Atom-chip Bose-Einstein condensation in a portable vacuum cell

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A ^{87}Rb Bose-Einstein condensate (BEC) is produced in a portable atom-chip system less than $30\times30\times15$ cm, where the ultrahigh vacuum is maintained by a small, 8 L/s, ion pump and nonevaporable getter. An aluminum nitride chip with lithographically patterned copper is used to seal the vacuum system, provide the electrical feedthroughs, and create the magnetic trap potentials. All cooling and trapping processes occur 0.6–2.5 mm from ambient laboratory air. A condensate of about 2000 ^{87}Rb atoms in $F=2, m_F=2$ is achieved after 4.21 s of rf forced evaporation. A magneto-optical trap lifetime of 30 s indicates the vacuum near the chip surface is about 10^{-10} torr. This work suggests that a chip-based BEC-compatible vacuum system can occupy a volume of less than 0.5 L.

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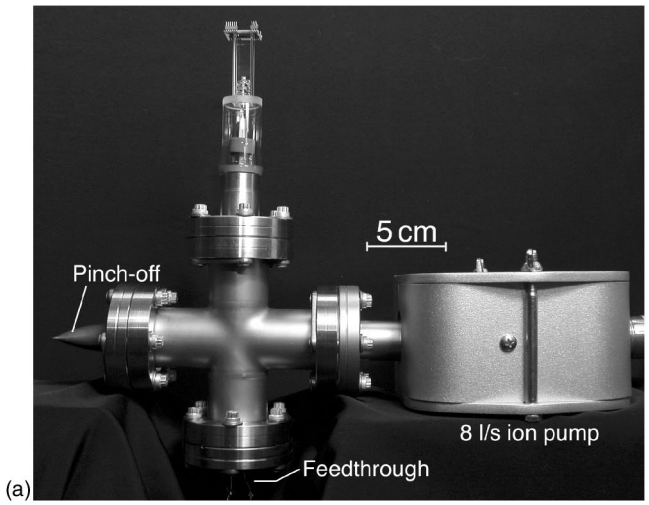
From the first Bose-Einstein condensation (BEC) in a neutral atom gas in 1995 [1,2], it seemed likely that practical applications for Bose condensates could be realized. However, the implementation of "atom lasers" is in much the same state as the first generations of optical lasers were in the 1960s. Cold atom guiding and manipulation using lithographically patterned wires on substrates have demonstrated the possibility of making small-scale devices for atom manipulation [3–6]. Indeed, the term "atom chip" connotes a picture of microscale atom-optical devices, perhaps integrated with optics and electronics on a single substrate. The realization of chip-based BEC in 2001 [7,8] was a scientific and technical milestone towards chip-scale coherent atom devices. Nevertheless, like all present BEC systems, chip-scale atomic systems still require an unwieldy assembly of electronic, optical, and vacuum instrumentation. This work reports on the significant simplification and size reduction of the vacuum system for atom-chip–based BEC production. The atom chip itself forms one wall of the vacuum system; we introduce a technique that enables direct electrical connections to the chip, thereby eliminating standard vacuum feedthroughs. We have produced a portable system that can be assembled, processed, and then inserted to an ultracold atom apparatus in much the same way that an electronic vacuum tube can be plugged into an existing receiver. By separating the vacuum processing from the remaining BEC instrumentation, we seek to speed up ultracold atom chip development and, eventually, to make ultracold atom science more accessible to those not having expertise in ultrahigh-vacuum (UHV) systems.

The vacuum system (see Fig. 1) consists of a single four-way cross which is attached to a small (8 L/s) ion pump, a four-pin feedthrough providing connections to a rubidium dispenser and nonevaporable getter, a pinch-off tube, and a glass cell (the BEC chip cell). A 0.5-mm-thick aluminum nitride wafer (the atom chip) closes the cell top, completing a UHV compatible seal.

The conductor pattern on the atom chip, shown in Fig. 2, is made using standard lithographic and electroplating techniques [3–6,9]. When augmented with an external *y*-directional bias field, the "U"-shaped wire creates a three-dimensional quadrupole field and the "Z"-shaped wire results in an Ioffe-Pritchard-type (IP) trap with a nonzero minimum. (For a comprehensive review on chip microtraps, see Refs. [9–11].) The 100-μm- and 200-μm-wide copper wires can support continuous currents up to 4 and 5 A, respectively, for more than 5 min.

Following Reichel *et al.* [9], a silver mirror is transferred to the chip surface. A quartz cell with an inner cross section of 1×1 cm is epoxied (Epotek 353ND) to the chip; this assembly is epoxied in turn to a UHV glass-to-metal transition using a glass disk with a 1 cm bore to compensate for the size mismatch. With this assembly technique, the atom-chip connections are brought directly out from the vacuum region, between the quartz cell and the chip substrate, into the ambient air, obviating bulky vacuum feedthroughs and the associated intravacuum wiring. Standard electronic pin headers enable a simple interface to the chip. The various components are assembled on the cross, including the nonevaporable getter, the rubidium dispenser, and a Pyrex helix (made in-house), all of which extend into the glass transition (see Fig. 1).

The cell is then attached to a UHV pumping station via the pinch-off tube. The cell is baked with the chip and quartz cell at 150 °C. While baking, the getter (SAES ST172/HI/16-10/300C) is activated consistent with the manufacturer's recommendations, typically 5 A for 3-min intervals separated by approximately 15 min for a total of 15 min activation. This procedure prevents components proximate to the getter from becoming overheated. Occasionally during bake-out, the dispenser is heated with a large current (6 A) for



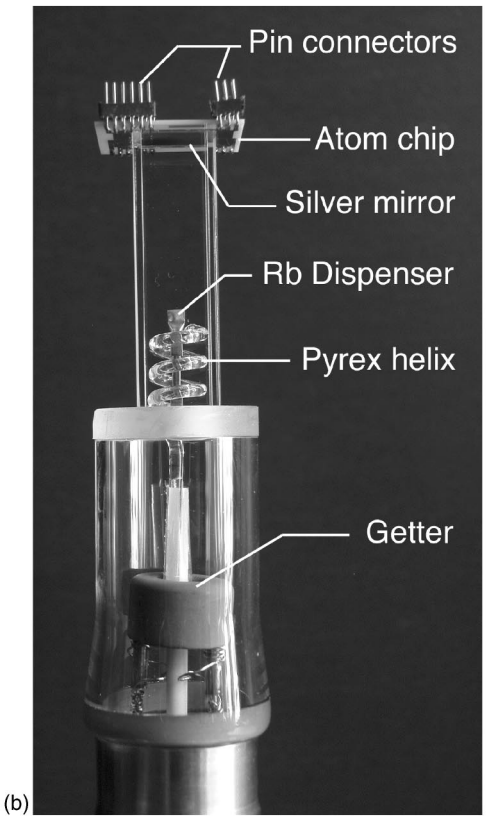


FIG. 1. Portable miniature vacuum cell for the production of a chip BEC. (a) Complete vacuum cell system, (b) detail of cell assembly.

30 s periods. After bakeout, the small ion pump (8 L/s) is turned on and the BEC cell is pinched-off from the pumping station. Gauge pressure on the station side of the pinch-off tube before pinch-off is below 3×10^{-11} torr. Shortly after pinch-off, the small ion pump current is below minimum readout, indicating a pressure of less than 1×10^{-10} torr. After pinch-off, the BEC cell vacuum system is portable with an approximate size of $30\times30\times15$ cm. The cell system is then fitted into a relatively small, fiber-coupled optical bench with the various optical beams, cameras, and magnetic coils prealigned to accept the cell.

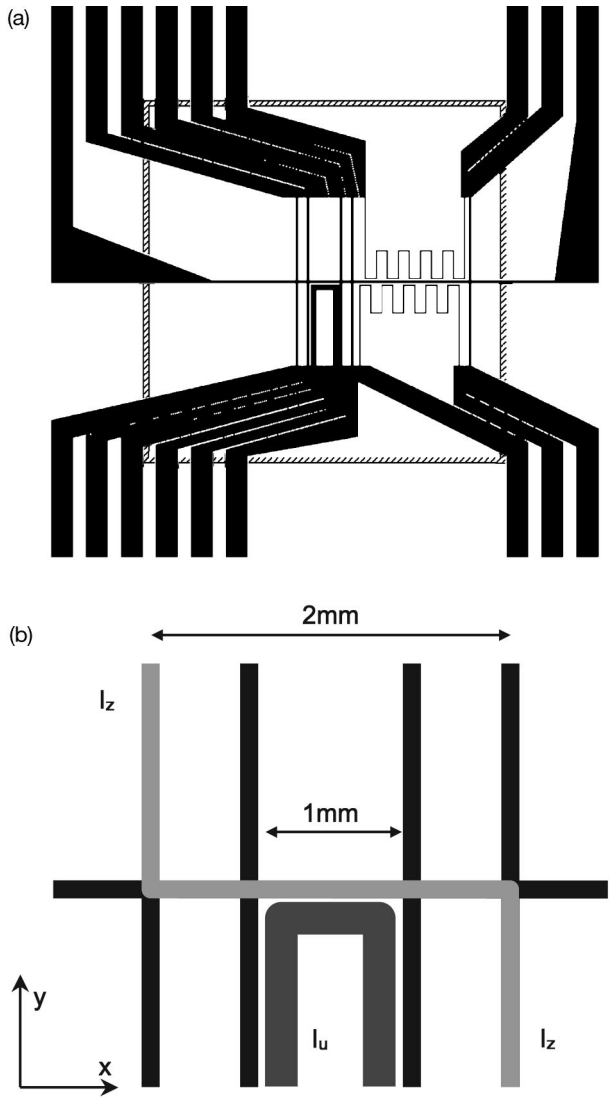


FIG. 2. The atom chip and its wire pattern. Hatch marks indicate placement of the cell (outside edges) on the chip. (a) View of the whole chip pattern; (b) center detail of wires where the BEC is produced. The U wire (I_U, 200 μm wide) is used to create chip MOT, and the Z wire (shown in gray, I_Z, 100 μm wide) is used to create an IP type magnetic trap by applying a y-bias field. The other wires seen in (a) are not used in this experiment.

To achieve large atom number in the magneto-optical trap (MOT) and to meet the UHV requirements of Bose-Einstein condensation, we rapidly modulate the rubidium partial pressure using light-induced atomic desorption (LIAD) [13–15] using two uv lamps (Norland 5011, 75W) placed 7 cm from the cell. We use mirror MOT lifetime measurements as an indication of the pressure in the cell. The lifetime is measured by turning off the uv lamps and fitting the decaying MOT florescence to an exponential. Typical measured lifetimes are on the order of 30 s. We verify the MOT lifetime is not determined by the Rb pressure decay after the LIAD loading. This is done by noting the number loaded into the MOT after introducing a delay between uv lamp turn-off and MOT field turn-on. By this method, we observe the Rb partial pressure in the cell decays very rapidly compared to the

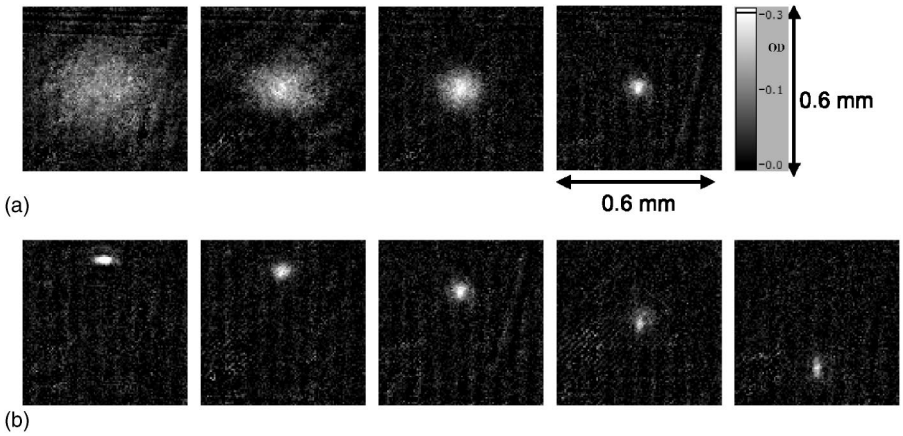


FIG. 3. Bose-Einstein condensation is observed. (a) Absorption images are taken after a 5 ms time of flight (TOF) with different final rf frequencies. From left to right: (1) $\nu=3.5$ MHz, $N=42\times10^3$, $T=4.4$ μK, $\langle\rho\rangle\approx6\times10^{-4}$; (2) $\nu=3.0$ MHz, $N=20\times10^3$, $T=1.4$ μK, $\langle\rho\rangle\approx7\times10^{-3}$; (3) $\nu=2.9$ MHz, $N=10\times10^3$, $T=515$ nK, $\langle\rho\rangle\approx10^{-1}$; (4) $\nu=2.85$ MHz, $N=3\times10^3$, $T=230$ nK, $\langle\rho\rangle\approx10$. (b) TOF images of BEC cloud after release with final rf frequency $\nu=2.85$ MHz. From left to right: TOF (1) $t=1$ ms, (2) $t=3$ ms, (3) $t=5$ ms, (4) $t=7$ ms, and (5) $t=9$ ms. The nonisotropic shape during TOF is a key signature of BEC. [The images in (a) are vertically offset relative to (b) no. 3 so that they are centered.]

MOT lifetime, and thus the MOT lifetime is determined by the background pressure in the cell. From the MOT lifetime, we infer the background pressure in the absence of the uv sources to be 10^{-10} torr. From the MOT loading $1/e$ time ($\sim$1 s), we estimate the uv light-induced pressure increase to be a factor of 30.

We use a mirror-MOT [12] for the first stage of cooling and trapping. The laser powers of cooling and repumping beams are 30 mW and 6 mW, respectively, with a beam diameter of 8 mm. The MOT is loaded by applying LIAD for 3 s to increase the rubidium vapor pressure followed by a 5 s holding time after uv light exposure to improve the pressure in the cell. The MOT loaded in this way typically traps about $(6-7)\times10^6$ ^{87}Rb atoms with a temperature of 200 μK, 2 mm away from the surface. The atoms then undergo a compressed MOT (CMOT) stage: the cooling laser red detuning jumps from 10 MHz to 23 MHz and repumping power is reduced from 6 mW to 100 μW, followed by ramping the quadrupole field gradient from 14 G/cm to 21 G/cm in 20 ms. At the same time, by adjusting bias fields, the atoms are moved toward the surface where the quadruple field is replaced with the field generated by the U wire ($I_U=2$ A and $B_y=1$ G). After 8 ms in the U wire chip CMOT, the atoms have a temperature of 100 μK. We then apply 1.7 ms of polarization gradient cooling by increasing the cooling laser red detuning to 70 MHz and switching off all magnetic fields. This further cools atoms to 20 μK. No substantial atom loss is observed during the MOT transfer and cooling steps.

After cooling and trapping, we optically pump the atoms into the $F=2, m_F=2$ state in preparation for loading into the Z trap. About $(2.5-3)\times10^6$ atoms are loaded into the Z trap by switching $I_Z=4$ A and $B_y=14$ G within 10 ms. Immediately after the loading, the (x,y,z) bias fields ramp from $(0,14,0)$ G to $(-4,60,0)$ G within 100 ms. The magnetic trap lifetime is about 3–5 s. The approximate factor of 10 difference between the MOT lifetime and the magnetic trap lifetime is caused by the difference of trap depth [18,19]. After compression, we commence forced evaporation by the application of an rf field. At the same time, the trap is further compressed by reducing I_Z from 4 A to 2.75 A in 2 s. The final trap position is 82 μm away from the surface with trap frequencies of $(23,3600,3600)$ Hz. Forced rf evaporation takes place through four logarithmic sweeps. The first rf sweep starts from 45 MHz to 13 MHz for 2.46 s. It is then followed by a 1 s sweep from 13 MHz to 5 MHz, a 500 ms sweep from 5 MHz to 3.5 MHz, and a final 250 ms sweep from 3.5 MHz to 2.85 MHz. At the end of the final sweep, we observe a Bose-Einstein condensate of 2000 ^{87}Rb atoms at a transition temperature of about 300 nK [Fig. 3(a)]. As shown in Fig. 3(b), the anisotropic shape during 9 ms TOF (time of flight) is a clear signature of a Bose-Einstein condensate.

A 4 μK/s heating rate that is independent of density leads to a 100 ms BEC lifetime. Lowering the trap frequencies by changing I_Z from 2.75 A to 0.65 A, and B_y from 60 G to 14.5 G, reduces the heating rate to 0.5 μK/s, which corresponds to a BEC lifetime of 300 ms. The total atom number in the trap is conserved during the BEC lifetime. This suggests the heating is not caused by three-body recombination, but by another mechanism.

Two additional remarks are perhaps appropriate. First, in many BEC vacuum systems a titanium sublimation pump is utilized to help achieve and maintain ultrahigh vacuum. The effective pumping of hydrogen is particularly important where heated rubidium dispensers are used because they also release substantial amounts of hydrogen. Our work suggests that the nonevaporable getter can serve the same purpose as the sublimation pump, at least in these small cells. The nonevaporable getter is rated by the manufacturer to have a pumping speed of 1 L/s and a large hydrogen capacity, 1 torr L at room temperature. Second, our first cell designs with quartz cells were unable to obtain sufficient atom numbers in the MOT through the LIAD technique. We introduced a Pyrex helix into the cell to increase the surface area from

which to desorb rubidium. Pyrex was chosen because prior LIAD experiments [13–15] were successfully performed using Pyrex. The helix shape, made in-house, was chosen arbitarily. Probably any shape that increases the surface area for desorption will suffice. In the hopes of eliminating the bulky uv lamps, we attempted LIAD using blue LED's as well as laser light at $\lambda = 532$ nm (100 mW) and 408 nm (10 mW). None were as effective as the incandescent lamps (150 W total). We were able to capture rubidium atoms even with the LED's, suggesting the possibility of a more efficient and compact LIAD source.

The achievement of BEC demonstrates the viability of small and portable chip-based vacuum cells for atom chip applications. Our results suggest that a BEC suitable vacuum cell can be made substantially smaller still. In particular, *all* of the key elements except for the ion pump reside within the glass-to-metal transition region, as shown in Fig. 1(b). The 8 L/s ion pump is in fact already limited by the cell structure itself to a pumping speed of about 2 1 L/s. Thus, we expect it is possible to reduce the total volume of the vacuum system to well less than 0.5 L, dominated by a small ion pump. As the cell itself becomes smaller, many of the practical parameters also improve, such as the size and power requirements of the magnetic coils. On the other hand, the MOT capture volume is small, resulting in a small MOT and subsequent small BEC. It should be noted that a small BEC does not prohibit its utility [16,17].

In summary, we have successfully demonstrated Bose-Einstein condensation in a compact and portable vacuum system. The size reduction and simplification are largely due to the techniques that allow all cooling steps to take place in a single small chamber and the chip-based electrical feedthroughs, which greatly facilitate chip connections. In our experiments, we have succeeded in realizing a "plug-in" concept where the atom chip vacuum cell is plugged into an existing optical and electronic system. Through this concept, we hope that atom chip development and experiments can proceed more rapidly.

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