

Amélioration de la technologie de microcellule de FEMTO ST : machine de soudure anodique dédiée

Improvement of micro-cell technology at FEMTO-ST: dedicated anodic bonding machine

Porteur(s) : R. Boudot, C. Gorecki (FEMTO-ST)

Partenaire(s) : S. Guérandel (SYRTE)

Résumé du projet en Français :

Nous visons à nous équiper d'un système de soudure anodique dédié pour la fabrication de nos microcellules à vapeur de césium, cœur de microhorloges atomiques. Dans ces dernières, il est primordial d'obtenir à la fois un scellement étanche en présence de vapeurs de Cs et de gaz tampon, une pression de gaz tampon contrôlée de façon rigoureuse et précise et un scellement de la cellule à une température relativement basse. La machine dont nous disposons au laboratoire ne permet pas de répondre de manière rigoureuse à l'ensemble de ces requêtes. Ainsi, une nouvelle machine de soudure sera réalisée, opérant à basse température, dotée d'un capteur de pression in situ et permettant un allongement précis de wafers constituant la microcellule.

Abstract in English:

Atomic frequency references deliver high-precision and stable signals on long integration times because their frequency is determined by an atomic transition frequency. During many years, the deployment of atomic clocks in mobile applications has been prevented due to their large size and power consumption. Over the last decade, many efforts have been produced to develop miniature atomic clocks combining a typical volume of 15 cm³, a power consumption of 100 mW and a fractional frequency stability better than 10⁻¹¹ at 1 day integration time.

In 2007, FEMTO-ST has proposed the development of an original Cs vapor microcell technology, heart of miniature atomic clocks. This microcell consists of a glass-silicon-glass sandwich where glass wafers are anodically bonded to each side of a silicon wafer.

The goal of this project is to acquire an anodic bonding machine equipment dedicated to the fabrication of our microcells. This equipment will ensure a hermetic sealing of the cell and an accurate in-situ control of the buffer gas pressure

Résultats marquants :

Le procédé de soudure anodique à FEMTO-ST a été significativement amélioré grâce à ce projet. Cette machine dédiée est un équipement clé et central pour le développement des microcellules à FEMTO-ST. Cette amélioration a permis d'améliorer nettement la maturité et la viabilité de notre technologie. Cette technologie de cellule est aujourd'hui clairement reconnue à l'international, transfère industriellement à l'industriel Tronics Microsystems.

Les améliorations majeures sont : meilleur dégazage avant le scellement de la cellule, tubes inox dédiés, implémentation d'une jauge de pression (0.1 Torr) pour un meilleur contrôle de la pression de gaz tampon.

Les cellules présentent désormais une pureté de gaz améliorée (99.84% au lieu de 98.75% auparavant) et une accélération significative du procédé de soudure anodique, réduit à environ 2 heures désormais.

En ce sens, cette machine est associée à l'ensemble de nos publications sur les résultats de microcellule depuis la date du projet.

Highlights:

The anodic bonding process in FEMTO-ST has been significantly improved thanks to this project. This dedicated new machine is the central key element and equipment for the development of microfabricated cells in FEMTO-ST. This upgrade has allowed to improve significantly the maturity and viability of our cell technology. This cell technology is clearly today internationally-recognized and now industrially-transferred to Tronics Microsystems. Main improvements are:

- Better outgassing before sealing

- Stainless steel tubing
- Implementation of an in-situ 0.1 Torr accurate pressure gauge for better control of the buffer gas pressure. The consequence is an improved gas purity of the micro-fabricated cells inner atmosphere: 99.84 % (98.75 % previously) and a significant acceleration of the anodic bonding process (<2 hours).
In that sense, this machine is connected to all of our last publications in the domain of the microcell technology (listed below).

Publications and communications linked with the funded project:

Peer-reviewed articles:

- 1/ X. Liu, J. M. Merolla, S. Guérandel, C. Gorecki, E. De Clercq and R. Boudot, Phys. Rev. A **87**, 013416 (2013).
- 2/ F. Gruet, E. Kroemer, L. Bimboes, D. Miletic, C. Affolderbach, A. Al-Samaneh, D. Wahl, R. Boudot, G. Mileti and R. Michalzik, Optics Express **21**, 5, 5781-5792 (2013).
- 3/ X. Liu, J.M. Merolla, S. Guérandel, E. De Clercq and R. Boudot, Optics Express **21**, 10, 12451-12459 (2013).
- 4/ M. Hasegawa, R. K. Chutani, R. Boudot, L. Mauri, C. Gorecki, X. Liu and N. Passilly, J. Micromech. Microeng. **23**, 055022 (2013).
- 5/ E. Kroemer, M. Abdel Hafiz, V. Maurice, B. Fouilland, C. Gorecki and R. Boudot, Opt. Express **23**, 14, 18373-18380 (2015).
- 6/ R. Chutani, V. Maurice, N. Passilly, C. Gorecki, R. Boudot, M. Abdel Hafiz, P. Abbé, S. Galliou, J. Y. Rauch and E. De Clercq, Nature Sci. Rep. **5**, 14001 (2015).
- 7/ T. Daugey, J. M. Friedt, G. Martin and R. Boudot, Rev. Sci. Instr. **86**, 114703 (2015).
- 8/ E. Kroemer, J. Rutkowski, V. Maurice, R. Vicarini, M. Abdel Hafiz, C. Gorecki and R. Boudot, Applied Optics **55**, 31, 8839-8847 (2016).
- 9/ R. Boudot, G. Martin, J. M. Friedt and E. Rubiola, Journal of Applied Physics **120**, 224903 (2016).
- 10/ V. Maurice, J. Rutkowski, E. Kroemer, S. Bargiel, N. Passilly, R. Boudot, C. Gorecki, L. Mauri and M. Moraja, Appl. Phys. Lett. **110**, 164103 (2017).

Patents and licenses:

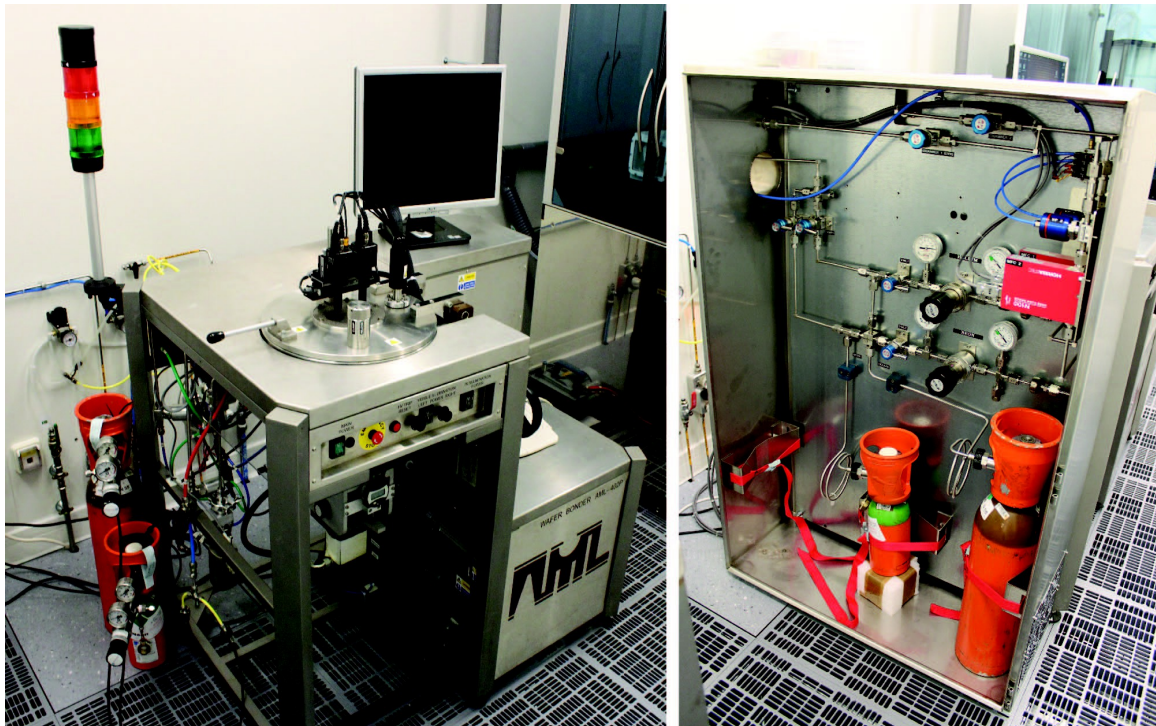
1. N. Passilly, C. Gorecki, R. Chutani, R. Boudot, *Alkali metal vapour cell, especially for an atomic clock, and manufacturing process*, US Patent, 20150277386 (2015).
2. R. Boudot, E. Kroemer, C. Gorecki, B. Fouilland, V. Maurice *Caesium atomic micro-clock microcell buffer gas mixture*. US Patent, 20160109859 (2016).

Oral communications:

- 1/ M. Hasegawa, R. K. Chutani, R. Boudot, V. Maurice, L. Mauri, C. Gorecki and N. Passilly *Wafer-level integration of getters in cesium-neon cells for miniature clocks applications*, Proceedings of the European Frequency Time Forum - International Frequency Control Symposium , 21-26 July 2013, Prague (Czech Republic).
- 2/ X. Liu, J. M. Merolla, S. Guérandel, C. Gorecki, E. De Clercq and R. Boudot, *Continuous and Ramsey spectroscopy of CPT resonances in Cs vapor cells with push-pull optical pumping* , Proceedings of the European Frequency Time Forum - International Frequency Control Symposium , 21-26 July 2013, Prague (Czech Republic).
- 3/ N. Passilly, R. Boudot, R. K. Chutani, C. Gorecki, A. Al-Samaneh, D. Wahl and R. Michalzik, *Developments of miniature atomic clocks based on coherent population trapping, VCSELs and MEMS* , 2nd European Workshop on VeCSELS, Invited, 17 October 2013, Montpellier (France).
- 4/ R. Boudot, N. Passilly, R. Chutani, V. Maurice, S. Galliou, V. Giordano, C. Gorecki, *Developments of miniature atomic clocks based on coherent population trapping, VCSELs and MEMS* , French-Russian-German Laser Symposium, 4-7 November 2013, Besancon (France).
- 5/ Vincent Maurice, Ravinder Chutani, Nicolas Passilly, Rodolphe Boudot, Serge Galliou, Moustafa Abdel Hafiz, Philippe Abbé, Emeric De Clercq and Christophe Gorecki *A novel alkali vapor microcell architecture for miniature atomic clocks*, Proceedings of the European Frequency Time Forum , 04-07 April 2016, York (UK).
- 6/ Rodolphe Boudot, Gilles Martin, Jean-Michel Friedt and Enrico Rubiola *Characterization of high-overtone bulk acoustic resonators : applications to ultra-low noise microwave oscillators and miniature atomic clocks*, Microwave Technology and Technique Workshop, 03-05 April 2017, Noordwijk (The Netherlands).
- 7/ C. Calosso, B. Francois, S. Micalizio and R. Boudot, *Local Oscillators and Digital Electronics for Compact Atomic*

Clocks, Microwave Technology and Technique Workshop, 03-05 April 2017, Noordwijk (The Netherlands).
8/ D. Brazhnikov, M. Abdel Hafiz, G. Coget and R. Boudot, Analytical Expressions for Parameters of the Dark Resonance in a Vacuum Vapour Cell, EFTF-IFCS Joint Meeting, 09-13 July 2017, Besancon, France.
9/ V. Maurice, J. Rutkowski, E. Kroemer, S. Bargiel, N. Passilly, R. Boudot, R. Chutani, S. Galliou, C. Gorecki, L. Mauri and M. Moraja, Microfabricated vapor cells for miniature atomic clocks based on post-sealing activated cesium dispensers, EFTF-IFCS Joint Meeting, 09-13 July 2017, Besancon, France.
10/ R. Vicarini, J. Rutkowski, V. Maurice, E. Kroemer, S. Galliou, C. Gorecki, and R. Boudot, Characterization of 894.6 nm VCSELs and application to a microcell-based atomic clock, EFTF-IFCS Joint Meeting, 09-13 July 2017, Besancon, France.
11/ R. Boudot, V. Maurice, E. Kroemer, J. Rutkowski, M. Abdel Hafiz, S. Bargiel, N. Passilly and C. Gorecki, Ramsey-CPT spectroscopy in buffer-gas filled Cs vapor micro-fabricated cells, EFTF-IFCS Joint Meeting, 09-13 July 2017, Besancon, France.

Pictures with captions (curve, photo, scheme ...):



Anodic bonding machine used in FEMTO-ST/MIMENTO for the production of microfabricated cells.