Tool for Surgical Insertion of Light-Activated Neurostimulator

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Chapter 1: Introduction

1.1. Nervous System

The nervous system is the part of the human body in charge of coordinating the reception of external stimuli and the response that the body gives to them. It is equipped with a type of sense organs called receptors, which are in charge of transforming the stimuli’s energy into nerve impulses [1]. To emit an external response, the nervous system uses effectors that can be either muscles or glands.

The nervous system can be divided in two separate systems: the central nervous system (CNS) and the peripheral nervous system (PNS). The CNS is formed by the brain and the spinal cord and is protected by the cranium and the vertebral column, respectively. The PNS is in charge of connecting the CNS with receptors and effectors. It uses a type of cells called neurons to transfer the information from one part of the body to another.

Neurons are in charge of a communicative function and perform two different types of activities. The first one consists in helping the conduction of a signal from one part of the cell to another. The second activity they perform is synaptic transmission, which means communication between adjacent cells.

![Neuron structure](http://webspace.ship.edu/)

Figure 1.1 – Neuron structure. Source: [http://webspace.ship.edu](http://webspace.ship.edu)

Neurons are composed of soma (the cell body), dendrites and axon. In every neuron there is a single axon and multiple dendrites. Dendrites are used to conduct the received signals to cell body. For its part, the axon conducts nerve impulses to other
neurons or muscle cells and is surrounded by myelin, a lipid-rich material that helps increasing the impulse propagation speed [2].

1.2. Spinal cord

The spinal cord is an extremely vital part of the nervous system. Its main function is the transmission of neural signals between the brain and the rest of the body. It is also composed of neural circuits capable of controlling involuntary reflexes. The three main functions performed by the spinal cord are conducting motor information that travels down, conducting sensory information that travels in the reverse direction and coordinating certain reflexes.

Figure 1.2 – Spinal cord structure. Source: [3]
It has a cylindrical appearance, a diameter of approximately 1 centimeter and a length ranges between 42 and 45 centimeters. The spinal cord begins in the caudal part of the medulla oblongata (lower part of the brain stem) and extends down into the vertebral canal. In adults, it ends approximately at the disk level between the first and the second lumbar vertebrae. It can be divided into different sections: pars cervicalis, pars thoracica, pars lumbalis and pars sacralis.

In total, it contains 31 pairs of spinal nerves: 8 cervical, 12 thoracic, 5 lumbar, 5 sacral and 1 coccygeal. Each pair of nerves has its corresponding segment. The spinal nerves roots exit the spinal canal through the intervertebral foramina (vertebra opening).

![Intervertebral foramen](http://www.mayfieldclinic.com)

The spinal cord is covered by the meninges, which consist of three layers: dura mater, arachnoid mater and pia mater. The dura mater is the most external of these and is made of elastic connective tissue that forms a sheath around the spinal cord. It is formed in a single layer and is separated from the inner surface of the bone by the epidural space, which contains mainly fatty tissue and veins. The arachnoid membrane is the middle layer and is attached to the inner surface of the dura mater. Finally, the pia mater is the most internal layer and covers the spinal cord.
1.3. Spinal Cord Injuries (SCI)

As explained above, the spinal cord is an extremely important part of the nervous system. Therefore, when spinal cord injury (SCI) occurs, even if small, it can cause severe disability.

According to World Health Organization, every year 500,000 new cases of SCI are diagnosed around the world and 90% of these are caused by traumatisms [4]. Other non-traumatic cause might be spina bifida, tumors or tuberculosis. SCI is especially worrying because it often occurs to young adults who after suffering from SCI, see their life expectancy reduce considerably.

When spinal cord injury is caused by trauma, we distinguish between two forms of injury: primary injury and secondary injury. The first one occurs immediately after the accident while the secondary injury is caused by the compression or instability of the spinal cord. Acting as quickly as possible once the injury happens can minimize the secondary injury.

The degree of disability after SCI depends on the area where the injury is produced and its severity. When the injury occurs in the upper cervical vertebrae there is a loss of control in arms, legs, breathing, bowel and bladder.

For example, if the injury occurs in the lower cervical or the upper thoracic vertebrae there is control over the shoulder, arms, hands and breathing. However, the breath is weaker than normal and the patient has no control over the bowel, bladder and lower extremities.

Finally, in lower thoracic, lumbar or sacral vertebrae injuries, the patient is able to breathe normally, move upper extremities and control the bowel and bladder. The patient has also some leg strength so is capable of walking by using knee-ankle-foot or ankle-foot orthosis [5].

Glial scar

After a spinal cord injury occurs, the body reacts forming a glial scar, which consists in accumulating glial cells around the CNS to protect it. The glial scar helps the
stabilization of the CNS by creating a barrier that reduces the amount of external tissue infiltration inside the CNS. This minimizes infections and the spread of neural damage. However, the glial scar also creates an obstruction that does not allow the regeneration of injured axons.

![Diagram where the glial scar phenomena can be observed](image)

Figure 1.4 – Diagram where the glial scar phenomena can be observed. Source: [6]

### 1.4. SCI Treatments

After SCI occurs, two different phases can be distinguished: an initial acute phase and a chronic one. As mentioned before, SCI is often a consequence of a severe accident. Therefore, initial treatment is generally focused on the stabilization of the patient.

Although it is not clear which is the best way to proceed during the acute phase of SCI, there are some protocols that medical centers follow. Therefore, patients are kept in an intensive care unit in order to monitor any possible respiratory or hemodynamic problems. During the first phase, depending on the type of injury, surgery to decompress the spinal cord or stabilize the spinal column is also performed. These types of surgeries help to accelerate the recovery and make the rehabilitation periods shorter but do not result in better functional results. Therefore, early surgical interventions are recommended only if there is spinal cord compression caused by bone fragments, which could cause spinal cord tissue.

To reduce the secondary injury after SCI, pharmacological treatments are also used. The most widely used treatment is a high dose of methylprednisolone sodium succinate (MPSS) during the first 8 hours after the injury. This substance, a
glucocorticosteroid, reduces the inflammation after the injury and limits the tissue loss. However, the use of this drug may cause secondary effects such as wound infections and myopathy [7].

To neutralize the glial scar effect, which prevents the axon regeneration, chondroitinase ABC (ChABC) can be used. This bacterial enzyme reacts with some of molecules that form the glial scar and reduces their barrier effect, which permits the regeneration of both ascending and descending axons [8, 9].

Recently, two new techniques have been developed and tested in order to treat SCI: stem cell therapy and micro-electrical stimulators.

Stem cell therapy consists in transplanting neural stem cells at the area where the injury occurred. This treatment improves the recovery after moderate SCI in Sprague-Dawley rats [10] but has a very limited effect when treating severe SCI. However, if combined with curcumin [11], it also helps to achieve a strong recuperation from severe SCI, permitting to improve the functional locomotor recovery.

Finally, the most recent technique developed to treat SCI is the use of micro-electrical stimulators. This technique consists in implanting a micro-electrical stimulator in the neural tissue of the spinal cord, typically a few millimeters below the pia mater layer. The stimulator permits recover locomotor and visceral functions, usually lost when suffering SCI.

![Figure 1.5 – Implantation of FLAMES. Source: [12]](image-url)
Engineers from New Jersey Institute of Technology and Boston University designed a floating light-activated micro-electrical stimulator (FLAMES) [12] could be used as a treatment for SCI. This device is wireless and activated by near infrared (NIR) light delivered by an optical fiber, whose tip is inserted inside the spinal column. The fact that the device is wireless makes it more suitable for long-term implantation, as the biggest problems when implanting devices are the tissue response to the wires and the breakage of them.

FLAMES has been tested in Sprague-Dawley rats by inserting a micro-electrical stimulator in the cervical area of the rats spinal cord. Then, the micro-stimulator received a train of pulses and the power was increased until twitches in the rats’ forelimb were observed.

![Figure 1.6 Scheme of FLAMES in vivo testing in rats. Source: [12]](image)

1.5. Aims of current thesis

Spinal cord injuries affect millions of people around the world. These people, normally young, will suffer from different degrees of disability during their life and will probably have a premature death because of the multiple infections or respiratory problems that appear after SCI. In many cases, they will also be dependent from other people and will need continuous attentions in their day-to-day life.
Therefore, scientists and engineers have been working hardly during the past years to find a cure for this terrible injury. Micro-electrical stimulators, and specially FLAMES due to its wireless characteristics, appear to be a very valid option in the following years to achieve the motor functional recovery of patients who have suffered SCI.

However, there are still some problems that make it difficult to apply this technology to human beings. One of the main one is the lack of tools that permit to insert the micro-electrical stimulator in the spinal cord precisely and without being too invasive.

In this thesis, our aim is to design a surgical tool that permits to address all of these problems. Consequently, we want to design a micro surgical tool made of biocompatible materials, with a simple fabrication process, inexpensive, minimally invasive and that permits to insert a micro-electrical stimulator very precisely inside the spinal cord of a patient who suffered from SCI.

1.6. References


Chapter 2: Design of the micro-surgical tool

2.1. Requirements of the material used

As mentioned in the introduction chapter, the objective of this thesis is to design and build a micro-surgical tool that permits to insert a micro-electrical stimulator in the spinal column of a SCI patient. Once the objective of the project has been defined, the next step is to decide which material will be used to build the micro-surgical tool. Many factors must be taken into account.

In the first place, it must be considered the surgical tool will be inserted in the patient’s body. What is more important, it will be in contact with the spinal cord, which is a vital part of the human body. Therefore, the material used to construct the micro-tool must be biocompatible to avoid causing any damage to the body.

It is also very important that the material used is cheap and that the process to build the device do not require special equipment or complex processes. This will make the device suitable for mass production.

Finally, another key factor is that the micro-surgical tool must be the least invasive possible. The reason, as mentioned before, is that it will be used in the spinal cord, which is a vital part of the human body.

2.1.1. Biocompatibility

When we talk about biocompatibility, it is important to bear in mind that biocompatibility requirements basically depend on the use that will be made of the device studied [1]. In our case, the micro-surgical tool will be inserted to the patient’s body but not implanted.

Biocompatibility can be divided in two different types of tests: in vitro and in vivo. In vitro examinations are easier to perform, as they are not performed on living beings. In vivo assays are more complicated to realize but provide more significant information about the body’s reaction. They also permit to analyze the way in which other parameters such as the shape, size or texture of the device affect the results.
Many studies have been performed to determine the impact that different material have in living beings, when implanted inside their bodies. For example, S. Roy et al [2] performed several in vitro tests following the ISO 10993 biocompatibility testing standards [3]. The materials tested, vastly used in micro-electro-mechanical (MEMS) applications, were silicon (Si), silicon dioxide (SiO$_2$), silicon nitride (Si$_3$N$_4$), polycrystalline silicon (polysilicon), silicon carbide (SiC), titanium (Ti) and SU-8 (a photo epoxy). Sterilization and cytotoxicity tests were performed. The first one consisted in sterilizing the samples by steam or radiation and using scanning electron microscopy (SEM) to observe whether the process had damaged the materials. The Cytotoxicity tests were performed depositing the material in a solution with L-929 mouse cells and observing the changes in pH. Both tests were rated on a scale of 0-4, where 0 meant no adverse reaction. All the materials tested had the minimum score in both tests, meaning that they were biocompatible and could be used in implantable medical devices.

<table>
<thead>
<tr>
<th>Material</th>
<th>Reactivity (0–4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive Control (tin stabilized polyvinylchloride)</td>
<td>4</td>
</tr>
<tr>
<td>Negative Control (high density polyethylene)</td>
<td>0</td>
</tr>
<tr>
<td>Si (monocrystalline silicon)</td>
<td>0</td>
</tr>
<tr>
<td>SiO$_2$ (silicon dioxide)</td>
<td>0</td>
</tr>
<tr>
<td>Polysilicon (polycrystalline silicon)</td>
<td>0</td>
</tr>
<tr>
<td>Si$_3$N$_4$ (silicon nitride)</td>
<td>0</td>
</tr>
<tr>
<td>SiC (monocrystalline 3C silicon carbide)</td>
<td>0</td>
</tr>
<tr>
<td>Ti (sputtered titanium)</td>
<td>0</td>
</tr>
<tr>
<td>SU-8 (epoxy photoresist)</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2.1 – In vitro cytotoxicity tests results of different MEMS materials. Source: [2]

Other in vitro and in vivo assays have been performed to test biocompatibility of MEMS materials [4]. G. Kotzar et al [5] studied the same materials as S. Roy et al [2] both in vitro and in vivo. In vitro tests consisted in testing the cytotoxicity and the effect of sterilization over the samples using SEM image analysis. The results showed that the materials were not damaged by radiation sterilization and that there was no adverse reaction when in contact with L-929 mouse fibroblast cells. The study was completed with an in vivo assay, which consisted in implanting devices made of the different materials in rabbit muscular tissue. Then, after 1 week and 12 weeks, the implant sites were examined to check if any signs of inflammatory reaction were
Present. Results showed that only in polysilicon, silicon carbide and SU-8 implants reaction could be perceived. In any case, though, the reaction could be considered as irritant.

Other in vivo tests have also been performed in Sprague-Dawley rats [4]. In this case, several devices made of silicon, silicon oxide, silicon dioxide, gold and SU-8 were implanted in rats. Different controls to measure the inflammatory response were performed after 4, 7, 14 and 21 days. The response was measured by counting the number of leukocytes, PMN, monocytes and lymphocytes. According to the results, the MEMS materials were found to be biocompatible and the body had similar inflammatory reactions to all of them after their implant.

<table>
<thead>
<tr>
<th>Surface</th>
<th>TIME (days)</th>
<th>Total leukocytes</th>
<th>PMN</th>
<th>Monocytes</th>
<th>Lymphocytes</th>
</tr>
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<tbody>
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<td>Empty cage</td>
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<td>23±5</td>
<td>89±14</td>
<td>6±1</td>
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<tr>
<td></td>
<td>7</td>
<td>20±25</td>
<td>5±4</td>
<td>41±20</td>
<td>4±2</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>25±0</td>
<td>1±0</td>
<td>16±6</td>
<td>9±6</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>25±0</td>
<td>0</td>
<td>21±2</td>
<td>4±2</td>
</tr>
<tr>
<td>Silicon wafer</td>
<td>4</td>
<td>117±02</td>
<td>17±1</td>
<td>86±18</td>
<td>13±4</td>
</tr>
<tr>
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<td>12±5</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>63±14*</td>
<td>2±0</td>
<td>50±10</td>
<td>11±2</td>
</tr>
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<td></td>
<td>21</td>
<td>43±8</td>
<td>0</td>
<td>29±6</td>
<td>11±6</td>
</tr>
<tr>
<td>Silicon nitride</td>
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<td>93±14</td>
<td>14±2</td>
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<td>4±1</td>
<td>20±1</td>
<td>1±0</td>
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<td></td>
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<td>25±0</td>
<td>0</td>
<td>22±1</td>
<td>3±1</td>
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<tr>
<td>Gold</td>
<td>4</td>
<td>125±21</td>
<td>19±12</td>
<td>96±50</td>
<td>10±2</td>
</tr>
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<td>32±9</td>
<td>6±2</td>
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<td>20±2</td>
<td>5±2</td>
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<tr>
<td>Silicon oxide</td>
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<td>28±7</td>
<td>87±2</td>
<td>10±3</td>
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<td>37±5</td>
<td>3±1</td>
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<td>0</td>
<td>21±2</td>
<td>4±1</td>
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<td>25±1</td>
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<td>19±9</td>
<td>6±2</td>
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<tr>
<td>SU-8</td>
<td>4</td>
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<td>28±2</td>
<td>88±7</td>
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<td>0</td>
<td>21±5</td>
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<td></td>
<td>21</td>
<td>25±0</td>
<td>0</td>
<td>20±3</td>
<td>5±2</td>
</tr>
</tbody>
</table>

Table 2.2 – In vivo leukocyte concentrations (cells/µL) measured 4, 7, 14 and 21 days after the device implantation. Source: [4]

2.1.2. Simple and low cost fabrication

Another very important quality that must have the material used to design the micro-tool is that it must be simple and inexpensive to fabricate. Many MEMS component materials such as gold, which cost exceeds $30,000/kg, have been proved to be biocompatible [4] and are suitable for building small parts of a device. However, using them as the device’s main material would make the cost excessive.
Others, such as silicon, have a very low price ($20-$30/kg) in comparison to gold or titanium. However, the devices made with silicon have smaller dimensions [6-8] than the ones our micro-tool will require or need the use of special equipment to build them [9].

![Gold price evolution from 1970 to 2014. Source: London Bullion Market Association](image)

Meanwhile, SU-8 photoresist have a cost of $600 per liter [10], which, although it is more expensive than silicon, it still makes it an inexpensive material. Furthermore, many studies have proved it is possible to build SU-8 high-aspect ratio structures using low cost methods [11-13]. The main reason why SU-8 can be fabricated using a low cost method is because it uses UV photolithography instead of X-ray photolithography [11, 14, 15]. This means that there is no need to use a synchrotron radiation source, which makes the process a lot more expensive.

### 2.1.3. Minimally invasive

The micro-tool that we aim to design will be used to insert a micro-electrical stimulator [16] in the spinal cord of a SCI patient. This area is very delicate and a vital part of the body. In addition, the patient previously will be suffering of an injury in his spinal cord, as the purpose of the surgery to implant the micro-electrical stimulator is to treat this previous injury. Therefore, it is very important that the surgical tool permits to insert the stimulator without causing any further damage in the spinal cord or spinal column.
To measure the impact that the insertion of the surgical tool could cause on the body we previously analyzed the biocompatibility of SU-8 and other materials. However, this is not the only factor that affects the impact that the surgical tool will have in the patient. It is also very important the surgical tool dimensions. SU-8 have been reported to have film thicknesses from 1µm to >1mm with a single coat [17]. The micro-electrical stimulator has a thickness of 100-150µm. In this case, the limitation will be the stimulator’s dimensions as SU-8 is can be used to build even smaller devices than the one it will be designed.

![Image of minimally invasive spine surgery](http://www.spine-surgery-croatia.com)

**Figure 2.2 - Image of minimally invasive spine surgery. Source: http://www.spine-surgery-croatia.com**

### 2.2. Material election: SU-8

After analyzing different alternatives, it has been decided that the material that will be used to design and build the micro-surgical tool will be SU-8. The main reasons are that it has been proved to be biocompatible [2, 4, 5], non-invasive surgical tools can be made with it and can be used in low-cost processes.

SU-8 is a high contrast, epoxy based, near-UV (350-400nm) photoresist that was first developed by IBM [18] in the mid 1990s and it is now a very common material used in MEMS components. It is composed by a combination of an epoxy resin, solvent and a photoacid generator (PAG). The most typical molecule of the resin is formed by 8 epoxy groups and this is what gives the name to SU-8 [19]. The solvent in SU-8 is gamma-butyrolacton (GBL) and the PAG used is made of triarylsulfonium salt.

When UV light is applied to SU-8, the PAG releases an acid. So, only in exposed areas the acid is present. If after the exposure, SU-8 is heated the acid allows it to crosslink and, consequently, be insoluble in developer solution. Using this procedure and a mask
aligner to select the desired exposed areas it is possible to create SU-8 structures with a thickness range of 1μm up to >1mm. Generally, the process to build SU-8 structures consists of 5 steps: coat, pre exposure bake, exposure, post exposure bake and development.

**Coating**

The resist’s coating to a substrate can be made by two different methods: spin coating and casting. The first one is the most used and consists in using a spin processor to achieve a thin flat layer. Thicknesses up to 1.5mm have been reported using single coating [19]. Thicker structures are possible to build using multiple coatings.

The second method consists in using retention walls to hold SU-8 in a specific area. In this case, the SU-8 is poured inside the area delimited by the walls. Structures up to 3.6mm thick have been reported using this method [20].

**Pre-Bake**

Pre-baking or soft baking is the step that follows after coating. In this step, the SU-8 is placed in an oven or a hot plate in order to evaporate the excess of solvent and densify the film. The temperature and time of the pre-bake will determine the amount of solvent present in the SU-8. In order to achieve better control of the solvent evaporation, it is recommended to start with lower initial bake temperatures and then ramp or step to a higher temperature [21]. Following this recommendation will help to achieve better coating and improve the adhesion of the resist to the substrate.

**Exposure**

After pre-baking SU-8, this is ready for the UV or X-ray exposure. This step allows the PAG to release the acid that later will permit the SU-8 to crosslink. X-ray sources are much more expensive than UV ones but offer higher aspect ratios, as the first ones allow aspect ratios of 360:1, while the UV sources can offer up to 25:1 [19]. The optimal exposure doses depend on the film thickness, as thicker layers require higher doses. It must be considered that the exposure dose received by the sample is not uniform because the top of the sample absorbs energy.
Post-bake

After the SU-8 has been exposed to UV or X-ray and the PAG has released the acids, it must now be heated on a hot plate or an oven to allow the acids cause the cross-linking of the SU-8. As in the pre-baking step, it is also recommended to start the post-baking with a lower temperature and ramp it to a higher one in order to obtain better results [21]. The temperature and the post-baking time used will depend on the characteristics of the sample.

Development

The final step consists in immersing the SU-8 in a solvent solution that will dissolve the unexposed areas of the SU-8 device. The most common developer used is Propylene glycol monomethyl ether acetate (PGMEA) and many development times are used diverse, depending on the sample. Once the development has finished, the structure presents the patterned SU-8.

2.3. Design

The micro-surgical tool to be designed will require having a channel shape so that the FLAMES [16] can be placed inside and then inserted to the spinal cord of the SCI patient. The dimensions of the microchannel should be around 500µm wide and 150µm thick, in order to be able to make the FLAMES device fit inside it. Also, the micro-tool needs to be designed in a way the chip remains inside the channel while it is being inserted inside the spinal cord.

![Diagram](image)

**Figure 2.3 – Micro-surgical tool section seen from above. The microchip is inserted on one end of the channel and is kept inside by using a vacuum pump and stoppers.**

To keep the microchip inside the channel, our tool will be connected to a vacuum pump. In order to avoid the microchip ending inside the vacuum pump, the surgical tool will be built with stoppers inside the channel. This way, the microchip will remain
inside the micro-surgical tool while surgery is taking place and it can then be precisely released in a specified area by disconnecting the vacuum pump.

Different alternatives on how to design and build the channel have also been studied. One of them was to use a sacrificial layer [22-25] in order to create the channel hole. Many materials have been used as a sacrificial layer for building microfluidic channels.

In H. Reed et al [23], a method using polycarbonates as a sacrificial layer is described. However, this method requires high temperatures (200-280ºC) to decompose the polycarbonates and they only achieved channel thicknesses up to 5µm. This contrasts with the SU-8 hard bake temperature (150-200ºC) [21] and the channel thickness needed (100-150µm) to insert the FLAMES in the spinal cord.

The most common type of materials used as a sacrificial layer is positive photoresists. These resists are used to build microfluidic structures and are dissolved using an organic solvent once the structure has been created. Different positive photoresists such as AZ 3330 [23], S1318, AZ P4620 [24] or AZ 4400[25] have been reported as sacrificial materials. However, none of them have been used in structures more than 10µm thick.

The use of a sacrificial layer technique, though, has been finally discarded as it did not meet the channel thickness requirements and needed the use of mask alignment in all of the steps. Instead, the micro-channel will be built in three stages: channel structure, channel bottom wall and bonding layer. This is, the channel structure and the bottom wall will be build separated and then bonded together.

This method has been chosen because it has two important advantages. The first one is that there is no need to align the different layers when building the channel structure. This is because the channel structure will be built in a single layer instead of casting one layer on top of another one, thanks to using a polydimethylsiloxane (PDMS) mold. The second advantage is that it is possible to achieve thicker channel holes. The reason is that instead of using a sacrificial layer to build the channel hole, it will be used a PDMS mold to create the channel structure.
Figure 2.4 – Schematic representation of the micro-channel building process by using three stages.

2.4. References


Chapter 3: Channel structure

As mentioned in Chapter 2, the micro-surgical tool that we were aiming to build had the shape of a micro-channel. In this chapter we will describe how the channel structure was designed and built. When we talk about the channel structure, we refer to the structure that has three out of the four walls of the micro-channel, which are the top wall and the two side walls.

3.1. PDMS mold and wall

In order to build the channel structures, the first step was to choose which method and process would be used. As mentioned in Chapter 2, we decided that a PDMS negative mold would be used in order to create the shape of the channel structure. By using this method, the channel top wall and side walls are built in a single cast instead of spinning or casting two different layers. The main advantage of building the top wall and the side walls in a single cast is that there is no need to align both layers when exposing them to UV light, as they will both be exposed at the same time and using the same mask.

![Diagram showing how the SU-8 channel structures are exposed to UV light.](image)

The PDMS molds were designed to build 100-150µm thick, 500µm wide and 17mm long channels. At first, were fabricated using the adhesive-tape soft lithography technique [1], which consists in sticking adhesive tape on a glass slide and cutting the tape using a blade or, as in our case, an electronic cutting tool. The next steps are to remove the parts of tape that and cover the glass and the tape with PDMS. Once the PDMS has been cured it is ready to be used as a mold to build the SU-8 channel structures.
As shown in the images above, the tape mold was designed as three rectangular areas separated by 500µm. These rectangles were then cut and removed. As we can see, the rectangle on the center is longer than the rest. The reason for doing so was to avoid the remaining tape being damaged when cutting it, as occurred when cutting three rectangles of the same height. As the separation between the rectangles is only of 500µm, the result was that the tape that was supposed to remain stuck to the glass peeled off or suffered cuts. With the final design, these problems were avoided.

When designing the first channel structures, the PDMS molds were attached to a glass slide and the SU-8 was spun over them. However, the results were not positive, as the SU-8 layer spun over the PDMS mold did not remain as a uniform layer after pre-baking it.
An alternative method to the one described was thought. Instead of spinning the SU-8 over the PDMS mold, it was casted. This means the SU-8 was poured over an area, which is limited by walls. In our case, the walls were also made of PDMS and surrounded the area occupied by the mold.

We wanted to build SU-8 structures with a thickness around 300-600µm, which was determined by the difference in thickness between the PDMS walls and molds.
However, the SU-8 thickness was proved to be always smaller than the theoretical one, which would be the difference between the PDMS wall and mold. In average, the SU-8 channel structures were 400-500µm thinner than the expected. This fact can be explained by two possible reasons. The first one could be that during the pre-baking step, big quantities of SU-8 solvent are evaporated. The second reason could be that the area occupied by the PDMS mold may be slightly smaller than the area surrounded by the walls, producing a gap. This gap may cause a decrease in the SU-8 thickness, as some of the volume poured over the mold is wasted to fill the gap instead of used to create thickness.

Taking into account that the thickness of the structures we wanted to build was around 300-600µm we decided to build PDMS walls and molds with 1mm of difference in thickness between them. The reason for choosing 1mm instead of the real thickness that we wanted to achieve was, as explained above, because of the SU-8 behavior once poured over the PDMS mold and pre-baked.

Once proven that we could build channel structures using PDMS molds and walls by pouring SU-8 inside the area bounded by the walls, we decided to build the PDMS molds using a SU-8 master instead of using the adhesive-tape soft lithography technique [1].

Before the PDMS molds and walls were ready for being used, though, they had to be silanized [2-4]. The silanization process consist in placing the mold inside a vacuum
chamber and pour a few drops of the silanizing agent, (Tridecafluoro-1,1,2,2-Tetrahydrooctyl)-1-Trichlorosilane, on a vial next to the mold. This avoids the SU-8 structures sticking on the PDMS mold, which would difficult the process of separating both layers. When silanization was used, the SU-8 channel structures were easily separated from the PDMS mold by using a knife and precise mechanical force. If we did not use silanization before pouring the SU-8 over the mold, PDMS parts remained between the lateral walls when we tried to separate the structure from the mold.

### 3.2. SU-8 cast

As mentioned earlier in this chapter, there are two options to apply SU-8 over the surface of a substrate or mold: spin coating and cast. The first one is the most widely used method and consists in spin coating SU-8 using a spin processor in order to get thin flat layers. In this case, the spinning speed will determine the thickness of the SU-8 layer of structure [5]. The second option is to cast the SU-8 over a surface. In this case, the method consists in pouring a certain volume of SU-8 over a surface, which is limited by walls in order to ensure the SU-8 remains inside the desired area.

In our case, we decided to use the casting method, as it is the recommended method when wanting to build thicker layers. Also the fact that our surface, a PMDS mold, was not flat made casting a more suitable method to build our channel structures.

![Image](image-url)

Figure 3.6 – In (a) we can see how we poured SU-8 inside the aluminum foil funnel. In (b) the image shows how SU-8 was then poured over the PDMS mold.

The SU-8 was poured over the PDMS mold in the area surrounded by the PDMS walls. We used an aluminum foil hand-made funnel to ensure that the SU-8 poured spread uniformly and that we had a better control of the SU-8 quantity poured over the mold.
To use it, once the SU-8 was poured inside the funnel we closed the top part to prevent the photoresist going out through there. Then, the funnel was pressed using manual force to expel the SU-8 out of the funnel. As the top part of the funnel had been previously closed, the SU-8 could only go out of the funnel through the bottom, filling the PDMS mold area.

Using a funnel to pour the SU-8 made the process more precise. However, once the SU-8 was poured over the PDMS mold, there was an excessive quantity of SU-8 that needed to be removed in order to achieve structures with the top part flat and uniform. In order to remove the excessive quantity of SU-8, a glass slide was used. The procedure was to place the glass over the PDMS mold in a perpendicular position with respect to the mold. Then, the glass was moved horizontally from one end of the mold to the other, removing all the SU-8 that exceeded the PDMS wall thickness.

Figure 3.7 – (a) SU-8 poured in excess over PDMS mold; (b) Use of glass slide to remove the SU-8 excess
3.3. Pre-Bake

Once the SU-8 had been poured correctly over the PDMS mold, it needed to be pre-baked (or soft baked). The pre-baking step consists in heating the SU-8 structures on an oven or a hot plate with the objective of evaporating excess solvent [6] and permitting the SU-8 to become a hard solid structure. The pre-baking was performed on a hot plate covered by a glass plate and aluminum foil. The glass plate was used to make sure the temperature on the hot plate was as uniform as possible. Meanwhile, the aluminum foil prevented the SU-8 to be exposed to light while pre-baking it.

The SU-8 100 manufacturer (MicroChem Corp.) recommends starting the pre-baking at 65ºC and then ramping or stepping the pre-bake temperature to 95ºC [5]. The reasons to start the pre-bake at a lower temperature are to have a better control of the solvent evaporation and to permit a better attachment of the resist to the substrate.

In our case, we were not looking to achieve a good attachment of the resist to the PDMS mold but we do wanted to control the solvent evaporation, minimize the amount of bubbles present in the SU-8 structure and build structures that were as regular as possible.

For the first attempts to build channel structures, we followed the parameters described by MicroChem. The temperature of the hot plate was set to 65ºC for 30 minutes and 95ºC for 90 minutes. However, the results were not positive, as the SU-8 surface presented a big quantity of bubbles and the structures did not present channel walls with enough definition.

Figure 3.8 – Channel structure after pre-baking step. Some bubbles can be observed.
After the first attempts using these settings, several changes were made in order to test which settings permitted to obtain better results. The variations were applied in both temperatures and baking times.

We started studying how the changes in the first temperature affected the SU-8 structures. When increasing the first temperature to 80ºC, the samples presented bigger bubbles on the SU-8 surface if compared with samples that had been pre-baked for the same time at 65ºC.

The pre-baking time at which the samples were baked at the low temperature also influenced the results. In this case, when increasing the first pre-baking time, the samples presented a smaller amount of bubbles on their surface. After trying different times, the range of temperatures that seem to offer a better result was from 50 minutes to 115 minutes.

![Figure 3.9 – Image of a channel structure with no bubbles after the pre-baking step.](image)

The second pre-baking times and temperatures were studied. As mentioned before, the initial settings were 95ºC for 90 minutes. Then, these settings were varied to analyze how they impacted in the resulting SU-8 structures.

We started varying the temperature. After trying different temperatures, we concluded that when using a temperature slightly higher than the one indicated by the SU-8 manufacturer, the acid diffusion after the exposure is lower than if pre-baked at 95ºC. This means that the acid did not expand to areas that had not been exposed to
UV light. Observing these results, we decided to use 105°C as the temperature at which we pre-baked the SU-8 channel structures.

![Figure 3.10 – Channel structure after development. Diffusion can be observed.](image)

After deciding which temperature would be used as the second pre-bake temperature, we studied how the variations in the pre-baking times affected the channel structures. The pre-baking times were varied from 45 minutes up to 140 minutes. We could not observe significant differences when varying the second pre-baking times. However, as the manufacturer recommended pre-baking SU-8 at least for 90 minutes at a higher temperature, we decided to use this time as the second pre-baking time.

### 3.4. Exposure

After the SU-8 channel structures were pre-baked and achieved the desired hardness, they were ready to be exposed to UV light. The exposure permits the photoresist release acid that will permit the SU-8 to crosslink when heated after, in the post-baking step.

We used a UV curing system equipped with a halide type lamp that emits in the wavelength range of 320nm-390nm (UVA light). The lamp peak irradiance is of 500mW/cm² at 2” from the base of the lamp head [7].

The initial settings we tried for the exposure were 81 seconds of UV light exposure and a distance of 37cm from the lamp to the SU-8 structure. We used a photolithographic
mask to control which areas were exposed to the UV light. This way, we could pattern precisely our channel structures.

The samples were exposed from above, as shown in Figure 3.1, so the light first illuminated the top wall and then the side walls. Using these settings, we managed to build 300-600µm thick structures with small index of diffusion and with good definition channel walls.

When the channel structures that we exposed to UV light were thicker than 600µm, this dose was not enough and the channel walls did not have the desired shape and texture, as they were soft and sticky. However, we were not aiming to build structures thicker than 600µm so these problems did not modify our exposure settings.

With structures of 300-600µm, we tried different exposure times and checked how the SU-8 responded. The range of exposure times used was between 50 seconds and 160 seconds.

When exposing for 60 seconds or less, we can talk of underexposure, as the structures did not achieve the correct hardness and could be easily bended. Using these settings, the channel walls did not have the correct definition either. Another characteristic fact when underexposing SU-8 structures is that they presented a negative curvature (towards the PDMS mold) [8].

![Figure 3.11](image) – Channel structure where we can clearly observe negative curvature due to underexposure.
On the other end, overexposure occurred when the SU-8 structures were exposed to more than 120 seconds. In this case, the structures had a correct texture and the channel walls had a good definition. However, the samples presented diffusion, as the SU-8 acid moved to unexposed areas, making them undevelopable. The same results could be observed in some structures when exposed to UV light for 100 seconds, although other samples did not present any visible diffusion with this exposure time.

![Figure 3.12 – Channel structure after being overexposed to UV light. The diffusion can be clearly observed.](image)

After studying how the SU-8 channel structures responded to the different exposure times, we determined that the best interval of exposure times for our structures was 70-100 seconds. As mentioned before, though, when using 100 seconds as the exposure time, some samples presented diffusion. All the other times in the interval offered similar results and we could not observe significant differences when varying the exposure time in the range of 70-100 seconds.

![Figure 3.13 – Channel structure exposed to 80 seconds of UV light. The picture was taken after developing the unexposed SU-8 areas.](image)
3.5. Post-Bake

After exposing the SU-8 structures to UV light, they needed to be heated to a higher temperature to permit crosslink the exposed areas. Therefore, the structures were post-baked on a hot plate.

However, the structures should not be baked for too much time or at an excessively high temperature, as it would increase the diffusion rate [9]. The most recommended baking times and temperatures are around 20-30 minutes and 50ºC-95ºC [9-11], for structures similar as the ones we built. In all cases, the temperature is ramped or stepped before reaching the post-baking temperature.

In our case, we decided to post-bake our structures on a hot plate, covered by a glass plate and aluminum foil. We set the temperature at 65ºC for 1 minute and at 95ºC for 20 minutes. These settings were chosen because they had been reported to work for layers up to 3.0 mm thick, without causing diffusion if controlled in the pre-baking and exposure steps.

3.6. Development

The final step in order to complete the channel structures was to develop the SU-8 areas that had not been exposed to UV light. This way, only the desired structure would remain on the PDMS mold.

![Figure 3.14](image-url)
The development process consisted in placing the sample inside a glass petri dish and covering it completely with Propylene Glycol Monomethyl Ether Acetate (PGMEA) solution.

The development time depends on the SU-8 thickness [12, 13] and has been described as short as a few minutes [10] or as long as several hours [9]. In our case, although the samples were thick (300µm-600µm), the development time was around 30 minutes.

![Image](image_url)

Figure 3.15 – Channel structure after the development step and separating it from the PDMS mold. In (a) we see the top view of the channel structure and the stoppers can be observed on the left side of (a) image. In (b) the image was taken with a microscope and we can see a front view of the channel structure.

3.7. References


Chapter 4: Channel bottom wall

In the previous chapter, we explained the way the SU-8 channel structures were built. Those structures consisted in the channel’s top wall and the two side walls. Therefore, the only missing part to complete the channel was the bottom wall. In this chapter we will describe how we designed and built the bottom wall for the micro-surgical tool.

4.1. PDMS substrate

To build the channel bottom layers we used a PDMS substrate, over which we spun a SU-8 layer. The substrate was around 2mm thick and was bonded to a 7.5cm x 5.0cm glass slide. Over the PDMS substrate, we would later pour SU-8 and then spun it using a spin processor. For this reason, the glass slide dimensions had to be wider than the spin processor chuck to avoid the SU-8 infiltrating inside the spin processor vacuum path and damaging the engine.

![Figure 4.1 – Glass slide and PDMS substrate over which we spun the bottom wall SU-8 layer.](image)

The thickness of the PDMS substrate was studied in order to determine whether it affected the behavior of the SU-8 layer we would spin over it posteriorly. In particular, we wanted to know if the substrate thickness conditioned the SU-8 thickness. We did not find any conclusive results, as no significant changes in the SU-8 layers thicknesses could be observed. However, we did observe that when using thicker PDMS substrates it was easier to separate the SU-8 structure from them after the development step.
Therefore, we decided to use PDMS substrates of around 2mm thick, as mentioned above.

4.2. Spin coat

Before pouring the SU-8 to build the channel bottom layer, we treated the PDMS substrate with oxygen plasma. The reason was because PDMS is inherently hydrophobic and, if we spun directly the SU-8 over the substrate without treating it before, the SU-8 would not remain as a flat uniform layer as the particles would move away from the PDMS substrate during the pre-bake process. On the contrary, if we exposed the PDMS surface with oxygen plasma we ensured it became hydrophilic for a certain amount of time [1], which enhanced the adhesion of the SU-8 to the substrate.

The SU-8 was poured using an aluminum foil funnel, as described in Chapter 3 of this thesis. The difference was that this time the excessive SU-8 thickness was not corrected by using a glass slide but by spinning the SU-8 to achieve a flat uniform layer.

As mentioned before, once the SU-8 had been poured over the PDMS substrate, we used a spin processor to spread it forming a uniform layer over the whole surface. The thickness of the SU-8 layer depended on the spin speed, as indicated by the manufacturer [2].
In our case, the thicknesses we obtained when spun SU-8 100 at a certain spin speed was slightly higher than the values indicated by the manufacturer in Figure 4.2. The reason for this variation might be explained by the fact that we are not spinning over a silicon wafer but over a PDMS substrate.

For this step, our initial objective was to spin coat an SU-8 layer as thin as possible, as the objective was to build a micro-surgical tool with the smallest possible dimensions. However, we decided to use a lower spin speed than the one initially thought because when spinning over PDMS at high speed, the SU-8 layer did not remain uniform in most cases. Also, if we spun at an excessively high speed, the SU-8 layer was too thin and, in consequence, too weak. To ensure that we obtained uniform SU-8 layers that were hard enough to be used as the channel wall, we reduced the spinning speed to values between 1200rpm and 2200rpm.

The procedure consisted in first ramping the spin speed to 500rpm with an acceleration of 136rpm/s and then maintaining this spin speed for 15 seconds. By doing this, we permitted the resist to spread until it covered the whole surface. Then we ramped the speed again until we reached the final speed, 1200rpm or 2200rpm. In this case, the acceleration was higher (300rpm/s) and the spin time was of 44 seconds. Using these spinning speeds we obtained bottom wall thicknesses around 300µm and 200µm, respectively.
4.3. Pre-Bake

As explained in Chapter 3, once the SU-8 coating was done, the SU-8 needed be pre-
baked in order to evaporate the excess solvent and to permit the SU-8 become a hard
flat layer. The procedure was also performed over a hot plate, covered by a glass and
aluminum foil.

The main difference between the pre-baking explained in Chapter 3 and the one we
performed for the bottom wall is that this time the SU-8 is spun in a flat uniform layer
instead of casted over a PDMS mold.

Another difference between when pre-baking the channel bottom wall was that the
SU-8 formed no bubbles at all after being pre-baked. The reason probably is that the
layer is thinner than in the channel structures case and that when spinning the SU-8,
we distributed uniformly over the surface, avoiding the bubble formation.

As the bubble formation was not a problem anymore, we decided to increase the pre-
baking temperature, as in Chapter 3 we saw that when pre-baking at higher
temperatures, the diffusion rate was lower. The temperatures and baking times we
chose were 90ºC for 30 minutes and 115ºC for 90 minutes. These settings are different
from the ones recommended by the manufacturer [2] but we could obtain bottom
walls with good texture and low diffusion rate when using them.
4.4. Exposure

After the channel bottom wall had been pre-baked for a total time of 2 hours over a hot plate, they were ready to be exposed to UV light in order to let the photoresist release the acid present in it.

The curing system used to expose the channel bottom was the same as used for exposing the channel structures. This is, a system that incorporates a halide lamp that emits with a peak irradiance of 500mW/cm² at a distance of 2” from the lamp head. The wavelength is within the UV range, 320-390nm [3].

![Figure 4.5](image)

Figure 4.5 – Channel bottom wall SU-8 layer after being exposed to UV light. The exposed area is the rectangle that has a slightly different color, in the center of the PDMS substrate.

In this case, the exposure should not be excessive because this layer will be exposed again after placing the channel structure over the bonding layer, as it will be explained in Chapter 5 of this thesis.

4.5. Post-Bake

As done with the channel structures, once the channel bottom wall had been exposed to UV light, we proportioned the necessary temperature for SU-8 to crosslink. The post-bake was performed over a hot plate, covered by a glass plate and aluminum foil.
We followed the same criteria that we used when post-baking the channel structures. We did not want to use very high temperatures or bake the bottom wall for a long period of time to avoid diffusion [4]. Therefore, the temperatures and times of the post exposure bake were the same as the ones used for the channel structures, 65ºC for 1 minute and 95ºC for 20 minutes.

![Figure 4.6 – Top view of the channel bottom wall after the post exposure bake. In this image, the exposed area is clearly visible.](image)

4.6. References

Chapter 5: Channel bonding

Once the channel structure and the bottom wall had been built, the final step was to stick both together in order to create our micro channels. To perform it we used another SU-8 100 layer, which we called bonding layer. This layer was thinner than the bottom wall and was spun over it. The bonding layer was partially pre-baked and, once it was hard enough but still conserved some of its viscosity and adhesive properties, the channel structure was attached to it.

![Diagram showing how the micro-surgical tool is created bonding together the channel structure and the bottom wall.](image)

5.1. Spin coat

As commented above, we used the spin coating method to spread the SU-8 bonding layer uniformly over the channel bottom wall. Before pouring the SU-8, the channel bottom wall was treated using oxygen plasma. By using this technique, we enhanced the adhesion of the SU-8 bonding layer to the bottom wall [1].

The objective of the spin coating was to obtain the thinnest layer possible as it was only to be used to bond together the channel structure (top wall and side walls) to the bottom wall. Therefore, we tried to spin SU-8 layers at very high spin speeds such (6000-8000rpm). However, when spinning at those speeds the spin processor was not stable. The reason is that the vacuum force from the spin processor [2] was sometimes insufficient to hold the glass slide attached to the chuck. Therefore, there was the risk of the glass slide impacting on the spin processor wall.
To ensure that the process was stable, we decided to use lower spin speeds than the ones mentioned above but higher than the ones used to spin coat the channel bottom layer. In this case, we tried spinning speeds between 3000rpm and 4000rpm. The thicknesses of the layers obtained when spinning at this range of speeds was around 70-130µm. This high variance in the thicknesses we obtained was, in part, because in most cases the first layer had a slope. The result was that the areas where the first layer was thinner were areas where the bonding layer was thicker and vice versa.

5.2. Pre-bake

As we did when building the channel structures and the bottom walls, we pre-baked the SU-8 in order to evaporate the excess solvent [3]. In this case, however, the pre-bake was done in two phases. The first one was before placing the channel structure on top of the bonding layer. The second phase took place once the channel structure had already been placed on top of the bonding layer.

In the first phase, we did not want to achieve a SU-8 layer completely hard. The reason was that after a certain amount of time, when the SU-8 layer was hard enough but still viscous and sticky, we would place the previously built channel structure on top. If the surface were not sticky, the channel structure would not attach to the bonding layer.

As in Chapter 4, we selected a pre-baking temperature of 90ºC, which is different from the one indicated by MicroChem [4]. Regarding the baking time, we tried different partial pre-baking times for the first phase and checked whether the channels bonded correctly.

![Figure 5.2 – Micro-surgical tool after bonding the channel structure and finishing the pre-baking. The channel hole is full of SU-8 in almost all its length. Only a little part on the left side has no SU-8 inside the channel hole.](image)

If the first phase pre-baking time was too short, the bonding layer was not strong enough to bear the weight of the channel structure. In these cases, the channel
structure collapsed into the bonding layer, causing the SU-8 from the bonding layer to cover partial or completely the channel hole.

On the contrary, if the bonding layer was baked for too much time, the SU-8 became too hard and not enough viscous and sticky. The consequence was that when placing the channel structure on top of the bonding layer, this would not attach to it properly and would separate from the bottom wall.

The optimal time to place the channel structure on top of the bonding layer was around 40-50 minutes. When placed the channel structures in this time interval, we obtained many satisfactory results. However, as we will explain in the next point, the partial pre-baking time before placing the channel structure on top of the bonding layer was not the only factor that influenced in building successful channels.

![Figure 5.3 – Image of the micro-surgical tool after correctly bonding the channel structure with the bottom wall. Unlike Figure 5.2, the channel hole is not filled with SU-8 and can be clearly observed.](image)

The second phase started after placing the channel structure on top of the bonding layer. In this phase we finished pre-baking the bonding layer with the channel structure attached to it. The temperature we chose was the same as in the first phase and the time was the remaining one in order to pre-bake the bonding layer for a total of 2 hours.

### 5.3. Attaching the channel structure to the bottom wall

Placing the channel structure on top of the bonding layer was one of the most important steps when building the micro-surgical tool. As we discussed when explaining the partial pre-baking process, it was very important to choose the correct moment to place the channel structure over the bonding layer. However, this was not the only important parameter that we had to consider.

Other important factors were the way we place channel structure and the dimensions of the channel structure. When we placed the channel structure gently over the
bonding layer and without pressing it down we obtained better results than when pressing the channel structure against the bonding layer. The reason was because when pressure was made the result was the channel hole getting full of SU-8, as the effect of pressing the channel structure caused the SU-8 on bonding layer, which was still not hard enough, to move to the sides and into the channel hole.

![Diagram](image)

Figure 5.4 – Recreation showing how the SU-8 of the bonding layer moves into the channel hole when the channel structure is placed after not enough partial pre-baking time.

The dimensions of the channel structure were another factor that seemed to affect the results. In particular, the parameter that seemed to alter the results was the thickness. The other dimensions, the horizontal ones, were fixed by the use of the same photolithographic mask when exposing the channel structure to UV light.

The thickness, however, depended on the difference between the PDMS wall and mold thicknesses and it was not constant. Thinner channels offered better results than the thick ones. The reason could be that the thicker the channel structure is, the more weight it has. Therefore, when placing it over the bonding layer, the force that the channel structure performed against bonding layer was bigger and more quantity of SU-8 got inside the channel hole.

5.4. Exposure

The exposure step for the bonding layer was a bit different than the channel structure and bottom wall exposures, as in this case the SU-8 layer we wanted to expose to UV light was in between two layers that had already been exposed to UV light and post-baked. Therefore, in this case the exposure time had to be bigger than the ones previously used because the UV dose that reached the bonding layer was lower.
Different exposure times were tested. When underexposing the bonding layer, the result was that the channel did not remain a single piece after the development, as the channel structure separated from the bonding layer. This happened because the bonding layer that had previously been spun over the bottom wall did not receive enough UV light to crosslink completely.

When exposing the channel to a range of 120 to 140 seconds, the channel bonded correctly and very little diffusion was observed. The exposure was tried from above the channel and from below and the exposure times mentioned in this paragraph, the results were satisfactory in both cases.

5.5. Post-bake

After exposing the whole channel (channel structure, bonding layer and bottom wall), we had to bake it so that the SU-8 present in the bonding layer could crosslink. The other parts, channel structure and bottom layer, did not need to be post-baked as they had already been exposed and post-baked. However, as the whole channel was already bonded together there was no way of avoiding post-baking the channel structure and the bottom layer again.

To perform the post-exposure bake, we placed the whole channel over a hot plate, covered by a glass plate and aluminum foil. The baking time and temperature used were the same as used in the post-exposure bakes of both channel structures and bottom walls: 1 minute at 65ºC and 20 minutes at 95ºC.
5.6. Development

After all the parts had been bonded together, exposed to UV light and post-baked there was only one step remaining to complete our micro-surgical tools: develop the unexposed SU-8 areas of both bonding layer and bottom walls.

As explained in Chapter 3, to develop the unexposed SU-8 areas we immersed the glass slide, the PDMS substrate and all the different SU-8 layers in Propylene Glycol Monomethyl Ether Acetate (PGMEA) solution inside a glass petri dish. It was important that the PGMEA solution covered completely all the SU-8 in order to ensure a good development.

Unlike when developing the channel structures, in this case the development time was not as short as before. We needed around 2 hours to develop completely all the unexposed SU-8 and some agitation of the petri dishes was needed. The reason was probably that now the unexposed area was bigger than before, as it occupied almost the whole PDMS substrate. However we had to be careful in not leaving the channels immersed in PGMEA for too much time as overdevelopment could cause swelling, softening and/or bending of exposed SU-8 areas [5].

Once the development process finished, we proceeded to separate the channel from the PDMS substrate. It must be commented that when separating the SU-8 channel from the PDMS substrate, some small parts of PDMS remained attached to the external part of the channel bottom wall. This did not always occur and depended on hardness of the PDMS substrate.

5.7. Results

After developing the unexposed SU-8 and separating the channel from the PDMS substrate we observed and analyzed whether the channels had been built correctly. We had previously checked the channel structures and only used the ones that met the requirements. Therefore, at this stage, we only evaluated if the channel – channel structure and bottom wall – had bonded correctly or not.

There were two conditions that a channel had to fulfill in order to be considered successfully built. The first condition was that the channel parts had to bond correctly.
This is, after developing the unexposed SU-8 areas; the channel structure remained attached to the bottom wall and the bonding layer. The second condition was that the channel hole had to be free of SU-8 after the bonding step.

![Image](image-url)

Figure 5.6 – Front view of the micro-surgical tool after the channel bonding. The microchannel can be observed with no SU-8 blocking it.

Not all the attempts to build micro-channels made of SU-8 were successful. Although using the same pre-baking, exposure and post-baking settings, some channels were built successfully while others were not. As explained earlier in this chapter, this was because there were some factors that affected the final result and were difficult to control. The most important one was the way in which we placed the channel structure over the bonding layer. As this action was performed manually, it is difficult to affirm whether all the channel structures were all placed in the same way.

Even though we had the difficulties mentioned above, we succeeded in building microchannels that accomplished the two conditions: correct bonding and channel hole not blocked by SU-8. Once we achieved channels that had been successfully built, we also studied whether they were suitable to be used to implant floating light-activated microelectronic stimulators (FLAMES) [6] in the spinal cord.

For this thesis, however, we did not test the actual surgical process but we limited our study to check whether it was possible to insert a FLAMES device inside the built microchannels. The results were positive and we managed to insert FLAMES microchips with a width and a thickness around 400µm and 100µm, respectively.
In conclusion, we can confirm that we built a micro-surgical tool in the form of a micro-channel. In addition, we proved it was possible to insert a microchip inside our surgical tool’s channel.

Figure 5.7 – Microscope image where it can be observed a top view of our micro-surgical tool with a FLAMES microchip inserted inside the microchannel.

5.8. References


Chapter 6: Conclusions and future work

At the beginning of this thesis we defined the aim as an attempt to design and build a micro-surgical tool that could be used in spinal cord surgery. More specifically, we wanted to design a microchannel that permitted the insertion of a floating light-activated microelectronic stimulator (FLAMES) device inside the spinal cord. In addition, we wanted our micro-surgical tool to be biocompatible, inexpensive and to be minimally invasive. The procedure was thought to be tested in rats initially and, if proven to work correctly, would then be carried out in human beings.

By using SU-8 as the material to build our microchannel, we ensured that the micro-surgical tool would be biocompatible and inexpensive. Also, we proved it was possible to build SU-8 microchannels by using a SU-8 100 bonding layer to attach two separate parts (channel structure and bonding layer). Finally, we proved that our microchannels were suitable for a FLAMES microchip to be placed inside them.

Many factors involved in the process of building SU-8 structures have been studied. We observed how parameters such as the spinning speed, the baking temperature or the exposure time directly affect the final result of our SU-8 structures. Also, in our case, the thickness and partial pre-baking time of the bonding layer had a high influence in the results. Another parameter that was difficult to control was the way the channel structure was placed on top of the bonding layer. This directly affected our results and reduced the percentage of successful outcomes when attempting to build our microchannels.

In the future, the micro-surgical tool should be tested to check if our proposal – including stoppers in the channel hole and using a vacuum pump to hold the microchip – works correctly and permits to insert FLAMES microchips safely and precisely inside the spinal cord. The results of these tests added to the observations made by spinal cord surgeons will determine if any modifications should be made in the design of the micro-surgical tool in order to improve its performance.
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