Microfabricated vapour cells for atomic magnetometry

Terry Dyer, 26-09-18

University of Strathclyde Science

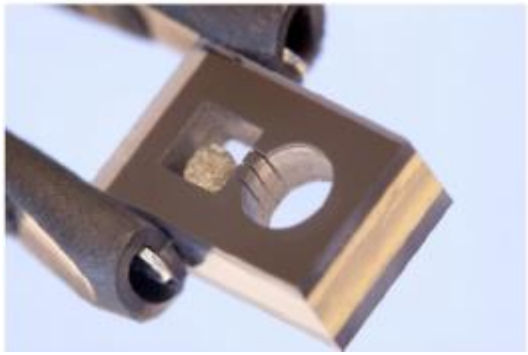
- MEMS vapour cells overview
- Inex Microelectronics collaboration (Innovate UK)
  - 1 mm cell – July 18
  - 2 mm cell – Oct 18
  - 5 mm cell – Feb 19
- Internal development
  - Alternative vapour cell architectures
  - New equipment/capability
- Commercial opportunity

MEMS vapour cells

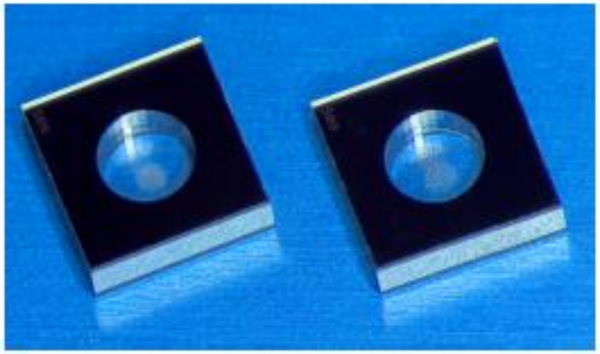
Vicarini et al, Sensors and Actuators A 280 (2018)

Karlen et al, Optics Express, 25,3, (2017)

FEMTO-ST
(Tronics Microsystems, TDK)
t_{Si}=1.5 mm

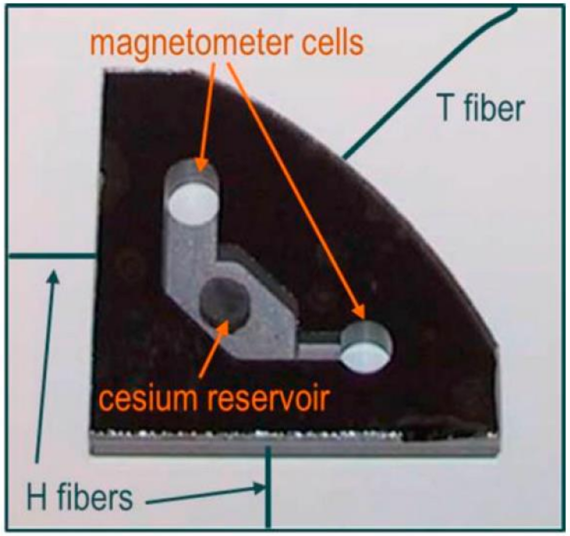


CSEM
t_{Si}=1 mm

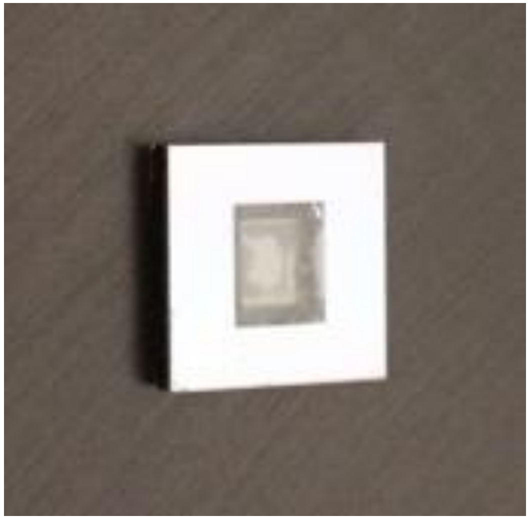


Schultze et al, Sensors, 17, 561, (2017)

IPT
t_{Si}=4 mm

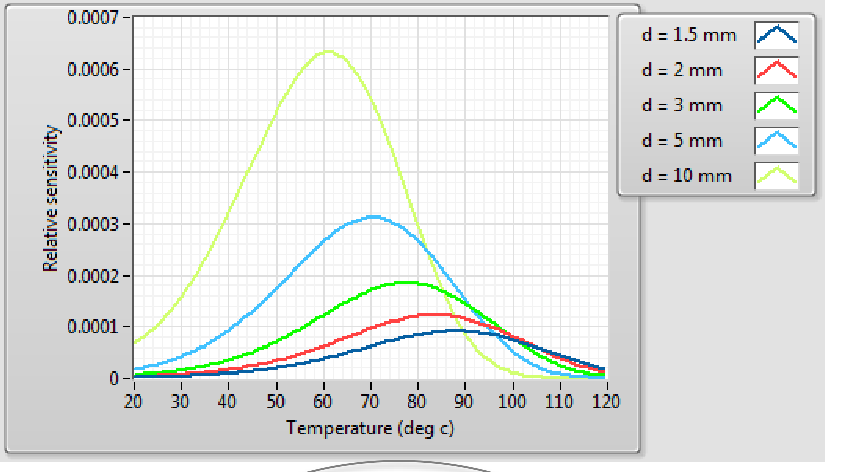


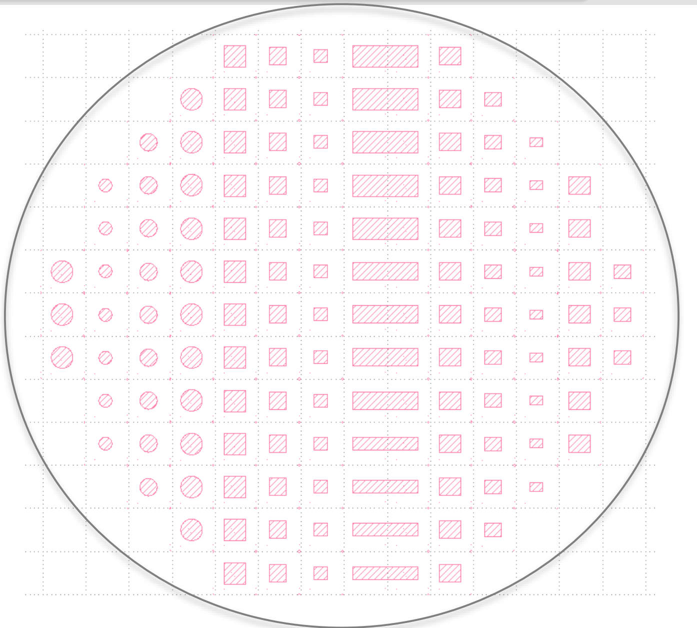
UoS
(Inex Microtechnology)
t_{Si}=1 mm



Design

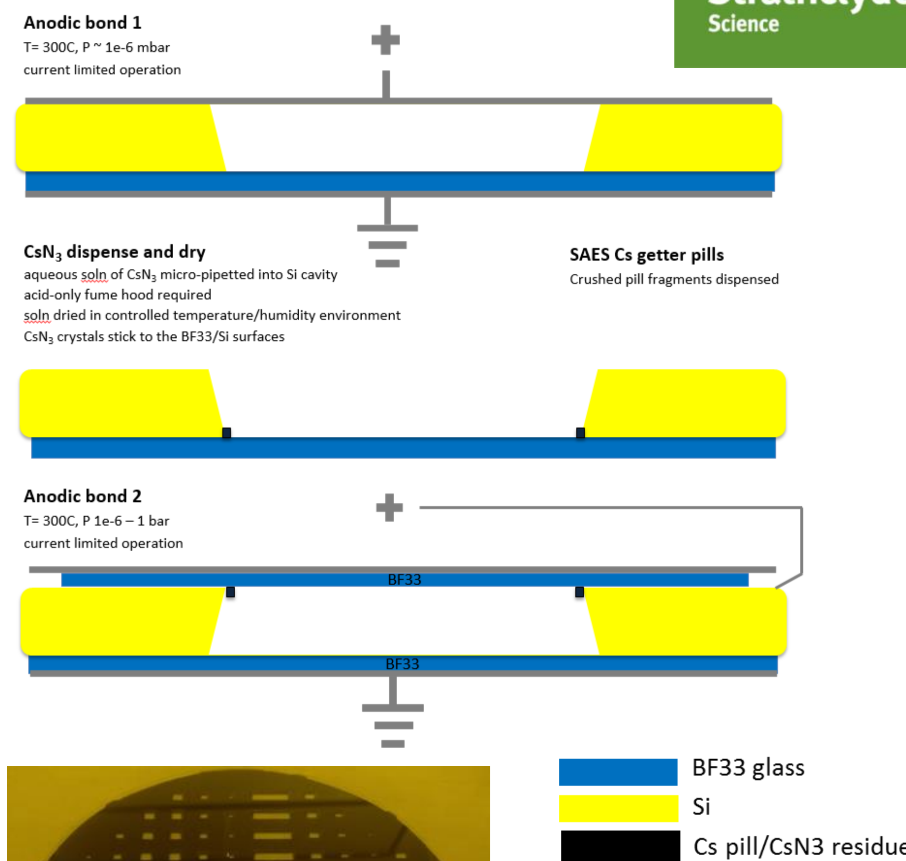
- Cell design software completed (Stuart)
  - Does not include effects of light narrowing
- Si wafer etch mask design
  - Parameterized (Klayout)
  - Range of cell dimensions
    - Layout can be used for 1 and 2 mm cells
  - 125 cells/ 150 mm wafer
  - 1 cm dicing pitch

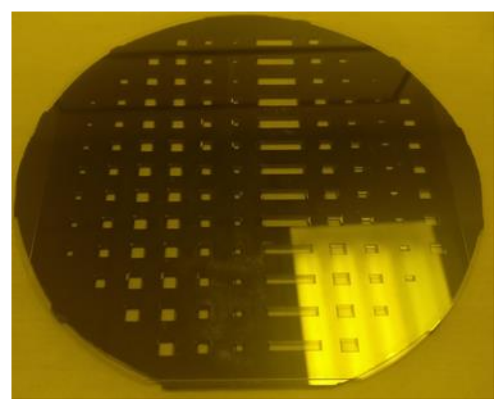




Process flow

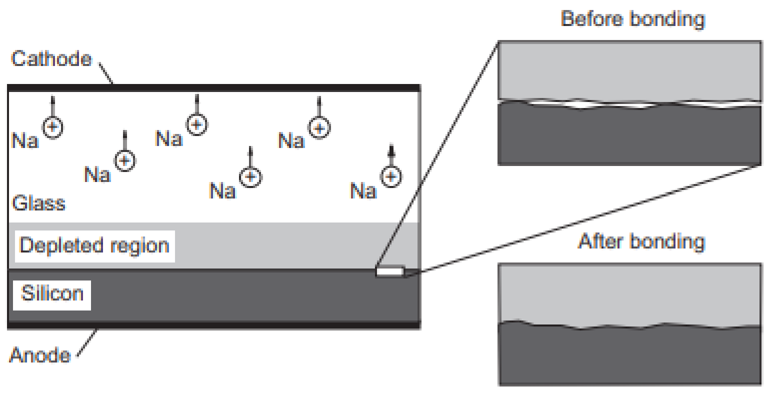
- Silicon Nitride hard mask deposited on 1 mm thick Si wafers at Edinburgh University
  - Dense LPCVD film critical for low defect KOH anisotropic wet etching
- Other processing at Inex Microtechnology
  - Anodic bonding process developed for Inex wafer bonder
  - No triple stack tooling reqd
- Activation of CsN_3 and SAES Cs getter pills at Strathclyde University



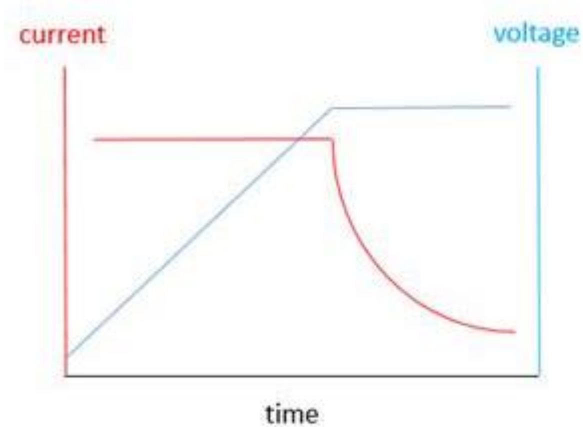


Anodic bonding process control

- Process control (of depletion layer width) by monitoring the total charge transferred
  - bond 1: function of wafer size and bonding parameters
  - bond 2: as 1 + Si wafer open area
- Current limited
  - no high current spikes during initial contact, reduces glass fracture frequency, improves vapour cell yield



Handbook of Silicon Based MEMS Materials and Technologies (Second Edition), p 599-610, Lapadatu and Jakobsen (2015)



CsN_3 and SAES Cs pill activation

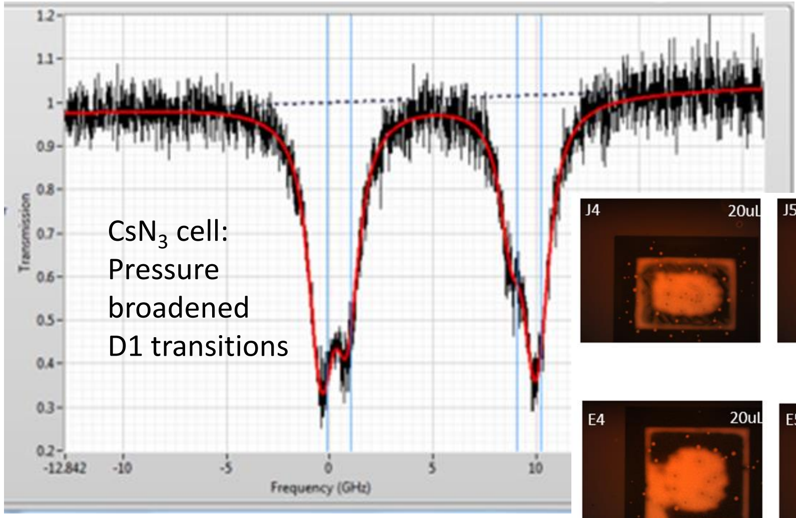
- CsN_3 activation
  - 254 nm exposure using Analytikjena UVP crosslinker

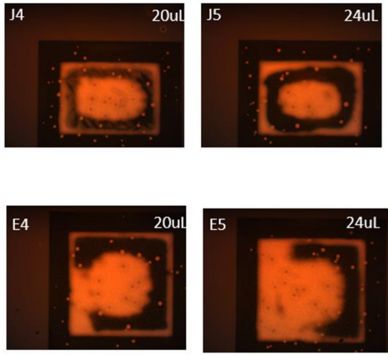
  $2CsN_3 \rightarrow 2Cs + 3N_2$

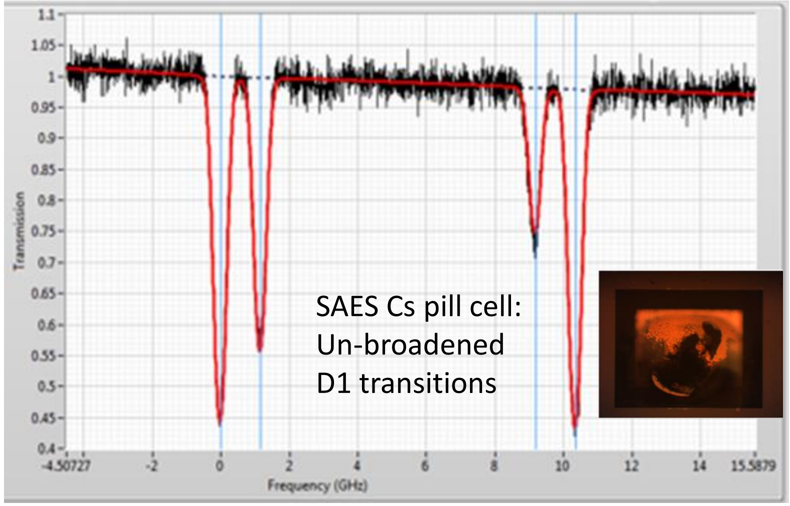
  - N_2 buffer gas is always present, min level ~ 40 torr
  - High cell-to-cell buffer gas pressure variation if the pattern/density of CsN_3 crystals at the cell base is uncontrolled
- SAES Cs pill activation
  - IR laser but propose to move to thermal

  $2Cs_2CrO_4 + ZrAl_2 \rightarrow 4Cs + Cr_2O_3 + Al_2O_3 + 3ZrO_2$

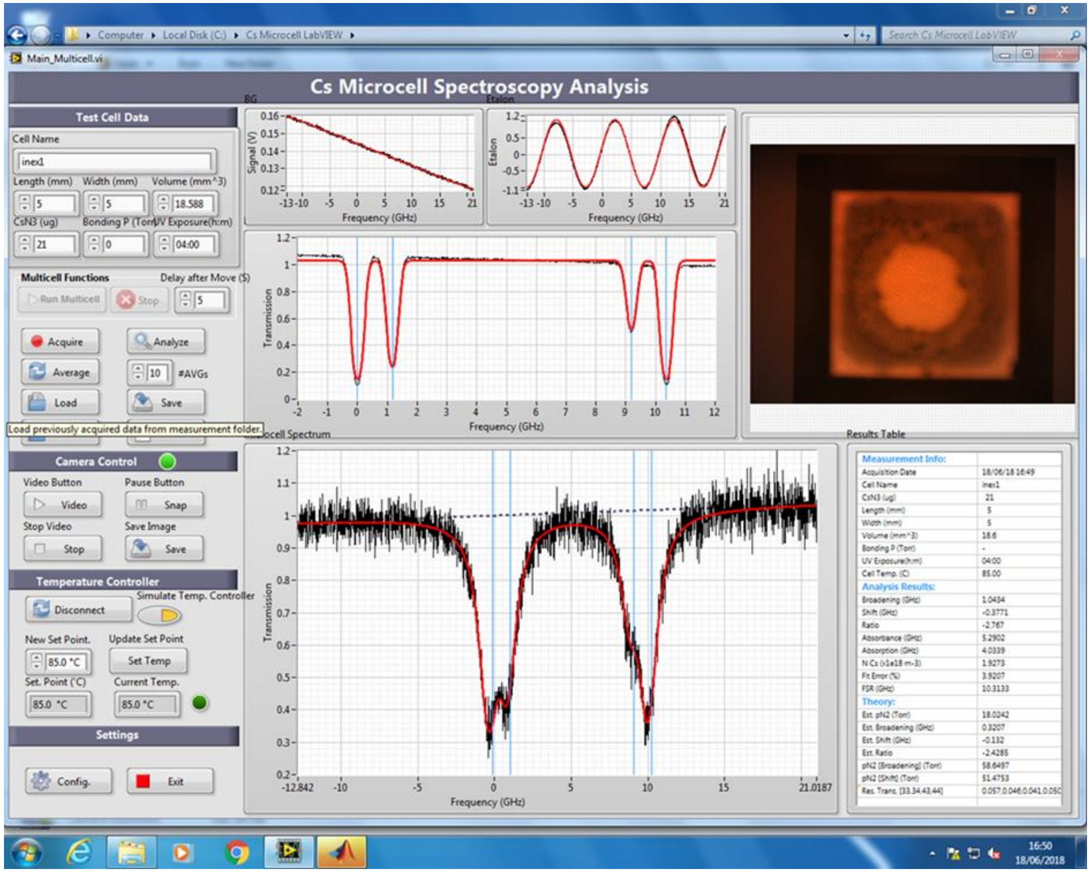
  - Lower cost paste option available
  - Buffer gas, if reqd, must be backfilled during the bonding stage
  - Cannot use N_2 buffer gas

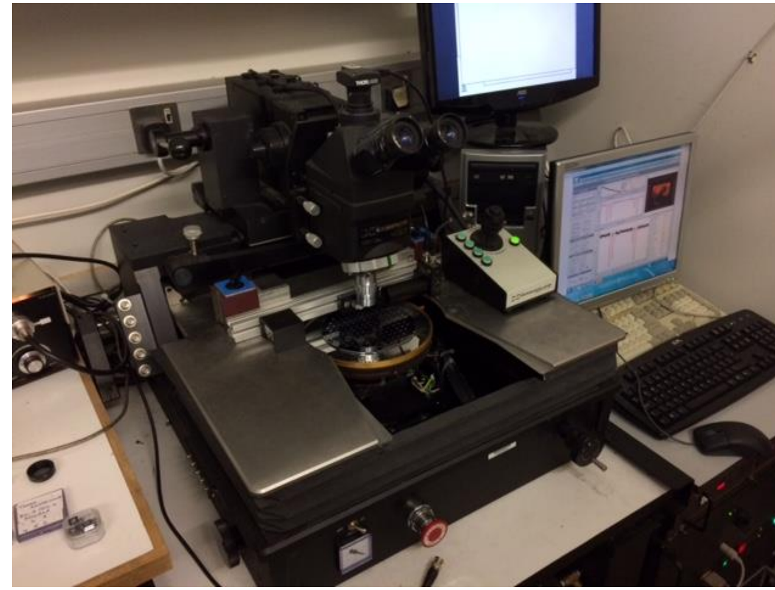


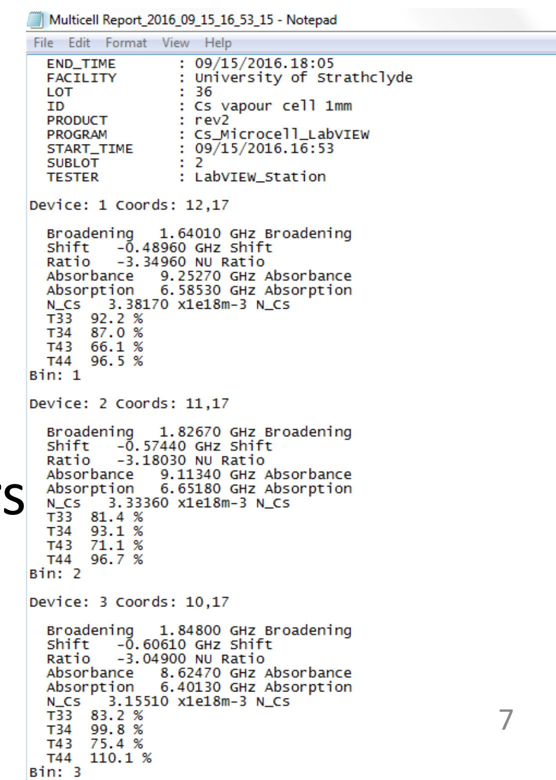




Wafer-level testing






Multicell Report_2016_09_15_16_53_15 - Notepad

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END_TIME       : 09/15/2016.18:05
FACILITY       : University of Strathclyde
LOT            : 36
ID             : Cs vapour cell 1mm
PRODUCT        : rev2
PROGRAM        : Cs_Microcell_LabVIEW
START_TIME     : 09/15/2016.16:53
SUBLOT         : 2
TESTER         : LabVIEW_Station

Device: 1 Coords: 12,17

 Broadening    1.64010 GHz Broadening
 Shift    -0.48960 GHz Shift
 Ratio    -3.34960 NU Ratio
 Absorbance    9.25270 GHz Absorbance
 Absorption    6.58530 GHz Absorption
 N_Cs    3.38170 x1e18m-3 N_Cs
 T33  92.2 %
 T34  87.0 %
 T43  66.1 %
 T44  96.5 %
Bin: 1

Device: 2 Coords: 11,17

 Broadening    1.82670 GHz Broadening
 Shift    -0.57440 GHz Shift
 Ratio    -3.18030 NU Ratio
 Absorbance    9.11340 GHz Absorbance
 Absorption    6.65180 GHz Absorption
 N_Cs    3.33360 x1e18m-3 N_Cs
 T33  81.4 %
 T34  93.1 %
 T43  71.1 %
 T44  96.7 %
Bin: 2

Device: 3 Coords: 10,17

 Broadening    1.84800 GHz Broadening
 Shift    -0.60610 GHz Shift
 Ratio    -3.04900 NU Ratio
 Absorbance    8.62470 GHz Absorbance
 Absorption    6.40130 GHz Absorption
 N_Cs    3.15510 x1e18m-3 N_Cs
 T33  83.2 %
 T34  99.8 %
 T43  75.4 %
 T44  110.1 %
Bin: 3
```

- Automated test station for ≤ 200 mm wafers
- Test rates up to 10 vapour cells/min
- Log file for cell traceability

Cell-level testing

- Free Induction Decay (FID) magnetometry
  - D. Hunter, S. Piccolomo, J. D. Pritchard, N. L. Brockie, T. E. Dyer & E. Riis, [Phys. Rev. Appl. **10**, 014002 (2018)]().
- For Inex 1 mm cell with 120 torr N_2 buffer gas, Cs spin relaxation rate ~ 2.1 kHz

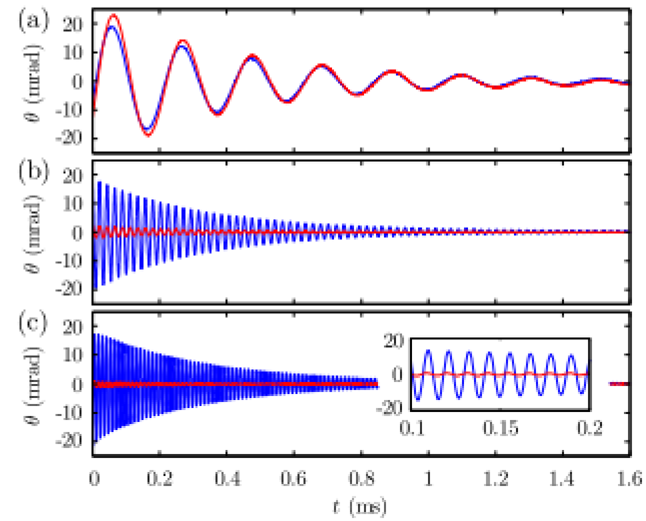

FIG. 5. Optical rotation signal (raw data) observed using single-pulse (red) and synchronous (blue) optical pumping for bias fields of (a) 1.5 μT, (b) 10 μT, and (c) 25 μT. The inset in plot (c) shows 100 μs of data to adequately resolve the oscillations resulting from the precessing atomic spins. The total measurement period was set to $T = 2$ ms showing the full decay of the atomic spin polarization to equilibrium.

- Double-resonance magnetometry (see Stuart's presentation)
  - S.J. Ingleby, C. O'Dwyer, P.F. Griffin, A.S. Arnold, & E. Riis, [Phys. Rev. A **96**, 013429 (2017)]().
  - S.J. Ingleby, P.F. Griffin, A.S. Arnold, M. Chouliara, E. Riis, [Rev. Sci. Instrum. **88**, 043109 (2017)]().

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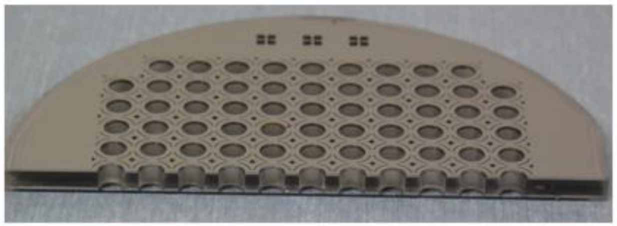
Cell development @ Inex

- $1 \rightarrow 2 \rightarrow 5$ mm cells glass-Si-glass anodic bonding
  - Tooling modifications/workarounds for thicker/heavier Si wafers
  - KOH etch process modified for thicker Si wafers
    - Dual etch processing to maintain CD
  - Automated CsN_3 dispense
  - Ensure that the CsN_3 crystals at the cell base are not in the magnetometer laser beam path
    - US9639062 (2017), modify for higher aspect ratios
  - Adding inert buffer gas backfill capability during anodic bond 2
    - Allow fabrication of cells with backfilled buffer gas pressure up to 1500 torr
  - Glass etch mask introduced to produce Cs reservoir/active cells connected by vias (FEMTO-ST)
    - Avoids convex corner issue in KOH etching
  - On-board heaters (symmetric/asymmetric), temp sensors and modulation coils

Multi-stack anodic bonding

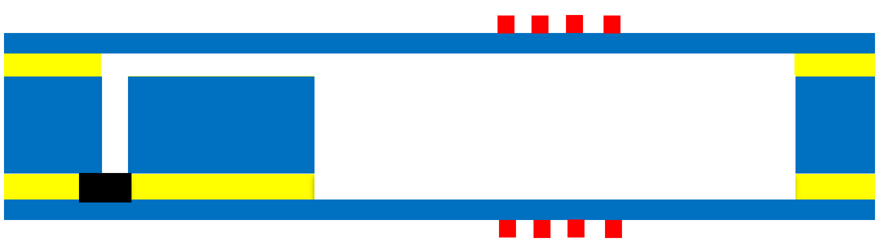


Pétremand et al, J. Micromech. Microeng. 22 (2012)

- **Examples of final diced cells using thick glass wafer**

Cell with CsN_3 or Cs pill reservoir. Longer optical path length set by 5 mm BF33 glass wfr with cavities fabricated by water jetting
- *in development Plan-Optik AG*

Cell without CsN_3 or Cs pill reservoir but with residue contained in a Si wfr recess around cell base



transparent ITO patterned heaters

Cell with patterned transparent ITO heaters in one or both windows which drive Cs droplet condensation towards the cell sidewalls

BF33 glass

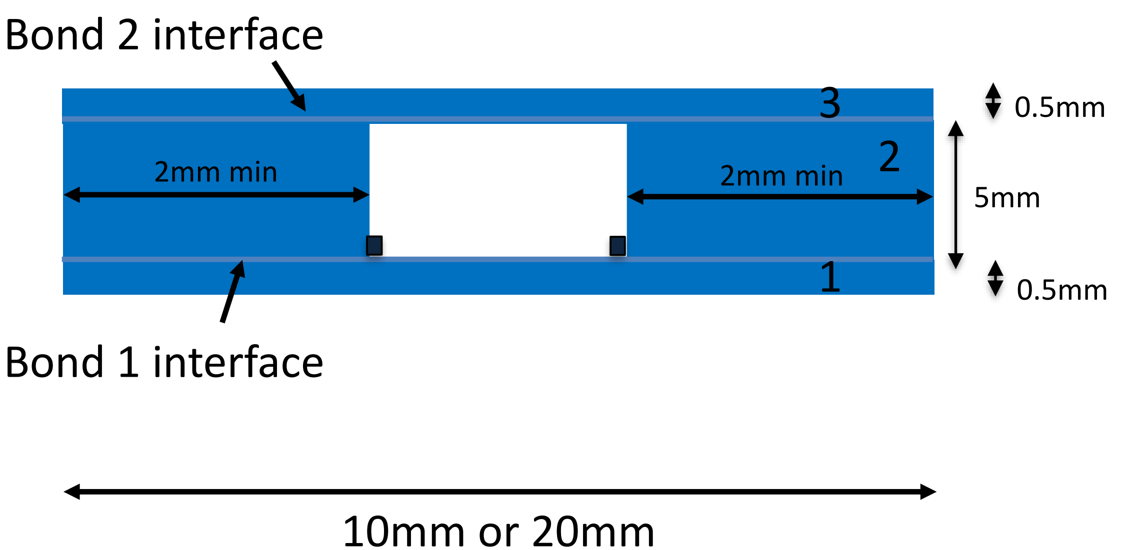
Si

Cs pill/CsN3 residue

All-glass cell

- 3x glass wafers, wafers 1,3 un-patterned
- wafer 2 has thru-wafer etched holes of varying lateral dimensions
- After bond 1, CsN_3 is dispensed into each open cavity.
- Thermo-compression bond 2 seals the cavity

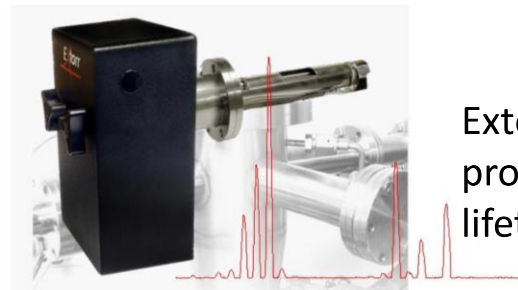
- Bond 1, using water jetting and thermo-compression bonding, in development- Plan-Optik AG



New capability/process control

Residual Gas Analyzers

Pirani, Ion Gauge, Quadrupole - All Included

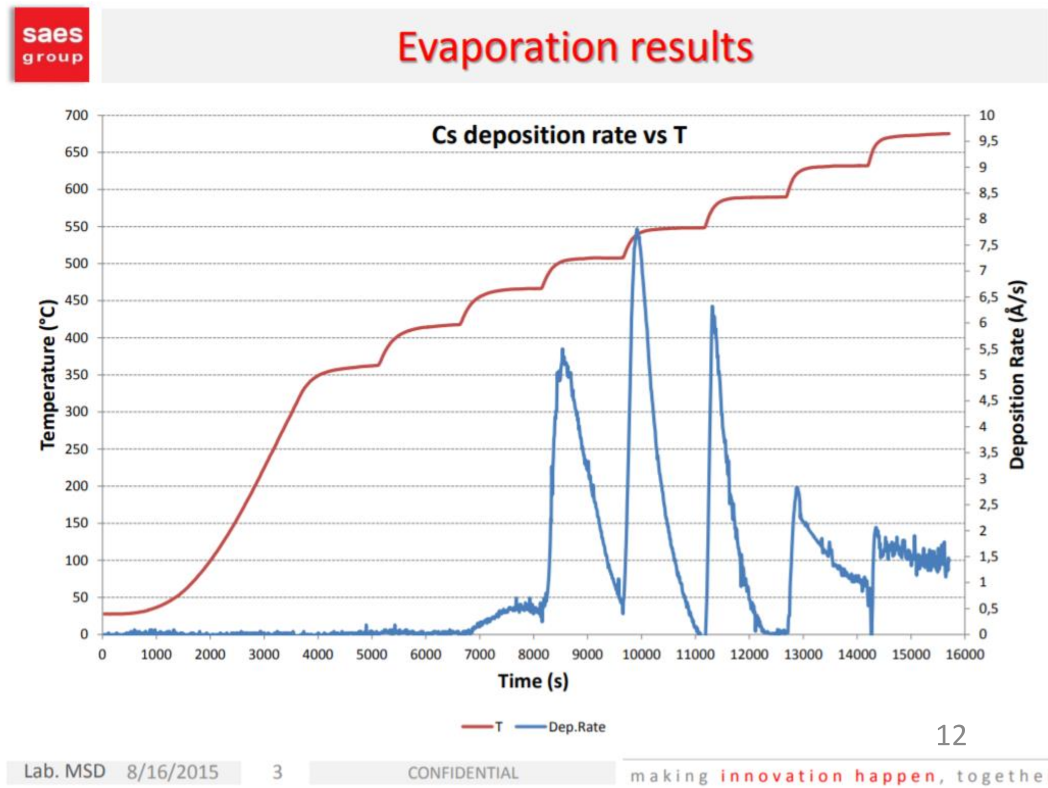


Extorr 200 amu RGA for process control and vapour cell lifetime testing

Customised anodic bonder eg modified EVG AB1 PV

Development work independent of Inex

In-situ thermal activation (550C) of SAES Cs getter pills



Commercial opportunity

What We Do — MEMSCELL.COM

https://www.memscell.com/what-we-do/

MEMSCELL

WHAT WE DO

EXAMPLES

PARTNERS

CONTACT

Our team of physicists and engineers offer a one-stop shop to design, manufacture and optically test MEMS alkali vapour cells with buffer gas pressures ranging from 0-2 bar (@ 85 C). Applications include magnetometers, inertial sensing and atomic clocks.

We don't offer an on-the-shelf product, our business model is to take on development projects with typical duration 3-6 months. Based on our customer's specification, we design a bespoke MEMS fabrication process using class 100 clean room facilities. Our high yield manufacturing and proprietary test capability is compatible with both small cell quantities for prototype devices and larger batch runs for higher volume applications.

MEMS cell features:

Hermetically sealed alkali vapour cell

Cs or Rb alkali vapour

Flexible vapour cell dimensions

Summary

- Inex collaboration (Innovate UK) on track
  - 1 mm cells fabricated
    - 120 torr N_2 buffer gas, Cs spin relaxation rate ~ 2.1 kHz
  - 2 & 5 mm cells in development
- Investigating alternative cell architectures
- New capability/process control
- Commercial opportunity

Strathclyde magnetometry team

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Dominic Hunter


Iain Chalmers


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