Trapping of Neutral ^{87}Rb Atoms on an Atomchip *

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We report an experiment of trapping of neutral ^{87}Rb atoms on a self-made atomchip. The H-shaped atomchip is made by magnetron sputtering technology, which is different from the atomchip technology of other teams. We collect 3×10^6 ^{87}Rb atoms in the mirror magneto-optical trap (MOT) using the external MOT coils, and 1×10^5 ^{87}Rb atoms are transferred to U-MOT using U-shaped wire in chip and a pair of bias coils.

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In the last decade, miniaturization and integration has been proven to bring about an advance of electronics and semiconductor physics. Now physicists aim at achieving the same for cold atom physics. Accurate metal wires at a scale of micron can be fabricated in a chip with lithographic or other standard surface-patterning process.[1] This chip can realize miniaturized electric and magnetic traps and guides that can manipulate neutral atoms close to the chip surface. Compared to the common magnetic coil, the atomchip can not only create tightly atom traps with large field gradients and high field curvature without the need for large current and large volume, but versatile and tiny traps without complex structure and design. This permits the controlled tunnelling of atoms over micron or sub-micron lengths and makes it a natural platform for applications in coherent matter-wave control such as miniaturized atom interferometer, quantum information process, and the study of low-dimensional quantum gases.[2]

In 1995 Weinstein and Libbrecht first noted that micron-sized wires fabricated on a substrate are capable of creating large magnetic field gradients and current required for trapping atoms in the Lamb–Dicke regime.[3] Then the team in Heidelberg finished a series of experiments with the guiding of atoms along free-standing wires.[4] In 1999 a new tool called the mirror magneto-optical trap (MOT) was invented by Reichel *et al.*[5] and a microfabricated magnetic trap is realized first in the world. After that, atom optical elements such as mirrors, waveguides, splitters, traps, and conveyor belts have been demonstrated successively.[6−9] In recent years several teams have succeeded in creating Bose–Einstein condensation in the atomchip.[10−12] This year, Reichel *et al.* realized an atom clock in an atomchip[13] and a team in JILA demonstrated an interferometer above an atomchip.[14] In China, some theoretical work has been carried out and some novel traps and guides in atomchip are proposed.[15−18]

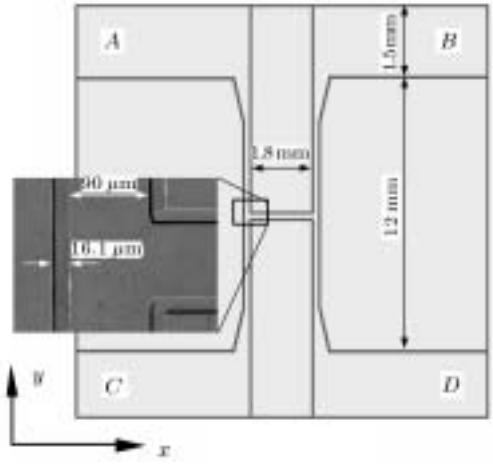


Fig. 1. A design of H-shaped chip. For clarity, the figure is not in scale. Light area is gold layer and dark area is fabricated off and acts as etching defining the wires. The inset shows a microscope image of a wire and its etching defining the wire. The wider area labelled by A, B, C and D is wiring points, and other areas are gold layers for reflecting laser beams.

In this Letter, we report an experiment of trapping of neutral ^{87}Rb atoms on an atomchip. Figure 1 shows the H-shaped atomchip used in our experiment. Several different traps can be created by the H-shaped chip with different current layouts. When A and B or C and D (Fig. 1) are connected with a dc power supply, it is a U-shaped wire, and a quadrupole trap will be created with a uniform external B_0. When A and

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D or B and C are connected with a dc power supply, an Ioffe–Pritchard trap will be created by a Z-shaped wire. Particularly, when A, B, C, and D are all used with appropriate current layouts and external field, there will appear two Ioffe–Pritchard traps above the chip.[19] Only the first layout (U-shaped wire) is used in the experiment. It will realize a U-MOT combined with three pair of orthogonal laser beams. However, the volume of this quadruple trap is too small to collect enough atoms for further experiments and it needs a pair of large external MOT coils. Cold atoms should be collected by the external MOT first and transferred to the U-MOT (created by the U-shaped wire and laser beams) on chip.

The chip is made by magnetron-sputtering technology which is different from other atomchip technology such as thin-film hybrid technology[20] or electroplate technology[21] and excellent smoothness and enough thickness will be provided simultaneously. A silicon wafer (n-type, $\langle 111 \rangle$ orientation, $\sim 80\,\Omega$cm resistivity) is adopted as a substrate of the atomchip, since Si has quite good thermal conductance. First, a thin SiO_2 layer (500 nm) was grown on the Si wafer surface with thermal oxidation at $\sim 1100^\circ$C. Then a thick gold film ($\sim 4\,\mu$m) was deposited on the SiO_2 layer by magnetron sputtering which can carry up current up to 2A. The magnetron-sputtered gold film shows excellent smoothness (AFM rms roughness of about 4.67 nm) and high reflectance (about 90% at 780 nm wavelength and 45° incident angle). Finally, gold wires with 90 μm width of H-trap were microfabricated with photolithography and wet etching method. Most of the gold layer is left and this leaves the chip as a gold mirror and it can be used to reflect the laser beams for an MOT and the small etchings defining the wires do not hinder the loading of a MOT.[22] After the making procedure the chip is glued onto an oxygen-free copper block with thermally conductive epoxy and this leads essential heat conductivity because there will be a dissipate power of 3.5 W in the chip if it carry up current of 2A. There are two ceramics blocks at either side of the copper block and four binding posts in either ceramics block (Fig. 2a). The binding posts are connected with area labelled by A, B, C or D in the chip (in Fig. 1) by dozens of gold wires (25 μm thick) using spot welding technique and they are also connected to the pins of a 10-pin vacuum feedthrough by gold plated UHV connectors and Kapton insulated wires. The other four binding posts are left unused. The whole setup is mounted upside down inside the UHV cell with an oxygen-free copper rod (Fig. 2b). This cell is part of a simple vacuum system pumped by a 40 L/s ion pump and there is a background pressure in the 10^{-6} Pa range. In the experiment a rubidium dispenser is used for producing thermal rubidium vapour. We operate it at low and constant current of 3.5 A, so that the rubidium partial pressure remains to be low. A commercial CMOS camera is used for taking photos of atom cloud and a photodiode (Hamamatsu S2386-44 k) for measuring the atom number. The photodiode is calibrated precisely and combined with a 50 mm lens to measure the atom cloud fluorescence, and the atom number can be estimated.

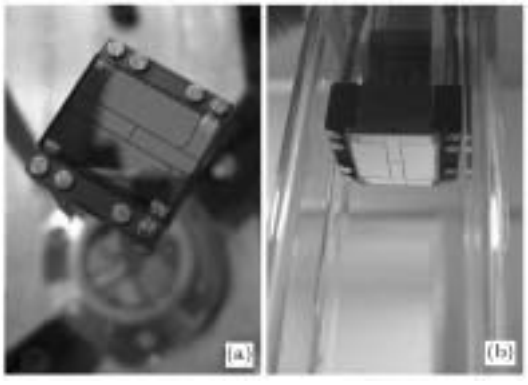


Fig. 2. The mounted chip before it is introduced into the UHV quartz cell (a) and after put into the cell (b).

Compared to the standard MOT experiment, there are three dissimilarities at least. Thus it is necessary to design a different experiment setup and procedure. Firstly there is an opaque chip near the trap centre, as shown in Fig. 3, a so-called mirror-MOT[5] uses four beams and a mirror (the gold layer on chip surface) to reproduce the arrangement of the standard MOT in the half-space limited by the mirror. There are two incidence laser beams at 45° and the other two in horizon. Secondly the axis of quadrupole field created by the U-shaped wire in chip is inclined, so the axis of two MOT coils is inclined at 45° in order to match for the field of the U-shaped wire, and the bias field B_0 can be created by the bias coils. Finally the atom cloud in a mirror-MOT will be very near to the chip surface and this will cause loss and heating of atoms. If the centre is located far away from the surface (more than 2 mm),[20] The mirror-MOT will achieve a performance comparable to a standard MOT, but usually it is difficult for a U-shaped wire in chip to create a quadrupole field so far like that. Misalignment of the mirror-MOT centre and U-MOT centre will also bring on heating and loss of atoms during transferring from the former and the latter. To circumvent the problem, the mirror-MOT is loaded far away from the chip surface, and then its centre is shifted to chip surface nearer by superposing a homogeneous magnetic field or changing one of the MOT coils current slightly.[20] In our experiment, there are 3×10^6 ^{87}Rb atoms collected from the background vapour in the mirror-MOT using the external MOT coils. After

loading, the cold atom cloud is shifted from its initial 2.4 mm far from the chip to about 1.0 mm by misbalancing the current in the MOT coils. Then the MOT coils is turned off and the U-shaped wire and bias coil are turned on simultaneously, using a current of 1.5 A in the U-shaped wire and homogeneous bias field $B_0 = 0.1$ mT. The atoms number in the U-MOT is about 1×10^5. There are several reasons for the loss of atom number during transferring. Firstly it will be made by mismatch of the trap position and gradient between mirror-MOT and U-MOT. Secondly U-MOT created by chip has much smaller trap volume than mirror-MOT created by external coils, so many atoms will place outside the trap after transferred to U-MOT. Loss will be reduced if atom cloud is compressed before transferred. The fluorescence signal decay is also measured (Fig. 5) when current in U-shaped wire and bias coils are shut down and the cooling laser is still working. Figure 5 shows a 87-ms lifetime of the U-MOT because of insufficient vacuum pressure in the 10^{-6} Pa range.

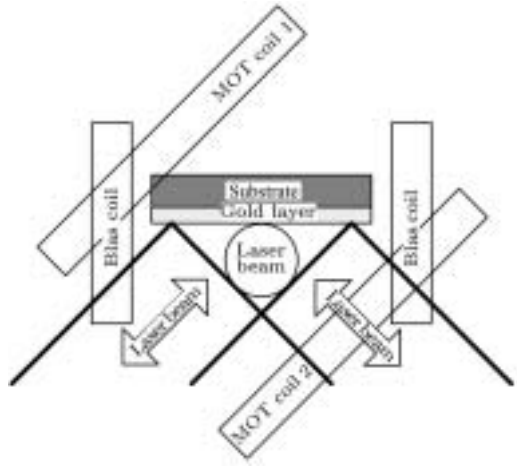


Fig. 3. The mirror-MOT and U-MOT schemes to enable trapping near a surface. The former uses four beams and a reflective surface of the chip combined with a pair of external anti-Helmholtz coils. The latter replaces the anti-Helmholtz coils with a U-shaped wire in chip and a pair of bias coils.

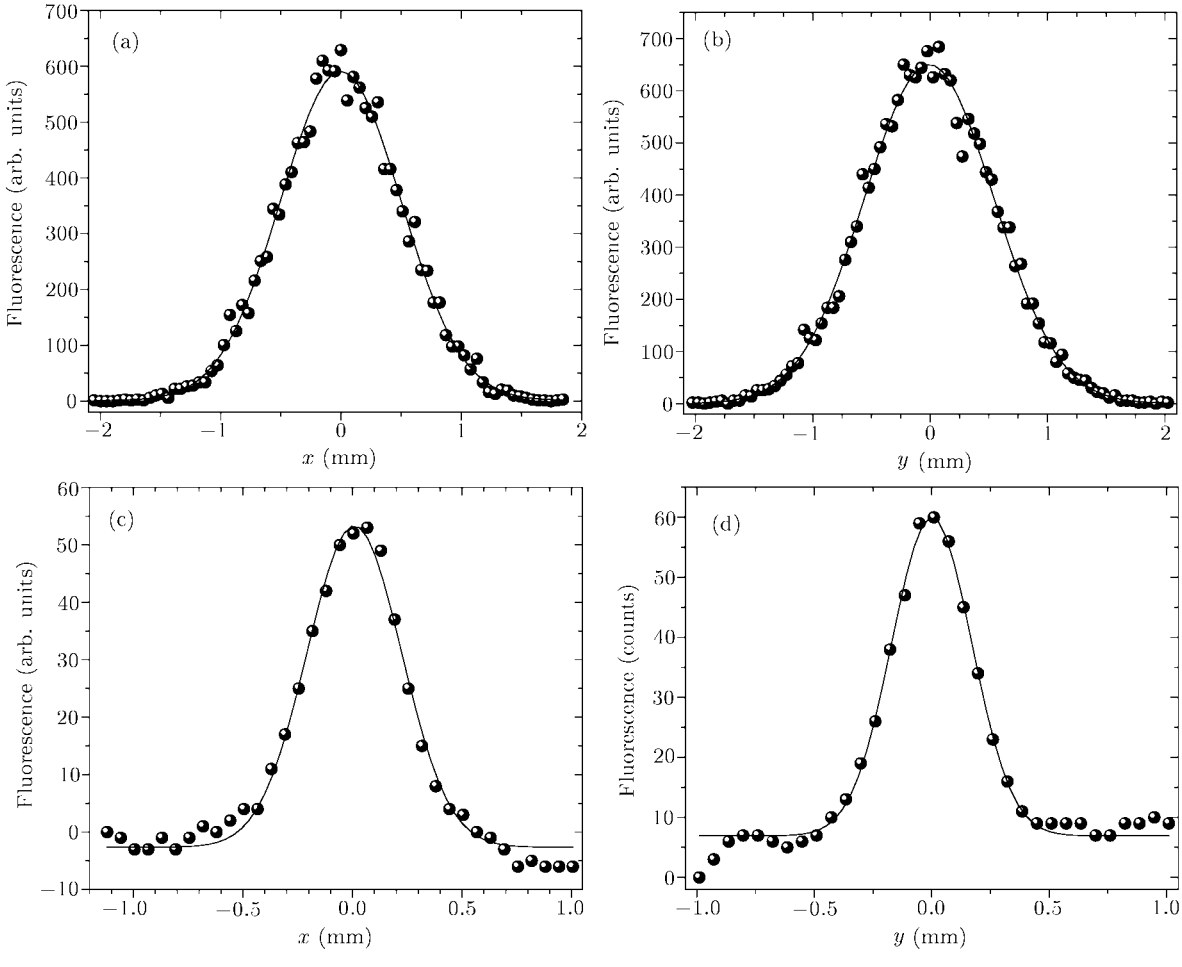


Fig. 4. The fluorescence distribution of the mirror-MOT (a, b) and U-MOT (c, d) in two horizontal directions (x and y defined in Fig. 1). Here (a) and (b) show that the atoms cloud size is 2.2 mm and 2.0 mm in the x and y directions (mirror-MOT), (c) and (d) show the size of 0.8 mm and 0.7 mm in the x and y directions (U-MOT). Full circles: fluorescence signal values, solid line: Gaussian fit curve.

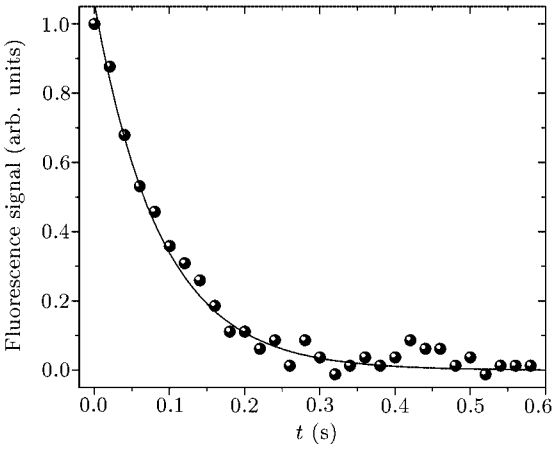


Fig. 5. The fluorescence signal decay after the U-wire in the chip and bias field are shut down. Full circles: fluorescence signal values, solid line: exponential fit.

In conclusion we have designed and made an atom-chip experiment setup and succeeded in trapping of rubidium atoms on the chip. This elementary experiment built a stable base for further experiments, for example, further cooling and transferring atoms to the static magnetic trap, realizing of Bose–Einstein condensation, and demonstrating of quantum entanglement and quantum information storage, etc.

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