Cold atoms near surfaces: Designing potentials by sculpturing wires

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Abstract. The magnetic trapping potentials for atoms on atom chips are determined by the current flow pattern in the chip wires. By modifying the wire shape using focused ion beam nano-machining we can design specialized current flow patterns and therefore micro-design the magnetic trapping potentials. We give designs for a barrier, a quantum dot, and a double well or double barrier and show preliminary experiments with ultra cold atoms in these designed potentials.

1. Introduction
Miniaturized atom optical elements integrated on an atom chip form the basis for robust controlled neutral atom manipulation [1]. Tailored magnetic and electric potentials allow to confine atoms in complex geometries of high spatial resolution with the accuracy given by the fabrication process. Possible applications of atom chips are abundant and range from fundamental studies of degenerate quantum gases in low dimensional potentials to mesoscopic physics of small atomic ensembles to the quest for implementations of quantum information processing (QIP) with neutral atoms.

2. Designing magnetic potentials
The basic design idea of microscopic magnetic traps and guides on the atom chip is to superimpose the field of a current-carrying wire with a bias field [1]. Atoms, with magnetic moment $\mu$, in a weak-field-seeking state see a magnetic potential $U_{\text{mag}} = -\mu \cdot B > 0$ and are consequently trapped in the potential minimum formed by the cancellation of the wire field and the bias field.

A straight wire and a homogeneous bias field result in a 2-dimensional (transversal) confinement where the atoms are free to move along the wire: a guide for atoms [2]. The value of the potential minimum depends on the longitudinal component of the magnetic field. If the current in the wire is exactly orthogonal to the bias field, the cancellation is perfect and the resulting magnetic field minimum is zero. Changing the angle between the current and the bias field will vary the longitudinal field component which is proportional to the component of the current in the direction of the bias field. Such a variation in the potential minimum along the guide will constitute a trap or barrier for the guided atoms. The standard solution to changing
the current flow is to bend the wire, A Z-shaped wire creates 3-dimensional confinement in a Joffe-Pritchard like trap [1].

In our present study we elected a different way to modify the current path and consequently design the potential landscape along the guide. Changing the boundary of a wire will slightly change the current path and direction [9]. The wire edge can be sculptured deliberately using a focused ion beam (FIB) technique. Even though changing the wire edge results only in small changes of the current direction these are sufficient to alter the potentials for ultra cold atoms [6]. This approach of micro machining the wires after fabrication of the atom chip [4] allows to design versatile potentials.

As an example we consider a flat straight wire where we cut a slab from one of its sides. The modified wire edge will create current components transversal to the direction of the wire (fig.1). These new transversal currents will result in a magnetic field that modulates the trap minimum, creating respectively a well and a trough in correspondence of the cut edges.

A different way of modifying the potentials are electric fields, which create an attractive potential: \( U = -\alpha \cdot E^2 \) where \( \alpha \) is the scalar polarizability. Sharp edges generate localized electric potential gradients, that modulate the magnetic trap created by a current in the trapping wire [3].

3. Experimental setup
In our experiment we prepare a BEC on the atom chip as described in [5]. Typically \( 10^8 \) \(^{87}\text{Rb}\) atoms accumulated in a MOT are transferred to a magnetic trap created by a large wire underneath the atom chip and cooled to \( \sim 5 \ \mu\text{K} \) by RF evaporation. The resulting sample of \( \approx 10^6 \) atoms is then loaded to the selected chip trap, where a second stage of RF evaporation creates either a BEC or an ultracold thermal cloud.

We image the atomic clouds by resonant absorption imaging with \( \sim 3.5 \ \mu\text{m} \) resolution. In order to determine the cloud’s distance from the surface \( d \), we slightly incline the imaging light with respect to the chip mirror surface by \( \sim 25 \ \text{mrad} \). For sufficiently small \( d \) (< 100 \( \mu\text{m} \)) this leads to a duplicated absorption image [5] allowing a direct measurement of \( d \). For distances below the optical resolution the values for \( d \) can be extracted from the known currents and fields.
Figure 2. A trap created by a sharp change in the wire edge. (a) Polishing a 200µm long stretch of a chip wire, leaves a sharp step in the wire edge at the end of the polished region. (b) A thermal atomic cloud placed over the wire shows the resulting potential minimum at the specific location of the steps. From the atom density (c) the potential (d) is reconstructed [7].

Figure 3. (a) Notches on wire, (b) potential modulation and (c) quantization of transmission coefficient; numerical simulation without atom-atom interaction.

4. Micro-machining the chip
To investigate the above techniques to structure potentials we micro-machined portions of a 10µm wide wire using a FIB. Its high precision < 20 nanometers can be exploited to create structures much smaller than the lithographic resolution, and with large aspect ratios (height/width) of > 30.

In a first example we polished the vertical faces of the wire over a distance of 200µm creating a situation similar to the one shown in figure 1. At the boundary of the polished section we find a step in the wire edge (fig.2). Loading atoms into the magnetic trap above the wire, they accumulate into the potential minimum created by the current flowing around the step in the wire edge. From the measured atom density we can estimate the trapping potential [7].

A second structure we realized is composed by two 100x500nm cuts in opposite edges of the trapping wire (fig.3, (a)). These small notches introduce a controlled modulation in the current flow, giving rise to a double-barrier potential, with a deep minimum in between (fig.3, left); a quantization of the transmission is expected (see fig.3, (b)); depending on the atom cloud density and on the availability of bound states in the minimum other non-linear effects can become predominant [8].

A third structure we realized is a tip to apply electric potentials modifying the magnetic confinement. The tip was obtained by separating a ‘T’ wire junction (see fig.4(a)). Using the FIB
Figure 4. A sharp tip to create electric modified potentials for trapped atoms. (a) A T-wire structure was cut with the FIB and the wire machined to a sharp tip. (b,c) Potential generated by the tip 7μm above the chip; left image: moving atoms along the tip; trap center: x = 0, y = 0 tip point: x = 0, y = 6 μm right image: changing the potential of the gold mirror structures (Vs) around the tip from 0.5 to -0.83 V. The tip sits always at 1 V (Vt)

allows to sculpture the tip 1μm away from the trapping wire. The sharp edge causes extremely localized electric fields and consequently a high resolution modification of the magnetic trap created by a current in the trapping wire. Changing the electric potentials applied to the tip and to the other structures in the vicinity we can change from single to double well potentials. Numerical simulations of the achievable well depth give values in the μK regime for voltages around 1V. We can modulate the transformation from a single to a double well potential by either moving the trap position along the tip (y direction) or by changing the electric potentials applied to the nearby conductors (see fig.4(b,c)).

5. Conclusion
Atom chips provide an environment with ample flexibility for the design and implementation of tailored potentials for complex matter wave manipulation. Standard lithography can be improved with chip sculpturing (FIB milling) to obtain high aspect ratio structures, with resolutions down to tens of nm.

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