Non-fouling thin polymeric films synthesized by PECVD

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Abstract
Polymeric films have been synthesized by a conventional PECVD technique at low temperature on COC substrates. Depending on the precursors chemistry and process conditions non-fouling property has been obtained which was correlated to chemical bonds similar to PEO/PEG bonds. The deposition process doesn’t involve any fragmentation of usual PEO/PEG precursors as mentioned in the literature but the direct synthesis of functional bonds by chemical reaction from elementary molecules which are eventually linked to a resistant and homogeneous teflon-like backbone. Unlike PEO/PEG solutions the films can also be tuned in surface energy hence offering hydrophobic or hydrophilic characters depending on process conditions. This latter property is especially interesting when integrating such materials in fluidics systems where a range of surface energies can be required. Finally structuration of the films combined with materials proper surface energy can further widen the wetting window for fluid flow management in bio-systems or other fluidic systems.

Keywords: polymer films, plasma deposition, PECVD, non-fouling, PEO, PEG, fluidic

1. Introduction
There are three most widely studied non-fouling systems for making surfaces repellant to biological species.
Poly (ethylene glycol) (PEG) or poly (ethylene oxide) (PEO) compounds are known for their ability to reduce adsorption of biomolecules [1] and cell adhesion [2]. The exact mechanism of PEO coatings that leads to protein resistance is not yet fully understood and several parameters seem to be involved (chain density, chain length, chain conformation) [3][4][5]. However, the nonfouling properties of PEO are mainly due to a self-repulsion of the chains in water. This reaction initiates a dynamic sweeping process, which limits the adsorption of proteins on the surface [6]. Several approaches can be used to produce PEO layers: physical adsorption [7], radiation and chemical cross linking [8], self-assembled monolayers [9], spin coating stabilized by ion beam treatment [10], covalent immobilization [11], chemisorption of PEO thiol on gold surfaces [12] or plasma polymerization of ethylene oxide [13]. However PEO/PEG coatings suffer from a susceptibility towards oxidative degradation and chain cleavage in aqueous environments.

A potential technique for reducing protein binding to synthetic polymer membranes is to mimic a membrane coating found in nature. The red blood cell plasma membrane, unlike synthetic polymer membranes, naturally resists protein fouling. This property is attributed to the unique phospholipid bilayer structure of the membrane. Orientation of phosphorylcholine derivatives at the external surface of the bilayer presents a neutral interface with the extra cellular environment which has little or no attraction for proteins. This phosphorylcholine structure can be mimicked on synthetic polymer surfaces and it has shown that protein adsorption can be reduced by 95% and the treatment of such devices prevents blood coagulation [14][15]. However such coatings are reliant upon weak van der Waals interactions with the phosphorylcholine molecules themselves being only weakly associated with each other and to the underlying substrate.

PEO/PEG coatings described above have been extensively used to obtain materials with a reduced tendency towards protein adsorption. However, the bulk and surface structure of these materials are not always well defined. In many cases the individual blocks are organized in separate phases, and the surface is not completely covered by PEG [16]. Furthermore, due to polymer degradation, the surface can be rapidly depleted of PEG [17], leading to changing surface properties with time. Self-assembled monolayers (SAMs) of alkanethiols on metal surfaces such as gold have been well established and allow for an easy and reproducible functionalization of such surfaces. However thiolate groups (Au-SR) are vulnerable to oxidation and desorption leading to a complete loss of the protein-resistant properties.

The non-fouling surfaces discussed in this paper are based on a novel material chemistry which relies on a resistant and homogeneous polymer backbone functionalized with non-fouling groups acting similarly to PEO/PEG groups.

2. Materials and experimental methods
Polymer films are synthesized by Plasma Enhanced Chemical Vapor Deposition (PECVD) which allows coatings on a large variety of substrates. Moreover, the deposition occurs in one step and can be performed on three-dimensional surfaces. The deposition process is carried out at low pressure (0.1-10 mbar) and at room temperature so to enable the coating of heat sensitive substrates. Chemical reactions are activated via a low-power (~300 Watts) RF plasma. Various chemical precursors have been assessed including perfluorocarbons and siloxanes molecules.

Nanotexturing of the surface prior deposition of thin conformal non-fouling films is also investigated in the peculiar case of COC substrates. The process is run in-situ by dry etching using an oxygen plasma.
Films are finally characterized by water contact angle measurement (DSA 10 KRÜSS Contact Angle Measuring Instrument), FT-IR (Nexus 870 E.S.P. spectrophotometer), and XPS (SSI-Sprobe spectrometer with monochromatic Al Kα source at normal incidence) techniques.

Cell lysates, sera and biopsy samples were labelled with fluorescent probes (Cy3 or Cy5). The excess probes are removed by gel filtration. The labeled samples (2 µg/µl or 20 ng/µl of labeled protein) are then manually contact printed on different slides. Proteins from biological samples which bind to the film are detected using a fluorescent scanner.

3. Results and discussion

One of the targeted applications for the films being their integration into microfluidic systems the wetting behaviour of the surface to water-buffered samples is of much importance. In that sense the water contact angle is monitored for each type of materials on smooth surface and textured COC surfaces. Water contact angle (WCA) values are presented in Table 1.

<table>
<thead>
<tr>
<th>Films</th>
<th>Texture</th>
<th>WCA (°)</th>
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<tbody>
<tr>
<td>CF</td>
<td>no</td>
<td>115</td>
</tr>
<tr>
<td>CFO#1,#2,#3 (tuneable)</td>
<td>no</td>
<td>100, 70, 30</td>
</tr>
<tr>
<td>CFO#1</td>
<td>yes</td>
<td>170</td>
</tr>
<tr>
<td>CFO#3</td>
<td>yes</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>SiOC low-C</td>
<td>no</td>
<td>30</td>
</tr>
<tr>
<td>SiOC low-C</td>
<td>yes</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>SiOC high-C</td>
<td>no</td>
<td>105</td>
</tr>
<tr>
<td>SiOC high-C</td>
<td>yes</td>
<td>162</td>
</tr>
</tbody>
</table>

The CF film is hydrophobic whereas the CFO and SiOC films show a large window of WCA going from the hydrophilic (30°) to hydrophobic (100-105°) domains, depending on the process conditions. These wetting behaviours can be correlated to the nature of chemical bondings which are presented on Figures 1-2.

The hydrophilic behaviour of SiOC low-C is related to hydroxyl groups (O-H band at 3000-3700 cm⁻¹) while CFO#3 hydrophilicity is related to both hydroxyl and carbonyl groups (C=O bond at 1752 cm⁻¹). The hydrophobic behaviour of CF and CFO#1 films is related to fluoromethyl groups (C-F bond at 1340 cm⁻¹, F-C-F bonds around 1100 and 1200 cm⁻¹) while methyl groups (Si-C, Si-CH3 and C-H3 bonds at 801, 1260 and 2960 cm⁻¹, respectively) play the same role in SiOC high-C films.

Furthermore the texturation of the COC substrate by dry plasma etching prior deposition of CFO or SiOC thin films (10 nm of thickness) widen the WCA range to nearly the theoretical [0; 180°] window hence demonstrating superhydrophilic [18] and superhydrophobic states [19]. This texturing effect has been shown previously where etching of polymer materials may reveal the macromolecular structure at the surface with resulting roughness values in agreement with Lotus dimensional conditions [20]. In the present case of study Rms values fit typically in the [50; 100 nm] window depending on etching conditions (mostly RF power and time). Wetting behaviours of the SiOC and CFO films are illustrated on Figure 3.

Protein binding experiments have been carried out on all types of films and on a glass slide surface as the reference. In all cases binding on the different films is more visible with the samples diluted 100 X (20 ng/µl of labelled protein) where free fluorescent probes are substantially reduced. The fluorescence-based analysis on these diluted samples indicates that none of the SiOC and CF films show any lower protein binding than glass while binding of labelled proteins from cell lysates, sera and biopsies to the CFO films is actually weaker than the binding to the glass slide (Table 2).
Further chemical investigation has been carried out on CFO films by XPS. A CFO#2 type of film has thus been analysed. Due to experimental issues related to polymer sample charging (use of flood-gun) and conductivity changes under X radiations (peaks shift) these initial results must be interpreted as indicative but not as absolute values at this stage. The XPS spectrum (Figure 4) shows XPS emission intensities for the fluor F1s (689 eV), oxygen O1s (533 and 534.8 eV) and carbon C1s. Amongst nine identified C1s contributions the four most responsive ones are presented in Table 3.

<table>
<thead>
<tr>
<th>C1s major contributions of CFO#2 (XPS)</th>
<th>eV</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_2$-CF$_3$</td>
<td>287.3</td>
<td>13.8%</td>
</tr>
<tr>
<td>CH$_3$-CF$_2$, CH$_2$-CF$_2$</td>
<td>288.5</td>
<td>22%</td>
</tr>
<tr>
<td>C=O</td>
<td>290.4</td>
<td>15.7%</td>
</tr>
<tr>
<td>C-F</td>
<td>291.9</td>
<td>14.5%</td>
</tr>
</tbody>
</table>

The C–O groups presented in Table 4 usually relates in the literature to the PEO character [21] (C2 component at 286.5 eV), O–C–O/C=O groups (C3 component at 288.0 eV) and a last component C4 at 289.2 eV, corresponding to COOR/H groups. This result correlated to C-O and C=O peaks observed by FTIR (Figure 2) indicates that the CFO films do mimic chemically PEO/PEG non-fouling films.

<table>
<thead>
<tr>
<th>C-O groups in CFO#2 (XPS)</th>
<th>eV</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_2$-CF$_2$, CH$_3$-CF$_2$, CH$_2$-CF$_3$</td>
<td>286.4</td>
<td>4.6%</td>
</tr>
<tr>
<td>C=O</td>
<td>288.5</td>
<td>22%</td>
</tr>
<tr>
<td>O-C=O</td>
<td>289.6</td>
<td>10.1%</td>
</tr>
</tbody>
</table>

A study has been initiated to understand the mechanisms of interaction between microorganisms, proteins, cells and the properties of such surfaces. Beyond the role of all atomic bonds described above the presence and effects of water inside the films (Figure 2) on surface energy and non-fouling property is also being investigated with care.

4. Conclusion

A process has been demonstrated for synthesizing non-fouling polymeric films by PECVD which exhibit functional groups identical to PEO/PEG materials. However this innovative approach doesn’t involve any fragmentation of usual precursors (e.g. glymes molecules) with associated process constraints (control and repeatability of low fragmentation levels) but the synthesis of the desired atomic bonds directly by a chemical reaction from elementary molecules. Furthermore the functional groups are linked to a resistant and homogeneous Teflon-like backbone. Unlike PEO/PEG solutions the CFO films can be tuned in surface energy and offer hydrophobic or hydrophilic characters depending on process conditions. This latter property is especially interesting when integrating such materials in fluidics systems where a range of surface energies can be required.

Structuration of the polymeric films can further widen the wetting window for fluid flow management. This topic is currently being addressed within the 4M network with polymer substrates micro-patternning by injection moulding and hot-embossing techniques.

Finally the CFO non-fouling films are currently being investigated for their stability and ageing behaviour in environments relevant to their potential fields of application (air and PBS solutions).

Acknowledgements

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Also, part of this work has motivated a proposal for a Cross-Divisional project (Micro- and nanostructured surfaces for the liquid and gas management in microstructured flowfields) within the framework of the EC Network of Excellence "Multi-Material Micro Manufacture: Technologies and Applications (4M)" which has been recently approved.

References