Electronic Supplementary Material (ESI) for ChemComm.

Supporting Information

Potent Affinity Material for Tracing Acetone and related Analytes based on Molecular Recognition by Halogen Bonds

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General remarks

All analytes were used in highest available quality (analytical grade) and without further purification. All reagents were used as purchased in highest available grades. Solvents were desiccated if necessary by standard methods.

Nitrogen which was used in the screening experiments was used in a purity of 99.998%.

γ-Cyclodextrin (**7**) was purchased from Wacker Chemie AG, Burghausen, Germany (>98%).

Reagents for the pretreatment: 1*H*,1*H*,2*H*,2*H*-perfluorooctyl-1-phosphonic acid (98%, ABCR) in ethanol.[1]

The experimental primary data were processed with Matlab 7.11.0 (R2010b) (The MathWorks Inc., Natick, Massachusetts, USA).

For the preparation of the diagrams OriginPro 8 SR0 (OriginLab Corporation, Northampton, Massachusetts, USA) were used.

PCAs were calculated with the program DataLab V2.1 (Software Development Lohninger, Pressbaum, Austria).

HFF-QCMs with a fundamental frequency of 195 MHz were used (KVG Quartz Crystal Technology GmbH, Neckarbischofsheim, Germany. Type: XA 1600).

The QCM is excited using an aperiodic oscillator circuit and oscillates with its specific load resonance frequency. Frequency counting is performed using a FPGA (field programmable gate array) which allows asynchronous 28-bit counting with an accuracy of ±0.5 Hz.

Evaluation of affinity

QCM setup

The resonance frequency of thickness-shear resonators, like the quartz crystal microbalances employed, is largely influenced by the oscillating mass. The sensitivity of the quartz resonator is influenced by several environmental factors and is described by the *Sauerbrey* equation (equation S1).[2] Wherein A is the oscillating area, N the frequency constant and ρ the density of the quartz material. A variation in the oscillating mass Δm directly results in a linear shift Δf_0 of the fundamental resonance frequency f_0.

$$\Delta f_0 = -\frac{f_0^2}{N \cdot \rho \cdot A} \Delta m \qquad \text{S1}$$

This correlation is an easy way to determine adsorption from various analytes towards selected affinity materials.[3]

The QCM is excited using an aperiodic oscillator circuit and oscillates with its specific load resonance frequency.[4] Frequency counting is performed using a FPGA (field programmable gate array) which allows asynchronous 28-bit counting with an accuracy of ±0.5 Hz. For testing purposes, a larger number of electronic circuits and QCMs can be combined to operate in a single setup.

Coating protocol

The coating of the quartz crystal microbalances is performed using an electrospray protocol.[5] This particular method is well established and allows the continuously monitoring of mass deposition onto the quartz upon spraying process. The electrospray solutions are prepared at concentrations of approx. 0.01 mg/mL in a 9:1 mixture of tetrahydrofuran/methanol.
The experimental setup for the coating unit is schematically displayed in Figure S1.

The solution for coating is placed in a glass syringe equipped with metal cannula. The metallic needle is contacted with an applied voltage of 5 kV relative to a counter electrode which is represented by the electrode of the QCM to be coated (distance needle tip/electrode: 0.15 m). The cannula represents the anode. A constant delivery of the solution during the coating process is achieved by using a syringe pump (5 µL/min). The coating process is monitored by measuring the frequency shift of the QCM. Since it is not possible the measure the thickness of the deposited film directly, the amount of affinity material on the quartz device is given as a frequency shift. For screening purposes, all compounds are deposited on 195 MHz QCMs until a frequency shift of 50 kHz is reached. This shift corresponds to a mass of approx. 10.4 ng of the deposited material.

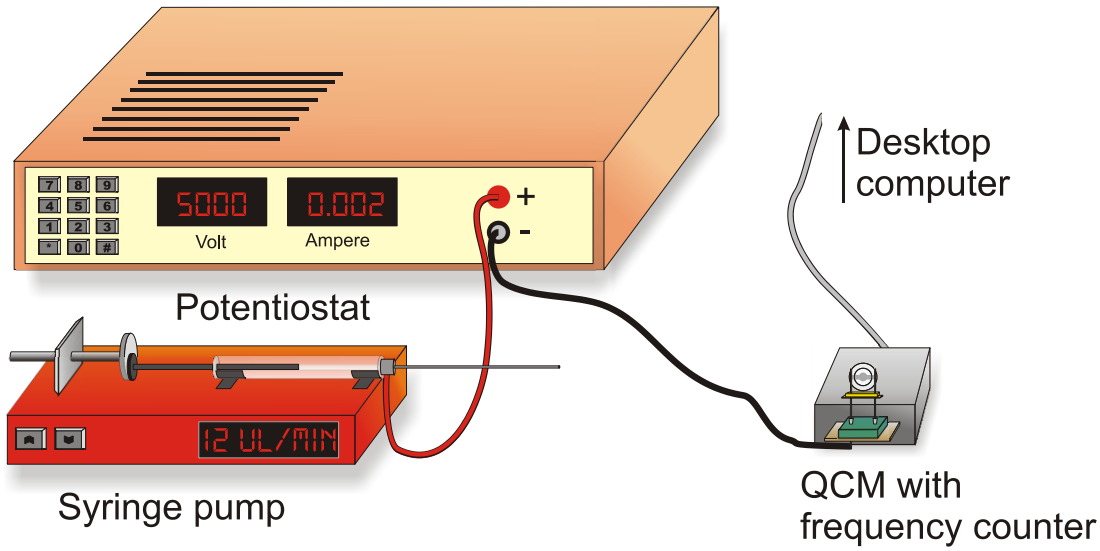

Figure S1. *Setup of the coating unit for electrospray.*

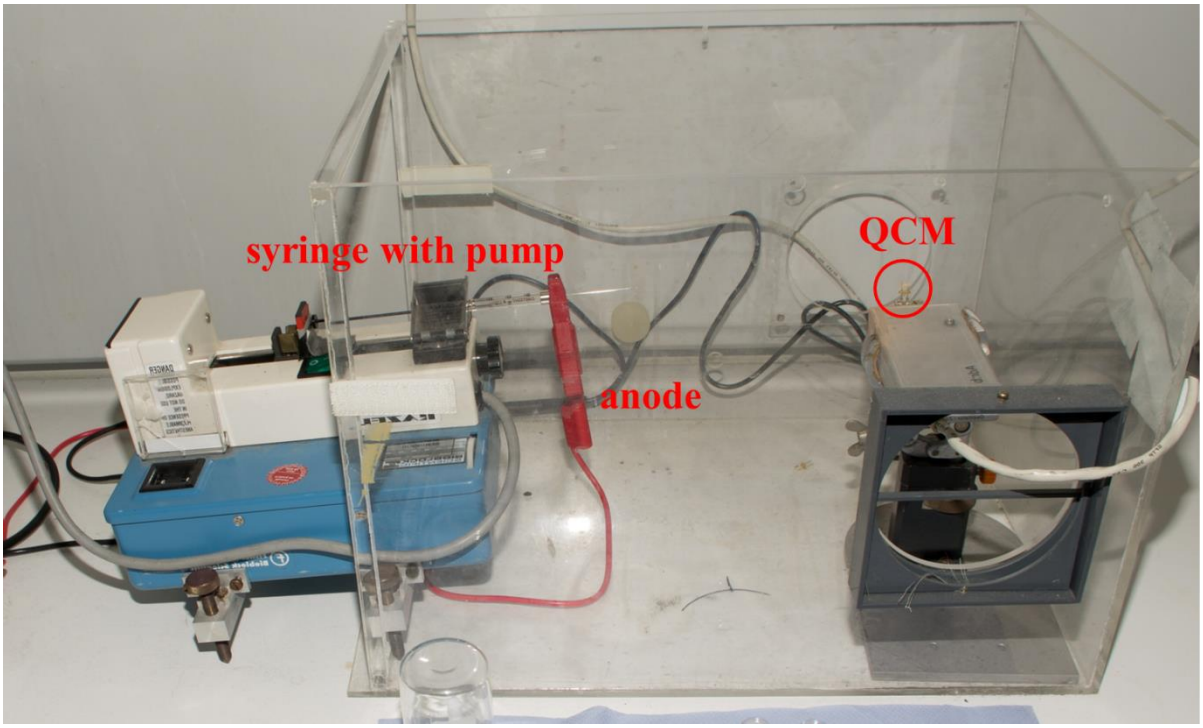

Figure S2. *The electrospray setup in the lab*.

Setup for measurement

For determination of affinities precise conditions and concentration of analytes are requires. Therefore, a "closed" system connected to a gas mixing unit is used (***Figure S3***). In this gas mixing unit, the inert nitrogen flow is divided into two streams, both controlled by individual mass flow controller (MFC) from the Brooks Instrument company (Model 5050S). Stream 1 remains unchanged in temperature and composition and is used as gas source for dilution purposes. Whereas, stream 2 is bubbled through an interchangeable analyte-reservoir which is adjusted to 293.1±0.2 K. The analyte-saturated gas stream 2 is recombined with the pure inert gas stream 1 and flows to the measuring chamber. The overall gas flow is set to 200 mL/min. By carefully controlling the flow of the both streams by the MFCs, it is possible to produce gas mixtures with a concentration of 1 to 100% of the vapor pressure of the pure analyte at 293.1±0.2 K.

The central part of the screening setup is the measuring cell which is connected to the gas mixing unit and placed in a temperature adjusted environment. We employed a slightly modified GC oven (Hewlett Packard, Palo Alto, CA, USA. Type: HP 5890). The cell is kept constantly at 308 K to exclude temperature influences and to prevent condensation effects within the cell. The cell is designed to operate up to 12 QCM in a parallel fashion.

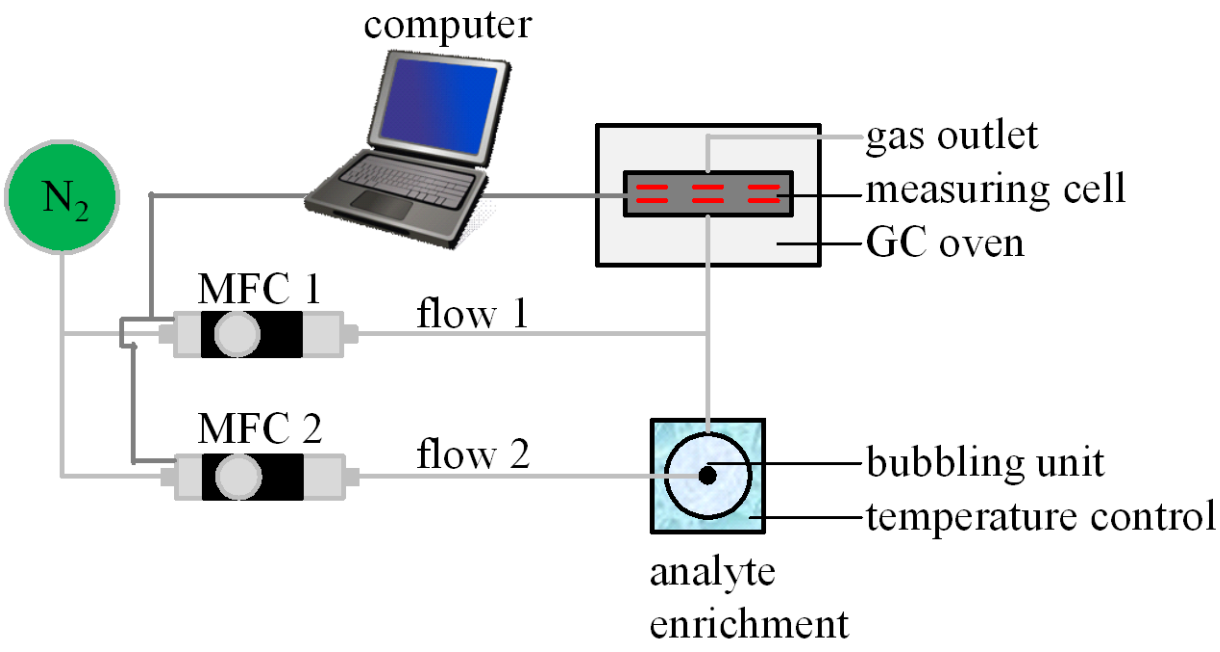

Figure S3. Setup for measurement.

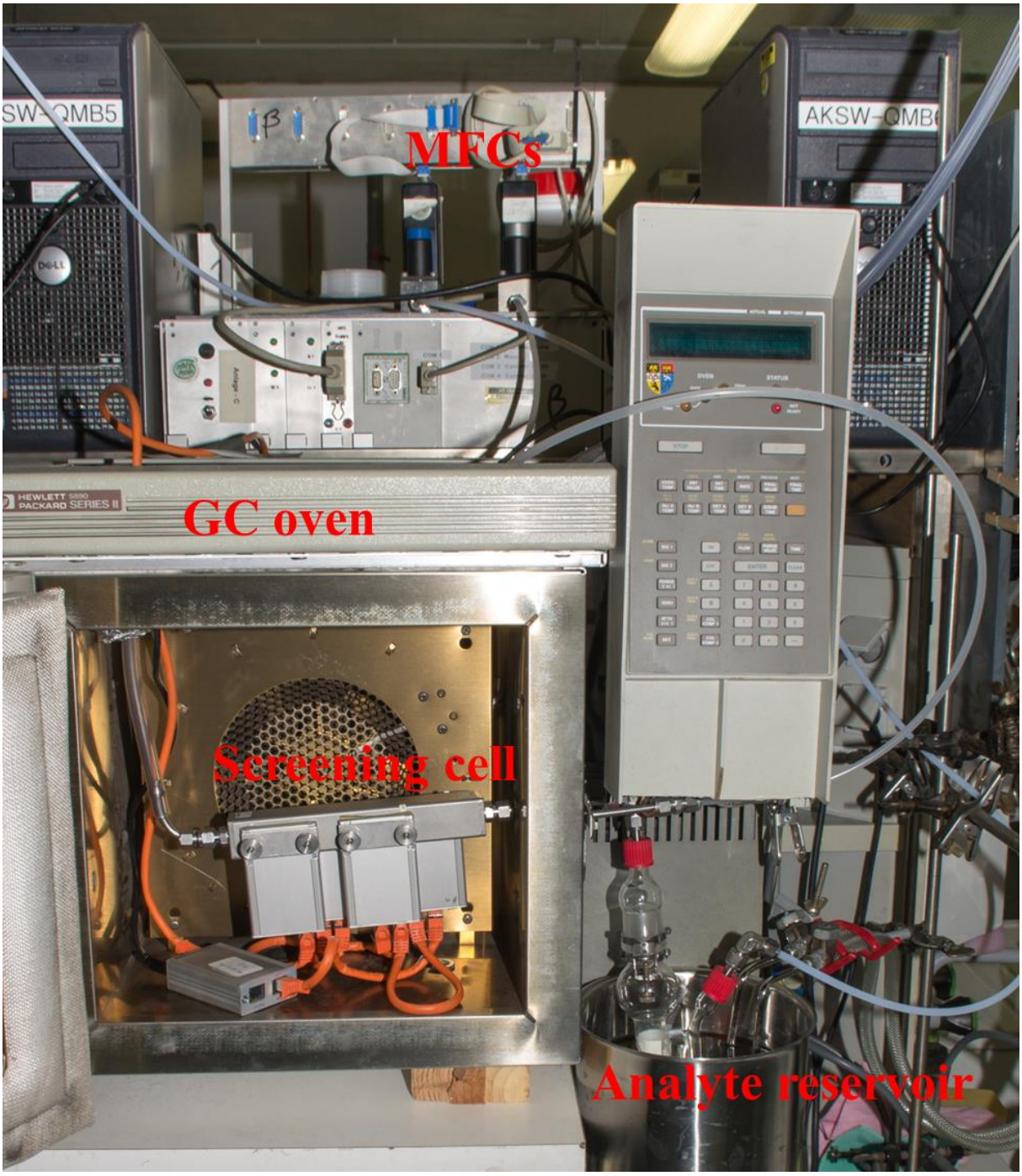

Figure S4. The experimental screening setup.

Screening

Five different compounds were selected for screening. The two halogen bond acceptors acetone and γ-butyrolactone (GBL) as well as the non-halogen bond acceptors but ubiquitous substances ethanol, water and cyclohexane.

The following example will show the procedure to determine the affinity. The screened compound in this example is the halogen bond donor **3** and the analyte is acetone. This procedure is carried out for every affinity material with the individual analyte. In ***Figure S65*** a typical measurement of an analyte is shown. The frequency shifts correspond to the different analyte concentration. In a complete measure the steps of concentration are 1%, 2%, 5%, 10%, 25%, 50%, 75% and 100% of saturated analyte vapor.

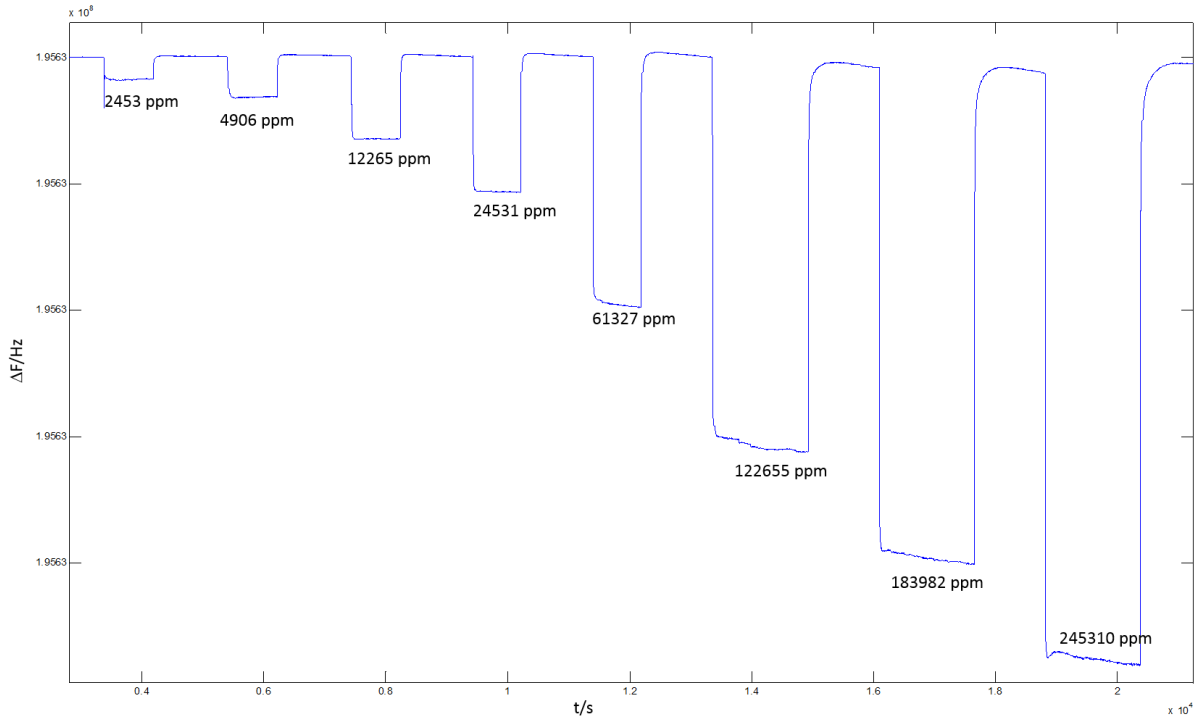

Figure S5. Frequency shift at different concentrations.

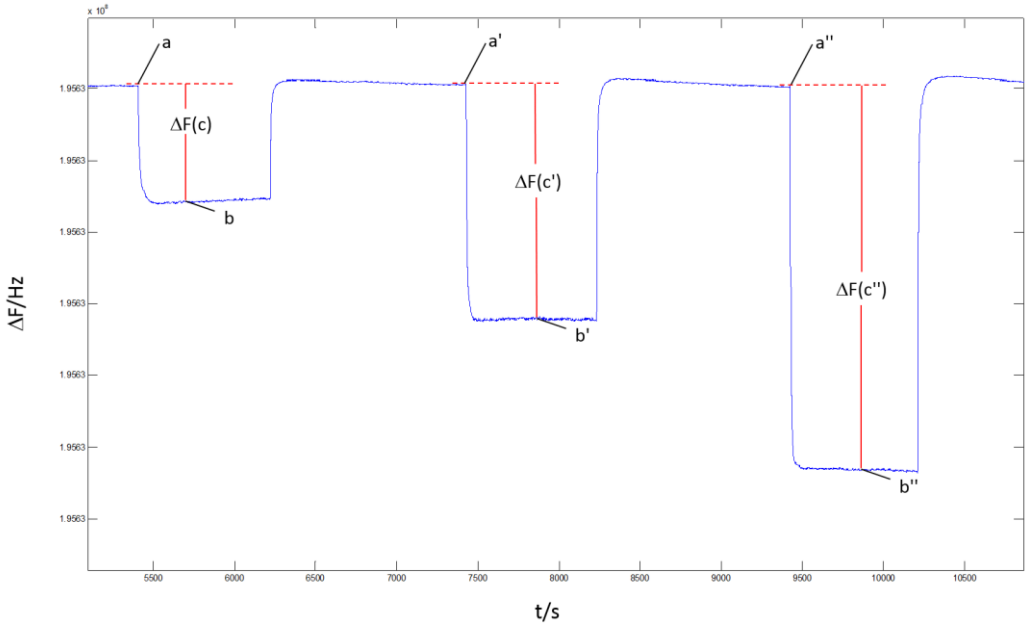

Figure S6. Detailed evaluation of frequency shifts.

To demonstrate the capability of halogen bond donors **1-3** the primary data is of those three compounds is depicted below. The blue graph is a good example for a decent affinity material with limited capacity even though there is a slight temperature drift. At higher concentration (last signal with 100% acetone vapour/245310 ppm) the signal is not as big as the 75% signal (183982 ppm) which is due to limited binding sites of the affinity material **2**. The differences n affinity of **1**, **2** and **3** towards acetone is clearly visible without any mathematic calculations.

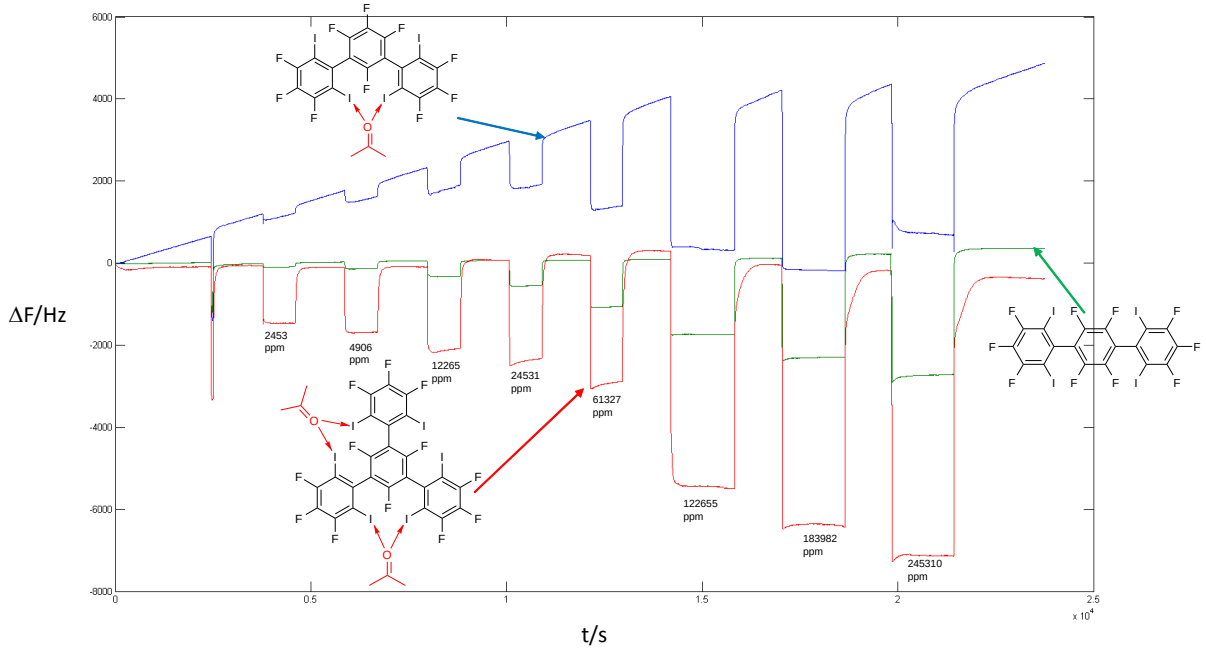

Figure S7. Primary data of affinity of XB donors **1-3** towards acetone.

By plotting the frequency shift vs. the analyte concentration the constants of the *Langmuir* adsorption isotherm was determined (***Figure S8***). The graph is obtained by fitting to equation 2.

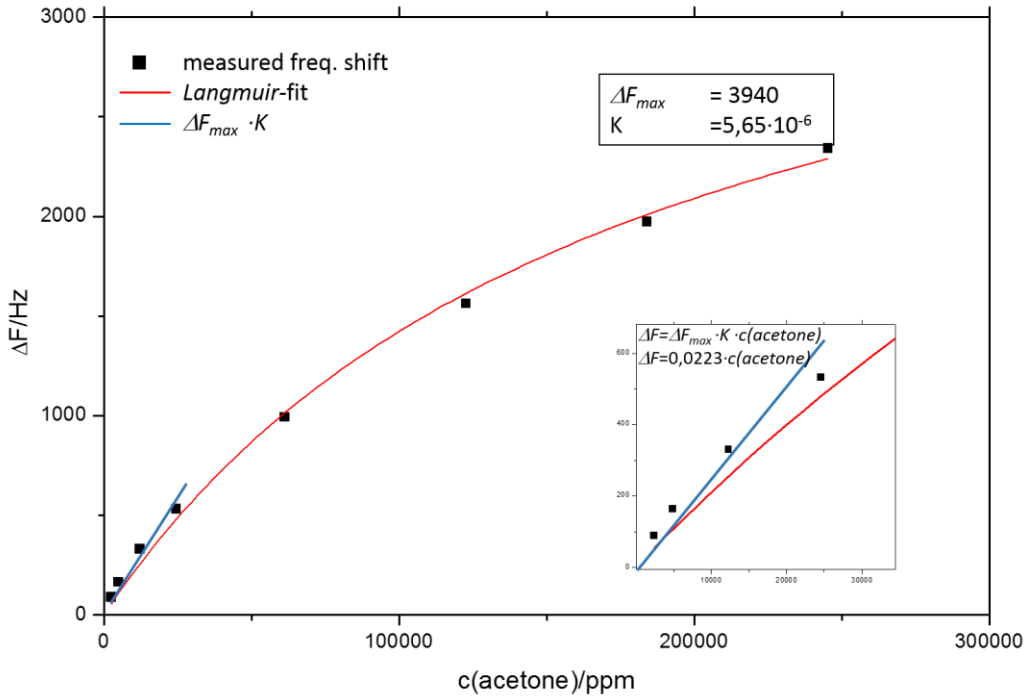

Figure S8. Determination of the affinity from the frequency shifts for different acetone concentrations (affinity material **2**).

$$\Delta F = \frac{\Delta F_{max} \cdot K \cdot c_{analyte}}{1 + K \cdot c_{analyte}} \qquad \text{S2}$$

The slope of the linear part of the *Langmuir* equation is the product of the *Langmuir* constants in equation S2.

Since the resulting value is a general information about the affinity of a film or porous material to a respective analyte, $\Delta F_{max} \cdot K$ will be used as the affinity within this study.

Table S1. Overview of screened analytes.

analyte	vapor pressure(at 20°C) /ppm	Applied concentration range /ppm
acetone	245310[6]	2453 - 245310
cyclohexane	103000[7]	1030 - 103000
ethanol	59000[7]	590 - 59000
water	23000[7]	230 - 23000
GBL	1500[8]	15 - 1500

Screening results

In order to obtain comparable results, the coating of the QCM was always made with the same mass of affinity material (50 kHz which corresponds to approx. 10.4 ng). By that, a comparable film thickness is achieved. In the following tables, the affinity is presented for the analytes mentioned in the former chapter. The affinities were obtained by the procedure described before.

Table S2. Affinities of halogen bond donors **1-3**.

	affinity / Hz·ppm^{-1}		
analyte	**1**	**2**	**3**
acetone	0.0218±0.0012	0,0557±7,31·10^{-4}	0,16027±0,00797
cyclohexane	0,02845±6,67182·10^{-4}	0,02291±6,90438·10^{-4}	0,02074±9,65727·10^{-4}
ethanol	0,06097±0,00176	0,07629±0,00297	0,06963±0,00359
water	0,52653±0,0109	0,56102±0,01387	0,57603±0,01294
GBL	1,86447±0,01437	2,76129±0,03061	4,99766±0,45151

Table S3. Affinites of non-halogen bond donors **4-6**.

	affinity / Hz·ppm^{-1}		
analyte	**4**	**5**	**6**
acetone	0.0304±8.02·10^{-5}	0,03501±2,26·10^{-5}	0,02897±6,52062·10^{-4}
cyclohexane	0,02039±0,00142	0,03118±0,00118	0,02238±0,0014
ethanol	0,06388±0,00256	0,08407±0,00225	0,06181±0,00301
water	0,61575±0,01494	0,57577±0,01411	0,63494±0,01377
GBL	1,35626±0,01431	1,50802±0,00663	1,30362±0,0087

Table S4. Affinities of γ-cyclodextrine **7** and cage compound **8**.

	affinity / Hz·ppm^{-1}	
analyte	**7**	**8**
acetone	0.047±1.82·10^{-3}	0,048±2,83·10^{-4}
cyclohexane	0,0548±0,00193	3,907±0,1159
ethanol	0,054±0,0048	0,0596±0,0026
water	0,838±0,023	0,857±0,015
GBL	1,604±0,027	1,50802±0,00663

Structure of compound **7, 8** and **9**:

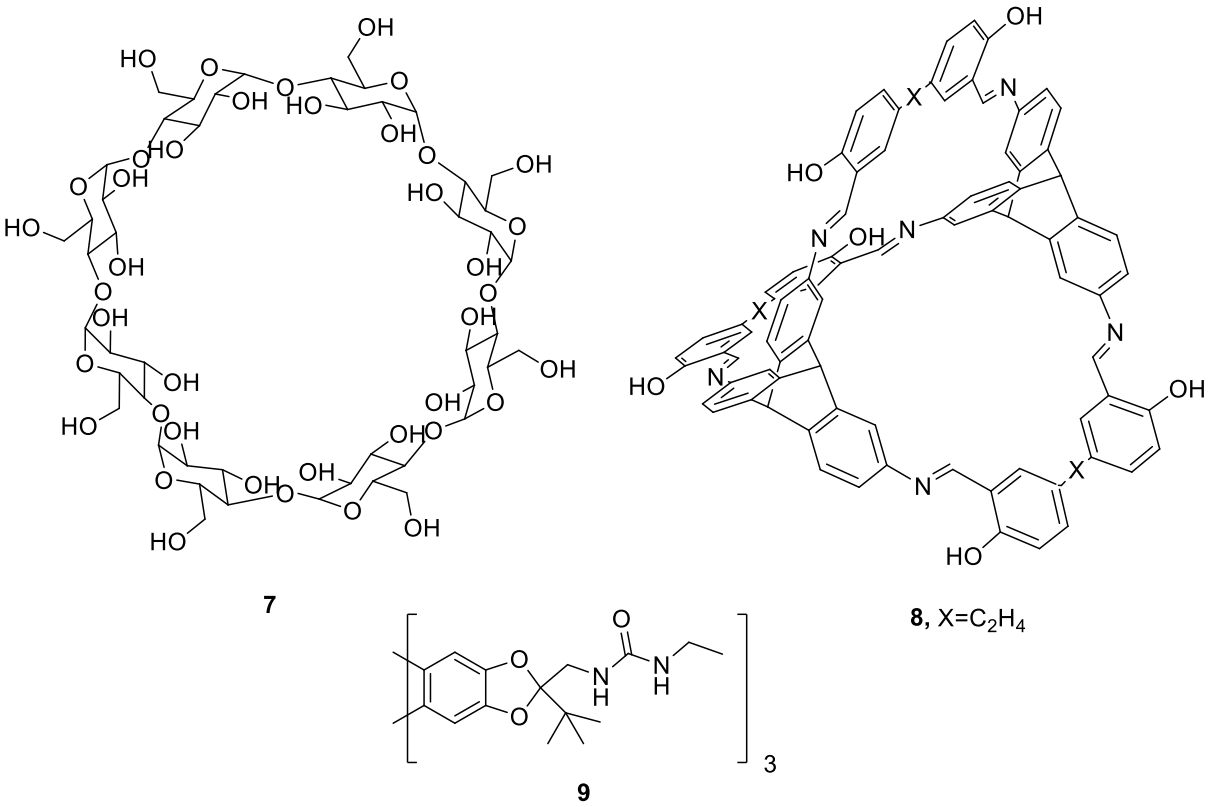

Figure S9. Structure of affinity material **7**, **8** and **9**.

Compounds **7, 8** and **9** (for acetone sensor array, see below) are examples of other potent affinity materials towards acetone and/or GBL.[10] They were chosen as a representative example of all affinity materials we have tested so far. Among those were typical literature known high potential materials as calixarenes, dendrimers, cyclophanes, cyclopeptides, polymers, triphenylenketals and other materials.

PCA

PCA input and output

The principal component analysis (PCA) is a mathematical procedure that transforms a number of correlated variables into a smaller number of uncorrelated variables called principal components (PCs).[11] By that, it is possible to reduce the dimensionality of

information into a smaller, more interpretable dimension without losing hardly any information.

In our work, we are interested in reducing the five dimensional data set of sensor responses into three or two dimensions. Since we intend a qualitative identification of analytes, the relative proportion of the responses of every QCM is required. To eliminate the influence of the absolute concentration, the signals (*S*) of all six QCMs (*i*) for every analyte at every concentration step were normalized on their sum (equation S3).

$$S_{i,norm} = \frac{S_i}{\sum_1^i S_i} \qquad \text{S3}$$

By that, we obtain a pattern which is independent of the concentration. Table S5 is an example set of data like it is used for the PCA. Every row is an individual concentration (column 2) of the respective analyte in column 1. The signals used for the PCA (Figure 3, see manuscript) were determined with a standard recovery time of 600 s between every concentration step.

Table S5: Example of a PCA input of the acetone sensor array (analyte: 0.1vol% acetone in aqueous solution)

	Normalized signals of genuine QCMs coated with				
Concentration [/ppm]	**7**	**9**	**2**	**3**	**6**
230	0,14293	0,26195	0,23754	0,21516	0,14242
460	0,15780	0,22936	0,24185	0,21318	0,15780
1150	0,16230	0,21458	0,24686	0,21397	0,16230
2300	0,16226	0,20911	0,25024	0,21602	0,16237
5750	0,16014	0,20223	0,25741	0,22026	0,15996
11500	0,15606	0,20030	0,26321	0,22445	0,15599
17250	0,15211	0,19906	0,26955	0,22696	0,15233
23000	0,14825	0,19895	0,27635	0,22813	0,14832

Table S6. Example of PCA output for the acetone sensor array (analyte: 0.1 vol% acetone in aqueous solution)

Concentration [/ppm]	PC1-74,18	PC2-14,56	PC3-7,62	PC4-3,57	PC5-0,07
230	0,002086	0,032567	-0,002543	-0,00818	-0,000226
460	-0,001295	0,019639	-0,000181	0,001271	0,000152
1150	-0,005534	0,013247	0,000416	0,004126	0,000175
2300	-0,009289	0,010383	0,000739	0,00411	0,000143
5750	-0,015614	0,006633	0,000488	0,00312	0,000184
11500	-0,021666	0,004381	0,000658	0,000813	-0,000262
17250	-0,025365	0,003348	-0,00034	-0,000503	-0,000485
23000	-0,028855	0,002394	-0,001387	-0,002048	-0,001233

Table S6 represents the respective PCA output of the input shown in table S5. The values are not correlated to an individual affinity material anymore. The resulting PCs are arranged in descending order, whereas the first component accounts for as much variability in the data as possible, the second component the second most and so on. The percentage in the header line represents the amount of variance (information) of the original data that is contained in the individual PC. By combination of PC1, PC2 and PC3 it is possible to display 96.39 % of information provided by the genuine sensor array, in only three dimensions. This can be seen from the individual coefficients of the PCs that are necessary to reconstitute the original results. The last two PCs contain only a minor amount of information and can therefore be neglected.

Coordinates of the DFT-optimized adduct

The adduct of halogen bond donor **3** with acetone was optimized with the Gaussian09 suite of programs (revision D.01) using the M06-2X density functional, the triple-zeta def2-TZVPP basis set (with pseudopotential for iodine), and dispersion corrections by Grimme (for references see the manuscript). The optimized structure was confirmed to be a minimum by the absence of imaginary frequencies. [12]

Coordinates:

C	0.31629800	1.07953600	0.84417200
C	0.40374900	1.33914400	-0.51302500
C	0.49576000	0.23759300	-1.34845500
C	0.50175800	-1.07022200	-0.89130200
C	0.41370500	-1.24608100	0.47913900
C	0.31654600	-0.19793600	1.37885200
C	0.53228200	-2.22830700	-1.81803700
C	-0.66416400	-2.73729700	-2.33282100
C	1.74270800	-2.82523700	-2.17215100
C	-0.63266300	-3.82680000	-3.18546500
C	1.75179800	-3.91484100	-3.02670300
C	0.56809200	-4.41886000	-3.53465100
C	0.34484900	2.72419000	-1.04169100

C	-0.88574800	3.28076600	-1.40426400
C	1.50796300	3.48449200	-1.17135800
C	-0.93479800	4.57720300	-1.88604400
C	1.43658000	4.77957600	-1.65606700
C	0.21910500	5.32971500	-2.01380300
F	0.20461600	2.11026400	1.67869700
F	0.39616100	-2.48831500	0.95660000
F	0.56292700	0.44620100	-2.65989000
F	-1.74599900	-4.33753100	-3.69281900
F	0.58543700	-5.46138700	-4.35061500
F	2.88359000	-4.50563400	-3.38228000
F	-2.08273600	5.13887500	-2.23820300
F	0.15966900	6.56915500	-2.47540400
F	2.52178900	5.52813000	-1.79139300
I	-2.65732400	2.19443300	-1.24633200
I	3.37764000	2.73392100	-0.65497800
I	3.56506100	-2.12481700	-1.45481000
I	-2.50161900	-1.87463000	-1.85785700
O	-4.70660400	-0.07418800	-0.78118900
C	-5.57255500	-0.33457600	0.02578600

C	-6.09432100	-1.73425100	0.19318900
H	-5.72420100	-2.12837900	1.14321900
H	-7.18306600	-1.73604900	0.24665900
H	-5.74889800	-2.36904000	-0.61795400
C	-6.15613500	0.72819400	0.91695000
H	-7.18056500	0.93057300	0.59688400
H	-6.20599400	0.37847100	1.94899700
H	-5.57045100	1.64183000	0.85237100
C	0.14710200	-0.43638200	2.83211800
C	-1.13631800	-0.51981200	3.37839000
C	1.25389300	-0.58529000	3.66861200
C	-1.30118000	-0.75002200	4.73263100
C	1.07156000	-0.81537200	5.02233800
C	-0.20103200	-0.89937200	5.55805200
I	3.19869000	-0.46662300	2.94417700
I	-2.82846400	-0.29253700	2.18885200
F	2.10092300	-0.96062800	5.84282000
F	-0.36530300	-1.11998700	6.85248100
F	-2.50598000	-0.83458500	5.27813700

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