Study of hygroscopic expansion of anode readout boards of gaseous detectors based on FR4

J. Bortfeldt, a F. Dubinin, b, * P. Iengo, a J. Samarati a and K. Zhukov b

a CERN, Esplanade des Particules 1, Geneva 23, 1211 Switzerland
b P.N. Lebedev Institute of Physics of Russian Academy of Science, 53, Leninskiy prospect, Moscow, Russia

E-mail: filipp.dubinin@cern.ch

ABSTRACT: The problem of hygroscopic expansion of FR4 based large-size PCBs is discussed using the example of Micromegas detector. The readout electrodes of the detector located on the anode printed circuit board assumed to have precise dimensions. During the production and delivery process, the readout PCB is exposed to different temperature and humidity conditions. As a result, the PCB size differs from the nominal one at the moment of assembly of the detector. The problem appears to be relevant for any other large-size gaseous detectors with the readout structure based on FR4.

The swelling of two test PCB samples during water absorption is studied. The size of the samples is $650 \times 500 \times 0.5$ mm$^3$. Both samples have copper strips on one side. The second side is naked on sample 1 and fully covered with a copper layer on sample 2.

The elongation of the samples from dry conditions to 50% RH is measured. The influence of the copper layers on the absorption rate and the value of equilibrium elongation is discussed. It is shown that elongation of sample 1 follows the Fick’s law while the absorption process in sample 2 is more complicated. The coefficient of linear hygroscopic expansion of sample 1 is measured and discussed.

KEYWORDS: Materials for gaseous detectors; Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc); Detector design and construction technologies and materials

*Corresponding author.
1 Introduction

The planned increase in the luminosity of the Large Hadron Collider involves the modernisation of the accelerator itself and the detector systems of the experimental facilities. The Phase 1 upgrade of the ATLAS experiment includes the replacement of a part of the muon tracker detectors — the Small Wheels (SM) — with the New Small Wheels (NSW) consisting of sTGC (small strip Thin Gap Chamber) and Micromegas (MicroMesh Gaseous Structure) [1, 2].

Micromegas is a gaseous planar chamber consisting of three electrodes: a cathode, a mesh and an anode, the chamber is filled with a working gas mixture (figure 1). The area between the cathode and the mesh is called drift gap. When passing through the detector, charged particles ionize the gas. The primary ionization electrons drift to the mesh under the influence of the field between the cathode and the mesh. The area between the mesh and the anode is called amplification gap. The electric field in the amplification gap is several orders of magnitude higher than the field in the drift gap (typically ~ 40 kV/cm and few hundreds of V/cm, respectively). Influenced by this intense field the electrons pass through the mesh and increase their energy that allows them to ionize other atoms of the gas. This process leads to the creation of an electron avalanche that grows until the electrons reach the anode. The electrons reaching the anode forms the fast component of the detector signal. The ions produced in the amplification gap are collected on the mesh and form the slow component of the detector signal.

The Micromegas detectors for NSW have a surface area of 2–3 m². The cathode and anode of each detector consist of single-layer trapezoidal printed circuit boards (PCB) joined edge-to-edge. The width of each PCB is about 50 cm and the length varies from 50 to 220 cm; the thickness of the PCBs is 0.5 mm.
The anode PCBs are based on a single-layer FR4 with copper pattern on one side. The copper layer consists of 1024 read-out copper strips parallel to the long side of the board, and high-voltage contacts. The NSW Micromegas use a resistive anode for spark protection. The copper layer of a PCB is covered with an insulating Kapton foil that has resistive strips deposited on top. The anode HV is applied to the resistive strips while the copper strips are protected against sparks and serve only as readout structure. On top of the resistive strips, a pattern of insulating spacers (pillars) made of Pyralux® precisely defines the amplification gap between the anode and the mesh.

The Micromegas detectors for NSW are part of the ATLAS muon spectrometer. One of the requirements for the spectrometer is to provide resolution of muons with a transverse momentum $p_T = 1\,\text{TeV/c}$ at the level of 10%. To ensure this resolution, high precision manufacturing and assembly of the detector components is required. The required maximum deviation of the anode board size from the nominal one is 100 $\mu$m or 0.2 mm/m in the direction perpendicular to the strips. The tolerance in the direction parallel to the strips is 500 $\mu$m.

A parameter that considerably affects the dimension of FR4 boards is the moisture absorption from the environment. The amount of moisture absorbed by FR4 of different manufacturers doesn’t exceed normally 0.1–0.3% in weight of the sample. However, manufacturers do not present information about hygroscopic expansion of FR4.

In this paper we present a detailed study of the hygroscopic expansion of FR4-based anode boards that is of general interest for precise detectors of large size. In section 2 the theoretical description of the water diffusion is reviewed, together with the most relevant studies available in literature. In section 3 the experimental techniques of the measurements of the board elongation are described. In section 4 we report the results and the interpretation of the data. In section 5 the summary of the work and conclusions are reported.

2 Theoretical base of the study

2.1 Diffusion in a plane sheet

The diffusion process is described by the Fick’s laws. The Cauchy problem for diffusion in infinite plane sheet with constant diffusion coefficient is given by

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2},$$

$$C = C_1, \quad x = l, \quad t > 0,$$

$$C = C_0, \quad x < l, \quad t = 0;$$
where $C$ is the concentration of the absorbent, $D$ is the diffusion coefficient, $l$ is the sheet thickness. Taking into account the symmetry of the problem w.r.t. the middle plane of the sheet, the limits of variation of $x$ are usually assumed $-l \leq x \leq l$.

The solution of the problem is a function $C(x,t)$ such that

$$\frac{C(x,t) - C_0}{C_1 - C_0} = 1 - \frac{4}{\pi} \sum_{n=0}^{\infty} \frac{(-1)^n}{2n+1} \exp \left\{ \frac{D (2n+1)^2 \pi^2 t}{4l^2} \right\} \cos \left( \frac{(2n+1) \pi x}{2l} \right).$$

In experimental studies of diffusion, instead of an absorbent concentration, an integral value $M(t)$ corresponding to the mass of the absorbed substance is used [3]. The corresponding expression for the function $M(t)$ is

$$\frac{M(t)}{M_0} = 1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp \left[ -\frac{D (2n+1)^2 \pi^2 t}{4l^2} \right].$$

### 2.2 Literature review

In the following we report a number of theoretical and experimental studies on hygroscopic swelling of FR4. It must be noted that all these experimental studies have been conducted on small-size sample, and we didn’t find any study on large-size FR4-based PCBs, that is of particular interest for specific applications.

The main theoretical works on diffusion in various materials are presented in the book [3]. The book considers the standard problems of diffusion in the one-dimensional, two-dimensional, and three-dimensional cases, with solutions for a constant diffusion coefficient and for diffusion coefficient dependent on the concentration of an absorbent. Solutions in inhomogeneous media are also discussed.

The book provides numerical methods for solving diffusion problems, methods for experimentally studying diffusion and determining diffusion coefficient. Particularly, the matters of diffusion in polymer-based amorphous media such as epoxy are discussed.

The work [4] is one of the first experimental studies of swelling of fiberglass during water absorption. It was experimentally shown that part of the water absorbed by a sample does not cause expansion of a board. This is due to the internal structure of FR4. FR4 consists of a pressed multilayer fiberglass grid bonded with epoxy. Fiberglass doesn’t absorb water; absorption occurs in epoxy. Absorbed water can be kept either in the so-called free volume, the space between polymer chains, or in the bound state that occurs by means of formation of hydrogen bonds between water and polymer molecules. According to the theory of absorption in polymers, only water in the bound state causes swelling of the material, and the molecules occupying the free volume do not cause swelling.

In the work several identical samples were studied. The simultaneous changes in the mass and size of samples relative to the nominal values were measured in different environmental conditions: some of the samples were immersed in water at a constant temperature, some were installed in a heat chamber. It was shown that the free volume has an inverse temperature dependence, that led in the temperature range $0$–$74^\circ C$ to observation of inverse thermal effect: with an abrupt decrease of temperature, the water preconditioned sample was able to absorb some additional water. As this effect is related to the free volume only, it does not affect the swelling of a board.
The work [5] is devoted to study the influence of copper layers of various configurations on the water absorption by PCBs. The amount of absorbed water was measured by weighing the samples. The measurement results were compared to modeling. It is shown that copper layers act as a barrier to the diffusion of water in a PCB and, thus, affect the rate of sorption. In addition, it is noted that during the study microcracks appeared in the samples, located mainly near the copper layers, that indicates the occurrence of significant internal stress near the FR4 — copper interfaces.

In [6], the absorption of water by ACF (anisotropic conductive film) and FR4 materials was studied. It was experimentally shown that the temperature dependence of the diffusion coefficient in these materials obeys the Arrhenius law, and also that an equilibrium mass of water in the samples linearly depends on relative humidity of air. Using the moiré interferometry method, the coefficient of linear hygroscopic swelling of the FR4 sample was measured. It is shown that the swelling coefficient has a temperature dependence, and nature of this dependence changes abruptly in the vicinity of the glass transition temperature. In addition, the reliability of ACF material exposed to water has been studied by finite element modeling.

The work [7] is devoted to the study of water diffusion in epoxies used in manufacture of chips based on FR4. It is shown that the absorption of water in epoxy resin is anomalous and just roughly obeys the Fick’s law. The authors show that the absorption of water in the studied samples can be described as absorption in two stages [3], and the diffusion coefficient in the second stage depends on the geometry of the material.

Also, desorption of water at different temperatures is studied. It is shown that drying at a low temperature (110–130°C) may not be enough to completely remove water from FR4. For complete removal of water, it is necessary to use temperature close to or above the glass transition temperature of the fiberglass.

Moreover, a method for measuring the coefficient of hygroscopic swelling of a single-layer fiberglass with a copper layer on one side is proposed in this paper. The method consists in measuring the warpage of a sample before and after exposure to water. It was shown that the results obtained using this method are comparable to the results obtained by the method based on controlling the mass and the volume of a sample during desorption. It should be noted that this method is convenient for comparison of experimental results with results of modeling the internal stresses in a sample. On the other hand, it is rather difficult to apply this method to large samples.

3 Experimental technique

3.1 Description of the samples

For studying the swelling of PCBs induced by moisture absorption two single-layer boards with a size of 650 × 500 × 0.5 mm³ were manufactured in the PCB workshop at CERN. Fiberglass FR4 EM-370DDM with high moisture resistance [8] was used for the PCBs production. The front and back sides of the PCBs were covered with a layer of copper 18 μm thick. Using the method of photolithography copper strips of 0.3 mm width and 0.45 mm pitch were made on the front side of the boards, parallel to the long side. On the first board (sample 1) the copper layer on the back side was removed, while on the second board (sample 2) it was kept.

Cross-shaped markers intended to measure the PCB sizes parallel and perpendicular to the strips are located along the contour of the front side of the samples (the same side of the strip
The scheme of the front side of the PCBs is shown at figure 2. The nominal distance between the markers is 638.00 mm and 484.00 mm on the long and short sides, respectively.

According to the material documentation, the manufacturer carried out a standard procedure test for moisture uptake by means of measuring the mass of absorbed water [9]. A sample of $2 \times 2 \times 0.5$ mm size, that had been previously conditioned at 110°C and weighted, was placed in water at 23°C for 24 hours, afterwards it was weighed again. The amount of absorbed water declared by the manufacturer was less than 0.1% of the mass of the dry sample.

### 3.2 Measurements of the boards’ elongation

The elongation of the boards has been measured by the relative position of the reference markers. Four markers located in the corners and four markers located in the middle of each side were used. Each measurement consisted of measuring three distances parallel to the strips, in the center and along the edges, and three distances perpendicular to the strips, similarly.

The elongation of the samples has been measured with glass ruler with a micrometer scale, the instrumental error is $\sigma_{\text{inst}} = 5$ μm. The measurement of each position was repeated from 2 to 5 times depending on the required measurement accuracy.

In order to compare the elongations of the samples parallel and perpendicular to the strips, the relative elongation $L = (l_t - l_0) / l_0 \cdot 10^6$ is used, in units of μm/m. Here $l_0$ is the initial length of the board, $l_t$ is the length of the board at time $t$.

### 4 Experimental results

#### 4.1 Initial dimensions of the samples

Several months after production, the test samples were stored in a room with rough temperature control and without humidity control. Before starting the measurements, the samples were dried
in the climatic chamber of CERN Bond lab at a temperature of 130°C during 24 hours, afterwards the dimension of the samples was measured. The measurement results are shown in table 1. The measured values have been assumed as the initial dimensions of the samples.

One can see that the dimensions of the dried boards are different from the nominal ones. This can be related to two facts: first, the boards had residual stresses occurred during the manufacturing process, and second, the water absorbed during storage might not be completely removed with used drying procedure [7].

| Sample | Along strips, mm | Across strips, mm |
|--------|-----------------|------------------|
|        | Top      | Middle | Bottom     | Left    | Middle | Right     |
| 1      | 638.068  | 638.062 | 638.071   | 484.079 | 484.075 | 484.062   |
| 2      | 638.082  | 638.036 | 638.034   | 484.032 | 484.022 | 484.020   |

**Figure 3.** Elongation of the samples along the strips at 21°C/50% relative humidity. Legend: sample 1: 1 — top, 2 — middle, 3 — bottom; sample 2: 4 — top, 5 — middle, 6 — bottom.

**Figure 4.** Elongation of the samples across the strips at 21°C/50% relative humidity. Legend: sample 1: 1 — left, 2 — middle, 3 — right; sample 2: 4 — left, 5 — middle, 6 — right.

### 4.2 Moisture absorption at 21°C/50% RH

In figure 3 and 4 the elongation of the samples along and across the strips respectively, as function of the time at 21°C/50% RH are shown. As a result of water absorption, the samples expand until the water concentration in the PCBs reaches equilibrium. The inhomogeneity of elongation in one direction at different positions for both samples is due to local inhomogeneity of a FR4 structure. This leads to the appearance of internal stresses in the boards during water absorption, the relaxation of that occurs nonuniformly. For the sample with the copper layer on the back face, there is a larger deviation of elongations, which can be related to two factors: the only way of water reaches the PCB is the surface between the strips, so the absorption occurs only at face side that results in
different elongations of face and back sides; and the elastic reaction of the copper layer could resist
the expansion and lead to increase of elongation’s inhomogeneity.

Nevertheless, one can see that the measurements performed at different positions of the boards
are consistent, within the instrument accuracy, and have the same dependence on time. Therefore,
to describe the elongation of the boards, the average value of elongation in each direction can be
used (figure 5).

It is found that the board without copper layer expands uniformly at different positions in both
directions. The saturation values in both directions are equal to each other and at 21°C/50% RH
reach ~ 350 μm/m.

The expansion of the board with copper layer is less uniform. Water absorption in the sample
occurs only through the open surface between the strips. This leads to the rapid expansion of the
PCB across the strips on the front side of the board where areas with the high and low concentration
gradient alternate in the considered direction. In the direction along the strips each point of the
board is superimposed to low and high concentration gradients that leads to a less uniform situation
and slowdown the elongation in this direction. This asymmetry of the concentration gradient at the
surface of the board leads to its bending in the direction across strips (figure 6).

However, according to figure 5 the equilibrium elongations of sample 2 in both directions are
approximately the same and equal to the elongation of sample 1 within the measurements’ errors.
The equality of the equilibrium elongations of both samples indicates that the influence of the elastic
reaction of copper layers on the hygroscopic expansion of FR4 is negligible at equilibrium.

4.3 Equilibrium elongation at different relative humidity

Measurements of the equilibrium elongation of sample 1 were also carried out at 20% RH (by
desorption, from 50% to 20%) and at 80% RH (by absorption, from 50% to 80%). To accelerate
the saturation process, during moisture desorption to 20% the board was kept at t = 40°C, while the
measurements were carried out at $t = 21^\circ C$. Results of the measurements are presented in figure 7. The relationship between the elongation and the relative humidity is linear in both along and across strips, the slope of the line corresponds to coefficient of linear hygroscopic swelling of the sample.

In [6], the measured coefficient of linear hygroscopic swelling of FR4 is reported to be: $\beta_{[6]} \approx 10^{-6} \ 1/\%$. The measurements were carried out at 85$^\circ C$ using the moiré interferometry method. The given coefficient is of the same order of magnitude as one measured by us. The difference is owed to both the differences in the measurement conditions and in the studied materials itself.

4.4 Partial diffusion coefficient

The diffusion coefficient of FR4 cannot be obtained by measuring the swelling of a board, because the method doesn’t take into account the water diffusing in the free volume of the epoxy [4, 6, 7]. Nevertheless, if the swelling of the board can be described by a solution of the Fick’s equation, one can estimate the partial diffusion coefficient $D'$ corresponding to the diffusion rate of that part of water that binds to the polymer molecules.

If the swelling of fiberglass obeys the Fick’s law it can be expressed as

$$\frac{L(t)}{L_{\infty}} = 1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n + 1)^2} \exp \left[ -\frac{D' (2n + 1)^2 \pi^2}{4l^2} t \right],$$

where $L_{\infty}$ is the elongation at equilibrium, $D'$ is the partial diffusion coefficient, $l$ is the half of the PCB thickness. At short times, i.e. at $L(t)/L_{\infty} < 0.55$, the partial diffusion coefficient can be calculated using the formula

$$\frac{L(t)}{L_{\infty}} = \frac{4}{l} \sqrt{\frac{D'}{\pi}} \sqrt{t},$$

where now $l$ indicates the full thickness of a PCB.

Figure 8 shows the swelling of PCBs, normalized to the equilibrium value, as a function of $\sqrt{t}$, expressed in $s^{1/2}$. In these coordinates the different behaviors of the elongation for samples 1 and 2 are clearly visible. The curves of sample 1 correspond to the Fickian absorption [3]. The behavior of sample 2 is anomalous (non Fickian) and is related to the single-side absorption of water, with consequent appearance of asymmetric internal stresses in the sample.

To estimate the partial diffusion coefficient, measurements of the elongation of samples at 21$^\circ C$/50% RH were repeated with higher accuracy (figure 9). During the first day both samples expands at the same rate, then the expansion rate of sample 2 slowed down. The elongation of sample 1 remains linear up to about 80% of saturation.

The absorption curves of the sample 1 were fitted with a linear function (figure 10). The partial diffusion coefficients of the sample along and across strips are $D'_\parallel = (3.4 \pm 0.2) \times 10^{-2} \mu m^2/s$ and $D'_\perp = (4.7 \pm 0.5) \times 10^{-2} \mu m^2/s$, respectively.

5 Conclusion

A study of water absorption from moist atmosphere by PCBs based on FR4 material with copper layers was carried out. A study of the boards’ elongation during moisture absorption, as well as
the effect of copper layers on the swelling rate and equilibrium elongation during water absorption, were performed.

It has been shown that the rates of elongation of both samples differ from each other as well as in directions along and across strips of each sample. This difference is accounted for the different copper pattern of the samples. Nevertheless, the equilibrium elongation in both directions of both samples is consistent within the measurement errors.

The relation between the equilibrium elongation and the relative humidity of the sample without copper layer was measured. The measured relation appeared to be linear and the linear swelling coefficient for the sample is $\beta = (7.0 \pm 0.2) \, \mu m/m/%$. 
The swelling of the boards against time was analyzed at constant temperature and humidity. For the sample without copper layer on the back side, the dependence is described by the solution of the Fick’s equation for an infinite sheet. Moreover, the elongation rate in the direction perpendicular to the strips was observed to be higher than in the direction parallel to the strips. Partial diffusion coefficients related to the rate of swelling was measured at 21°C/50% RH along and across the copper strips, the respective values are $D_\parallel = (3.4 \pm 0.2) \times 10^{-2}$ μm²/s and $D_\perp = (4.7 \pm 0.5) \times 10^{-2}$ μm²/s.

For the sample with copper layer on back side, the elongation curves are more complex and cannot be described by the solution of the Fick’s equation.

Acknowledgments

We would like to express gratitude to Rui De Oliveira and CERN PCB Production Workshop for the production of the samples and the valuable discussions, and the CERN Bond Lab for the usage of the climatic chamber and the working space in the clean room of the lab.

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