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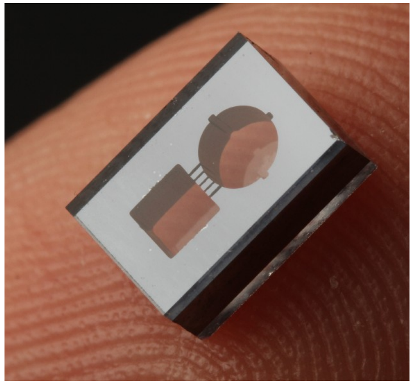
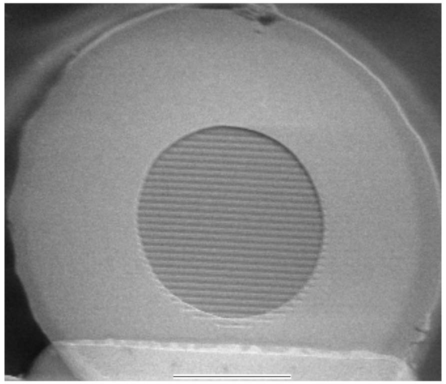
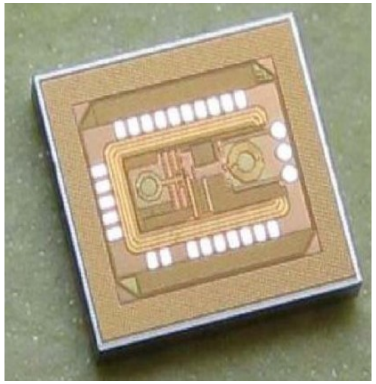
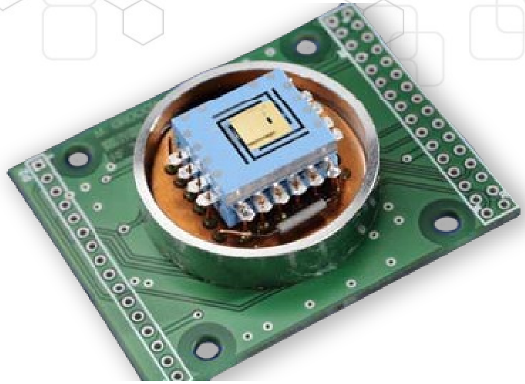






# Developments of miniature atomic clocks based on Coherent Population Trapping


***<u>Rodolphe Boudot</u>**, Nicolas Passilly, Ravinder Chutani, Vincent Maurice, Serge Galliou, Vincent Giordano, Christophe Gorecki*

*FEMTO-ST Institute, Besancon, France*


UFC cnrs ensmm utbm

# Context

The performances of numerous systems directly depend on the time or frequency reference they use.

Objectives:

Current technology = quartz crystal oscillators → reach their limit

Develop a portable, battery-powerable, stable and cheap time reference : Miniature <u>atomic</u> clock

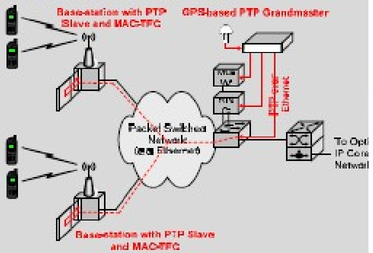
***Specifications :*** - Total volume: 10 cm3
- Power consumption: 100-150 mW
- Frequency stability performances: 10-11 @ 1h and 1 day integration (1 µs/day)

Applications:

**4G LTE base stations:**
Phase time synchronization for online TDD and MBSFN

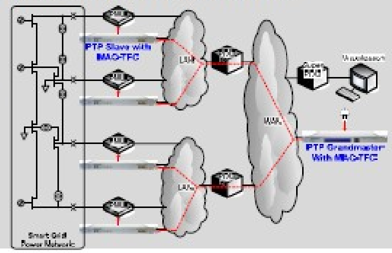
MAC-TFC
High jitter rejection
Holdover >> 24 h

Total market 500K /year




**POWER Smart Grid:**
1 µsecond synch of Phase Measurement Units

MAC-TFC
Holdover >> 24 h



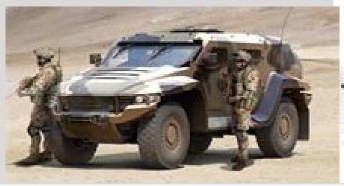

**Defense Fast localization:**
Long lasting time keeping to allow GNSS ultra fast localization

MAC-TFC:

High Accuracy Holdover >> 24 h
Battery operated, Ultra low power

Total market >> 500 K/year

cost target must be met
→ Industrial challenge




**Professional Mobile Radio :**
Phase time synchronization for online video

MAC-TFC
> 24 hours of Holdover
Low Power for Battery operation
Fast warm-up


**Seismic exploration:**
Net of free running independent clocks:

MAC-TFC
Higher frequency stability + Lower power
→ longer the undersea mission.

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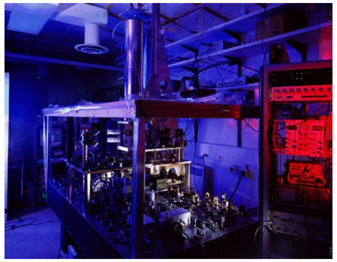
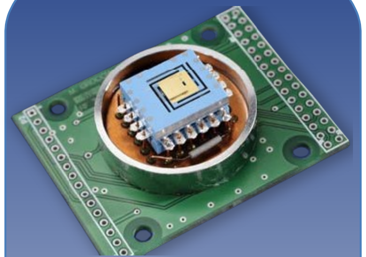
# Context

<u>Goal:</u> Bring atomic timing to the size and power range previously covered by quartz oscillators



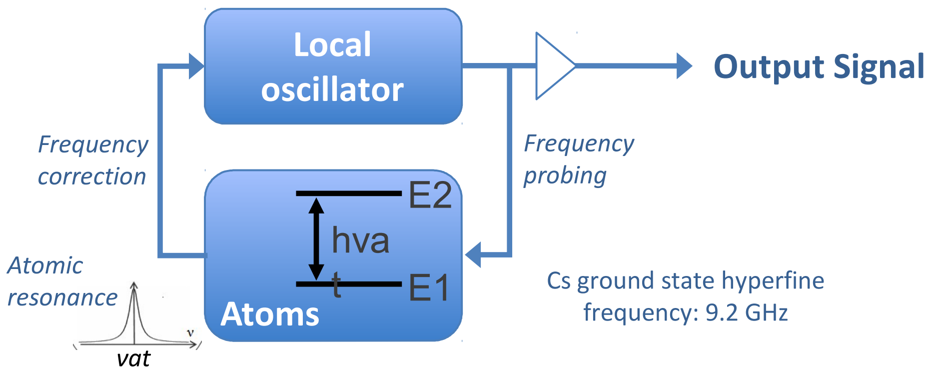




| | Cs Primary standard | Commercial Cs beam clock | Compact atomic clock | Miniature Atomic clock | Precision quartz | Wristwatch quartz |
|---|---|---|---|---|---|---|
| **Accuracy:** | 10-15 | 10-13 | 10-11 | 10-10 | 10-7 | 10-5 |
| **Timing error:** | 10ns / year | 10µs / year | 0.1µs / day | 1µs / day | 100µs / day | 1s / day |
| **Size:** | 107 cm3 | 104 cm3 | 102 cm3 | 10 cm3 | 1-10 cm3 | 10 mm3 |
| **Power:** | kW | 100’s W | 1 W | 150 mW | 100 mW | 10 µW |
| **Cost:** | >1M$ | 50k$ | 2k$ | 300$ | 100$ | 1$ |
| **Frequency stab:** | 10-14 | Few 10-12 | 10-11 | 10-10 | 10-10 | 10-9 |

Decreasing performance/size/power/cost

# Principle

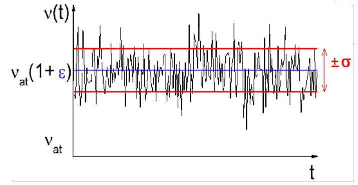
**Atomic clock**: Lock the frequency of a local oscillator onto an atomic transition frequency




Cs ground state hyperfine frequency: 9.2 GHz

Accuracy

*vosc= vat ( 1+ ε + y(t) )*

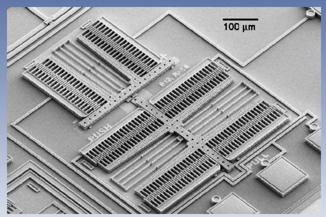



Frequency stability: signal relative frequency fluctuations (Allan deviation)

$$\sigma_{y(\tau)} = \frac{\Delta\nu}{\nu_0}\frac{1}{S/N}\tau^{-\frac{1}{2}}$$

How to miniaturize such a clock?

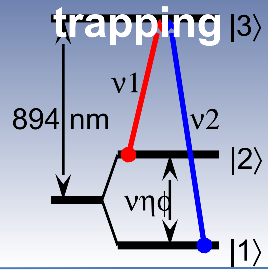
**MEMS techniques**




*Alkali atom container*

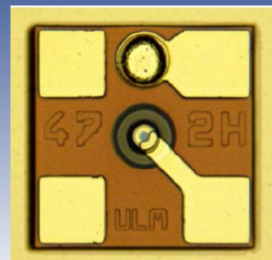
**+**

**Coherent Population trapping**




**+**

**VCSELs**

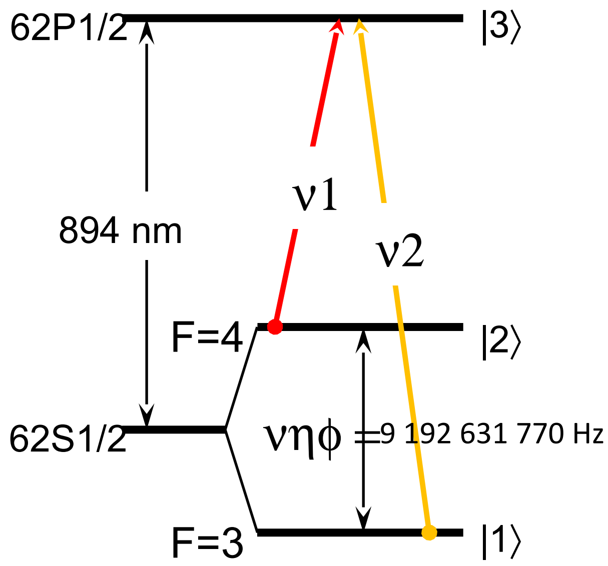


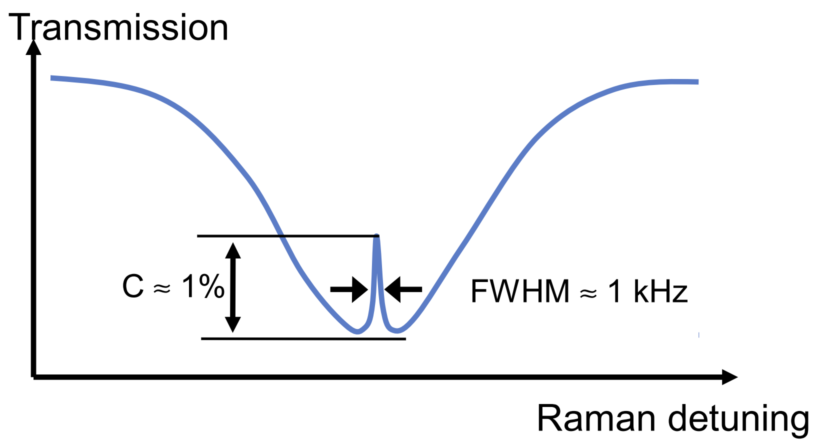
*Laser source*

« All-optical » atomic clock – No resonant cavity **Extreme miniaturization**

# CPT Principle

2 long-lived ground states connected to a common excited state using 2 phase-coherent optical lines




**Frequency splitting = ground-state hyperfine splitting**

**Dark state = CPT state** : The transparency of the atomic vapor is increased

All-optical interrogation : No microwave resonant cavity ➡ miniaturization

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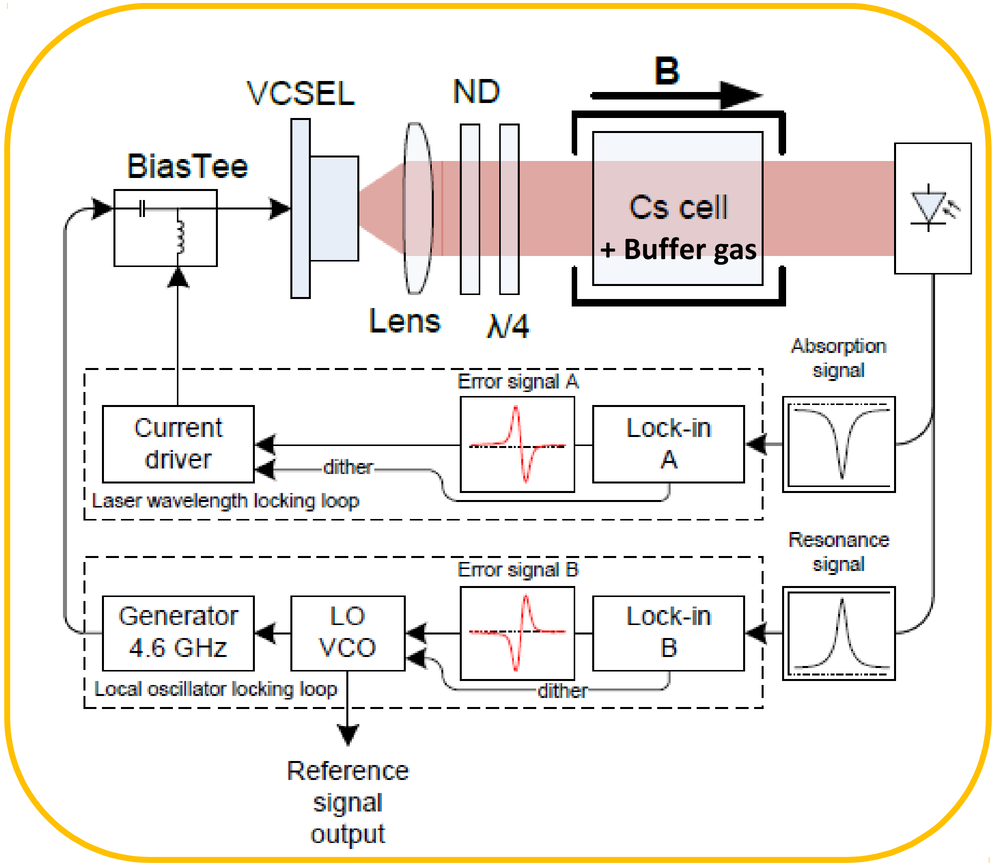
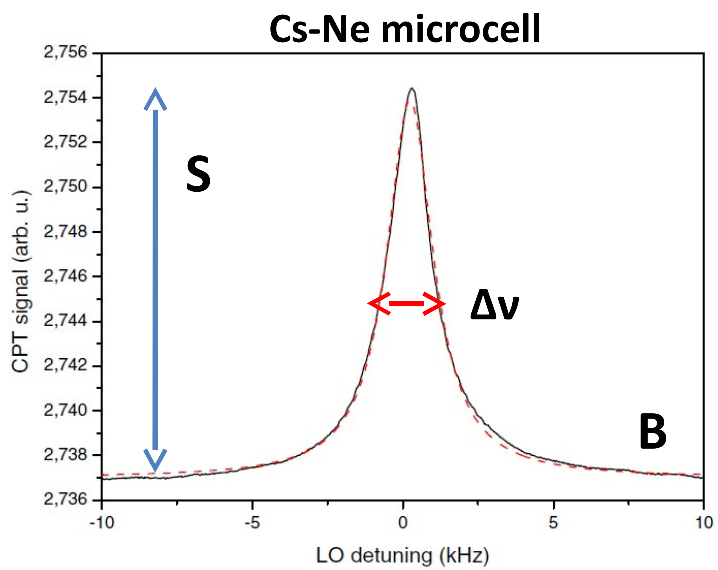
# Miniature CPT clock




**Alkali vapor cell:** - Strong sealing for long term operation
- Pure atmosphere filled with Cs and buffer gas at target pressure

**Laser:** - 2 lines at λ=894.6nm (D1) splitted by 9.2 GHz (Bias Current modulation)
- Shaped beam (collimated)
- Circular polarization state

- **Packaging/Electronics:** - Including thermal control, magnetic field generation, local oscillator, optical beam shaping, etc.




$$\mathbf{C} = \frac{\mathbf{S}}{\mathbf{B}}$$

$$\sigma_{y(\tau)} = \frac{\Delta\nu}{\nu_0} \frac{1}{S/N} \tau^{-\frac{1}{2}}$$

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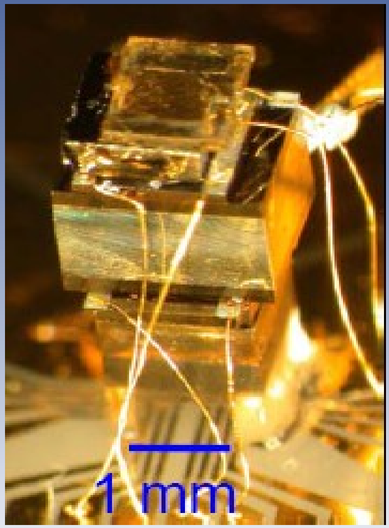
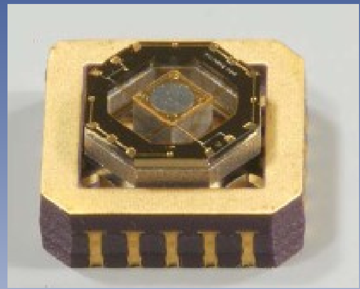
# State of the art

**NIST 2004**




**First world CSAC prototype**

**2007** **SYMMETRICOM**



16 cm3
115 mW
2 10-10 at 1s
10 MHz output

**2011**


**First commercially-available CSAC**

**Need for a European chip-scale atomic clock**

Innovative scientific and technological solutions for high-performance

Initiated by FEMTO-ST in 2005 → **MAC-TFC Project** in 2009

# Projects

MAC-TFC
Collaborative project
*2009-2012*

10 industrial and academic partners

femto-st *Coordinator*

ISIMAC
ASTRID project
*2012-2015*

2 academic partners

femto-st *Coordinator*

# Microfabricated cells - Buffer gas selection

Operation in the Dicke regime ➡ kHz-linewidth in mm-scale cells

Issue: **Temperature-dependent frequency shift of the clock transition**

1st option:

$$\Delta\nu_{bg} = P_0\left[\beta + \delta(T - T_0) + \gamma(T - T_0)^2\right]$$

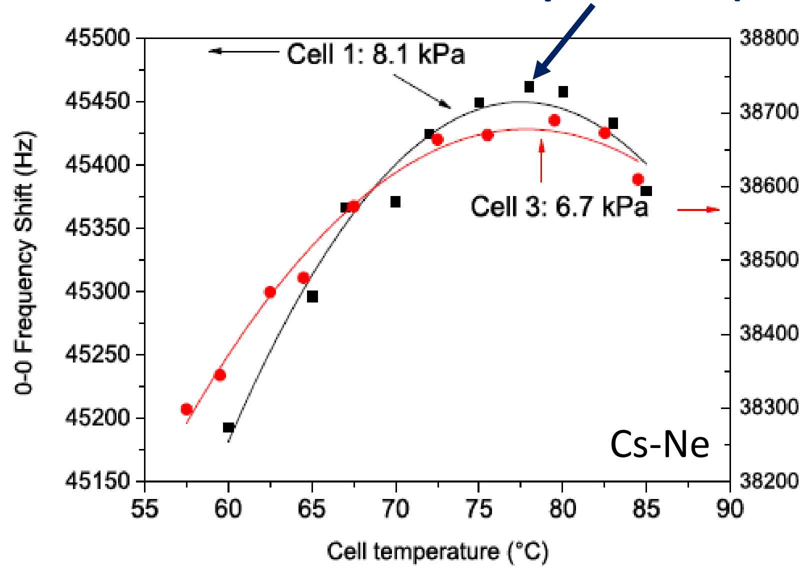
⬇

Buffer gas mixture with appropriate partial pressures for compensation

⬇

- **Difficult to control (especially in microcells)**
- **Coefficients poorly known or wide dispersion**

**Ne: Inversion temperature (~80°C)**



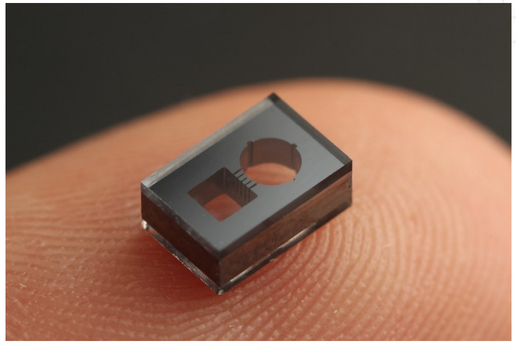

No mixtures required ➡ relaxed constraints on the buffer gas pressure control

Ne buffer gas is a good candidate for Cs miniature clocks

*D. Miletic et al., Elec. Lett., 2010*
*R. Boudot et al., Journ. Appl. Phys., 2011*

# Microfabricated alkali cells - Technology

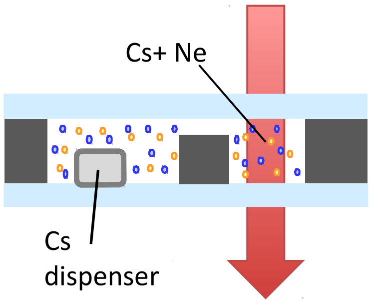
Requirements: Cs Cell with pure atmosphere and long term hermicity
- Collectively fabricated

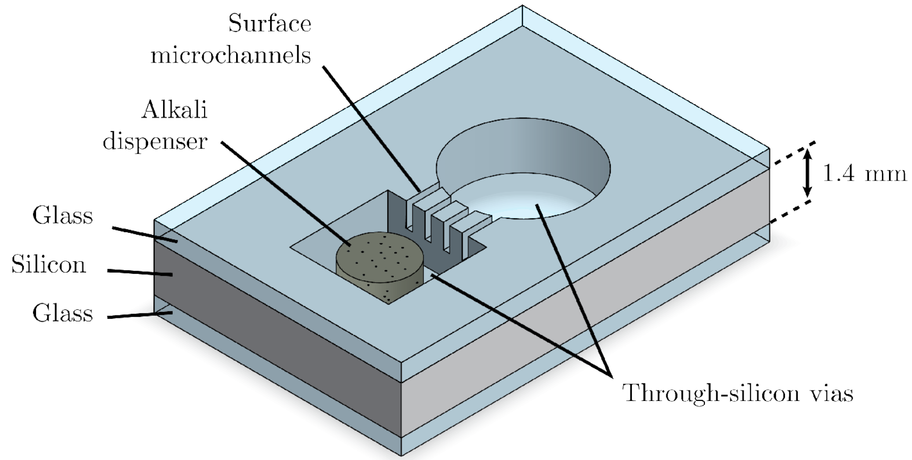


**Specificity:**

- instead of fulfilling Cs by pipetting or chemical reaction before cell sealing
  - use of functionalised **alkali dispensers** from SAES Getters
  - activation of Cs by **local laser heating** of the dispenser

**Advantage:**
*no conflict between the anodic bonding process and Cs chemistry*

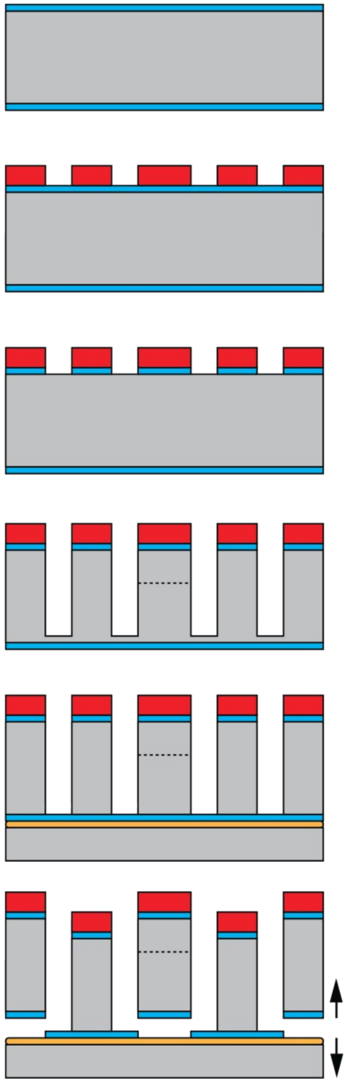


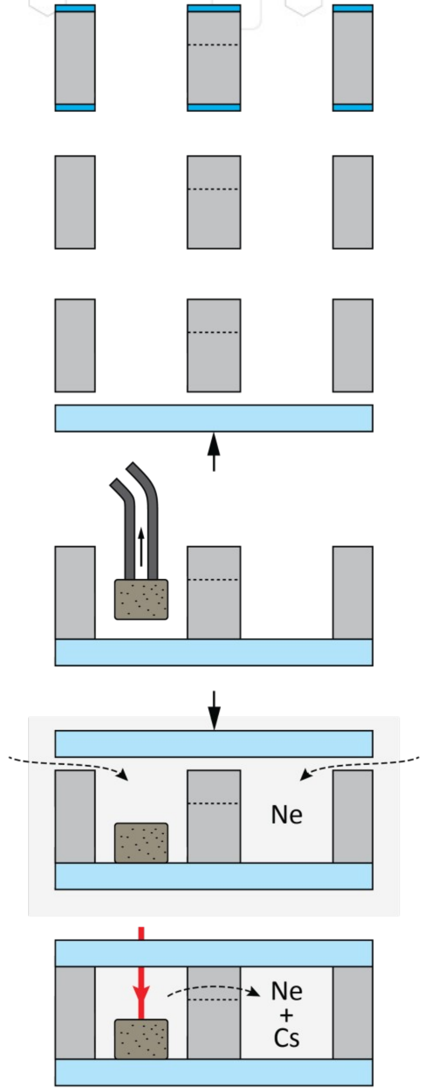

*A. Douahi et al., Elect. Lett, 2007*
*L. Nieradko et al. Micro/Nanolith. MEMS & MOEMS, 2008*

# T-cell flow-chart

1. 1.5 mm thick Si wafer + 1 µm thick thermal $SiO_2$
2. Photolithography
3. $SiO_2$ etching
4. 1st DRIE step
5. 2nd DRIE step with oil-bonded holding-wafer
6. Wafer separation and resist stripping



7. $O_2$ plasma cleaning and KOH polishing
8. $SiO_2$ stripping in HF
9. 1st anodic bonding
10. Dispenser introduction
11. 2nd anodic bonding under Ne atmosphere
12. Dispenser activation



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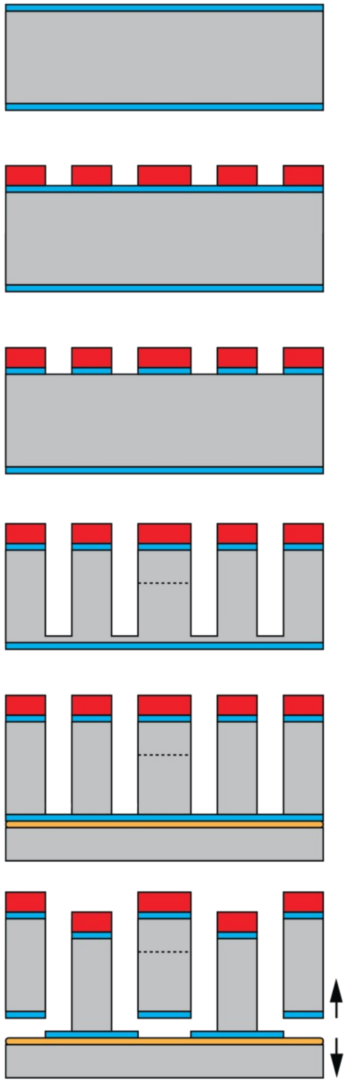

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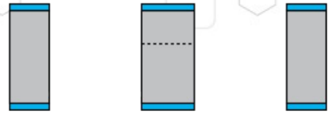
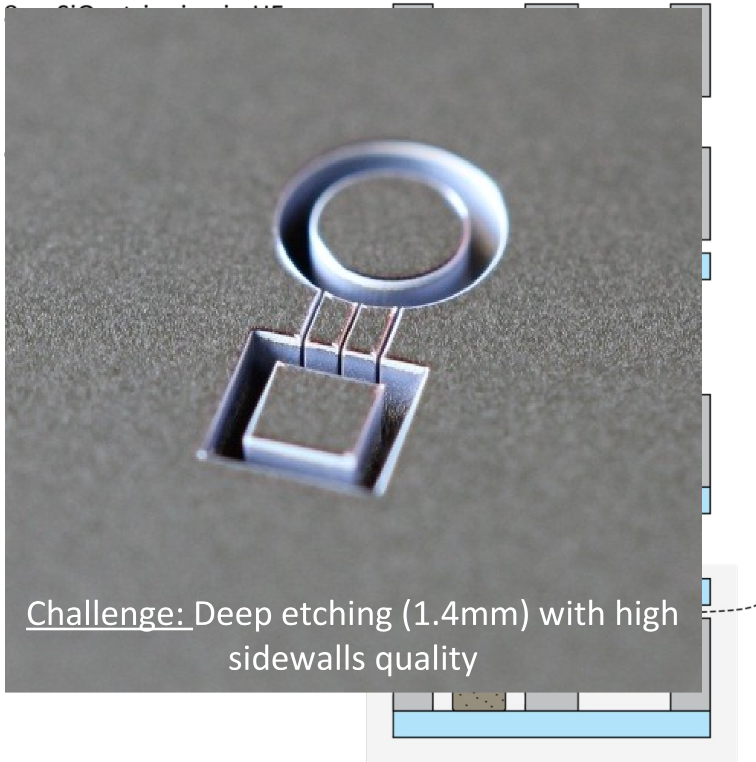
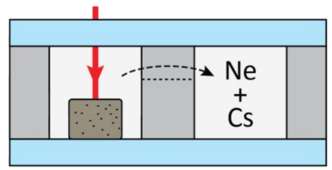





12. Dispenser activation



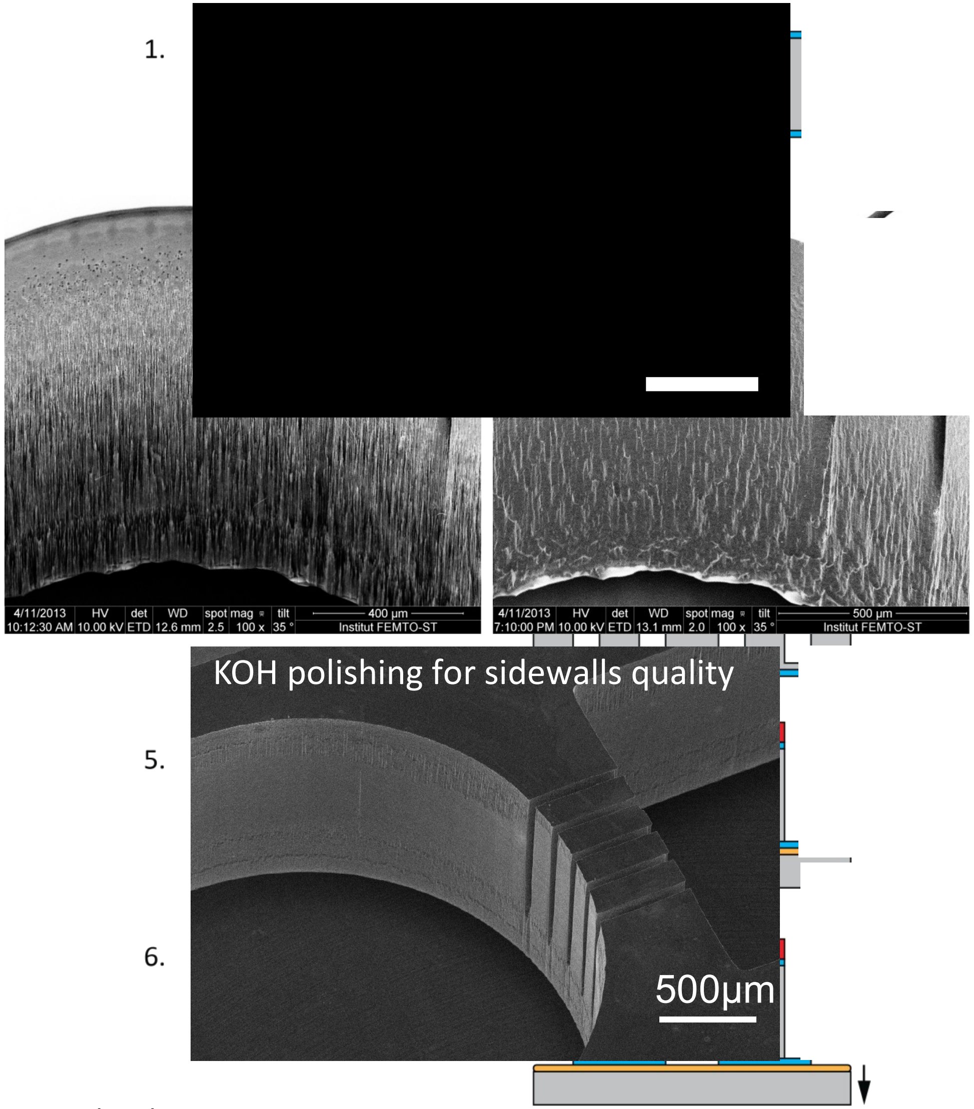

*Chutani et al. Sub. Sens Act A 2013*

# T-cell flow-chart

1.

5.

6.




*Chutani et al. Sub. Sens Act A 2013*

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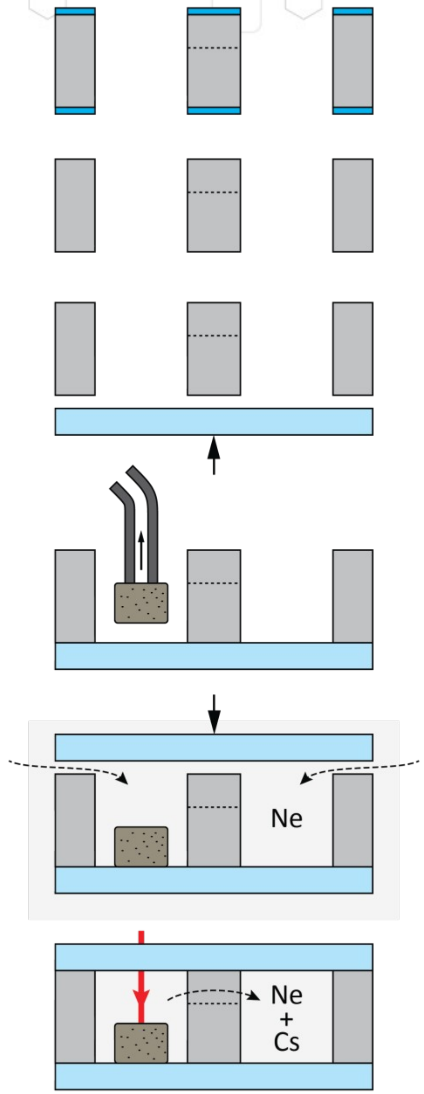

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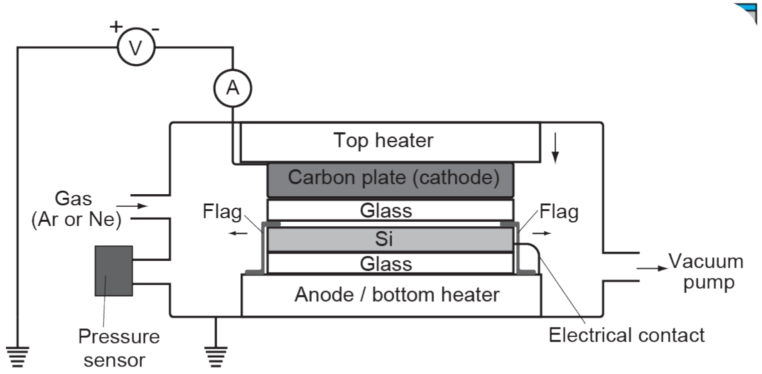
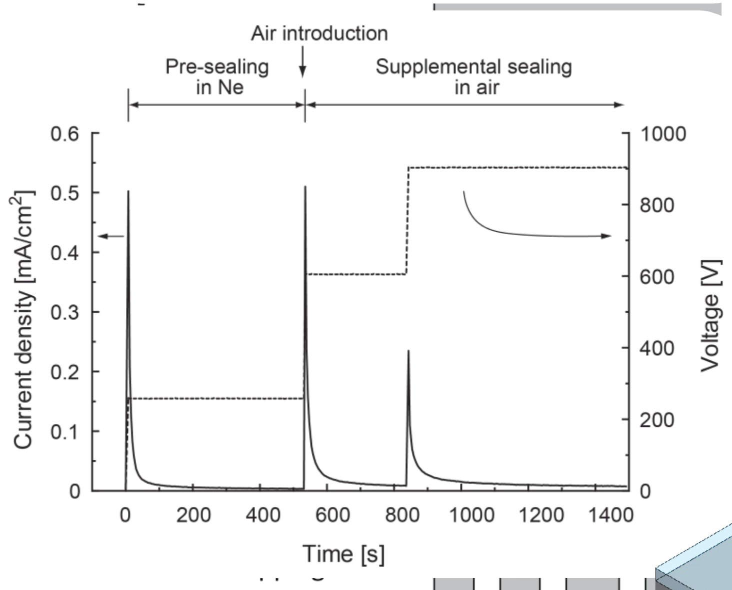
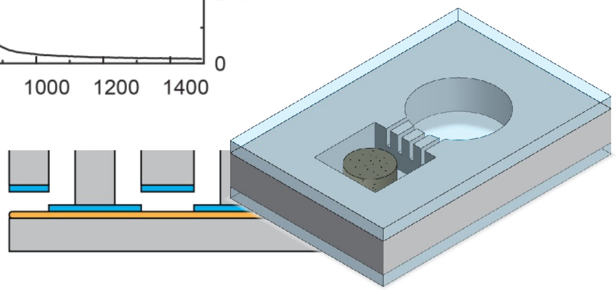



2-steps anodic bonding
Pre-sealing in Ne to avoid discharge



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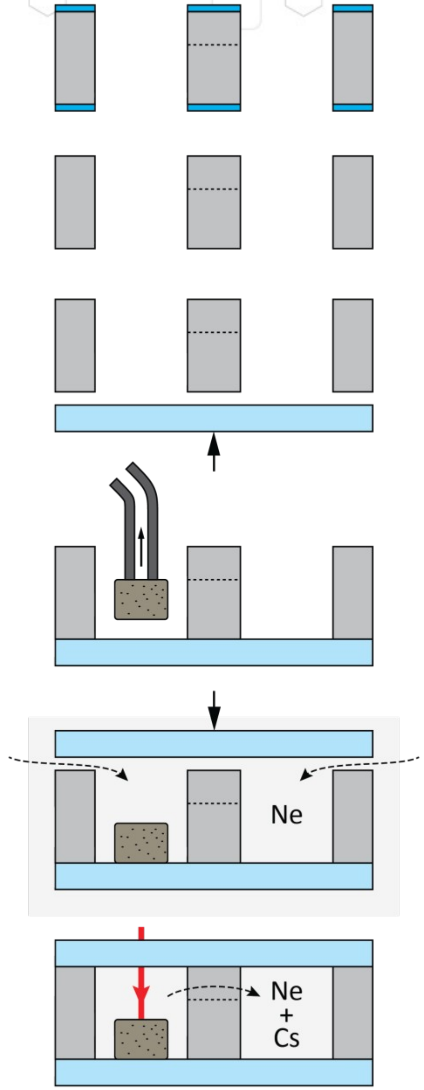


*Hasegawa et al., Sens. Act. A, 2011*

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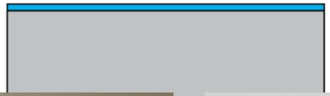
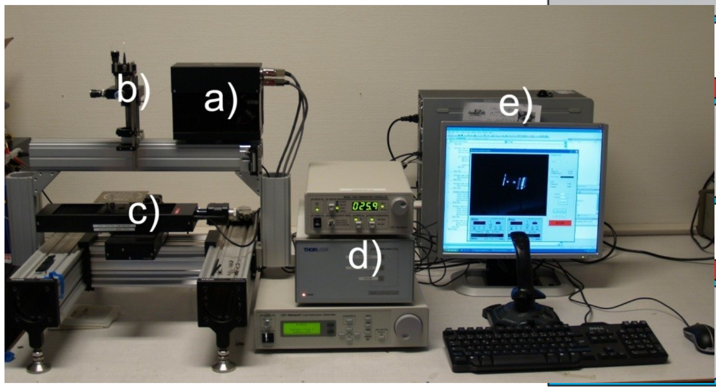
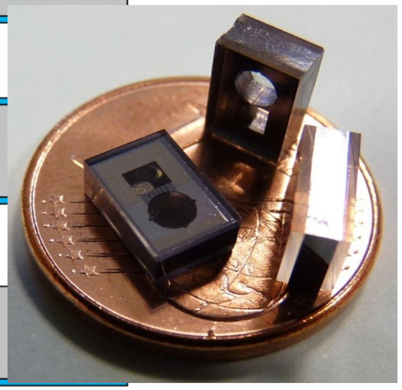


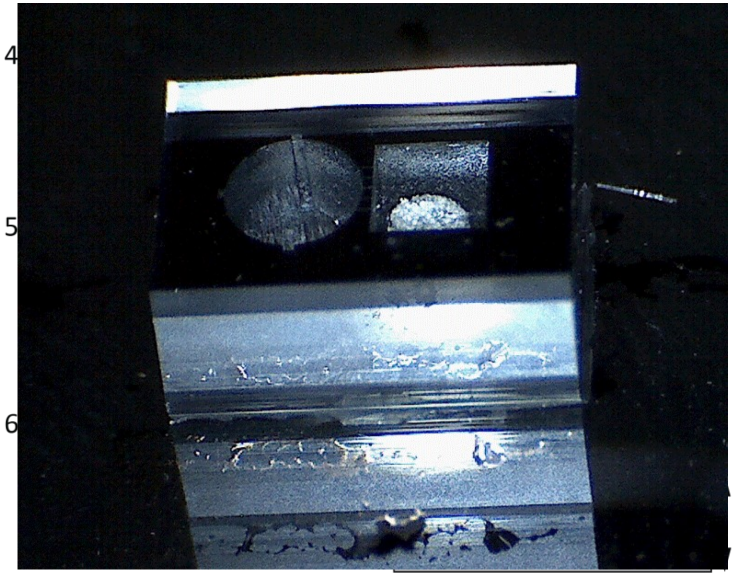


4

5

6



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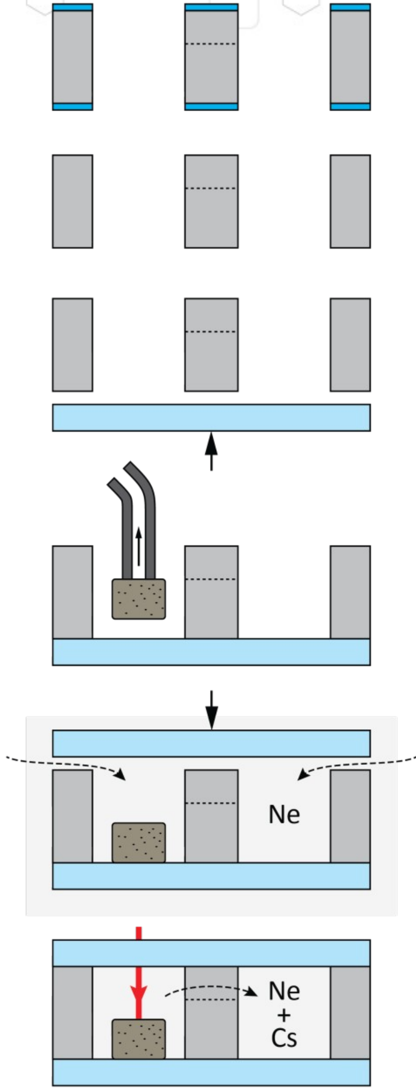
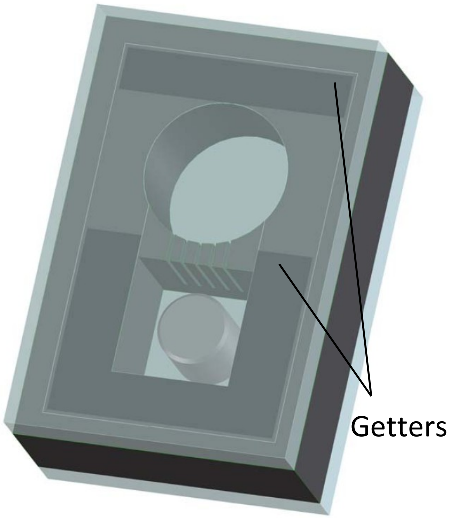
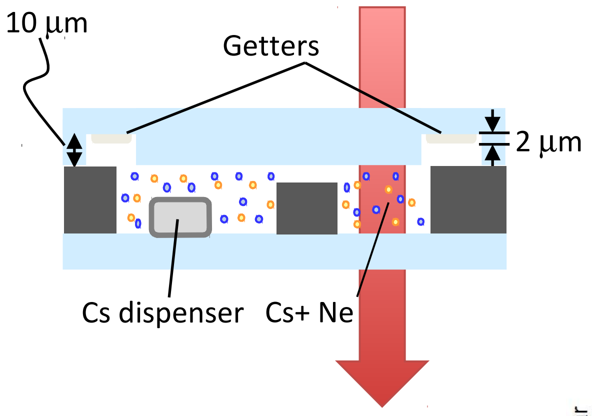


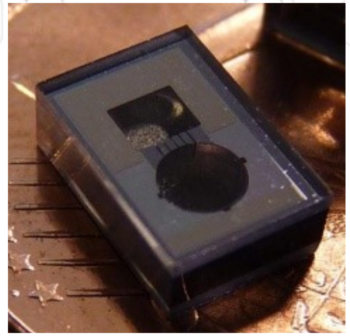
# Getters integration

Wafer-level integration technique of getter films SAES PageWafer®



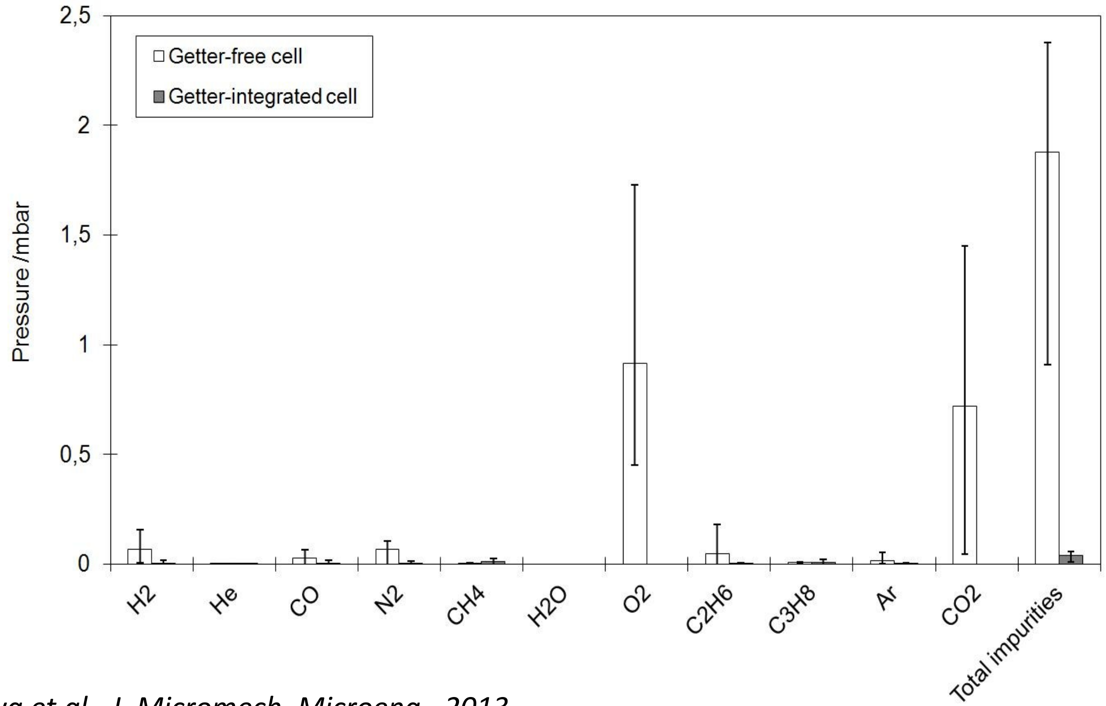

Adsorbs impurities generated during anodic bonding



**improvement of the microcell internal atmosphere**

**50x less impurities** without affecting Cs and Ne contents

*> 3 years lifetime demonstrated*




*Hasegawa et al., J. Micromech. Microeng., 2013*

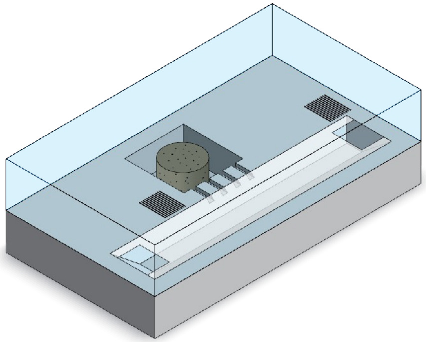
# A new architecture: R-cell

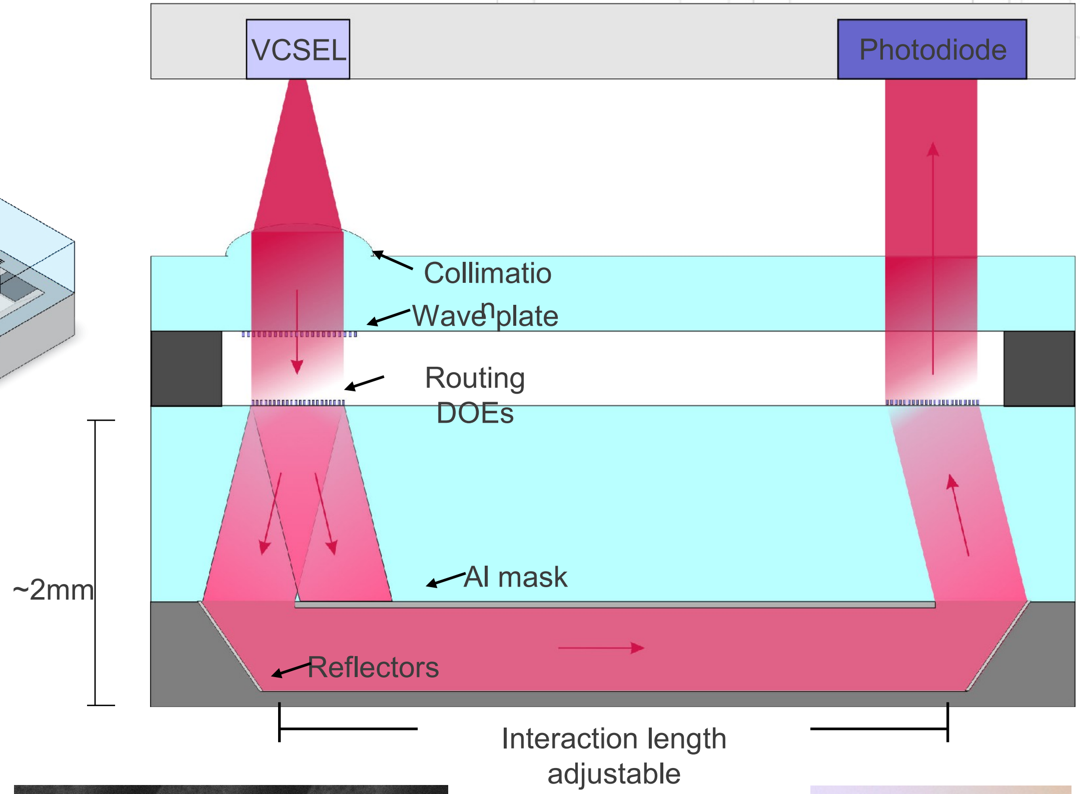
Reflection of light along a Si wet-etched cavity

➢ <u>Required components:</u>

- Diffraction gratings for routing
- Mask for diff-orders discrimination
- Coatings for efficient reflectors

**Strict vertical alignment**





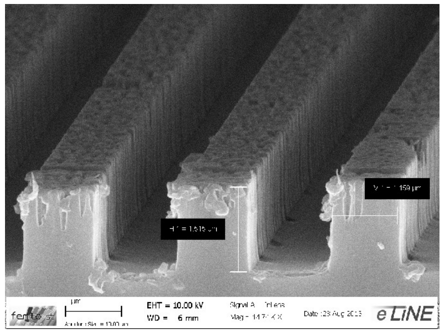

- Adjustable optical cavity
- Better thermal control
- Integration of optics at wafer level

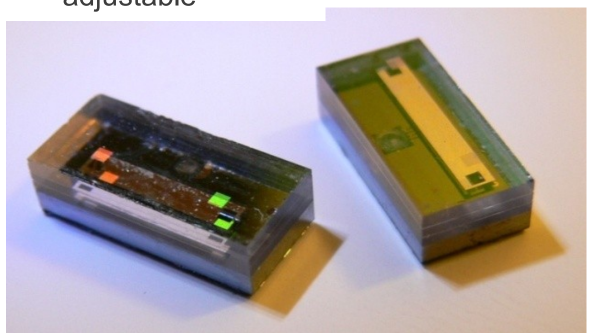
➡ **Accurate Alignments**

- Smaller beam diameter
- Laser & detector on the same plane

➡ **Reduction of overall thickness**

*Passilly et al. Patent 2012*





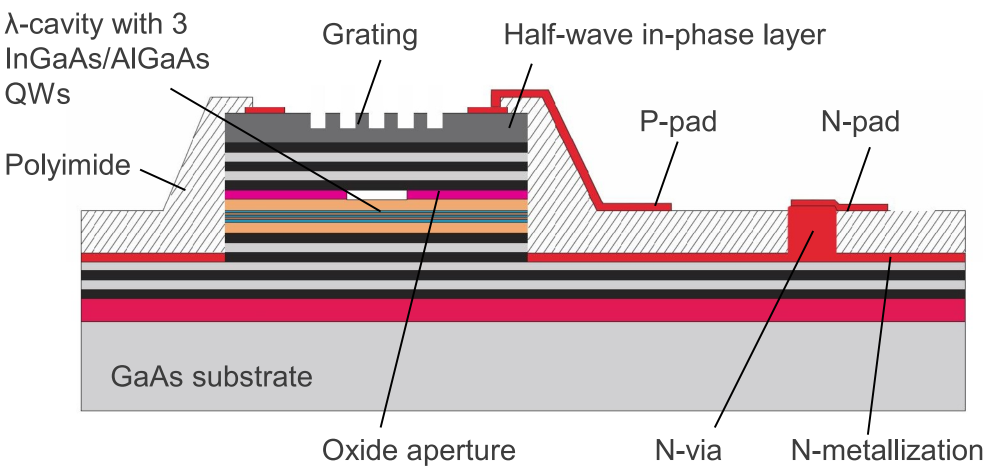
# VCSELs for atomic clocks

Requirements:

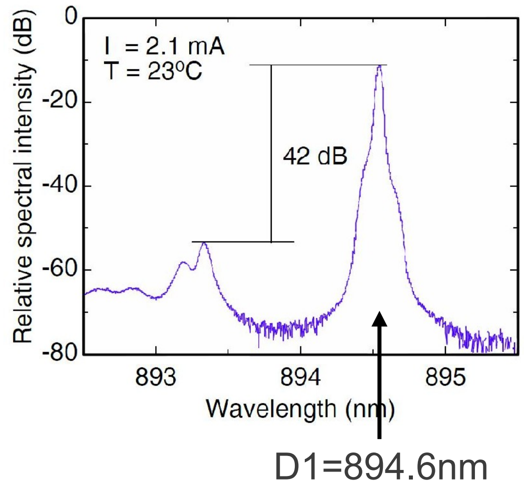
**Many!**

- **Single mode operation** at a frequency exactly equal to **D1** (preferred) or D2 lines
- **Narrow linewidth** ➡ Any frequency noise is converted to amplitude noise in the transmission signal
- **High operating temperature** (e.g. 60-80°C)
- **Flip-chip** bondable
- **Single linear polarization** operation
- **Low consumption** ➡ Low threshold current (typ. <1mA)
- **Frequency modulation** bandwidth > 4.5GHz

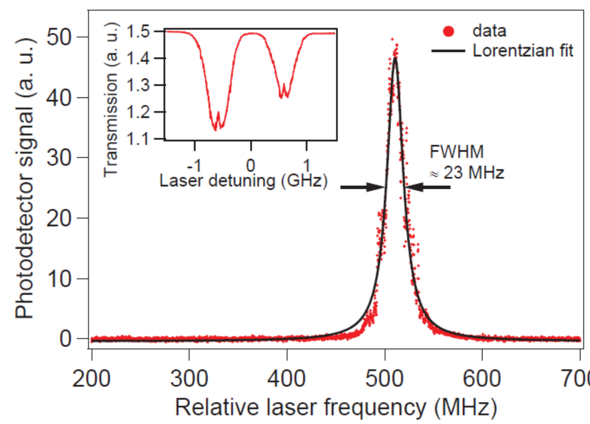
Layout: flip-chip bondable VCSEL




*Al-Samaneh et al. IEEE PTL 2011; APL 2012; Miah et al. IEEE JSTQE 2013*



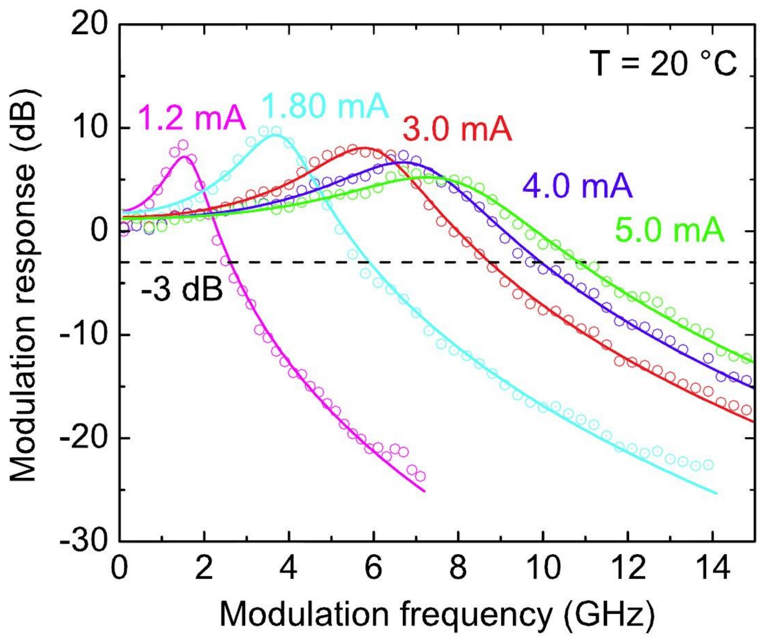

SMSR: **42dB**




Linewidth: **20-25MHz**
*Smaller would be even better*

# Performances

## Modulation




Max 3dB bandwidth of 11.8 GHz obtained at I=7.0mA
**Bandwidth of 5.6 GHz obtained at I=1.8mA**
(0.9mA above threshold)

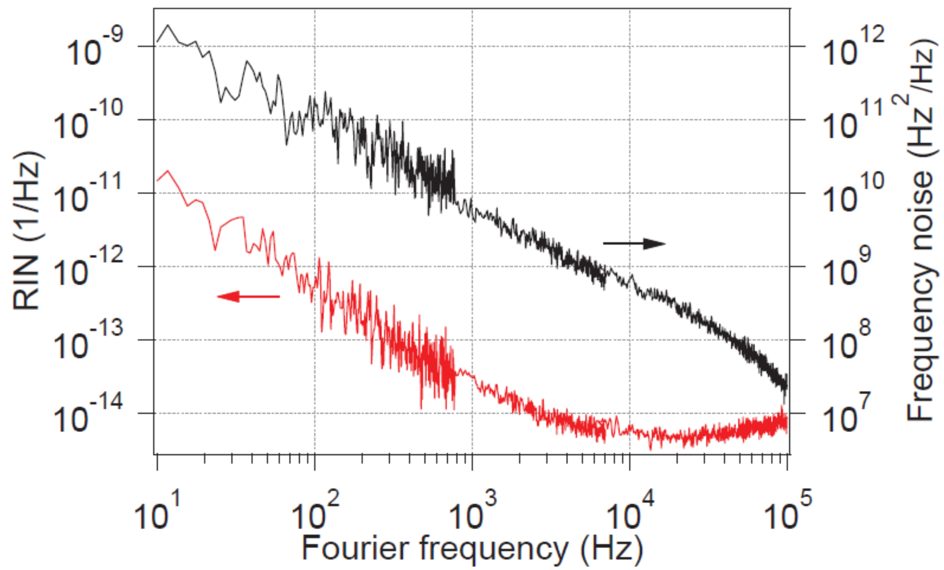
RIN: 1.10-11 Hz-1 at 10Hz Fourier Freq. (P = 700µW)

**VCSEL frequency noise : 1013 . *f -1* Hz2/Hz [10Hz;105Hz]**

**VCSEL Allan deviation: 1.10-8 at 1s**

**Critical for atomic clocks: The VCSEL FM noise is the main limitation to the clock short-term stability.**

## RIN and FM noise

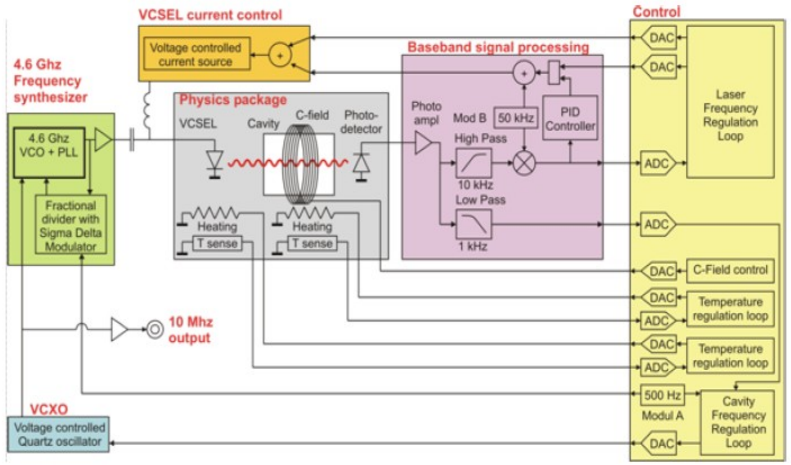



*Al-Samaneh et al. IEEE PTL 2011; APL 2012; Miah et al. IEEE JSTQE 2013, F. Gruet et al., Optics Express (2013).*

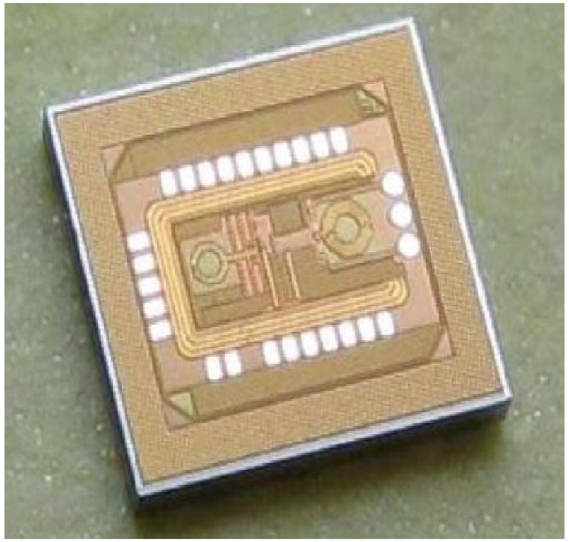
# Electronics

Functions:

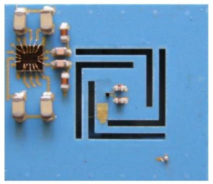
- Cell temperature and B-field control
- Laser current, temperature and frequency stabilization.
- CPT signal reading
- **4.596GHz signal generation and LO frequency servo**




**4.596 GHz Local oscillator**:



*4.6 GHz LC-VCO phase-locked to a 10 MHz reference using a N-fractional PLL in a 130 nm CMOS technology ASIC*



**Surface footprint = 4mm2**
**Power consumption = 12 mW**
**Output power up to 0 dBm to drive the VCSEL**
**Frequency resolution at the mHz level**

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

*Zhao et al., Sub. IEEE TMTT 2013*

# Electronics – Local Oscillator at 4.596 GHz

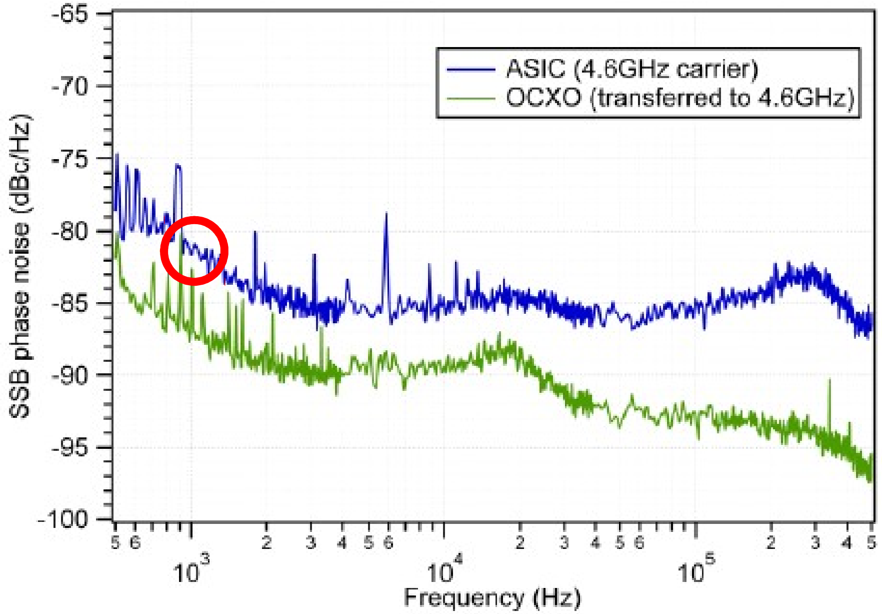
**Dick effect – Intermodulation effect**

The short-term stability of the clock can be degraded by the LO phase noise.

( *- 80 dBc/Hz at f = 1 kHz for 2 10-11 at 1 s)*

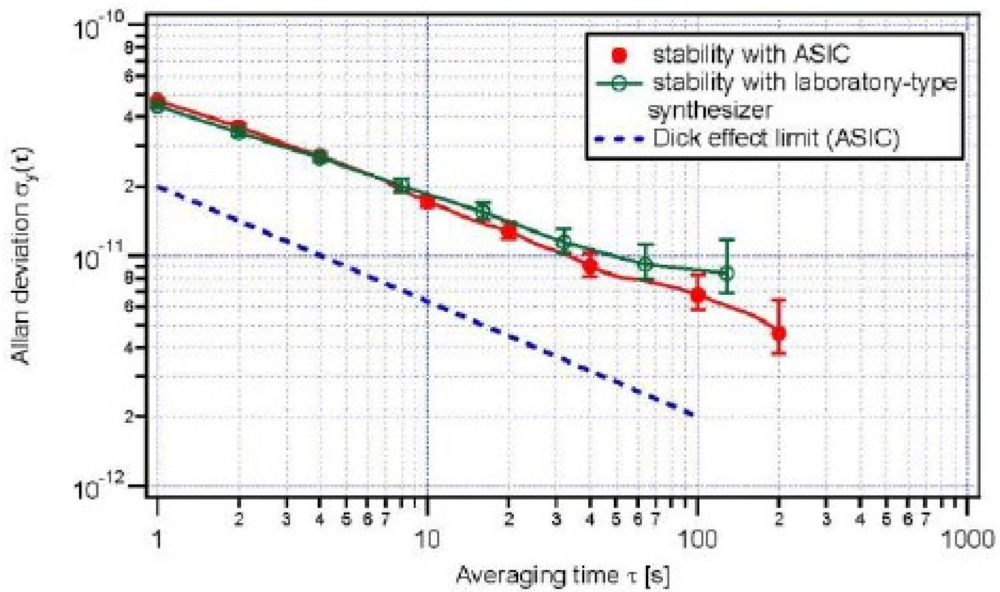
$$\sigma_y(\tau) = \sqrt{\sum_{n=1}^{\infty} C_{2n} \cdot S_\varphi(2nf_m)} \cdot \tau^{-1/2}$$

**ASIC synthesizer phase noise**



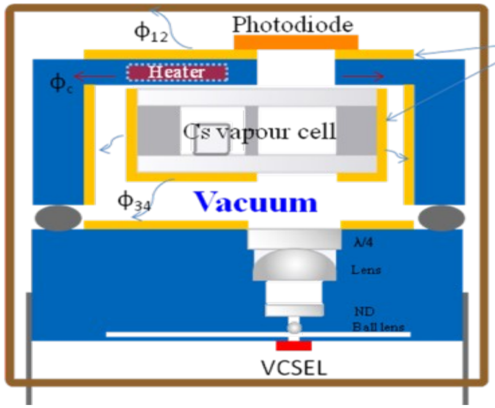

All electronics functions were validated for miniature clock applications

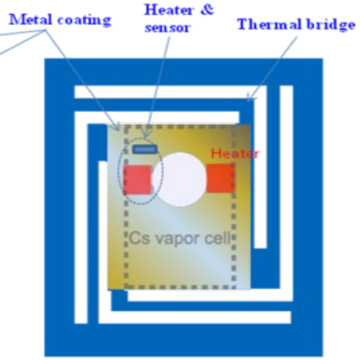
**Short-term stability**



# Packaging

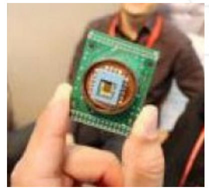
LTTC based package with embedded coils and heaters, vacuum encapsulated

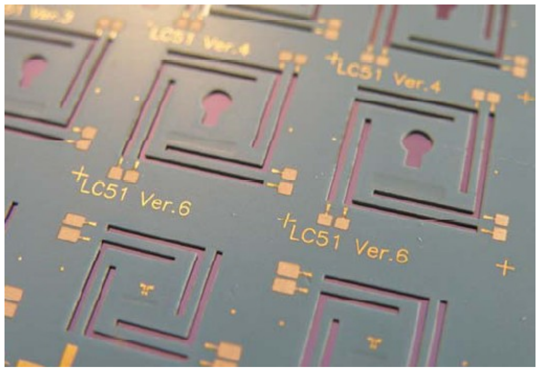


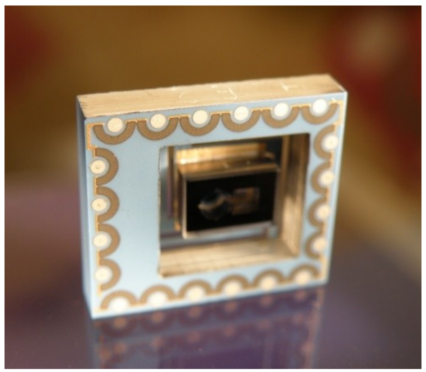

*Chutani et al., Sens. Act. A., 2012*

Cell thermal control:
50mK for Text=[0,55°C]

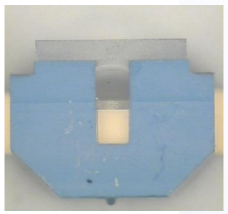




Thermally controllable multilayer LTCC platforms



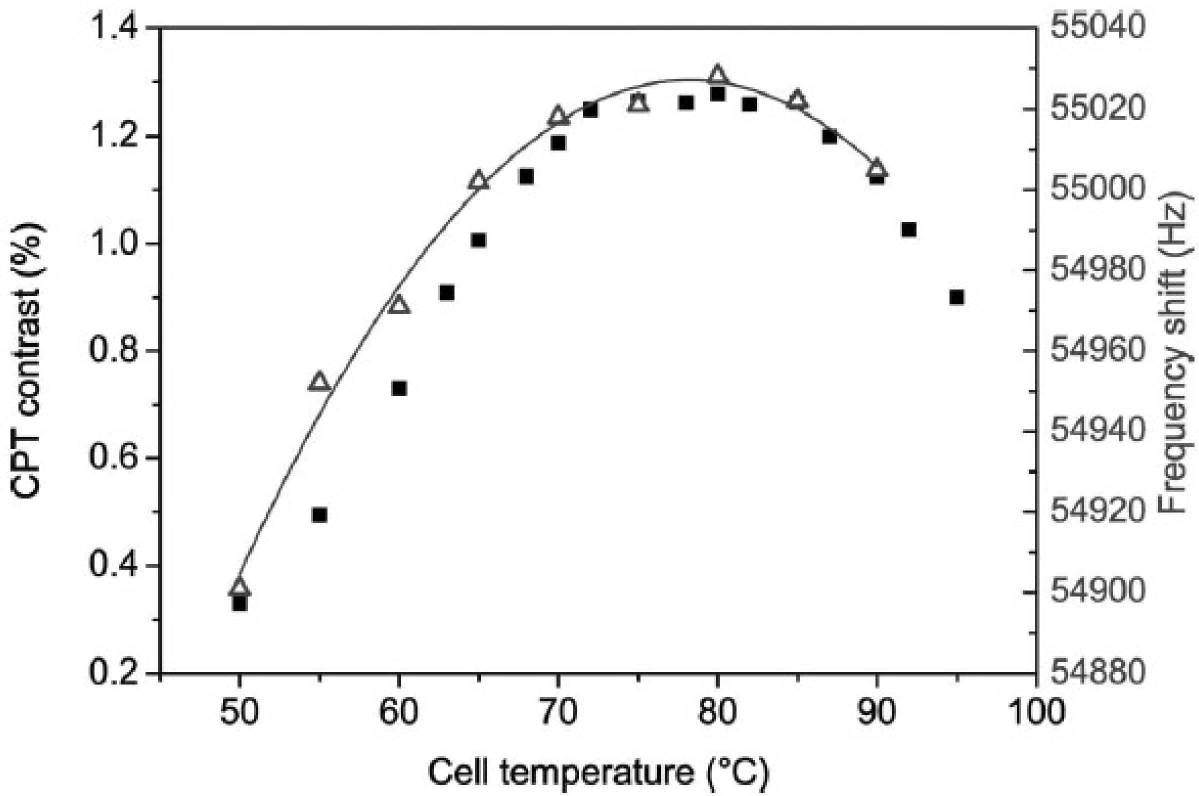
Cs cell subsystem



Optics subsystem

# Optimizations: CPT spectroscopy (D1 line)

**Cs D1 line is better for CPT interaction**



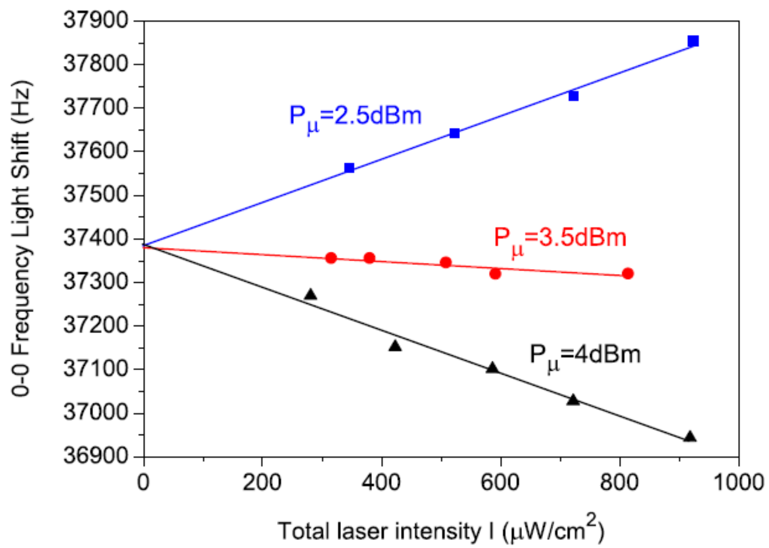

**By adjustment of the Ne pressure, the CPT contrast is optimized at 79-80°C where the temperature-dependence is cancelled.**

# LSC: Light shift cancellation

Light-shift: major effect in CPT clocks ➡ one of the main limitations for long-term performances

↳ **Clock frequency shift** due to laser intensity & frequency variations, sidebands power fluctuations,..

**Total light shift can be cancelled by adjusting finely the RF modulation power**




Solution: Find the « magic » zero light-shift point and stabilize the clock operation on this point

*R. Boudot et al., J. Appl. Phys. 2012; IEEE UFFC 2012*

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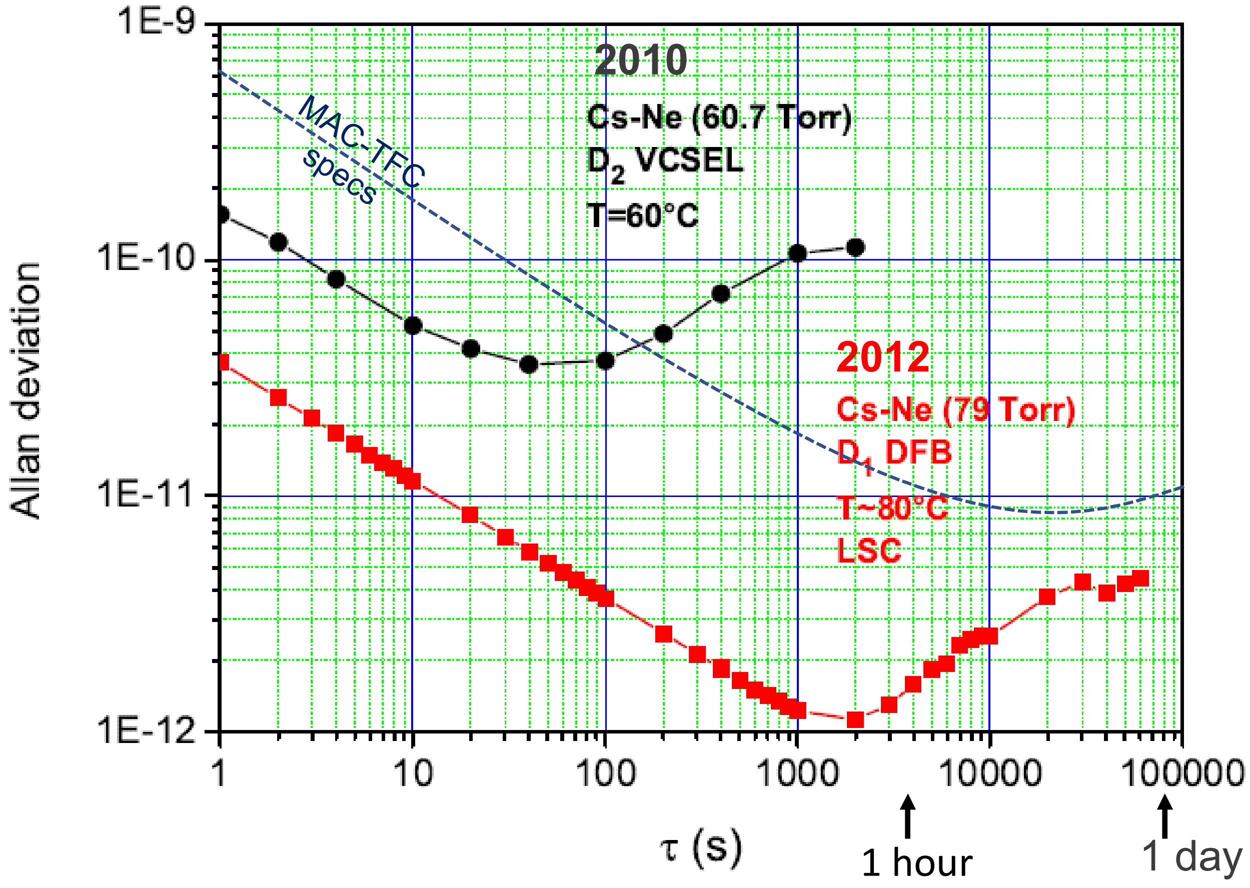
# Frequency Stability Performances

Short-term improved by the use of a laser resonant on the Cs D1 line

Long-term improved by active Light Shift Correction, Tcell~80°C, …




Cs-Ne Microcell

\+

laser D1

\+

Specific packaging and electronics

**Frequency stability better than**
**3.10-11 at 1s**
**10-11 at 1 day (1 µs /day)**

High-performance CPT clocks

*R. Boudot et al. IEEE UFFC (2012)*

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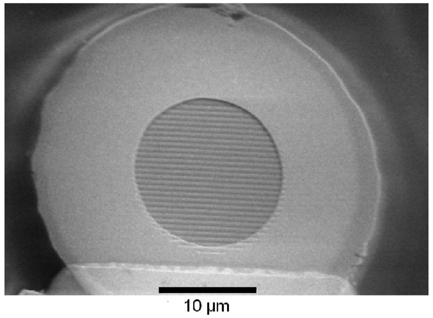
**Thanks to all MAC-TFC and ISIMAC partners**

**Thank you for your attention**

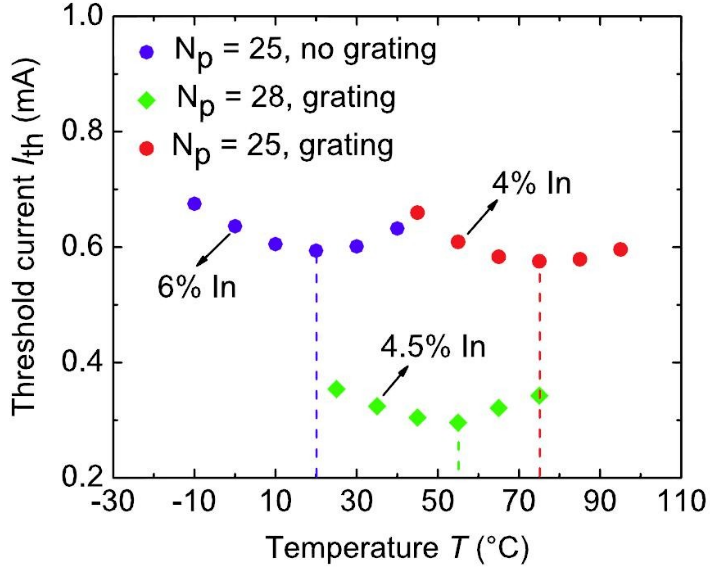
# Surface gratings

For polarization stabilization: - Period *d*=600nm (sub-wavelength), duty cycle 50%

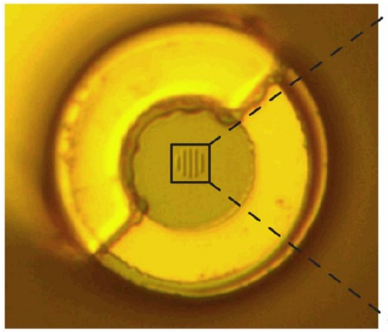
2 versions:

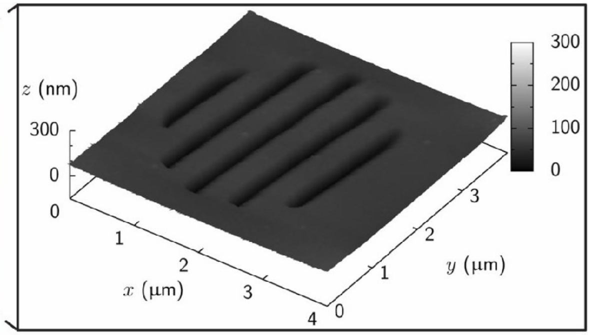



**- V1: large inverted gratings**
(etched in Quarter-wave antiphase layer)
Depth = 70nm
Polarization orth. to gratings line (along [011])



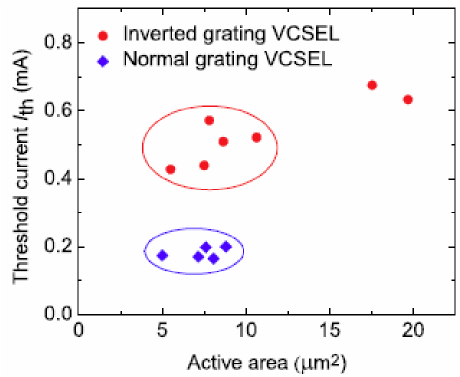

Tradeoff between Np and gratings efficiency






**- V2: $\varphi$=3µm diameter normal gratings**
(etched in Half-wave in-phase layer)
Depth = 120nm
Polarization paral. to gratings line

Threshold current reduced by 40% compared to inverted gratings




*Al-Samaneh et al. IEEE PTL 2011; APL 2012; Miah et al. IEEE JSTQE 2013*

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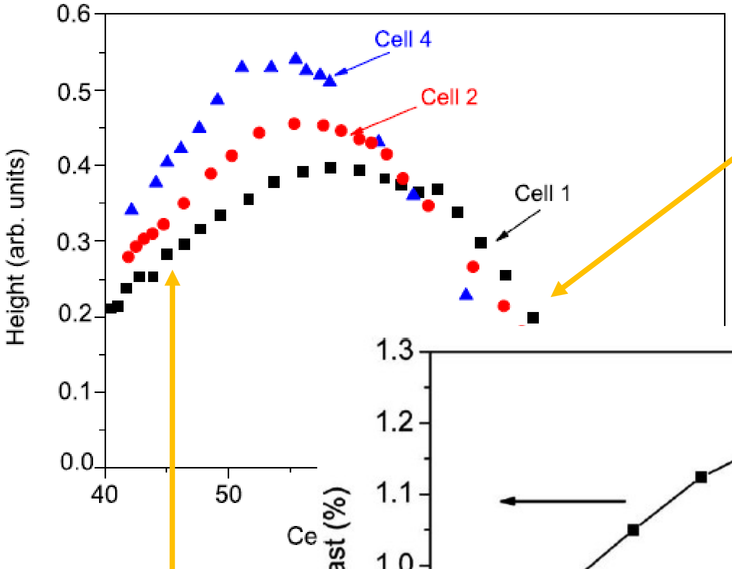
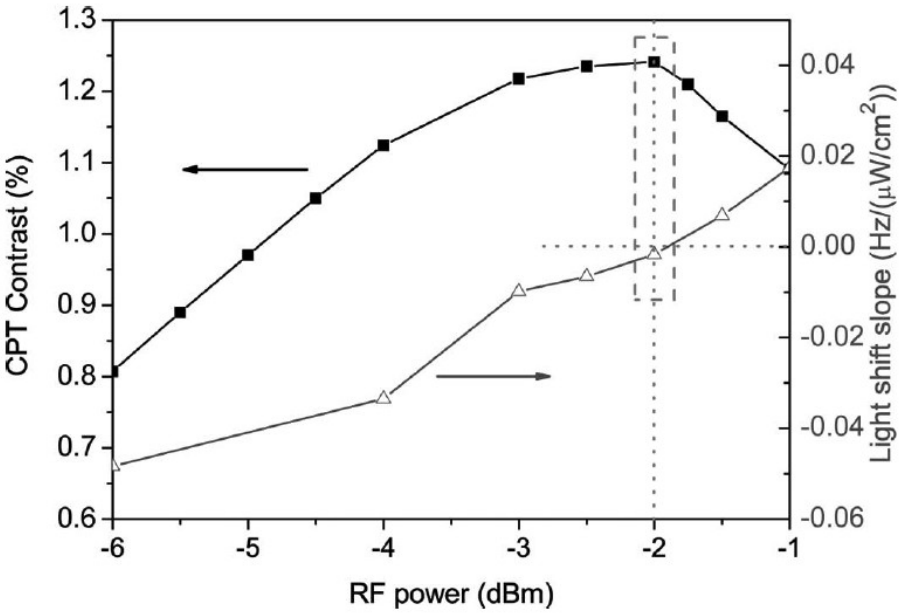
# CPT spectroscopy (D2 line)

## Cell temperature



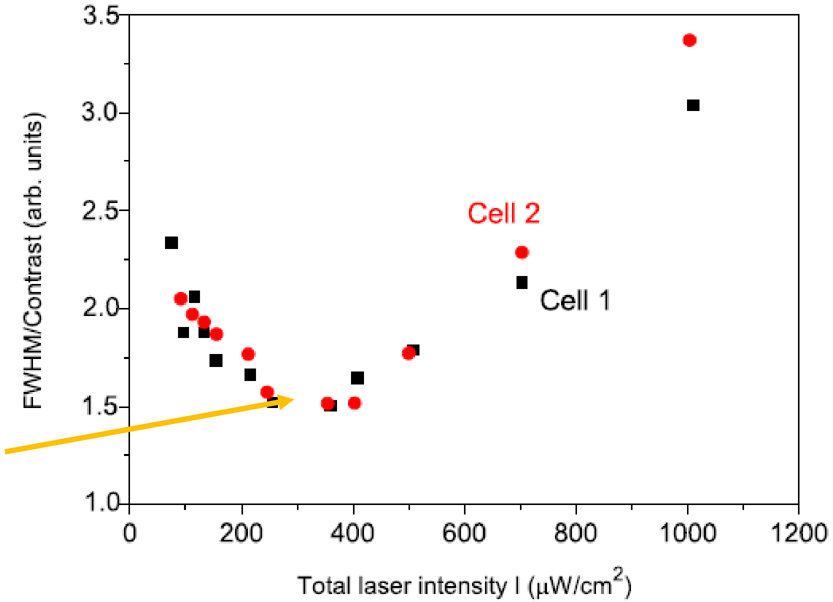

The vapor becomes optically thick.

The CPT signal increa
increase of the Cs de




The light shift slope can be cancelled by adjusting the RF modulation power.

## Laser intensity

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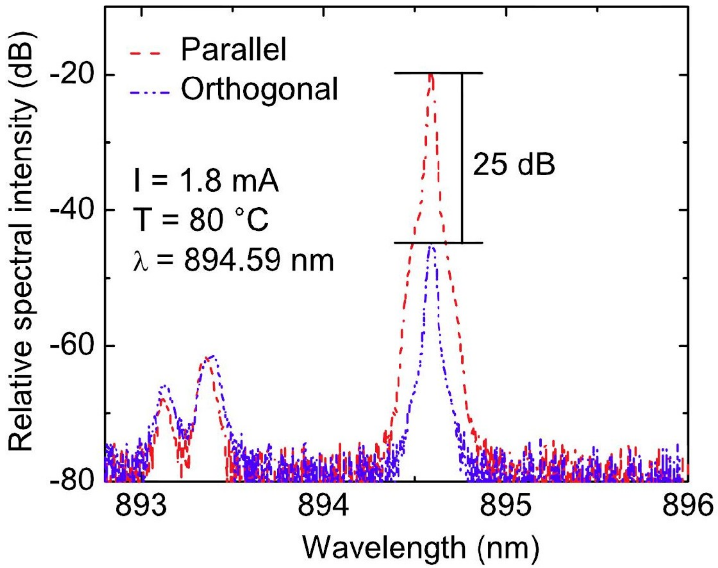
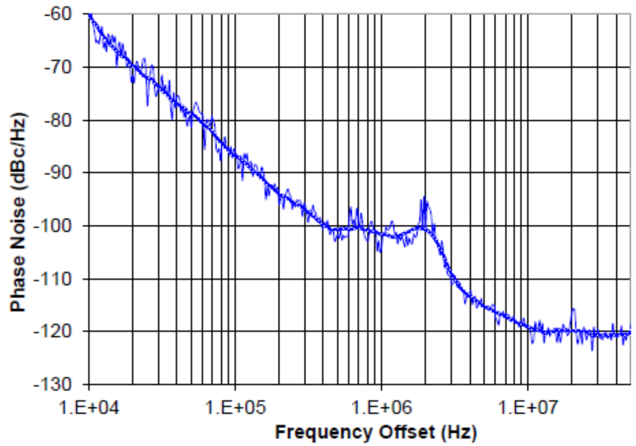



# VCO phase noise

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# Prospects

**Research studies:**

- Optimized CPT pumping schemes with new laser system architectures.
- Anti-relaxation coatings for microfabricated cells.
- New-generation BAW MEMS microwave oscillators.
- New buffer gases for high-temperature operation.

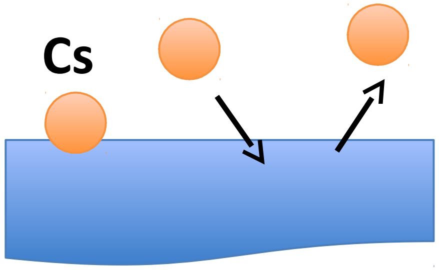
**Transfer studies in progress:**

- Microcell technology process.

# CPT relaxation mechanisms

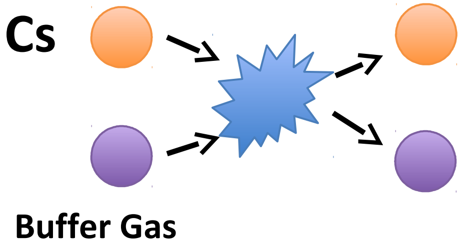
**Long CPT coherence relaxation times are needed (for a narrow linewidth) but..:**

**Collisions to the cell walls** + **Alkali-buffer gas collisions** + **Spin exchange** = **FWHM at I=0**



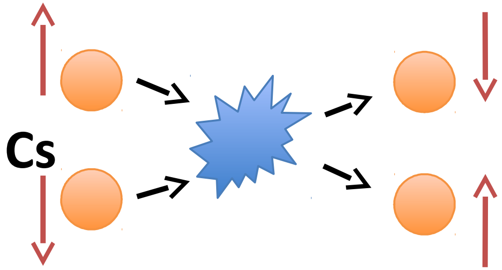

**Collision between Cs atoms and the cell walls, the atoms are trapped by the wall and are replaced by a unpolarized atom.**

$$\gamma_w = \left[\left(\frac{2.405}{R}\right)^2 + \left(\frac{\pi}{L}\right)^2\right] D_0 \frac{P_0}{P}$$




**Introduce the buffer gas to slow the diffusion of Cs atoms and decreases the CPT resonance linewdith.**

$$\gamma_{csbg} = L_0 \bar{v}_{rel} \sigma_{csbg} \frac{P}{P_0}$$




**Collision between Cs atoms and Cs atoms cause randomly exchange of electron spins.**

$$\gamma_{se} = \frac{6I+1}{8I+4} \bar{v}_r n_{cs} \sigma_{se}$$

$$\gamma_2 = \gamma_w + \gamma_{se} + \gamma_{csbg}.$$

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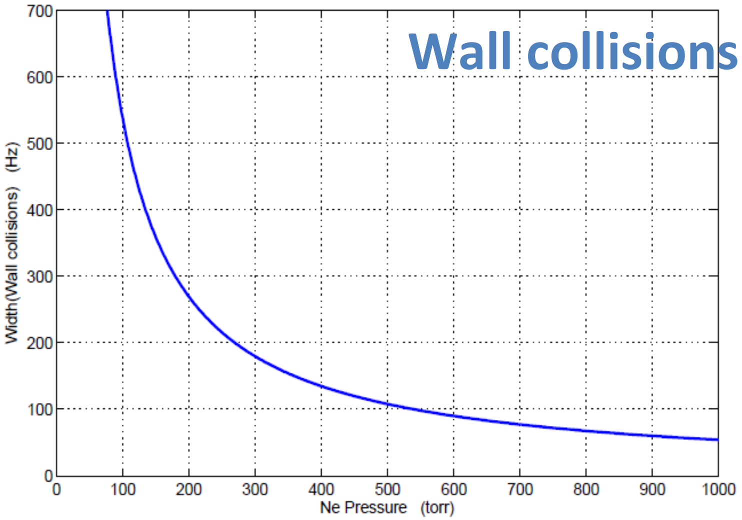
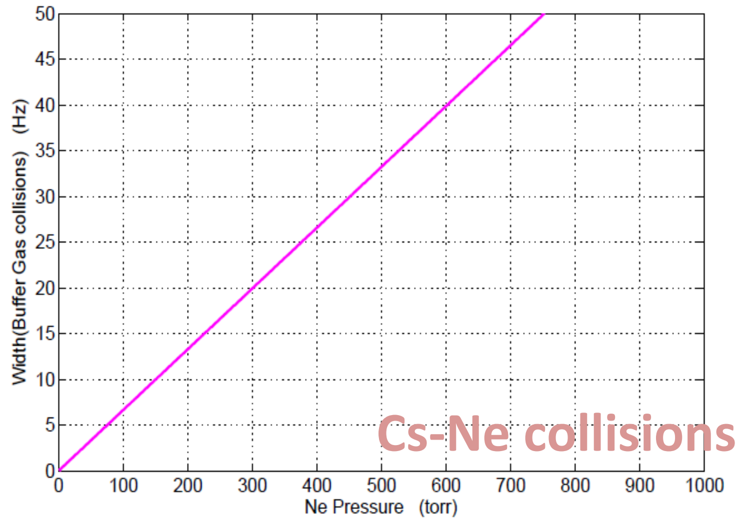
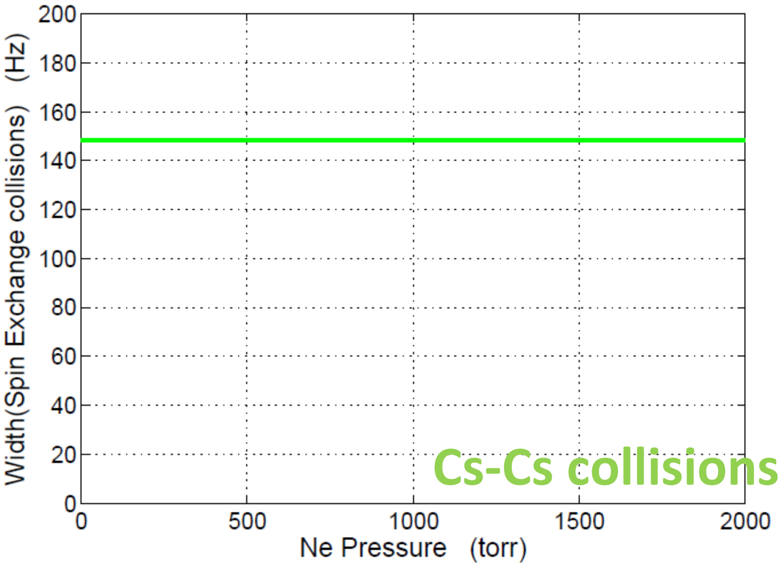
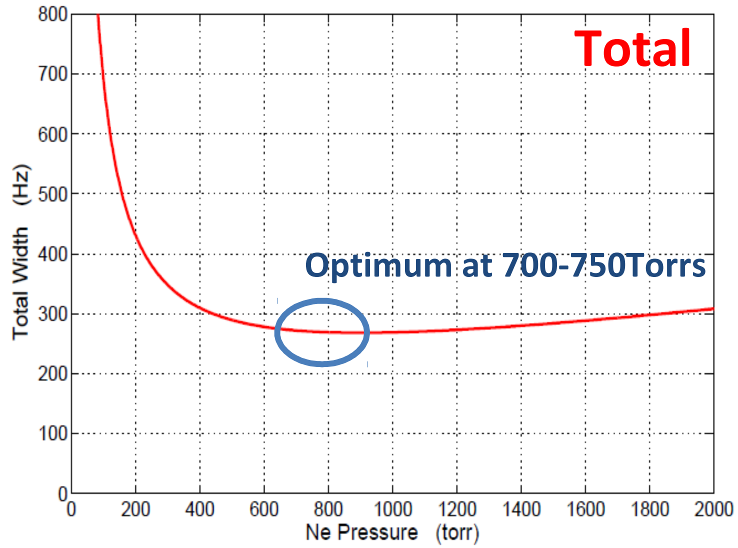
# CPT linewidth with buffer gas pressure




**Cs-Ne microcell (D=2mm, L=1.4mm, T=60°C)**



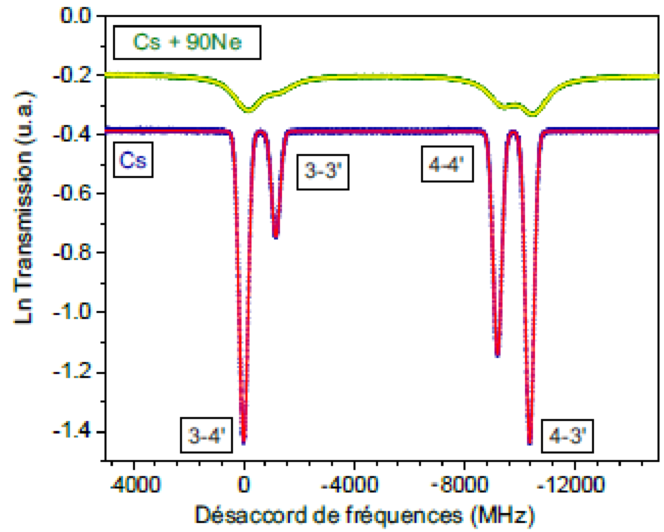
# CPT signal with buffer gas pressure

**The presence of buffer gas shifts and broadens optical lines.**

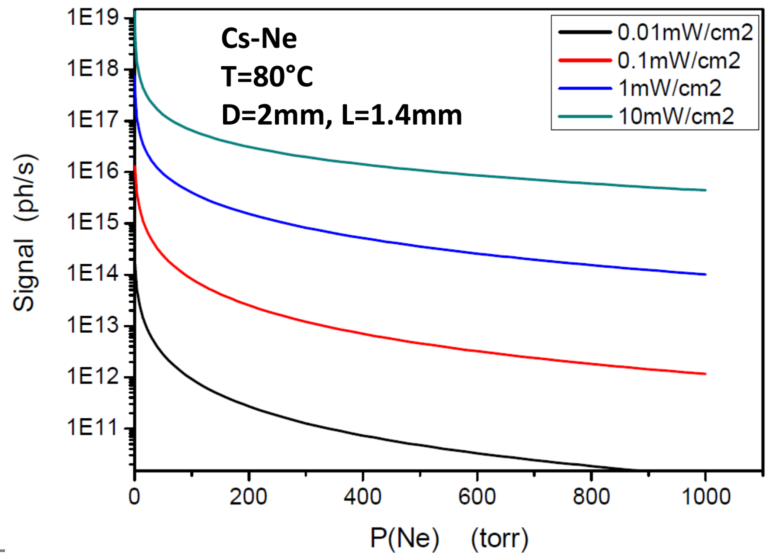
| Buffer gas | $T_1$ (K) | $\gamma_1$ [a] (MHz/torr) |
|---|---|---|
| He | 323 | 24.13 ± 0.07 |
| $^3$He | 323 | 26.00 ± 0.05 |
| Ne | 313 | 10.85 ± 0.02 |
| Ar | 313 | 18.31 ± 0.16 |
| Kr | 313 | 17.82 ± 0.05 |
| Xe | 313 | 19.74 ± 0.08 |
| $H_2$ | 328 | 20.81 ± 0.09 |
| HD | 318 | 20.06 ± 0.12 |
| $D_2$ | 318 | 18.04 ± 0.04 |
| $N_2$ | 318 | 15.82 ± 0.05 |
| | 323 | 16.36 ± 0.02 |
| | 333 | 15.66 ± 0.08 |
| $CH_4$ | 333 | 29.00 ± 0.10 |
| $C_2H_6$ | 331 | 26.70 ± 0.03 |
| $CF_4$ | 318 | 18.84 ± 0.05 |

*Broadening coefficients in Cs*

**G. Pitz et al., PRA 80, 062718 (2009).**




**O. Kozlova Thesis, LNE-SYRTE (2012)**




**Optical broadening = decrease of optical pumping rate populating the dark state = reduction of CPT signal.**

**Buffer gas pressure: trade off signal – linewidth**