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Editorial

Atom chips: manipulating atoms and molecules with microfabricated structures

Atom chips are micro fabricated, integrated devices in which electric, magnetic and optical fields can confine, control and manipulate cold atoms. Through miniaturization, atom chips offer a versatile new technology for implementing paradigmatic ideas in quantum optics, quantum measurement and quantum information processing. Over the last decade, there has been spectacular progress in miniaturizing cold atom physics which culminated in preparing and manipulating the quantum states of atom clouds on chips. This special issue collects recent advances in various fields of atom chip physics and technology.

Recent advances in science and technology have demonstrated that miniaturization and integration are important steps towards the robust application of fundamental physics. Prominent examples are semiconductor physics and its application in integrated circuits and information processing, or optics and the development of integrated micro-optical devices, which lead to sensors and many applications in telecommunication. The atom chip aims at a similar step for quantum optical systems based on neutral atoms and photons: the implementation of quantum optics and atomic physics experiments and quantum measurement technology with the help of miniaturizing and integration.

In micro electronics, electrons move *through* micro fabricated wires, switches, transistors, etc. in integrated circuits, to perform elaborate tasks. In devices we call atom chips, atoms are trapped or move in microscopic potentials *above* a surface. The traps, guides and other devices, are formed by electric, magnetic and light fields which originate from (microscopic) structures built on the surface of the atom chip. The structures have scales similar to those of the de-Broglie wavelength of the atoms, and hence quantum effects become important. In fact potentials for atoms on atom chips are similar to those produced for electrons in mesoscopic quantum electronic devices, but since the atoms can be much better isolated from the surrounding environment, much longer coherence times can be achieved. The long lived quantum coherence allows a robust quantum tool box to be developed. Atom chips thereby potentially combine the best of two worlds: the ability to use cold atoms — a system well suited for precise quantum manipulation, and the immense technological capabilities of nano fabrication.

The first experiments on micro traps started as early as 1990 with the demonstration of guiding atoms along free-standing wires and investigation of the trapping potentials in simple geometries. From there the scientific progress in the manipulation of atoms in micro traps has been enormous. It has led to the micro-fabrication of atom-optical elements down to 1 μm size and below on atom chips. In the last years atom chip traps proved themselves to be advantageous in creating in a simple way a BoseEinstein condensate in a miniaturized surface trap. Currently atom chip based BEC experiments and experiments on degenerate Fermi gases are under way in many groups throughout the world. Recently we have seen first attempts to integrate light optics and micro cavities on the atom chip.

Atom chips thus provide a unique environment that opens new aspects of atomic physics and ultra-cold matter wave optics. For example, by trapping ultra-cold samples near a surface, one gets access to atom-surface interactions that distort trap potentials or involve transitions between trapped quantum states. This access is the more promising in view of the flexibility of applying optical, electrical, or magnetic fields for atom manipulation, sometimes even in "real time". We currently observe the trend that the dynamics of atomic de-Broglie wave themselves provide diagnostic tools for surface interactions, e.g., via the striking phenomenon of "quantum reflection" off a classically attractive potential. Cold atoms can thus be added to the long list of spectroscopic probes (electromagnetic radiation, neutron and electron beams, etc.) that disclose information about atomic energy levels and other quantum systems in general.

Bose-Einstein condensates on atom chips are among the most spectacular realizations of a "macroscopic quantum object". They can be manipulated accurately using time-dependent, micron-scale potentials. In particular, atom chips can realize trap geometries with extreme aspect ratios, allowing one to realize low-dimensional systems with either high or low densities. Inter-atomic interactions enrich matter wave dynamics by the corresponding non-linearity and turn, for example, the familiar tunnelling in a double-well potential into intricate Josephson oscillations.

Getting better control of the dynamics of external and internal states of trapped atoms on the atom chip may naturally lead to implementing a q-bit for quantum information processing. At the level of single atom manipulation atom–atom interactions may provide the mechanism for the controlled phase shifts needed to implement the quantum gate. Additional flexibility and robustness can be achieved by combining center of mass manipulation in dynamic microstructures with excitation of internal atomic Zeeman or hyperfine states. The possibilities are many and not yet all explored, and we anticipate realizations of neutral atom information processing on an atom chip in the not too distant future.

We see the atom chip as an integrated device which will allow us to develop a robust experimental toolbox and permit new insights into fundamental quantum physics, for example in areas such as decoherence, entanglement, low-dimensional mesoscopic systems, disordered systems and degenerate quantum gases beyond mean-field theory. A successful implementation may lead to widespread applications from highly sensitive sensors (atomic clocks, inertial sensors, electro-magnetic field and surface measurements) to quantum information technology.

To build this quantum toolbox, the atom chip must be able to perform numerous functions. It needs an atom source, has to perform cooling and loading of cold atoms into the tiny traps just above the surface of the chip. Versatile guides, traps, and networks then must perform complex tasks with the atoms. Furthermore the atom chip must allow efficient quantum state preparation, manipulation, storage and transfer and detection, ideally all integrated on a single device. All these requirements put *extreme* demands on component fabrication and integration techniques. Even though there are many open questions, we firmly believe that we are only at the beginning of a new era of robust quantum manipulation of atomic systems with many applications.

In this issue, we have collected papers on recent results in this rapidly expanding community. The papers cover a wide range from aspects of atom-surface interactions to implementations of new traps and guides, from technological issues of new materials for atom chip fabrication to ideas about implementing quantum information processing. They give a good overview of the recent activities and developments in this fascinating research field at the interface between quantum optics, atomic physics and surface science.

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In memoriam Bilha Segev (Ben-Gurion University of the Negev, Beer Sheva, Israel) who passed away while preparing her last paper (p. 3).

The editors of the topical issue:

Carsten Henkel
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