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Berry Phase and Dissipationless Currents in Solids

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It is now recognized that the electronic band structures in solids are characterized by nontrivial quantum topological nature associated with Berry phase. This situation is analogous to the quantum Hall system under the strong magnetic field, but occurs in almost every material even without the magnetic field. Anomalous Hall effect in ferromagnets is a representative example, where the anomalous velocity induced by Berry phase leads to the transverse motion of the electrons to the applied electric field. In paramagnetic materials, on the other hand, the Kramers degeneracy makes the Berry connection non-Abelian. The spin dependent anomalous velocity leads to the spin Hall effect in semiconductors such as GaAs. These charge and spin currents are distinct from the usual transport current since it is not due to the deviation from the equilibrium electron distribution in momentum space, but is driven by the anomalous velocity of all the occupied states in equilibrium. Therefore it is essentially dissipationless. However, in real situation, the disorder effect and contact to the leads introduces the dissipation. This aspect is discussed in detail using the Keldysh formalism for each problem. Ideas of anomalous Hall insulator and spin Hall insulator are also proposed to avoid this dissipation. Applications to optical phenomena are also discussed. This work has been done in collaboration with Z. Fang, S. Murakami, K. Ohgushi, M.Onoda, S.Onoda, K. Sawada, R.Shindou, N. Sugimoto, K. Terakura, and S.C.Zhang.