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3D Nanoarchitectures – a Novel Class of Materials: Perspective for Sustainable Development

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Extending nanostructures into the third dimension has become a vibrant research avenue in condensed-matter physics, because of geometry- and topology-induced phenomena. Modern advances of high-tech fabrication techniques have allowed for generating geometrically and topologically nontrivial manifolds at the nanoscale, which determine novel, sometimes counterintuitive, electronic, magnetic, optical and transport properties of such objects and unprecedented potentialities for design, functionalization and integration of nanodevices due to their complex geometry and non-trivial topology [1]. I will focus on three directions of key importance for sustainable development of technologies.

Firstly, recently suggested Möbius-strip microcavities [2] as integrable and Berry-phase-programmable optical systems are of great interest in topological physics and emerging classical and quantum photonic applications. For photons resonating in a Möbius-strip cavity, the occurrence of an extra phase—known as the Berry phase—with purely topological origin is expected due to its non-trivial evolution in parameter space. However, despite numerous theoretical investigations, characterizing the optical Berry phase in a Möbius-strip cavity has remained elusive. Here we report the experimental observation of the Berry phase generated in optical Möbius-strip microcavities. In contrast to theoretical predictions in optical, electronic and magnetic Möbius-topology systems where only Berry phase π occurs, we demonstrate that a variable Berry phase smaller than π can be acquired by generating elliptical polarization of resonating light.

Secondly, an efficient tailoring of acoustic phonon energy spectrum in rolled-up multi-shell tubular structures [3] opens up prospective applications in microelectronics, in cases when low heat conduction is required. The phonon energy spectra in the Si/SiO_2 multishell nanotubes are obtained using the atomistic lattice dynamics approach. Thermal conductivity is calculated using the Boltzmann transport equation within the relaxation time approximation. Redistribution of the vibrational spectra in multishell nanotubes leads to a decrease of the phonon group velocity and the thermal conductivity as compared to homogeneous Si nanowires. Phonon scattering on the Si/SiO_2 interfaces is another key factor of strong reduction of the thermal conductivity in these structures (down to 0.2 $Wm^{-1}K^{-1}$ at room temperature). We demonstrate that phonon thermal transport in Si/SiO_2 nanotubes can be efficiently suppressed by a proper choice of nanotube geometrical parameters: lateral cross section, thickness and number of shells.

Thirdly, prospect directions and challenges in the domain of superconductivity and vortex matter in curved 3D nanoarchitectures and their great potential for magnetic field sensing, bolometry, and information technology have been demonstrated [4]. A topological transition between the vortices and phase slips under a strong transport current is found in open superconductor Nb nanotubes with a submicron-scale inhomogeneity of the normal-to-the-surface component of the applied magnetic field [5]. This transition determines the magnetic-field–voltage and current–voltage characteristics, which imply a possibility to efficiently tailor the superconducting properties of nanostructured materials by inducing a nontrivial topology of superconducting screening currents. A transition between the vortex and phase-slip regimes depends on the magnetic field only weakly if the magnetic field and/or transport current are switched on gradually. In the case of an abrupt switch-on of the magnetic field or transport current, the system can be triggered to the stable phase-slip regime within a certain window of parameters. A hysteresis effect in the current-voltage characteristics is predicted in superconductor open nanotubes [6]. Dynamic topological transitions in open superconductor nanotubes occur under a combined dc+ac transport current [7]. The key effect is a transition between two regimes of superconducting dynamics. The first regime is characterized by a pronounced first harmonic in the Fast Fourier Transform (FFT) spectrum of the induced voltage at the ac frequency. It is typical of two cases, when the dominant area of the open tube is superconducting at relatively low magnetic fields and/or weak dc currents or normal at relatively high magnetic fields and/or strong dc currents. The second regime is represented by a rich FFT spectrum of the induced voltage with pronounced low-frequency components due to an interplay between the dynamics of superconducting vortices or phase slips and those driven by the ac.

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