

# Nonequilibrium spin polarization and spin-orbit torques in graphene deposited on a magnetic insulator

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Two-dimensional van der Waals (vdW) heterostructures are currently intensively studied in both fundamental and applied physics research. By stacking graphene on atomically thin two-dimensional magnetic insulators (e.g., CrI<sub>3</sub>, EuO, or CrBr<sub>3</sub>)[1-3], a wide range of tunable electronic, topological, and transport properties can be realized through magnetic and spin-orbit proximity effects[4-6]. Moreover, these magnetic vdW heterostructures allow for efficient control via external electric fields, electrostatic gating, strain, or relative twisting of the layers.

We present a theoretical analysis of the proximity-driven transport phenomena in graphene on magnetic substrates, focusing on different forms of spin-orbit and exchange couplings and on their interplay, that results in remarkably different spin and topological properties [7]. Our theoretical study has been done within the low-energy effective Hamiltonian of proximitized graphene and the Green's function formalism, yielding analytical expressions with broad applicability to graphene-based magnetic van der Waals heterostructures. We focus especially on charge-to-spin conversion, i.e., spin Hall effect and nonequilibrium spin polarization, as well as on topological properties, that can arise in such structures and can be observed in the behavior of the anomalous Hall effect [7]. We will also discuss spin-orbit torques induced by nonequilibrium spin polarization, with a primary focus on the anti-damping components.

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