Coherent Spin Helices in Semiconductors: From Transport and Interference to Multiplexed Information Processing

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Spin helices originate from the coherent precession of electron spins around an effective magnetic field generated by spin–orbit interaction [1,2]. When the spin–orbit field satisfies a uniaxial condition associated with SU(2) symmetry, spin relaxation is strongly suppressed while spatial spin precession is preserved [3,4]. This leads to long-lived and spatially periodic helical spin textures exhibiting wave-like functionalities such as interference and multiplexing [5]. Spin helices enable information to be encoded not only in amplitude but also in wavelength, phase, and spatial mode structure, thereby opening the door to multiplexed and parallel processing analogous to mode-division multiplexing in photonics. Multiple spin helices with distinct wave vectors can coexist within the same material platform, propagate simultaneously, and interact coherently, providing a physical foundation for multimode processing in semiconductor systems. Here, we demonstrate coherent control of spin helices experimentally in (001)-oriented GaAs/AlGaAs quantum wells under the persistent spin helix regime. Using time- and spatially resolved Kerr rotation microscopy, we directly visualize their spatiotemporal evolution at cryogenic temperature. By splitting the optical pump beam into multiple excitation spots with controlled phase and delay, we observe both constructive and destructive interference between spin helices, confirming their intrinsic wave-like nature. Building on this capability, we further demonstrate a prototype majority-gate operation based on the interference, where the output spin polarization reflects the majority of the input spin helix phases. In addition, we achieve long-distance spin-helix transport by combining drift-driven propagation with quasi-1D confinement in wire channels. Under an in-plane electric field, spin helices propagate coherently over distances exceeding 200 μm, representing an approximately fivefold enhancement compared to conventional two-dimensional channels. These results establish coherent generation, interference-based logic functionality, and long-range transport of spin helices in semiconductor heterostructures, highlighting their potential for multiplexed and parallel information processing.

References:

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