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Group IV Semiconductor Spintronics

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Group IV semiconductors are natural material choices for quantum and classical spintronic devices. As for conduction electrons, space-inversion symmetry precludes their spin relaxation by the Dyakonov-Perel mechanism. Hyperfine interactionsare suppressed due to the natural abundance of zero-spin nuclear isotopes. As a result, the intrinsic spin lifetime is relatively long (reaching ~10 ns at room temperature in nondegenerate n-type silicon). Combined with the fact that Si and Ge are important material choices in the semiconductor industry, there is awide interest in recent spintronics experiments with Si and Ge.

The conservation of angular momentum during the interaction between radiation and matter allows one to study the spin angular momentum of charge carriers from the state of light polarization. However, even though Si was the first material studied in optical orientation experiment in the 1960s, a parameter-free method of accurately determining the degree of spin polarization of electrons in Si and Ge was missing for decades. This missing link is established with a comprehensive theory in this dissertation which provides concise relations betweenthe degrees of spin polarization and measured circular polarization for each of the dominant phonon-assisted optical transitions. The crystal translation symmetry mandates that optical transitions across the indirect absorption edge also involve the electron-phonon interaction. The phonon symmetries play a key role in elucidating recent spin injection experiments in Si and Ge. The theory also studies the effect of strain on spin-dependent optical transitions in Si and Ge. The applied strain lifts the energy degeneracy in the band edges and controls the mixing between hole species with different spin angular momentum. It could be used as a valuable experimental knob to regulate and validate the relation between the measured circular polarization degree and the spin polarization of carriers.

The availability of transparent spin-dependent theories in direct gap semiconductors has spurred the field of semiconductor spintronics. Prior to our work, however, elaborate numerical methods were required to study spin-orbit properties in indirect bandgap Group IV semiconductors in spite of their significant potential in spintronics. The importance of lucid and compact theories that accurately describe spin properties of conduction electrons in Si and Ge with relatively simple means is thus clear. In this dissertation, we derive a spin-dependent Hamiltonian that captures the symmetry of the zone edge X-point states in Si. We present analytical expressions of the spin-dependent states and of spin relaxation due to electron-phonon interactions in the multivalley conduction band, showing excellent agreement with experimental results. Similar to the usage of the Kane Hamiltonian in direct band-gap semiconductors, the new Hamiltonian can be used to study spin properties of electrons in Si. In addition, we investigate the intrinsic spin relaxation of conduction electrons in Ge due to electron-phonon scattering. Intravalley and intervalley spin-flip matrix elements are derived for a general spin orientation and quantify the resulting anisotropy in spin relaxation. The form of the intravalley spinflip matrix element is derived from the eigenstates of a compact spin-dependent k.p Hamiltonian in the vicinity of the *L*-point (where thermal electrons are populated in Ge). Spin lifetimes from analytical integrations of the these matrix elements show excellent agreement with independent results from elaborate numerical methods.