NEW VAPOR CELL TECHNOLOGY FOR CHIP SCALE ATOMIC CLOCK

A. Douahi, L. Nieradko, J.C. Beugnot, J.Dziuban, H. Maillote, R. Boudot, S. Guérandel[*], M. Moraja [⌘], C. Gorecki, V. Giordano.

Institut FEMTO – ST UMR 6174 CNRS – Université de Franche – Comté
32 av. de l'Observatoire, 25044 Besançon Cedex, France

[*]SYRTE. UMR 8630 – Observatoire de paris 61 av. de l'Observatoire
75014 Paris, France

[⌘] SAES Getter viale Italia 20020 Lainate, Italy

***Abstract*—Microfabrication techniques are used to realise an original cesium vapor microcell (1mm^3). This microcell has a very stable cesium vapor which is generated after the cell is sealed. In addition the microfabrication techniques used allow a production at the industrial scale and in an economic way. The applications aimed are chip scale atomic clocks (CSAC).**

I. INTRODUCTION

The development of highly miniaturized, battery powered atomic frequency references based on micromachining techniques would enable significant advancements in telecommunication and satellite navigation systems. This new category of atomic frequency standard uses an extremely compact vapor of alkali atoms (cesium or rubidium) whose ground state hyperfine transition is used as a frequency reference. A mixture of buffer gases is also introduced in the microcell to prevent resonance line broadening.

The aim of our studies in progress is the demonstration of frequency instability lower than 1×10^{-11} and exactitude of the same order in a volume about 10cm^3. In this category, we find well-known commercial rubidium clocks with several performances levels. The stability of these devices is typically about 1 to 3×10^{-11} in the short term and of 3×10^{-11}/month [1]. The interaction between the atomic vapor and the interrogation signal at 6.8GHz is carried out in a cylindrical cavity whose dimensions are large. And thus the volume of the most compact units is about 0.2dm^3. Using the principle of coherent population trapping (CPT), makes possible to realise very compact atomic clocks with reliable results [2].
CPT resonance is observed in a cesium or rubidium vapor excited simultaneously by two coherent laser radiations linking the two ground state hyperfine levels to the same excited level. This can be realised on a laboratory test bench by using, for instance, two phase-locked laser diodes. The applied modulation induces two optical lines in the output laser spectrum. The frequency separation between these two lines is equal to the double of the modulation frequency. When the latter is equal to the one-half to clock transition frequency, the resonance condition is realised and the absorption presents a minimum. The photodiode signal is used to stabilise the local oscillator modulating the laser. The frequency CPT standard does not require a microwave cavity to probe the atomic resonance authorizing the very compact physical package of the clock. The micro-clock performance depends drastically on the quality and on the long term stability of the alkali vapor and the ability to fill the microcell with accurate buffer gas pressure.

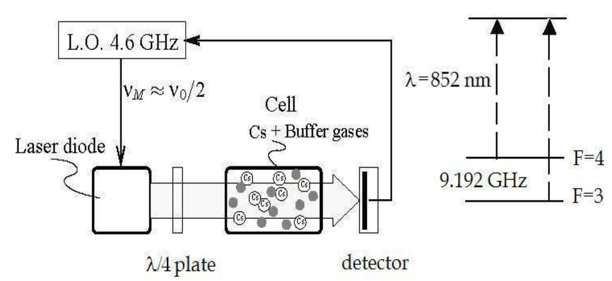

Fig.1 – Schematic of a modulated CPT-based atomic clock.

Several prototypes of CSAC have been already demonstrated [4, 5]. In these devices, the alkali metal vapor microcell is formed by sandwiching a silicon wafer with a through-hole between two glass plates and joining silicon and glass plates by means of anodic bonding thus formed a sealed cavity of about 1mm^3. The main difficulty for the microcell fabrication is to fill it with the alkali vapor and the appropriate buffer gas mixture while preserving compatibility with most of the subsequent steps of the cell fabrication, and in particular with the anodic bonding sealing the cavity.

II. Microcell Fabrication With Cesium Metalic Dispenser

We propose a microfabrication method for filling the microcell based on the cesium vapor generation from a solid Cs dispenser commercialised by the company SAES Getters [6]. The microcell proposed in this paper is formed in a silicon wafer with two glass wafers bonded to both sides, containing two cavities, as shown in Fig. 2.

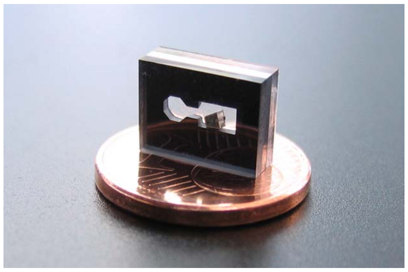

Fig. 2 – Cesium microcell

The first cavity contains the metallic Cs dispenser. The second cavity constitutes the vapour cell where the laser beam interacts with atoms. The laser beam of a VCSEL laser diode passes through the window to excite cesium atoms. Both cavities are connected by a filter. The internal volume of the microcell does not exceed 5.5 mm^3. The length of the microcell is determined by the thickness of the silicon wafer used.

The choice of microcellule length is not an easy task, because the frequency long-term stability depends on the interaction time and consequently on the size of the microcellule. Thus there is a compromise to make between the miniaturization and the performance of the micro atomic clock. The expected frequency stability of the Chip Scale Atomic Clock (CSAC) is given by :

$$\sigma_y(\tau) = \frac{1}{Q(S/N)\sqrt{\tau}}$$

Where Q is the atomic resonance quality factor, (S/N) is signal-to-noise ratio and τ is the integration time. Q and S/N depend on the dimensions of the cell. According to the literature, 10^{-11} frequency stability at 1s can be achieved with a cell length of 1mm [7]. In our case the silicon wafer thickness is 1400µm.

III. Microfabrication Steps

The two cavities are realised using the Deep Reactive Ions Etching in a 3'' (100) oriented silicon wafer, 1400µm thick and double-side polished. A hard mask of NiCr is deposited on both sides of silicon to protect the silicon wafer again SF_6 ions. The areas of the silicon wafer treated with the photolithography will be sensitive to the SF_6 ions and thus etched (see Fig. 3-a). The DRIE is carried out in two times, in the first time, the front side is etched until a depth of 800 µm to produce an aperture having the microcell cavities shape. The back side is etched in second time to remove the remainder matter and thus to finish the patterned window illustrated in Fig. 3-b.

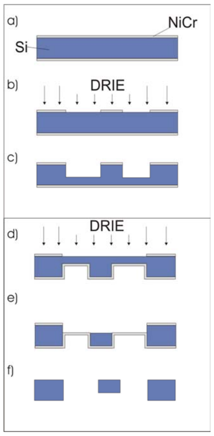

Fig. 3-a – Steps of Deep Reactive Ions Etching to realise the microcell cavities

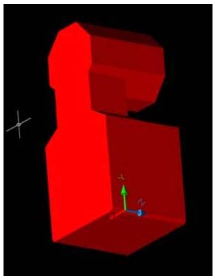

Fig. 3-b – The shape of the microcell cavities

The second step of the microcell fabrication consists to use twice the Anodic Bonding technique at a vacuum about 10^{-5}mbar. For the first Anodic Bonding, Glass (Borofloat 33, Schott) and silicon wafers are heated at 350°C and placed between two metal electrodes. A high DC potential ~1000V is applied between the electrodes creating an electrical field. The electrical field at elevated temperature allows connecting the molecules of both wafers (see Fig. 4-a). When a vacuum about 10^{-5}mbar is obtained in the Anodic Bonding chamber, the top glass is finally bonded (see Fig. 4-b). After the second

Anodic Bonding, the microcell is completely sealed and cesium atoms stay in the solid state (see Fig. 4-b).

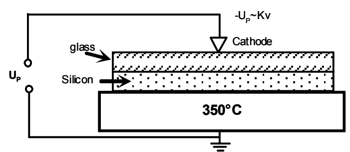

Fig. 4-a – Anodic bonding principle

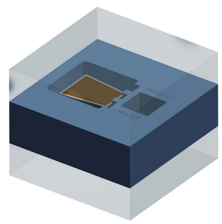

Fig. 4-b – The microcell sealed with a solid cesium dispenser in the dispensing cavity

IV. Solid Cesium Metalic Dispenser

Solid metallic cesium dispensers are small source of cesium atoms, available in wires. These wires are normally used for the preparation of photocathode. The cesium dispenser is a mixture of a cesium metal chromate Cs_2CrO_4 with reducing agent (St101). The pill cuted from a wire is about $1mm^3$, containing about 0.5mg of cesium atoms [6]. The heating at 800°C starts the oxidoreduction reaction between the chromate and the St 101 alloy and subsequently the cesium is evaporated.

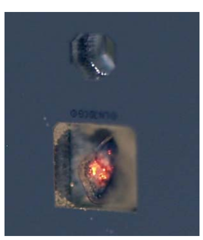

Fig. 5-a – The bright red spot resulting from the laser heating

The heating is released by focusing a laser beam on the pill. We used a 1455nm CW Raman fibre laser delivering about $2W/mm^2$. The laser is collimated onto the dispenser about during 5min (see Fig. 5-a). After the chemical reaction, liquid cesium forms a metal thin-film layer on the inner glass window, as shown in Fig. 5-b.

Fig. 5-b – Cesium atoms deposition on the glass surface

V. D2 Line Spectroscopy In Microcell

Optical absorption measurements are used to test the presence of Cs atoms in the microcell. VCSEL laser beam is sent through a microcell containing cesium atoms. The laser frequency is swept around the D2 transition - 852 nm. The cesium microcell is heated between 30 and 100°C and the laser intensity is measured by photodiode detector connected to an oscilloscope.

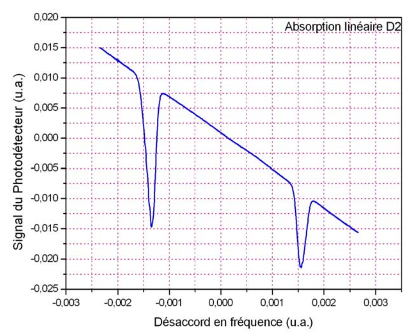

Fig. 6-a – Two absorption signals separated by 9.2GHz

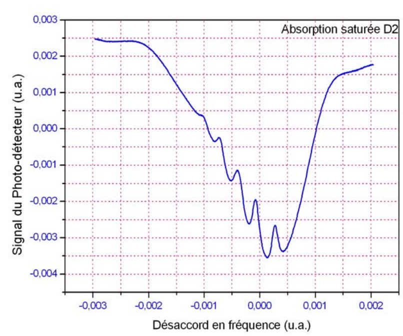

Fig. 6-b – Hyperfine transition between |F=4> and the excited state $6P_{3/2}$ of cesium atom

Two optical transitions occur, $|F=3\rangle \rightarrow 6P_{3/2}$ and $|F=4\rangle \rightarrow 6P_{3/2}$ separated by the frequency splitting of the lower states. The pumping of atoms from the two levels of the fundamental state towards the excited state creates a loss of energy of the laser beam. The two experimental transitions of the D2 line are shows in Fig. 6-a.

It's also possible to realised saturated absorption spectroscopy on our microcell, The Fig.6-b shows the aturated absorption signal corresponding to the |F=4>→$6P_{3/2}$ transition. The microcell was heated at 60°C. All the resonances are well defined.

VI. CPT MESUREMENTS

The manufacture of the cesium microcells is intended for miniature atomic clock applications. Therefore, in order to validate definitively our microfabrication technique, we were interested by coherent population trapping (CPT) resonances. The experimental set-up is shown in Fig. 7-a. The cesium microcell is enclosed in a small thermostat whose temperature can be adjusted between 30 and 100°C. The first laser spectrally narrowed below 100 kHz is swept across the D1 atomic transition (894nm) and other laser is shifted by the frequency of the hyperfine separation 9.192GHz. Both lasers are locked in phase in order to assure perfect phase coherence between them.

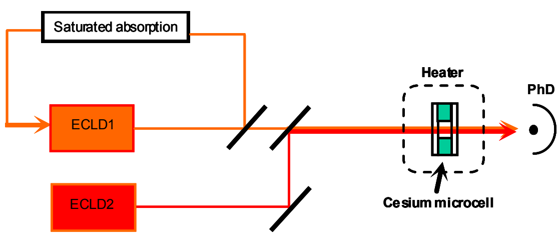

Fig. 7-a – Optical bench schema of coherent population trapping spectroscopy

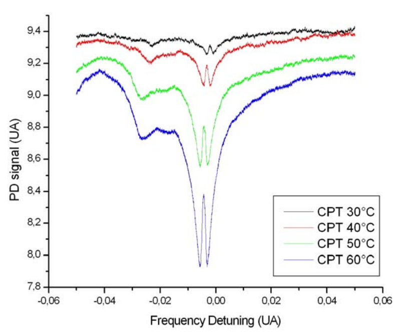

Fig. 7-b – Coherent population trapping signals at different temperatures between 30 and 60°C

The CPT resonances obtained The CPT resonances obtained for different microcell temperatures are shown in figure 7-b. The CPT resonances are well defined, demonstrating the quality of the microcell. The microcell does not contain buffer gas and is not then adapted for a clock operation owing to the large broadening of resonance line. The introduction of a controlled buffer gas pressure will be made in the near future. To define the reliability of our fabrication technique over the long term, the realised microcells have been tested periodically for six months and any signal degradation has been observed.

VII. CONCLUSIONS AND PERSPECTIVES

New vapor microcell technology for Chip Scale Atomic Clock is demonstrated. The original idea to use a source of cesium in a solid state which allows to use the anodic bonding method at a high temperature without disturbing the internal atmosphere of the microcell.

The inclusion of a controlled buffer gases pressure will be the next step of this work, improving the stability of future CPT atomic micro-clocks.

ACKNOWLEDGMENT

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