Universität Basel

Research Project

Electro-optics of semiconductor nanostructures III

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Quantum communication and quantum computation offer compelling advantages over their classical counterparts. Quantum communication over short distances is a reality; over long distances it is not. A fully-fledged quantum computer remains a very distant prospect but its potential to solve hard problems in chemistry and materials science make it an extremely important goal. Application of these quantum concepts with semiconductors offers a route to creating small, fast and scalable devices. However, while the materials have powerful advantages they are also complex with several inter-connected subsystems (electronic charge, electronic spin, nuclear spins, phonons, photons). The physics of these materials, particularly with structure on the nano-scale, needs to be understood. The overriding goal of this project is to make leading contributions to the development of semiconductor-based quantum technology. There are three inter-linked strands, development of a quantum device, an investigation into some of the key physics, and an exploration of new materials.Tunable quantum dots in a tunable micro-cavityA self-assembled quantum dot has emerged as a leading contender for a source of single photons. The photons should be bright, pure and indistinguishable. Quantum dots far beneath the surface of the semiconductor emit pure and highly indistinguishable photons but the brightness is poor on account of the difficulties of extracting photons from the high-index semiconductor. High-brightness devices rely on nano-fabrication. In many cases, the nano-fabrication is both complex and invasive such that device yield is poor, and the photon purity and indistinguishable suffer. The proposal here is to solve this conundrum by embedding electrically-contacted quantum dots in a vertical micro-cavity: tunable quantum dots in a tunable micro-cavity. Nano-fabrication is bypassed: the quantum dots in the device are guaranteed to have ultra-high quality; contacting the device is trivial. The mirrors are built with known, ultra-high quality materials and techniques. Calculations show that two ideal limits can be reached, optimized photon collection and strong coupling. Remarkably, only a modest micro-cavity finesse (1,000) is required for ultra-high photon extraction. These ideas will be implemented paying attention to all the crucial details which have hindered progress in the past. The technology will be simplified in order to create a device. An efficient spin-photon interface will be built by trapping a single spin (either electron or hole) in the quantum dot. Spin-photon entanglement protocols will be applied, and, on success, entanglement swapping operations to create high-rate spin-spin entanglements.Phononics with an embedded quantum dotThe electron-phonon interaction results in spin dephasing in a semiconductor. This is not inevitable. The phonon modes and their occupations can be controlled, a process of ”phononics”. Compared to ”photonics”, phononics has received almost no attention in the context of quantum dots. A phononic crystal will be created with a gap in the density of states in the few-GHz regime. When the electron spin Zeeman frequency lies in this gap, phonon-related spin relaxation should be suppressed.

Conversely, the spin relaxation rate will be used to probe the local phonon density of states. A localized high-Q phonon mode will be created by using a phononic crystal to shield a small element from the bulk phonon modes. An embedded quantum dot will couple to the localized phonon mode. The aim is to reach the resolved sideband regime which allows the phonon number to be controlled, possibly to the phonon ground state, by optically driving the quantum dot.Quantum photonics with 2D semiconductorsThe only known way of ”wiring up” self-assembled quantum dots is via photons. A ”circuit” of self-assembled quantum dots does not exist largely because the quantum dots must be located deep below the surface. A tantalizing prospect is to create a quantum dot circuit with a two-dimensional semiconductor where, by its very nature, all the action takes place on or very close to the surface. Only the most rudimentary quantum dot-like elements exist in this materials class, for instance confined excitons in WSe2. The aim here is to create quantum dots in pre-defined locations with an electrical technique.

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