Novel Manifestations of the Aharonov-Bohm Effect in Quantum Rings and Möbius Rings

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***Abstract* — An overview is given on the recent experimental and theoretical advancements in studies of novel manifestations of the Aharonov-Bohm quantum-interference effect for excitons confined to self-assembled quantum rings and other semiconductor nanostructures with ring-like states of charge carriers as well as for electrons in Möbius rings at the micro- and nanoscale. The exciton Aharonov-Bohm effect can be effectively controlled by an out-of-plane magnetic field, a vertical electric field, a spin disorder. A "delocalization-to-localization" transition for the electron ground state occurs in a Möbius ring as it is made more inhomogeneous.**

***Index Terms* — Aharonov-Bohm quantum-interference effect, cross-sectional Scanning Tunneling Microscopy (XSTM), excitons, magneto-photoluminescence (MPL), Möbius rings, persistent currents, quantum rings, topology.**

I. INTRODUCTION

Recent magneto-photoluminescence (MPL) studies have revealed surprising exciton properties [1] of ring-like nanostructures via the "optical" Aharonov-Bohm quantum-interference effect that occurs if confined neutral excitons are sufficiently polarized [2,3]. Though self-assembled quantum rings and type-II quantum dots are singly connected, they can manifest the Aharonov-Bohm behavior because the states of constituent charge carriers are shaped similar to those in doubly-connected topologies. The Aharonov-Bohm oscillations can be straightforwardly traced by patterns of the MPL spectra under increasing magnetic field.

II. TYPE-I QUANTUM RINGS

The emission energy of an ensemble of self-assembled InAs/GaAs quantum rings ("quantum volcanoes") is analyzed [4-6] in high magnetic fields at cryogenic temperatures. The importance of Coulomb forces in the MPL spectra is emphasized and, in particular, it is shown that the Coulomb attraction between an electron and hole in an exciton can suppress the Aharonov-Bohm oscillations in quantum rings with a finite ring width. The ring-like topology of the nanostructures results in (i) non-equidistant exciton energy level splittings and (ii) a magnetic-field-induced splitting of each excited state into two states, in contrast to what is observed in quantum dots. The measured optical transition probabilities are interpreted within a dedicated theoretical model [7], based on the cross-sectional Scanning Tunneling Microscopy (XSTM) characterization of a realistic self-assembled quantum ring [8].

Aharonov-Bohm quantum-interference effects due to neutral excitons observed in type-I self-assembled InAs/GaAs quantum rings are shown to reveal signatures of built-in piezoelectric fields and temperature [9]. It is found that the built-in piezoelectric fields may play an important role in strained quantum rings by changing the sequence of maxima and minima of the Aharonov-Bohm oscillations. Self-assembled InGaAs quantum rings grown on GaAs substrate by molecular beam epitaxy combined with *in situ* $AsBr_3$ etching [10] enable effective tuning of the Aharonov-Bohm oscillations in MPL by applying a vertical electric field to the quantum rings (rather than an out-of-plane magnetic field within the conventional detection setups) owing to a modification of the exciton confinement. The Aharonov-Bohm effect observed in the MPL energy and intensity of a single neutral exciton [10] is attributed to a radial asymmetry in the effective confinement for electrons and holes.

III. TYPE-II QUANTUM DOTS

In type-II ZnTe/ZnSe quantum-dot structures, the hole is localized in a ZnTe quantum dot, while the electron in ZnSe orbits around the hole bound by the Coulomb attraction force. Thus, a ring-like geometry of electron states emerges in this structure, leading to a remarkably robust Aharonov-Bohm effect at elevated (up to 180 K) temperatures [3]. The potential of this geometry to support the optical Aharonov-Bohm effect is demonstrated in type-II ZnMnTe quantum-dot structures, where the magnitude of the Aharonov-Bohm oscillations is extremely sensitive to the magnetic properties of the quantum dots; as a consequence, the strength of the exciton Aharonov-Bohm effect can be effectively controlled by a spin disorder in the system [3].

IV. MÖBIUS RINGS

Nanostructure fabrication techniques can be exploited to generate non-trivially shaped objects with energy spectra determined by man-designed topological space metrics (see, e. g., [11]). A Möbius ring has been analyzed with an inhomogeneous twist, which is spread over a part of its circumference. A “delocalization-to-localization” transition for the electron ground state has been revealed as the Möbius ring is made more inhomogeneous [12]: the corresponding wave function is expelled from the twisted region.

The inhomogeneity of the twist allows for a quantification of the space-dependent metric in the Möbius ring threaded by a magnetic flux Φ using the Aharonov-Bohm quantum-interference effect. When increasing the relative length of the untwisted part, the expulsion of the electron wave function from the twisted region leads to a flattening of the ground-state energy as a function of the magnetic flux because of an enhanced trend to localization. The delocalized states reveal a slow (quadratic) decay of the persistent current, while the effectively localized states are characterized by a fast (exponential) decay of the persistent current as a function of the ratio of the length of the untwisted part of the Möbius ring to the whole circumference. These findings are of practical relevance because the emerging experimental realizations of topologically nontrivial manifolds at the nanoscale are likely to generate inhomogeneities.

V. CONCLUSION

Already these initial studies on the topology-governed physics of excitons confined to self-assembled quantum rings and other nanostructures with ring-like states of charge carriers suggest exciting possibilities to design and fabricate novel elemental base for optoelectronics, sensorics and information processing. Further intriguing perspectives are provided by nanostructures with complicated topologies, in particular, Möbius rings at the micro- and nanoscale.

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