A BATCH FABRICATED RUBIDIUM-VAPOR RESONANCE CELL FOR CHIP-SCALE ATOMIC CLOCKS

Chung-Hoon Lee, Hang Guo, Shankar Radhakrishnan, and Amit Lal
School of Electrical and Computer Engineering, Cornell University
Ithaca, NY 14853

Csaba Szekely, and Thomas A. McClelland
Frequency Electronics, Inc.
Mitchel Field, NY 11553

Albert P. Pisano
Department of Mechanical Engineering
University of California, Berkeley
Berkeley, CA 94720

ABSTRACT

We present a batch-fabrication process for Rubidium⁸⁷ (Rb⁸⁷) vapor cells appropriate for chip-scale atomic clocks. The Rb⁸⁷ cells are fabricated by anodic bonding of glass to bulk micromachined cavities in silicon, enabling batch production of hundreds of cells per (four-inch) wafer. We describe a method to enable parallel filling of the sealed cavities with Rb⁸⁷. We present a novel method by which the cells containing Rb⁸⁷ are wax-sealed to produce individual Rb⁸⁷ cells after dicing. For the fabricated Rb⁸⁷ cells, we measured a hyperfine interaction linewidth of 956.8 Hz at the center frequency of 6.84 GHz, realizing a quality factor of 7.14×10^6 .

INTRODUCTION

Atomic clocks are used for satellite communications, global positioning systems (GPS), cellular phone communications, radar and other applications requiring precision timing. Currently their use is limited due to their large volume (150-250 cm³) and high power consumption (>10 Watts). Hence, the feasibility of realizing a microscale low-power chip-scale atomic clock (CSAC) is intriguing and could have high payoffs for precision timing applications. Atomic clocks are based on the hyperfine energy shifts of the electronic states due to the electron-nucleus spin interactions. In most cases alkali atoms are used due to a single electron in the outermost shell, resulting in a well-defined singular hyperfine transition. The energy shifts in many cases are in the gigahertz range. By populating the atoms in the higher energy state by optical pumping, and then measuring the absorption under a microwave signal corresponding to the hyperfine energy, one can obtain a very pure microwave frequency source. The purity or the quality factor of these sources is limited by the coherence time of the atoms, which is determined by collisions the atoms undergo with other atoms and the chamber. In many atomic clocks, the coherence length is maintained by creating polarized atomic beams that are used up when they hit the detector. In the most common rubidium or cesium clocks, the alkali atoms are immersed in a package filled with inert gas such as argon, neon, or nitrogen. The atomic collision of the alkali atoms with the gas atoms is elastic leading to the preservation of the alkali atom hyperfine atomic energy state. However if the atoms collide with the chamber surfaces, the coherence is lost. Therefore, miniaturization of the alkali-vapor-inert gas chamber could lead to broadening of the atomic transition due to higher surface to volume ratio. Hence, a key question is if the linewidth of a micromachined device can be as narrow as that of macroscale resonance cells. In this paper we demonstrate that a batch fabricated micromachined cell can have linewidths less than one kilohertz (1 kHz). A second consideration in clock design is the method of atomic interrogation.

One popular candidate for miniaturized atomic clocks is the use of VCSELs (vertically cavity surface emitting laser) with the output wavelength tuned at the optical transition of the alkali atoms [1,2] using the coherence population trapping technique. The laser light is modulated at half the hyperfine frequency to create coherent population trapping of atoms in the laser beam pathway. The laser modulation frequency is stabilized by feedback of the absorption of the light. One drawback of this approach is the drift in the laser frequency due to temperature variations, necessitating very accurate temperature control. The temperature control will require considerable power, making the advantage of the small size optical source less useful. In contrast the traditional Rb-based clocks utilize plasma lamp-based pumping. In this approach the resonance cell is pumped with photons from a Rb⁸⁷/buffer gas plasma lamp. The emitted photons are then filtered by Rb⁸⁵ atoms which absorb photons corresponding to only one of the emitted photon energy levels. The Rb⁸⁵ can be mixed in the lamp itself, or can be a separate filter cell. The resulting photon flux is then incident on a resonance cell where the absorption of these highly specific photons is measured as the frequency of a microwave magnetic field is phase modulated. The advantage of plasma lamp technique is that the lamp-generated photons are already specifically tuned to that needed to sample the resonance cell rubidium atoms, requiring less temperature tuning compared to that for VCSELs. The temperature stability requirement for the lamp is to control the temperature to within one Kelvin, which is easier than that for VCSELs. The disadvantages of the plasma lamp approach include possible high power consumption for realizing spectrally pure plasma at the microscale.

We present a clock architecture using the plasma lamp and RF interrogation of the resonance cell using Rb⁸⁷. Commercially available atomic clock systems typically use resonance cells fabricated out of glass tubing. The fabricated glass cells are individually filled with Rb⁸⁷ and sealed by fusing the glass inlet. Some of the recent chip-scale resonance cell fabrication has been done using anodic bonding but each cell is filled serially, which would still keep the cost of the end products prohibitively high. In this work, we present a novel way of batch fabricating Rb⁸⁷ cells to address some of these issues. We also present results of linewidth measurements using batch fabricated cells. We experimentally confirm the hyperfine-resonance by RF-interrogation of the fabricated cells inside a commercially available clock resonant cavity.

MICROMACHINED CAVITIES FOR Rb⁸⁷ CELLS

A method for batch fabrication of Rb⁸⁷ cells is described in the following sections. Rb⁸⁷ cell fabrication uses anodic bonding of a bulk-micromachined silicon wafer to a glass wafer, which

Travel support has been generously provided by the Transducers Research Foundation and by the DARPA MEMS and DARPA BioFlips programs.

poses thermal constraints. Anodic bonding requires high temperature ($\sim 400^\circ\text{C}$) processing, while the melting point of Rubidium (39.3°C at 1 atm) is low. Therefore Rb^{87} /buffer-gas cannot be placed before the bonding process. To solve this, we have developed a method to fill an entire wafer of cavities (after wafer-bonding) with Rb^{87} -vapor and buffer gas, and then seal each cell with a low-melting-point high-molecular-weight wax.

Figure 1 describes the three-mask process flow to batch fabricate the Rb^{87} cells. We use four-inch double-side-polished high-resistivity silicon wafers to realize the cells.

Figure 1. Batch fabrication of Rb^{87} cells using anodic bonding and wax-sealing.

The first mask step defines channels on the back side of the wafer. We then deposit $1\ \mu\text{m}$ of low-stress LPCVD Silicon nitride (SiN) to act as an etch mask, and form membranes for subsequent process steps. Mask 2 and 3 define the back side cell cavity and the front side wax sealing hole. An anisotropic etch (20 % KOH, 80°C) of the results in the final structure. Several cavities on the backside are connected by the channel, and in turn to an input cavity. Finally, the cavities on the backside are sealed by anodically bonding to glass wafer (Corning 7740) forming a wafer sandwich.

THERMAL CHASING OF Rb^{87}

Figure 2 shows an input cavity connected to a cell cavity. A glass capillary is attached to the inlet using a commercially available vacuum-compatible epoxy-based seal (Torr seal). Anodic bonding of a square glass capillary is also a way to attach the glass tubing to the wafer sandwich.

Figure 2. An input cavity connected to several cells. The attached glass capillary connects to a Rb^{87} reservoir.

The wafer sandwich is pumped down to $\sim 10^{-8}$ torr by connecting the inlet pipe to an ultra-high vacuum (UHV) system via glass blowing. A molecular flow resistance and capacity models for the flow path was developed to calculate the time to reach 10^{-6} torr pressure in the deepest cavity. This calculation yields a pumpdown time of about two hours. The entire wafer is kept at 70°C and pumped down overnight to bake out any impurities. After the pumpdown, the wafer is filled with nitrogen to 20 torr pressure. The glass cavity is filled with Rb^{87} from a small glass transfer chamber. Then the inlet with solid Rb^{87} is sealed, creating a Rb^{87} reservoir at the entry point of the wafer (Figure 3). The wafer sandwich is then heated uniformly at 70°C . The Rb^{87} reservoir is heated to 90°C . The cavities are flooded with a pool of isotopically pure Rb^{87} by creating a pressure driven flow or thermal “chasing”.

Figure 3. Pressure driven flow from reservoir in to Rb^{87} cells.

THE WAX-SEALING PROCESS

After filling the cavities with Rb^{87} , the individual cells are sealed and isolated as illustrated in Figure 4 (left). First, the wax is molded into a micromachined mold to form wax strips that intimately fit into the anisotropically etched wax seal holes.

Figure 4. (Left) Laser drilling is used to create holes that allow wax to penetrate and seal channels after Rb^{87} and buffer gases are filled. (Right) Photographs of one section of formed cells and an entire wafer of Rb^{87} cells.

Figure 5. The cross-section of a diced resonance cell and a pool of Rb^{87} in a bent-in SiN membrane indicate filled-in resonance cell.

Next the wafer is heated to the wax softening temperature (90°C). This causes the wax flow into the microchannels inside silicon nitride bulk micromachined windows through laser cut holes in the nitride membrane to form airtight seals. The wax (W-40) chosen has a low vapor pressure of 10^{-9} torr at 100°C , which is higher than the sealing temperature (90°C) and the clock operation temperature (75°C). The wafer is then diced using a high speed saw to obtain 100 to 120 cells (Figure 4 right). Figure 5 shows the dimensions of a typical Rb^{87} cell fabricated by this method and the photograph of a Rb^{87} -filled cell.

LINEWIDTH MEASUREMENT

A RF absorption spectroscopy system as shown in Figure 6 is used to measure the linewidth of the fabricated Rb^{87} cells. The fabricated devices were placed in a RF cavity to measure the hyperfine resonance. The output of a RF-excited Rb^{87} lamp is projected into a temperature-controlled microwave cavity consisting of a filter cell consisting of Rb^{85} .

Figure 6. Current atomic clock architecture

The temperature control at 75°C is necessary to maintain Rb in gas phase. A RF field of 120 MHz is projected into the microwave cavity, which is designed to have a TE 101 mode [4]. The microwave cavity resonates at its 57th harmonic, which is generated using a step-recovery diode mode with a modal frequency equal to the hyperfine frequency of Rb^{87} . A low phase noise quartz oscillator is used in a voltage controlled oscillator (VCO) loop to achieve a stable, low phase noise frequency to drive the cavity. Figure 7 shows a photograph of the physics package of the clock architecture shown schematically in Figure 6.

Figure 7. RF-cavity of commercially available Rb atomic clock from Frequency Electronics, Inc. to measure atomic resonance of the Rb in the resonance cell.

RESULTS AND DISCUSSIONS

For linewidths measurements, a 120 MHz input for RF field projection in to the microwave cavity was generated by using a 12 X multiplication of a 10 MHz input from a function generator. This frequency is swept over a small range (50 Hz) to observe the hyperfine resonance of Rb^{87} .

Figure 8. A sub-1kHz linewidth measured with silicon resonance cell using setup in Figure 7, over the center frequency of 6.84 GHz.

Figure 8 shows the first derivative of the microwave double resonance spectral line, obtained by modulating the microwave frequency at 120 Hz. A computer code finds the integrated output

of the measured data to obtain the hyperfine resonance linewidth of the cell of 956.8 Hz at the center frequency of 6.84 GHz, realizing a quality factor of 7.14×10^6 .

Figure 9. Left: 3-D finite element analysis (using ANSYS) showing TE 101 mode for the RF cavity partially loaded with dielectrics (to reduce the physical dimensions of the cavity). Right shows a schematic sketch of the cavity containing a Si/glass cell. Change in resonant frequency between glass and Si cell, $\Delta f = 37$ MHz.

The use of silicon poses a RF-design issue. The higher silicon substrate resistance increases loss for the RF cavity, and the higher dielectric constant reduces the effective speed of light. The electric field is more focused near the silicon cell, as compared to when a glass cell is placed. Figure 9 shows a finite element simulation of the resonant frequency of TE101 mode and field crowding at the resonant mode. Simulations for a glass resonance cell show a resonant frequency that is ~ 37 MHz higher than that for a Si resonance cell. The cavity resonance frequency shift implies that the microwave gain from the signal to atomic absorption was not as high as possible.

CLOCK ARCHITECTURE

Given our fabrication and demonstration of the resonance cells, and a process to fill bulk-micromachined cavities with Rb^{87} , we are pursuing to implement a complete physics package (Figure 10) that would enable power and volume reduction to the required for a CSAC. The resonance cell will be attached to a plasma lamp which utilizes radioactive thin films to excite the Rb^{87} and buffer gas mixture, in addition to high frequency and dc magnets to induce a low power plasma [5]. Two bulk micromachined cavities made out of Silicon are bonded in an inert ambience (glove box) to result in a sealed cavity with a small amount of Rb^{87} . This forms the Rb^{87} plasma lamp for optical pumping into another Rb^{87}

Figure 10. Proposed Chip-scale atomic clock architecture. Two cavities filled with Rb^{87} and nitrogen buffer gases are required. The RF interrogation requires a SiN membrane with RF coils or micromechanical choppers to project B field into resonance cell.

resonance cell (top cavity in figure 10). A radioactive thin film of Nickel⁶³ (Ni^{63}) can be used to project electrons in to the lamp cavity that induce optical transitions resulting in photons [5]. A RF coil integrated underneath the lamp cavity could be used to generate regulated plasma. The Allan deviation, $\sigma_y(\tau)$ of the atomic clock is expected to be

$$\sigma_y(\tau) \propto \frac{1}{Q \times S / N \times \sqrt{\tau}},$$

where Q is the physics package quality factor, S/N ratio is the signal to noise ratio dominated by the photo detector for light absorption, and τ is the integration time. Given the measured Q with 1 kHz linewidth is 7.14×10^6 , and the required Allan deviation is 10^{-11} integrated over one hour, the signal to noise ratio required is 233. Our estimate is that in the case of shot noise limited optical detection, the required number of photons detected is 10^{10} photons/seconds or approximately 2.5 nW of optical power. This flux should be obtainable from the kinetic energy emitted from a 1-5 mCi radioactive source. The micro magnets are integrated into the cavities to create a magnetic field in the cavity that increases the residence time of the projected electrons in the lamp cavity, thereby increasing the plasma efficiency. The preliminary results we have obtained so far from the analysis and simulations of the proposed structure are merely a feasibility study and the results would be reported elsewhere. Further, the results underscore the importance of developing an inexpensive way of fabricating Rb cells for CSAC.

CONCLUSIONS

The main accomplishment presented in this paper is the realization of sub-1 kHz linewidth for a batch fabricated Rb^{87} /nitrogen cells. A process flow utilizing wax sealing was developed to address the conflicting requirements of vacuum filling and low-temperature sealing of microfabricated resonance cell. The rubidium hyperfine linewidth was measured using a RF-interrogation technique implemented using a commercial RF cavity used in commercial atomic clocks. The high quality factor obtained for the chamber confirms the possibility of achieving CSACs.

ACKNOWLEDGEMENTS

This project was funded under DARPA-MTO CSAC program. This research was conducted in part at the Cornell Nanofabrication facility, and Frequency Electronics, Inc.

REFERENCES

1. L. Lewis and M. Feldman, "Optical pumping by lasers in atomic frequency standards" *Proceedings 35th Annual Freq. Control Symp.* USAERADCOM, May 1981, pp. 612-624.
2. J. Kitching, S. Knappe, M. Vukicevic, L. Hollberg, R. Wynands, W. A. Weidmann, "Microwave frequency reference based on VCSEL-driven dark line resonances in Cs vapor", *IEEE Transactions on Instrumentation and Measurement*, Vol. 49, (6), 2000 pp. 1313 - 1317
3. M. Hashimoto, M. Ohtsu, "Experiments on a semiconductor laser pumped rubidium atomic clock", *Quantum Electronics*, IEEE Journal of, Volume: 23, Issue: 4, Apr 1987 pp. 446 - 4511.
4. H. E. Williams, T. M. Kwon, and T. McClelland, "Compact rectangular cavity for rubidium vapor cell frequency standards", *Proc. 37th Annual Frequency Control Symposium*, 1983; New York, IEEE, 1983, xi+529 pp. 12-17.
5. Hang Guo, Amit Lal, "Self-powered photon source", *TRANSDUCERS*, 12th International Conference on Solid-State Sensors, Actuators and Microsystems, June 2003, Vol. 2 pp. 1474 - 1477.