Laser cooling in a chip-scale platform

J. P. McGilligan, 1, 2 a) K. R. Moore, 2 A. Dells, 1, 2 G. D. Martinez, 1, 2 E. de Clercq, 3 P. F. Griffin, 4 A. S. Arnold, 4 E. Riis, 4 R. Boudot, 5, 2 and J. Kitching 2

1) University of Colorado, Department of Physics, Boulder, Colorado, 80309, USA
2) National Institute of Standards and Technology, Boulder Colorado, 80305, USA
3) LNE-SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, 75014 Paris, France
4) Department of Physics, SUPA, University of Strathclyde, Glasgow, G4 0NG, UK
5) FEMTO-ST, CNRS, 26 chemin de l’Epitaphe, 25030 Besançon, France

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Chip-scale atomic devices built around micro-fabricated alkali vapor cells are at the forefront of compact metrology and atomic sensors. We demonstrate a micro-fabricated vapor cell that is actively-pumped to ultra-high-vacuum (UHV) to achieve laser cooling. A grating magneto-optical trap (GMOT) is incorporated with the 4 mm-thick Si/glass vacuum cell to demonstrate the feasibility of a fully-miniaturized laser cooling platform. A two-step optical excitation process in rubidium is used to overcome surface-scatter limitations to the GMOT imaging. The unambiguous miniaturization and form-customizability made available with micro-fabricated UHV cells provide a promising platform for future compact cold-atom sensors.

Laser-cooled atomic samples have led to significant advances in precision metrology as a result of increased measurement time and reduced environmental interactions compared to room temperature ensembles. The magneto-optical trap (MOT) is commonly used as a source of cold atoms in state-of-the-art atomic clocks and interferometers 1, 2. Although there has been important progress toward portable systems and instruments based on laser-cooled atoms 3, 4, for use on mobile platforms such as vehicles, aircraft and ships, these systems still typically occupy volumes of >100 L and consume many watts of power to operate.

Further miniaturization to sub-liter volumes is underway. The generation of cold-atoms have been demonstrated using a single laser beam reflected from a pyramidal 5, 6 or cone-shaped structures 7, 8, and cell geometries are being explored to reduce size 9, 10. On-chip magnetic confinement of laser-cooled atoms 11, 12 also offers unique opportunities for compact instrumentation 13, but such traps are still typically loaded from a liter-volume vacuum apparatus.

Recent advancements in the miniaturization of cold atom packages have focused on the micro-fabrication of optical elements 14, alkali vapor density regulators 15, 16 and low-power coils 17 to facilitate a compact cold-atom device. However, the miniaturization of UHV vacuum packages 18 remains limited to bulk machining of chamber materials, which lacks the scalability made possible with micro-fabrication.

The micro-fabrication of vacuum cells has been demonstrated for room-temperature atomic ensembles 19, 20 using micro-electro-mechanical-systems (MEMS) alkali vapor cells 21 containing buffer gases to reduce relaxation due to wall collisions. However, buffer-gas mixtures require critical temperature stabilization to reduce sensitivity to pressure shifts and introduce large frequency offsets that prohibit accurate realization of the SI second 22.

Recent work has showed that anodic bonding of silicon frames and aluminosilicate glass (ASG) can reduce the effects of He permeation to a level that would in principle allow a MOT to persist in a UHV environment for six months without active pumping 23. The use of passive pumping in MEMS cells could mitigate the scalability and power consumption limitations placed by currently available active pumping mechanisms.

In this paper, we demonstrate laser cooling of 85Rb in a glass-silicon-glass UHV cell, with a traditional 6-beam MOT connected to an ion pump for active pumping. The apparatus is miniaturized further by using a micro-fabricated grating chip in conjunction with a micro-fabricated cell to realize a compact 4-beam MOT with only a single input beam. The association of these two technologies constitutes a promising solution for the development of miniaturized MOTs, compatible with lithographic fabrication techniques.

However, in such a set-up imaging of the MOT at 780 nm is made difficult due to background light, scattered from the grating chip surface and Si cell walls. To overcome this issue, a two-step excitation to the 5D1/2 level in rubidium is used to generate fluorescence from the laser-cooled atoms at 420 nm, which with appropriate filtering, overcomes surface scatter and enables imaging of the cold atoms even with the low atom numbers that results from the small beam overlap volume 24, 25. With a total cell volume of 4 cm3, this amalgamation of micro-fabricated components is a promising platform for future compact cold-atom sensors and instruments.

The MEMS vacuum cell is initially implemented in a 6-beam MOT set-up, shown in Fig. 1. The cell consists of a 40 mm × 20 mm × 4 mm silicon frame with a 4 mm-wide rim at the bonding surfaces. The dimensions are chosen to provide a large surface bond area for increased probability of a hermetic seal, while providing a 12 mm inner dimension for optical access. The silicon is etched using a potassium hydroxide wet-etch through the complete 4 mm silicon thickness, via 2 mm-deep etches from both sides of the wafer. To avoid walls at angles defined by the crystal orientation, an over-etching technique is used to produce smooth inner wall surfaces, orthogonal to the upper and lower bonding surfaces 26.

The frame is anodically bonded to two 40 mm × 20 mm
glass wafers with 700 μm thickness. The process of anodic bonding is usually carried out at a temperature near 300°C to enable fast diffusion of the alkali ions within the glass. However, the use of glass doped with lithium instead of sodium or potassium allows anodic bonding at temperatures as low as 150°C. Low-temperature anodic bonding is required for MEMS vapor cells that are hindered by vapor diffusion into the glass cell windows at high temperatures. Reducing the bond temperature also alleviates the risk of damage to integrated components and circuitry. In addition, we have found that the lithium-doped glass has a 6× larger initial bonding current and also bonds 8× faster compared to other comparable glass wafers (SD-2 Hoya) when bonded at 300°C. A 6 mm-diameter hole is laser-cut in the upper ASG window. A silicon washer and borosilicate glass tube are anodically bonded over the hole. The end of the glass tube is fused to a silicon washer and glass tube. The MEMS cell is aligned in a retro-reflected 6-beam MOT.

To further simplify the cooling apparatus, the MEMS cell was implemented into a grating MOT package. Unlike the traditional 6-beam MOT, the GMOT requires no critical alignment of the MEMS cell for optical access, and can instead be placed above the grating chip in a planar stack, as shown in Fig. 2 (a). Additionally, the cooling optics used for the 6-beam MOT are streamlined by implementation of the GMOT, providing atom cooling and trapping of 85Rb using a single incident beam, rather than three mutually-orthogonal counter-propagating beam pairs. The overlapped cooling (780 nm) beam and imaging (776 nm) beam are aligned with the center of the grating chip while the zeroth diffraction order is retro-reflected along the incident path.

A 1 cm² segmented diffraction grating is placed outside and immediately below the MEMS cell; to ensure that the laser overlap volume is well within the 4 mm height of the cell. The smaller grating size used here compared to other GMOTS was chosen to reduce the size constraints of the MEMS cell inner dimension. However, the smaller size leads to a reduced beam overlap volume and correspondingly lower steady-state trapped atom number in each arm. Each cooling beam was then circularly polarized by a λ/4 waveplate immediately before the vacuum cell. CCD imaging is aligned to avoid saturation of pixels from reflecting regions of the cell surfaces. When a steady-state Rb density is achieved from the resistively heated Rb₂MoO₄/AlZr alkali source, an atom number of 6.1(5)×10⁵ is observed from standard fluorescence imaging with a simultaneous rise-time extracted pressure of 1.1(5)×10⁻⁷ mbar.

FIG. 1. MEMS vacuum cell. An etched silicon frame is anodically bonded at upper and lower surfaces to glass wafers. The top glass wafer is drilled and bonded to a Si washer and glass tube. The MEMS cell is aligned in a retro-reflected 6-beam MOT.

FIG. 2. (a): MEMS cell GMOT illustration. (b): Optics set-up for laser cooling and two-photon spectroscopy. (c): Coupled energy levels employed for blue fluorescence. BS: Beamsplitter. PBS: Polarizing beam splitter.

with maximum incident power of 20 mW and a red-detuning of δ≈2Γ, where Γ≈2π×6 MHz is the transition’s natural linewidth.

The retro-reflected 6-beam MOT beams were aligned with 1/e² diameter of 4 mm and approximately 1.5 mW in each arm. Each cooling beam was then circularly polarized by a λ/4 waveplate immediately before the vacuum cell. CCD imaging is aligned to avoid saturation of pixels from reflecting regions of the cell surfaces. When a steady-state Rb density is achieved from the resistively heated Rb₂MoO₄/AlZr alkali source, an atom number of 6.1(5)×10⁵ is observed from standard fluorescence imaging with a simultaneous rise-time extracted pressure of 1.1(5)×10⁻⁷ mbar.

The cooling and re-pumping light is derived from a single distributed-Bragg-reflector (DBR) laser, by frequency modulating the injection current at 2.9 GHz to generate the required re-pumping light. The laser is frequency stabilized to the 780 nm cycling transition 5S₁/₂(F = 3)→5P₃/₂(F’ = 4) with saturated-absorption spectroscopy. The cooling/re-pumping light is fiber-coupled into a polarization maintaining fiber and separately injected into the 6-beam and grating MOT systems, providing optical pumping for background-free imaging, an additional 776 nm laser was added to the optical set-
up, illustrated in Fig. 2 (b). The 776 nm light is derived from an external-cavity diode laser (ECDL). The light is locked to the $5D_{3/2}, F'' = 5$ state for maximum fluorescence by counter-propagating it with the 780 nm light through a 10 cm-long heated vapor cell, and detecting the ladder transition $5S_{1/2} \rightarrow 5P_{3/2} \rightarrow 5D_{3/2}$, illustrated in Fig. 2 (c), via the absorption of the 776 nm light. The remaining 776 nm light is combined with the cooling light on a polarizing-beam-splitter (PBS), and coupled into the same fiber as the cooling light to ensure good beam alignment. As a result of combining the beams on a PBS, both beams have orthogonal linear polarizations, later converted into orthogonal circular polarization using a $\lambda/4$ plate. The single incident beam was then expanded and apertured to a 1 cm diameter.

Due to the 4 mm silicon walls, which are highly opaque to 420 nm to 780 nm light, a CCD was aligned at $\lambda \approx 420$ nm to 780 nm light, a CCD was aligned at and apertured to a 1 cm diameter.

The authors declare they have no competing interests. Approved for Public Release, Distribution Unlimited. Data available upon request from the authors.
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