Stability of a superconductive atom chip with persistent current

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The lifetime of ^{87}Rb atoms trapped in a **z** wire trap generated by a closed-circuit superconductive current on a MgB_2 strip is measured as a function of the distance between the atom and the strip. The lifetime is found to be longer than 10 s at a distance of 40 μm. This value is an order of magnitude longer than the lifetime of a trap generated by a normal current at the same distance. However, it is many orders of magnitude shorter than the theoretical decay rate induced by the spin-flip transition caused by the fluctuation of the current. This shows that for a type-II superconductor the dominant trap loss mechanism is not the spin-flip transition caused by noise as with a normal current atom trap. An analysis of our measurement suggests that magnetic field distortion resulting from flux penetration into the superconductor leads to much faster decay.

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I. INTRODUCTION

An atom chip is a device for manipulating the motion of cold atoms near a solid surface along the bottom of the magnetic potential generated by electric current wires on the chip and the external bias magnetic field. Various types of atom manipulation have been demonstrated [1–4]. The atom chip is especially successful in efficiently generating a Bose-Einstein condensate of alkali atoms [5–8] owing to its efficient evaporative cooling process. In principle the atom chip can be used for the coherent manipulation of the external quantum states of trapped atoms, which opens up important applications such as atom interferometry, quantum information processing, and quantum computers. However, for the coherent manipulation of external states, the atoms must be placed very close to the current wire, typically at a distance less than a few μm, because a sharp potential slope is needed to keep them in a single-quantum mode of external motion. Unfortunately it was found that the trapping lifetime decreases rapidly as the atomic distance from the surface decreases [9–13]. The theoretical explanation for this phenomenon is that the loss is caused by the spin-flip transition induced by the thermal noise of the current, which produces the trapping potential [9,10,12–14]. With the hope of removing this decay process, atom trapping with superconductive current has been demonstrated [15–18]. Recently, the lifetime with a superconductive current has also been evaluated theoretically [19–23]. The conclusion was that the lifetime is many orders of magnitude longer than that with a normal current, and is practically infinite if the temperature is much lower than the transition temperature of the superconductor. The trapping lifetime on a superconductive Nb atom chip was also measured recently [24]. They reported a rapid decrease in the lifetime to a value much shorter than that of the above theory, when the distance of the atomic cloud was reduced. This paper reports the first systematic measurement of the lifetime of a rubidium (Rb) atom trap with a closed-circuit superconductive current on magnesium diboride (MgB_2). The result is qualitatively similar to Ref. [24]. The measured value ranged from 12 to 40 s at heights of 40–800 μm. This value was certainly longer than the lifetime with a normal current but many orders of magnitude shorter than the predicted spin-flip transition time. Therefore, the dominant loss mechanism is not the same as with a normal current. We undertook a statistical analysis of our measurement and concluded that the main mechanism is the disturbance of the magnetic field caused by the penetration of magnetic-flux quanta into the MgB_2 strip.

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II. EXPERIMENTAL PROCEDURES

The basic experimental apparatus was a double ultrahigh-vacuum chamber in which atoms were cooled, trapped, and transported by lasers and a magnetic field [17]. The first chamber was a standard cylindrical glass cell designed to produce a magneto-optical trap (MOT) for Rb atoms. The second chamber was a cryogenic chamber in which the atom chip was mounted upside down on a cold finger at a temperature of 4 K. The base of the atom chip was a 10×10 mm^2 sapphire wafer, and the current circuit was a single loop consisting of a 100-μm-wide and 1.6-μm-thick MgB_2 strip. A 60 nm gold layer, which was used during the fabrication process, was left on top of the MgB_2. Its geometric shape is shown in Fig. 1. The circuit was equipped with a **z**-shape trap (top left corner in the figure) and a nipple (bottom right corner). The latter was used as a laser-driven thermal switch. The procedure for loading the circuit with persistent current was as follows. First, the nipple was heated with a focused argon laser beam to open the superconductive loop circuit. Then, a uniform magnetic field (1.1 mT) was applied perpendicular to the chip surface (z direction). The argon laser was turned off, and after the temperature of the nipple had fallen below the transition temperature, the bias magnetic field was removed. The current induced in the circuit was typically 4.5 A.

We measured the number of atoms trapped in the z-shape trap as a function of the time t_{delay} after atom loading using

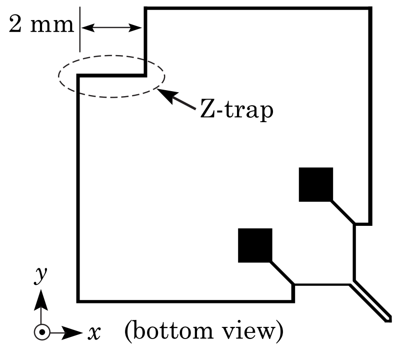

FIG. 1. Chip pattern of the superconductive strip.

the steps described below. This is a standard technique and is detailed in our previous report [17]. However, we repeat the description here to clarify subsequent discussions. First, we collected approximately 5×10^{8} ^{87}Rb atoms in a standard six-beam MOT. The atoms were cooled by polarization gradient cooling, optically pumped to the $F=2$, $m_F=2$ ground hyperfine state, and recaptured in a quadrupole magnetic trap that utilized the same pair of coils as in MOT. By moving the coils along the precision linear translator we were able to transfer approximately 3×10^{7} atoms to the cryogenic chamber. Then we applied a magnetic field in y direction of 1.2 mT which created the **z** trap potential minimum at approximately 800 μm below the chip surface. We turned on simultaneously a uniform magnetic field in z direction to move a part of the atomic cloud up to the **z** trap. Then, both the quadrupole and z bias fields were switched off. The number of atoms in the **z** trap was typically 10^{6}. After the atoms were captured in the **z** trap we ramped up the y bias field to bring the atoms to the intended height. The number of trapped atoms was measured from the absorption image of the atomic cloud pattern.

The trapped atoms were released by switching off the y bias magnetic field. When the atoms fell a few millimeters below the chip, an illuminating laser resonant with the cooling transition was sent from the back of the first chamber in the x direction, and the absorption image was captured with a charge-coupled device camera with a $f=150$ mm focusing lens and a magnification of two. The absorption image provided information on the total number of trapped atoms. For the trap height measurement, the illuminating laser was transmitted from the y direction at an angle of 5° to the chip surface. This provided information on the atomic cloud shape in the x and z directions. We estimated the temperature of the trapped atoms from the atomic image, and it was approximately 300 μK at $B_{bias}=6.2$ mT. The value was higher by a factor of two at a higher $B_{bias}=10.9$ mT as a result of heating when the y bias was ramped up. The absorption image was composed of the direct atomic image and the image reflected from the chip surface. The height of the image was deduced from the distance between the two images. We repeated the entire process from the trapping of atoms into MOT to the absorption measurement to obtain a single experimental value of the atomic number or cloud height.

III. TRAP HEIGHT AND CURRENT DISTRIBUTION

The current distribution of a thin pure superconductive strip is given by

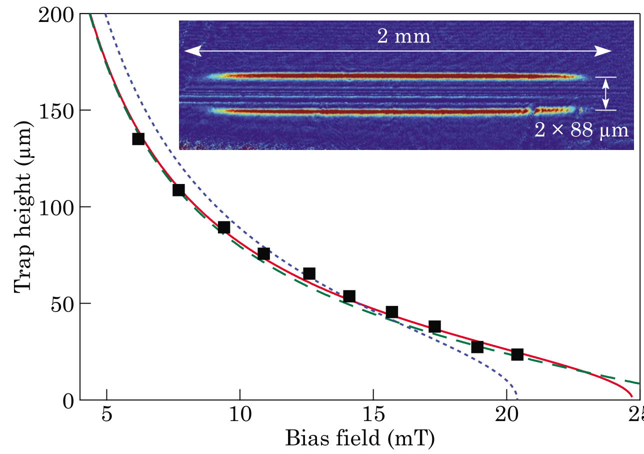

FIG. 2. (Color online) Trap height vs y bias magnetic field B_{bias}. The filled squares are experimental data. The solid curve is the height calculated from Eq. (2) with a strip width of 72 μm and a superconductive current of 4.45 A. These values were selected from the curve fitting by taking the superconductive current I_0 and the strip width $2a$ as adjustable parameters. The errors were ±10 μm and ±0.3 A, respectively. The dashed curve is the height when $2a=100$ μm and $I_0=4.45$ A for a uniform normal conductor [Eq. (3)]. The dotted curve is the best fit ($I_0=5.1$ A) of Eq. (2) with $2a=100$ μm. The inset shows an example of the absorption image of trapped atoms.

$$I(y) = \frac{I_0}{\pi}\frac{1}{\sqrt{a^2 - y^2}}, \tag{1}$$

where I_0 is the total current on the superconductive strip and $2a$ is the strip width. Then, the trap height z_{trap} is given as a function of the y bias field B_{bias} by

$$z_{trap} = \sqrt{\left(\frac{\mu_0 I_0}{2\pi B_{bias}}\right)^2 - a^2}, \tag{2}$$

where μ_0 is the magnetic susceptibility of vacuum. The trap height data were fitted with Eq. (2) with I_0 and $2a$ as adjustable parameters (see Fig. 2). They were $I_0=4.45\pm0.3$ A and $2a=72\pm10$ μm, respectively. The observed $2a$ was nearly 30% less than the geometrical width of the strip. This is clear evidence of the penetration of flux into the superconductive strip. The influence of the flux penetration has recently been theoretically discussed [25]. Flux quanta penetrate from the edge of the strip, where the current density is maximum, and reduce the current-density variation. An extreme case is a uniform distribution, which is equal to the current distribution of a normal conductor with uniform resistance. In this case the trap height is expressed by

$$z_{trap} = \frac{a}{\tan\dfrac{2\pi a B_{bias}}{\mu_0 I_0}}. \tag{3}$$

The observed height should fall between Eqs. (2) and (3) with the actual geometric value of a. The broken line shows the curve with the same I_0 as the solid line and $2a$ $=100$ μm. There is very little difference between the two

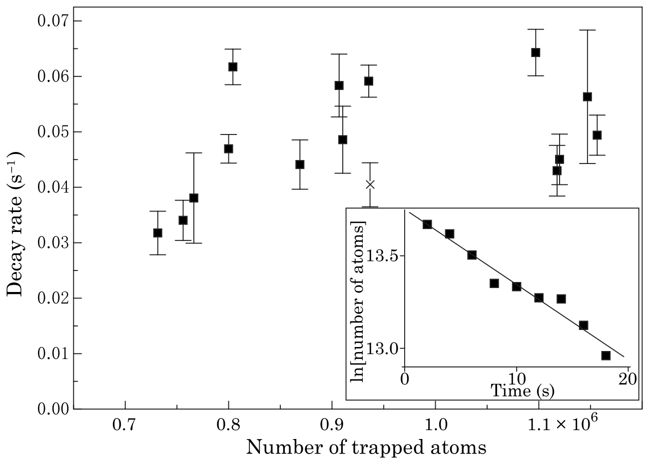

FIG. 3. Distribution of the decay rate as a function of the initial number of trapped atoms. The error bars show the errors of the individual decay rate measurements. All the data were obtained over a period of two months. The inset shows an example of the decay curve of the trapped atoms. These data correspond to the data points indicated by "×."

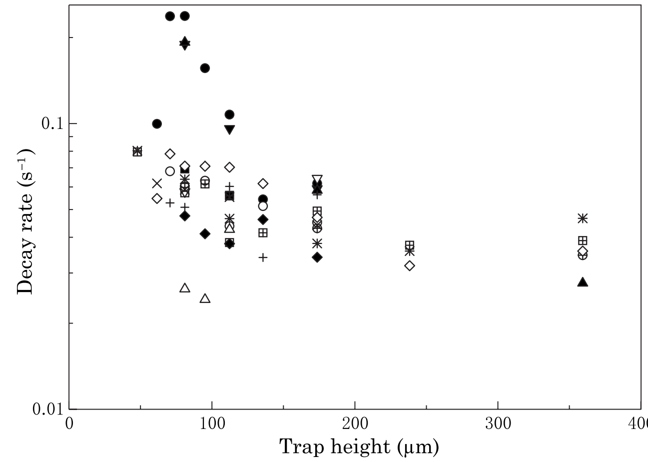

FIG. 4. Distribution of the measured decay rate of a trapped atomic cloud as a function of the trap height. Different symbols indicate data obtained on different dates. Clearly the distribution of data obtained on the same day is much smaller than the distribution of all the data. The error of each point is approximately ±10% of the measured value.

curves except at very small distances, and our data agree with either curve. However, they do not agree with Eq. (2) with the geometrical width $2a=100$ μm.

IV. DECAY RATE MEASUREMENTS

The sequence of the decay rate measurement is as follows. First, the y bias field B_{bias} was fixed, and the atomic number was measured between 5 and 20 different delay times t_{delay}. It usually took 1 h to obtain a single decay rate value. The measurement was repeated for various y bias fields. The y bias field was varied from 1.2 to 14.9 mT, and a total of 70 decay rate data were accumulated. The error in the decay rate measurement was largely caused by the variation in the number of trapped atoms in the first vacuum chamber, which originated from the fluctuation in the trapping laser power and the pointing instability. The error for all 70 decay rate data was approximately ±10%. However, we found that the variation in the observed values obtained at different times was several times larger than this error. Figure 3 shows the data at $B_{bias}=4.9$ mT accumulated over two months as a function of the initial atomic number and no atomic number dependence can be seen. Therefore, the major decay mechanism was not the collisions of the trapped atoms but the decoherence caused by external sources. Figure 4 shows the distribution of 70 data points plotted as a function of trap height. Different symbols are used to distinguish data obtained on different dates. The large variation in the data points meant we could not determine the exact functional shape. The decay rate was approximately 0.02 s^{-1} at a distance near 1 mm, and started to increase at around 100 μm. At 40 μm the value was typically 0.1 s^{-1}. Our measurement does not contradict with the result in Ref. [24]'s shorter distances. However, at large distances our values were considerably shorter. This, we believe, is caused by the difference in background pressure of the vacuum since we did not have an adequate method to measure the vacuum near the atom chip.

V. DISCUSSION

Our magnetic atom trap potential was formed with only two current sources: one from the superconductive current of a closed circuit, and the other one from large diameter coils whose current was supplied by a regulated current source. Therefore, the trap should have been very stable, and it should not have been possible to observe a large fluctuation. The most plausible mechanism for explaining all the experimental results is the deformation of the magnetic field due to the penetration of the magnetic flux into the superconductor. Since MgB_2 is a type-II superconductor, at a field intensity larger than the first, critical-field flux penetration is inevitable [25–27]. The trap height measurement clearly reveals penetration. The field penetration extends approximately 15 μm on average from both edges of the strip. If the penetration is uniform, its influence is limited to a reduction in the effective width of the current. However, the field penetration occurs with a complicated pattern [26,27]. This disturbs the magnetic field pattern that forms the atom trap. Without flux penetration the field at the bottom of the trap is equal to the transverse (x direction) part of the bias field. This was typically 0.1 mT. The transverse field generated by the penetrated flux can exceed this value. Then, a zero-field point may appear near the bottom of the trap potential, which induces a Majorana transition and releases trapped atoms. A single flux quantum $h/(2e)$ produces a field larger than 0.1 mT only at distances of less than a few μm. However, judging from the magnitude of the reduction in the effective strip width, a large number of flux quanta must have been trapped in a small area of the strip. The influence of the flux penetration will be largest near the atom chip surface and will disappear when the height of the trap becomes larger than the strip width $2a$. This agrees with our observation that the decay rate started to increase at around 100 μm. Further evidence of flux penetration is found in the fluctuation of the decay rate measurement. The penetrated flux generally moves when one changes the superconductive current by trying to penetrate magnetic field through the superconductor. Most flux quanta intrude inside the strip when the closed-circuit current is loaded on the strip. This operation was performed every few hours or at a longer time interval. During a single measurement of the atomic number, the magnetic field perpendicular to the atom chip changed when the moving quadrupole magnet was moved and when the y bias field was swept. The maximum variation in the z field was less than 0.5 mT and was smaller than the variation that occurred when the main current was loaded. Therefore, there was little variation during the single decay rate measurement while the variation in the different decay rate measurement was several times larger. Another possible decay mechanism is the spin-flip transition induced by the magnetic field noise resulting from the diffusion of the penetrated flux quanta. The transition rate is approximately $\pi(\mu/\hbar)^2|B|^2(\omega_0)$, where μ is the magnetic-dipole moment and $|B|^2(\omega_0)$ is the power spectrum of the magnetic field at the atomic resonance ω_0. Its magnitude can vary widely depending on the distribution of the pinning potential of the penetrated flux quanta. However, since the flux noise is caused by the diffusion of flux quanta in a shorter time period than the measurement time, it is not easy to explain the long term variation in the decay rate that we observed in our experiment.

VI. CONCLUSION

In conclusion we have demonstrated experimentally that a superconductive atom chip can trap atoms for a sufficient length of time to enable us to realize single-mode trapping or guiding for a period of several seconds. However, the observed lifetime was many orders of magnitude shorter than that expected from the spin-flip transition as a result of the residual current noise of the superconductor. The detailed analysis on the fluctuation of the decay rate measurement strongly indicates that the dominant trap decay mechanism is the magnetic field disturbance caused by the flux penetrating the superconductor. This decay process may be avoided with a type-I superconductor. A narrower strip is another choice because the field deformation occurs only at the distances of less than the current width, a narrower strip will produce a more stable trap at a shorter distance.

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