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Invited Paper

Atomic Flux Circuits

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ABSTRACT

Atomic vapors are a crucial platform for precision metrology but in their simplest implementation, a thermal vapor, the intrinsic optical resonances are broadened due to the random and isotropic thermal motion of the atoms. By structuring the container of a thermal vapor with narrow emission apertures, the velocity distribution can be modified to create a directed beam of atoms.[1] These atomic beams can then interact sequentially with a series of optical fields, or interaction zones, and ultimately allow precision control over the internal state of the atom. This is useful for optical frequency standards and precision spectroscopy[2,3] and may also provide the means to build a simple flying qubit platform.[4] Furthermore, atomic beams on a chip can be used as a compact, directed source to load magneto-optical traps (MOTs) while minimally increasing the ambient pressure.[5] We apply microfabrication techniques to microscopically structure silicon to deterministically control the flow of Rb between connected cavities. We describe a methodology to measure the experimental parameters that govern the flux of atomic vapors in these microfabricated structures with a goal of creating an equivalent electrical circuit model. This toolkit will provide a simple platform for the creation of atomic beams on a chip with controllable pressure profiles and a thorough understanding of the influence of adsorptive effects and pseudo-ballistic trajectories on the resultant atomic beam.

Keywords: Atomic Physics, Microfabricated Vapor Cells, Optical Frequency Standards, Atomic Sensors, Atomic Beams, Quantum Metrology

1. INTRODUCTION

Atomic spectroscopy is an important class of technologies relating to the readout of internal energy states of atoms. This technology pathway provides a direct link to SI-traceable standards[6] as well as ultra-sensitive sensors.[7,8] Thermal vapors of atoms are the simplest building block of atomic technologies. One interesting feature of thermal vapors of atoms is their motion: in most cases this motion degrades the performance of a device due to finite interaction times and isotropic thermal velocity profiles. However, the velocity distribution of a vapor of atoms can be controlled through the appropriate configuration of pressures in confined geometries.[1]

One powerful miniaturization pathway for atomic technologies is the microfabrication of alkali vapor cells.[8] This technique typically combines glass and microstructured silicon to form a hermetically sealed microcavity suitable for optical spectroscopy. By leveraging microfabrication processes, the silicon structure can be molded into a desirable form with microscopic precision. One form is to have a 'source cavity', filled with alkali metal, connected to a second 'optical measurement cavity' (or 'optical cavity' for short) by a thin channel. The vapor flux between these two cavities will primarily depend on the pressure differential and the geometry of these channels. Alkali metals form a vapor pressure which is purely a function of temperature so long as macroscopic volumes of alkali metal are present.[9] As the thin channel geometry influences the atomic flux, these channel geometries can be likened to electrical equivalent circuit elements as resistors. The filling of these cavities can be similarly likened to capacitors due to the loading effect associated with wall adsorption. Determining the physical principles between these analogies is the goal of this work. Some experiments have so far elucidated the need for empirical results in these systems as the flux is a complex function of material choices and geometry.[3,10]

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In other experiments,[11] the filling of microfabricated channels with dimensions of 30 μm wide, 170 μm deep, and 3 mm long were observed to contain Rb vapor at high densities (OD in excess of 1) in significantly less than an hour when heated to 160 °C. In one standard vapor cell fabrication method used at NIST,[12] 500 μm wide channels with typical depths of 1 mm and lengths of 1 mm are routinely used to couple a source chamber (containing a Rb 'pill' composed of $Rb_2CrO_4/Zr/Al$[13]) with an optical measurement chamber and are observed to transport Rb in timescales of minutes or less at temperatures of less than 90 °C. These results in comparison to the results of[3,10] indicate that some sub-mm regime of channel geometries may incur an alkali transport penalty that deviates from traditional conductance theory.[14,15]

To investigate the alkali transport regime in sub-mm geometries, a wafer of silicon was etched to produce a multitude of geometries to identify the various geometrical impacts on atomic flux. The result of this work will provide a toolkit to control the pressure of an alkali vapor source suitable for creating chip-scale atomic beams that can deterministically operate in the molecular flow regime. We seek a low-order lumped element model to account for the geometrical impact on atomic flux and choose to represent these structures as equivalent electrical networks.[16,17]

2. FACTORS AFFECTING ATOMIC FLUX

The material system for these experiments consists of borosilicate glass, silicon, and silicon dioxide. These materials are compatible with alkali vapor cells but some considerations must be kept in mind. Alkali atoms are highly polarizable and can interact strongly with oxide surfaces. An atom can be assumed to have a sticking probability coefficient and a residence time each time it collides with a surface. When the atom sticks to a surface, it first thermalizes with the surface and can either diffuse into the surface or be remitted in an angle governed by Lambert's Cosine Law of Effusion.[18] The diffusion coefficient will depend in a sophisticated manner on both the material and the concentration of diffused alkali atoms into it. Silicon is typically regarded as inert with respect to alkali atoms and is assumed to not promote the diffusion of Rb into its surface; glass, however, readily absorbs Rb and Cs.[19] As the diffused alkali density increases, the probability of diffusing into the surface decreases and so after some amount of time a 'passivation layer' forms at which point the cell is said to be 'cured' and will nominally reach a steady state where alkali atoms will cease to be absorbed. Furthermore, long, thin channels will be expected to have non-diffusive Rb transport due to the ballistic trajectory of atoms at low pressures. Thus, line-of-sight geometries should have higher fluxes than those with bends and angles. The vapor pressure of Rb is dependent only on the temperature of the system when Rb vapor coexists with Rb metal[9] making Rb droplets a nearly-ideal atomic vapor pressure source.

The previous factors will depend on the material choices, the temperature, and the geometry. Three primary geometrical considerations are made: 1) the channel conductance will modify the flux. 2) The channel and cavity surface areas will modify the characteristic time to reach steady-state behavior. 3) The directionality of the channels will modify the ballistic transport of atoms.

3. WAFER EXPERIMENTAL DESIGN

To tease apart these various factors, we fabricated a set of roughly 100 individual experiments (illustrated in Figure 1) to evaluate the impact of geometry on chip-scale atomic flux circuits. Optical lithography is used to define lateral feature sizes with sub-micron precision. The z-dimension is controlled by using a silicon-on-insulator (SOI) wafer with a handle of 1 mm, 2 μm thick oxide, and 10 μm thick device layer. The oxide layer is used as an etch stop and the device layer is the layer used to define these thin channels. After silicon etching, the oxide layer is removed with an HF etch leaving un-exposed oxide in tact. The handle layer is used to locate the optical and source cavities. The source cavities are circular features that contain a Rb 'pill' which is laser-activated to produce macroscopic droplets of Rb metal. An example of a single source cavity connected to an optical cavity is depicted in Figure 2.

Photolithography makes it simple to design a computer-generated pattern and imprint that into a photoresist for further processing. We choose to procedurally generate the patterns using open source software in order to create a reproducible set of test structures. Furthermore, procedural generation allows us to tweak various parameters in an iterative fashion and to evaluate a variety of physical phenomena with an array of structures.

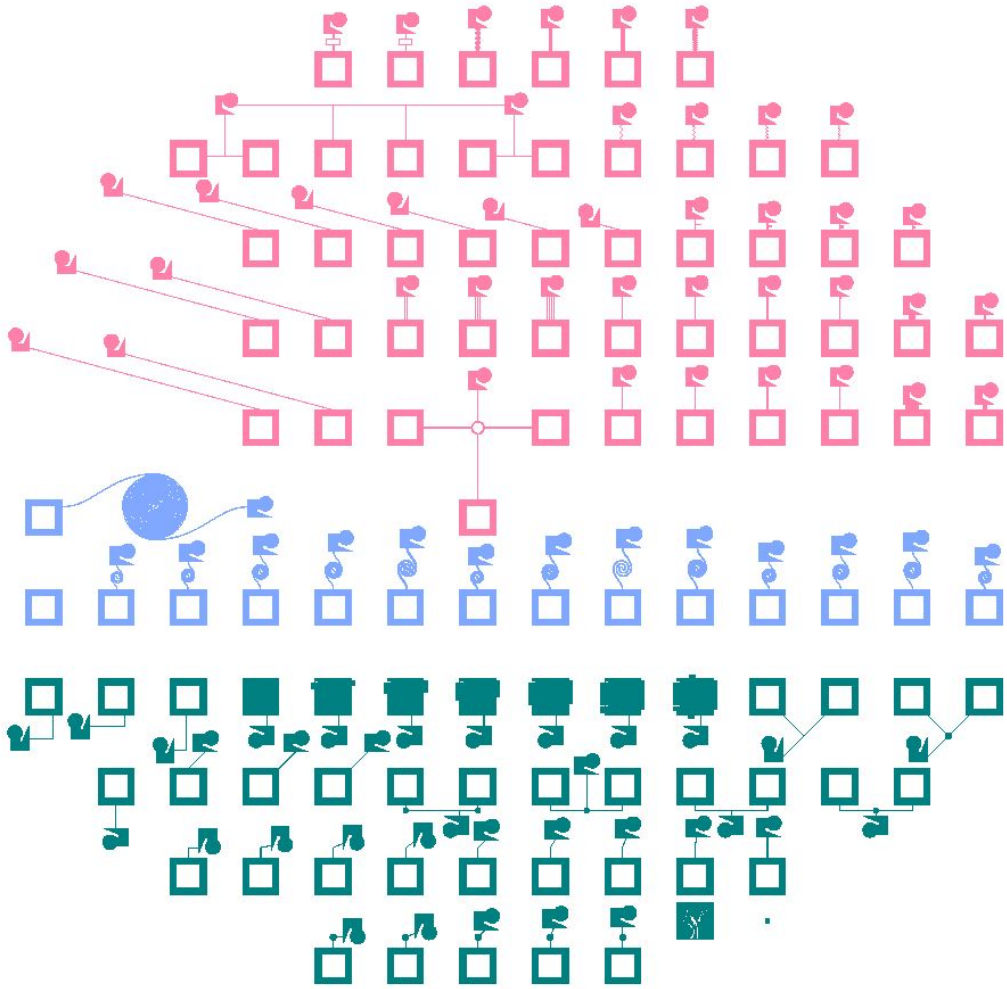

Figure 1. Illustration of the wafer layout for the total series of experiments. The upper set of structures focus on the influence of the channel geometry on the flux. The middle set of structures focus on long, spiral paths of lengths from 10 mm to over 200 mm for compact control of the pressure. The bottom set of structures focus on evaluating the impact of non-ballistic transport and the loading of the various cavities (i.e. flux capacitive effects).

We use deep reactive ion etching (DRIE) to ensure that the fabricated structures have nearly vertical sidewalls ensuring that the imprinted photolithgraphic pattern is highly uniform in vertical cross section. The minimum lateral feature size we choose is 10 μm to safely reside within DRIE aspect ratios of 1 or less (depth:lateral feature size). DRIE is a time-multiplexed etching method that can leave scalloped sidewalls. This sidewall roughness is not present on the upper glass wafer nor is it present after oxide removal on the bottom surface. The role of surface roughness is mitigated in most experiments by making the lateral dimension much larger than vertical dimension ensuring the vast majority of the surface area is composed of specular surfaces as opposed to diffuse surfaces whose actual surface area may be difficult to accurately evaluate. Because DRIE includes a fluorocarbon deposit, the wafer is cleaned with a solvent to remove any contaminants from the silicon surface.

After the SOI wafer is etched into shape, we use anodic bonding to hermetically seal the silicon microcavities using borosilicate glass. Prior to the final glass encapsulation step, Rb_2CrO_4/Zr/Al pills are added to the source cavity of each experiment and the total structure is bonded under vacuum. After the pills are laser activated, the wafer is placed on a hot plate with a translation stage. Spectroscopy is measured through each optical cavity over time in an automatic fashion. A reference spectrum is simultaneously recorded for frequency calibration.

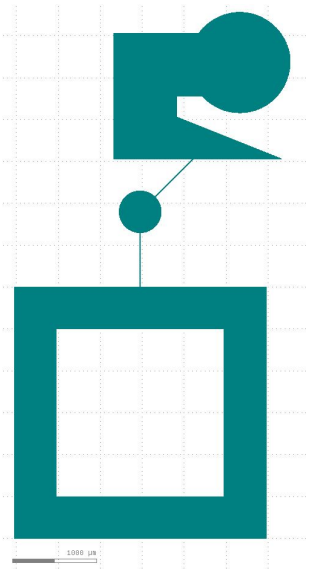

Figure 2. Example test structure. Note the source cavity which houses a circular pill which is laser activated post-bonding to generate Rb metal. This source cavity is connected to an optical cavity by a thin channel without line-of-sight access to the channel.

As the Rb accumulates in the optical cavity, the absorption will increase until the vapor saturates and condenses on the walls of the chambers.

We choose to apply lumped element analysis (LEA) to model the time dependence of these atomic flux circuits. The geometries we investigate include three types of experiments: resistors, capacitors, and cascaded/parallel elements. The resistors are composed of a variety of long (5-25 mm), thin (10 μm deep, (10-500 μm wide) channels with various bends and angles. The capacitors are composed of a variety of different chamber volumes and surface areas; an example of an experiment aimed to evaluate the effect of surface area while maintaining a constant volume is depicted in Figure 3. The cascaded elements are composed of resistor and capacitor primitives that are aligned either in parallel or in series to verify the expected dependencies (i.e. parallel channels of resistance $R_{channel}$ yields an effective resistance $\frac{1}{R_{eff}} = \sum \frac{1}{R_{channel}}$). Whenever possible, as many features are held constant as feasible to identify each parameter of interest individually. The source cavities are kept the same to ensure the uniformity of the pressure source and no line-of-sight is permitted from the pill to the entrance of the thin channel.

4. INITIAL MEASUREMENT RESULTS

The first measurements investigate the directional loading effect of the optical cavity under the influence of various thin channel coupling angles and is depicted in Figure 4. We use a centrally located circular diffuser cavity to see if the diffuser cavity captures and randomizes the atomic trajectory down the center of the channel. The dimensions of these channels are 5 mm long with cross sections of 10 μm x 10 μm. The pills were activated releasing observable volumes of Rb metal. The wafer was heated to 90 °C but no observed Rb spectroscopy was seen in the optical cavity after 19 days of continuous monitoring. We chose these dimensions based on previously observed experimental results[11] indicating sub-hour Rb transport in dimensions of 30 μm x 170 μm cross section and 3 mm length. Standard conductance theory in the molecular flow regime (proportional[14] to d^3/L where d is the diameter and L is the length of a circular pipe) would suggest that the time to observe Rb transport would be 570 times longer (5/3 times longer due to the longer length and approximately 7^3 times longer due to the reduction in the cross section) than in those initial measurements in the comparative system. Because the actual transport time is only known as an upper bound, we chose to err on the side of caution and make the channels long enough to ensure that Rb transport would require approximately two days if the initial experiments filled in a minimum lower bound of 5 minutes. It appears more likely that the Rb transport took

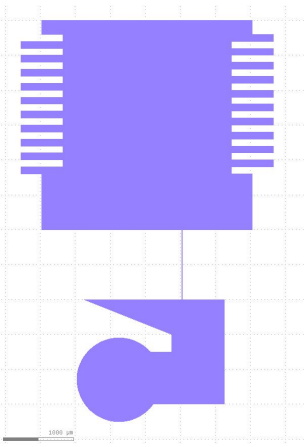

Figure 3. An example of a surface area modification for extracting the impact of surface area while maintaining a constant volume.

significantly longer in those initial experiments and our current experiment should have an upper bound of 35 days of heated transport to observe a strong Rb flux. We note this estimate also includes a reduction in the pressure due to the practically-limited wafer heater temperature of less than 115 °C. A second set of experiments with deeper channels is being pursued to extract these parameters of interest in a shorter timeframe.

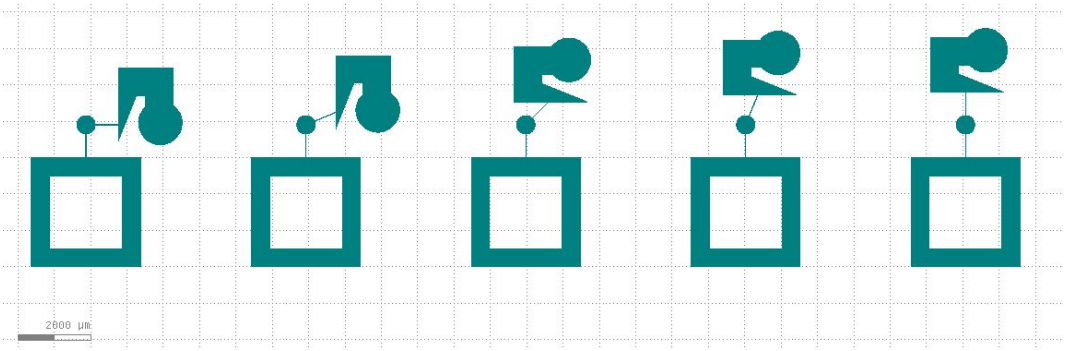

Figure 4. Test structures evaluate in the first phase of this work. The only difference between structures is the angle that the thin channel makes with the diffuser cavity. It is assumed that the straight channel will have the highest conductance due to the high probability of a ballistic atom making it way through the entire structure while the right angle channel should have the lowest conductance due to the need for the diffuser cavity to emit atoms into the exit channel.

5. CONCLUSION

A method of measuring the effect various geometries of microstructured silicon and glass channels have on the transport of alkali vapors has been developed. Creating simple analogies with electrical equivalent networks will produce a robust and general framework for the controllable design of atomic fluxes. By utilizing wafer-level methodology, a large array of test structures can be simultaneously formed and be reproduced due to the widely available source materials, namely alkali 'pills', SOI wafers, and borosilicate glass wafers. The wide availability of wafers and the robust assembly using standard microfabrication processes further ensures the reproducibility of the results developed in these experiments.

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