Microfabricated atom traps for quantum information science and precision measurements

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Motivation

Microfabrication holds great promise for a new class of atomic and molecular quantum systems based on scalable and compact trapping structures. These systems have found applications both in quantum information science, novel types of quantum sensors and precision experiments. We design, fabricate, characterize and operate microfabricated neutral atom and ion chip-scale traps both at LNQE and in the PTB cleanroom facility.

Surface-electrode ion traps

Trapped ions are currently one of the most advanced scalable experimental systems for implementing elements of quantum information science. Single ions can be trapped in UHV conditions using combinations of static and time-dependent electric and magnetic fields for time scales of hours to months. The internal atomic states of the ions serve as a quantum bit or "qubit". In order to implement interactions between qubits ("quantum logic gates"), one exploits the repulsive Coulomb interaction between ions trapped in a common potential, combined with additional external driving fields, which are typically implemented using focused laser beams [1]. In a scalable architecture [2,3], multiple ion-qubits would be held in different individual zones of a trap array and physically transported between dedicated gate, manipulation and readout zones. A scalable way of realizing such a "quantum CCD" device is given by surface-electrode traps, where all the electrodes supplying the trapping potentials lie in a plane and are produced using standard microfabrication techniques [4]. We design and fabricate surface-electrode traps for single $^9Be^+$ ions, where the external control fields for multi-qubit gates are realized using microwave conductors integrated into the trap structure [5,6]. This holds great promise for scalability and operation fidelity. Towards this end, we perform high-quality numerical simulations of microwave current flow in integrated waveguide structures and analyze the emanating magnetic near-fields [7,8]. We have recently trapped single ions in such a structure and are currently characterizing the magnetic near-fields experimentally using the ion itself as a field probe.

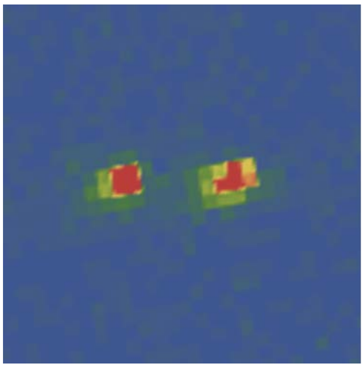

Figure 1: False-color image of the fluorescence from two $^9Be^+$ ions in a surface-electrode trap

Neutral atom chip traps

Since the first demonstration of Bose-Einstein-Condensation (BEC) in 1995 [9,10], different approaches for an efficient creation of this new state of matter have been investigated. One approach is to use microfabricated current-carrying wire structures to produce high-gradient magnetic fields, needed for trapping and efficient cooling of the neutral atoms to BEC [11]. This compact and robust atom chip technology has enabled the development of highly compact, robust and low power consuming BEC machines [12] to make use of the beneficial properties of BECs for e. g. atom interferometry for inertial sensing. By using the coherence properties of the atomic ensemble in an interferometry scheme, inertial forces such as accelerations and rotations can be measured extremely accurately. This leads to the development of new devices to perform fundamental tests of physics or for earth observation in geodesy.

Based on recent advances in atom chip technology, we have developed BEC apparatuses which operate in harsh environments like the drop tower Bremen [13] or on sounding rocket missions performing atom interferometry in space. Furthermore, a new type of portable atom interferometer using BECs for gravity sensing is under investigation.

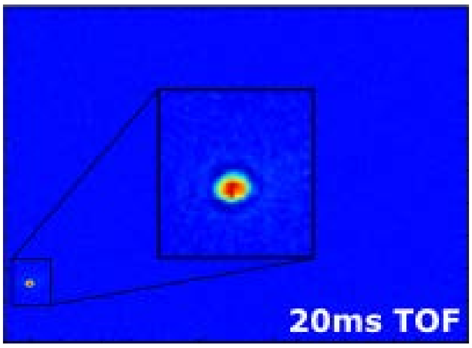

Figure 2: Absorption image of a BEC with $4x10^5$ atoms created with an atom chip after 20 ms of free expansion

Sample fabrication and implementation

We fabricate neutral atom and ion traps using a combination of metal deposition, photolithography, electroplating and etching steps. Our standard wafer is polished Aluminum Nitride because of the high thermal conductivity at room temperature. We first deposit a layer of 20 Å of Titanium as an adhesion layer on top of the substrate. We then evaporate a 500 Å seed layer of gold. On top of this seed layer, we spin photoresist with a typical thickness exceeding 10 µm. The photoresist is exposed and developed. Using electroplating, on top of the exposed seed layer, we grow a film of up to 10 µm of gold in the gaps between the remaining resist structures. The resist and the remaining seed and adhesion layers between the areas where we have grown the gold film are then removed using a series of etching steps. This produces a set of electrically insulated gold conductors, separated by minimum gaps about 4 µm wide. We assemble these structures and align the whole setup within a vacuum system under cleanroom conditions. We connect the chips to a set of vacuum feedthroughs, close and leak test the system before implementing the pumped out vacuum system in an experimental apparatus.

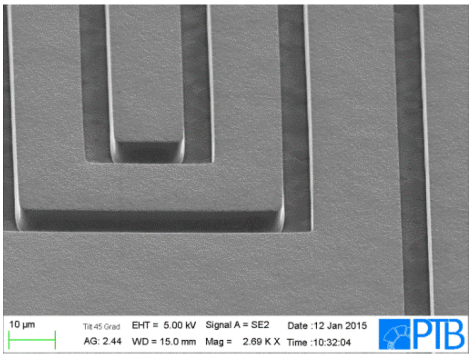

Figure 3: SEM picture of microfabricated surface-electrode ion trap structure

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