Transport signatures and the origin of non-collinear spin textures

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Spin and charge transport is vital for spintronics, whereas the origin, detection and understanding of spin textures in magnets is of utmost importance in magnetism. In this thesis, we combine these two research directions to find transport properties of metal/graphene placed on top of a spin textured magnetic insulator. We also study a magnetic system with a very unusual spin texture. In this thesis, we discuss the phenomenological theory behind the spin Hall magnetoresistance in Pt|$\text{Cu}_2\text{OSeO}_3$ heterostructure (Chapter 2), find the resistance anomaly of Graphene|$\text{Spiral magnet}$ (Chapter 3), and explain the origin of the unusual 90° spin ordering in the multipiezo magnetic insulator Pb$_2$MnO$_4$.

The transport of electrons in bulk metals and in graphene is modified by of magnetic impurities and crystal defects. In conducting magnets, the presence of non-collinear spin structures, such as domain walls and spirals, is known to alter resistivity. In non-magnetic metals or graphene, however, these structures are absent. Recently fabricated heterostructures of these metals/graphene with spin textured magnetic insulators facilitate the interaction of ordered spins with conduction electrons. Properties of the metal/graphene electrons are modified as a result of such interaction.

Conversion of the electrical current to a spin current is known as spin hall effect. The inverse effect is called the inverse spin Hall effect. An essential ingredient for these effects in non-magnetic metals is the spin-orbit coupling. A non-magnetic metal with strong spin-orbit coupling placed on top of an insulating magnet gives rise to spin Hall magneto-resistance (SMR) resulting from the simultaneous action of the spin Hall and inverse spin Hall effects. The SMR in collinear ferromagnets and antiferromagnets shows a characteristic dependence on the angle between the electric current and applied magnetic field. If the substrate magnetic insulator hosts a non-collinear spin structure, the magneto-resistance behaviour of the metal changes. An anomalous dependence of SMR on the strength of the applied magnetic field
can be used to detect magnetic phase transitions. A heterostructure made of Platinum, a metal with strong-spin orbit coupling, and Cu$_2$OSeO$_3$, an insulating magnet hosting non-collinear spiral and skyrmion crystal states, works as a prototype system providing a signature of magnetic phase transitions probed by the spin Hall magneto-resistance.

The first two-dimensional material that was found to host the Dirac electrons, Graphene, has a wonderful physical properties. However, it lacks tunability necessary to make a functional devices that are interesting for applications. Creating an heterostructure is a way to harness additional functionalities without sacrificing the physical properties of the parent materials. For example, graphene put on top of an insulating magnet shows the anomalous Hall effect. In heterostructures with transition metal dichalcogenides it acquires strong spin-orbit coupling. Now if this magnet hosts a non-collinear spin texture, such as a spin spiral, the conduction electrons interact with the magnetic spiral, which modifies their behavior of the conduction electrons and changes the shape of the Fermi surface. The anisotropy of the Fermi surface is reflected in the graphene resistance along the x and y directions. We found an exact solution of the Boltzmann equation describing the graphene|FeCl$_3$ heterostructure and showed that the graphene resistivity is affected by the onset of the spiral ordering in FeCl$_3$. The resistivity anomaly is electrically tunable by an electrostatic gating.

Coming back to the origin of such non-collinear spin textures, it is a result of many competing interactions, such as the Heisenberg exchange, magneto-crystalline anisotropy and Dzyaloshinskii-Moriya (DM) interaction. We investigate the origin of the spin non-collinearity in a well-studied material, Pb$_2$MnO$_4$, where spins were found to form a 90°-state. In this state, neighboring spins in the $ab$ layers arrange at 90° angle to each other. From the symmetry arguments, we deduce the allowed Heisenberg exchanges, DM interactions and anisotropy parameters. We find that the unusual 90° state results from the geometric frustration of exchange interactions between the antiferromagnetic chains running along the $c$ axis, but it is also affected by DM and longer-range exchange interactions. We also find that by varying parameters of the spin Hamiltonian, we can stabilize various spiral states and meron-antimeron lattices.

In this thesis we find the transport signatures of noncollinear magnetism using graphene and metal heterostructures with magnetic insulator and investigate the origin of the non-collinear magnetism. We study the spin Hall magnetoresistance (SMR) in Pt|Cu$_2$OSeO$_3$ heterostructure. We show that SMR hitherto investigated only for collinear magnets can become an electrical probe for complex magnetic spin states exhibited by a ferromagnet. Following experimental detection, we show that discontinuities in the magnetic field dependence of SMR indicate the magnetic phase transitions in the Cu$_2$OSeO$_3$. Extending the framework developed earlier for
collinear magnets, we explain, the sign change of the SMR signal in the conical spiral state under an applied magnetic field.

Graphene and other two-dimensional conductors showing proximity-induced magnetism provide a new avenue for studies of next-generation spintronic devices. Proximity-induced ferromagnetism in graphene provides a rich playground to explore electrically tunable magnetic effects. We consider graphene placed on a magnetic insulator hosting a spin spiral. This heterostructure splits the Dirac dispersion of electrons in graphene in two cones separated by the ordering wave vector of the magnetic spiral. The splitting of the Fermi surface changes the electrical resistivity below the magnetic ordering temperature. Electrically tunable anisotropic resistivity makes possible to detect the spiral ordering in a magnetic insulator by means of transport.

Multi-piezo Pb$_2$MnO$_4$ is shown to exhibit exchange frustration and chirality. The allowed Heisenberg exchange couplings and Dzyaloshinskii-Moriya interactions are found using the symmetry of this system. The 90° angle between neighbouring Mn spins is found to arise from competing exchange interactions and from Dzyaloshinskii-Moriya interactions. The helical and conical spiral, meron anti-meron lattice and the unusual 90°-phase are found in the phase diagram with a variable exchange coupling and magnetic anisotropy.

The studies described in this thesis provide understanding of the origin and transport signatures of non-collinear spin textures in the graphene/Pt and spiral magnet heterostructures. The resistivity of nonmagnetic metal and graphene is influenced by the presence of the spiral within the magnet. The spiral emerges as a result of the crystal structure, spin frustration and relativistic spin interactions. These findings may lay bricks of spin-based devices utilizing noncollinear magnets.