Bose-Einstein condensation on an atom chip

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(Dated: December 15, 2008)

We report an experiment of creating Bose-Einstein condensate (BEC) on an atom chip. The chip based Z-wire current and a homogeneous bias magnetic field create a tight magnetic trap, which allows for a fast production of BEC. After an 4.17s forced radio frequency evaporative cooling, a condensate with about 3000 atoms appears. And the transition temperature is about 300nK. This compact system is quite robust, allowing for versatile extensions and further studying of BEC.

Keywords: Bose-Einstein condensate, atom chip
PACC: 3280P, 4250

1. Introduction

The realization of Bose-Einstein condensation is a great achievement in physics [1, 2]. Although many groups in the world have produced BEC, making BEC is still a challenge to a new group [3]. Now, BEC has been produced in several type of systems, such as magnetic trap [4], dipole trap [5], mini trap [6, 7] and atom chip [8, 9]. Among them, atom chip is specially intriguing. It allows for a fast production of BEC since it provides a much tighter trap compared with the traditional magnetic trap. A tighter trap means a higher elastic collision rate, which leads to a less strict vacuum requirement. A pressure about $10^{-8}$ Pa is enough. Also, the wires on the atom chip can be designed flexibly to meet different goals, like Ioffe-Pritchard trap [10], magnetic lattice [11] and double traps [12]. In addition, optical components can be easily integrated on an atom chip, such as micro-cavity [13], optical fibre [14] and so on. Atom chip is an useful platform to study BEC extensively. In this paper, we report our experiment of making BEC on an atom chip.

2. Our experimental setup

Our experimental system is a single-chamber system, as shown in Fig. 1. A quartz cell of $40 \text{mm} \times 40 \text{mm} \times 120 \text{mm}$ is used as the main working chamber, a chip is placed upside down in the cell. The atom source is provided by a $^{87}\text{Rb}$ dispenser which can be controlled by electric current conveniently. A background pressure below $1 \times 10^{-8}$ Pa is maintained by an ion pump and a sublimation pump.

For the optical system, we use three diode lasers to form our four laser beams: the trapping light, the repumping light, the pumping light and the probe light. All lasers are locked to the saturated absorption spectrums, then are modulated by acousto-optical modulations (AOM) to the right frequencies and intensities. Finally they are coupled into four single mode fibers and injected to the cell. The trapping light and the repumping light are used in magneto-optical trap (MOT), the pumping light is used to pump atoms to $m_F=2$ state which increases the efficiency of loading atoms to the chip-based Z-trap.

Our chip is shown in Fig. 2. A gold layer with a thickness of $5 \mu m$ is deposited on a Si wafer with a $500 \text{nm} \text{SiO}_2$ film. The wires are defined by photolithography which produces gaps to insulate the wires from the rest gold layer. The width of the gap is about $10 \mu m$. The surface of the gold layer is excellently smooth with a 90% reflection at 780nm wavelength when the incident angle is 45°. Since we use the gold layer as a mirror to reflect the laser beams to form a mirror-MOT [8]. Good reflection increases atom number collected by the mirror-MOT. There are two U-shaped wires with width of $200 \mu m$, a Z-shaped wire with width of $100 \mu m$ and a W-shaped wire on the chip. More details of the chip fabrication can refer to [13, 14]. The Z-wire combining with a bias field create an Ioffe-Pritchard-like trap which has no zero-field point. It is useful for evaporative cooling since the ”Majorana flops” can be avoided [17]. And we use the W-wire as the radio frequency (RF) terminal for RF-evaporative cooling, because it is near to the Z-wire,

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which avoids the shield effect of the gold layer. Many researchers show that gold layer absorbs Rb atoms, which leads to a reduction of the light reflectivity and pollutes the vacuum [18]. In order to overcome this disadvantage, a thin 10nm quartz film is deposited on the chip surface. This thin film does not effect the reflectivity since the thickness is much smaller than the laser wavelength, and can isolate the strong attractive interaction between Au and Rb atoms.

3. Vacuum and lifetime

The preconditions of creating BEC is extremely strict. One of the most important demands is ultra-high vacuum (UHV). Even for an atom chip system, where the vacuum limitation is a bit loose, a pressure of $10^{-8}$ Pa is still required. So special attentions should be paid to the vacuum system. All the components in the vacuum are UHV compatible and pretreated in strictly clean processes. After installed, the whole system is baked at 120°C for 72 hours continuously. And the vacuum of our system can reach about $1 \times 10^{-8}$ Pa. It is maintained by a 40L/s ion pump and a sublimation pump which works once a week. We also place a getter in the cell to improve the pump rate. It is a passive pump by absorbing gases and works even in the room temperature.

Our atom source is a Rb dispenser. When heated by an electric current, it releases Rb atoms. Such a device provides a convenient way for time-dependent control of Rb pressure. It is useful for achieving a UHV environment [19, 20]. The critical current for our dispenser starting to release atoms is about 3.5A. In the experiment of BEC, we use a pulsed method: heating the dispenser with a 5.7A current pulse for 30s, then waiting for 60s to recover the vacuum, and then starting the MOT to collect cold atoms. In this way, adequate atoms are collected in MOT while a relative good vacuum pressure is obtained. In our experiment, typically $2 \times 10^7$ atoms are collected in MOT, and $3.5 \times 10^6$ atoms are loaded to the Z-trap, the temperature of atoms in the Z-trap is about 100µK, the lifetime is 11s. It is the beginning of the forced evaporative cooling.

4. Forced radio frequency evaporative cooling and Bose-Einstein condensate

Up to now, the evaporative cooling is the only way to achieve BEC [21]. In order to evaporate effectively, a runaway evaporative cooling regime should be reached. The elastic collision rate $\gamma_{el}$ and the lifetime of atoms in the Z-trap $\tau_{loss}$ should satisfy [22]:

$$\gamma_{el} \tau_{loss} > 150,$$

(1)

which is usually called good-to-bad collision ratio. In order to increase the elastic collision rate, we adiabatically compress the Z-trap to $I = 3.6A, B_x = 4G, B_y = 72G$, corresponding to a trap frequency of (26, 3900, 3900)Hz. It is about 90µm away from the chip surface. The measured good-to-bad collision ratio is $\gamma_{el} \tau_{loss} > 1000$. Runaway evaporation regime is reached. After an optimized 3.5s RF-evaporative cooling from 74M to 4.3M, 1.3 x $10^5$ atoms are left, the temperature is about 10µK. In order to reduce the heating rate and three-body collisions, we decompress the trap to $I = 2A, B_x = 2.8G, B_y = 33.6G$, corresponding to (21, 1900, 1900)Hz. It is about 110µm away from the chip surface. This decompress process lasts 160ms, and at the same time a RF sweep from 4.3M to 2.7M is present. The atom cloud is further cooled, 1.1 x $10^5$ atoms are left and the temperature drops to 3.4µK. Finally, we apply an RF sweep from 2.7M to 2.315M, lasting 510ms, and BEC appears. We use the time of flight method to determine the result of phase transition. In order to get a good signal-to-noise ratio, we decompress the Z-trap before releasing the atoms. Atoms are decompressed to a trap of $I = 3.6A, B_x = 0, B_y = 24G$, the trap frequency is (38, 700, 700)Hz. The adiabatic decompression does not change the phase space density but reduces the temperature and moves atoms away from the chip surface, so a better signal to noise ratio is obtained. As shown in Fig. 3. The nonisotropic expansion of the atom cloud in free space is observed which is a strong evidence of achieving BEC. The flight time is 2ms, 6ms, 10ms, 14ms and 20ms respectively. The transition temperature is about 300nK, and there are about 3000 atoms in the pure BEC.

The aspect ratio after atoms are released from the Z-trap is measured. For a thermal cloud, it expands isotropically, the aspect ratio approaches one as the flight time becomes longer. For a BEC released from a cigar shape trap, the radius along the tightly trapped direction expands rapidly. This is a fundamental difference between BEC and thermal gases [23, 24]. We observe this phenomena when we detect the time of flight signal as shown in Fig. 4. The aspect ratio becomes much bigger than one when the flight time is longer than 10ms. The change of aspect ratio during free expansion is also an important criteria of achieving BEC.

In order to measure the critical transition point of our BEC, we stop the RF sweep at different frequency. As shown in Fig. 5, the pictures are taken after 12ms of flight. When the end frequency is 2.36M or 2.34M, they are still thermal gases since the profiles of optical depth are Gauss distributions. But when we sweep to 2.33M, a bimodal
distribution appears, the optical depth increases suddenly and the cloud size reduces suddenly. At this time, a partial condensate appears. When we sweep further to $2.32 M$, it is clearly shown that a sharp peak lies on a low thermal gas background. At this time, the BEC is quite pure. There are some stripes shown in the photo when BEC appears, it is due to the diffraction of the imaging system [23].

We also measure the lifetime of BEC in the Z-trap. The dominating limitation of the lifetime is the heating rate when atoms are held in the trap. We measure the temperature when atoms are held in the Z-trap for different time. A heating rate of $3.4 \mu K/s$ is detected. The thermal radiation of the chip, the stray light scattering and the current noise are all possible heating sources [10]. In this condition, the measured lifetime of BEC is about 90ms. In order to increase the lifetime, a RF field at the end frequency is present when atoms are held. In this way, heated atoms are evaporated away by RF radiation before interacting with other atoms and do not destroy the BEC. And the lifetime is prolonged to 500ms.

6. Conclusion and acknowledge

In conclusion, We have achieved BEC on our atom chip system. As we know, it is the first chip BEC in China. The nonisotropic expansion, bimodal distribution profile and aspect ratio measurement after releasing provide the strong evidences of BEC creation. Such a fast production of BEC (evaporative cooling time is less than 5 seconds and the circle time is about 2 minutes) provides a robust and convenient platform to study the properties of this special matter. Further experiments are being carried out and we hope to go deeper into the research of BEC.

We acknowledge Wei rong, Zhou Shuyu and Xu Zhen for helpful discussions, Zhou Shanyu, Xu Daming and Wu Haibing for technical supports. The project is supported by the National Basic Research program of China under Grant No. 2006CB921202.

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FIG. 2: The picture of our chip. The gold layer is $5\mu m$ thickness. The wires are isolated from the rest gold layer by $10\mu m$ gaps. The width of two U-wires is $200\mu m$, and $100\mu m$ for the Z-wire. Each chip wire is connected to the electrode by spot welding of 20 thin gold wires as shown in the picture.

FIG. 3: Time of flight images of the atom cloud after released from the trap. The free flight time is 2ms, 6ms, 10ms, 14ms and 20ms respectively from top to bottom. The nonisotropic expansion is a strong evidence of BEC.

FIG. 4: The measurement of aspect ratio of free expansion between the cloud radius in $y$ direction and $x$ direction as shown in Fig. 3. The radius in the tight trapped direction expands rapidly, and the aspect ratio is much bigger than one when time of flight is longer than 10ms. It is an important criteria of achieving BEC.
FIG. 5: Determining the critical frequency where BEC appears. (a) When the end frequency is 2.34MHz, it is still a thermal cloud, and the profile is a Gauss distribution. When end at 2.33MHz, partial condensate appears. And when end at 2.32MHz, a more pure BEC is created and a sharper peak of the profile appears. (b) is the section profile of the cloud. A sudden increasing of optical depth and a bimodal distribution appear when sweep to 2.33MHz which is the critical frequency when BEC appears.

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