Fabrication of Atom Trap Chip for Quantum Information Processing

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1. Introduction

Recently, laser-cooling technology with neutral atoms has progressed rapidly in the field of ultra-cold atomic physics [1]. Prof. Katori and his colleagues at the University of Tokyo are interested in the demonstration of “quantum information processing (QIP)” [2] with these cold atoms. They have proposed a new method that enables one to manipulate neutral atoms with electric fields where the fields can be produced by micron-sized electrodes on an atom chip [3]. After the atoms are trapped they are planning to use those atoms as qubits (quantum-bits) for the QIP. As a first step, they have trapped strontium (Sr) atoms [3]. As collaboration, we have fabricated this “atom trap chip” with our micro fabrication technology. This paper reports the design and the process of the fabrication to satisfy the required functions for the structure of the atom chip. Though a special technique of nano-micro fabrication was needed, we overcame with unique methods. We will also show the chip that was actually fabricated. The experiment of trapping Sr atoms on this chip has been demonstrated by the Katori group [4].

2. Electro-dynamic Trapping of Atoms (Proposed by Katori Group)

2.1. Principle

Here we will mention the principle of the electric trapping of atoms and the basic structure of the electrodes. The static voltage on the 4 symmetrical electrodes shown in figure 1 forms a saddle-type Stark potential. Neutral atoms usually experience a quadratic Stark effect, \( U = -(1/2) \alpha E^2 \), where \( \alpha \) is the dipole polarizability of the atom. For atoms in a stable state \( \alpha \) is positive, therefore they will be attracted toward field maximum in an inhomogeneous field. By rotating the configuration of the voltages applied on the electrodes by 90 degrees, it forms another saddle-type potential which is spatially rotated 90 degrees in the electrode plane. As discussed in detail in reference [3], by switching mutually these two potentials, the atoms are trapped in the center of the potential. (Figure.1)

2.2. Experiment Procedure (Proposed by Katori Group)

The electro-dynamic trapping of ultra-cold atoms was carried out as the following procedure. (1) Cool and pre-trap Sr atoms above the electrodes. For this experiment, the atoms were cooled and collected by magneto-optically trapping them near a mirror surface (“Mirror MOT”). (2) Switch on and load the collected atoms into a standing-wave confining potential which is produced by counter-propagating far off resonance lasers. Then the loaded atoms are transferred to the center of the electrodes by modulating one of the frequencies of the standing-wave lasers. (3) Apply the switching electric fields and perform the electro-dynamic trapping. (4) Transfer back above the electrodes by the moving standing-wave potential, and then observe the atoms that have been trapped by the electric fields from the micron-sized electrodes. The experiment is performed in an ultrahigh vacuum of ~10⁻¹⁰ Torr. (Figure.2)
3. Requirements of the Atom Trap Chip

The atom trap chip needs to satisfy the following requirements. **FR(1):** High reflectivity ($R > 95\%$) for 45 degrees incident beam at wavelength of 460nm and 689nm, which are used for the “Mirror MOT”. (Laser beam diameter: 12mm). **FR(3):** The basic structure is explained in section 2.1. **FR(2),(4):** Optical transmission ($T > 90\%$) of the laser for the standing-wave laser at wavelength of 800nm (Laser beam diameter: 50$\mu m$) (figure.3). In addition, the requirement that the chip will be introduced into ultrahigh vacuum has to be considered.

![Figure 2](image2.png)

**Figure 2.** Experiment procedure of electro-dynamic trapping. (Proposed by Katori Group.)

4. Design and Fabrication Process

First, the gap-size $d$ and the voltage $V$ of the electrodes are estimated from the requirements mentioned in section 3. Since the confinement potential scale as $Vd^2$, the smaller the structure is, a lower voltage will be needed for a given potential depth that the atoms can be trapped [3]. However, the $50\mu m$ lasers for the standing-wave potential (FR(2)) have to be transmitted through the center of the electrodes, so the gap-size of the electrodes is determined as $d=50\mu m$. Therefore, thickness $t$ of the electrode is determined as $t=100\mu m$ [4]. The voltage is set to $\pm 200V$ and with these conditions, a stable trap is expected when the switching frequency is about 10kHz [4].

Next the structure and the materials are discussed for each required functions. **FR(1)(High reflectivity):** To obtain low surface roughness and high surface flatness, metallic thin film on a thick glass substrate ($t=100\mu m$), which have high Young’s modulus and can be ground easily, was used. We took advantage of the metallic surface of the electrodes and used it also as a mirror for collecting atoms in the MOT. The mirror area needs to be more than $17mm$, since the MOT lasers ($12mm$) are irradiated from 45 degrees. Therefore, a $25mm$ glass substrate was used. This includes the wiring pads which has a width of 5mm. **FR(2),(4)(Optical transmission):** To make a clear space for trapping, we fabricated a through-hole in the center of the electrodes of the thin glass substrate. The $100\mu m$ thickness substrate is fragile so it was glued at the rim on a thicker ($t=1mm$) glass, which was also used as a window that separates air and vacuum and has an AR(Anti-Reflection)-coating on it to have good transmission for the standing-wave lasers. **FR(3)(Electrodes):** The same electric field can be obtained in between the electrodes whether they are made from metallic thin film on a glass substrate or just fabricated directly from a metallic bulk. To minimize the fabrication time, we took the process of fabricating the glass substrate with metallic thin films.

![Figure 3](image3.png)

**Figure 3.** Requirements of the atom trap chip.
The details of the fabrication process are mentioned in the following. (1) Fabricate the cross through-holes at the center of the glass substrate (φ25mm, t100µm) with high flatness by FIB. (2) Make the silver thin film on the entire surface (topside, inside, backside) except the outer rim of the substrate by sputtering. (3) Etch the thin films to make 4 electrodes. FIB is used for etching in an angle, such as the surface inside the cross through-hole. The details about the FIB are discussed in section 5. (4) Further etch the thin film to the rim by YAG(Yttrium-Aluminum-Garnet) FHG(Forth Harmonic Generation) laser, whose fabrication rate is high, and insulate the 4 electrodes. The area far from the center (about 500µm square) is etched by laser, since the effective trapping potential are not sensitive to the electrode roughness far from the center region. Further fabrications for insulating the electrodes to the electrical feedthroughs, which are capable of introducing high-voltage into vacuum. The chamber port and the chip are sealed by Torr-Seal which has very low outgas rate in vacuum. Figure 5 shows a SIM(Scanning Ion Microscope) view and a SEM(Scanning Electron Microscope) view of the atom trap chip. On the SIM view, surface of glass is shown dark.
5. FIB (Focused Ion Beam) System

The feature of the FIB system we used is mentioned in the following. This FIB is an ion beam accelerated and focused down to 50-500 nanometers by electric fields. It can etch nano-micro scale structure without any masks. Therefore there are some features, such as, positioning directly by observing with the FIB, fabricating various depths and any shape continuously, easy additional fabrication, fabricating with an angle (refer to figure 5.(b) SIM view). These are very suitable for fabrication of atom trap chip. Especially, no other beam except FIB can fabricate obliquely with accuracy of less than 1µm. (Figure. 6)

![Feature of FIB](image)

**Figure 6. Feature of FIB.**
(a) Outline of micro etching.  
(b) Etching from a tilted angle.

7. Conclusion

The atom trap chip that satisfies the requirement by the experimental process was designed and fabricated by using FIB for micro etching on the side surfaces. Furthermore, the electric trapping of Sr atoms on this chip was demonstrated by Katori group recently.

8. Acknowledgement

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References