Characterization of Ionic Permeability and Water Vapor Transmission Rate of Polymers Used for Implantable Electronics

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Abstract— Biocompatible polymers used as encapsulation and packaging materials for implantable electronic devices have to comply with numerous requirements. Especially their barrier properties against water molecules and ions are of particular interest regarding the reliability of the encapsulation as well as functional integrity of the electronic components since water and ions on the circuit board may evoke corrosion, leakage current and finally the failure of the device. This paper describes a measurement setup to investigate the ionic permeability under *in vitro* conditions of polymeric membranes manufactured from various biocompatible polymers. Ionic permeability and water vapor transmission rate representing the barrier properties of these membranes were investigated. First results were obtained for polyimide, silicone, polyether ether ketone and polyamide, whereas polyimide evinced the best properties.

I. INTRODUCTION

Recent developments and increasing miniaturization in MEMS (microelectromechanical systems) technology require the application of novel materials and electronic packaging techniques for implantable electronic devices. Typically, innovative packaging and encapsulation approaches are discussed in connection with retina implants, neural prostheses, permanent monitoring systems for vital parameters as well as smart implants [1]–[5]. Therefore, biocompatible polymers are increasingly utilized due to their advantages in weight, space, processing, various chemical and mechanical properties as well as electromagnetic permeability. However, they do not provide a hermetic encapsulation and with regard to a permanent implant where rigid and sealed titanium or ceramic cans are still preferred, not a reliable protection of the electronic system [6]. The reliable protection which is one of the most important requirements placed on the biocompatible electronics packaging and encapsulation implies that all harmful interactions between the living and the dead matter are eliminated. Consequently, on the one hand the host tissue is not affected by the material used for electronic devices and the encapsulation itself. On the other hand the implanted electronic device is protected against the aggressive biological environment during its intended lifetime. It is known, that the chemical, electrical and mechanical properties of polymers alter over time due to their interactions with the environment. They are semipermeable for molecules and ions. In particular, water absorption causes swelling, chemical degradation, decrease of mechanical and adhesive strength as well as reduction of the electrical resistivity. In case of cavities or delamination within the encapsulation, water absorbed by the polymer matrix can condensate in this interstice. In the presence of ions corrosion, leakage current, short circuits on account of dendrite formation and electrolytic decomposition of water may occur and cause failure of the electronic device [7].

In order to investigate the reliability of polymeric encapsulation materials and packaging technologies for an implantable electronic device, typically optical, mechanical, electrical and electrochemical tests are performed under various *in vitro* conditions [8]–[11]. These methods allow the examination of the different failure mechanisms as a whole, but not in particular. Therefore, this paper describes a measurement setup to investigate the ionic permeability as a single cause of failure under *in vitro* conditions of several polymers used as encapsulation materials. In combination with the water vapor transmission rate (WVTR) measurement which is already a common method to characterize barrier properties [12], the suitability of different polymers for implantable electronic devices is determined.

II. MATERIALS AND METHODS

A. Fabrication of polymeric membranes

In order to characterize the permeability of ions and water molecules through polymer layers, dense membranes fixed in a ceramic frame with a 45 mm by 50 mm opening are produced. Thus, the exposed membrane area is $2250\,mm^2$. In case of pourable polymers like silicone solution a sacrificial layer process depicted in figure 1 is utilized. Polyimide solution is applied directly on the silicon wafer by spin coating and peeled with tweezers. Thermoplastic polymers like polyether ether ketone (PEEK) and polyamide (PA) are available as foil material and fixed directly on the frame.

For a 2 µm thick sacrificial layer, gelatin solution (G2500-100g, Sigma-Aldrich Co. LLC, USA, gelatin concentration in purified water $0.025\,g/m^3$) is spin-coated with a spin-coater (WS-650Mz-8NPP, Laurell Technologies Corporation, USA) on a silicon wafer and dried. Afterwards the polymer is deposited on the gelatin covered wafer. To obtain the membrane, the polymer layer is fixed on a ceramic frame using silicone Sylgard 184 (Dow Corning Corporation, USA). The last step implies the removal of the gelatin layer by placing the covered wafer in purified water at 50 °C. Thus, the polymer layer is separated from the wafer. For the first trials, silicone, polyimide, PEEK and PA membranes shown in table I were produced.

1. Wafer with sacrificial layer

2. Application of first polymer layer

3. Fixation on ceramic frame with adhesive

4. Removal of sacrificial layer

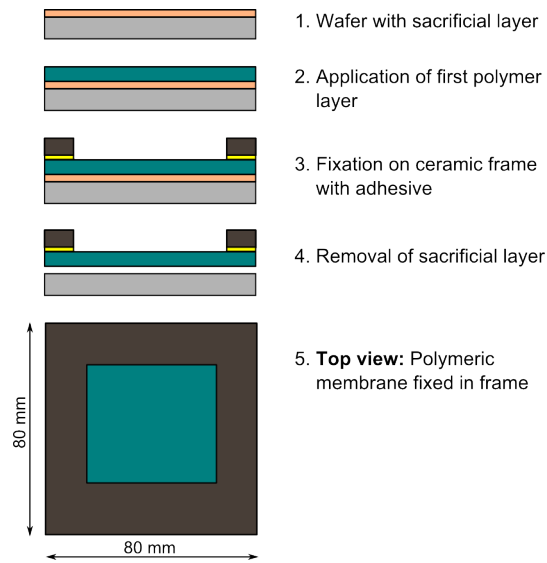5. **Top view:** Polymeric membrane fixed in frame

80 mm

80 mm

Fig. 1. Process flow of polymeric membranes by means of sacrificial layer process

TABLE I

MATERIALS AND THICKNESS OF PRODUCED MEMBRANES

Polymer	Manufacturer	Type, processing	Membrane thickness
Silicone MED6-6606	NuSil Technology, USA	Pourable, spin-coating	$12\,\mu m$
Polyimide PI2611	HD MicroSystems, USA	Pourable, spin-coating	$9\,\mu m$
PA6	MF-Folien GmbH, Germany	Foil	$18\,\mu m$
PEEK	VICTREX Europa GmbH, Germany	Foil	$8\,\mu m$

B. Ionic permeability measurement setup

The ionic permeability measurement setup (see figure 2) essentially consists of two glass chambers separated by the membrane under test which is clamped between a silicone seal and the glass chambers by means of a fastening device. Each chamber stores a volume of $225\,cm^3$. During the measurement the left chamber is filled with a sodium chloride feed solution, the right chamber contains ultra pure water (UPW) as a permeate solution. A heating stirrer ensures a steady measurement temperature set to $40\,°C$ (near to human body temperature) and an uniform ion distribution within both chambers. The ion concentration alteration in both chambers is conductometric monitored every $5\,min$ by means of conductivity probes (right chamber: Inlab 730 and left chamber: Inlab 740, Mettler-Toledo Intl. Inc.) controlled by SevenMulti system (same company, measuring accuracy: $\pm0.5\,\%$) which is an accepted method to measure the electrolyte transport through membranes [13]. Afterwards, the ion concentration in the permeate solution c_2 is evaluated utilizing a reference curve determined from known conductivity for certain sodium-chloride concentrations measured at $40\,°C$ (see (2)).

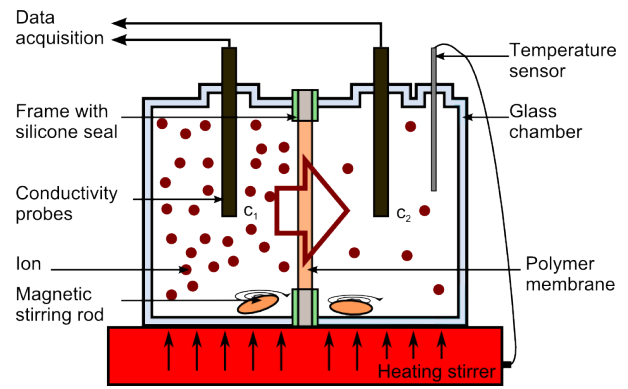The whole measurement procedure contains the following

Fig. 2. Schematic drawing of ionic permeability measurement setup in cross section, left chamber with feed solution and right chamber with permeate solution

experimental sections:

1) Membrane storage in UPW at $40\,°C$, both chambers filled with UPW (renewed every $48\,h$) until a conductivity equilibrium is reached implying the membrane is free from contamination.
2) Measurement with ion concentration gradient from left (initial NaCl concentration in feed solution $c_1 = 0.1\,g/cm^3 = 1.71\,mmol/cm^3$) to right chamber (initial NaCl concentration in permeate solution $c_2 = 0\,g/cm^3$).

C. Water vapor transmission rate measurement setup

WVTR of polymer membranes is measured by means of permeability measurement system HiBarSens® (Sempa Systems GmbH, Germany) which is based on diode laser spectroscopy. The structure of the system is similar to the ion permeability measurement setup and also consists of two chambers (pre-chamber with $90\,\%$ humidity and measurement chamber with a constant dry inert gas flow) separated by the membrane to be tested [14]. The operating temperature was set to $38\,°C$. An increasing water vapor concentration which is directly proportional to the WVTR in the measurement chamber decreases the laser intensity according to Beer–Lambert law.

III. RESULTS

A. Transport mechanisms in membranes

The transport of molecules and ions through a dense membrane can be described with the solution-diffusion model with the following phases [15]:

1) Absorption of the feed solution components at the membrane surface, depending on the solubility of the components in the membrane,
2) Diffusion through molecular interstices of the membrane following the concentration gradient,
3) Desorption at the low-concentration membrane side into the permeate solution.

Thereby, diffusion is commonly expressed with Fick's laws of diffusion. Fick's first law:

$$J = -D\frac{\partial \phi}{\partial x} \qquad (1)$$

correlates the diffusion flux J directly with the concentration gradient $\partial \phi / \partial x$ and a diffusion coefficient D under steady state conditions.

Several models describe permeability processes in polymers [13], [16]. Thus, transport mechanisms base on the thermal oscillation of polymer chain segments inducing a free volume which is dependent on temperature and the polymer structure as well as the chemical affinities between the permeate components and the polymer matrix.

B. Ionic permeability measurements

Before the described isothermal measurements were carried out, a conductivity reference curve was prepared on the basis of sodium chloride solutions with known concentration $c(NaCl) = 0 \, mol/m^3 \ldots 17.1 \, mol/m^3$ at $40\,^\circ C$ by means of the Inlab740 conductivity probe. The measured conductivities $\kappa(NaCl)$ were approximated mathematically with following linear equation:

$$\kappa(NaCl) = 0.4 \, \frac{\mu S}{cm} + 168.9 \, \frac{\mu S \cdot m^3}{cm \cdot mol} \cdot c(NaCl), \quad (2)$$
$$R^2 = 0.99947$$

During the measurement no significant change in conductivity was observed in the chamber with high electrolyte concentration c_1 which remains constant. However, conductivity changes $\kappa(NaCl)$ in the permeate solution were recorded and are shown in figure 3.

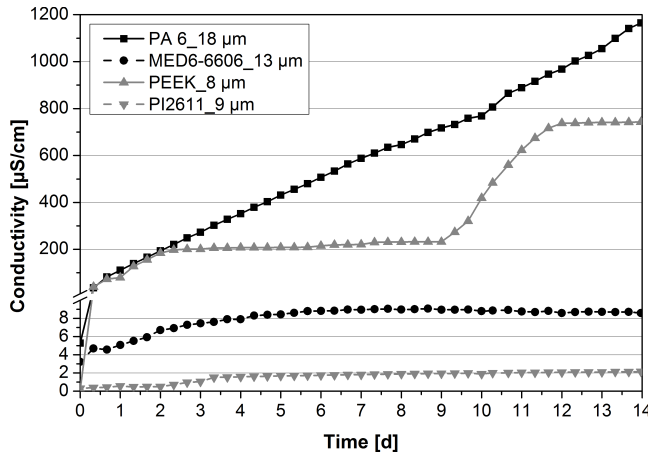Fig. 3. Changes in conductivity $\kappa(NaCl)$ measured in permeate solution at $40\,^\circ C$ for several membranes (see table I) and a feed solution concentration of $c_1 = 1711 \, mol/m^3$

Using (2) and assuming that Na^+ and Cl^- ions permeate through the membrane material equally, the obtained changes of electrolyte concentrations in the permeate solution $\Delta c_2 = c_2(t) - c_2(t=0)$ for the first 120 min are illustrated in figure 4.

Assuming a negligible change of concentration Δc_2 ($c_1 \gg c_2$) and a constant flux J (linear concentration gradient) for a limited time span in the beginning of the experiment, the diffusion coefficient D can be determined by measuring the amount of substance $\Delta c_2 \cdot V$ diffusing through
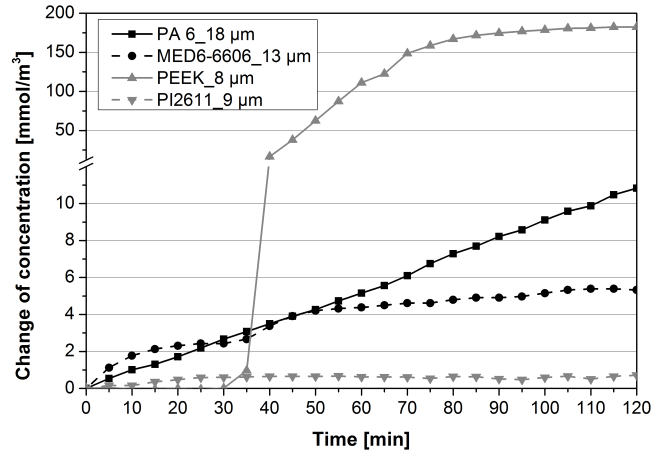

Fig. 4. Change of NaCl concentration Δc_2 monitored in permeate solution at $40\,^\circ C$ for several membranes (see table I) and a feed solution concentration of $c_1 = 1711 \, mol/m^3$ for the first 120 min of measurement

the membrane in a given interval Δt [17]:

$$D = \frac{\Delta c_2 \cdot V}{\Delta t} \cdot \frac{d}{A \cdot (c_2 - c_1)} \quad (3)$$

where V is the chamber volume, A the membrane area and d the membrane thickness. Substituting (3) in (1) results in:

$$J = \frac{\Delta c_2 \cdot V}{\Delta t \cdot A}. \quad (4)$$

The diffusion flux J and the diffusion coefficient D within the first 30 min were calculated for each membrane and are depicted in table II. For the PEEK membrane where phases of membrane saturation and constant diffusion flux were observed the first concentration gradient was used for the evaluation.

TABLE II
CHANGE OF CONCENTRATION Δc_2 AFTER 60 MIN, 24 H AND 7 D AS WELL AS CALCULATED DIFFUSION FLUX J AND COEFFICIENT D FOR THE FIRST 30 MIN OF PRODUCED MEMBRANES

Membrane	MED6-6606	PI2611	PEEK	PA6
Δc_2 ($t = 60$ min) [mmol/m^3]	4.4	0.6	111.4	5.2
Δc_2 ($t = 24$ h) [mmol/m^3]	11.0	1.7	472.6	624.7
Δc_2 ($t = 7$ d) [mmol/m^3]	33.9	9.2	1307.4	3450.1
D [10^{-15} m^2/s]	-1.0	-0.2	-28.9	-1.6
J [10^{-7} mol/(s m^2)]	1.3	0.3	61.9	1.5

Surprisingly, the PEEK membrane, showing nearly a 20-times higher diffusion coefficient compared to the other membranes in the beginning of the experiments, induces not the highest change of concentration Δc_2 after one week measurement. But this was observed for the PA6 membrane with a 2.5-times higher NaCl concentration compared to PEEK. All membranes indicate a different barrier behavior against the investigated electrolyte. Polyimid PI2611 presents the lowest ionic permeability of $9.2 \, mmol/m^3$ after seven

days, followed by silicone MED6-6606 where a saturation after five days at a concentration of 33.9 mmol/m^3 was observed. However, with the PEEK membrane a first saturation level was reached after 110 min involving further phases of diffusion and saturation. This polymer evince an unsteady permeability behavior, whereas ions diffuse through the PA6 membrane continuously without reaching a saturation within the measurement duration.

C. Water vapor transmission rate

WVTR was measured for the four membranes under the described conditions. The results are shown in figure 5. The lowest water vapor transmission rates were measured for PI2611 (WVTR= 6 ± 0.03 g/(m^{2}d)) and MED6-6606 (WVTR= 7 ± 0.04 g/(m^{2}d)). More than 18-times higher values were obtained for PEEK and PA6 membrane.
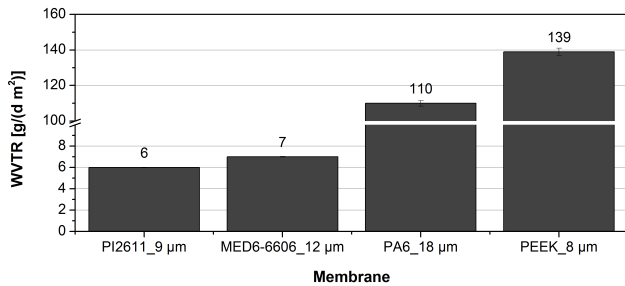

Fig. 5. Water vapor transmission rate for several membranes measured at 38 °C and a feed humidity of 90 %

Summarizing the results of ionic and water vapor permeability, the diffusion flux and the WVTR are comparative represented by figure 6 which may indicate a correlation between both parameters.
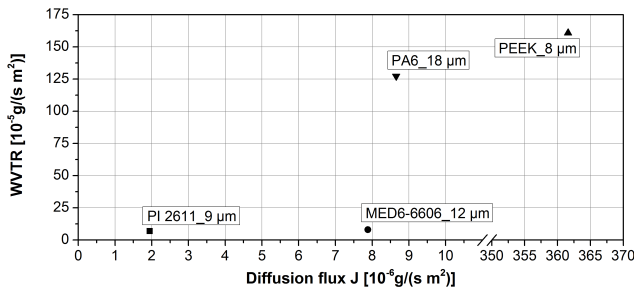

Fig. 6. Water vapor transmission rate versus diffusion flux for several membranes (measurement units were converted for comparability)

IV. CONCLUSIONS

The best barrier properties were determined for the PI2611 membrane with the lowest ionic permeability and water vapor transmission rate, indicating a reliable protection of the electronic device for the use as encapsulation and packaging material. Despite, silicone features a slightly higher permeability for ions and water molecules compared to PI2611, it is a commonly used encapsulation material and promising for long-term applications. However, according to the presented results PEEK and PA6 are not appropriate

as encapsulation material. Nevertheless, barrier properties can be improved by a multi-layer encapsulation combining polymers with different positive attributes. In this context polyimid is typically used as flexible printed circuit board and silicone as encapsulation of the whole system. Other polymers like parylene C and epoxy resins are conceivable and investigated prospectively.

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