Silicone Biomaterials Obtained by Plasma Treatment and Subsequent Surface Hydrosilylation

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Akademisk avhandling
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Abstract
The need for safe and functional implants has led to an increased demand for improved biomaterials. The performance in vivo depends on the interaction between the biological surrounding and the surface of the material. By tailoring the surface of a material with suitable bulk properties, biomaterials with an ability to interact with the biological system in a specific and controlled way are obtained. Silicone elastomers have been used as biomaterials for several decades, but it is widely recognized that they are difficult to modify by the conventional methods used for organic polymers due to the partly inorganic structure of silicone.

This thesis presents a strategy to obtain silicone biomaterials by covalent coupling of molecules to the surface using silicon chemistry. The first step is to introduce Si-H groups onto the surface of silicone elastomers by plasma treatment. The second step is to react a terminal double bond of a molecule with the formed Si-H group by a catalyzed hydrosilylation reaction. The coupled molecule may either provide the desired properties itself, or have a functionality that is able to couple another molecule with suitable characteristics.

The influence of plasma treatment in hydrogen, argon and oxygen on the silicone elastomer was characterized by X-ray photoelectron spectroscopy (XPS). To quantify the effect of plasma treatment, the method of ternary XPS diagrams was developed. It was found that undesired silica-like layers were formed under severe treatment conditions. Argon plasma at low power and short treatment time was the most suitable parameter setting. Subsequent hydrosilylation grafting of allyltetrafluoroethylether, aminopropylvinylether and N-vinylformamide showed that it was possible to functionalize the surface via a covalent link to the surface. The primary amino groups introduced onto the surface were accessible for further coupling reactions. Heparin surfaces were obtained by a coupling reaction with the introduced amino groups.

Keywords: Silicone elastomers, PDMS, XPS, ESCA, surface modification, plasma
LIST OF PUBLICATIONS

This thesis is a summary of the following papers:

I. “Evaluation of surface modification processes using a ternary XPS diagram”  
   Björn Olander, Ann-Christine Albertsson  
   *Surface and Interface Analysis, 2002, 33, 541-544.*

II. “Oxygen microwave plasma treatment of silicone elastomers: Kinetic behavior and surface composition”  
    Björn Olander, Anders Wirsén, Ann-Christine Albertsson  
    *Journal of Applied Polymer Science, In press.*

III. “Silicone elastomers with controlled surface composition using argon or hydrogen plasma treatment”  
    Björn Olander, Anders Wirsén, Ann-Christine Albertsson  

IV. “Argon microwave plasma treatment and subsequent hydrosilylation grafting as a way to obtain silicone biomaterials with well-defined surface structures”  
    Björn Olander, Anders Wirsén, Ann-Christine Albertsson  
    *Biomacromolecules, 2002, 3(3), 505-510.*

V. “Silicone elastomer surface functionalized with primary amines and subsequent coupled with heparin”  
   Björn Olander, Anders Wirsén, Ann-Christine Albertsson  
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1 Purpose of the study

Silicone elastomers have been used as biomaterials for several decades. The combination of their suitable polymer properties and the minor host response compared to the behavior of alternative materials has made them a preferred choice for many applications. The increasing interest in tailoring surfaces for the intended biological environment has been quite successful for other polymers, whereas silicone elastomers are still considered to be a challenge. This is due to the fundamental chemical differences between organic polymers and the partly inorganic silicones. In many cases, the conventional organic reactions used for tailoring surfaces introduces bonds to silicone that will eventually lead to hydrolysis of the grafted structures in the presence of water. The methods used in this thesis takes advantage of the possibilities of silicon chemistry instead of regarding the differences compared to conventional organic chemistry as a disadvantage.

The main aim of the study presented in this thesis has been to determine whether new hydrolytically stable surface structures can be coupled onto silicone elastomer surfaces using plasma treatment followed by hydrosilylation reactions. To assess this, the following issues are also addressed:

- How is the resulting surface composition related to the plasma parameters (type of gas, power, pressure and treatment time)?
- In what way does the surface composition change as a result of the different steps of modification?
- Are the conventional methods of following the changes in surface composition sufficient or are new strategies desired?
- Are the grafted structures available for further coupling reactions?
2 Introduction

2.1 Background

Many parts and functions of the human body can now be replaced with artificial materials. This is the outcome of several decades of research within the multidisciplinary field of biomaterials science. A biomaterial is “a nonviable material used in a medical device, intended to interact with biological systems”\(^1\). Biological interactions are mainly taking place at the surface of the device, which implies that the surface properties are crucial for the performance of many biomedical applications. The progress of biomaterial science has gradually changed the surface requirement from that of a minor host response towards an ability to interact with the host in a specific and controlled way. This requires the surface to be tailored for the biological environment surrounding the device by a surface modification technique.

Our group has previously developed methods for surface modification of polymers for biomedical applications. Electron beam irradiation followed by graft polymerization of acrylamide was used to modify the surface of linear low-density polyethylene (LLDPE)\(^2-4\), poly(\(\varepsilon\)-caprolactone) and poly(1,5-dioxepan-2-one)\(^5-7\). Heparin surfaces on LLDPE were obtained by converting the amide groups of the grafted poly(acrylamide) chain to primary amino groups followed by heparin coupling\(^8\). We have also modified high-density polyethylene tubes with chitosan, chitosan hydrogel and heparin as a way to improve the blood compatibility and antibacterial properties of the material\(^9\).

Silicone elastomers are widely used for various biomedical applications and it would be of great interest to improve their surface properties. We tried to apply the methods we have used for other materials on silicone elastomers, but they were not successful. The reason was that the partly inorganic structure of silicone requires other methods than those suitable for organic polymers.
2.2 Silicone elastomers

2.2.1 Short history of silicones

F. S. Kipping published more than 50 articles in the field of organo-silicon compounds between 1907 and 1944. It was he who introduced the term “silicone”, a contraction of “silicon ketone”, based on an early assumption of the chemical structure that was later proven to be wrong. In 1937, he gave a lecture at the Royal Society in London in which he stated that the organic derivatives of silicon “are very limited in their reactions ... and the prospect of any immediate and important advance in this section of organic chemistry does not seem to be very hopeful.”

At the same time, Kipping’s basic discoveries drew the attention of industrial research laboratories. J. F. Hyde at Corning Glass Company developed various organo-silicon resins and, inspired by this work, E. G. Rochow of General Electric developed the first polymeric silicone material published and patented in 1941. After World War II, the commercial production of silicone grew rapidly. In 1999, the annual global consumption of silicone elastomers had grown to approximately 170,000 tonnes.

2.2.2 Structure and general properties of silicone elastomers

Silicone elastomers, also known as silicone rubbers, are based on polydimethylsiloxane (PDMS) which has a siloxane backbone consisting of alternating silicon- and oxygen atoms with two methyl groups attached to each silicon atom (Figure 1).

![Figure 1. The repeating unit of polydimethylsiloxane](image)

Linear PDMS has a glass transition temperature (T_g) of –123 °C which is very low compared to most other polymers. Silicone is a liquid at room temperature, but by
crosslinking the polymer one can produce an elastomer. The crosslinking is referred to as “curing” or “vulcanizing”. Silicone chemistry provides different ways to obtain molecular architectures to achieve desired properties. Depending on the mechanism and processing conditions, silicone elastomers can be divided into one- or two component room temperature vulcanizing silicone rubbers (RTV-1 or RTV-2, respectively), high temperature vulcanizing (HTV) and liquid silicone rubber (LSR)\(^{15}\). Silicone elastomers often contain silica as a filler that improves the mechanical properties of the material.

### 2.2.3 Miscellaneous silicone reactions

It is important to recognize the fundamental differences between silicone chemistry and “normal” organic chemistry. This section is intended to give a brief introduction to some of the most relevant reactions of silicones.

**Hydrosilylation** is the addition of a silicon-hydrogen bond to a terminal double bond\(^{17}\). The reaction is normally catalyzed by a platinum complex\(^{18}\).

![Scheme 1. Hydrosilylation of Si-H to a terminal double bond.](image)

Hydrosilylations normally gives high yield with a catalyst concentration of a few ppm. The reaction is widely used for the crosslinking of silicone elastomers and it is also an important reaction for building controlled molecular architectures. The reaction is irreversible and can be carried out at room temperature.

**Condensation** of two silanol groups, Si-OH, results in a relatively stable siloxane bond, Si-O-Si, as illustrated in Scheme 2.
Introduction

\[
\begin{align*}
\text{Si-OH} + \text{H-O-Si} & \rightarrow \text{Si-O-Si} + \text{H}_2\text{O} \\
\text{Scheme 2. Condensation of silanol groups.}
\end{align*}
\]

The silicone main chain consists of siloxane linkages. It should be noted that the formation of siloxane bonds is in fact an equilibrium reaction. The rate of reaction around neutral pH values is low and is of little practical importance for most applications.

**Hydrolysis** of Si-O-C linkages is an equilibrium reaction, but this linkage is readily hydrolyzed in the presence of water as opposed to the Si-O-Si linkages.

\[
\begin{align*}
\text{Si-OR} + \text{H}_2\text{O} & \rightarrow \text{Si-OH} + \text{ROH} \\
\text{Scheme 3. Hydrolysis of alkoxy group bonded to silicon.}
\end{align*}
\]

This hydrolysis is important for silane coupling agents used as adhesion promoters and for one-component silicone rubber, RTV-1, that cures in the presence of water from the surface or from humidity in the surrounding air.

### 2.3 Silicone elastomers as biomaterials

#### 2.3.1 Biocompatibility of silicone elastomers

The term “biocompatible” is often used to describe the performance of a biomaterial. The most widely accepted definition was proposed by D. F. Williams in 1987:

“Biocompatibility is the ability of a material to perform with an appropriate host response in a specific application.”

This definition implies that biocompatibility has to be evaluated in a way that reflects the conditions in a given application. Furthermore, one has to determine what host response can be considered appropriate, *i.e.* to what extent adverse events are acceptable. Chauvel-Lebret *et al.* has recently reviewed the biocompatibility of
elastomers including their material properties and applications, as well as evaluation of biocompatibility.\textsuperscript{19} Although the specifications of a material depend on the application, some general properties of silicone elastomers used in biomedical applications are listed in Table 1.

\textit{Table 1. Properties of silicones for use in biomedical applications.}\textsuperscript{20}

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good elastomeric and relatively uniform properties over a wide temperature range</td>
<td></td>
</tr>
<tr>
<td>Physiological indifference</td>
<td></td>
</tr>
<tr>
<td>Good low temperature resistance and stability at high temperatures</td>
<td></td>
</tr>
<tr>
<td>Excellent resistance to biodegradation</td>
<td></td>
</tr>
<tr>
<td>Excellent resistance to oxidation and ultraviolet radiation</td>
<td></td>
</tr>
<tr>
<td>Moderate biocompatibility</td>
<td></td>
</tr>
<tr>
<td>Outstanding resistance to ageing</td>
<td></td>
</tr>
<tr>
<td>Excellent dielectric behavior over a wide range of temperatures</td>
<td></td>
</tr>
</tbody>
</table>

The relevance of the various listed criteria may differ depending on the intended use. Note that the biocompatibility is generally considered to be moderate, even though it is dependent on the specific application.

\subsection*{2.3.2 Biomedical applications of silicone elastomers}

One of the first successful attempts to use silicone elastomer as a biomaterial was a hydrocephalic shunt procedure performed by F. E. Nulsen and E. B. Spitz in 1956.\textsuperscript{21} Numerous biomedical applications have taken advantage of the properties provided by silicone elastomers since then. Some of the most important biomedical applications are listed in Table 2.
**Table 2. Biomedical applications of silicones.**

<table>
<thead>
<tr>
<th>Encapsulants for metal implants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extrusions for carrying blood, drugs, or nutrients</td>
</tr>
<tr>
<td>Implants for plastic, orthopedic and other surgical specialties</td>
</tr>
<tr>
<td>Process aid for pharmaceutical manufacturing</td>
</tr>
<tr>
<td>Special fabrications – rods, rings, sheets, seals, tubes, valves, etc.</td>
</tr>
<tr>
<td>Membranes of blood oxygenators in heart-lung circulation</td>
</tr>
<tr>
<td>Drug delivery systems</td>
</tr>
</tbody>
</table>

The usage of silicones in medical and pharmaceutical applications in 1989 was about 11,000 tonnes, including about 90 tonnes for long-term medical devices. Implants manufactured from silicone elastomers are used in a wide range of surgical fields. Some applications where silicone implants are used are listed in Table 3.

**Table 3. Implant applications for medical grade silicone elastomers.**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstructive surgery</td>
<td>Reconstruction of breast, nose, chin and ear.</td>
</tr>
<tr>
<td>Ophthalmology</td>
<td>Correction of detached retina and prosthetic eye.</td>
</tr>
<tr>
<td>Orthopedic surgery</td>
<td>Reconstruction of fingers, wrists, elbows and tendons.</td>
</tr>
<tr>
<td>Cardiovascular surgery</td>
<td>Construction in artificial hearts and heart assist devices, coatings on pacemaker and lead-wires.</td>
</tr>
</tbody>
</table>

As indicated in Table 1, the biocompatibility of silicone elastomers can be regarded as moderate in many implant applications. Whether or not a material is biocompatible is something that has to be determined in each specific case. Furthermore, even applications with extensive clinical documentation may lead to different conclusions regarding safety issues. One example is the well-known controversy about the safety of silicone breast implants.

Considering the wide range of biological environments to which the implants are exposed, it is not surprising that no single material is optimal for all these conditions. The performance *in vivo* is often related to events taking place at the surface of the
foreign material. If the surface can be adapted to the specific environments to which the implant is exposed, it is likely that a significant improvement in the in vivo performance can be achieved. A strategy that may be successful is to create a surface that interacts in a controlled and defined way with the biological system of the host.

2.4 Plasma surface modification of silicone elastomers

2.4.1 Brief introduction to plasma technology

Plasma is the fourth state of matter besides solid, liquid and gas. It is a gas that has been partially ionized and thus contains ions, electrons and neutral species. Plasmas can be produced through the action of either very high temperatures or strong electric or magnetic fields.\textsuperscript{25} Plasmas used for the surface modification of polymers are normally formed in a gas at low pressure in an electromagnetic field, and are often referred to as “cold” or “non-equilibrium” plasmas.\textsuperscript{26} The most common are radio frequency (“RF”) and microwave (“MW”) normally operated at 13.56 kHz and 2.45 GHz, respectively.

Plasmas used for the surface modification of polymers can be divided into three different classes\textsuperscript{27}:

\textbf{Plasma treatment} leads to a reaction between the surface and reactive species in the plasma. This introduces new functional groups at the surface, and internal surface reactions may lead to cross-links. The gas is typically oxygen, argon, nitrogen, air or some other gas that is not able to deposit a layer from the reacted gas at the surface.

\textbf{Plasma polymerization} is obtained by using a gaseous monomer. The monomer forms a plasma composed of reactive species. These will react with the surface under the deposition of a crosslinked film. Depending on the monomer used, unique film properties can be obtained on various materials. Fluorinated surfaces are obtained by plasma treatment in the presence of a fluorinated gas\textsuperscript{28-30}, glassy layers with hexamethyldisiloxane\textsuperscript{31-35}, aminated surfaces with allylamine plasma\textsuperscript{36-39} etc. Silicone elastomers have also been provided with a surface of plasma-polymerized 2-hydroxyethyl methacrylate\textsuperscript{40}.
Cleaning and etching are methods used to remove contaminants and protective layers, respectively. The difference between cleaning and etching is mainly the amount of material that is removed.

In all of these cases, the specimen is placed in a chamber that is evacuated to a low pressure before an electromagnetic field ignites the plasma. The main parameters determining the effect of a plasma process are treatment time, power, pressure, flow and type of gas.

Corona treatment is a technique in which electrical discharges are produced, normally in air at normal pressure. Both corona and e.g. oxygen or air plasma oxidize polymer surfaces, but one must distinguish between the results obtained by the different methods.

2.4.2 Influence of plasma treatment on silicone elastomers

One of the first investigations into how silicone elastomers are affected by plasma was performed by Hollahan and Carlson in 1970. Based on IR measurements they concluded that hydroxyl groups are formed at the surface of oxygen RF-plasma treated silicone. They also observed that not all of the methyl groups were affected by the plasma treatment. They suggest that the dominating form of the hydroxyl groups is as -SiCH$_2$OH rather than as silanol (-SiOH). Corona treatment, on the other hand mainly produced silanol groups. Later studies by Morra et al. found no evidence for the formation of -SiCH$_2$OH species after treatment in oxygen RF plasma. Chou et al. treated silicone films in oxygen RF-plasma and X-ray photoelectron spectroscopy (XPS) data showed that oxygen increased and carbon decreased after the plasma treatment. Furthermore, the binding energy of silicon suggested an increase in the number of oxygen atoms bonded to silicon. This has also been observed by Morra et al.

Argon is normally an inert gas, but argon plasma treatment of a silicone elastomer leads to oxidation of the surface despite the intended absence of oxygen. Urban and
Stewart suggested that this is due to residual traces of air in the chamber or in the material.\textsuperscript{44} They also propose that there may be residual radicals that reacts with oxygen in the air after the treatment. Owen and Smith made similar observations on silicone elastomers treated in argon as well as in nitrogen and helium RF-plasmas.\textsuperscript{45} The oxidation of polymer surfaces treated in \textit{e.g.} argon or nitrogen substantially free from oxygen is a common phenomenon observed for other polymers as well. It has been demonstrated that this occurs also without post-plasma exposure to air.\textsuperscript{46} The occurrence of carbonyl species after argon RF plasma treatment of silicone elastomer has also been found in some cases.\textsuperscript{44} Gaboury and Urban found that Si-H groups are formed at the surface of silicone elastomers treated in argon MW-plasma.\textsuperscript{47-49}

That a silica-like layer is formed at the surface of a silicone elastomer exposed to sufficiently oxidizing conditions has become generally accepted.\textsuperscript{42,43,45,50,51} The densification of the siloxane structure during the formation of these layers leads to the development of internal stresses. These layers and related phenomena has been studied in detail.\textsuperscript{52-54} The layers have a tendency to crack spontaneously due to the stress in combination with the brittleness introduced. These conditions should be avoided when biomaterials with a uniform surface layer are desired.

The hydrophilic surface formed during plasma treatment has a tendency to recover at least a part of its original hydrophobicity.\textsuperscript{55} This effect is very pronounced in silicone elastomers. Some possible mechanisms for the recovery of hydrophobicity of silicone elastomer surfaces have been discussed by Owen and Smith\textsuperscript{45}:

- Reorientation of surface hydrophilic groups away from the surface
- Migration of treated polymer chains into the bulk
- Migration of untreated polymer chains to the surface
- Loss of volatile oxygen-rich or other polar entities to the atmosphere
- Surface silanol condensation preventing chain reorientation
- Changes in surface roughness
- External contamination of the polymer surface
Introduction

The most widely accepted explanation is the migration of silicone species to the surface. The kinetics of hydrophobic recovery has also been studied in detail.\textsuperscript{42,45,56-62} The silicone species migrating to the surface consist mainly of low molecular weight cyclic siloxanes that are formed spontaneously in the bulk of the material.\textsuperscript{63-65} Ratner \textit{et al.} performed XPS analysis of grafted silicone elastomers with and without water present at the surface before evacuation.\textsuperscript{66} The hydrated specimens undergo a freeze-drying process that locks the structures in the outermost surface layer within the depth of the XPS analysis.

\subsection*{2.4.3 Plasma-induced surface grafting onto silicone elastomers}

Silicone elastomers have been surface modified by various methods of plasma-induced graft polymerization. Radical polymerization grafting initiated by hydroperoxides introduced at the surface has been achieved. Radicals are introduced at the surface by \textit{e.g.} argon plasma treatment. The high chain mobility and lack of crystallinity leads to termination of the radicals, but air or oxygen exposure creates relatively stable hydroperoxides at the surface. Hydroperoxides can also be introduced by corona treatment. The specimens are placed in a monomer solution and when the temperature is elevated the peroxides decompose and initiate a polymerization. This results in chains of different lengths provided with functional groups from the monomer. Peroxide-initiated polymerization from the surface of silicone elastomers has been performed using acrylic acid\textsuperscript{67-74}, acrylamide\textsuperscript{70,75}, methacrylic acid\textsuperscript{67}, glycidylmethacrylate\textsuperscript{67}, 2-hydroxyethyl methacrylate\textsuperscript{71,76-80} and some other monomers\textsuperscript{70,71,81}. The functional groups of the grafted polymer chains have been used for immobilization of polyethylene oxide\textsuperscript{74}, collagen\textsuperscript{69,70,75}, fibronectin\textsuperscript{67,70} and gelatin\textsuperscript{70}.

This way of modifying surfaces may lead to extensive surface functionalization, but the structures are not as well-defined as may be required in specific applications. The chains may be of different lengths and the functional groups are likely to be incompletely reacted with the molecule of interest. These unspecified structures may be acceptable for some applications. However, many of the peroxides formed at the surface of the silicone elastomer will be linked directly to silicon. When they
decompose and initiate the polymerization, the linkage to the material will be via a Si-
O-C bond that will hydrolyze in the presence of water, as stated in Section 2.2.3. This
hydrolytically instable linkage will have implications for the long-term stability of the
grafted structures and there may also be concerns about the toxicological aspects of
leaking surfaces.

Radical graft polymerization at the surface can also be initiated by irradiation of a
material immersed in a monomer solution. This leads to the formation of radicals in
the material that initiate polymerization reactions where the monomers are
accessible.\textsuperscript{66,82-84} However, the irradiation also changes the mechanical properties of
the silicone elastomer due to the combination of radicals in the bulk of the material.\textsuperscript{86}

One method that has become popular is plasma treatment of silicone elastomers
followed exposure to organofunctional silanes. The technology has been used for
preparing stamps for microcontact printing\textsuperscript{87-89}, introducing sites for atom-transfer
radical polymerization\textsuperscript{90}, obtaining hydrophobic surfaces\textsuperscript{91} and other surface
properties\textsuperscript{92-97}. The main disadvantage of these methods is that the condensation
reaction used for coupling is reversible and will eventually lead to hydrolysis of the
grafted structure when used as a biomaterial. If the silane has more than one group
available for hydrolysis and condensation reactions, the formed structure will to some
extent be three-dimensional without possibilities to control the molecular architecture.
3 Experimental

3.1 Silicone elastomer

Silicone elastomers were prepared by thoroughly mixing 9 g (30-35%) methylhydro-(65-70%)dimethylsiloxane copolymer with a molar mass of about 2000-2100 g/mol (PS123), 205 g vinyldimethyl-terminated polydimethylsiloxane with a molar mass of about 17250 g/mol (PS442) and 50 µl platinum-divinyltetramethyldisiloxane catalyst (PC072) purchased from United Chemical Technologies, USA. This resulted in a SiH:vinylic ratio of approximately two$^{98}$. The mixture was immediately cast in glass Petri dishes to a thickness of 3 mm and allowed to cure at room temperature for 7 days. The sheet obtained was Soxhlet extracted in analytical grade hexane from Labscan Ltd, Ireland, for 7 days followed by deswelling and drying in air and under vacuum below $1\cdot10^{-5}$ Torr.

3.2 Plasma treatment

The plasma treatment was carried out at 2.45 GHz in a microwave plasma system model V15-G from Plasma-Finish GmbH, Germany, connected to a Pfeiffer DUO 035 DC vacuum pump. The plasma treatment chamber was subjected to a cleaning process involving at least 20 minutes of oxygen plasma treatment before use. The specimens were placed on a glass sample holder in the center of the chamber. Each run started with evacuation down to 1 Pa and at least three degassing cycles where the pressure was reduced to below 1 Pa followed by flushing with the treatment gas to a pressure exceeding 100 Pa. The plasma treatment was conducted at a preset power, pressure and treatment time. Immediately after the treatment, the chamber was flushed with hydrogen at a pressure of about 80 Pa during 300 s. The chamber was then ventilated to ambient pressure. Argon ($\geq 99.996\%$), nitrogen ($\geq 99.996\%$) and hydrogen ($\geq 99.9999\%$) were purchased from AGA, Sweden.
3.3 Hydrosilylation grafting of allyltetrafluoroethyl ether (ATFEE)

The grafting solution was prepared by mixing 35.0 g allyl-1,1,2,2-tetrafluoroethyl ether (ATFEE), 39.0 g toluene and 100 µl PC072 catalyst unless otherwise stated. Immediately after plasma treatment the PDMS sheets were placed in a flask containing the grafting solution, which was then sealed. The flask was shaken occasionally during a period of seven days. The solution was then replaced by toluene followed by two consecutive changes to fresh toluene. Finally, the toluene was replaced by acetone and the sheets were kept in a flask for three days before Soxhlet extraction in acetone for seven days followed by slow deswelling and drying in vacuum. The ATFEE was of 99% purity and purchased from Aldrich, UK.

3.4 Hydrosilylation grafting of aminopropylvinylether (APVE)

Immediately after the plasma treatment, the silicone elastomers were put in a solution prepared by 0.5 ml distilled aminopropylvinylether from BASF, 19.5 ml distilled analytical reagent grade toluene, Labscan, Ireland, and 50 µl PC072 catalyst. After seven days with continuous stirring, the specimens were repeatedly washed with analytical reagent grade acetone, Labscan, Ireland, and dried in vacuum before being submersed in Milli-Q ultrapure water for 5 days followed by drying in vacuum.

3.5 Derivatization using pentafluorobenzaldehyde (PFB)

The specimens grafted with APVE were put in a hexane solution containing 2 volume-% pentafluorobenzaldehyde (PFB), Acros, New Jersey, USA. After 48 h, the specimens were removed from the solution and Soxhlet extracted in hexane for 72 h, before deswelling and drying in vacuum.
Experimental

3.6 Heparin coupling

Heparin with an activity of 185 IU/mg was purchased from Pharmacia, Stockholm, Sweden. The preparation of diazotized heparin and subsequent coupling to the surface amino groups was carried out according to the procedure described by Larm et al.\textsuperscript{99}. In short, diazotation by NaNO\textsubscript{2} treatment resulted in heparin chains bearing a terminal aldehyde group. The aldehydes were coupled to the grafted amino groups via a Schiff base formation that was reduced to a stable secondary amine linkage using NaBH\textsubscript{3}CN at 50 °C and pH 3.4 for 48 h. The specimens were washed with 0.5 M NaCl solution for 24 h followed by repeated washing in Milli-Q water for 24 h before drying in vacuum.

3.7 X-ray Photoelectron Spectroscopy (XPS)

An AXIS-HS X-ray Photoelectron Spectrometer (Kratos Analytical, Manchester, UK) was used with a monochromatic Al K\alpha X-ray source operated at 15 kV and 20 mA. A take-off angle of 90° with respect to the specimen surface was used unless otherwise stated. The pass energies of the spectra used to determine the elemental composition and to acquire the curve resolutions were 80 and 20 eV, respectively. The curve resolutions were obtained by a least-squares minimization procedure involving simultaneous fitting of all C1s and Si2p peaks of each specimen. The curve shape was assumed to be gaussian. The Si2p\textsubscript{1/2} was assigned a binding energy 0.61 eV higher than that of the Si2p\textsubscript{3/2} with an intensity ratio of 1:2. Background subtractions were made by drawing a straight line between two suitable points\textsuperscript{100}, and the sensitivity factors were supplied by the manufacturer. Measurements of the plasma-treated surfaces were performed on the following day at a pressure below 10\textsuperscript{-8} Torr. The grafted surfaces were analyzed after thorough drying in vacuum after Soxhlet extraction.
3.8 Scanning Electron Microscopy (SEM)

The specimens were sputter coated with Au/Pd (60/40) using a Desk II from Denton Vacuum operated at 45 mA for 10 s. A JEOL JSM-5400 scanning electron microscope operated at 10 kV was used to examine the surfaces. Representative pictures were acquired and the extent of cracking was determined visually.

3.9 Contact angle measurements

Contact angle measurements were made using a NRL contact angle goniometer model 100-00 230, Ramé-Hart Inc. (USA) with deionized water further purified with a Millipore Milli-Q Synthesis A10 system resulting in a resistivity of 18.2 MΩ⋅cm. Dynamic advancing and receding contact angles were measured while adding and withdrawing water from the drop, respectively. The reported values are the average ± standard deviation of measurements on two sides of the drop at three different locations of the specimen surface. To limit the influence of time-dependent processes such as hydrophobic recovery, the measurements were carried out approximately one month after the treatment.
4 Ternary XPS diagrams

The development of a modified surface is dependent on the surface characterization method. This presumes not only that the data is obtained, but also that it can be properly interpreted. Surface modification processes are often followed by X-ray Photoelectron Spectroscopy (XPS), also called Electron Spectroscopy for Chemical Analysis (ESCA), due to its ability to quantify the resulting surface concentrations of all elements except hydrogen. There are two dominating ways of presenting the data; elemental percentage and elemental ratio. The elemental percentage is calculated from the raw area and adjusted by a sensitivity factor specific for each element. The elemental ratio is expressed as a quota of two elemental percentages, e.g. C/Si. An example of the two ways of presenting data is given in Table 4, where "Treatment time" is the time silicone specimens have been exposed to hydrogen plasma. The results are further discussed in Section 5.

Table 4. Elemental compositions and elemental ratios according to XPS after hydrogen plasma treatment of silicone elastomers at different treatment times.

<table>
<thead>
<tr>
<th>Treatment time [s]</th>
<th>C [%]</th>
<th>Si [%]</th>
<th>O [%]</th>
<th>C/Si</th>
<th>O/Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>52.1</td>
<td>22.2</td>
<td>25.8</td>
<td>2.35</td>
<td>1.16</td>
</tr>
<tr>
<td>5</td>
<td>51.3</td>
<td>23.5</td>
<td>25.1</td>
<td>2.18</td>
<td>1.07</td>
</tr>
<tr>
<td>15</td>
<td>47.0</td>
<td>24.4</td>
<td>28.6</td>
<td>1.93</td>
<td>1.17</td>
</tr>
<tr>
<td>30</td>
<td>41.9</td>
<td>23.6</td>
<td>34.4</td>
<td>1.78</td>
<td>1.46</td>
</tr>
<tr>
<td>45</td>
<td>36.9</td>
<td>25.1</td>
<td>38.0</td>
<td>1.47</td>
<td>1.52</td>
</tr>
<tr>
<td>60</td>
<td>31.3</td>
<td>25.8</td>
<td>42.9</td>
<td>1.21</td>
<td>1.66</td>
</tr>
<tr>
<td>120</td>
<td>25.5</td>
<td>24.2</td>
<td>50.4</td>
<td>1.06</td>
<td>2.08</td>
</tr>
<tr>
<td>240</td>
<td>16.3</td>
<td>24.7</td>
<td>59.0</td>
<td>0.66</td>
<td>2.39</td>
</tr>
</tbody>
</table>

The elemental percentages shows a trend of decreasing carbon and increasing oxygen percentages with increasing treatment time. Similar observations are made with regard to the elemental ratios. Figure 2 and 3 shows the graphical representation of elemental composition and elemental ratios, respectively, as a function of treatment time.
Figure 2. Elemental composition data from Table 4 of plasma-treated silicone elastomers in hydrogen presented as elemental percentages plotted against treatment time.

Figure 3. Elemental composition from Table 4 of plasma-treated silicone elastomers in hydrogen presented as elemental ratios plotted against treatment time.
Figure 2 shows that the carbon concentration tends to decrease and the oxygen concentration to increase as the treatment time is prolonged, whereas the change in silicon concentration is very small compared to that of the other elements.

Figure 3 shows that, since the change in silicon is relatively little, the elemental ratios C/Si and O/Si have trends similar to the percentages of carbon and oxygen, respectively. However, only one elemental ratio is considered, and it is therefore not possible to establish e.g. whether an increase in the elemental ratio is caused by an increase in the numerator or by a decrease in the denominator. Any change in one elemental percentage or ratio must therefore be discussed in relation to the changes in the other elements. It is difficult to quantify the rate of change in surface composition as a function of treatment time from this type of diagram.

4.1 Introducing the ternary XPS diagram

When three elements have been quantified, each elemental percentage can be assigned an axis in a three-dimensional orthogonal coordinate system. Since the sum of the three elements is by definition 100%, the surface composition is represented by a point located on the triangular plane with corners located at 100% on each of the three axes, as shown in Figure 4.
Figure 4. The elemental composition of a surface containing three elements, e.g. carbon, silicon and oxygen, is represented as a point on the triangular plane in a three-dimensional orthogonal coordinate system with each elemental percentage on separate axes. The broken lines represent values of elemental ratios for comparison.

This plane is a two-dimensional plane ternary diagram, and the term “ternary XPS diagram” is therefore proposed. Davis et al. introduced surface behavior diagrams (SBD) for ternary phase diagrams based on XPS data as opposed to the commonly used bulk methods$^{101}$. In that case, the phases were identified using curve-resolved XPS data and plotted in a ternary phase diagram. It should be emphasized that a ternary XPS diagram provides a new way of presenting and interpreting changes in elemental composition and has little in common with a phase diagram.

The graphical representation of the elemental ratios C/Si, O/Si and O/C in the ternary XPS diagram is also shown in Figure 4. Each line corresponds to a constant elemental ratio. If only one elemental ratio is presented, the surface composition can be anywhere along that line. This illustrates the importance of simultaneous
interpretation of two elemental ratios, compared to the single point required when using ternary XPS diagrams. Processes that gradually change the elemental composition are difficult to interpret by these methods. The data from Table 4 plotted in a ternary XPS diagram is presented in Figure 5.

![Figure 5](image)

**Figure 5.** The data of Table 4 plotted in a ternary XPS diagram.

In contrast to Figures 2 and 3, the trend of the changes in overall surface composition is easily identified in the ternary XPS diagram. This way of presenting the data makes the changes in surface composition easy to follow and evaluate.

### 4.2 Stoichiometric distance

The fact that a surface composition is represented as a single point makes the ternary XPS diagram suitable for following surface modification processes like the one presented in Figure 5. The distance between the treated and untreated compositions in the diagram is a measure of the overall change in surface composition. This distance is related to the changes in stoichiometric composition and is therefore called the “stoichiometric distance”, denoted $R_n$, which is the length of the vector $v_n$ as illustrated in Figure 6.
To obtain quantitative data for the rate of a surface modification process, the stoichiometric distance must be calculated. A vector from the point representing the untreated specimen to the point corresponding to the treated specimen composition is given by:

$$\mathbf{v}_n = (\Delta C_n, \Delta Si_n, \Delta O_n)$$  \hspace{1cm} (Eq. 1)

where $\Delta C_n = C_n - C_0$, $\Delta Si_n = Si_n - Si_0$ and $\Delta O_n = O_n - O_0$, with subscripts 0 and n denoting untreated and treated specimens, respectively. The length of the vector, i.e. the stoichiometric distance, is calculated as

$$R_n = |\mathbf{v}_n| = \sqrt{\Delta C_n^2 + \Delta Si_n^2 + \Delta O_n^2}$$  \hspace{1cm} (Eq. 2)

Tóth et al. investigated oxygen plasma-treated PDMS and introduced an expression for changes in the stoichiometric distances C/Si and O/Si instead of for changes in the
elemental percentages of all the elements\textsuperscript{102}. In this thesis, the stoichiometric distance refers to all three elements present in the surface. Figure 7 shows the stoichiometric distance plotted against treatment time.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{stoichiometric_distance_plot.png}
\caption{Stoichiometric distance from the untreated to the plasma treated surface composition in Figure 5 plotted against treatment time.}
\end{figure}

The progressing change in elemental composition is followed graphically in Figure 5. In Figure 7 the stoichiometric distance between the points representing the untreated and plasma treated compositions are plotted against treatment time. This way of presenting the rate of change in surface composition is of particular interest when kinetic aspects of different treatment conditions are compared. This is due to the fact that when the method of stoichiometric distance is used, only one data point per composition has to be evaluated. As an example, the data of Figure 7 includes eight data points, whereas the elemental percentages would be three elemental compositions that must be interpreted together for each of the eight specimens analyzed.

\subsection{4.3 Stoichiometric direction}

The stoichiometric distance is a measure of the overall change in surface composition, whereas the stoichiometric direction provides information about the way in which the
composition has changed. The angle to the vector $v_n$ is calculated by defining a suitable reference vector $u$. Figure 6 shows the vector parallel to a line from 100% silicon to 100% oxygen, i.e. the vector $u_{SiO} = (0, -1, 1)$, that represents a constant carbon percentage. The stoichiometric direction, $\theta_{SiO}$, is then given by:

$$
\theta_{SiO} = \arccos \frac{u_{SiO} \cdot v_n}{|u_{SiO}| \cdot |v_n|} = \arccos \left( \frac{(0, -1, 1) \cdot (\Delta C, \Delta Si, \Delta O)}{|u_{SiO}| \cdot |v_n|} \right) = \arccos \frac{\Delta O_n - \Delta Si_n}{\sqrt{2} R_n} \quad (Eq. 3)
$$

The stoichiometric distance and stoichiometric direction can be used together as quantitative measures of how the surface composition changes as a result of a surface modification process. The stoichiometric distance is a measure of how much the composition has changed whereas the stoichiometric direction provides information of the way it has changed. Figure 8 shows the stoichiometric direction for the data of Figure 5 plotted against treatment time.

![Figure 8](image_url)

**Figure 8.** Stoichiometric direction between a vector parallel to the SiO-axis and a vector from the untreated to the plasma treated surface composition in Figure 4 plotted against treatment time.

The first five seconds of plasma treatment results in a stoichiometric direction of almost $150^\circ$ with reference to the SiO-vector, but the angle decreases to a value
between 60° and 70° as the treatment time is prolonged. Figure 8 emphasizes that small changes in elemental composition, *i.e.* small stoichiometric distances, can have a large impact on the stoichiometric direction.

The concept of the ternary XPS diagram can be applied to a wide variety of surface modification processes. Stoichiometric distances and directions of vectors between points corresponding to untreated, modified and desired surface structures can be used to determine the extent to which the surface has changed and whether the change is in the expected or desired direction. Even though the graphical presentation is limited to three elements, the calculation of the stoichiometric distance may also be used to interpret surface changes involving more than three elements.
5 Plasma treatment of silicone elastomers

Silicone elastomers were plasma treated at predetermined settings of power, pressure and treatment time in oxygen, argon and hydrogen. The resulting elemental surface compositions were determined by X-ray photoelectron spectroscopy (XPS). The ternary XPS diagrams presented in Section 4 were used to evaluate the influence of various plasma conditions on the resulting surface composition. Curve resolution of XPS data provided further insight in the molecular structure in the surface region, and scanning electron microscopy (SEM) was used to characterize the structural changes in the surface.

5.1 Elemental composition after oxygen, argon and hydrogen plasma

The surface composition of silicone elastomers treated in oxygen plasma under four different combinations of power (100 or 300 W) and pressure (25 or 75 Pa) are presented in ternary XPS diagrams in Figure 9.
The original composition is close to what is expected from the repeating unit, i.e. 50% carbon, 25% oxygen and 25% silicon. The general trend is for carbon to decrease and for oxygen to increase. The silicon percentage remains relatively unchanged, although a slight increase is observed on prolonged treatment. Surface oxidation is expected in such an oxidative environment. There is a pronounced change in surface composition already after five seconds of plasma treatment, but the changes after this initial oxidation are more gradual. These results will be discussed further in later sections.
The surface compositions of silicone elastomers treated in argon plasma with similar treatment parameters as those of the oxygen plasma are presented in Figure 10.

Figure 10. Elemental composition of argon plasma treated silicone elastomers at different treatment times for four combinations of power and pressure.

The rapid initial change in surface composition of specimens treated in oxygen plasma was not observed for the specimens treated in argon plasma. The general trends in the ternary XPS diagrams for the argon plasma treatment are similar to those for treatment in oxygen plasma, i.e. oxygen increases and carbon decreases. Removal of methyl groups from the surface will result in a higher oxygen percentage. However, this would also lead to an increase in the silicon concentration and this is not observed.
to the extent that could be expected if this was the only explanation of the change in surface composition. The argon was substantially free from oxygen-containing species, but there can be other external sources. For instance, the walls in the chamber or the silicone elastomers may contain traces of water or oxygen.\textsuperscript{45} The repeating unit of silicone itself contains 25\% oxygen if hydrogen is excluded, but this is already bonded in the material and it is not therefore likely to contribute to the additional oxygen concentration at the surface.

Hydrogen plasma treatment of silicone elastomers was performed under experimental conditions similar to those used for oxygen and argon. The elemental percentages are presented in Figure 11.
The change in surface composition after treatment in hydrogen plasma shows a behavior similar to that of argon plasma-treated silicone elastomers. The initial rapid change in surface composition observed in oxygen plasma did not occur under these conditions either. The hydrogen data points are less scattered than the data points from the argon plasma treated silicone elastomers. Hydrogen may to some extent participate in reactions during the plasma treatment, *e.g.* terminate radicals formed at the surface, whereas the reactive sites formed during argon plasma treatment possibly
have to be terminated by internal surface reactions, which leads to an irregularity in the data points.

Plasma treatments carried out in oxygen, argon and hydrogen show similar trends in the ternary XPS diagrams. After the pronounced initial change in surface composition with oxygen, the composition changes in about the same direction as the specimens exposed to argon and hydrogen plasma. Figure 12 shows the stoichiometric direction after plasma treatment in oxygen, argon and hydrogen plotted against stoichiometric distance.

![Stoichiometric direction plotted against stoichiometric distance for all investigated combinations of power and pressure during plasma treatment in oxygen, hydrogen and argon. Silica (SiO2) is indicated separately as well as the linear route to silica from the untreated composition.](image)

**Figure 12.** Stoichiometric direction plotted against stoichiometric distance for all investigated combinations of power and pressure during plasma treatment in oxygen, hydrogen and argon. Silica (SiO2) is indicated separately as well as the linear route to silica from the untreated composition.

An increase in the silicon content corresponds to a stoichiometric direction with an angle greater than 60°. The initial effects of plasma treatment in oxygen, argon and hydrogen are different. Oxygen leads to a rapid change in surface composition whereas treatment in the other gases results in a gradual change in composition. After the initial stage of plasma treatment, the stoichiometric direction is about 60° for all plasma conditions. However, at a stoichiometric distance of about 40%, the stoichiometric direction increases to about 70°. As indicated in Figure 12, this
corresponds to the formation of a silica-like surface layer. A complete change from the untreated surface composition to that of SiO$_2$ would give a stoichiometric direction of 70º and a stoichiometric distance of 67%. The maximum stoichiometric distance observed in the present case is only about 55%. This can be explained by the formation of silica-like layers on prolonged exposure. These have a tendency to crack which leads to exposure of less oxidized material in the surface region. These effects are further discussed in Section 5.4.

In oxygen plasma, the observed change in surface composition may be caused by the immediate replacement of methyl groups by oxygen species, as is discussed in the next section. In the case of hydrogen plasma, the stoichiometric direction is initially higher than 60º, but it decreases on prolonged exposure. This is consistent with an increase in silicon concentration, and it may indicate that the removed methyl groups are replaced by hydrogen under the formation of Si-H groups. Since hydrogen cannot be detected by XPS, the concentration of silicon becomes higher during this initial stage of the process before the formation of silica-like surface layers.

5.2 XPS curve resolution of Si2p and C1s

To obtain further insight into the molecular changes taking place during oxygen and hydrogen plasma-treatment of silicone elastomers, curve resolution of the Si2p and C1s XPS regions was performed. The XPS data of the Si2p region was obtained from silicone elastomers exposed to oxygen and hydrogen plasma as presented in Figures 13 and 14, respectively.
**Figure 13.** Curve resolution of the Si2p XPS peak for oxygen plasma treatment in a) 100 W, 25 Pa, b) 300 W, 25 Pa, c) 100 W, 75 Pa and d) 300 W, 75 Pa. Silicon bonded to two, three and four oxygen atoms are denoted Si(O)2, Si(O)3 and Si(O)4, respectively.
Figure 14. Curve resolution of the Si2p XPS peak for hydrogen plasma treatment in a) 100 W, 25 Pa, b) 300 W, 25 Pa, c) 100 W, 75 Pa and d) 300 W, 75 Pa. Silicon bonded to two, three and four oxygen atoms are denoted Si(O)2, Si(O)3 and Si(O)4, respectively.
The oxidative states of Si2p after oxygen and hydrogen plasma treatment are quite different. In the vast majority of the silicon atoms, the number of bonded oxygen atoms increases from two to three within the first five seconds of plasma treatment in oxygen. The hydrogen plasma treatment (Figure 14) gradually increases the number of oxygen atoms bonded to silicon from two to three and eventually four, denoted Si(O)₂, Si(O)₃ and Si(O)₄, respectively. Specimens exposed to oxygen plasma at the higher power, 300 W, tend to have a larger proportion of silicon atoms bonded to many oxygen atoms. Oxygen plasma treatment under high power and long treatment times leads to a silica-like surface layer, as is discussed in Section 5.4. During the plasma treatment, untreated silicone species becomes exposed to the oxidizing environment leading to a rapid reaction from Si(O)₂ to Si(O)₃ as observed for specimens treated in oxygen plasma at 300 W, 75 Pa and 240 s.

The oxidative state of silicon is plotted as a function of treatment time. The average numbers of oxygen atoms bonded to a silicon atom for oxygen and hydrogen plasma treatment are presented in Figure 15 a and b, respectively.

![Figure 15](image)

Figure 15. Average number of oxygen atoms bonded to silicon according to curve resolution of Si2p XPS peak after plasma treatment in a) oxygen plasma and b) hydrogen plasma.
The rapid initial change in elemental composition on exposure to oxygen plasma treatment also has an impact on the oxidative state of silicon. The average number of oxygen atoms increases from two to three already after five seconds and then slowly increases to approximately 3.5 oxygen atoms per silicon atom. The average oxidative state of silicon exposed to hydrogen plasma increases to about the same level, but the rate of change is almost linear from the starting point, with a higher rate for the specimens exposed to the higher power (300 W). Despite the initial differences between the oxygen and hydrogen plasma treatments, both processes eventually lead to silicon with similar oxidative environments. The significance of the 3.5 oxygen atoms per silicon atom must be interpreted with caution, since the structure may not be homogeneous throughout the whole analysis depth. The data show that silicon bonded to four oxygen atoms, *i.e.* in a silica configuration, is formed with both oxygen and hydrogen plasma. However, this silica configuration will also contain other silicon configurations, and the term “silica-like” is therefore preferred.

Curve resolution of Si2p shows that the two methyl groups originally bonded to silicon are gradually substituted by oxygen when the silicone elastomers are exposed to plasma. To further elucidate the processes taking place when silicone elastomers are treated in plasma, it is also important to follow the way in which the methyl groups initially present at the surface are affected by the plasma treatment. The C1s region was performed in a similar way as of the Si2p region. The shift in carbon towards higher binding energy makes it possible to distinguish between carbon atoms with different numbers of oxygen bonds to carbon. The results for oxygen and hydrogen plasma treated silicone elastomers are shown in Figures 16 and 17, respectively.
Plasma treatment of silicone elastomers

Figure 16. Curve resolution of the C1s XPS peak for oxygen plasma treatment in a) 100 W, 25 Pa, b) 300 W, 25 Pa, c) 100 W, 75 Pa and d) 300 W, 75 Pa. Carbon with two, three, four and five bonds to oxygen atoms are denoted C1, C2, C3 and C4, respectively.
Figure 17. Curve resolution of the C1s XPS peak for hydrogen plasma-treatment in a) 100 W, 25 Pa, b) 300 W, 25 Pa, c) 100 W, 75 Pa and d) 300 W, 75 Pa. Carbon with two, three and four bonds to oxygen atoms are denoted C1, C2 and C3, respectively.

The dominating form of carbon after plasma treatment in oxygen or hydrogen plasma is the unoxidized form. This is remarkable considering the increase in oxygen percentage from 25% to over 50% as the treatment is prolonged. The highly oxidative environment in oxygen plasma could be expected to lead to a higher proportion of oxidized carbon. However, Morra et al. also observed the presence of unchanged
methyl groups when they exposed silicone elastomers to $^{18}$O$_2$ plasma and analyzed the surface by static secondary ion mass spectrometry and XPS. Since the carbon decreases from 50% to a level below 20% during the plasma treatment, the methyl groups cannot be considered to be inert in the plasma. The explanation is either that the methyl groups are removed from the surface without prior oxidation, or that the methyl groups are readily removed after oxidation. The preferred configuration in the oxygen plasma-treated silicone appears to be silicon bonded to three oxygen atoms, since this is the predominant configuration regardless of plasma parameters or treatment times. This indicates that the first methyl group is easier to replace by an oxygen atom than the second methyl group.

### 5.3 Rate of change in elemental composition

The rate of change in elemental composition as a result of a plasma treatment process has rarely been investigated. However, as in the case of kinetic investigations of reactions carried out in solution, the “kinetic” aspects of surface modification processes may provide an additional understanding of the mechanisms taking place during the modification. The stoichiometric distance introduced in Section 4.2 is a measure of the overall change in elemental surface composition. By plotting this change against treatment time, a “kinetic” profile of each plasma condition is obtained. The stoichiometric distances for elastomers exposed to oxygen, argon and hydrogen plasmas are plotted against treatment time in Figure 18.
Figure 18. Stoichiometric distance plotted against treatment time after plasma treatment in a) oxygen b) argon c) hydrogen under different conditions of power and pressure.
Plasma treatment of silicone elastomers

The rapid initial increase in stoichiometric distance to about 30% observed in oxygen plasma is not observed for specimens treated in argon or hydrogen. Both argon and hydrogen exhibit a gradual change on prolonged treatment from the original composition to a stoichiometric distance of about 50%. This is about the same level as is reached on prolonged treatment in oxygen plasma. As expected, higher power leads to a faster change in surface composition that gradually levels off at a stoichiometric distance of about 50%. The data for oxygen plasma treatment during 240 s is somewhat scattered, probably due to the formation of a silica-like layer, as will be discussed later. The pressure has much less influence on the rate of change in stoichiometric distance than the power.

The argon and hydrogen plasma treatments are quite similar in terms of stoichiometric distance as a function of treatment time. In addition to a visual comparison, they can also be characterized in a more formal way. This provides not only a quantitative comparison, but also tools to predict to what extent the elemental composition will change under different plasma conditions. If sufficient data has been acquired, the method can also be used to choose suitable parameters for a process aiming at a certain surface composition.

The shapes of the argon and hydrogen curves suggest that the expression

\[ R = R_{\text{max}} \cdot (1 - e^{-At}) \]  

(Eq. 4)

can be used for fitting the data, where \( R_{\text{max}} \) is the level of stoichiometric distance that eventually may be obtained on prolonged treatment, \( t \) is the treatment time and \( A \) is a constant specific for each plasma condition. The experimental data of Figure 18 were fitted to Equation 4 using a least-squares minimization procedure to determine the values of \( R_{\text{max}} \) and \( A \).

Since the initial fitting led to only small variations in \( R_{\text{max}} \)-value for the different treatment conditions, the model assigned the same value of \( R_{\text{max}} \) for all the conditions. This resulted in an \( R_{\text{max}} \)-value of 50.2. The values of \( A \) obtained for argon and hydrogen are presented in Figure 19 a and b, respectively.
Figure 19. The constant $A$ for different conditions of power and pressure during plasma treatment in a) argon and b) hydrogen.

The constant $A$ is a measure of the rate of change in elemental composition under given plasma conditions. Figures 19 shows that the power has a large impact on the rate of change in surface composition, with a value for the specimens treated in 300 W about three times higher than those treated in 100 W. The pressure during the treatment has a small impact on the rate. To demonstrate the similarities of the different conditions, all stoichiometric distances are plotted against $A \cdot t$ in Figure 20.
Figure 20. Experimental stoichiometric distance plotted against $A \cdot t$ together with the solid line given by the model according to Equation 4.

The fit of the experimental data to the model shows that the rate constant $A$ is sufficient to characterize the differences between the conditions in plasma in terms of stoichiometric distance regardless of gas (hydrogen or argon), power (100 or 300 W) or pressure (25 or 75 Pa). The scatter in the data at the highest values of $A \cdot t$ in Figure 20 can be attributed to the formation of silica-like layers under these severe plasma exposures, as is discussed in Section 5.4. When the constant $A$ has been determined for a certain parameter setting, the model can be used to predict the stoichiometric distance achieved in a certain treatment time. Moreover, it is possible to determine the treatment time required to reach a certain stoichiometric distance for a certain plasma condition.
5.4 Silica-like surface layers

Oxygen plasma is the most reactive and leads to a higher rate of oxidation than argon or hydrogen plasma. As shown in Figure 9 and to some extent also in Figures 10 and 11, the stoichiometric direction for the most severely treated specimens, i.e. with a stoichiometric distance above 50%, becomes greater than 60° and the data approach the expected stoichiometric distance for silica. Silica has the structural formula SiO₂ corresponding to 33% silicon and 67% oxygen. However, a better term is “silica-like” since there is no evidence supporting the formation of a pure silica layer. The surface layer is still attached to the underlying material and the silicon atoms in silicone are not sufficient for the formation of a complete layer of silica when the methyl groups have been removed from the structure. The gradual change towards a silica-like layer introduces internal tension that eventually leads to spontaneous cracking of the surface layer. The formation of silica-like surface layers during oxygen plasma treatment of silicone elastomers has been reported previously. 43,45,50,102

Plasma treatment in all of the investigated gases eventually leads to these silica-like layers, but the severe conditions in oxygen plasma lead to a more pronounced effect compared to the other gases within the plasma treatment times investigated. Oxygen plasma treated silicone elastomers were studied by scanning electron microscopy (SEM). Specimens exposed to milder conditions of power and treatment time showed no cracks in the surface layer. The extent of cracking was rated on an arbitrary scale ranging from no cracks (0) to severe cracking (8). The reason for using this scale is that it was possible to distinguish these levels of cracking from each other. All investigated oxygen plasma conditions eventually lead to cracked surface layers on prolonged exposure (Figure 21).
**Figure 21.** Crack formation at the surface of oxygen-plasma-treated silicone elastomer. The specimens were rated from no cracks (0) to severe cracking (8) on an arbitrary scale based on observations of SEM images.

The first minor cracks at the specimens treated at 100 W could be observed at 120 s, and after 240 s the crack formation was pronounced. The specimens exposed to 300 W of oxygen plasma were cracked already after 60 s. The specimens treated at 300 W underwent a more rapid change in surface composition than the ones exposed to 100 W. The cracking of the silica-like layer leads to the exposure of virgin material that has not been subjected to plasma treatment. This explains the apparent increase in unchanged silicone species observed in the curve-resolutions of Si2p and C1s for some of the more severely plasma treated surfaces.
6 Hydrosilylation grafting onto silicone elastomers

Plasma treatment of polymers generally leads to a range of functional groups at the surface that can be utilized for further surface reactions. Plasma treatment of silicone elastomers eventually results in a silica-like surface layer, but the fact that it may crack is a disadvantage if the modified silicone elastomers is to be used as a well-defined biomaterial. The mechanical instability and inhomogeneous surfaces are expected to have adverse effects on the biocompatibility. To avoid these effects, oxygen plasma was not used in this case. The similarities of the treatments carried out in argon and hydrogen led to the conclusion that argon is to be preferred over hydrogen due to the potential safety concerns when hydrogen plasma is used. Argon plasma was therefore chosen as the only gas used for plasma treatment processes preceding further surface reactions. The shorter plasma treatment time was chosen to avoid the risk of introducing silica-like surface layers that may exhibit cracking.

In the earlier stages of the treatment some of the methyl groups are removed from the siloxane backbone. Gaboury and Urban identified the formation of Si-H as one of the species formed during the argon microwave plasma treatment of silicone elastomers. These groups can react with terminal double bonds in solution or in bulk phase in the presence of a catalyst.

6.1 Fluoro-functionalization of silicone elastomers

Hydrogen cannot be detected by XPS, and this means that the Si-H groups formed during the plasma treatment have to be derivatized before quantification is possible. It can be difficult to distinguish between different groups when surface modified polymers are analyzed by XPS. The derivatizing molecule should preferably contain an element with a high XPS sensitivity factor that is not present in the surface from the beginning. The quantification is also easier if each molecule contains more than one atom of this element.
In the present case, the Si-H groups were derivatized by allyltetrafluoroethyl ether (ATFEE). The terminal double bond participates in hydrosilylation reactions and ensures that the ATFEE is covalently bonded to the surface (Scheme 4).

The high sensitivity factor for fluorine and the fact that each ATFEE molecule contains four fluorine atoms per grafted site contribute to a favorable signal-to-noise ratio of the derivatized groups. The fluorine concentration is a measure of the amount of Si-H groups available for hydrosilylation grafting at the surface after plasma treatment. Fluorinated silicone surfaces may have interesting properties themselves, but the main interest in this case is focused on the formation and reactivity of the Si-H groups.

Experiments under the same grafting conditions with and without catalyst show that the presence of a catalyst is necessary to obtain grafting (Table 5). It is concluded that the grafting is a result of hydrosilylation rather than of a radical reaction.
Table 5. Elemental composition according to XPS of untreated and plasma-treated (50 W, 60 Pa and 50 s) specimens exposed to different graft solutions.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>C1s</th>
<th>Si2p</th>
<th>O1s</th>
<th>F1s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated</td>
<td>53.0</td>
<td>23.8</td>
<td>23.1</td>
<td>n.d.</td>
</tr>
<tr>
<td>Untreated, graft solution with catalyst</td>
<td>52.4</td>
<td>24.2</td>
<td>23.5</td>
<td>n.d.</td>
</tr>
<tr>
<td>Plasma-treated</td>
<td>46.2</td>
<td>24.5</td>
<td>29.3</td>
<td>n.d.</td>
</tr>
<tr>
<td>Plasma-treated, graft solution without catalyst</td>
<td>45.9</td>
<td>24.9</td>
<td>29.2</td>
<td>n.d.</td>
</tr>
<tr>
<td>Plasma-treated, graft solution with catalyst</td>
<td>44.2</td>
<td>24.6</td>
<td>29.6</td>
<td>1.6</td>
</tr>
</tbody>
</table>

n.d. = Not detected.

Table 2 also shows that Si-H groups are introduced by the plasma treatment since fluorine is not present at the surface after attempts to graft ATFEE onto untreated silicone elastomer. The XPS data for the plasma-treated specimens before and after grafting of ATFEE are presented in Table 6.
Table 6. Elemental composition according to XPS of allyltetrafluoroethyl ether-grafted silicone elastomer for the different plasma parameters treatment time, pressure and power.

<table>
<thead>
<tr>
<th>Plasma parameters</th>
<th>After plasma treatment</th>
<th>After ATFEE grafting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Time [s]</td>
<td>Pressure [Pa]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>100</td>
</tr>
</tbody>
</table>

Most of the grafted specimens have lower carbon percentages than the specimens exposed only to plasma. This is probably due to the removal of carbon-containing degradation products from the surface during the Soxhlet extraction that followed the grafting procedure.
The presence of fluorine on all specimens shows that all grafting procedures to some extent lead to a reaction with ATFFE. To provide a better overview of the relations between plasma parameters and the resulting fluorine concentration, the data are plotted separately in Figure 22.

**Figure 22.** Fluorine content of ATFFE-grafted surfaces according to XPS for the investigated plasma parameters at (a) 50 W and (b) 150 W.

The yield in terms of fluorine concentration increased during about 50 seconds and leveled off or decreased depending on the plasma conditions. Treatment at 60 Pa generally resulted in a yield higher than or about the same as the treatments carried
out at 20 and 100 Pa. Higher power (150 W) leads to a faster process than lower power (50 W).

The silica-like layers should be avoided when a homogeneous surface structure is desired since they have a tendency to crack, as previously mentioned. A combination of high fluorine concentration and a short stoichiometric distance is therefore desired. As shown in Figure 23, there is to some extent a trade-off between these two effects.

![Graph showing fluorine content at the surface of grafted specimens](image)

**Figure 23.** Fluorine content at the surface of grafted specimens exposed to different plasma conditions plotted against stoichiometric distance. The unfilled symbol (50 W, 60 Pa and 50 s) indicates the specimen chosen for further investigation of the surface properties.

The treatments with the lowest surface change resulted in low fluorine contents, but at a stoichiometric distance greater than 6% there was no pronounced increase in the fluorine content. The specimen treated at 50 W, 60 Pa and 50 s represented by the unfilled symbol in Figure 23 was chosen for further investigation of the surface properties since it represents a combination of relatively high fluorine concentration and a relatively short stoichiometric distance.
The XPS measurement is performed in vacuum, and contact angle measurements provide additional information about the surface characteristics in solution. In simple terms, the advancing and receding contact angles reflect the properties in the dry and wet states, respectively. The contact angle data for silicone elastomers treated in argon plasma at 50 W, 60 Pa and 50 s before and after ATFEE-grafting are presented in Table 7.

**Table 7. Advancing (θₐ) and receding (θᵣ) contact angle (mean ± standard deviation) for the grafted specimen exposed to plasma at 50 W, 60 Pa and 50 s.**

<table>
<thead>
<tr>
<th></th>
<th>θₐ  [º]</th>
<th>θᵣ  [º]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated</td>
<td>103.8 ± 0.8</td>
<td>93.1 ± 1.0</td>
</tr>
<tr>
<td>Plasma-treated</td>
<td>102.8 ± 1.9</td>
<td>87.8 ± 2.1</td>
</tr>
<tr>
<td>ATFEE-grafted</td>
<td>104.8 ± 1.4</td>
<td>92.9 ± 0.6</td>
</tr>
</tbody>
</table>

Plasma treatment results in a decrease in the receding contact angle that can be attributed to the introduction of polar functional groups, as indicated by the increase in oxygen and decrease in carbon concentrations in the surface region shown by the XPS-measurements. The receding contact angle of the grafted surface was slightly greater than that of the plasma treated silicone elastomer due to the hydrophobic properties of the -CF₂CHF₂ group, which is in agreement with studies using other fluorinated molecules located at the surface on silicone elastomers.¹³,¹⁰⁴ The mean value of the advancing contact angle decreases after plasma treatment and increases to a value higher than the untreated after ATFEE grafting. The differences are however small in comparison to the standard deviation so their significance is doubtful. The advancing contact angles showed the same pattern of change, but the differences were not statistically significant. Silicone elastomers as well as fluorinated surfaces are hydrophobic, so no major changes in wettability are expected. Moreover, silicone is known to always contain low-molecular silicone species with a tendency to migrate to the surface even after extensive extraction. This may be an explanation of the relatively small differences in advancing contact angle. The surface region is also expected to possess some mobility that leads to exposure of the groups that match the
surrounding environment best, e.g. the polar fluorinated segments are preferably oriented towards the bulk of the material when the surface is exposed to water.

The graft yield in terms of molecular percentage is calculated using a simple approximation of the desired surface structure with the stoichiometric composition \( \text{SiO(CH}_3\text{)}\text{CH}_2\text{CH}_2\text{CH}_2\text{OCF}_2\text{CHF}_2 \), i.e. \( \text{SiO}_2\text{C}_6\text{F}_4 \), since hydrogen cannot be detected by XPS. The graft yield, as a percentage of the surface consisting of ATFEE, can then be calculated as

\[
G \% = \frac{F_{\text{Detected}} \%}{F_{\text{Theoretical}} \%}
\]

(Eq. 5)

where \( F_{\text{Theoretical}} = \frac{4}{1+2+6+4} = \frac{4}{13} \) is the theoretical fluorine percentage expected, considering the elemental composition of the desired structure. The theoretical surface composition expected under these assumptions as well as XPS data of grafted silicone elastomers are shown in Table 8.

**Table 8. Comparison of measured XPS data and theoretical percentages as expected from the elemental composition.**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Elemental percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C1s</td>
</tr>
<tr>
<td>PDMS, theoretical</td>
<td>50.0</td>
</tr>
<tr>
<td>SiO(CH3)(R), theoretical</td>
<td>46.2</td>
</tr>
<tr>
<td>Grafted</td>
<td>44.2</td>
</tr>
<tr>
<td>R = \text{CH}_2\text{CH}_2\text{CH}_2\text{OCF}_2\text{CHF}_2</td>
<td></td>
</tr>
</tbody>
</table>

The typical fluorine concentration, \( F_{\text{detected}} = 1.5\% \), corresponds to a graft yield in terms of grafted ATFEE molecules of 4.9\% according to these assumptions. The approximation does not consider e.g. partial oxidation of the surface in the plasma treatment step, which would lead to lower carbon values and higher oxygen values than those assumed in this model. However, the impact on the results is only minor.
The elemental composition was also analyzed by angle-dependent XPS. The information depth is dependent on the take-off angle and the greatest depth is obtained when the analyzer is perpendicular to the specimen surface, \(i.e.\) at a take-off angle of 90°. For polymers this depth is normally about 10 nm. The relative depth is defined as the ratio between the depth, \(d\), from the surface at a certain take-off angle \(\phi\) and the escape depth, \(D\), of the electrons. The relative depth is proportional to \(\sin \phi\). When \(\phi = 90^\circ\) the relative depth is unity. A low take-off angle gives more surface-specific XPS-data. Angle-dependent XPS-data of ATFEE-grafted silicone elastomer exposed to 50 W, 60 Pa and 50 s, collected at 90°, 45° and 30°, are presented in Table 9.

**Table 9.** Angle-dependent XPS data for the specimen plasma-treated at 50 W, 60 Pa and 50 s and grafted with allyltetrafluorethyl ether.

<table>
<thead>
<tr>
<th>Take-off angle</th>
<th>Relative depth</th>
<th>Elemental percentage [%]</th>
<th>Stoichiometric distance [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\phi)</td>
<td>(\sin \phi)</td>
<td>C1s</td>
<td>Si2p</td>
</tr>
<tr>
<td>90°</td>
<td>1.00</td>
<td>44.2</td>
<td>24.6</td>
</tr>
<tr>
<td>45°</td>
<td>0.71</td>
<td>46.3</td>
<td>24.4</td>
</tr>
<tr>
<td>30°</td>
<td>0.50</td>
<td>47.7</td>
<td>24.3</td>
</tr>
</tbody>
</table>

As the measurements become more surface-sensitive, the fluorine percentage decreases. The increase in carbon and decrease in oxygen concentration is consistent with the presence of a layer of low-molecular weight silicone species on the surface. Table 9 also presents the stoichiometric distance calculated from the theoretical silicone composition, \(i.e.\) 50% carbon, 25% silicon and 25% oxygen. To further elucidate the possible presence of a layer of silicone species present at the surface, the stoichiometric distance is plotted against relative depth in Figure 24.
Figure 24. Stoichiometric distance from untreated silicone elastomer plotted against relative depth obtained from angle-dependent XPS analysis.

The lower the value of stoichiometric distance, the greater is the similarity between the grafted composition and that of the untreated silicone. Figure 24 therefore supports the assumption that there is a layer of silicone species at the outermost surface that to some extent will screen the fluorine. Considering these factors, the estimated graft yield of about five percent ATFEE is therefore higher when only the modified layer is considered.

6.2 Amino-functionalization of silicone elastomers

Primary amino groups attached to surfaces makes it possible to couple a wide range of molecules suitable for biomaterial surfaces. Heparin is one of the molecules that have been successfully coupled to amino groups at a surface. Since silicone elastomers are common materials in biomedical applications, there is a particular interest in the covalent binding of amino groups at the surface to provide a hydrolytically stable bond to the material.

The results of the fluoro-functionalization in the previous section showed that covalent grafting of silicone elastomers can be achieved by plasma treatment followed by hydrosilylation grafting of a molecule with a terminal double bond. The first route for amino functionalization of the silicone elastomer surface was hydrosilylation of N-
vinyl formamide (VFA) to the Si-H groups formed during argon plasma-treatment (Scheme 5).

\[ \text{Scheme 5. Hydrosilylation grafting of N-vinylformamide to Si-H groups formed by argon plasma treatment of silicone elastomer.} \]

After the VFA is grafted to the surface, a separate hydrolysis step at high or low pH is required to convert the formamide group to a primary amino group. The grafting of VFA was evaluated by XPS analysis and the yield was calculated with respect to the theoretical composition, \( i.e. \) the elemental percentages expected from the molecular formula. It is assumed that the composition of the desired structure is the repeating unit \( \text{SiO(CH}_3\text{)(CH}_2\text{CH}_2\text{NHCHO)} \) which has a theoretical nitrogen proportion of \( 1/8 \) since hydrogen cannot be detected by XPS. The graft yield in terms of percentage of the surface consisting of this structure in this case is calculated as

\[ G[\%] = \frac{N_{\text{detected}}[\%]}{N_{\text{theoretical}}[\%]} \]  
(Eq. 6)

where \( N_{\text{detected}} \) is the measured nitrogen content and \( N_{\text{theoretical}} \) is equal to \( 1/8 \). The results for the grafted surfaces are presented in Table 10.
Table 10. Elemental compositions of silicone elastomers grafted with VFA according to XPS. Graft yield calculated with respect to expected theoretical composition.

<table>
<thead>
<tr>
<th>Power</th>
<th>Time</th>
<th>Pressure</th>
<th>C</th>
<th>Si</th>
<th>O</th>
<th>N</th>
<th>[%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>10</td>
<td>20</td>
<td>49.99</td>
<td>26.05</td>
<td>23.87</td>
<td>0.09</td>
<td>0.7</td>
</tr>
<tr>
<td>50</td>
<td>10</td>
<td>60</td>
<td>48.92</td>
<td>26.39</td>
<td>24.40</td>
<td>0.28</td>
<td>2.2</td>
</tr>
<tr>
<td>50</td>
<td>30</td>
<td>20</td>
<td>45.71</td>
<td>27.71</td>
<td>26.44</td>
<td>0.15</td>
<td>1.2</td>
</tr>
<tr>
<td>50</td>
<td>30</td>
<td>60</td>
<td>45.83</td>
<td>26.01</td>
<td>27.99</td>
<td>0.17</td>
<td>1.4</td>
</tr>
<tr>
<td>150</td>
<td>10</td>
<td>20</td>
<td>47.32</td>
<td>27.40</td>
<td>25.08</td>
<td>0.20</td>
<td>1.6</td>
</tr>
<tr>
<td>150</td>
<td>10</td>
<td>60</td>
<td>46.55</td>
<td>28.27</td>
<td>25.18</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>150</td>
<td>30</td>
<td>20</td>
<td>45.56</td>
<td>26.35</td>
<td>28.09</td>
<td>0.00</td>
<td>0.0</td>
</tr>
<tr>
<td>150</td>
<td>30</td>
<td>60</td>
<td>43.44</td>
<td>27.34</td>
<td>29.01</td>
<td>0.21</td>
<td>1.7</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
<td>40</td>
<td>46.73</td>
<td>27.15</td>
<td>26.03</td>
<td>0.09</td>
<td>0.7</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
<td>40</td>
<td>46.32</td>
<td>28.01</td>
<td>25.57</td>
<td>0.11</td>
<td>0.8</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
<td>40</td>
<td>47.50</td>
<td>27.01</td>
<td>25.32</td>
<td>0.17</td>
<td>1.4</td>
</tr>
<tr>
<td>Untreated</td>
<td></td>
<td></td>
<td>52.19</td>
<td>25.39</td>
<td>22.41</td>
<td>0.00</td>
<td>0.0</td>
</tr>
</tbody>
</table>

No nitrogen could be detected on the silicone elastomers exposed to the grafting solution without prior plasma treatment. The graft yield listed in Table 10 shows that VFA can be grafted using this method, although the scatter in nitrogen concentration and hence graft yield is relatively wide for the different plasma treatment conditions. The graft yield of the specimens exposed to the higher power (150 W) had a more pronounced scatter than the specimens exposed the lower power (50 W). The three replicate plasma treatments carried out at 100 W, 20 s and 40 Pa showed a graft yield between 0.7 and 1.4%. The scatter in data can be caused by several factors. Firstly, the nitrogen percentage is relatively low even in the desired surface structure. The conditions of analysis, instrument configuration and the relatively low sensitivity factor for nitrogen may contribute to the variations in data. It is also possible that some of the grafted molecules are buried in the bulk phase under the analysis conditions or that silicone oligomers are present at the surface in a manner similar to.
that discussed in relation to the ATFEE grafting. The hydrolysis step required to obtain the primary amino groups should be carried out at high or low pH and this may potentially lead to partial hydrolysis of the silicone material itself, although the effect depends on the time of exposure and the pH. The challenges associated with the characterization and the need for optimization of the hydrolysis step led to the decision to use another molecule to obtain primary amino groups at the surface in the hydrosilylation step. However, this route is potentially interesting for future studies.

A direct functionalization of the surface with primary amino groups was carried out by hydrosilylation grafting aminopropylvinyl ether (APVE) to the Si-H groups formed by argon plasma treatment. The limited possibility to quantify nitrogen at the relative low concentrations obtained was overcome by derivatization of the amino groups with pentafluorobenzaldehyde (PFB). The reaction is summarized in Scheme 6.

![Scheme 6. Hydrosilylation grafting of aminopropylvinylether to Si-H groups formed by argon plasma treatment of silicone elastomer and subsequent derivatization using pentafluorobenzaldehyde.](image)

The derivatization of amino groups from the grafted APVE leads to a higher sensitivity in the XPS analysis. The sensitivity factor of fluorine is defined as unity whereas the value for nitrogen is only 0.42. In addition, each PFB molecule contains five fluorine atoms compared to the single nitrogen atom in the original structure. A simple estimate of the increase in sensitivity as a result of this derivatization is thus
Hydrosilylation grafting onto silicone elastomer

1/0.42 due to the differences in sensitivity factor and 5/1 due to the stoichiometrical differences. This gives a combined effect of an almost twelve times higher sensitivity in XPS analysis under the assumption that complete derivatization is obtained. The derivatization may also reduce the mobility in the surface layer during the analysis due to the bulkiness of the grafted molecule.

The graft yield was determined by measuring the fluorine concentration and relating that value to the expected concentration of the desired structure having the stoichiometric composition SiO(CH₃)(CH₂CH₂OCH₂CH₂CH₂N=CHC₆F₅). Since hydrogen cannot be detected by XPS, the structure can be summarized as SiC₁₃O₂NF₅, i.e. with a theoretical fluorine content, F_{theoretical}, of 5/22. The graft yield as a percentage of the surface consisting of this structure, is thus expressed as in Equation 5. The elemental concentrations and graft yields of the specimens exposed to different plasma conditions are presented in Table 11.

The reference specimen not exposed to plasma had a minor amount of fluorine at the surface corresponding to a graft yield of 0.8%. This can be explained either as being due to remaining traces of unreacted species despite the extensive extractions performed after the reaction or by a reaction of residual Si-H groups possibly present in the material itself.
Table 11. Elemental compositions of silicone elastomer grafted with APVE and derivatized by PFB according to XPS. The graft yield is calculated with respect to the expected theoretical composition.

<table>
<thead>
<tr>
<th>Power</th>
<th>Time</th>
<th>Pressure</th>
<th>Elemental percentage [%]</th>
<th>Graft yield [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>C</td>
<td>Si</td>
</tr>
<tr>
<td>50</td>
<td>10</td>
<td>20</td>
<td>52.69</td>
<td>22.95</td>
</tr>
<tr>
<td>50</td>
<td>10</td>
<td>60</td>
<td>51.94</td>
<td>23.56</td>
</tr>
<tr>
<td>50</td>
<td>30</td>
<td>20</td>
<td>46.91</td>
<td>26.04</td>
</tr>
<tr>
<td>50</td>
<td>30</td>
<td>60</td>
<td>49.48</td>
<td>23.51</td>
</tr>
<tr>
<td>150</td>
<td>10</td>
<td>20</td>
<td>52.55</td>
<td>22.94</td>
</tr>
<tr>
<td>150</td>
<td>10</td>
<td>60</td>
<td>49.45</td>
<td>24.88</td>
</tr>
<tr>
<td>150</td>
<td>30</td>
<td>20</td>
<td>49.53</td>
<td>23.65</td>
</tr>
<tr>
<td>150</td>
<td>30</td>
<td>60</td>
<td>51.98</td>
<td>21.81</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
<td>40</td>
<td>49.19</td>
<td>24.45</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
<td>40</td>
<td>49.07</td>
<td>24.25</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
<td>40</td>
<td>48.92</td>
<td>25.19</td>
</tr>
<tr>
<td>Untreated</td>
<td></td>
<td></td>
<td>53.72</td>
<td>23.21</td>
</tr>
</tbody>
</table>

The three replicates of the PFB-grafted specimens exposed to argon plasma at 100 W, 20 s and 40 Pa had graft yields between 1.4 and 2.2%. The average graft yield under the investigated conditions was about 2.9% which is significantly higher than the 0.8% found on the specimen not exposed to plasma if the scatter in the three replicates at 100 W, 40 Pa and 20 s is considered to be typical. The concentration of nitrogen was below the quantifiable level due to the low concentration and the relatively low sensitivity factor of the N1s in XPS.

The graft yields of hydrosilylation grafted ATFEE and APVE derivatized with PFB for different plasma parameters are presented in Figure 25.
Figure 25. Graft-yield of ATFEE (a and c) or APVE derivatized by PFB (b and d) after plasma treatment at 50 W (a and b) or 150 W (c and d).

The results of direct fluoro-functionalization using ATFEE and the fluoro-derivatized amino groups using APVS and PFB show some degree of correlation in terms of graft yield. The higher pressure and longer treatment time leads to the highest yields, as has been reported in Section 6.1 where ATFEE grafting was performed for an extended plasma parameter setting.
7 Heparin coupling to amino-functionalized silicone elastomers

In the previous section, it was shown that primary amino groups can be covalently linked to the surface of a silicone elastomer by plasma treatment followed by hydrosilylation grafting. Moreover, the amino groups are accessible for reaction with the aldehyde groups of pentafluorobenzaldehyde (PFB). Heparin is a naturally occurring polysaccharide that can be modified to have a terminal aldehyde group. About one third of the heparin molecules have an antithrombin-binding sequence of five saccharide units. Antithrombin inhibits thrombin and other coagulation factors in the coagulation cascade by forming a complex. When antithrombin is bound to the active site of a heparin chain it undergoes a change in conformation that increases the rate of inhibition. When the inhibited complex has been formed, it detaches and the antithrombin-binding sequence is available for the binding of another antithrombin molecule. This catalytic activity of heparin prevents blood from coagulation, and by immobilizing heparin on a surface one can obtain a bioactive surface with enhanced blood compatibility. Heparin with a terminal aldehyde group is obtained by diazotization, where the heparin main chain is mildly degraded.

The derivatization of APVE-grafted silicone elastomer by PFB demonstrated that coupling between aldehyde groups and amino groups at the surface is possible. Using a similar reaction, diazotized heparin was coupled to APVE functionalized silicone elastomer surfaces according to Scheme 7.
Heparin coupling to amino-functionalized silicone elastomers

Scheme 7. Hydrosilylation grafting of aminopropylvinylether (APVE) to Si-H groups formed by argon plasma treatment of silicone elastomer and the subsequent coupling of heparin.

The heparin coupling follows the same reaction pathway as the PFB coupling except that the double bond in the Schiff base formed is reduced to a hydrolytically stable secondary amine using NaBH₃CN during the coupling reaction (Scheme 8).

Scheme 8. Hydrolysis equilibrium and reduction of double bond using sodium cyanoborohydride.

The XPS data for the silicone elastomer grafted with APVE and subsequently coupled with heparin are presented in Table 12.
**Table 12.** Elemental compositions of silicone elastomer grafted with APVE and coupled with heparin according to XPS.

<table>
<thead>
<tr>
<th>Power</th>
<th>Time</th>
<th>Pressure</th>
<th>Elemental percentage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>50</td>
<td>10</td>
<td>20</td>
<td>54.48</td>
</tr>
<tr>
<td>50</td>
<td>30</td>
<td>20</td>
<td>54.05</td>
</tr>
<tr>
<td>50</td>
<td>30</td>
<td>60</td>
<td>53.46</td>
</tr>
<tr>
<td>150</td>
<td>10</td>
<td>20</td>
<td>56.96</td>
</tr>
<tr>
<td>150</td>
<td>10</td>
<td>60</td>
<td>56.22</td>
</tr>
<tr>
<td>150</td>
<td>30</td>
<td>20</td>
<td>52.58</td>
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<tr>
<td>150</td>
<td>30</td>
<td>60</td>
<td>53.63</td>
</tr>
<tr>
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<td>20</td>
<td>40</td>
<td>55.90</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
<td>40</td>
<td>53.08</td>
</tr>
<tr>
<td>Untreated</td>
<td></td>
<td></td>
<td>55.78</td>
</tr>
</tbody>
</table>

n.d. = not detected

Heparin contains sulfur, but due to the pronounced slope in the S2p region, it is difficult to quantify by XPS if only small amounts are present. As a comparison, LLDPE grafted with a dense layer of poly(acrylamide) reacted to chains with pendant amino groups was coupled with heparin in a comb-like configuration. This resulted in a maximum sulfur concentration of about 2% according to XPS. In the present case, each anchoring site at the surface consists of a single amino group available for heparin coupling instead of a chain with a large number of pendant amino groups. It is therefore expected that a thinner and less dense heparin layer is obtained with a considerably lower sulfur concentration. These levels are difficult to quantify under the present analysis conditions since the detection limit probably lies at about 0.3% for sulfur. However, the changes in concentration of the other elements support the coupling of heparin. Firstly, the nitrogen concentration that could not be detected from the PFB-coupled surfaces, is on average almost one per cent in this case. This nitrogen probably originates mainly from heparin. Secondly, the average silicon concentration is about 20%, which is lower than that of untreated silicone elastomer,
plasma treated silicone elastomer and the other grafted and derivatized surfaces. This supports the presence of a heparin-coupled surface layer. The silicon concentration also appears to be negatively correlated to both nitrogen and carbon as shown in Figures 26 a and b, respectively.

\[\text{Figure 26. Data from Table 12 plotted as a) carbon and b) nitrogen concentration against silicon concentration.}\]

This correlation can be explained by the fact that specimens with relatively high amounts of heparin are expected to have higher percentages of carbon and nitrogen.
Heparin also screens parts of the silicone elastomer, and this results in lower silicon percentage for those specimens. Even though sulfur could not be reliably quantified in the relatively low concentrations given by this grafting procedure, the combined indications of the elemental composition according to XPS support the presence of heparin at the surface. It is emphasized that XPS has limitations when such thin layers containing low concentrations of a unique element are analyzed.

Further investigations of these surfaces would include further optimizations with respect to performance in vitro, i.e. cell- and protein adsorption from different solutions and activity with respect to different coagulation factors. There is also a potential to elucidate other molecular architectures in the grafting step as well as coupling of other potentially interesting molecules based on the findings reported in this thesis.
8 Conclusions

The main conclusion of this thesis is that controlled surface structures can be obtained at the surface of silicone elastomers by plasma treatment followed by hydrosilylation grafting. In contrast to other methods, the reaction leads to covalent bonds that are hydrolytically stable. Various surface functionalities can be tailored by choosing suitable molecules and conditions. Conclusions drawn from the different parts of the thesis are here presented separately.

8.1 Ternary XPS diagrams

The ternary XPS diagrams presented in this thesis are a useful way of interpreting XPS data involving three elements obtained from surface modification techniques. In contrast to the traditional techniques, a ternary XPS diagram presents the data as a single data point. When a modification process is evaluated, a single line is obtained in the diagram, as opposed to the other methods where several curves have to be interpreted together. Furthermore, simple mathematical expressions of the changes taking place as a process progresses provide additional tools for evaluating the data in a structured way. It is concluded that a ternary XPS diagram provides a powerful way of interpreting XPS data from a surface modification process.

8.2 Plasma treatment of silicone elastomers

Plasma treatment of silicone elastomers in oxygen, argon and hydrogen all led to an increase in oxygen and a decrease in carbon concentrations at the surface, whereas the silicon concentration remained at about the same level (25%) under moderate treatment conditions. However, under severe treatment conditions, the composition had a tendency to move towards the composition corresponding to silica (SiO₂) in the ternary XPS diagram. This also corresponded with the observation that silica-like surface layers are formed. These eventually cracked. Curve resolution of XPS data after hydrogen and oxygen plasma showed that the remaining carbon consisted mainly
of unoxidized methyl groups and that the dominating configuration of oxygen was to be bonded directly to silicon. This process was very rapid in the case of silicone elastomers exposed to oxygen plasma. Already at the shortest treatment time (5 s) almost half of the methyl groups were replaced by oxygen. It was also observed that silicon bonded to three oxygen atoms was far more common than silicon bonded to four oxygen atoms. This indicates that the first methyl group is much easier to replace with oxygen than the second methyl group.

8.3 Hydrosilylation grafting onto silicone elastomers

Plasma treatment generally introduces a range of different functional groups. Argon microwave plasma treatment of silicone elastomers introduces Si-H groups onto the surface. It was shown that these were available for coupling reactions with molecules with a terminal double bond using a hydrosilylation catalyst. The different plasma parameters (power, pressure and treatment time) had relatively little influence on the graft yield. For example, the graft yield of allyltetrafluoroethyl ether typically corresponded to about 5 per cent of the analyzed surface region consisting of reacted molecules. This figure should be quite sufficient for the formation of a dense surface layer when larger molecules are used for surface functionalization. Furthermore, the plasma treatment affects only the outermost surface layer. It is therefore likely that the analysis method used for quantification also includes virgin material present below the modified layer. The low-molecular weight species always present in silicone elastomers also has a tendency to migrate towards the surface. This will to some extent screen the grafted layer and contribute to a lower measured value under the analysis conditions.

Amino groups were covalently introduced onto the plasma treated silicone elastomer surface by hydrosilylation grafting using aminopropylvinyl ether. This made it possible to functionalize the surface with various molecules using common coupling chemistry. The accessibility of these groups for further reactions was determined by derivatization using pentafluorobenzaldehyde before XPS analysis.
8.4 Heparin coupling to amino-functionalized silicone elastomers

An attempt was also made to couple heparin covalently to the surface using the introduced amino groups. Diazotized heparin containing a terminal aldehyde group was reacted with the primary amino groups at the surface and reduced to a stable linkage using sodium cyanoborohydride. The methods for coupling molecules to primary amino groups are well established and make it possible to achieve other relevant surface structures. Although there are some problems related to the XPS quantification of these relatively thin layers, we conclude that the heparin is covalently bonded to the silicone surface via hydrolytically stable silicon-carbon bonds. Further optimization of the plasma parameters, grafting conditions, grafted molecules and subsequent coupling of molecules of interest for biomaterial surfaces with respect to various in vitro assays would lead to further insight into the full potential of the methods presented in this thesis.
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