Non-linear anomalous Hall effect of two-dimensional spin-3/2 heavy holes

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Understanding of the anomalous Hall effect (AHE), unlike ordinary Hall effect, has been a key issue for modern physics. In two-dimensional hole gas systems, a similar effect in the linear regime induced by the planar magnetic field is presented by our group. [1]. In current work, we identify a sizable non-linear anomalous Hall effect of spin-3/2 heavy holes in zincblende nanostructures, driven by a quadrupole interaction with the electric field formerly believed to be negligible [2]. The interaction is enabled by \(T_d\)-symmetry, reflects inversion breaking and in two dimensions results in an electric-field correction to the in-plane \(g\)-factor. The effect can be observed in state-of-the-art heterostructures, either via magnetic doping or by using a vector magnet, where even for small perpendicular magnetic fields it is comparable in magnitude to topological materials.

We show that tetrahedral symmetry terms lead to a non-linear anomalous Hall effect in a symmetric hole quantum well. The effect occurs in the presence of both in-plane and out-of-plane Zeeman fields, the latter of which can be produced either by a small magnetic field or by magnetic impurities in a ferromagnetic semiconductor. The role of the \(T_d\) terms can be understood as an electric-field induced shear term in the in-plane \(g\)-factor. We find a large non-linear anomalous Hall current density along the \(y\)-axis, accompanied by a much smaller non-linear longitudinal current density. The effect can be easily measured in readily available hole nanostructures, which provide a straightforward set-up for probing the existence of tetrahedral-symmetry terms. Aside from the novelty of identifying a non-linear electrical response purely due to holes, as opposed to well-known optical transitions linking the valence and conduction bands, a sizable tetrahedral contribution beyond the Luttinger model will have important repercussions for hole-based quantum computing.

[1] Cullen, J., Bhalla, P., Marcellina, E., Hamilton, A. & Culcer, D. Generating a topological anomalous Hall effect in a nonmagnetic conductor: An in-plane magnetic field as a direct probe of the Berry curvature. Physical Review Letters. \textbf{126}, 256601 (2021)

[2] Gholizadeh, S. & Culcer, D. Non-linear anomalous Hall effect of two-dimensional spin-3/2 heavy holes. \textit{ArXiv Preprint ArXiv:2206.11916}. (2022)