Considerations on using SU-8 as a construction material for high aspect ratio structures

Joost Melai, Cora Salm, Sander Smits, Victor M. Blanco Carballo, Jurriaan Schmitz and Ben Hageluken

Abstract—**This paper discusses two material aspects of SU-8 that have up till now been insufficiently documented. We present initial results on the outgassing behavior and a study on the dielectric properties of SU-8 at high bias voltage. The dielectric strength is determined to be at least 2 MV/cm. These elements are investigated in the light of plans to manufacture an SU-8 based Micro-Channel Plate (MCP). Although the outgassing properties and dielectric strength are favorable the patterning capabilities are expected to limit the use of such an MCP.**

Index Terms—**CMOS compatibility, SU-8, wafer-scale post-processing, outgassing, dielectric strength**

I. INTRODUCTION

SU-8 is a photo-imagable polymer that is often used for MEMS devices and other applications where permanently remaining high-aspect ratio structures are needed. The material was originally developed by IBM, [1] and [2], as a photo-resist sacrificial mask, but lately it is mostly used a building block for High Aspect-Ratio (HAR) structures. At the moment of writing the main vendor is Microchem [3].

Del Campo and Greiner have recently published a very good review publication [4] on SU-8, this paper focuses mostly on lithographic patterning capabilities. The mechanical aspects have also been studied widely [5], [6] and [7]. Other studies have been performed on the radiation hardness of SU-8 [8], which is interesting for sensor applications.

However, we found that several key properties of SU-8 are as yet undocumented. In this paper we will present results towards the characterization of dielectric strength and outgassing properties of this widely used photo-resist.

II. STANDARD PROCESSING

Like most photo-resists SU-8 contains three main components. The first component is the SU-8 polymer strands themselves. They are highly cross-linkable in an acidic environment. Next is a salt-based Photo Acid Generator (PAG). The last component is a solvent. The results in this paper have all been obtained with the original Microchem SU-8 formulation which uses Gamma-Butyrolactone (GBL) as a solvent. There are currently two other SU-8 types available as well. SU-8 2000 provides improved coating and allows faster soft-bakes, SU-8 3000 is a version with improved adhesion to many materials, especially to glass substrates.

SU-8 is spun on using a conventional spin coater with spin speeds in the range 1000-3000 rpm. After spinning the layer is soft baked on a hotplate. The temperature is ramped up and down very slowly, from room temperature (RT) to 95 °C, to prevent cracking of the layers.

Usually conventional UV contact lithography is used to pattern the SU-8. SU-8 is a negative tone Photo-Resist. In the illuminated regions an acid will be generated by the PAG, this acid initializes the cross-linking of the polymer material. After the exposure a Post-Exposure Bake (PEB) is performed to accelerate the cross-linking reaction and the contrast of the image. For the PEB it is also important to prevent temperature shocks, the heating is slowly increased from RT to 80 °C and then lowered back to RT. Normally the layers are then developed in a solvent, most often this is acetone or the dedicated SU-8 developer PGMEA. After the development the wafers are rinsed with Isopropyl Alcohol (IPA) as water may seep into the layers and deteriorate the layer quality and performance.

After development a final Hard-Bake (HB) step may be given to strengthen the layer, remove small cracks and improve adhesion. This is normally done on a hotplate at temperatures between 120 and 180 °C.

III. ELECTRICAL TEST STRUCTURES

The test structures used for dielectric strength evaluation are Metal-Insulator-Metal (MIM) capacitors with a mesa layout. The illustration below shows a square and a circular layout.

Following the nomenclature of InGrid devices ([9], [10]) we refer to the bottom electrode as the anode and the top electrode as the cathode. The overlap of the anode over the dielectric is always 0.2 mm on all sides, the overlap of SU-8 over the cathode is 0.2 mm as well. These large overlap values are intended to keep surface leakage current minimal.

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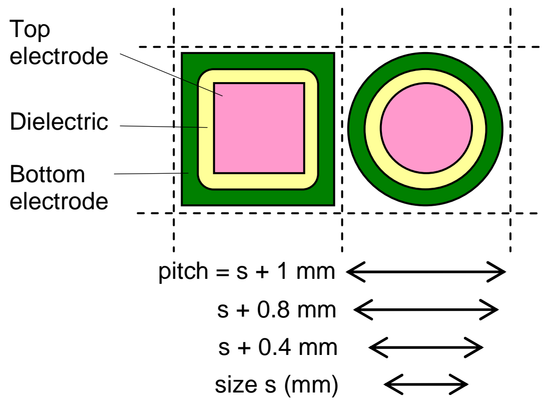

Figure 1: Illustration of a square and a circular layout.

The size of the devices is in the (sub-)mm regime. The following device sizes are available in both circular and square layout: 0.1, 0.2, 0.3, 0.5, 0.7, 1.0, 1.2, 1.5 and 2.0 mm. Of the circular version additional structures are available with diameters of 3, 5, 7, 10, 15 and 20 mm. There are also rectangular devices with varying aspect ratio.

The abnormally large areas of the devices are needed to obtain measurable results, both in leakage current and capacitance, when the dielectric thicknesses are increased to tens of micrometers. A typical MCP needs to be at least 50 μm thick [11] to reach a gain of ~ 1000 in a single stage.

The range is chosen around a nominal value of 2 mm that is such that with a 50 μm thick SU-8 layer a capacitance of > 1 pF is expected. This capacitance can easily be measured.

IV. Processing of Test Structures

The test structures presented in this paper are made in a manner similar to that of the suspended grid structures presented in [9] and [10]. The main difference with the standard processing described in section II above is the delay of the development step until after the top metal electrode has been patterned. This is the most straightforward method to reliably define mesa structures of this type. Additionally this makes the comparison between these structures and the InGrid devices more easy. The processing sequence is shown in Figure 2 below.

First the metal anode is made by sputtering 1 μm of Al on top of a substrate. The devices are made on top of a carrier Si substrate with a thermally grown oxide layer of app. 900 nm. The Al is patterned using lithography, wet etch (PES etchant at 55 °C) and strip (fuming HNO_3), see Figure 1a.
The SU-8 layer is spin coated with varying thickness, the layer is soft-baked following the standard recipe (95 °C for 5 minutes), the SU-8 is exposed (140 mJ/cm^2) and the PEB is performed (80 °C for 4 minutes, slow temperature ramping). The situation after this is shown in Figure 1b.

On top of the SU-8 layer a 500 nm thick Al cathode layer is deposited by low power sputtering. This metal layer is patterned in the same way as the anode, Figure 1c.
Finally the SU-8 layer is developed. All un-exposed, un-cross-linked regions are directly exposed to the developer. Development is done by immersion in acetone at 30 °C using ultrasonic excitation. The development time that is needed is checked visually. Depending on the layer thickness it is between 5 and 10 minutes. The final result is shown in Figure 1d.

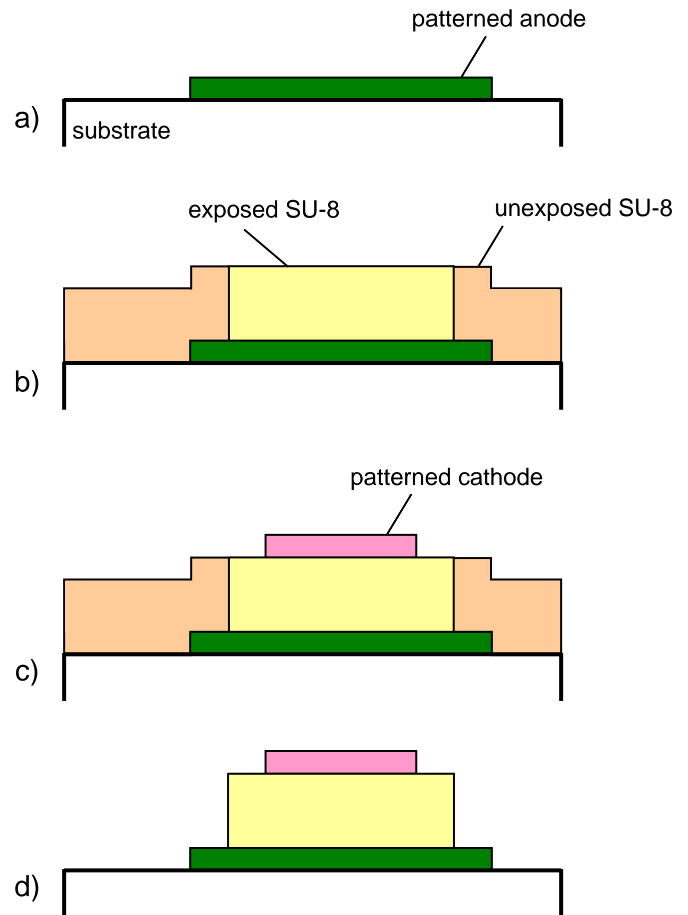

Figure 2: Overview of the processing sequence followed to make the test structures.

The layer thickness of SU-8 was varied by using the spin conditions given in the table below. Two different dilutions of SU-8 have been used to reach the required thicknesses.

Intended thickness [μm]	Material type -	Spin speed [rpm]	Measured thickness [μm]
2	SU-8 2	2000	2.25
3	SU-8 2	1500	2.85
4	SU-8 2	1000	3.93
5	SU-8 5	2000	7.36

Table 1: SU-8 thickness variations

The final thickness after processing has been measured using a Dektak profiler. For the three thinnest layers the measured values are in good agreement with the intended thickness. The thickest layer however is much thicker than intended.

V. ELECTRICAL CHARACTERIZATION

The mesa structures have been characterized using High Voltage (HV, up to 2.5 kV) IV measurements performed on wafer-scale in a Karl Süss PM8 probestation, the measurements are performed using continuous N_2 flushing. A HV DC signal is applied to the cathode using a Fug HCN 200 K-12500 HV source. To prevent discharges a special, dedicated, probe has been made. In a normal probe the coaxial (or triaxial) orientation of the signal and ground/shield leads is maintained to very close to the probed surface in order to limit aberrations due to capacitive/inductive coupling. With our HV probe however the shield ends some distance (several cm) before the probe needle to prevent discharges. The probe arm is made out of Teflon (in stead of metal). The mechanical manipulators are those of a standard Karl Süss probe.

The other terminal of the device is contacted with a standard SMU of an Agilent 4156-C parameter analyzer. This terminal is kept at 0 V and the current is sampled continuously.

To limit the discharge current in the event of dielectric breakdown as well as to shield the current sensing SMU from the high voltage a protection resistor is connected in series with the device at the high side. For the presented measurements we have used a 1 MΩ resistor network with a maximum power rating of 8 W.

The results of our measurements are presented in paragraph VIII below.

VI. DISCUSSION: AN SU-8 MICRO CHANNEL PLATE

Because of the good qualities of SU-8 as a structural material we have investigated the use of SU-8 to manufacture a post-processed Micro Channel Plate (MCP) on top of the top metal layer of a finished IC made using a conventional CMOS IC process. The SU-8 will be used as the material to make the porous dielectric body of the MCP. For engineering an MCP there are three main requirements to consider, for more details on these see [11].

1. Geometry, it is needed to obtain pores with an aspect ratio (AR) of at least 50:1.
2. Outgassing, the material needs to be compatible with the vacuum environment needed for MCP operation.
3. Dielectric strength, the material needs to withstand the bias voltages that are needed when the MCP is used.

The way in which SU-8 responds to these requirements is discussed below in detail for each of the three domains.

VII. GEOMETRY

There are several alternative methods available to pattern SU-8. The first one is photo-lithographic patterning, the way SU-8 is normally patterned. Also SU-8 can be etched using dry plasma etch techniques. In both cases the mass transport of the removed material forms a problem for very high aspect ratio structures.

There are a lot of publications focusing on the use of SU-8 for HAR structures made with lithography [4]. Many of these are dark-field structures where most of the SU-8 is removed leaving only narrow long pillars and other structures. For Light-Field structures (narrow holes in SU-8 fields) the AR limits vary between 10:1 [12] up to 20:1 [13]. Although these values may be even further improved it is hard to imagine that SU-8 can be patterned leaving 100:1 or even 50:1 holes. This means it will be impossible to operate a lithographically defined SU-8 MCP with high enough gain [11].

Another option to pattern SU-8 is by etching the material using Reactive Ion Etching in plasmas of CHF_3 or SF_6. With this method we have attained etch speeds of 0.12 and 0.34 µm/min respectively. The AR limits are still under investigation. The results are shown in Figure 3.

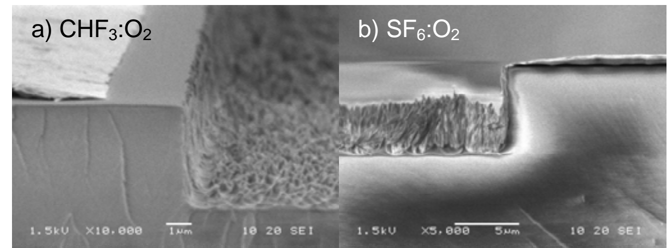

Figure 3: SEM images of etched SU-8 pits, using two different chemistries (indicated)

An alternative to standard RIE could be a Bosch-like etching process for polymers where O_2 plasma etching is alternated with C_4F_8 polymer passivation. One interesting publication [14] reports etched holes with a straight sidewall and an AR of 20:1.

Despite the increased process complexity of dry etching SU-8 it does not seem to increase the patterning capability, in terms of AR, compared with photo-lithography. The conclusion remains, so far, that the highest aspect ratio obtainable for pores in SU-8 is 20:1.

VIII. DIELECTRIC STRENGTH

We have measured cathode current as a function of (positive) bias voltage applied to the anode. The bias was increased in steps of 50 V, each time a reading is taken after the current has stabilized. The current increases steadily with voltage, in a few cases the current shows a drop (usually in the 600 to 900 V range). Figure 4 is typical, it shows J-V curves for circular devices with an SU-8 thickness of 3.9 µm. The current density is calculated by dividing the current with the anode area as measured after processing. We assume the current mainly consists of a bulk component that scales with electrode area and a surface (overlap) component that scales with the perimeter. From the initial results we conclude that well before breakdown ($V < 1000$ V) the area component is dominant, this is in agreement with Figure 4.

When the bias is increased we are unable to measure intrinsic, bulk breakdown of the SU-8 structure. Instead breakdown occurred in all cases on the perimeter of the device. At this end of the range the perimeter current will of course dominate.

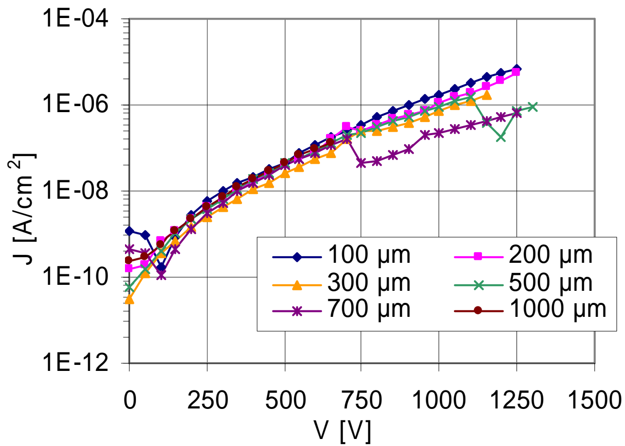

Figure 4: J-V characteristic of a series of circular devices (diameter indicated), the SU-8 thickness is 3.93 µm.

It is thought that the breakdown mechanism is the formation of a low resistive path between the two electrodes along the dielectric surface, this can also be seen from the damage visible after breakdown, see Figure 5. To check this hypothesis a new mask-set needs to be made incorporating a series of devices with varying SU-8 over cathode overlap.

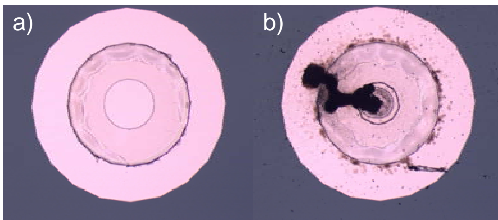

Figure 5: Micrographs before (a) and after (b) the breakdown event, the anode is 0.2 mm in diameter.

The breakdown measurements do however provide a lower limit to the dielectric strength (DS). The breakdown voltages (V_{BD}) and the (minimum) dielectric strengths derived from this are given below. The values are an average over different device geometries on each wafer.

Wafer	Thickness [µm]	V_{BD} [V]	DS [MV/cm]
A	2.25	0	-
B	2.85	650	2.28
C	3.93	1283	3.27
D	7.36	1342	1.82

Table 2: Apparent dielectric strength of different SU-8 layers

The thinnest layer clearly shows a problem. This layer starts to conduct readily at very low bias levels, no breakdown voltage can be determined.

The other 3 values are reasonably consistent. It must be said that the dielectric strength indicated is a lower limit, the real value may be higher. From this it can be concluded that for high voltages SU-8 is a fairly strong dielectric reaching at least 25 to 30 % of the DS of thermally grown SiO_2 (~ 8 MV/cm for thick layers).

The values that are found are certainly sufficient for the use of SU-8 as a dielectric in an MCP.

IX. Outgassing of SU-8

The outgassing characteristics have been investigated by placing samples of Si coated with various layers of SU-8 in a vacuum chamber, a mass spectrometer (Pfeiffer QMS Prisma) is connected in front of the pump to sample the gas flow coming out of the system. The entire chamber can be elevated in temperature. In the spectra we always find peaks at 18, 28 and 32 amu, these originate from water, nitrogen and oxygen respectively. These form the background signal also present in reference measurements without any SU-8. If we introduce the SU-8 coated samples we start to see prominent signals from heavier clusters, these are mostly carbohydrate groups emanated from the organic SU-8 surface. The samples that we used were 2 cm × 2 cm, they had a layer of 50 µm SU-8 that has been processed in the standard manner. All the SU-8 is cross-linked with a blanket exposure.

Figure 6 in the appendix below shows traces of different masses sampled over time while the system is heated from Room Temperature (RT) to 150 °C and subsequently let to cool down. The down going traces before the heating are related to the sample introduction. We see that some of the carbohydrate compounds are released and depleted within 20 minutes (labeled A). Other groups are more persistent (labeled B), they are not completely released after 90 minutes.

To check in more detail a long series of analog mass scans was made. Each cycle takes 2 minutes. During this series the sample was first heated to 150 °C (until cycle 30), it remains at 150 °C for 30' (cycle 30 to 45), then it is heated further to 200 °C, the T stays constant (cycle 50 to 75), after that the temperature is decreased and kept constant at 20 °C (last 100 cycles). The result of these scans is plotted in Figure 7 in the appendix below. The sample that was used for this also underwent a Hard-Bake step after development for 20' at 150 °C. It is clear the outgassing is very different, due to the additional Hard-Bake step all outgassing is completed in 45 minutes, further outgassing is limited to CO_2 (mass 44), which is a background signal that can be neglected.

X. Conclusion

SU-8 remains to be a very popular constructive material for high aspect ratio structures. This paper presents first results on material characterization of aspects that have so far not been sufficiently documented. The dielectric strength is found to be at least 2-3 MV/cm, or more than 25% of the value for thick layers of thermally grown SiO_2. The real value is probably higher since the intrinsic, bulk, breakdown voltage could not be reached.

The outgassing characteristics have also been studied, initial results are presented. There are significant organic components that need to be released, an outgassing step will certainly be needed before operating an SU-8 based device in an (Ultra-) High Vacuum environment. A hard-bake step of

the cross-linked SU-8 seems to be essential in preconditioning the material for this.

Concerning the fabrication of an MCP out of SU-8 the main challenge remains to be patterning the structure into a porous matrix with high aspect ratio holes.

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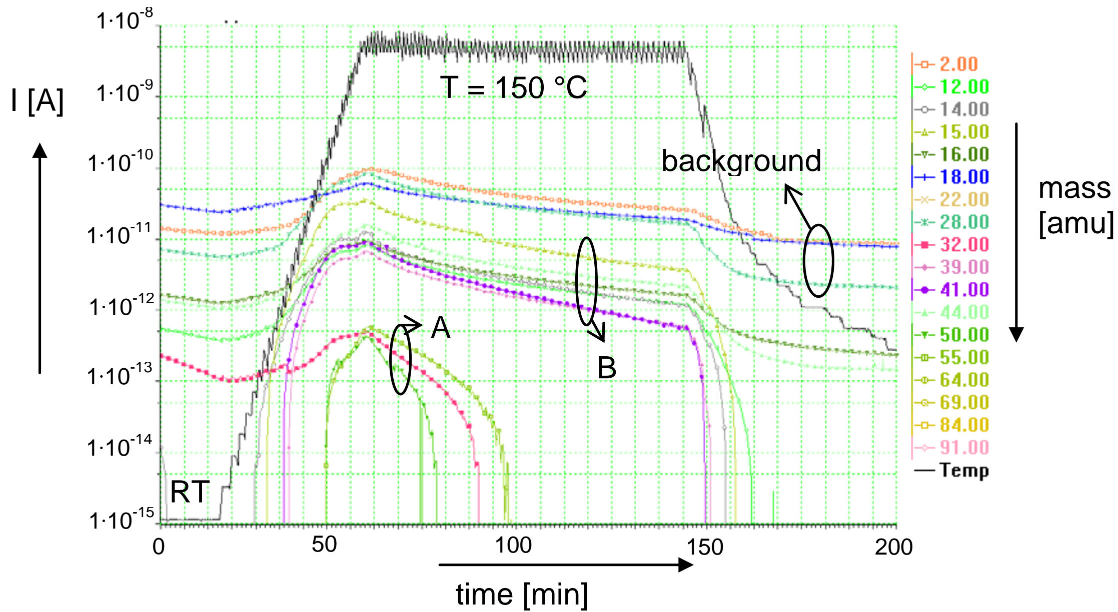

Figure 6: Mass sampling over time with T ramped to 150 °C. We see a group of carbohydrates (mass 50 and 64, labeled A) that is depleted quickly as well as a group (mass 41, 44, labeled B) that is not depleted after 90' outgassing at 150 °C. There is also a strong background signal present from H_2 (mass 2), H_2O (mass 18) and N_2 or CO (mass 28), these masses are also found in reference measurements without any sample.

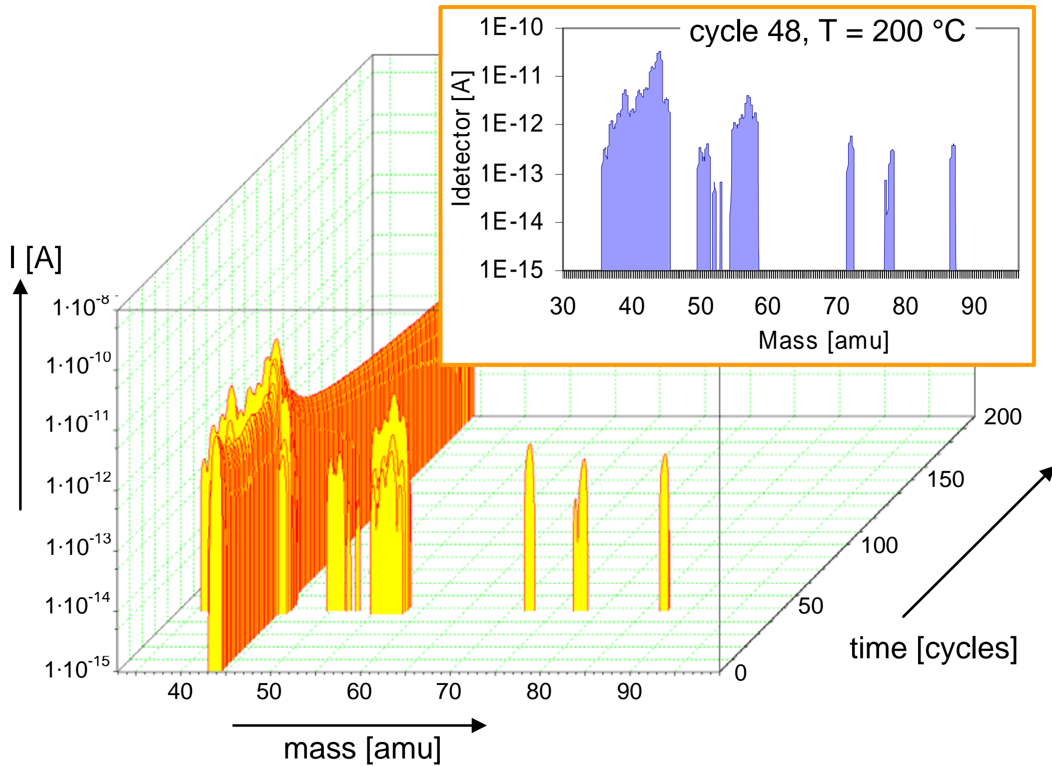

Figure 7: Series (z-axis) of 200 analog mass spectra (from mass 33 to 100, x-axis), the y-axis displays the detector current in A. This sample has received a high temperature (150 °C) Hard-Bake during processing. The inset shows mass spectrum 48 (T = 200 °C), when most material is released, in a few cycles all this is depleted and from ~ cycle 70 onwards further outgassing is limited to background CO_2 (mass 44).