Magnetic trapping on an atom chip

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Received August 29, 2013; accepted September 30, 2013; published September 30, 2013

Abstract—The article reviews briefly the rapidly evolving field of so-called atom chips for neutral atoms. Emphasis is placed on magnetic microtraps – on-chip Ioffe-Prichard and dimple trap issue is covered in some detail. The experimental setup for cooling and trapping ^{87}Rb atoms is also presented together with some early results of on-chip magnetic trapping.

The concept of atom chips was born in 1995 after neutral atoms were trapped for the first time with a magnetic potential of a current-carrying wire by J. Schmiedmayer [1] and after the first experimental realization of Bose-Einstein condensate (BEC) in 1995 [2- 3]. J.D. Weinstein and K.G. Libbrecht proposed to use planar, nanofabricated surface currents for microscopic magnetic traps [4]. Then there emerged experiments on cold atom guiding [5-6] and manipulation [7-8] using atom chips with wires lithographically patterned on substrates. Atom chips attracted growing interest in chip-scale cold atom optics [9].

However, despite the fast development of atom chip experiments, the first BEC on a chip was not realized until 2001 [10-11]. The main difficulty was to load a large number of atoms to a chip trap having a small volume and depth. In addition, the atoms are pre-cooled in a magneto-optical trap (MOT) before being loaded to the chip magnetic trap and the procedure of transport between both traps is associated with an atom loss.

In the experiment [10], the atom chip serves as a mirror for the MOT (so called mirror magneto-optical trap), in such a configuration the distance between the MOT and the designated magnetic atom chip trap is minimalized and, in consequence, the loss in the number of atoms is reduced.

In atom-chip experiments it is essential to keep atoms near the trapping wires, yet atoms should not be trapped to close to the surface of an atom chip. At distances of the order of 10 μm, atoms in a chip microtrap interact with a surface by Casimir-Polder potential, they are also more sensitive to Johnson's current noise than those in a free space. Those atom-surface interactions cause negative effects like heating and reduction the trap lifetime [12-13].

The main profit of the trapping wires miniaturization comes from the fact that high currents are not necessarily needed to create steep trapping potentials. Lower currents that do not require additional cooling, allow greater compactness of the experimental system and make it more mobile. Still, high currents densities of up to 10^7 A/cm^2 to several seconds are possible [14]. Atom chips could be fabricated with wires in the nanometre regime and they allow trapping atoms at a distance of about a micrometer from the trapping current wires [14].

What is more, the multi-layer atom chip technique enables the fabrication of wires crossing without electric contact between them. This leads to a broad range of possibilities creating complex and extremely well defined magnetic potentials with a high resolution [7].

The steep potential indicates high trap frequencies, leading to a higher collision rate. This results in fast thermalization which significantly reduces the time for radio-frequency-assisted evaporative cooling. Feasible frequencies of atom chip traps are up to kHz [10].

It is also advantageous that the steep trapping potential positions the atom cloud near the centre of the magnetic trap, so that the impact of gravitation force on uniformity of the evaporation process is rather small. Due to fast thermalization, collisions with background atoms become less important, so that vacuum requirements may be relaxed contrary to classical magnetic traps.

These are major advantages of micro-fabricated atom chips compared to classical magnetic traps. So far atom chips have appeared to be one of the most flexible toolboxes for quantum optical experiments, opening the door for integrated matter-wave sensors and quantum computation [15]. Currently the number of BEC atom chip systems developed around the world is constantly growing.

A magnetic trap makes use of the interaction between the magnetic moment of a neutral atom and an external magnetic field $\boldsymbol{B}(\boldsymbol{r})$. For an atom trapped in a Zeeman sublevel $|F, m_F>$ the potential can be written as $U(\boldsymbol{r})=\mu_B g_F m_F B(\boldsymbol{r})$, where μ_B and g_F are the Bohr magneton and the Landé factor, respectively. The atoms in the week field seeking state ($g_F m_F>0$) can be trapped in a magnetic field minimum. The most commonly used magnetic trap for BEC experiments has become the Ioffe-Prichard (IP) trap, as it allows to avoid Majorana spin flip losses in the trap center. The magnetic field around the IP potential minimum is approximately given by

$$B = B_0 + \frac{1}{2} B''_{\varrho} \varrho^2 + \frac{1}{2} B''_x x^2, \quad (1)$$

where B_0 is the trap offset, $B''_\rho = B'_\perp{}^2/B_0 - B''_x/2$ [16] and B''_x are the field curvatures in the radial and axial directions, $B'_\perp = \mu_B I/2\pi z^2$. The trap frequencies can be calculated as $\omega_i = (\mu_m B''_i/m)^{1/2}$.

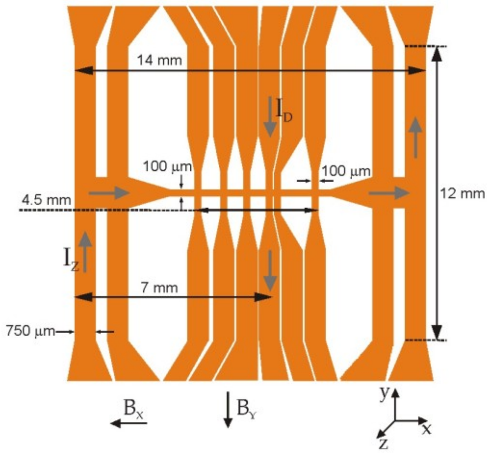

Fig. 1. Scheme of the vacuum side of the atom chip. Arrows represent the current flow through the Z-wire and dimple wire (vertical). The bias fields as well as the coordinate system are depicted.

The on-chip IP microtrap in our setup is created by a Z-shaped wire and proper bias fields (B_Y – see Fig. 1), Fig. 2 shows the calculated trap potential for a set of exemplary experimental parameters. Calculated trap frequencies [Eq. (1)] are υ_x=8 Hz and υ_ρ=584 Hz, which is not enough for efficient evaporative cooling. Adding an extra wire along the y direction and B_X bias field allows to produce a micro-size small dimple potential below the cross point. Such a potential helps to increase the atomic density and obtain a BEC efficiently. Typical trap frequencies are in the order of 500Hz and 2 kHz (or even more [17]) for the axial and radial direction, respectively. The dimple trap, shown in Fig. 3, is situated 180µm beneath the chip.

The heart of the experimental setup is a glass two-chamber RuBECi™ vacuum, coils and chip system from ColdQuanta company, designed for obtaining Bose-Einstein condensation in a magnetic trap on an atom chip (based on [17]). The bottom vacuum cell contains a dispenser providing a Rb pressure between 10^{-8} and 10^{-7} mbar, while in the upper cell the UHV pressure is maintained with a 2 l/s ion pump and a nonevaporable getter. Differential pumping between the two cells is achieved with a silicon disk with a 750µm hole drilled in the center. The upper cell top is covered with the atom chip – a 450µm-thick silicon substrate with 100µm-wide, 10µm-thick copper conductors deposited onto it (Fig. 1). The system includes also the magnet assembly providing a 2D quadrupole field for 2D magneto-optical trap, the coil assembly consisting of three pairs of rectangular coils (designed to give the required field gradients and offset fields for magneto-optical and magnetic trapping) and the transfer Z-coil with RF loop for the transportation and evaporative cooling of atoms. The Z-coil is placed just above the chip and its configuration corresponds to the layout of the traces on the atom chip.

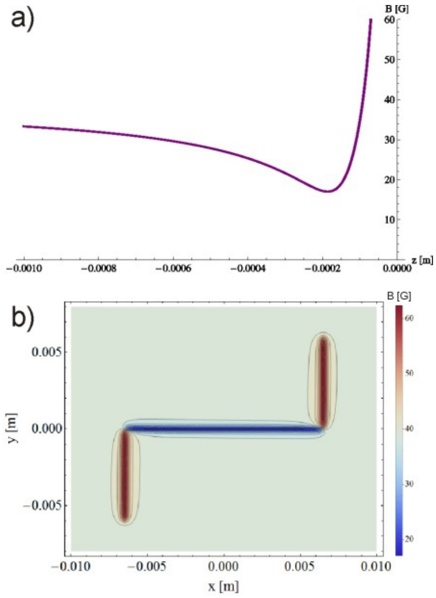

Fig. 2. The modeled on-chip IP trap: a) the magnetic potential along the z direction (below the chip) at x=y=0 and b) in the x-y plane at $z=z_0$. The trap parameters are I_Z=3.25 A, B_X=−17 G, B_Y=−35 G, B_Z=0 G and the B minimum is z_0=186µm beneath the chip.

The 2D magneto-optical trap is created in the lower cell and acts as a source of cold atoms for the upper MOT – the lower trap is not vertically confined and an additional "push" beam drives the atoms upwards through the hole in the silicon disk. Moreover, by retroreflecting this beam off the disc, additional cooling is provided, thereby creating a $2D^+$ MOT [18]. The main, six-beam 3D MOT is prepared in the upper cell, the number of atoms in this MOT saturates typically at 10^9 atoms.

In the setup three lasers at 780nm are used. Two Toptica DL100, locked to spectral lines in Rb vapor cells, provide light for optical pumping, absorption imaging and repumping. An oscillator-amplifier Toptica TA pro, offset-locked to one of the DL100s with a dedicated PLL system, is used for cooling, yielding 130 and 50mW of light for the $2D^+$ and 3D MOT, respectively.

After loading into the 3D MOT, the atomic cloud is spatially compressed [19] by increasing the magnetic field gradient from 13 to 30G/cm, reducing the repump power and red-detuning the cooling light from 2.4 to 6.2Γ, where Γ=2π·6.0MHz is the natural linewidth of the cooling transition. The atoms are then further cooled with 5 to

7ms of optical molasses to temperatures below 40μK and optically pumped into the |F=2, m_F=2> ground state.

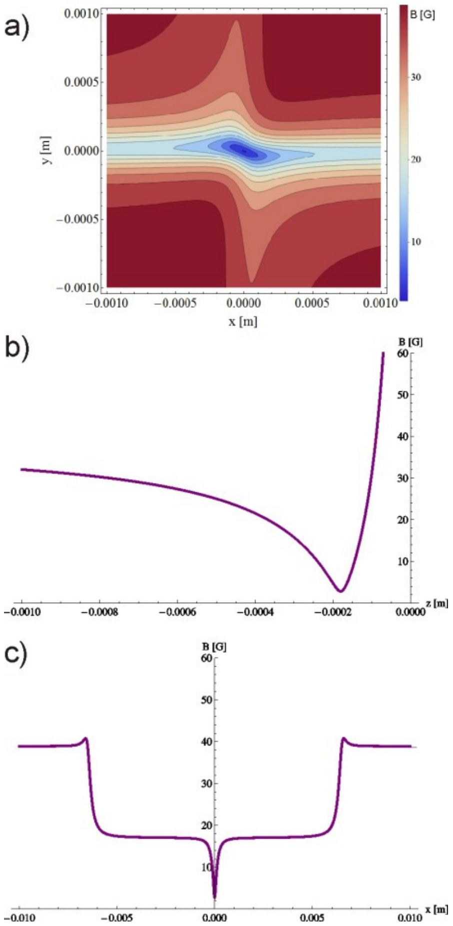

Fig. 3. The modelled dimple trap: a) the magnetic potential in the x-y plane at $z=z_0$; b) along the z direction (below the chip, at x=y=0) and c) along the *x* direction at $z=z_0$ (the dimple in the IP trap is visible). The trap parameters are as in Fig. 2, I_D=-1.3A. The rotation angle, calculated numerically on the basis of the modeled potential, is -21° with respect to the x axis.

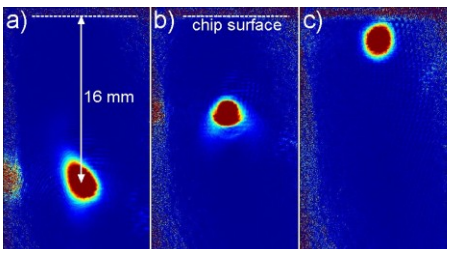

Fig. 4. A set of absorption images (saturated at optical density OD=1.5) demonstrating the transport of cold atoms to the chip: a) the compressed MOT (OD>3.5); b) atoms in the external IP trap on their way to the chip; c) atoms in the on-chip IP trap.

Afterwards, the cloud is loaded into the external IP trap created by the external Z-coil (25 A) together with the bias fields: B_X=8.7 G, B_Y=−29 G, B_Z=2.3 G. The atoms are then transported vertically and transferred to the on-chip IP trap by ramping off the Z-coil while ramping up the chip-Z current to ca. 3A (Fig. 4). The bias fields need to be properly tuned, with B_X changing its sign. The next step is to load atoms into the dimple trap and apply RF evaporative cooling to achieve condensation.

In conclusion, we have modelled and accomplished two subsequent Ioffe-Prichard type magnetic traps for ^{87}Rb atoms and have cold trapped atoms close to the atom chip ready for further manipulation.

This research project was supported by the grant no 2011/01/N/ST2/00479 from the National Science Centre and grant no N N202 124536 from the Polish Ministry of Science and Higher Education, Poland. Financial support of the European Regional Development Fund (contract no. POIG.02.02.00-00-003/08) is greatly acknowledged.

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