ANTI-SOILING PROTECTIVE COATING FOR CSP REFLECTORS

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Capstone Report

Student Statement:

I, Ikhlas Aoukli, sincerely affirm that I have applied ethics to the design process and in the selection of the final proposed design. And that I held the safety of the public to be paramount and addressed this in the presented design wherever may be applicable.

Ikhlas Aoukli

Approved by the Supervisor

Dr. Asmae Khaldoun
Acknowledgement

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Abstract

The purpose behind this project is to study and implement an anti-soiling coating that can be used and deposited on CSP reflectors. First, different materials are discussed and Titanium Dioxide (TiO₂) is chosen among other materials because of its hydrophilicity and photocatalytic activity when under exposure to UV light. Furthermore, spin coating deposition techniques is investigated. Eight samples of glass substrate are made using this technique. They differ in terms of the number of layers of TiO₂ and the annealing temperature. A smooth surface, a low contact angle with water that ranges between 28.5° and 35.4° and a high surface free energy between 27.7 mJ/m² and 26.6 mJ/m² are found for samples annealed at a temperature of 600°C showing a better hydrophobicity compared to the samples annealed at 400°C. Finally, a comparative study is performed to compare between the samples previously studied and a commercial CSP mirror. To do so, the work of adhesion is computed between the surface, the quartz (main component in sand) and water as a medium. A negative work of adhesion ranges between -49.72 mJ/m² and -48.6 mJ/m² is obtained for the coated samples, while a value of 35.3 mJ/m² for the commercial CSP mirror is found. These results show that no work is needed to clean coated CSP mirrors in the presence of water as a medium in TiO₂ coated mirrors.

Keywords: CSP, reflectors, coating, soiling, TiO₂, Spin coating, roughness, contact angle, surface free energy, work of adhesion.....
1 Introduction

1.1 Context & Motivation

It is everyone’s concern nowadays to treat one of the main challenges of the 21th century: Global warming. This worldwide problematic is threatening the life of many living organism including human being. The effects include icebergs in the poles melting, sea levels rising, ocean getting warmer, fires spreading and desertification. The reason behind the rising temperature of the earth is mainly due to the increasing concentration of greenhouse gases. The main cause behind such an increase is the burning of fossil fuels. The latter releases greenhouse gases into the atmosphere such as CO$_2$ provoking an increase in the earth’s temperature. As the earth’s population is increasing, the need for energy is increasing exponentially. Sonner or latter, these resources will run out.

One of the promising solutions to such an alarming problem is the use of renewable energies along with fossil fuels to reduce the emission of CO$_2$ and reduce the effect of greenhouse gases. Many free energies are available in each and every country as long as people are willing to use them and reduces their daily consumption.

Solar energy is a type of renewable energies that can be exploited in many ways either as a direct source of heating or to produce electricity. Photovoltaic cells or concentrated solar power are a kind of technologies that converts solar radiation to electricity in huge solar power plants. However, they differ in terms on efficiency and cost. Photovoltaic modules are way less expensive compared to Concentrated Solar Power, but the latter has an efficiency that can reach 92% which exceeds by far the efficiency of PV cells.

1.2 Problematic

Due to the growing demand in energy and the extensive use of nonrenewable resources, it has become a must to switch the focus towards sustainable energies. One form of renewable energies that represents a great potential for Morocco is solar energy represented in the huge investment in NOOR project in Ouarzazate.

One way to benefit from solar energy is through Concentrated Solar Power. This technology is based on a simple principle of focusing solar energy into a central point to heat a specific medium and trap this energy. This heat will be further used to generated steam and rotate turbines to
generate electricity. To concentrate solar energy, huge mirrors are installed and orientated in an optimum way to reflect light into a specific direction. However, many problems are faced while using CSP reflectors, mainly soiling as the deposition of dust and soil on mirrors decreases their reflectance, and thus decreases their efficiency.

The continuous cleaning and maintenance of the CSP reflectors is crucial in maintaining their high effectiveness. Throughout the years, this process becomes very costly, time consuming and unsustainable due to the large amount of water used which is problematic in dry regions such as Ouarzazate. It is stated that they need an amount of 0.25 l/m² of distilled water every week. Thus, the search for a better way to protect CSP reflectors is a must which can be achieved through coating.

1.3 Objectives & Methodology
To solve the problematic behind the maintenance of CSP mirror is to deposit a protective film on these reflectors to protect them from external factors especially from soiling. The major objective behind this research is to determine the optimum material to use for anti-soiling protective coating and study a deposition technique, mainly spin coating, using the selected material. The spin coating technique will involve many parameters that will be changed in order to deduce the most effective one.

After the deposition is performed, the characterization of the films will unveil the properties of the protective film obtained and will allow for a better understanding of its applications. The focus will revolve around the surface roughness, water contact angle and the surface free energy. By doing so, the cost of maintenance will considerably decrease improving the lifespan of the CSP reflectors. Moreover, the efficiency of the CSP mirror will be maintained making solar energy even more profitable.

2 STEEPLE ANALYSIS
Before diving into the analysis of the project, it is very important to determine the implications of the project and how it will contribute to different sectors. This study of the implications is called the STEEPLE analysis and consists of the following factors

- Societal Implications

Energy consumption and energy production in Morocco are not increasing at the same rate. Indeed, there is a growing demand of energy and the fulfillment of these needs is a must. Therefore,
development of renewable energy technologies has great potential in terms of satisfying the demand of energy. This is the main aim behind NOOR project that consists mainly of CSP technology. However, many factors can affect their efficiency, especially soiling. Preventing soiling or finding more effective way to remove dust particles from the reflectors will drastically improve the efficiency of CSP power plants. Moreover, any advancement to today’s renewable energy technologies and creating cost effectiveness can attract people to opt for this sustainable energy source.

- **Technological Implications**
  It is of great importance to develop new depositions techniques of anti-soiling protective coatings on CSP reflectors to improve nowadays existing cleaning methods. Investigating the most appropriate materials to use for coating is critical and depends on the area where the CSP mirrors are installed. One of these techniques is the spin coater. To determine how reliable and effective the coating obtained is, many characterization technologies will be used. Thus, the deposited coating can give a clearer vision of the methodology to use and a better alternative to today’s cleaning methods.

- **Economic Implications**
  The current maintenance and cleaning of CSP reflectors is very costly and time consuming as it is a repetitive process that requires weekly attention. As, for huge projects, such as NOOR in Morocco, mirrors spread over thousands of kilometers. The deposition of a protective coating will drastically decrease the cost of cleaning, maintain a high reflectance, improve the life span of the reflectors and decrease the payback period. Moreover, CSP technology is very expensive because of its high efficiency. Thus, finding an effective solution to the soiling of the mirrors that is more efficient and cost effective will have a great economic impact.

- **Environmental Implications**
  This work focuses on improving CSP which will encourage the use of renewable energies by more countries over the world making energy production more sustainable. Moreover, the cleaning of CSP mirrors, as mentioned before, requires huge amounts of water which constitutes a huge constraint for large projects that use CSP in desert regions. By providing mirrors with an anti-soiling property through depositing a protective coating, less water will be used during the cleaning process.
• **Political Implications**

Energy production is an important factor that highly affect how independent a country is. For that reason, the energy department is highly concerned with the growing demand in terms of energy as it imports from abroad to satisfy these needs. However, the investment made for implementing NOOR project works toward creating a little be more independence. Switching focus to solar energy can represent a great and sustainable solution to fulfill the growing energy consumption. Making the best out the latest technologies is a must to create a sustainable environment that serves future generations, especially for huge projects such as the one in Ouarzazate for CSP.

• **Legal Implications**

The deposition of coatings does not conflict with any legal requirements in the Moroccan law, but rather promotes the use of solar energy.

• **Ethical Implications**

Each and everyone has a moral and ethical implication when working on any project that involves renewable energies. Being aware of the challenges of the 21th century is a must in order to work toward solving them. Two of these challenges involve improving and maintaining a high efficiency of renewable energy technology and decreasing the use of water during the cleaning process. It is a responsibility to think about future generations and protect earth’s resources. The improvement of renewable energy technologies serves this purpose. Especially technologies such as CSP that are expensive because of their high efficiency compared to PV.

2.1 **STEEPLE Chart**

The following chart summarized the numerous implications of this project:

- **Societal Implications**
  - Fulfill the society’s growing energy demand by maintaining Concentrated Solar Power’s effectiveness

- **Technological Implications**
  - Develop today’s technology to replace the current maintenance of Concentrate Solar Power’s reflectors
3.1 Concentrated Solar Power

Concentrated solar power is one of the many renewable energy technologies that utilizes solar energy to generated electricity. It is also the one with the highest efficiency until now. However, it required bigger investment compared to other technologies. As shown in figure 1, CSP technology consists of huge mirrors, also called reflectors, that concentrate the solar energy into specific points to generate heat. The latter is trapped in a medium such as oil or molten salt to produce steam. The generated steam is used to drive a turbine, and thus produce energy. The mechanism behind the power plant is constrained within a close loop. In other works, the medium used to retain heat is returned to the solar field after the heat has been transferred to create steam. Many aspects must be taken into consideration when determining which liquid will create optimum effectiveness. This liquid should be able to store the heat for a longer period of the time to maximize the efficiency of the power plant at night. Indeed, one of the advantages of CSP is the ability to store energy in the
form of heat rather than electricity. This means that the power plant can keep producing electricity for longer hours compared to other technologies. Finally, the steam generated, after driving the turbine, is returned into a condenser and reused again in the process [1].

The concept behind CSP is straightforward, however, it does come with some constraints. The reflectors used to concentrate solar energy must be maintained in a regular basis. The reason behind this is that any dust deposition on the reflectors can cause a dispersion of light which will reduce the effectiveness of CSP mirrors, generating less heat and decreasing the power plant efficiency. Furthermore, the cleaning of these reflectors can, on the long run, damage the reflecting surface which will reduce the efficiency.

3.1.1 Concentrated Solar Power Mirrors

Concentrated solar power systems convert solar energy reflected by mirrors into heat then into electricity. Mirrors, usually placed on trackers that follow the sun’s direction, play the role of concentrators that focus the sunlight. The main requirement of CSP mirror is providing a high specular reflectivity higher that 90% and a durability that leads to a lifetime greater than 20 years [25]. There are different types of CSP mirrors depending on the receiver. In other words, the receiver where the light should be focused can be either a line or a precise point. Depending on the type of focus required, there is two types of CSP mirrors for each type of receivers that can be summarized in figure 2.
Parabolic Trough Mirror
With a parabolic shape, this type of mirrors is used to reflect light and create a linear focus on a tube that contains oil or molten salt fixed on top of the parabolic mirrors. The whole installation is placed over a tracker that follows the movement of the sun as represented in figure 3 [3].

Linear Fresnel Reflector
Linear Fresnel reflectors (LFR) falls into the category that focuses light on a line rather than a point. Unlike parabolic trough, LFR uses long flat or slightly curved mirrors that rotate independently to reflect the light on a fixed tube receiver as represented in figure 4 [3].
Parabolic Dish
For the parabolic dish, the light is focused on a specific precise point in a receiver. They can heat up to 1000 °C since all the radiation are reflected on a point rather than line. It is also considered one of the CSP technologies with the highest solar conversion efficiency as it does not experience as much optical loss as the other types of CSP [3].

Solar Tower
Also called central receiver tower, solar tower consists of an array of mirrors build on trackers that follow the sun’s radiations. All energy is reflected and focused on a single point receiver which allows a high conversion efficiency reaching very high temperature and less losses [3].
3.1.2 Types of CSP Reflector Surfaces

In concentrated solar power, the most important and critical part is the mirrors. There are different types of mirrors in terms of structure, reflecting surface and many other parameters.

Most mirrors are made from silver or aluminum as reflecting surfaces deposited on metal back layer [4]. The reflectance, resistance to abrasion and stability are the main characteristics considered when choosing which alternative is better. The Silver has a better reflecting surface compared to aluminum. However, more layers of silver are required compared to aluminum making the cost more significant for silver reflecting mirrors. Aluminized mirrors are considered for their light weight, ductility, flexibility and low cost. However, its main disadvantage is its low durability. On the other side, silver mirrors are known for higher reflectance, great flexibility and light weight, but they have a low life due to the low adhesion between the ‘polymer’ substrate and the silver coating [5].

To protect the reflective surface from external factor such as soiling and aging and to improve their life and efficiency, the protective coating is deposited on the top of the silver or aluminum film. However, this film can be deposited in different configurations. There are two types of structures used in mirrors that differ in terms of where the protective coating is deposited:

- First or front surface reflector: The protective thin film is deposited directly on the reflective surface as in Figure 7. The advantage for first surface mirrors is that the

Figure 6 - Solar Tower [3]
light is directly reflected with no medium between the coating and reflecting surface. With no coating, these types of mirror are subject to a lot of damage due to outdoor conditions such as soiling [6].

- Second surface reflector: There is a glass that separates between the coating and the reflective surface as in Figure 8. In other words, light must cross the glass to be reflected. There is a better adhesion between the deposited protective film on the glass compared to first surface mirrors. The presence of glass protects the reflecting coat of either silver or aluminum coating [5].

**Figure 7 - First surface mirror [6]**  
**Figure 8 - Second surface mirror [6]**

### 3.2 Anti-Soiling Surfaces

The main challenge behind solar energy is the maintenance over a long period of time. External factor such as harsh weather conditions can damage mirrors used in CSP and lower their efficiency. One of the principle problematics due to environmental conditions and the location is soiling which is defined as the dust particles deposited on the mirrors. These soil particles on the reflective surfaces will absorb sun radiations and scatter the light rather than focus it on a specific direction decreasing drastically the reflectance of CSP mirror [7] as shown in Figure 9.

**Figure 9 - Reflection loss due to soiling [8]**
There are mainly two types of anti-soiling surfaces that allow for a self-cleaning ability: either super-hydrophobic or super-hydrophilic surface.

### 3.2.1 Types of Anti-Soiling Surfaces

**Superhydrophobic Surface**

Hydrophobicity is a phenomenon that was first observed in nature, more specifically, in the lotus leaves. This plant is characterized by its super hydrophobicity as water droplets slid off its surface. Nowadays, researchers are trying to mimic this behavior to create a hydrophobic surface coating that ‘repels’ water droplets [9]. The principle factor responsible for hydrophobicity are as followed:

- The contact angle between water and the surface plays an important role in hydrophobicity. A contact angle that ranges between 90° and 150° characterizes hydrophobic surface shown in figure 8. If the angle exceeds 150°, the surface is characterized as superhydrophobic as shown in figure 7 [10].

    ![Figure 10- The contact angle for super-hydrophobic surface](image)
    ![Figure 11 - The contact angle for hydrophobic surface](image)

- Low surface energy which is positively correlated with the chemical composition of the surface [10].
- The roughness that creates an uneven surface where air bubbles are trapped between the surface and liquid, thus, the liquid is not fully in contact with the surface as in figure 12 [10].
Due to the high contact angle, the low surface energy and a high surface roughness, the surface friction is decreased. Consequently, water droplets slip easily on super-hydrophobic surfaces providing a self-cleaning and anti-soiling material where water droplets roll off the mirrors surface taking away dirt and soil particles.

**Super Hydrophilic Surface**

Hydrophilic surfaces are known for being highly attracted to water. Super-hydrophilic surfaces are a type of anti-soiling coating that allows water to spread across the mirror rather than forming droplets of water that stay stuck on top of the mirrors [11]. It is characterized by the following properties:

- Super-hydrophilic surfaces have a surface angles less than 5 such that water spread over the surface and no droplets are formed [11]
- High surface energy [11]
- Low surface roughness which means that there are no fluctuations in the surface as it is very smooth [11]

Super hydrophilic behavior is considered for anti-soiling surface because of the water spreads over the surfaces, no drops are forms and all the soil is cleaned away.
3.3 Surface Free Energy

In the study of thin film deposition, it is critical to understand the concepts behind the surface free energy and the surface tension. The interactions between atoms and molecules at an interface is a physical phenomenon defined as the surface free energy. However, surface tension is defined for liquids rather solids. There are different types of interactions that occur such as the Van Der Waals interaction, Lewis acid-base interaction and many other forces [12]. Starting by explaining DLVO’s theory will clarify this concept.

3.3.1 DLVO Theory

Derjaguin, Landau, Verwey and Overbeek (DLVO) came up with a theory that explains the stability of particles in colloidal state. It states that this stability is due to the Van Der Waals and the electrostatic interactions. The electrostatic interaction, also called the electrical double layer repulsive interaction, is mainly due to the superposition of the electric layer of two particles as they approach one another. On the other side, to balance the repulsion between the particles, there is the Van Der Waals force which represents an attractive inter-molecular force due to the fluctuating dipole between particles. However, the classic DLVO does not consider the case of water as a medium. Thus, it is important to explore the extended DLVO theory which takes into account polar interaction as well as the ‘Lewis acid-base interactions’ [12].

The apolar interactions corresponding to the Van Der Waals forces include three types of interaction. First, the London interactions that happens between two induced dipoles and is considered as one of the weakest forces. It occurs when the cloud of electrons is asymmetric, during a brief time, creates a dipole temporarily. Furthermore, the Debye interaction that happen between an induced dipole and a permanent one. The latter is the result of the difference in electronegativity between atoms. Finally, the Keesom interaction requires two permanent dipoles as the electric field due to permanent dipole orients the other atoms of the permanent atom. Lifshitz’s approach to the Van Der Waals interaction states that the contribution to the surface tension is the addition of each type interaction (eq 1) [12].

\[ \gamma_{LW} = \gamma_L + \gamma_D + \gamma_K \]  

(1)

On the other hand, the polar interactions, also called Lewis acid-base interactions. These forces are mainly due to hydrogen bonding. The latter can be considered as the interaction between acids,
hydrogen donors, and bases, hydrogen acceptor. A more general concept was also introduced to overcome the restriction of hydrogen bonding, that includes accepting or giving electrons. The surface tension due to the Lewis acid-base interactions is symbolized by $\gamma^{AB}$ [12].

### 3.3.2 The Van Oss-Chaudhury-Good Method

The van Oss Chaudhury Good method is used to determine the surface free energy. It is based upon the assumption that surface energy is related to the sum of the surface free energy component due to each interaction. Young first came up with an equation that relates interfacial tension between solids and liquids to: The surface tension, the surface free energy and the contact angles as shown in equation 2 [13].

$$\gamma_{SL} = \gamma_S - \gamma_L \cos \theta$$

(2)

Based on vOOG method, a surface free energy can be expressed as the sum of the surface energy due to Lifshitz Van Der Waals $\gamma^{LW}$ and Lewis acid-base component $\gamma^{AB}$ as in equation 3 [13].

$$\gamma = \gamma^{LW} + \gamma^{AB}$$

(3)

Furthermore, the polar component due to hydrogen bonding can be expressed in terms of two parameters: $\gamma^+$ corresponds to the surface free energy of the electron acceptor, meaning the Lewis acid, and $\gamma^-$ corresponds to the surface free energy of the electron donor, meaning the Lewis base. Equation 4 represents this relationship [13].

$$\gamma^{AB} = 2\sqrt{\gamma^+ \gamma^-}$$

(4)

Finally, they came up with a relationship for the interfacial surface energy between two phases as shown in equation 5

$$\gamma_{LS} = \gamma^{LW}_S + \gamma^{LW}_L - 2\sqrt{\gamma^{LW}_S \gamma^{LW}_L} + 2 \left( \sqrt{\gamma^{+}_S \gamma^{-}_S + \gamma^{+}_L \gamma^{-}_L} - \sqrt{\gamma^{+}_S \gamma^{-}_S} - \sqrt{\gamma^{+}_L \gamma^{-}_S} \right)$$

(5)

vOOG have combined Youngs equation (eq 1) and the equation that expresses interfacial surface energy (eq 6) to find the surface free energy. Measuring the SFE depends on the contact angle between the liquid on the surface as shown in equation 6. However, there are three unknowns which implies three equations are needed to determine the surface free energy. Thus, vOOG method
consists of measuring the contact angle between the surface and three different liquids and solving a system of three equations.

\[
2 \left\{ \sqrt{\gamma_S^{\text{LW}} \gamma_{L1}^{\text{LW}}} + \sqrt{\gamma_S^{\text{LW}} \gamma_{L2}^{\text{LW}}} + \sqrt{\gamma_S^{\text{LW}} \gamma_{L3}^{\text{LW}}} \right\} = \gamma_{L1} (1 + \cos \theta_1) \\
2 \left\{ \sqrt{\gamma_S^{\text{LW}} \gamma_{L2}^{\text{LW}}} + \sqrt{\gamma_S^{\text{LW}} \gamma_{L1}^{\text{LW}}} + \sqrt{\gamma_S^{\text{LW}} \gamma_{L3}^{\text{LW}}} \right\} = \gamma_{L2} (1 + \cos \theta_2) \\
2 \left\{ \sqrt{\gamma_S^{\text{LW}} \gamma_{L3}^{\text{LW}}} + \sqrt{\gamma_S^{\text{LW}} \gamma_{L2}^{\text{LW}}} + \sqrt{\gamma_S^{\text{LW}} \gamma_{L1}^{\text{LW}}} \right\} = \gamma_{L3} (1 + \cos \theta_3)
\]

Where:

- \( \gamma_S^{\text{LW}} \): The solid’s surface free energy component from the Lifshitz Van Der Waals interactions.
- \( \gamma_{L}^{\text{LW}} \): the liquid’s surface tension component from the Lifshitz Van Der Waals interactions.
- \( \gamma_S^{-} \): The solid’s surface free energy component of the Lewis base.
- \( \gamma_{L}^{-} \): The liquid’s surface tension component of the Lewis base.
- \( \gamma_S^{+} \): The solid’s surface free energy component of the Lewis acid.
- \( \gamma_{L}^{+} \): The solid’s surface tension component of the Lewis acid.
- \( \theta \): The contact angle between the liquid and the surface.

### 3.3.3 Work of Adhesion

On one side, there is adhesion, which is the tendency that two distinct particles or surfaces have to stay and cling to each other. On the other hand, there is cohesion. The latter differs from the first concept in one aspect: it concerns similar particles or surfaces. “The reversible thermodynamic work required to a separation for a liquid-solid combination” [14] is the definition of the work of adhesion. In other words, it the energy required to separate a liquid from a solid. The higher the work of adhesion, the more adhesion between the liquid and the surface and the more energy is needed to separate the two phases. To express this work, Dupre came up with a relation as shown in equation 7 [14].

\[
W_{12} = \gamma_1 + \gamma_2 - \gamma_{12}
\]
Where:

- $W_{12}$ is the work of adhesion
- $\gamma_1$ is the surface tension of the liquid
- $\gamma_2$ is the surface free energy of the surface
- $\gamma_{12}$ is the interfacial surface energy

Dupre expands this equation into the work of adhesion between two solids in a medium as shown in figure 13. The work of adhesion between 1 & 2 in medium 3 can be expressed as $W_{123}$, as indicated in equation 8 [14].

$$W_{123} = \gamma_{13} + \gamma_{23} - \gamma_{12}$$  \hspace{1cm} (8)

Where:

- $\gamma_{13}$ is the interfacial surface energy between the surface 1 and the medium 3.
- $\gamma_{23}$ is the interfacial surface energy between the surface 2 and the medium 3.
- $\gamma_{12}$ is the interfacial surface energy between the surfaces 1 and 3.

![Figure 13 - Adhesion of two surfaces in a liquid medium](image)

The expression of the interfacial surface energy is shown in equation 9

$$\gamma_{12} = \gamma_{1}^{LW} + \gamma_{2}^{LW} - 2\sqrt{\gamma_{1}^{LW} \gamma_{2}^{LW}} + 2 \left( \sqrt{\gamma_1^+ \gamma_1^-} + \sqrt{\gamma_2^+ \gamma_2^-} - \sqrt{\gamma_1^+ \gamma_2^-} - \sqrt{\gamma_1^- \gamma_2^+} \right)$$  \hspace{1cm} (9)

After obtaining the surface free energy of the surfaces and the surface tension of the medium liquid, we can determine the interfacial energy and calculate the work of adhesion to understand how much energy will be needed to separate the two phases [14].

### 3.4 Spin Coating

Spin Coating is a deposition technique of thin and homogenous films of a solution on a substrate. The technique relies of centrifugal force due to high speed rotation so that the liquid spreads
uniformly over the surface. Spin coating consists of four main steps as shown in figure 14. First, the solution is applied on the substrate which then rotates at relatively low speed so that the liquid expands over it. Afterwards, as the rotational speed increases, the excess of liquid flows outside the substrate. The thickness of the film obtained is highly affected by the speed at which the surface rotates. The higher the speed, the thinner the film. Finally, the solvent starts to evaporate, and the thickness of the film decreases radically [15].

![Figure 14 - Spin coating main steps: a) deposition, b) acceleration, c) flow domination, d) evaporation [15]](image)

4 Coating Materials

4.1 Aluminum Oxide

Structure
Aluminum oxide (Al₂O₃), also called alumina, is an important material in the field of engineering. The ore, which is the primary source of alumina, is called Bauxite. However, the most common and stable crystalline structure of Al₂O₃ is called Corundum, also known as sapphire, which has a hexagonal structure [16]. Table 1 displays the different structures of Alumina.
Table 1 - List of Alumina's crystal structure [16]

<table>
<thead>
<tr>
<th>Alumina Crystal</th>
<th>Structure</th>
<th>Lattice Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corundum/Sapphire $\alpha$</td>
<td>Hexagonal</td>
<td>$a = 4.758\text{Å}, c = 12.991 \text{Å}$</td>
</tr>
<tr>
<td>Eta $\eta$</td>
<td>Cubic</td>
<td>$a = 7.9 \text{Å}$</td>
</tr>
<tr>
<td>Gamma $\gamma$</td>
<td>Tetragonal</td>
<td>$a = 7.95\text{Å}, c = 7.79 \text{Å}$</td>
</tr>
<tr>
<td>Delta $\delta$</td>
<td>Tetragonal</td>
<td>$a = 7.97\text{Å}, c= 23.47\text{Å}$</td>
</tr>
<tr>
<td>Theta $\theta$</td>
<td>Monoclinic</td>
<td>$a = 5.63\text{Å}, b = 2.95\text{Å}, c = 11.86\text{Å}$</td>
</tr>
<tr>
<td>Kappa $\kappa$</td>
<td>Orthorhombic</td>
<td>$a = 8.49\text{Å}, b = 12.73\text{Å}, c = 13.39\text{Å}$</td>
</tr>
</tbody>
</table>

Depending on the annealing temperature, the alumina experiences a phase change from amorphous to certain crystalline structure. With increasing annealing temperature, crystals are formed in the following order: $\gamma$-$\text{Al}_2\text{O}_3$ -> $\delta$-$\text{Al}_2\text{O}_3$ -> $\theta$-$\text{Al}_2\text{O}_3$ -> $\alpha$-$\text{Al}_2\text{O}_3$. However, transition from gamma to alpha directly is also possible at higher temperatures [16]. According to literature, the transition from amorphous to crystalline starts at $800^\circ\text{C}$ to obtain $\gamma$-$\text{Al}_2\text{O}_3$ and $1120^\circ\text{C}$ to get $\alpha$-$\text{Al}_2\text{O}_3$ [17].

**Material Characteristics**

Alumina has many properties that can be summarized as follow [16]:

- Young’s Modulus is 403 GPa that decreases to 364 GPa at higher temperatures ($1200^\circ\text{C}$)
- Brittle material
- A high ultimate strength of 58 GPa. As the temperature increases, the strength decreases
- One of the hardest oxides with a value of $3000 \text{ kg/mm}^2$ at $25^\circ\text{C}$
• The $\alpha$-Al$_2$O$_3$ has a density of 3.96g/cm$^3$
• Boiling point of 2517°C
• High thermal conductivity of 18 W/m K
• Low dielectric constant around 9.6.
• Transparent
• Hydrophobic
• Surface free energy of around 6.0 J/m$^2$

4.2 Zinc Oxide

Structure
Zinc Oxide (ZnO) is a well-known semiconductor that has drawn interest in the field of optoelectronics, combination of light and electronics. The most common crystalline structure of ZnO is called wurtzite, but there are other occurring structures like zinc-blende and rocksalt as shown in table 2. They are obtained at different conditions. The most thermodynamically stable structure is wurtzite, while zinc-blende is only stable when growing on cubic substrates. For rocksalt, stability can be obtained at high pressure of around 2 GPa [18].

<table>
<thead>
<tr>
<th>Zinc Oxide Crystal</th>
<th>Structure</th>
<th>Lattice Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wurtzite</td>
<td>Hexagonal</td>
<td>$a = 3.296\text{Å}, c = 5.2065\text{Å}$</td>
</tr>
<tr>
<td>zinc-blende</td>
<td>Cubic</td>
<td>$a = 4.61\text{Å}$</td>
</tr>
<tr>
<td>Rocksalt</td>
<td>Cubic</td>
<td>$a = 4.283\text{Å}$</td>
</tr>
</tbody>
</table>

Properties of Zinc Oxide.
The following are the properties of zinc oxide [19]:
• Boiling temperature of 2360 °C
• Melting point of 1975°C
• Density of 6 g/cm³
• Young Modulus of 111.2 GPa
• Hardness of 5 GPa
• High thermal conductivity: around 50 W/m K that decreases with an increase in temperature.
• Low surface roughness that decreases from 14.8 nm to 6.8 nm from a temperature of 800°C to 1000°C.
• Piezoelectric semiconductor which means it can convert ‘mechanical energy into electric signal’ [18]
• Thermochromic as it changes color from white to yellow at temperatures greater than 300°C.
• Hydrophilic

Applications
Zinc oxide has a large number of applications thanks to its many properties. It has applications such as photocopy paper and painting materials. It is also used in the rubber, ceramics, oil, gas and solar industry. It has a considerable potential for the use in LEDs, transistors and many others. Zinc oxide has particularly drawn a lot of attention in the field of optoelectronics for its optical and electrical properties such as liquid crystal display (LCD) and solar energy. In this field, the semiconductor can play an important role for photovoltaic cells. On the other hand, for its piezoelectric property, ZnO can serve as a ‘torque and pressure sensor’ [18] and in the telecommunication industry [18].

4.3 Titanium Dioxide

Structure

Titanium Dioxide exists in different crystal forms as shown in table 3. The transformation from the amorphous state to the different crystal forms depends on temperature.
<table>
<thead>
<tr>
<th>TiO₂ Crystal</th>
<th>Crystal Structure</th>
<th>Representation</th>
<th>Lattice Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Anatase phase</strong></td>
<td>Tetragonal</td>
<td><img src="image" alt="Anatase phase" /></td>
<td>$a = b = 3.7842 \text{ Å}$, $c = 9.5146 \text{ Å}$</td>
</tr>
<tr>
<td><strong>Rutile</strong></td>
<td>Tetragonal</td>
<td><img src="image" alt="Rutile" /></td>
<td>$a = b = 4.5937 \text{ Å}$, $c = 2.9581 \text{ Å}$</td>
</tr>
<tr>
<td><strong>Brookite</strong></td>
<td>Orthorhombic</td>
<td><img src="image" alt="Brookite" /></td>
<td>$a = 9.16 \text{ Å}$, $b = 5.43 \text{ Å}$, $c = 5.13 \text{ Å}$</td>
</tr>
</tbody>
</table>

Crystallization of titanium dioxide depends on the temperature at which the amorphous TiO₂ is exposed to in air and vacuum. The presence of oxygen vacancies affects the annealing temperature of TiO₂ [20]. It can be summarized as followed:

- From amorphous to anatase structure:
Between 300°C and 510°C in air
- Between 260°C and 440°C in vacuum

- From anatase structure to rutile structure:
  - Between 510°C and 800°C in air
  - Between 440°C and 650°C in vacuum

**Titanium Dioxide Properties**

Titanium Dioxide (TiO2) is a known and commonly used oxide semiconductor [21]. It has drawn attention because of its numerous attractive properties [22]:

- High UV absorption
- Large volume to mass ration
- Photocatalyst
- High crystalline structure
- Density around of 4g/cm3
- A melting point of 2100 K
- Young’s modulus of 230 GPa
- Hardness around 10 GPa
- Low coefficient of thermal expansion: around $8.4 \times 10^{-6} \text{ K}^{-1}$ at 300 K
- Low dielectric constant of 10
- Thermal conductivity around 4.8 W/m K
- Antimicrobial properties
- Hydrophilic

**Titanium Dioxide as a photocatalyst**

Photocatalysis is defined as the process of accelerating a reaction by the means of a material, such as a semiconductor, with a combination of light with a specific wavelength and energy. Reactive oxidizing species are produced during photocatalysis [23]. In the case of TiO2, with a band gap of 3.2ev, ultra-violet light with a wavelength less than 387 nm can excite electrons in the valence band by absorbing the photons’ energy creating a positive hole as followed:
This positive hole (h$_{VB}^+$) oxidizes water to obtain ‘OH radical’. At the same time, the excited electrons react with oxygen molecules trapped in titanium dioxide leading to “superoxide radical anion O$_2^-$” [22]

\[
\begin{align*}
\text{H}_2\text{O} + h_{VB}^+ & \rightarrow \cdot\text{OH} + \text{H}^+ \\
\text{O}_2 + e_{CB}^- & \rightarrow \text{O}_2^-
\end{align*}
\]

OH radical and superoxide radical anion, called reactive oxygen species (ROS), are considered to be powerful oxidants that play an important role in destructing microorganism [22].

**Hydrophilicity and Superhydrophilicity**

Another property of titanium dioxide is its hydrophilicity. When exposed to ultraviolet radiations, the contact angle with water reduces considerably to 0±1 degree making the titanium dioxide film super hydrophilic. This behavior was observed in both the anatase and rutile TiO$_2$ crystals. This was explained by the oxygen vacancies created by the ultraviolet irradiations that led to Ti$^{3+}$ instead of Ti$^{4+}$ sites which favor dissociative water adsorption and increase hydrophilicity. This property can be maintained when unexposed to ultraviolet irradiation for a limited amount of time. Moreover, the improvement of the hydrophilicity can also happen under exposure to ultraviolet from sunlight [24].

**Application**

Titanium dioxide, with its numerous properties, has drawn attention in many fields. TiO$_2$ nanoparticles are used in toothpaste, UV protecting, painting materials, solar energy in photovoltaics and dye sensitized solar cells, anti-fogging material in mirrors and eyeglasses and wastewater treatment [22].

Titanium dioxide also represents a promising material to be used as an anti-soiling protective material coating for CSP reflector. Under ultraviolet light from the sunlight, the TiO$_2$, as a photocatalyst, will get enough energy to release electrons and leave positive holes in the surface to produce OH radical and superoxide radical anion. With this reactive oxygen bacteria, the coating can decompose all organic dust or bacteria. Also, with its superhydrophobic behavior, water will spread over the whole surface, washing away all the dirt and leaving no soil nor water droplets.
behind. Thus, TiO\textsubscript{2} can be considered one of the most effective materials to deposit as a protective thin film for CSP mirrors.

5 Spin Coating Deposition

5.1 Procedure

We tested the deposition of a thin film of TiO\textsubscript{2} on glass substrates using spin coating. First, we prepared the precursor solution of titanium dioxide by dissolving titanium (IV) Isopropoxide Ti[OCH(CH\textsubscript{3})\textsubscript{2}]\textsubscript{4} in a solvent of ethanol to obtain a solution of known low concentration 9.11 mM. To do so, we took 371 ml of ethanol and we added 1ml of titanium (IV) Isopropoxide. The mixture is stirred for 1 hour under 60°C. The obtained solution is homogeneous and transparent. Afterwards, eight samples of glass were cut in a way that fits the spin coater’s dimensions, cleaned using distilled water and ethanol, and placed on a hot plate to pre-heat at 280°C during 10 min before placing them on the spin coater. The preheating of the samples allows a better deposition on the spin coater and a better adhesion between the substrate and the precursor. One sample at a time is placed on the spin coater and few drops of the precursor are placed on the glass substrate. Each sample rotates at a speed of 3000 rpm for 30s and is placed again on the hot plate. Each glass defers in the number of layers deposited. After the deposition, the samples are placed inside an oven. Four samples are annealed at 400°C and four are annealed at 600°C at a rate of 10°C/min.
Figure 17 - Spin Coater

Figure 18 - The oven used for annealing the glass substrates
Table 4 summarized the number of layer deposited and annealing temperature of each sample.

Table 4 - Summary of the substrates depending on the number of layer and the annealing temperature

<table>
<thead>
<tr>
<th>Glass substrate</th>
<th>Number of layers</th>
<th>Annealing temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
<td>400</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>400</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>400</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>400</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>600</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>600</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>600</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>600</td>
</tr>
</tbody>
</table>

Using a profilometer, the roughness of each sample is calculated. In order to obtain accurate results, each sample is placed, and the roughness is calculated at different positions six times and the average of the results is computed. The profilometer is set to calculate a range for the roughness of 6.5μm, a length of 2000μm and a stylus force of 3 mg for a duration of 10s.

Afterwards, the contact angle of water is calculated using a syringe to deposit one drop of water on the surface and take a snapshot of the drop of water as soon as it touches the surface of the substrate. Using ImageJ and the plugin ‘Contact Angle’, the contact angle was determined with accuracy.

In order to determine the surface free energy, the contact angles of three different liquids with known surface tension were investigated: water, ethanol and hexane. The same procedure is followed to determine the contact angle of water.
All the results concerning the contact angle and the surface free energy obtained will be compared to the existing properties of a commercial CSP mirror.

Table 5 - The surface free energy of water, ethanol and hexane

<table>
<thead>
<tr>
<th>Liquids</th>
<th>$\gamma_{L}^{LW}$ (mJ/m²)</th>
<th>$\gamma_{L}^{+}$ (mJ/m²)</th>
<th>$\gamma_{L}^{-}$ (mJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water H₂O</td>
<td>21.6</td>
<td>25.4</td>
<td>25.4</td>
</tr>
<tr>
<td>Ethanol (ethyl alcohol)</td>
<td>21.4</td>
<td>0.02</td>
<td>68</td>
</tr>
<tr>
<td>Hexane</td>
<td>18.4</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

5.2 Results

5.2.1 Apparent Transparence

One of the first things to observe with the naked eye is the transparence of the samples. The four glass substrates coated and heated at 600°C have a better transparence compared to the four substrates heated at 400°C. These samples have an apparent white coating on the top surface that is appears transparent for the other samples.

5.2.2 Roughness

Using the profilometer, each substrate sample roughness and thickness are measured six times. All readings that may misrepresent the overall roughness are disregarded. The tables (3,4,5,6,7,8,9,10) represent a summary of the data obtained for each sample as well as the thickness of the film. M stands for the measurement. All the data is in nanometers. The 2D topography is in Appendix A.

Table 6 - Roughness measurement in nm of sample 1

<table>
<thead>
<tr>
<th>Sample 1</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughness (nm)</td>
<td>29.28</td>
<td>33.391</td>
<td>34.162</td>
<td>32.969</td>
<td>30.005</td>
<td>64.956</td>
<td>31.9614</td>
</tr>
</tbody>
</table>

Table 7 - Roughness measurement in nm of sample 2

<table>
<thead>
<tr>
<th>Sample 2</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughness (nm)</td>
<td>45.453</td>
<td>48.281</td>
<td>107.846</td>
<td>32.826</td>
<td>80.799</td>
<td>73.706</td>
<td>64.8185</td>
</tr>
</tbody>
</table>
Table 8 - Roughness measurement in nm of sample 3

<table>
<thead>
<tr>
<th>Sample 3</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughness (nm)</td>
<td>65.257</td>
<td>62.178</td>
<td>71.535</td>
<td>77.006</td>
<td>61.345</td>
<td>57.076</td>
<td>65.733</td>
</tr>
</tbody>
</table>

Table 9 - Roughness measurement in nm of sample 4

<table>
<thead>
<tr>
<th>Sample 4</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughness (nm)</td>
<td>86.951</td>
<td>108.055</td>
<td>78.25</td>
<td>89.046</td>
<td>70.367</td>
<td>78.039</td>
<td>85.118</td>
</tr>
</tbody>
</table>

Figure 19 - Graph of the roughness of samples 1, 2, 3 & 4

Table 10 - Roughness measurement in nm of sample 5

<table>
<thead>
<tr>
<th>Sample 5</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughness (nm)</td>
<td>34.831</td>
<td>35.996</td>
<td>32.427</td>
<td>28.257</td>
<td>38.456</td>
<td>34.092</td>
<td>34.010</td>
</tr>
</tbody>
</table>
Table 11 - Roughness measurement in nm of sample 6

<table>
<thead>
<tr>
<th>Sample 6</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughness (nm)</td>
<td>308.645</td>
<td>33.24</td>
<td>82.533</td>
<td>82.826</td>
<td>71.335</td>
<td>34.441</td>
<td>60.875</td>
</tr>
</tbody>
</table>

Table 12 - Roughness measurement in nm of sample 7

<table>
<thead>
<tr>
<th>Sample 7</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughness (nm)</td>
<td>302.815</td>
<td>238.4</td>
<td>292.387</td>
<td>344.294</td>
<td>183.313</td>
<td>243.571</td>
<td>267.463</td>
</tr>
</tbody>
</table>

Table 13 - Roughness measurement in nm of sample 8

<table>
<thead>
<tr>
<th>Sample 8</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughness (nm)</td>
<td>448.613</td>
<td>446.641</td>
<td>522.981</td>
<td>593.6</td>
<td>498.117</td>
<td>456.243</td>
<td>494.366</td>
</tr>
</tbody>
</table>

![Graph of the roughness of samples 5, 6, 7 & 8](image)

Figure 20 - Graph of the roughness of samples 5, 6, 7 & 8

3.2.2 Water Contact Angle

After taking multiple snapshots of the contact between a droplet and the glass substrates using a high-resolution camera, ImageJ is used with a plugin ‘contact angle’ that identifies multiple points to detect the water droplets and calculate the contact angle. The results of the measurements are summarized in table 14.
Table 14 - Water contact angles of each sample

<table>
<thead>
<tr>
<th>Sample</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>No Coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Angle</td>
<td>63.9°</td>
<td>56.6°</td>
<td>53.5°</td>
<td>66.6°</td>
<td>33.2°</td>
<td>31°</td>
<td>35.4°</td>
<td>28.2°</td>
<td>49.2°</td>
</tr>
</tbody>
</table>

5.2.3 Surface Free Energy

The surface free energy is obtained by determining the contact angle of water, ethanol and hexane with each sample. Table 15,16 & 17 summarize the data obtained using ImageJ software.

Table 15 - Water contact angle of each sample

<table>
<thead>
<tr>
<th>Sample</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>No Coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Angle</td>
<td>63.9°</td>
<td>56.6°</td>
<td>53.5°</td>
<td>66.6°</td>
<td>33.2°</td>
<td>31°</td>
<td>35.4°</td>
<td>28.2°</td>
<td>49.2°</td>
</tr>
</tbody>
</table>
Table 16 - Ethanol contact angle of each sample

<table>
<thead>
<tr>
<th>Sample</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Angle</td>
<td>79.6°</td>
<td>73.9°</td>
<td>63.6°</td>
<td>74.1°</td>
<td>79°</td>
<td>79.5°</td>
<td>72.5°</td>
<td>64.8°</td>
</tr>
</tbody>
</table>

Table 17 - Hexane contact angle of each sample

<table>
<thead>
<tr>
<th>Sample</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Angle</td>
<td>74.4°</td>
<td>77.4°</td>
<td>81°</td>
<td>69.8°</td>
<td>39.6°</td>
<td>38.6°</td>
<td>44°</td>
<td>37.9°</td>
</tr>
</tbody>
</table>

Using Van Oss-Chaudhury-Good method, each equation is solved for the eight sample in order to find the surface free energy. Using MATLAB, the following results are obtained:

**Sample 1:** $\gamma_S^{LW} = 7.4079$  \hspace{1cm} $\gamma_0^S = 60.7503$  \hspace{1cm} $\gamma_S^+ = 0.0015$

**Sample 2:** $\gamma_S^{LW} = 6.8235$  \hspace{1cm} $\gamma_0^S = 72.2630$  \hspace{1cm} $\gamma_S^+ = 0.0514$

**Sample 3:** $\gamma_S^{LW} = 6.1527$  \hspace{1cm} $\gamma_0^S = 74.4645$  \hspace{1cm} $\gamma_S^+ = 0.2906$

**Sample 4:** $\gamma_S^{LW} = 8.322 *$  \hspace{1cm} $\gamma_0^S = 53.0716$  \hspace{1cm} $\gamma_S^+ = 0.008$

**Sample 5:** $\gamma_S^{LW} = 14.422$  \hspace{1cm} $\gamma_0^S = 105.7627$  \hspace{1cm} $\gamma_S^+ = 0.3520$

**Sample 6:** $\gamma_S^{LW} = 14.59$  \hspace{1cm} $\gamma_0^S = 109.41$  \hspace{1cm} $\gamma_S^+ = 0.38$

**Sample 7:** $\gamma_S^{LW} = 13.54$  \hspace{1cm} $\gamma_0^S = 100.8$  \hspace{1cm} $\gamma_S^+ = 0.1296$
Sample 8: \( \gamma_S^{LW} = 14.74 \quad \gamma_S^- = 105.678 \quad \gamma_S^+ = 0.0784 \)

Based on these values obtained when solving the system and on equations 3 and 4, the total surface free energy of each surface can be found.

\( \gamma_S = \gamma_S^{LW} + \gamma_S^{AB} \), knowing that \( \gamma_S^{AB} = 2\sqrt{\gamma_S^+ \gamma_S^-} \). The results are summarized in table 18.

<table>
<thead>
<tr>
<th>Samples</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFE (mJ / m²)</td>
<td>8.0069</td>
<td>10.6765</td>
<td>15.4556</td>
<td>9.6286</td>
<td>26.6245</td>
<td>27.486</td>
<td>20.769</td>
<td>20.497</td>
</tr>
</tbody>
</table>

5.3 Discussion of Results

From the results, the transparence of the samples considerably increases with the increase in the temperature of annealing. In other words, the reflectance of the samples significantly drops in the four first sample where the temperature is only raised to 400°C.

Another parameter that plays an important role in increasing the hydrophilicity of a surface is a low surface roughness. The sample’s surface roughness calculated using the profilometer shows a tendency to decrease as the layers of TiO₂ increase. It is important to take both the numerical value as well as the 2D model in Appendix A simultaneously into account to interpret the surface roughness results. Indeed, the 2-dimensional representation of the surface gives a better understanding of the surface topology of each sample. It can be seen that the surface with 12 and 10 layers are the one that displays the less amount of fluctuations. The roughness slightly increases at 7 layers and is very high for 5 layers, no matter the annealing temperature. These results do agree with the fact that the more layers of titanium oxide are deposited, the smoother the surface gets with no apparent correlation with the annealing temperature.
It is important to point out and take into consideration the margin of errors in terms of calculating the contact angles. Since the sessile drop, a method of determining the contact angles, was not available, another alternative is used that may lead to a higher margin errors. Regarding the contact angle between water and the surfaces, a more hydrophilic behavior can be observed for sample 5, 6, 7, 8 compared to samples 1, 2, 3, 4 as shown in figure 21. The samples with a low annealing temperature display a contact angle that increased compared to the sample glass with no coating, while it decreases for the samples annealed at 600°C. This can be explained by the fact that the annealing temperature of 400°C was not enough to form crystals and that the titanium dioxide is still at the amorphous state. This experiment illustrates the hydrophilic behavior of the titanium dioxide coating when in the crystalline structure as **water contact angle decreases at annealing temperature of 600°C.**

![Figure 22 - Graph representing the water contact angle of each sample](image-url)
Concerning the surface free energy of the sample, we can see higher values for the sample 5, 6, 7 and 8 compared to the rest of the samples. However, since the roughness of the sample with 7 and 5 layers is high, sample 3, 4, 7, 8 are disregarded from the analysis. From these results, we can say that an increase of the annealing temperature at 600°C increases the surface free energy of the coated surface.

![Figure 23 - Graph representing the surface free energy of each sample](image)

### 5.4 Comparison with a commercial CSP mirror

After the characterization of the samples was performed by studying their roughness, water contact angle and surface free energy. They can be compared them with an uncoated commercial CSP mirror used in the market. In table 19, the values of the water contact angle and surface free energy components of the commercial CSP mirror can be found.

<table>
<thead>
<tr>
<th>CSP commercial mirror</th>
<th>Water Contact Angle</th>
<th>$\gamma_s^{\text{LW}}$</th>
<th>$\gamma_s^+$</th>
<th>$\gamma_s^-$</th>
<th>$\gamma_s^{\text{Total}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>45.56°</td>
<td>27.61</td>
<td>43.74</td>
<td>0.61</td>
<td>37.94</td>
<td></td>
</tr>
</tbody>
</table>

From the table 14 and 19, we can see that the contact angle of the samples coated with titanium dioxide annealed at 600°C exhibit a lower contact angle compared to the commercial mirror. The
contact angles range between 28.2° and 33.2° meaning that water spreads more on the surface with a coating annealed at a higher temperature. However, it is not the case for the samples coated at 400°C which have a higher water contact angle in comparison with the commercial CSP mirror. Also, in order to compare the adhesion of dust on coated samples and commercial mirrors, the work of adhesion between the mirror, dust and water is calculated. The surface free energy of the mirrors and the water is already calculated. Since the mirrors are installed in Ouarzazate, soiling is mainly due to sand. The main composite of sand is silicon dioxide in the form of quartz. Table 20 summarized the surface free energy component related to quartz. In literature, these measurements were found by calculating the contact angles of three different liquids on quartz plates with a purity of 99.98% [25].

<table>
<thead>
<tr>
<th>Surface Free Energy Component (mJ/m²)</th>
<th>( \gamma_s^{LW} )</th>
<th>( \gamma_s^+ )</th>
<th>( \gamma_s^- )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>41.3</td>
<td>2.21</td>
<td>35.68</td>
</tr>
</tbody>
</table>

Based on their low surface roughness, low contact angle with water and high surface free energy, the samples 1, 2, 5 and 6 are used for comparison with the commercial CSP mirror. First, the results previously obtained are summarized in table 21.

<table>
<thead>
<tr>
<th>Sample</th>
<th>( \gamma_s^{LW} )</th>
<th>( \gamma_s^+ )</th>
<th>( \gamma_s^- )</th>
<th>( \gamma_s^{Total} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>7.4079</td>
<td>0.0015</td>
<td>60.7503</td>
<td>8.012</td>
</tr>
<tr>
<td>Sample 2</td>
<td>6.8235</td>
<td>0.0514</td>
<td>72.263</td>
<td>10.678</td>
</tr>
<tr>
<td>Sample 5</td>
<td>14.422</td>
<td>0.352</td>
<td>105.7627</td>
<td>26.625</td>
</tr>
<tr>
<td>Sample 6</td>
<td>14.59</td>
<td>0.38</td>
<td>109.41</td>
<td>27.486</td>
</tr>
</tbody>
</table>

Afterwards, using Excel, the work of adhesion is computed. The results can be found in table 22. For the work of adhesion \( W_{123} \), ‘1’ represents the samples or the commercial CSP mirror, ‘2’ is for quartz and ‘3’ is water, which is the medium.
To interpret the data obtained for the work adhesion, it is important to understand the meaning of the positive and negative value. When $W_{123}$ is negative “The attachment of 1 and 2 in liquid 3 is not favored.” In other words, it means that there is a repulsion between the two surfaces in the presence of water. On the other hand, when $W_{123}$ is positive, there is adhesion between the two surfaces and an input energy is required to separate them from each other. In our case, there is a negative work of adhesion between the coated samples, the quartz and water compared to the positive work of adhesion obtained using the commercial CSP mirrors. Furthermore, a more negative work is to be noticed for the samples annealed at 600°C showing even more repulsion.

We can conclude that **the cleaning of CSP mirrors coated with TiO$_2$, in the presence a water as medium, requires less work compared to the uncoated commercial CSP mirrors available in the market**. Also, based on their low contact angle, water will spread more and can carry more soil particles in samples annealed at 600°C with more TiO$_2$ layers compared to the CSP commercial mirrors.

### Table 22 - Summary of the work of adhesion between the samples, water and quartz

<table>
<thead>
<tr>
<th></th>
<th>$\gamma_{13}$ (mJ/m$^2$)</th>
<th>$\gamma_{23}$ (mJ/m$^2$)</th>
<th>$\gamma_{12}$ (mJ/m$^2$)</th>
<th>$W_{123}$ (mJ/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>-23.841</td>
<td>-3.468</td>
<td>8.452</td>
<td>-35.762</td>
</tr>
<tr>
<td>Sample 2</td>
<td>-29.173</td>
<td>-3.468</td>
<td>8.180</td>
<td>-40.822</td>
</tr>
<tr>
<td>Sample 5</td>
<td>-45.915</td>
<td>-3.468</td>
<td>-0.791</td>
<td>-48.593</td>
</tr>
<tr>
<td>Sample 6</td>
<td>-47.265</td>
<td>-3.468</td>
<td>-1.013</td>
<td>-49.721</td>
</tr>
<tr>
<td>Commercial CSP mirror</td>
<td>-12.862</td>
<td>-3.468</td>
<td>51.655</td>
<td>35.324</td>
</tr>
</tbody>
</table>
6 Testing: Cleaning

6.1 Digital Microscope Setting

To demonstrate the results obtained from the work of adhesion between a coated and uncoated sample, a digital microscope is set up to display how much dust is left before and after cleaning with water.

To do so, a handheld digital microscope is used with a magnification power that ranges from 20x to 200x. The microscope disposes of a high-quality lens with an imaging sensor of MP (1600 x 1200 resolution). To set up microscope, a RaspberryPi 3 model B+ plugged into a monitor is used. After all the hardware is interconnected, ‘fswebcam’ is installed onto the RaspberryPi to be able to take pictures with the microscope. To do so, the command ‘sudo apt-get install fswebcam’ is run into the terminal. Finally, just by running the command ‘fswebcam image.jpg’, the microscope takes a picture that is stored in a jpg file under the name ‘image’.

6.2 Image Results

The microscope is set to take picture of two sample. An uncoated glass substrate and the sample 6 that has 10 layers of TiO₂ and was annealed at a temperature of 600°C. This sample is chosen because of the low work of adhesion with quartz. Figure 20 and 21 displays the difference between a coated and an uncoated glass as sand particules were deposited manually to simulate soil deposition. For the uncoated glass, the cleaning left some dust particles behind and did not wash the sample entirely. The trail of water is still visible while some particles were simply displaced. On the other hand, the coated glass with twelve layers of titanium dioxide that was annealed at 600°C shows that most of dust particles are washed away with water no matter how big or small the particles are. This simple comparison confirms the data obtained from the study.

⇒ The use of spin coating to deposit 10 to 12 layers of TiO₂ displays beneficial results. When annealed at a 600°C, low roughness, low contact angle and high surface energy explain the negative work of adhesion obtained. Water spreads over the surface cleaning away all soil. Thus, coating CSP reflectors will play an important role in improving the cleaning process and maintain the good efficiency of the mirrors.
Figure 25 - Uncoated glass substrate with dust particles before cleaning (on the left) and after cleaning (on the right) with water

Figure 26 - TiO2 coated glass (sample 5) substrate with dust particles before cleaning (on the left) and after cleaning (on the right) with water
7 Conclusion and Future Work

Concentrated solar power is one the most effective ways to convert solar energy into electricity. However, soiling on CSP reflectors causes an important obstacle that lowers the effectiveness of this technology, especially in the region of Ouarzazate where NOOR is implemented. The maintenance of these mirrors requires huge volumes of water. This need will only increase as the project is still expanding. The deposition of a protective anti-soiling coating is a very promising solution. Titanium dioxide, for its hydrophilic behavior and photocatalytic properties under UV light exposure is to be highly considered for this application. However, many factors should be considered during the deposition. The annealing temperature plays a critical role in the crystallization of titanium dioxide. To obtain a superhydrophilic surface so that water can spread over it and wash away all the dust, the thin film should have a low roughness, a high surface free energy, which can lead to a low work of adhesion with water and soil. The use of the spin coating technique, as shown in this study, has a great potential.

Many challenges were encountered during this research because of the lack of materials and technologies that are used for characterization. For instance, XRD technique would have allowed to determine which crystals are on the surface of the samples. Sessile drop technique would have given more accurate measurements of contact angles.

There is still a lot of work to explore in this field. More deposition techniques should be studied, and more work should be done to obtain the same characteristics at lower temperatures. Moreover, investigating the component of soil can help improve the type of coating to use depending on regions. A deeper study of the effect of wind and humidity on the deposition of soil can help adapt and design a better coating that will suit different conditions.

Improving the cleaning process of CSP reflectors is a promising field of research from which the outcome can have many great implications, especially now that the focus has shifted towards the use of solar energy to fulfill society’s needs. Because of the high cost behind investing in CSP technology, it is a must to keep research going in order to maintain their high efficiency, no matter the factors.
8 References


9 Appendix A

Figure 27 - 2D representation of the roughness of sample 1

Figure 28 - 2D representation of the roughness of sample 2
Figure 29 - 2D representation of the roughness of sample 3

Figure 30 - 2D representation of the roughness of sample 4
Figure 31 - 2D representation of the roughness of sample 5

Figure 32 - 2D representation of the roughness of sample 6
Figure 33 - 2D representation of the roughness of sample 7

Figure 34 - 2D representation of the roughness of sample 8