Unravelling Parallel Conduction Channels in Sputtered Topological Insulator Films

J.P. Maganinho[1]
M. Moreira[1], A. L. Pires[1], and A. M. Pereira[1]*

[1]IFIMUP – Institute of Physics for Advanced Materials, Nanotechnology and Photonics, Department of Physics and Astronomy, Faculty of Sciences, University of Porto, Rua do Campo Alegre, 4169-007 Porto, Portugal

*ampereira@fc.up.pt

Over the past two decades, three-dimensional (3D) topological insulators (TIs) have attracted sustained theoretical and technological interest due to their nontrivial band topology, characterized by a gapped bulk coexisting with topologically protected surface states (TSSs). The robustness of TSSs against nonmagnetic disorder [1], combined with strong spin-orbit coupling, provides 3D TIs with exceptionally efficient spin-to-charge conversion (spin-Hall angles ~ 1 at room temperature [2]). This positions TIs as transformative materials for next-generation spintronic devices [3], provided scalable fabrication routes and reliable TSS transport identification can be achieved.

Sputtering deposition offers an industry-compatible pathway to produce ultrathin TI films over wafer-scale areas, naturally enhancing the surface-to-bulk ratio and the contribution of TSSs to conduction. Recent theoretical and experimental [4,5] studies further suggest that topological protection can persist even in strongly disordered regimes, motivating the use of sputtering for scalable TI integration into magnetic multilayer stacks for spintronic applications. Despite these advantages, sputtered 3D TI films often exhibit competing bulk, surface, and disorder-driven conduction channels (associated with amorphization, granularity, and polycrystallinity) making reliable identification of TSSs transport challenging, particularly when direct band-structure probes such as ARPES are inaccessible. In this scenario, identifying signatures of TSS conduction requires indirect transport probes combined with robust analytical ability to untangling background effects introduced by local disorder. In our work, we introduce a general magnetoconductivity analysis framework that sequentially incorporates weak anti-localization (WAL), quadratic ($\beta.B^2$), and disorder-induced linear magnetoresistance (LMR) contributions, enabling physically consistent extraction of the WAL pre-factor (α) and phase-coherence length (L_Φ). Applying this approach to previously published results on granular sputtered Bi_2Te_3 films with varying thickness and disorder levels [5], we show that post-annealing improves granules' structural order, while amplifying mobility inhomogeneity, requiring the inclusion of the LMR term to avoid nonphysical $\alpha(T)$ and $L_\Phi(T)$ dependences.

The refined analysis reveals a thickness-driven transition from bulk-mediated coupling to fully decoupled TSS channels ($\alpha \rightarrow 1$), together with an annealing-induced crossover from 3D to 2D electron-electron interaction dephasing. Overall, this framework will provide a robust and transferable methodology for identifying TSS conduction and unravelling intertwined transport contributions in sputtered, polycrystalline, and granular 3D TI films, offering a powerful characterization tool for scalable quantum materials and spintronic device platforms.

References

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