 170-year-old puzzle solved, *Sci. China-Phys. Mech. Astron.* **64**, 217531 (2021), <https://doi.org/10.1007/s11433-020-1618-7>

Thomson [1], the later Lord Kelvin, reported an increased electric resistance in iron and nickel when the magnetization is parallel rather than normal to the current direction, an effect now called anisotropic magnetoresistance (AMR). The AMR allows sensing magnetic fields by simply measuring the resistance change when the magnetization realigns. While the magnetoresistance of magnetic tunnel junctions is larger, AMR sensors are attractive by their simplicity and robustness. Alloys of the transition metals Fe, Ni, and Co are the materials of choice because they combine a large AMR ratio with other convenient properties [2]. In a convergence and culmination of methods and ideas developed in the past decades, a collaboration led by Zhe Yuan from Beijing Normal University (theory) and Yizheng Wu from Fudan University (experiments) recently solved the conundrum of the AMR for the generic alloy $\text{Co}_x\text{Fe}_{1-x}$ [3].

The AMR is a relativistic effect, caused by the Zeeman-like interaction of the electron spin with velocity-dependent magnetic fields transverse to the electron wave vector, or, on average, the electric current direction. In metallic magnets, the majority and minority-spin electrons carry the current in parallel. The low-resistance channel dominates transport by short-circuiting the high resistive one. When the magnetization is parallel to the current, however, electron spins precess in the relativistic magnetic fields. Rotating the magnetization relative to the current direction mixes up spin channels, blocks the short circuit, and increases resistance.

Atomic-like s-d model theories of the AMR capture the essentials of the AMR for various materials [4], but depend on adjustable parameters and therefore do not have predictive power. First-principles calculations based on density functional theory, on the other hand, are very successful in quantitatively capturing many properties of transition metal magnetic systems, including the AMR [5]. However, without a deeper analysis such “numerical experiments” often provide only limited insight into the underlying physics.

The topology of the electronic band structure throughout the Brillouin zone is a very active research subject. “Accidental” degeneracies and the associated geometric Berry phase acquired by electronic wave packets affect many physical properties. In this vein, the magnetism community has made great progress to understand a cousin of the AMR, viz. the anomalous Hall effect (AHE) [6]. Impurities with spin-orbit interaction deflect the transport electrons sideways and generate “extrinsic” voltages in magnetic metals that are transverse to current and magnetization directions. On the other hand, the spin-orbit effective fields in a clean crystal precess the spins, rendering part of the applied bias into the transverse direction, thereby causing “intrinsic” AHE voltages. The latter contribution can be formulated in terms of the Berry curvature, which is large in the proximity of (near) band crossings. The computed intrinsic AHE Hall angles often agree well with experiment, which implies that in many materials the intrinsic effects dominate [6].

Zeng et al. [3] used a sophisticated first-principles code designed to calculate the transport properties in the presence

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of impurities, spin-orbit interaction, as well as magnetic, thermal and alloy disorder [7]. The excellent agreement of the calculated results with the AMR measured at Fudan and Argonne supports the validity of the method.

Ref. [3]’s breakthrough is the subsequent analysis of the numerical results in terms of the band structure topology as a function of applied magnetic field, current direction, and alloy concentration. The authors identified not just points, but full circles of crossing bands or “nodal lines” in reciprocal space when the magnetization is normal to a mirror plane (blue lines in Figure 1(a)). Gaps open by the reduced symmetry (red lines) when the tilted magnetization breaks the mirror symmetry. Since the projection of the Fermi surface onto the plane normal to the current direction governs electric transport [8], these nodal lines are most relevant when current is normal to the magnetization. Hence, rotating the magnetization direction lifts the degeneracy and opens gaps at the nodal circle that suppresses transport normal to it. The spin-orbit interaction governs the magnitude of the band gaps, the reduction of the number of transport channels and resistance increase. The hybridization of the states close to the gap causes back scattering even by normal disorder, which suppresses the conductance also when the Fermi energy is not lying exactly in the gap (dashed line in Figure 1(a)). Gap formation and scattering are the microscopic equivalent of the spin-mixing phenomenology of the AMR mentioned above.

While the nodal ring is a topological feature, its effect on transport depends on its vicinity to the Fermi energy. In the virtual band model, the alloying shifts the Fermi energy closer to the topological nodal ring, which increases the AMR by more efficiently profiting from the band gaps. The remarkable crystalline anisotropy of the observed and calculated AMR has a similar origin, viz. the distance of the nodal ring from the Fermi energy depends on the magnetization direction relative to the crystal axes.

Zeng et al. [3] not only provide a satisfactory explanation of the AMR, but also solicit new questions and research directions:

(1) Are the nodal lines ubiquitous in metallic ferromagnets and topologically protected?

(2) The energy gaps close to the Fermi energy govern also the intrinsic AHE [6] and, for high-density metals, the magnetic anisotropy energy [9]. Naively, we may therefore expect correlations of these properties with the AMR. But

Figure 1 (Color online) (a) Band crossing (blue lines) close to the Fermi energy, which opens by rotating the magnetization out of the x, z mirror plane (red line). Proximity of the Fermi energy to the band edge (green dashed line) enhances back scattering by disorder (dashed arrow). (b) Projection of a model Fermi surface in the transport z -direction (red lines) that illustrates the suppression of the transmission probability (blue shading) by the formation of a gap in the k_x, k_y plane.

why has NiFe (permalloy) a large AMR and is still magnetically soft?

(3) Only a small number of groups can compute transport properties in disordered systems truly from first principles. The intrinsic AHE angle, on the other hand, follows from the band structure of perfect crystals and non-experts can compute them by freely available *a priori* electronic structure codes. Since the intrinsic band structure topology appears to govern the AMR, simplified calculations based on e.g., relaxation time or ballistic approximations should have predictive value that could facilitate combinatorial search for the best magnetoresistive materials.

- 1 W. Thomson, *Phil. Trans. Royal Soc. Lond.* **146**, 649 (1856); *Proc. Royal Soc. Lond.* **8**, 546 (1857).
- 2 T. McGuire, J. Aboaf, and E. Klokholm, *IEEE Trans. Magn.* **20**, 972 (1984).
- 3 F. L. Zeng, Z. Y. Ren, Y. Li, J. Y. Zeng, M. W. Jia, J. Miao, A. Hoffmann, W. Zhang, Y. Z. Wu, and Z. Yuan, *Phys. Rev. Lett.* **125**, 097201 (2020).
- 4 S. Kokado, M. Tsunoda, K. Harigaya, and A. Sakuma, *J. Phys. Soc. Jpn.* **81**, 024705 (2012), arXiv: 1111.4864.
- 5 J. Banhart, and H. Ebert, *Europhys. Lett.* **32**, 517 (1995); I. Turek, J. Kudrnovský, and V. Drchal, *Phys. Rev. B* **86**, 014405 (2012), arXiv: 1111.4793.
- 6 N. Nagaosa, J. Sinova, S. Onoda, A. H. MacDonald, and N. P. Ong, *Rev. Mod. Phys.* **82**, 1539 (2010), arXiv: 0904.4154.
- 7 A. A. Starikov, Y. Liu, Z. Yuan, and P. J. Kelly, *Phys. Rev. B* **97**, 214415 (2018), arXiv: 1805.10062.
- 8 K. M. Schep, P. J. Kelly, and G. E. W. Bauer, *Phys. Rev. Lett.* **74**, 586 (1995).
- 9 G. H. O. Daalderop, P. J. Kelly, and M. F. H. Schuurmans, *Phys. Rev. B* **41**, 11919 (1990).