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Ensuring Minimal Humidity Levels in Hermetic Implant Housings

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***Abstract*—The electronic circuitry of active implantable devices is commonly protected against the risk of water-induced corrosion by using gas-tight (hermetic) packages, preventing moisture from the host body to reach the electronics. However, when closing the package, one has to ensure that the packaged components do not contain moisture that could rise humidity inside the package to critical levels by outgassing. For our miniature metal/ceramic packages, we found a drying procedure of 120°C at 180 mbar absolute pressure for one hour, followed by a dry helium purge sufficient to keep the relative humidity below 2.5% over a time span of 300 days at 80°C, corresponding to over 15 years at 37°C. The additional integration of a desiccant inside the package permits to keep the relative humidity below 0.1%, the detection limit of the integrated sensor. This sensor was selected based on an evaluation of 17 commercially available humidity sensors.**

I. INTRODUCTION

Since decades it is common knowledge that humidity is a major cause of failure for complex integrated electronic circuitry [1],[2]. Therefore, when extreme reliability is required, e.g. in space missions, military equipment or life supporting implanted medical devices, humidity has to be kept away from electronic circuitry. This is commonly achieved by placing the electronics in a gas-tight (hermetic) capsule that prevents humidity from outside the capsule to reach the circuits. However, the environment of the package is only one of three potential water sources. The other two are water that is generated inside the package by chemical reactions and water that was adsorbed by components inside the package before hermetic sealing and is slowly outgasses into the packaged atmosphere over time. In previous work we were able to fabricate miniature hermetic packages (volume $V = 0.71$ mm³) with very low leakage rates of $R_{He} \leq 10^{-12}$ mbar·l/s [3]. These leakage rates permit to neglect the effect of humidity from outside the package entering the package. In the work presented here we address the problem of component outgassing inside the package.

II. MATERIALS AND METHODS

A. Measuring Humidity

There is a large number of commercially available humidity sensors. In order to select the best suited sensor for our application one has to define the specifications.

A commonly cited limit for acceptable humidity inside a hermetic implant package is 5000 ppm_V [4]. Presuming atmospheric pressure inside the implant package and an ambient temperature of 37°C, this corresponds to a relative humidity (RH) of 8.1%. Thomas found 17000 ppm_V or more to be required for keeping corrosion of aluminium thin-film interconnects on an integrated circuit progressing [1], translating to 27 %RH at 37°C. We therefore define that the range of humidity levels measureable by the sensor should be from 0 %RH (ensuring to begin with a very dry package) to 27 %RH. This range also defines the maximum acceptable sensor drift. Presuming a sensor drifts by 0.5 %RH/year, we loose confidence in the measurements over time. After 54 years, the sensor reading might show 0 %RH which means for the worst case that the actual humidity level is at critical 27 %RH. Many commercially available sensors require individual calibration after assembly. For practical reasons, this should be avoided. The sensors should be shipped fully calibrated by the supplier.

Tab. 1: Requirements for an implant package humidity sensor

Property	Value	Importance*
range of measurement	0 ... 70 %	H
drift over time	< 0.5 %RH/year	H
accuracy @ 37°C, low RH	±5%RH	H
calibration	by supplier	H
size of sensor	« 1 cm³	H
format of measured data	digital	M
temp.sensor integrated	yes	M
power consumption	≤ 1 mW	M
sampling time	≤ 10 s	L

*Importance is ranked high (H), medium (M) or low (L)

Implant packages are kept as small as possible, therefore the sensors should be as small in size as possible, too, preferably available as bare die. In an intact package, the humidity level is expected to rise very slowly over time. Sampling of the humidity might be sufficient once per month. However, in experimental packages, where failure modes are not entirely understood, faster sampling might be beneficial. During operation, the sensor should not consume excessive amounts of electrical power especially in battery-based implants, although it is switched on only for a short time with large intervals between two measurements. Preferably, the sensor data is provided digitally, easy for the commonly digital processing unit of the implant to read.

Based on these demands (summarized in Tab. 1) we evaluated 17 commercially available humidity sensors by

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their technical datasheet and selected the most suitable. This task was carried out in early Summer 2010, when our experiments started. Later developments on the sensor market could not be taken into account.

B. Use of Desiccants

In case of water vapour entering the package or outgassing of components inside the package, a water getter (or desiccant) can be used for absorbing the water, keeping the atmosphere inside the package dry. Desiccants can bind water molecules either chemically or physically. Chemical binding usually is a non-reversible process based on metal oxides reacting with oxygen. The process is exothermal and therefore generates heat. The most prominent chemical desiccant is CaO. Although chemical desiccants absorb water even at very low humidity levels, we decided for our study to use physically binding desiccants. Their underlying adsorption process is reversible and therefore they are easier to implement into our packaging process, during which they are glued to the implant printed circuit board (PCB) and dried (activated) just before the package is sealed. Three major technological classes of physical desiccants exist: 1.) Silica gel: highly porous silicon dioxide offers a large surface for water molecules to adsorb. Silica gel works most efficiently at room temperature at humidity levels of larger than 30 %RH, where 100 g gel adsorbs 15 g H_2O. At 60 %RH, 100 g silica gel is able to adsorb 35 g H_2O. 2.) Molecular sieves: a framework of pores and open cavities, which sizes are designed to adsorb molecules of certain polarity and size. Various base materials are used, such as glasses, aluminosilicate minerals, zeolites, clays, charcoals, active carbons, etc. Molecular sieves adsorb moisture over a wide temperature range and are most efficient at a humidity of 8 %RH and larger, where it adsorbs about 22 g to 25 g H_2O per 100 g desiccant, independent from the relative humdity. 3.) Activated clay: layers of silicate are attracted to each other by electrostatic forces. Water molecules can adsorb between these layers. This naturally occurring desiccant is most efficient at very high levels or relative humidity. In the range below 30 %RH its performance is between that of silica gel and molecular sieves. At 5 %RH, 100 g clay adsorbs about 5 g H_2O. With rising humidity level, the adsorption capacity increases almost linear to about 20 g H_2O at 60 %RH.

In the study presented here, we investigated the humidity inside packages without any desiccant, with two different molecular sieves (*Tri-Sorb*, pill-shaped ∅=6 mm, 2.5 mm height, based on crystalline metal aluminosilicate zeolite, Sued-Chemie AG, Munich, Germany; *SafetySorb 551*, zeolit beadlets, ∅≈0.7 mm, W.R.Grace & Co, Columbia, MD, USA) and with silica gel (*Orange Chameleon*, bead, ∅≈2.5 mm, BASF Catalysts LLC, Islen, New Jersey, USA).

C. Fabrication of Implant Packages

The concept and fabrication of our miniature implant packages was described in detail by Schuettler et al. [3]. For a general understanding, we summarize the fabrication procedure: A 0.635 mm 96% alumina substrate was used as base for the package, as printed circuit board for the implant electronics and as electrical feedthrough structure. Therefore, Pt/Au tracks were screen printed on it, forming feedthroughs and contact pads for electronics. A dielectric frame and subsequently a Pt/Au frame were printed on top. A layer of glass was printed to cover the dielectric and to electrically insulate the metal tracks (Fig. 1-a). To this substrate (25.4 x 25.4 mm²), two surface-mount components: a humidity sensor and a ceramic capacitor were soldered. To some substrate, a desiccant was glued using two-part silicone rubber (Fig. 1-b). A lump of solder was placed on the top of a brass cap. A 1 mm hole was drilled through cap and lump and the cap was soldered to the metal frame on the substrate (Fig. 1-c). At this stage, the punctured package was transferred into the chamber of a sealing tool, described by Schuettler et al. [5], where it was heated in low vacuum atmosphere in order to remove unwanted water molecules from inside the package (see next section) and to activate the desiccant (Fig. 1-d). Subsequently, the package was backfilled with 100 % helium atmosphere (Fig. 1-e). Finally the package was hermetically sealed by melting the punctured solder lump (Fig. 1-f). The hermeticity of the package was evaluated by helium leakage tests.

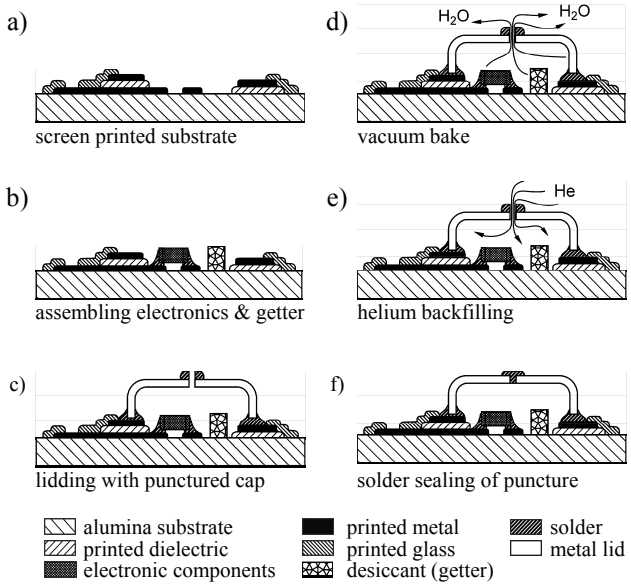

Fig. 1: Fabrication, drying and sealing of miniature hermetic package.

The fabricated packages had a total number of 360 radial feedthroughs. The package internal volume was 0.71 cm³.

D. Drying of Implant Packages

There is a variety of recipes reported on how to properly dry packages, removing water adsorbed on metal surfaces or driving vapour out of plastic packages. However, the humidity sensor inside our package is limited to an operation temperature of T = 120 °C (we used the packaged

sensor for monitoring the actual drying process) and our vacuum supply does not exceed an absolute pressure of p_{abs} = 100 mbar, we are limited to these maximum values and take the option to investigate the treatment time as well as the influence of the desiccants inside the packages. Tab. 2 lists the types of drying procedure applied, type of built-in desiccant and the corresponding sample name.

Tab. 2: Sample name, drying procedure and built-in desiccant

Sample	Drying Procedure	Desiccant
A	10 min, 120°C, 180 mbar	none
B1-B4	step 1: 4 days, 80°C, 120 mbar step 2: 10 min, 120°C, 180 mbar	none
C1-C2	1 h, 120°C, 180°mbar	none
D1-D2	1 h, 120°C, 180°mbar	1 silica gel bead
E1-E2	1 h, 120°C, 180°mbar	1 Tri-Sorb pill
F1-F2	1 h, 120°C, 180°mbar	~20 SafetySorb beadlets

All samples except *B1-B4* were dried in the processing chamber of our sealing device. *B1-B4* were pre-dried in a separate oven and then transferred to the sealing chamber. The transfer time was in the order of 3-5 minutes during which the samples were exposed to ambient atmosphere.

E. Evaluation of Drying Success

During drying in the sealing chamber, the humidity inside the package was monitored by reading the measurements taken from the sensor inside the package. Each package was sealed once the relative humidity inside the package at 37°C was 0.1 %RH or less. All packages were stored at 80°C in a dry oven (0.7%RH, corresponding to 10 %RH at 25°C) at P_{abs} = 125 mbar for accelerated lifetime testing. The intention for applying a low vacuum was to ensure a low humidity environment. By this way, potential rise of humidity inside the package can be attributed to outgassing of enclosed components or desorption of water molecules from the package lid or substrate. After 180 days, corresponding to 10 years at 37°C accelerated lifetime (according to an Arrhenius model using a reaction rate of Q_{10} = 2.0 [6]), samples *A* and *B1-B4* were removed from the test bench and opened in order to check the function of the built-in sensors at room temperature against two reference sensors that did not undergo accelerated aging. The remaining samples *C1-F2* were placed in 80°C tap water at atmospheric pressure in order to see a potential effect of vapour entering the package from outside. Measurements of relative humidity were taken once per week, in the beginning two weeks of the experiments at least once per day. For taking the measurements, the samples were cooled down to 27°C in order to operate the sensors close to the lowest relative error. A measurement (including the cool-down) took about 5 minutes. Subsequently, the samples were returned to their 80°C storage.

III. Results

A. Humidity Sensor Selection

The sensor features varied strongly in many aspects according to their datasheets. Tab. 3 lists a selection of these features. Only the SHT15 sensor by Sensirion met all our requirements and was therefore integrated in the hermetic packages. Its basic working principle was capacitive sensing of humidity absorbed in a polymer.

B. Sample Fabrication

A screen-printed alumina substrate with assembled sensor, capacitor and desiccant (silica gel) before and after lidding is shown in Fig. 2.

C. Evaluation of Drying Success

At the time this manuscript was submitted, the samples were under test for 300 days. The measurements taken are displayed in Fig. 3. After 30 days, the sensor of sample *E3* (Tri-Sorb desiccant) stopped responding, caused by a faulty solder joint.

Tab. 3: List of humidity sensors and selected properties. A dash indicates missing information.
A gray background indicates that a requirement for use in implant packages is met.

manufacturer	sensor model	range (%RH)	max.drift (%RH/year)	accuracy (±%RH)	calib-rated?	temp. sensor?	size (mm³)	power (mW) x time (s)	output signal
E+E Elektronik[1]	HC103M2	0..100	-	-	no	no	5.9·2.9·0.6	- x 3	capacity
E+E Elektronik[1]	HC104-K00	0..100	1.5	-	no	no	5.6·2.9·0.6	- x 6	capacity
E+E Elektronik[1]	HC105	0..100	1.5	-	no	no	5.9·1.4·0.6	- x 6	capacity
E+E Elektronik[1]	HC109	0..100	1.5	-	no	no	4.2·1.0·0.3	- x 6	capacity
Galltec+Mela[2]	FE 09/4	0..100	1	-	no	no	18·5.1·4.6	- x 10	capacity
GE Sensing[3]	ChipCap	0..100	-	3	yes	yes	9.5·6·3.2	2.5	dig.+anal. volt.
Honeywell[4]	HIH-4031	0..59	1.2	3.5	yes	no	13·4.2·2.7	1 x 5	analog volt.
Honeywell[4]	HIH-5031	0..100	1.2	3	yes	no	13·4.2·2.7	0.66 x 5	analog volt.
HopeRF[5]	HH10D	1..99	0.5	3	yes	no	24·8·-	0.45 x -	frequency
HopeRF[5]	HHT02X	0..100	0.5	4.5	yes	yes	14·10·-	2.75 x 30	digital
Hygrosens[6]	KFS140MSMD	0..100	-	-	no	no	4·2·0.4	- x 6	capacity
Hygrosens[6]	HYT 271-H	0..100	0.5	1.8	yes	yes	10·5.1·2.0	4.95 x 4	digital
IST AG[7]	P14 Femto-Thermo	0..100	-	-	no	yes	4·2·0.4	-	capacity/resist.
Meas. Specialities[8]	HTS2030SMD	1..99	0.5	-	no	yes	14·12·9.3	- x 5	capacity/resist.
Precon[9]	HS-2000DD	0..100	0.5	2	yes	yes	23·12·9.3	5.5 x 25	digital
Sensirion[10]	SHT15	0..100	0.5	4	yes	yes	7.5·4.9·2.6	1.82 x 8	digital
Sensirion[10]	SHT21	0..100	0.5	7	yes	yes	3·3·1.1	0.9 x 8	digital

[1] Engerwitzdorf, Germany, [2] Mohlsdorf, Germany, [3] Pforzheim, Germany, [4] Morristown, NJ, USA, [5] Shenzhen, Guangdong, China
[6] Löffingen, Germany, [7] Wattwil, Swizerland, [8] Hampton, VA, USA, [9] Memphis, TN, USA, [10] Staefa, Switzerland

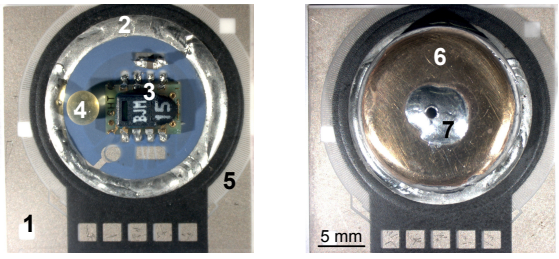

Fig. 2: Photograph of miniature implant package. Left: Substrate (1) with solder frame (2), sensor (3), silica gel desiccant (4), radial feedthroughs (5). Right: Same substrate but with lid (6) soldered to it. The puncture in the solder lump (7) is used for drying and backfilling of the package before the final sealing.

The drying procedure of sample *A* led to a humidity inside the package larger than 5000 ppm_V within a week and seem to stabilize between 15 and 20 %RH at 37°C. Pre-drying for four days led to better results in samples *B1-B4*, however, after 180 days it reached between 6 and 12 %RH at 37°C with a positive trend. The Samples *C1-C2* showed a humidity of 0.5 and 1.0 %RH, respectively, while all samples *D1-F2* containing desiccants had no detectable relative humidity (RH ≤ 0.1%). Breaking the seal of the packages *A-B4* and comparing the reading of the sensors to that of two reference sensors showed a good match. The aged sensors showed values between 44.4 and 46.3 %RH while reference sensor 1 (SHT15) measured 45 %RH and reference sensor 2 (SHT21) read 47 %RH at 25°C.

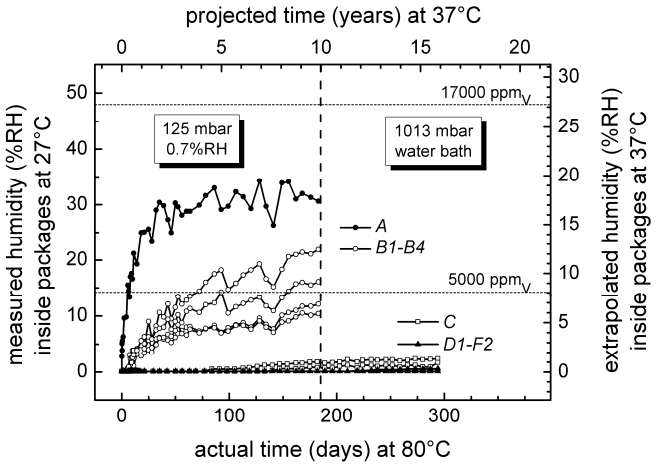

Fig. 3: Humidity inside the packages versus time. The lower x-axis shows the actual time of the experiment, the left y-axis shows the scale for humidity as measured at 27°C. The right y-axis is the humidity scale extrapolated to body temperature. The top x-axis is the time scale of the experiment, extrapolating the time at 80°C to the time at body temperature.

Immersion of samples *C1-F2* in water did not show an obvious change in package humidity. After 300 days, samples *C1-C2* were at 1.7 and 2.4 %RH, sample *D1* (silica gel) measured 01 and 0.6 %RH, while the humidity inside the packages with integrated molecular sieve desiccant was still at or below the detection limit of the sensor .

IV. Discussion

The selection criteria for the humidity sensor where to some extend arbitrary to suit our miniature capsule technology. Other applications might put a stronger emphasis e.g. on size or power consumption. The selected sensor was best suited when selected, however, new sensors were introduced since. Of particular interest might be the SHT25 sensor by Sensirion, which combines small dimensions, high accuracy and low power consumption.

Of the three procedures for drying our miniature implant packages, clearly the baking at 120°C for one hour led to the best results. The use of a desiccant is highly recommended, although this study does not permit (yet) the identification of the best suited desiccant technology. The materials to be dried might differ from application to application. In our case, we had to desorb water from metal, glass-ceramic and ceramic surfaces. The sensor consisted of a FR4 PCB and a housing made from liquid crystal polymer.

The study is a collection of data over a period of 300 days at 80°C. The acceleration factor was presumed to be 19.7, based on a commonly applied Arrhenius model for diffusion processes. Unfortunately, there is no proof that this acceleration factor is correct. Furthermore, based on the comparison of non-aged and ages sensors (*A-B4*) days, we assume that no relevant aging occurred to the remaining sensors *C1-F2*. This remains to be proven.

V. Conclusion

When using hermetic packages for implanted devices, one has to ensure that as little humidity as possible is sealed inside the package. For our miniature package, we identified a suitable drying process preceding the actual sealing, ensuring humidity levels below 2.5 %RH after 300 days at 80°C (equivalent to 15 years and 10 months at 37°C). The additional use of a molecular sieve desiccant can keep the humidity inside the package below 0.1 %RH. As humidity sensor, SHT15 by Sensirion was selected from a list of 17 commercially available sensors.

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