Design of Planetary System to resolve film thickness variation in Film Deposition

Internship report CTI

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Preface

This report was written as part of my internship at Centro De Tecnologia Da Informação Renato Archer (CTI) in Campinas - Brazil during the period from the first of September 2014 to the fifth December 2014. CTI is a research and development center of the Brazilian Ministry of Science and Technology. It aims to develop and implement scientific and technological research in the areas of information technology, microelectronics and automation. One of its missions is to establish collaborative ties with the corresponding industrial sectors in Brazil, according to Centro De Tecnologia Da Informação Renato Archer (n.d.). My most sincere thanks go to Vinicius do Lago Pimentel for serving as my supervisor. I also would like to thank my colleagues of Divisão de Mostradores da Informação (DMI) and the technicians of the workshop of CTI for giving support by providing suggestions and technical know-how.

Abstract

The main project, during the time at CTI, was to design a planetary system for the EV400 physical vapor deposition machine. The EV400 is a commercial system, operating under vacuum, and used for thin film deposition. In the lab of DMI, the display department of CTI, physical vapor machines are used for research in the areas of microelectronics and displays. In the current configuration of the E400 workpiece samples are mounted stationary on the sample holder which results in film thickness variations of about 50 percent.

The whole project can be divided into three parts. Firstly, a literature study is performed to ensure a thorough understanding of film thickness variation. The following topics have been studied:

- thin film deposition;
- basic principles of vacuum and equipment used in vacuum (e.g. vacuum pumps, measurement gauges and connections);
- epicyclic gearing and feedthroughs.

Secondly, film thickness variation is analyzed by constructing multiple theoretical mathematical models to signify the problem. One of the main conclusions is that by using a planetary system in thin film deposition film thickness variation reduces by 80 percent, in theory. Thirdly, multiple concepts are generated, analyzed and combined which resulted in a detailed design. Throughout the project the interaction between DMI and the technicians of the workshop of CTI was fundamental for the design, development and construction of the planetary system. The interaction mainly consisted of support by providing suggestions and technical know-how.

Contents

1 Introduction

The process of manufacturing semiconductors, or integrated circuits (commonly called ICs or chips) typically consists of more than a hundred steps, during which hundreds of copies of an integrated circuit are formed on a single wafer. Generally, the process involves the creation of eight to 20 patterned layers on and into the substrate, ultimately forming the complete integrated circuit. This layering process creates electrically active regions in and on the semiconductor wafer surface.

In the lab of DMI, the display department of CTI, physical vapor machines are used to apply dielectric layers on various workpiece samples, e.g. semiconductors. One of the main challenges consists of optimizing the electrical resistivity of semiconductor workpiece samples by optimizing film deposition parameters. Increasing film thickness results in a decreasing electrical resistivity. The goal is to obtain a low electrical resistivity. The resistivity of semiconductor workpiece samples are measured experimentally using a four point probe. A four point probe is a simple apparatus consisting of four probes. By passing a current through two outer probes and measuring the voltage through the inner probes allows the measurement of the workpiece samples resistivity.

One of the physical vapor depositions machines at DMI is the EV400. In the current configuration, of the EV400, the workpiece samples are mounted stationary on the sample holder which results in film thickness variation among the surface of workpiece samples. Due to a varying film thickness the electrical resistivity is not constant among the surface and introduce additional waste. This report encompasses the design and development of a planetary system to resolve film thickness variation problems for the EV400 physical vapor deposition machine. It is decided to consider the EV400 only, but the proposed solution is also applicable for other machines.

2 Thin Film Deposition

Thin film deposition is the act of applying a thin film onto various workpiece surfaces. The deposited thin film is a layer of material ranging from fractions of a nanometer to several micrometers in thickness. And is mainly used for the manufacturing of optics, electronics, packaging and contemporary art. Deposition techniques fall into two broad categories, namely, chemical and physical film deposition. The focus will be on physical vapor deposition and in particular evaporation deposition since this technique is used at CTI. In this section an introduction on Physical Vapor Deposition and will be given with the emphasis on evaporation deposition.

2.1 Introduction to Physical Vapor Deposition

Physical vapor deposition describes a variety of vacuum deposition methods used to deposit thin films by the condensation of a vaporized form of the desired film material onto various workpiece surfaces. The working principle of physical vapor deposition is among the different techniques the same. A film material to be deposited is placed in an entropic environment, allowing particles to escape from its surface. Subjecting these particles to a cooler workpiece surface, which draws energy from these particles when they arrive, allowing them to form a solid layer. The whole system is kept in a vacuum deposition chamber to allow the particles to travel as freely as possible. In the vacuum chamber particles tend to follow a straight path (directional). There are multiple vapor deposition techniques, examples include:

- **Carhodic Arc Deposition**: In which a high-power electric arc discharged at the film material, which results in blasting away some film material into highly ionized vapor to be deposited onto the workpiece surface.
- **Electron Beam Physical Vapor Deposition**: In which the film material is heated to a high vapor pressure by electron bombardment in high vacuum and is transported by diffusion to be deposited by condensation on the cooler workpiece surface.
- **Evaporative Deposition**: In which the film material is heated to a high vapor pressure by electrically resistive heating in medium vacuum.
- **Pulsed Laser Deposition**: In which a high-power laser ablates film material into a vapor.
- **Sputter Deposition**: In which a glow plasma discharge bombards the film material sputtering some away as a vapor for subsequent deposition.

2.2 Evaporation Deposition

Evaporation Deposition involves two 'basic' principles, namely, evaporation and condensation. A film material is heated to a high vapor pressure by electrically resistive heating, allowing the particles to evaporate. Subjecting these particles to a cooler workpiece surface, which draws energy from these particles, allowing them to condensate and form a solid layer. Evaporation Deposition takes places in medium to high vacuum, allowing particles to travel directly to the workpiece without colliding or reacting with the surrounding gas in the vacuum chamber. Due to the vacuum the vapor pressure of a element, in this case a film material, change at a given temperature. Vapor pressure is defined as the pressure exerted by a vapor in thermodynamic equilibrium with its condensed phase (solid or liquid) at a given temperature in a closed system. In other words, in equilibrium there are just as many molecules vaporizing as condensing (at a given temperature and for a given element). Figure 1 shows the vapor pressure curves of several elements. It can be seen that some elements are easier to evaporate. This is due to low intermolecular forces or low atomic mass. For example, having an element with low intermolecular forces or low atomic mass results in a high vapor pressure. Overall lowering the pressure inside the vacuum chamber results in less average kinetic energy or temperature is needed to vaporize an element.

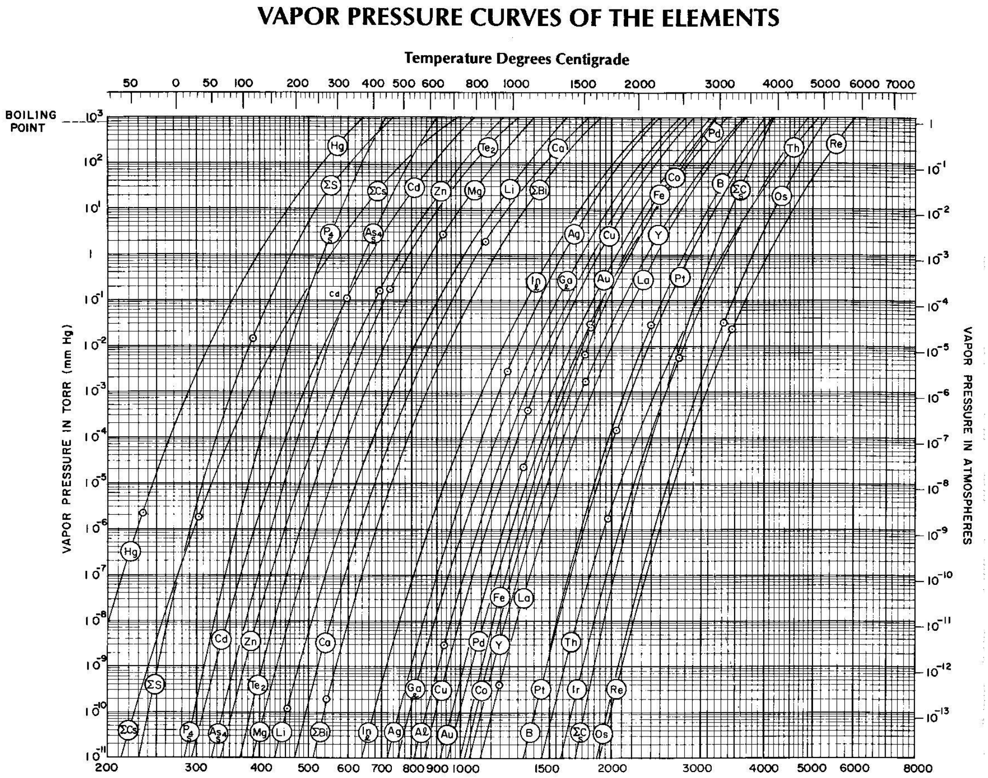

Figure 1: Vapor Pressure Curves of Elements

3 Vacuum

Physical vapor deposition requires a vacuum chamber to allow particles to follow a straight directional path. Obtaining a vacuum yields removing of gases from a chamber. In this section the basic principles of vacuum and equipment used in vacuum will be discussed.

3.1 Introduction to vacuum

The creation of a vacuum typically requires a chamber, piping and a pump (or pumps). Figure 2 of Farrow (2009) shows a simplified sketch to help to understand how the pump reduces the number of molecules inside a vacuum chamber. The term 'vacuum' is used to describe the zone of pressure below atmospheric pressure. Pressure can be measured in several units, e.g. Bar, Pascal and Torr. Since most of the literature about vacuum is given in Torr, this report will only contain pressures in Torr. Table 1 shows the values of one atmosphere in the different units.

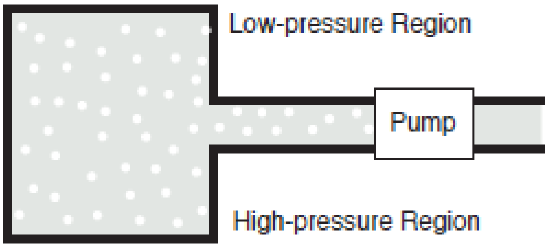

Figure 2: The pump reduces the number of molecules inside the vacuum chamber

Bar	Pascal	Torr
1.01325	101.325	760

Table 1: One atmosphere in Bar, Pascal and Torr

3.2 Regimes of vacuum

According to Farrow (2009) there are four regions of vacuum described: rough, medium, high and ultra-high vacuum. The boundary of each region cannot be rigidly defined. A brief description of the several regimes will be given.

- Rough Vacuum $\left(760 \text{ Torr to } 75 \cdot 10^{-3} \text{ Torr}\right)$: In this stage the gas molecules in the chamber interact with each other according to the laws of thermodynamics in the manner of a viscous fluid (Figure 3). To obtain rough vacuum mechanical pumps are needed.

- Medium Vacuum $\left(75 \cdot 10^{-3} \text{ Torr to } 1 \cdot 10^{-6} \text{ Torr}\right)$: In this stage the interaction between the gas molecules are still significant but the fluid flow characteristics of the gases breaks down and molecule gas collisions with the chamber walls also begin to affect the gases behavior. To obtain medium vacuum a combination of rough and high vacuum pumps (in series) are usually used. Examples of high vacuum pumps are molecular drag pumps and turbo molecular pumps.

- High Vacuum $\left(1 \cdot 10^{-6} \text{ Torr to } 1 \cdot 10^{-9} \text{ Torr}\right)$: In this stage the interaction between the gas molecules has stopped and therefore the gas cannot be considered as a viscous flow anymore. The gas is dominated by molecule and chamber wall collisions (Figure 4), in other words, the free path between gas molecules are far greater than the dimensions of the chamber. Due to the behavior of the gas a combination of rough and high vacuum pumps are necessary. High vacuum pumps cannot (directly) suck or release gas at atmospheric pressure.

- Ultra-high Vacuum $(\text{Below } 1 \cdot 10^{-9})$: In this stage most gas molecules are somewhat embedded in the chamber wall. A dominant element in ultra-high vacuum is usually hydrogen. Hydrogen is light and mobile and therefore very difficult to pump, requiring a ultra-high vacuum pump to remove. Examples of ultra-high vacuum pumps are ion pumps.

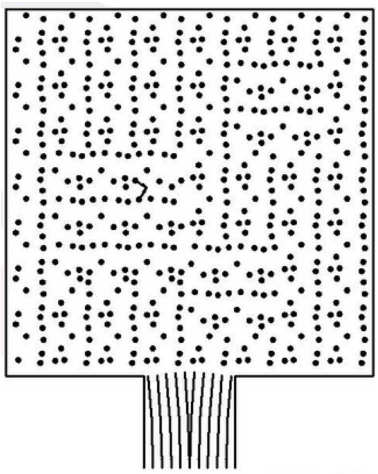

Figure 3: Rough vacuum: molecules interact in the manner of a viscous fluid

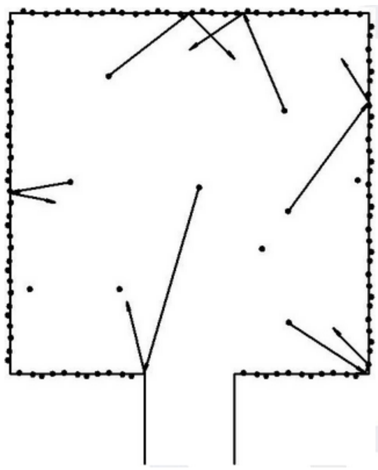

Figure 4: High vacuum: dominated by molecule and wall collisions

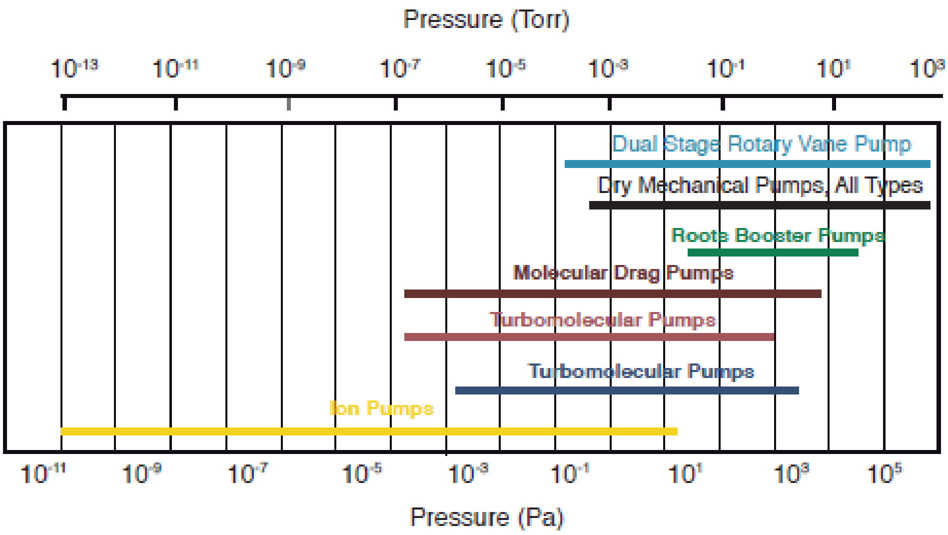

Figure 5: Typical vacuum pump operating ranges

3.3 Pumps

As mentioned before, obtaining a vacuum yields removing of gases from a chamber. The main component herein are vacuum pumps. There are different pumps and combinations of pumps required to obtain different regimes of vacuum. An overview is given in figure 5 of Farrow (2009) of typical vacuum pump and their operating ranges. Firstly, positive displacement pumps, used to obtain rough to medium vacuum of figure 5, will be briefly discussed. And secondly, momentum transfer pumps and entrapment pumps of figure 5, used to obtain high to ultra high vacuum, will be discussed.

3.3.1 Rough to medium vacuum pumps

Positive displacement pumps or mechanical pumps are used to obtain rough to medium vacuum. There are roughly three types of positive displacement pumps, namely, rotary pumps, membrane/diaphragm pumps, and reciprocating pumps. The working principle of positive displacement pumps are all the same. Gas molecules inside the vacuum chamber are sucked into the pump by increasing the volume of the pump. By closing the inlet of the pump and opening the outlet of the pump the gas molecules are discharged. This is usually done repeatedly to create a vacuum. A brief explanation of rotary pumps and membrane/diaphragm pumps will be given. Reciprocating pumps will not be discussed because these type of pumps are usually not used for thin film deposition.

Rotary vane pump Rotary vane pumps, shown in figure 6, use a circular rotor (indicated with 2) which rotates inside a larger circular cavity (indicated with 1). The centers of these two circles are off-center, causing eccentricity. Vanes (indicated with 3) are allowed to slide into and out of the rotor and seal on the circular cavity by springs (indicated with 4). On the intake side of the pump, the chamber (created by the vanes) is increasing in volume forcing the gas molecules to flow into the pump. On the discharge side of the pump, the chamber (created by the vanes) is decreasing in volume forcing the gas molecules out of the pump.

Roots booster pump Roots booster pumps, shown in figure 7, use a pair of meshing lobes to increase and decrease the volume of a chamber inside the pump. Two symmetrically '8' shaped lobes rotates in opposite direction. One is driven by a motor and the other shaft is synchronized by a timing gear. The intake side of the pump, the chamber is increasing in volume forcing the gas molecules to flow into the pump. On the discharge side of the pump, the chamber is decreasing in volume and forcing the gas molecules out of the pump.

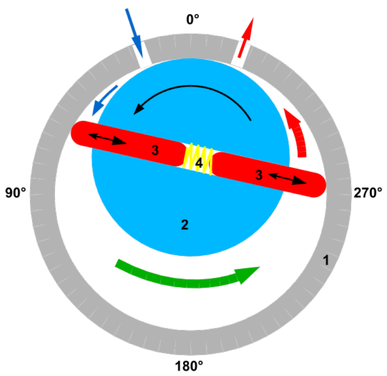

Figure 6: Schematic of an eccentric rotary vane pump

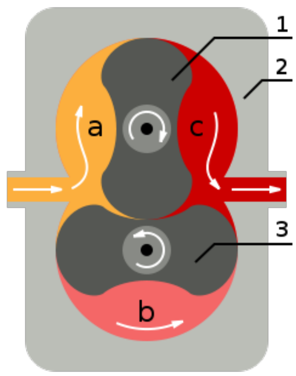

Figure 7: Schematic of an roots booster pump

Diaphragm pump Diaphragm pumps, shown in figure 8, are dry mechanical pumps. It uses a diaphragm to increase and decrease the volume of a chamber inside the pump. When the volume is increased (the diaphragm moving down in figure 8) the inlet valve opens and the pressure decreases, forcing the gas molecules into the pump. When the volume is decreased (the diaphragm moving up in figure 8) the outlet valve opens and the pressure increases, forcing the gas molecules of the pump. Usually butterfly valves are used for the inlet and outlet to ensure the gas molecules to flow in only one direction.

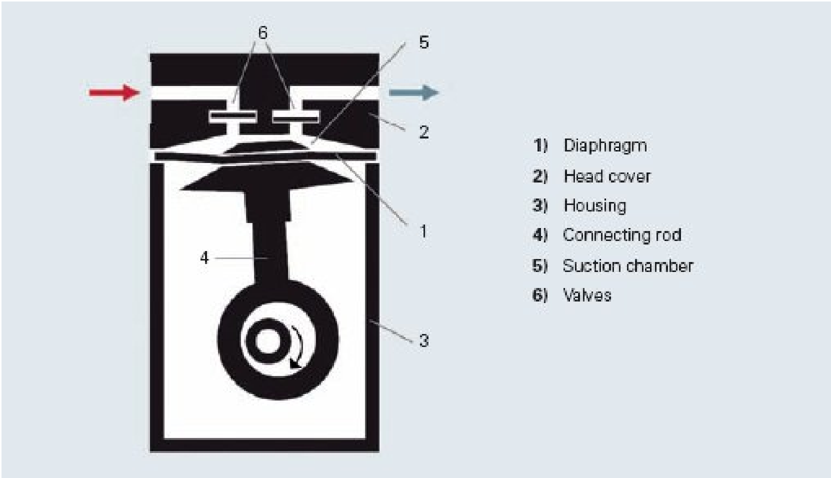

Figure 8: Schematic of a diaphragm pump

3.3.2 High to ultra high vacuum pumps

To obtain high to ultra high vacuum different type of pumps are required since the gas acts no longer as a viscous fluid. There are roughly two sort of pumps capable of obtaining this vacuum, namely, momentum transfer pumps and entrapment pumps. A brief explanation of momentum transfer pumps and entrapment pumps will be given. Momentum transfer pumps use high speed jets of dense fluid or high speed rotating blades to knock gas molecules out of the chamber. The principle of knocking gas molecules out of the vacuum chamber implies that they are always combined with one or two positive displacement pumps. Since they are not capable of pumping atmospheric pressure. The positive displacement pumps are used to avoid back streaming of gas molecules. Entrapment pumps capture gases in a solid or adsorbed state. Even though they are capable of pumping atmospheric pressure, in practice they are usually combined with one or two positive displacement pumps. Entrapment pumps require periodic regeneration of the surfaces that trap air molecules or ions. And have a low mass flow rate in rough to medium vacuum. The positive displacement pumps are used to obtain a rough to medium vacuum. When this is obtained the entrapment pump is used to obtain (ultra) high vacuum. Two main types of momentum transfer pumps, namely, diffusion pumps and turbo molecular pumps will be given and two main types of entrapment pumps will be given, namely, cryopumps and ion pumps.

Diffusion pump Diffusion pumps, shown in figure 9, use a high speed jet of vapor to direct gas molecules into pump. Oils gets vaporized by an electrical heater and is directed through a jet assembly, the nozzles make the vapor hit the outer cooled shell of the diffusion pump and the liquid condensates and flows back downwards as a film along the wall into the boiler.

Turbo molecular pump Turbo molecular pump, shown in figure 10, use high speed rotating blades to knock gas molecular out of the chamber. Gas molecules are given momentum in a desired direction by repeated collision with a moving solid surface, in this case rotating blades.

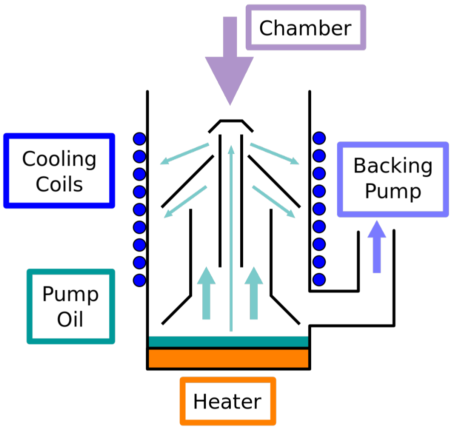

Figure 9: Schematic of a diffusion pump

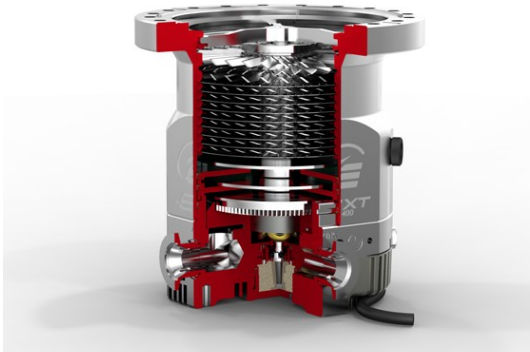

Figure 10: Interior view of a molecular pump

Cryopump Cryopumps, shown in figure 11, trap gas molecules by condensing them on a cold surface. Formation of condense usually require different temperatures because gas molecules have different freezing and boiling points. To overcome this problem cryopumps are (usually) equipped with multiple stages of cold surfaces at various temperatures. Cooling is done by compressed helium or liquid nitrogen.

Ion pump Ion pumps, shown in figure 12, ionize gas molecules and trap them by employing a strong electrical potential. Inside the ion pump multiple arrays of short positively charged stainless steel cylinders (anode) are mounted. Perpendicular to the cylinders are two negatively charged titanium plates (cathodes). All is situated within a strong magnetic field created by permanent magnets outside the ion pump. By applying a high voltage between the anodes and cathodes electrons are created and move in long helical trajectories through the anode tubes. The free electrons strike incoming gas molecules and ionize them. As soon as the gas molecules are ionized they are accelerated towards one of the negatively charged titanium plates with sufficient kinetic energy to pierce them.

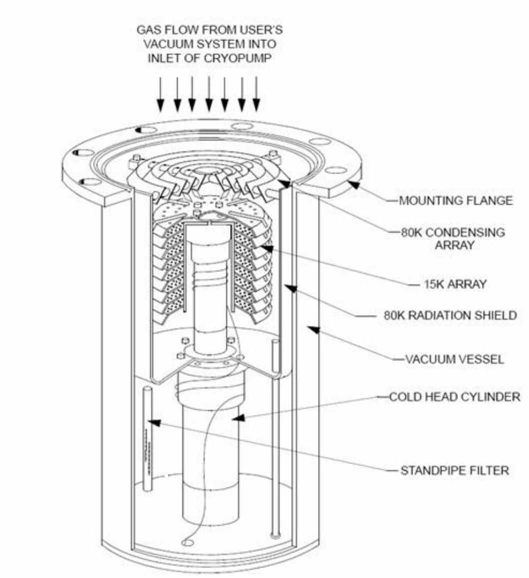

Figure 11: Schematic of a cryopump

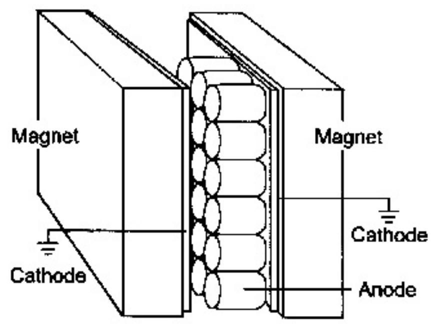

Figure 12: Schematic of a ion pump

4 Epicyclic Gearing

Epicyclic gearing is used to obtain gear reduction or prescribe certain motions. In this section firstly epicyclic gear systems and epicyclic arrangements will be discussed. And secondly, the gear ratios of the various epicyclic arrangements will be discussed.

4.1 Working Principle

Before starting the discussion on epicyclic gears a common terminology needs to be set out. In literature a lot of confusion exist: what some call epicyclic gear systems and epicyclic arrangements. The following definitions are adopted:

- Epicyclic gear systems define the components involved in the design
- Epicyclic arrangements define the input, output and fixed world of epicyclic gear systems

4.1.1 Epicyclic Gear Systems

Epicyclic gear systems consist of several components: sun, carrier, planets and annulus. The sun is the center gear which meshes with the planets, while the carrier houses the gear shafts of the planets. As the carrier rotates, planets rotate on their gears shaft while orbiting the sun. The annulus is the internal gear which meshes with the planets. Figure 13 shows the components and arrangement of an simple planetary epicyclic gear system.

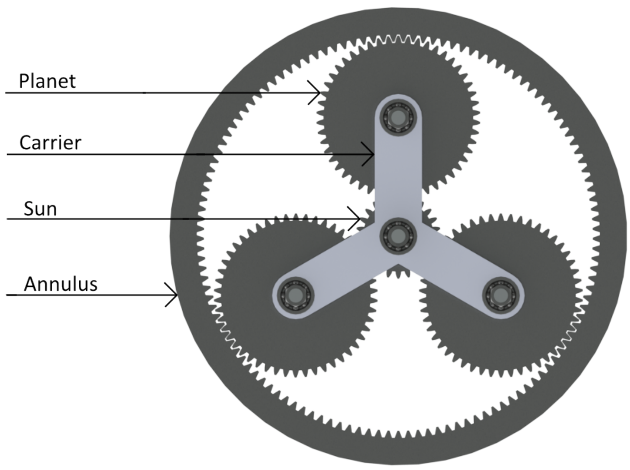

Figure 13: Components used in epicyclic gear systems

Epicyclic gear systems can be divided into two types: simple epicyclic and compound epicyclic. Simple epicyclic have one sun, one planet set (e.g. three or four planets), one carrier, and one annulus, see figure 14. It is the most simple epicyclic gear system design due to the minimal amount of components.

Compound epicyclic involve one of the following three types of structures: meshed-planet, stepped-planet and multi-stage structures. With meshed-planet structures (Figure 15) there are at least two more planets in mesh with each other in each planet train. With stepped-planet structures (Figure 16) there exists a shaft connection between two planets in each planet train.

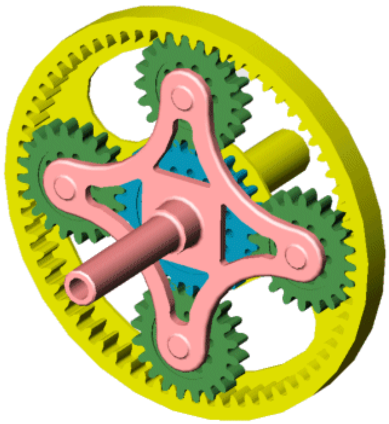

Figure 14: Simple epicyclic gear system

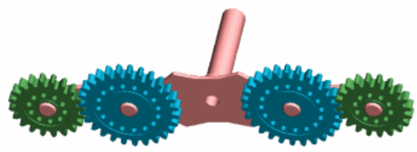

Figure 15: Compound epicyclic gear system (meshed-planet), note the annulus is missing

With multi-stage structures (Figure 17) the system contains two or more planet sets. Compared to simple epicyclic, compound epicyclic and coupled epicyclic sets have the advantages of larger reduction ratio, higher torque-to-weight ratio, and more flexible configurations.

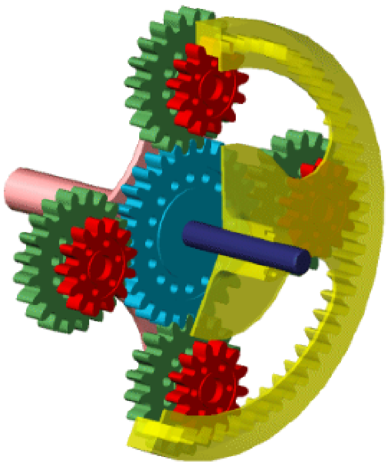

Figure 16: Compound epicyclic gear system (stepped-planet)

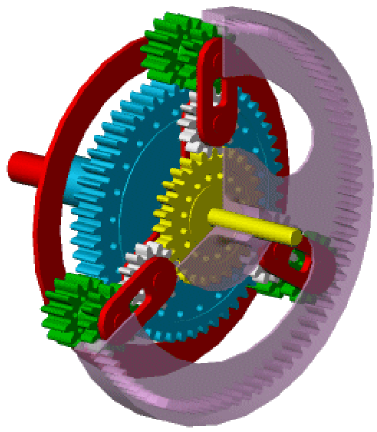

Figure 17: Compound epicyclic gear system (multi-stage)

4.1.2 Epicyclic Arrangements

In epicyclic gearing systems one of the components (i.e. sun, carrier and annulus) is held stationary; one of the two remaining components is an input, providing power to the system, while the last component is an output, receiving power from the system. The ratio of input rotation to output rotation is dependent upon the number of teeth in each gear, and upon which component is held stationary. According to Flanagan and Marsch (2008) there are three epicyclic arrangements: planetary, star and solar. In planetary epicyclic arrangement the annulus is held stationary, the sun in an input and the carrier is an output (Figure 18). When the input sun gear shaft is driven keeping the annulus fixed, the planet gears simultaneously rotate around their axes and revolve around the input sun gear axis along the inner circumference of the annular gear. Consequently, the carrier and the output shaft, which support the planet-gear axes, also rotate, but slower than the input shaft. In star epicyclic arrangement the carrier is held stationary, the sun is an input and the annulus is an output (Figure 19). When the input sun gear shaft is driven keeping the carrier fixed, the planet gears rotate around their axis. Consequently, the angular gear and the output shaft also rotate, but slower than the input shaft. In solar epicyclic the sun is held stationary, the annulus is an input and the carrier is an output (Figure 20). When the input annulus gear shaft is driven keeping the sun fixed, the planet gears simultaneously rotate around their axes and revolve around the input sun gear axis along the inner circumference of the annular gear. Consequently, the carrier and the output shaft, which support the planet-gear axes, also rotate, but slower than the input shaft. In next subsection the overall gear ratios of the various arrangements will be determined.

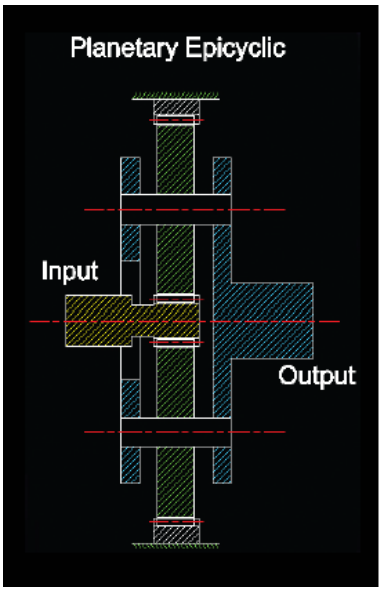

Figure 18: Planetary Epicyclic arrangement

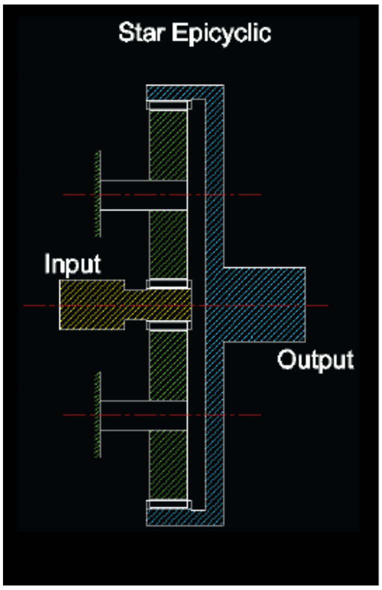

Figure 19: Star Epicyclic arrangement

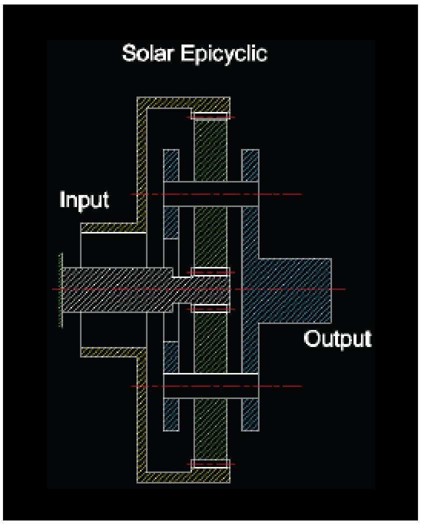

Figure 20: Solar Epicyclic arrangement

4.2 Gear Ratio

The overall gear ratio of a simple planetary gear set can be calculated using the following two equations. As mentioned before, simple epicyclic have one sun, one planet set, one carrier and one annulus.

$$N_s\omega_s + N_p\omega_p - (N_s + N_p)\omega_c = 0 \tag{1}$$
$$N_a\omega_a - N_p\omega_p - (N_a - N_p)\omega_c = 0 \tag{2}$$

Equation 1 and 2 represents the sun-planet and planet-annulus interactions respectively. Combining leads to the following equations.

$$N_s\omega_s + N_p\omega_p - (N_s + N_p)\omega_c = -(N_a\omega_a - N_p\omega_p - (N_a - N_p)\omega_c)$$
$$N_s\omega_s + N_p\omega_p - (N_s + N_p)\omega_c + N_a\omega_s - N_p\omega_p - (N_a - N_p)\omega_c = 0$$
$$N_s\omega_s + N_a\omega_a - (N_s + N_a)\omega_c = 0 \tag{3}$$

4.2.1 Planetary Epicyclic Arrangement

In planetary epicyclic arrangement the annulus is held stationary. This means the angular velocity of the annulus is equal to zero ($\omega_a = 0$); equation 3 can be reduced and reformulated to:

$$\omega_c = \left(\frac{N_s}{N_s + N_a}\right)\omega_s \tag{4}$$

Equation 4 describes the angular velocity of the carrier in terms of the number of teeth of the sun and carrier and the angular velocity of the sun. With the result of equation 4 and equation 1 or 2 it is possible to determine the angular velocity of the planets. In this case equation 2 is used.

$$\omega_p = \left(\frac{N_a}{N_p}\right)\omega_a - \left(\frac{N_a - N_p}{N_p}\right)\omega_c$$

Substitution of equation 4 leads to:

$$\omega_p = \left(\frac{N_a}{N_p}\right)\omega_a - \left(\frac{N_a - N_p}{N_p}\right)\left(\frac{N_s}{N_s + N_a}\right)\omega_s \tag{5}$$

Also here the annulus is stationary ($\omega_a = 0$), equation 5 can be reduced to:

$$\omega_p = -\left(\frac{N_a - N_p}{N_p}\right)\left(\frac{N_s}{N_s + N_a}\right)\omega_s \tag{6}$$

Equation 6 describes the angular velocity of the planets in terms of the number of teeth of the annulus, planets and sun and the angular velocity of the sun.

4.2.2 Star Epicyclic Arrangement

In star epicyclic arrangement the carrier is held stationary. This means the angular velocity of the carrier is equal to zero ($\omega_c = 0$); equation 3 can be reduced and reformulated to:

$$\omega_a = -\left(\frac{N_s}{N_a}\right)\omega_s \tag{7}$$

Equation 7 describes the angular velocity of the annulus in terms of the number of teeth of the sun and annulus and the angular velocity of the sun. Similar to the planetary epicyclic arrangement it is possible to calculate the angular velocity of the planets with the result of equation 7 and equation 1 or 2. In this case the 'general' equation of the angular velocity of the planets of the planetary epicyclic arrangement (equation 5) is used. Substitution of equation 7 in equation 5 leads to:

$$\omega_p = -\left(\frac{N_a}{N_p}\right)\left(\frac{N_s}{N_a}\right)\omega_s \tag{8}$$

Also here the carrier is stationary ($\omega_c = 0$), equation 8 can be reduced to:

$$\omega_p = -\left(\frac{N_a - N_p}{N_p}\right)\left(\frac{N_s}{N_s + N_a}\right)\omega_s \tag{9}$$

Equation 9 describes the angular velocity of the planets in terms of the number of teeth of the annulus, planets and sun and the angular velocity of the sun.

4.2.3 Solar Epicyclic Arrangement

In solar epicyclic arrangement the sun is held stationary. This means the angular velocity of the sun is equal to zero ($\omega_s = 0$); equation 3 can be reduced and reformulated to:

$$\omega_c = \left(\frac{N_a}{N_s + N_a}\right)\omega_a \tag{10}$$

Equation 10 describes the angular velocity of the carrier in terms of the number of teeth of the sun and annulus and the angular velocity of the annulus. Similar to both the planetary and star epicyclic arrangement it is possible to calculate the angular velocity of the planets with the result of equation 10 and equation 1 or 2. Also in this case the 'general' equation of the angular velocity of the planets of the planetary epicyclic arrangement (equation 5) is used. Substitution of equation 10 in equation 5 leads to:

$$\omega_p = \left(\frac{N_a}{N_p}\right)\omega_a - \left(\frac{N_a - N_p}{N_p}\right)\left(\frac{N_a}{N_s + N_a}\right)\omega_a \tag{11}$$

$$= \left(\frac{N_a}{N_p} - \left(\frac{N_a - N_p}{N_p}\right)\left(\frac{N_a}{N_s + N_a}\right)\right)\omega_a \tag{12}$$

Equation 12 describes the angular velocity of the planets in terms of the number of teeth of the annulus, planets and sun and the angular velocity of the annulus.

5 Problem description

The project concerns the design of a planetary system; it will be used to prescribe a certain motion to workpiece samples during thin film deposition. In the lab of DMI, the display department of CTI, multiple physical vapor deposition machines are available. The physical vapor deposition machines are used for research in the areas of microelectronics and displays. The planetary system will be designed for a particular machine, namely, the EV400 evaporation deposition machine. The EV400 is a commercial system, operating under vacuum and used for thin film deposition. In the current configuration the workpiece samples are mounted stationary on the sample holder. This results in a film thickness variation among the surface of the workpiece samples. The aim of this project is to redesign the sample holder of the EV400 machine to a planetary system to resolve film thickness problems. The workpiece samples should rotate around their axis and revolve around the sun gear axis along the inner circumference of the annulus gear. The planetary system will be designed, developed and produced within CTI. Main production facilities within CTI are lathes, milling machines and laser cutting machines. CTI proposed multiple requirements and design criteria which the design must satisfy. The requirements and design criteria are listed in table 2 and table 4, respectively. The difference between the two types of specifications is that the requirements consist of quantity parameters and the design criteria consist of design guidelines. In table 4 can be seen that a Bosch F006WM0310 electric motor should be used. The specifications of this motor can be found in table 3.

Parameter	**Value**
Dimensions of vacuum chamber	See figure 21
Amount of sample holders	3
Minimum size of sample holder plate	120 mm
Angular velocity of planets	5-15 RPM
Angular velocity of carrier	5-15 RPM

Table 2: Overview of requirements

Parameter	**Value**
Voltage	24 Volt
Speed	45 RPM
Maximum torque	48 Nm

Table 3: Specification of Bosch F006WM0310

General	
Workpiece samples should rotate around their axis and revolve around the sun gear axis	
Design planetary system as separate system (keep the EV400 in original state)	
Planetary system must be mounted on the existing feedthrough	
Bosch F006WM0310 electric motor available	
SKF 605ZZ bearings available	
Minimize costs	
Design	
Maximize sample plate holder area	
Production	
Producible within CTI	
Materials	
Availability of steel, stainless steel, and aluminum materials	
Availability of round bars, round tubes, rectangular bars and plates	

Table 4: Overview of design guidelines as proposed by CTI

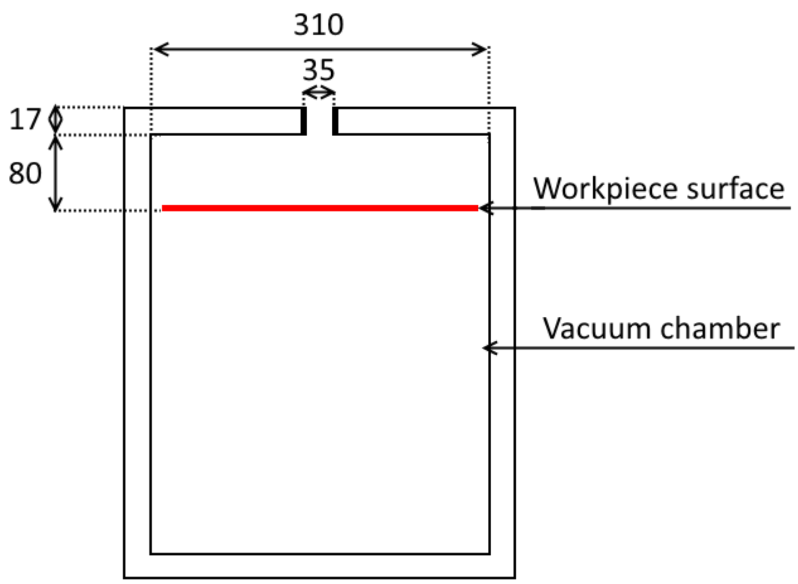

Figure 21: Dimensions of the vacuum chamber of the EV400

6 EV400 Evaporation Deposition machine

In this section, firstly, the EV400 evaporation deposition machine and its components will be introduced. And secondly, the film thickness variation problem stated in section 5 will be analyzed.

6.1 Introduction to the EV400

The EV400 evaporation deposition machine is can be seen in figure 22. Figures 23, 24, 25 and 26 show an overview of the components inside the vacuum chamber. The components will be briefly described.

Figure 22: Overview of the EV400 evaporation

Crucibles

A crucible is a container that holds, in this case, a film material (e.g. gold, titanium and aluminum). A crucible which contains a film material is heated to a high vapor pressure by electrically resistive heating, allowing the particles of the film material to evaporate. To ensure the crucible don't evaporate it is made of a material with a very high melting point. The crucibles in EV400 evaporation deposition machine are made of tungsten, with a meltion point of 3687 Kelvin makes it an excellent crucible. In figure 25 can be seen there are two crucibles present in the machine, a small one and a big one. The reason to have different sizes of crucibles is because (usually) the film material is quite expansive. When the sample is relative small it can be sufficient to use the small crucible.

Crucible cover

In the EV400 evaporation deposition machine a crucible cover is present to prematurely stop the evaporation process. This can be necessary when a certain (required) film thickness is reached.

Feedthroughs

Freedthroughs are used to transfer electrical power through the system wall of the vacuum chamber. They can be divided into two main categories, namely, power and instrumentation feedthroughs. In this report and at CTI the term feedthrough is also used to indicate a device that transfer mechanical energy through the system wall of the vacuum chamber. Figure 23 indicates two feedthroughs. The upper (instrumentation) feedthrough is used to carry electrical signals on behalf of the thermocouple. The lower feedthrough (in the center of the machine) will be used to transfer mechanical energy of the planetary system. Feedthroughs are an unavoidable source of leakage of atmospheric air into the system.

Hydraulic lift

The hydraulic lift is used to lift the cover from the vacuum chamber. This is obviously necessary to disassemble and mount workpiece samples.

O-ring seal

In the EV400 evaporation deposition machine multiple O-rings are used to obtain a sealed system. An O-ring is a mechanical gasket in shape of a torus, designed to be seated in a groove and compressed during assembly between two or more parts, creating a seal at the interface. The O-ring in figure 24 is used to seal the vacuum chamber and cover. Maintaining low pressure and avoiding leakage are key issues when it comes to creating a vacuum. Like feedthroughs, connections are an unavoidable source of leakage of atmospheric air into the system. Maximum vacuum is created when the leak throughput equals to the pump throughput.

Thickness measurement sensor

The thickness measurement sensor measures the film thickness during a film deposition. The film thickness can range from fractions of a nanometer (mono-layer) to several micrometers in thickness. Therefore accurate measurement tools are necessary.

Thermocouple

The thermocouple is a temperature measuring device consisting of two dissimilar metals that are joined together at one end. When the junction of the two metals is heated or cooled a voltage is produced that can be correlated back to the temperature. In the EV400 evaporation deposition machine thermocouples are used to control the evaporation process by adjusting the temperature of the crucible.

Sample holder

The sample holder is used to fix samples. The sample holder has a round shape and is fixed in a metal frame which is attached to the vacuum chamber cover. By moving the sample holder upwards it can be removed from the assembly (out of the sample height adjuster indicated in figure 24). Workpiece samples are prepared outside the vacuum chamber and afterwards fixed by using tape on the sample holder. When the workpiece samples are fixed the sample holder is placed back into the metal frame inside the vacuum chamber.

Sample height adjustment

The sample height adjustment is used to place workpiece samples at a certain height. It was designed to optimize the distance between the crucible and workpiece samples for optimal film thickness distribution.

Vacuum pump

Evaporation Deposition takes places in medium to high vacuum, allowing particles to travel directly to the workpiece without colliding or reacting with the surrounding gas in the vacuum chamber. Figure 25 shows the piping which lead to the inlet of the pump. Since a medium to high vacuum is required in the EV400 evaporation deposition machine a positive displacement pump is used, namely, a rotary vane pump. The benefit of using a rotary vane pump, instead of a roots booster pump or diaphragm pump, is the high pump velocity (about $14\frac{m^3}{h}$) and low cost.

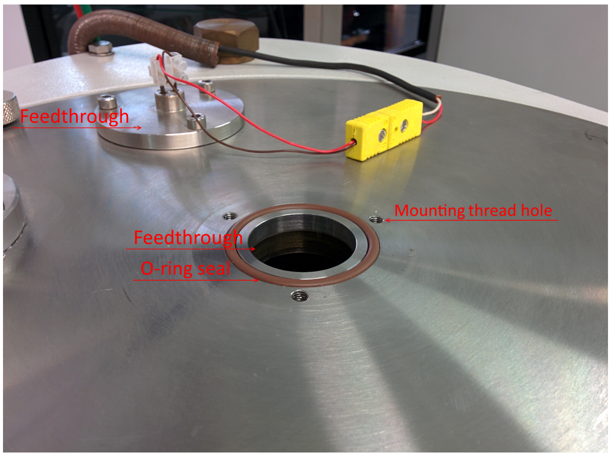

Figure 23: Feedthroughs

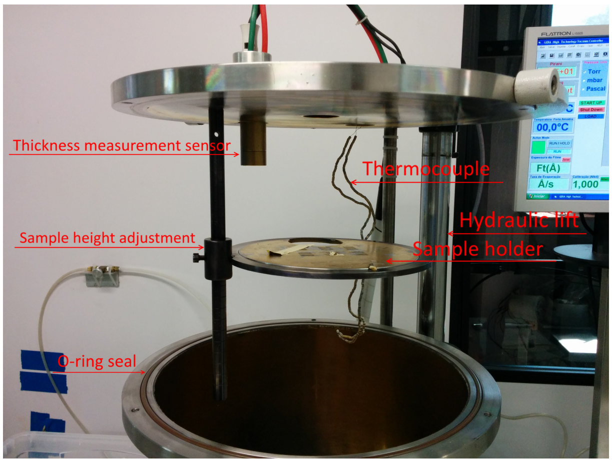

Figure 24: Components inside vacuum chamber

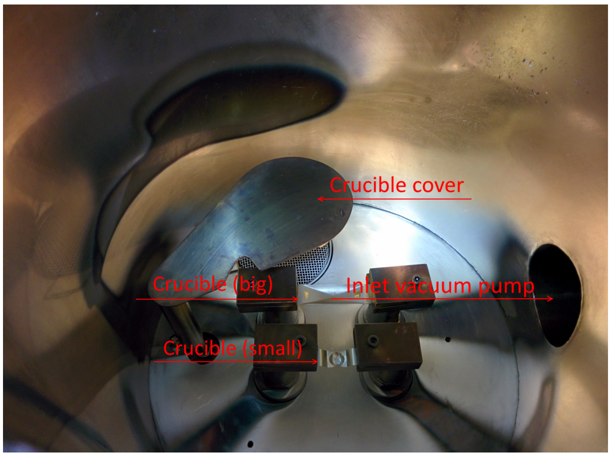

Figure 25: Components inside vacuum chamber

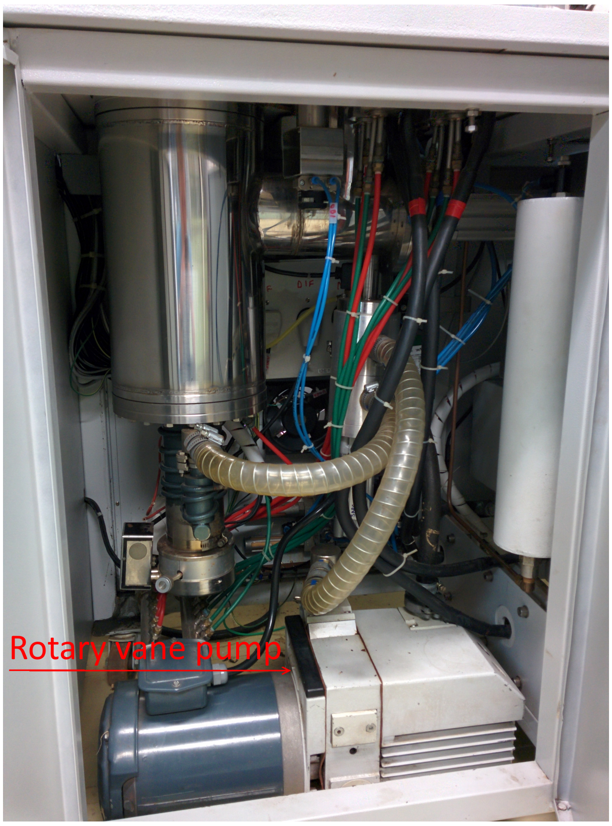

Figure 26: Rotary vane pump

6.2 Problem analysis

In the current configuration the workpiece samples are mounted stationary on the sample holder inside the vacuum chamber. This result in film thickness problems among the surface of the workpiece samples. This phenomena occurs due to different travel distances of particles between the film material and workpiece surface. Firstly, mathematical models of the film thickness variation in stationary and planetary case will be constructed. And secondly, the mathematical models will be compared.

Figure 27 shows a schematic front view of a spherical vacuum chamber used construct the mathematical models. The black dot in the middle of the vacuum chamber indicates a point deposition source. A point deposition source is a infinitesimal small piece of film material with a mass and density. In this case it is placed in the middle of the vacuum chamber, hereby, the particles will escape the film material and subject proportional to cooler surfaces all around the chamber. This assumption is made for convenience, the mathematical models can also be constructed for different type of deposition sources. The red horizontal line in the upper half of the sphere represents the sample holder. In this case, the shape of the sample holder round and mounted inside the vacuum chamber against the wall. Another assumption is perfect vacuum inside the chamber. This allows particles to follow a perfect straight path (directional) and proportional distribute inside the chamber. A summary of the assumptions:

- Shape of vacuum chamber is a sphere
- Point deposition source
- Shape of sample holder in stationary case is round and mounted inside the vacuum cham-

ber against the wall

- Perfect vacuum

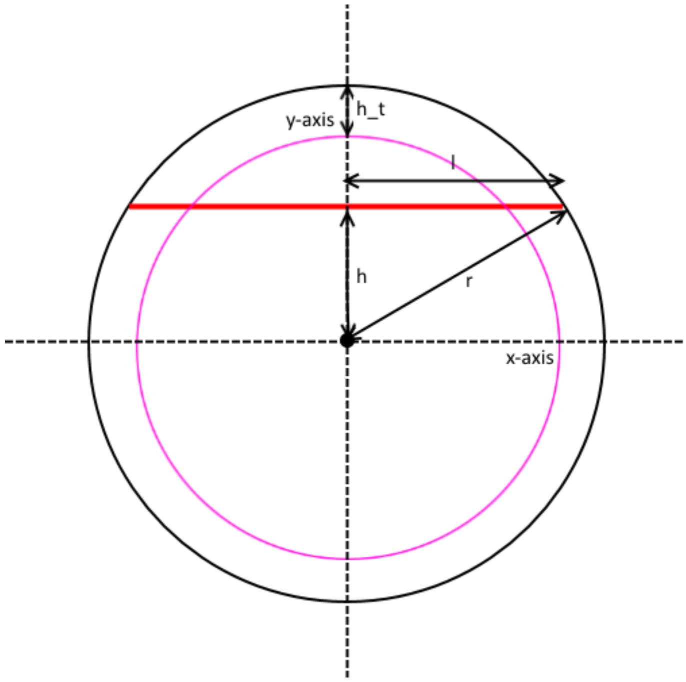

Figure 27: Schematic overview of a physical vapor deposition vacuum chamber (current configuration)

The pink line indicates the deposited film material on the vacuum chamber wall when there is no sample holder present inside the vacuum chamber. Equation 13 express the volume in terms of the mass and density of the film material. And equation 14 express the volume in terms of geometrical properties of the film material.

$$V_{material} = 4\pi r^2 h_t \tag{13}$$

$$V_{material} = \frac{m_{mat}}{\rho_{mat}} \tag{14}$$

Combining equation 13 and equation 14 leads to equation 15 which expresses the film thickness on the vacuum chamber wall. The deposited film material is proportional distributed inside the vacuum chamber with constant film thickness (h_t). Therefore, another solution to resolve film thickness variation is to mount workpiece samples around the sphere inside the vacuum chamber. The disadvantage hereof is that this solution only works for smaller workpiece samples (when flat workpiece samples are considered).

$$h_t = \frac{m_{mat}}{4\pi r^2 \cdot \rho_{mat}} \tag{15}$$

Equation 15 will be used to determine the film thickness variation among workpiece samples on the sample holder. The distribution of the deposited film on the sample holder can be described by equation 16. Equation 16 consist of the following parameters: film thickness on vacuum chamber wall (h_t), film thickness on sample holder (d)) on position (x) and sample holder height (h). The radius of the spherical vacuum chamber can be described in terms of height (h) and radius (r) of the vacuum chamber by using Pythagroas Theorem, see equation 15.

$$h_t = d\frac{\sqrt{h^2 + x^2}}{h} \tag{16}$$

$$r^2 = h^2 + l^2 \tag{17}$$

Substituting equation 16 and equation 17 in equation 15 and solving for d results in an expression for the film thickness variations on the sample holder in stationary case, see equation 18.

$$d = \frac{m_{mat} h}{4\pi r^2 \rho_{mat} \sqrt{h^2 + x^2}} \tag{18}$$

The maximum film thickness can be found by substituting $x = 0$, see equation 19. Position $x = 0$ indicates the shortest travel distance of particles between the film material and the workpiece surface. Equation 19 is similar to equation 15 as expected, because the maximum film thickness should be equal of the sample holder and vacuum chamber wall.

$$d_0 = \frac{m_{mat}}{4\pi r^2 \rho_{mat}} \tag{19}$$

It is decided to construct the fraction of the film thickness variation and the maximum film thickness, see equation 20. By doing so many parameters disappear (m_{mat}, ρ_{mat} and r) and the relative variation in film thickness $\left(\frac{d}{d_0}\right)$ can be plotted against the relative distance $\left(\frac{x}{l}\right)$. Matlab is used to construct plots to visualize equation 20. Figure 29 shows the relative film thickness variation plotted against the relative distance for the current configuration used at CTI. The minimum and maximum values of the relative distance are $\left(\frac{x}{h}\right)_{min} = -\frac{1}{2}$ and $\left(\frac{x}{h}\right)_{max} = \frac{1}{2}$. These values correspond to the dimensions of the EV400 machine. The same data is used to construct surface and contour plots, see figure 31 and figure 32. In the current configuration the film thickness variation among the surface of the sample holder is about 10 percent.

$$\frac{d}{d_0} = \frac{\frac{m_{mat} h}{4\pi r^2 \rho_{mat} \sqrt{h^2+x^2}}}{\frac{m_{mat}}{4\pi r^2 \rho_{mat}}} = \frac{h}{\sqrt{h^2 + x^2}} = \frac{1}{\sqrt{1 + \frac{x^2}{h^2}}} \tag{20}$$

The planetary system is modeled using equation 21. There are two cases considered, namely, planetary system symmetric case and planetary system antisymmetric case. The difference between symmetric and antisymmetric case is the size of the sample holder, and therefore the rotation point of the sample holder inside the vacuum chamber, see figure 28. In case of the planetary system symmetric the minimum and maximum values of the relative distance $\left(\frac{x}{h}\right)_{min} = 0$ and $\left(\frac{x}{h}\right)_{max} = \frac{1}{2}$ are used, red line in figure 28. In case of the planetary antisymmetric case the arbitrary minimum and maximum values of the relative distance $\left(\frac{x}{h}\right)_{min} = 0.05$ and $\left(\frac{x}{h}\right)_{max} = 0.35$ are used, green line in figure 28. It is assumed that the sample holder turns exactly 1 round around their axis during the whole film deposition process. Matlab is used to construct a 2 dimensional plot to visualize equation 21 and to compare the different cases. Figure 30 shows the relative film thickness variation plotted against the relative distance for the stationary, planetary system symmetric and planetary system antisymmetric case. In the planetary symmetric case the film thickness variation among the surface of the sample holder is about 2 percent. This means the proposed solution of a planetary system will reduce the film thickness variation by 80 percent. In the planetary antisymmetric case the film thickness variation among the surface of the sample holder is about 1 percent. In figure 30 can be seen that the sample thickness of the planetary system antisymmetric case increases compared to the planetary system symmetric case. This is as expected because the sample holder is placed closer to the upper center of the sphere.

$$\left(\frac{d}{d_0}\right)_{planetary}(i) = \frac{\frac{d(i)}{d_0} + \frac{d(n+1-i)}{d_0}}{2} \qquad \text{for } i = 1...n \tag{21}$$

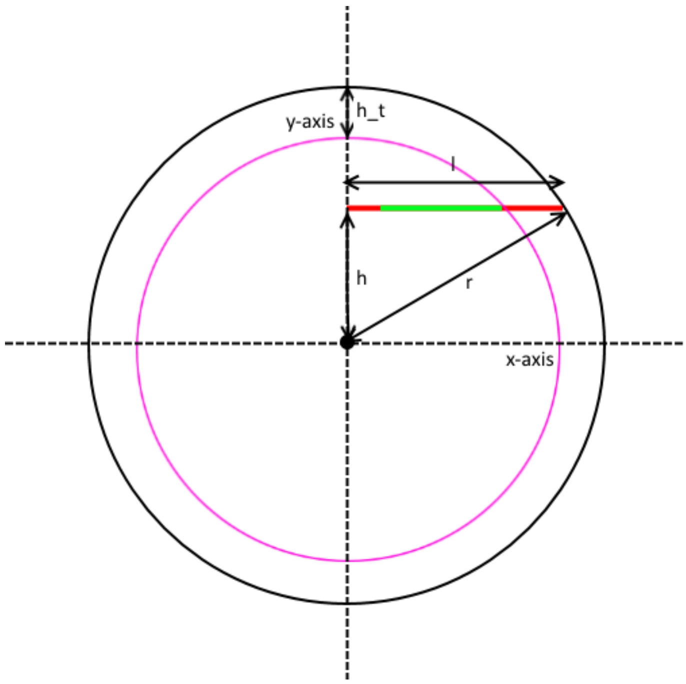

Figure 28: Schematic overview of a physical vapor deposition vacuum chamber (new configuration)

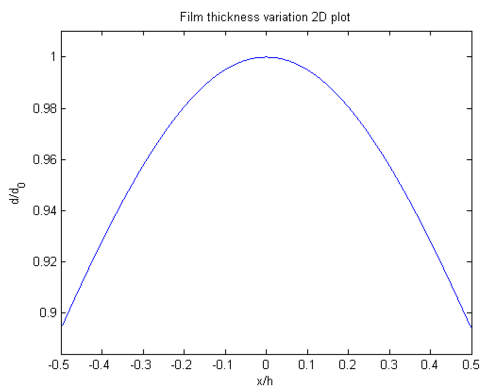

Figure 29: 2D plot of film thickness variation in stationary case for upper half of the vacuum chamber

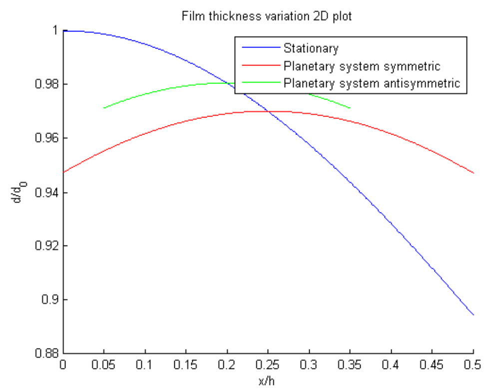

Figure 30: 2D plot of film thickness variation in stationary, planetary system symmetric and planetary system unsymmetric case

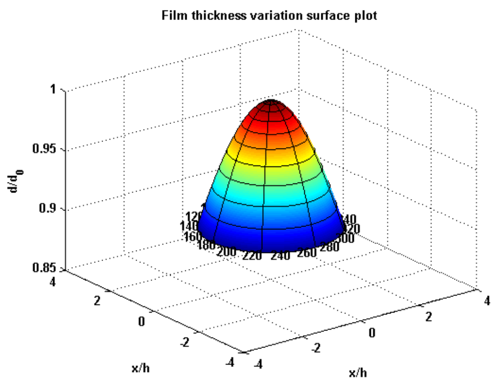

Figure 31: Surface plot of film thickness variation in stationary case for upper part of the vacuum chamber

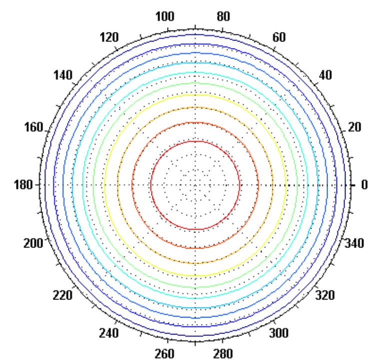

Figure 32: Contour plot of film thickness variation in stationary stationary case for the complete vacuum chamber

7 Concepts

In this section multiple concepts concerning the epicyclic gearing and feedthrough will be discussed.

7.1 Epicyclic Gearing concepts

In this subsection different concepts concerning the epicyclic gearing will be discussed. As mentioned before, epicyclic gearing consist of several components: sun, carrier, planets and annulus. Usually planetary systems are used to obtain a certain gear ratio between the input and output shaft. In this case the planetary system will be used to prescribe a certain motion to workpiece surfaces. The workpiece surface should rotate around their axis and revolve around the sun gear axis along the inner circumference of the annulus gear. There a multiple epicyclic arrangements which succeed in prescribing this motion and will be discussed in this section.

7.1.1 Concept 1

Concept 1 can be classified as a simple epicyclic gearing system consisting of one sun, one planet set, one carrier and one annulus. It is arranged in such way the annulus is held stationary, the sun is an input and the carrier is an output, also called planetary epicyclic arrangement. As mentioned before in such configuration when the input sun gear shaft is driven keeping the annulus fixed, the planet gears simultaneously rotate around their axes and revolve around the input sun gear axis along the inner circumference of the annular gear. Consequently, the carrier and the output shaft, which support the planet-gear axes, also rotate, but slower then the input shaft. Figure 33 illustrates the simple epicyclic gearing system and arrangement of concept 1. In this concept the diameter of the planet spur gears will be maximized. The reason is to use the area of the planet as sample plate holder.

The angular velocity of the carrier is described in terms of the number of teeth of the annulus and sun and the angular velocity of the sun (Equation 4). Equation 4 indicates the gear ratio is a reduction, independent of the number of teeth of the sun and carrier. For example, when the sun (input) turns 60 rounds per minute the carrier (output) will rotate 10 rounds per minute. This can be seen as positive characteristic. In section 5 is stated that the angular velocity of the carrier (i.e. rotation of planet gears around sun gear) must be between 5 and 15 rounds per minute. Since the electro motor has its maximum torque at 45 rounds per minute it is beneficial to have a gear ratio that reduce the angular velocity of the output and not increase it. Equation 6 describes the angular velocity of the planets in terms of the number of teeth of the annulus, planets and sun and the angular velocity of the sun. Equation 6 can be reformulated by using the number of teeth relationship between the sun, planets and annulus. For simple epicyclic gearing the number of teeth relationship is described by:

$$N_a = N_s + 2N_p \tag{22}$$

Substituting equation 22 into equation 6 leads to:

$$\begin{aligned}
\omega_p &= -\left(\frac{N_s + 2N_p - N_p}{N_p}\right)\left(\frac{N_s}{N_s + N_s + 2N_p}\right)\omega_s && (23)\\
&= -\left(\frac{N_s + N_p}{N_p}\right)\left(\frac{N_s}{2(N_s + N_p)}\right)\omega_s && (24)\\
&= -\left(\frac{N_s}{2N_p}\right)\omega_s && (25)
\end{aligned}$$

Equation 25 also indicates the gear ratio is a reduction. It can be assumed the number of teeth of the planet is more then the number of teeth of the sun since the planet gear will be maximized. This also can be seen as a positive characteristic, for the same reason as mentioned above. In section 5 is stated that the angular velocity of the planets (i.e. rotation of planets around their axis) must be between 5 and 15 rounds per minute. Since the electro motor has its maximum torque at 45 rounds per minute it is beneficial to have a gear ratio that reduce the angular velocity of the output and not increase it.

Pros

- Simple design due to the minimal amount of components
- Gear ratio between sun (input) and carrier (output) is a reduction
- Gear ratio between sun (input) and planets is a reduction

Cons

- Maximizing planet spurs requires more material and thus more cost

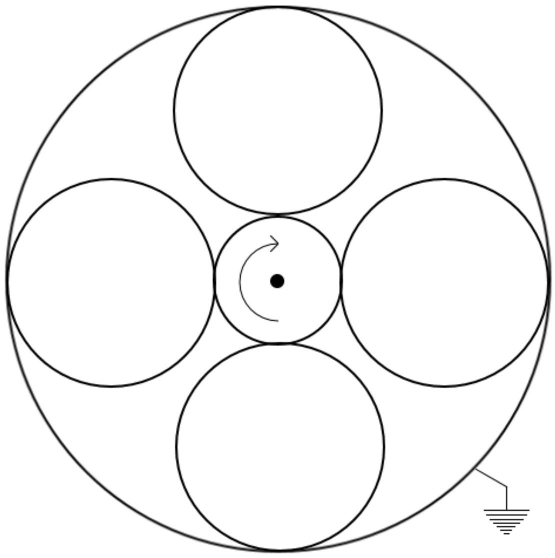

Figure 33: Schematic overview of concept 1 (Epicyclic gearing)

7.1.2 Concept 2

Concept 2 can also be classified as a simple epicyclic gearing system since it also consist of one sun, one planet set, one carrier and one annulus. Only in this case it is arranged in such way the sun is held stationary, the annulus is an input and the carrier is an output, also called solar epicyclic arrangement. As mentioned before in such configuration when the input annulus gear shaft is driven keeping the sun fixed, the planet gears simultaneously rotate around their axes and revolve around the input sun gear axis along the inner circumference of the annular gear. Consequently, the carrier and the output shaft, which support the planet-gear axes, also rotate, but slower than the input shaft. Figure 34 illustrate the simple epicyclic gearing system and arrangement of concept 2. In this concept the diameter of the planet spurs will also be maximized. The reason is to use the area of the planet as sample plate holder. As mentioned before, in this concept a solar epicyclic arrangement is chosen. This implies the annulus is used as an input and a complex structure is needed to attach the input shaft of the motor to the annulus. This can be seen as a disadvantage.

The angular velocity of the carrier is described in terms of the number of teeth of the sun and annulus and the angular velocity of the annulus (Equation 10). Equation 10 indicates the gear ratio increase, independent of the number of teeth of the sun and carrier. For example, when the annulus (input) turns 60 rounds per minute the carrier (output) will rotate 50000 rounds per minute. This can be seen as negative characteristic. In section 5 is stated that the angular velocity of the carrier (i.e. rotation of planet gears around sun gear) must be between 5 and 15 rounds per minute. Since the electro motor has its maximum torque at 45 rounds per minute, and used as input of the system, it is beneficial to have a gear ratio that reduce the angular velocity of the output and not increase it. Equation 12 describes the angular velocity of the planets in terms of the annulus, planets and sun and the angular velocity of the annulus. Equation 12 can be reformulated by using equation 22. Substituting equation 22 into equation 12 leads to:

$$\omega_p = \left(\frac{N_s + 2N_p}{N_p} - \left(\frac{N_s + 2N_p - N_p}{N_p}\right)\left(\frac{N_s + N_p}{N_s + N_s + 2N_p}\right)\right)\omega_a \tag{26}$$

$$= \left(\frac{N_s + 2N_p}{N_p} - \left(\frac{N_s + N_p}{N_p}\right)\left(\frac{N_s + 2N_p}{2(N_s + N_p)}\right)\right)\omega_a \tag{27}$$

$$= \left(\frac{N_s + 2N_p}{2N_p}\right)\omega_a \tag{28}$$

Equation 28 also indicates the gear ratio increase. This also can be seen as a negative characteristic, for the same reason as mentioned above. In section 5 is stated that the angular velocity of the planets (i.e. rotation of planets around their axis) must be between 5 and 15 rounds per minute. Since the electro motor has its maximum torque at 45 rounds per minute it is beneficial to have a gear ratio that reduce the angular velocity of the output and not increase it.

Pros

- Simple design due to the minimal amount of components

Cons

- Maximizing planet spurs requires more material and thus more cost
- Complex structure needed to attach input shaft of motor to annulus
- Gear ratio increases between annulus (input) and carrier (output)
- Gear ratio increases between annulus (input) and planets is a reduction

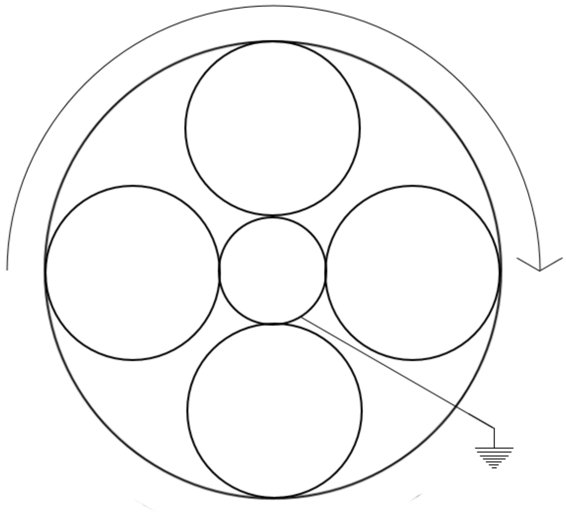

Figure 34: Schematic overview of concept 2 (Epicyclic gearing)

7.2 Feedthrough concepts

In this subsection different concepts concerning the feedthrough will be discussed. As mentioned before, the feedthrough is a device that transfer mechanical energy through the system wall of the vacuum chamber. Therefore, the concepts will be mainly characterized by the method to transfer mechanical energy and the used seals. A distinction can be made between static and dynamic seals. Static seals is a generic term used for seals applied to fixed parts. Dynamic seal is a generic term for seals used seal the moving part.

7.2.1 Concept 1

In concept 1 the transfer of mechanical energy between the motor and epicyclic gearing is based on the method of magnetic coupling, see figure 35 for a schematic overview. In this method the atmosphere side and the vacuum side are separated by a barrier wall or housing. The magnetic force of the magnet (indicated with magnetic) on the atmosphere side rotates the shaft (indicated with rotor) on the vacuum side. The vacuum and atmosphere sides are sealed from each other by a nonmagnetic barrier wall. This results in the advantage that the vacuum chamber will not be contaminated by a dynamic seal and long service life. Also, due to the lack of a dynamic seal this design is fairly simplistic. A possible disadvantage is that motion is transferred by magnetism, causing idling if the load is great.

The bearing arrangement of a shaft generally requires two bearings to support and locate it radially and axially. The (locating) bearing in housing 2 provides radial support and at the same time locates the shaft axially in both directions. It must, therefore, be fixed in position both on the shaft and in the housing. The (non-locating) bearing in housing 1 provides radial support but allows axial displacement in both directions. In such arrangement the bearings don't mutually stress each other, for example, when the shaft length changes as a result of thermal expansion.

Concept 1 is divided into two housing parts. Housing 1 fits into the existing feedthrough hole of the EV400 machine, see figure 23. Housing 2 geometrical constraint housing 1 and is attached on the mounting thread hole of the EV400 machine. The bolts are used to compress the O-ring between the two surfaces, which result in a seal at the interface. In this concept, due to the magnetic decoupling, it is necessary to use different housing parts for the bearings. A disadvantage hereof is the high concentric tolerances between housing 1 and housing 2. This will increase manufacturing cost.

Pros

- No contamination of vacuum chamber due to magnetic coupling (absence of seal)
- Long service life
- Simplistic due to the lack of dynamic seal

Cons

- Magnetic coupling can cause idling if the load is great
- High concentric tolerance between housing 1 and housing 2

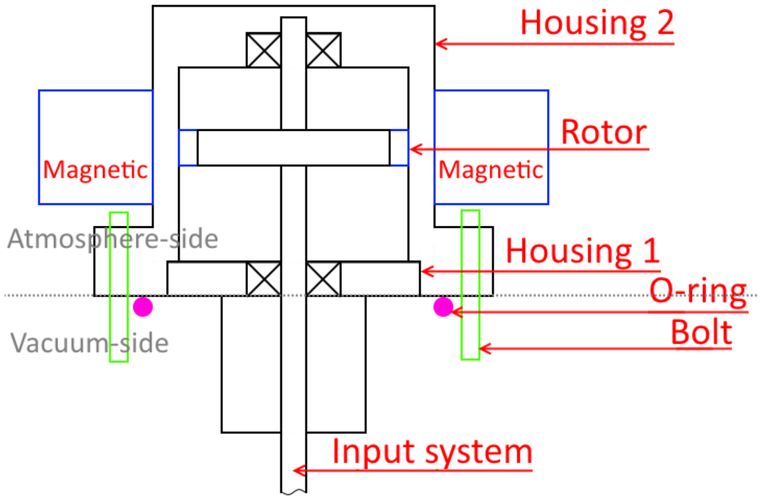

Figure 35: Schematic overview of concept 1 (Feedthrough)

7.2.2 Concept 2

In concept 2 the transfer of mechanical energy between the motor and epicyclic gearing is simply done by a shaft, see figure 37 for a schematic overview. In such case an extra sealing is necessary, which in concept 2 is done by a so-called rotary feedthrough. In this method the atmosphere side and the vacuum side are separated by magnetic fluid. Magnetic fluid is held in a gap between the shaft and a pole piece along magnetic flux lines generated by a magnet. Figure 36 illustrate the basic structure of a rotary feedthrough. Magnetic fluid, also called ferrofluid, is a liquid that becomes strongly magnetized in the presence of a magnetic field. The strength with which the magnetic fluid is held in the gap is determined by the magnetic. Advantages of a rotary feedthrough, in concept 2, are low friction and thus eliminating particle generation (no contamination), long service life and supporting high rotational speeds. Another advantages is, due to the direct connection between the motor and epicyclic gearing, accurate motion. A disadvantage hereof is the necessity of a dynamic seal and results in a possible source of leakage, increased complexity of design and costs.

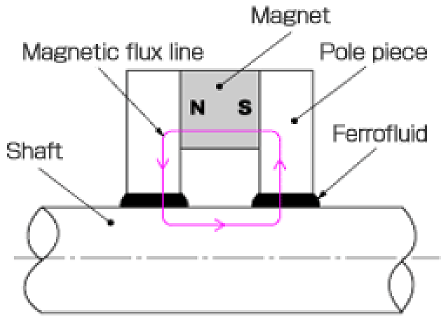

Figure 36: Basic structure of a rotary feedthrough

The bearing arrangement of the shaft of concept 2 also require two bearings to support and locate it radially and axially. The upper (locating) bearing provides radial support and at the same time locates the shaft axially in both directions. It must, therefore, be fixed in position both on the shaft and in the housing. The lower (non-locating) bearing provides radial support but allows axial displacement in both directions. In such arrangement the bearings don't mutually stress each other. Both the bearings are placed in the housing.

The housing of concept 2 fits into the existing feedthrough hole and is attached on the mounting thread hole of the EV400 machine, see figure 23. The bolts are used to compress the O-ring between the two surfaces, which result in a seal at the interface.

Pros

- No contamination of vacuum chamber due to low friction
- Long service life
- Supporting high rotational speeds
- Accurate motion due to direct connection between motor and epicyclic gearing

Cons

- Possible source of leakage due to dynamic seal
- Increased complexity of design due to dynamic seal
- Increased cost due to dynamic seal

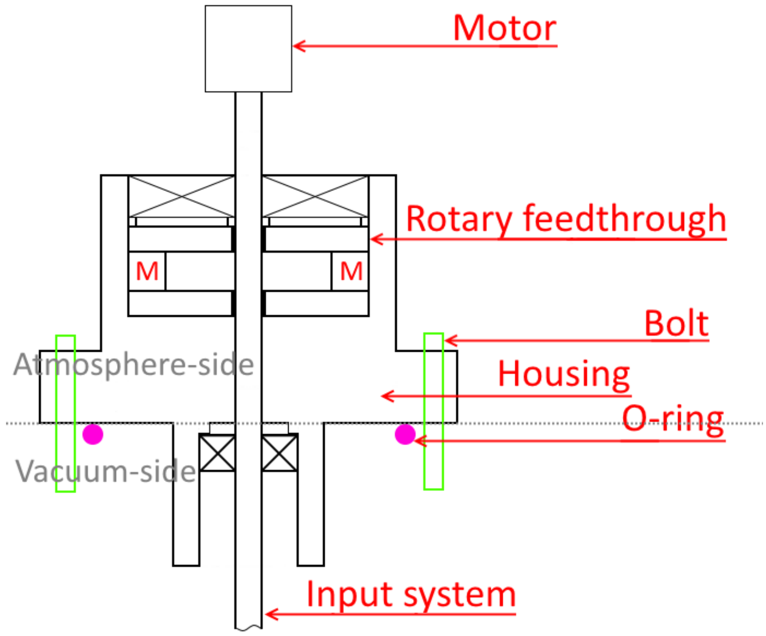

Figure 37: Schematic overview of concept 1 (Feedthrough)

8 Concept choice

In this section a epicyclic gearing concept and feedthrough concept will be chosen for further development. Eventually they will be combined which leads to a detailed design.

8.1 Concepts Epicyclic Gearing

Concept 1 is classified as a simple epicyclic gearing system. It is arranged in such way the annulus is held stationary, the sun is an input and the carrier is an output, also called planetary epicyclic arrangement. Concept 2 is also classified as a simple epicyclic gearing system. It is arranged in such way the sun is held stationary, the annulus is an input and the carrier is an output, also called solar epicyclic. Both concepts succeed in giving the workpiece surface the desired motion. The difference between the two is the type of arrangement, this results in different structures and gear ratios. The obvious choice is the choose concept 1 when the pros and the cons are compared. Concept 1 has a gear reduction between sun (input) and carrier (output) and between sun and planets gearing. While the gear ratio of concept 2 increases between the annulus (input) and carrier (output) and between annulus and planets gearing. Also the structure needed to attach the input shaft of the motor to the annulus of concept 2 is much more complex then concept 1. In next chapter concept 1 will be further developed what eventually leads to a detailed design.

8.2 Concepts Feedthrough

Concept 1 transfer mechanical energy between the motor and the epicyclic gearing by the method of magnetic coupling. As a result, no dynamic seal is needed to seal the input shaft of the epicyclic gearing. Concept 2 transfer mechanical energy directly between the motor and the epicyclic gearing by a shaft. As a result, a dynamic seal is needed to seal the vacuum-side from the atmosphere-side of the shaft. When the pros and the cons are compared between concept 1 and concept 2 no obvious choice can be made. Both concepts don't contaminate the vacuum chamber and have a long service life, so these pros are not considered anymore. What counts heavily is the simplistic design of Concept 1, which is a result of the lack of a dynamic seal. In the problem description is explained that the planetary system needs to be designed, developed and produced within CTI. The production resources are limited within CTI, there is a lathe, milling machine, various 3D printers and various laser cutting machines. Also the extra (dynamic) seal of concept 2 introduce a possible source of leakage when not done correctly. In next chapter concept 2 will be further developed what eventually leads to a detailed design.

9 Detailed design

In this section the concepts chosen in section 8 are combined and further developed. Firstly, in subsection 9.1, an overview of the planetary system will be given. And secondly, in subsection 9.2, subsection 9.3 ans subsection 9.4 the components involved and some design related decisions will be explained and discussed in more detail. It is decided to begin this section with the completed planetary system to obtain a better understanding of the working principle and thus the involvement and arrangement of components in the system. Combining the chosen concepts resulted in the detailed design shown in figure 38.

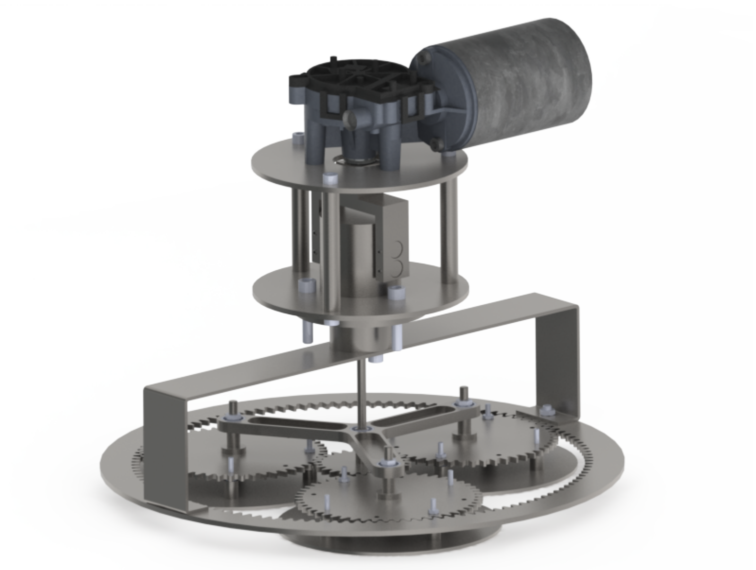

Figure 38: Detail design of planetary system

9.1 Overview planetary system

An exploded view of the completed planetary system is given in figure 39. The planetary system can be divided into three segments, namely, epicyclic gearing (concept), feedthrough (concept) and the interconnection between the epicyclic gearing and feedthrough. The following components are involved in the various segments (Figure 39 is used as reference with related table 5):

- Epicyclic gearing: 1, 2, 3, 5, 6, 16, 17 and 18
- Feedthrough: 4, 7, 8, 9, 10, 11, 12, 13, 14, 20, 21, 22, 23, 24, 25 and 26
- Interconnection: 15, 16 and 19

The chosen epicyclic gearing and feedthrough concepts, can clearly be retrieved from the planetary system model. However, the interconnection is not really discussed yet but will be discussed later.

A brief explanation of the working principle of the planetary system will be given. As can be seen the annulus spur gear (fig. no. 3) is held stationary by the fixture bracket (fig. no. 15) which is attached to the inner piece of the feedthrough (fig. no. 10). The outer piece of the feedthrough (fig. no. 14) geometrical constrain the inner piece of the feedthrough and is fixed on the mounting thread hole of the EV400 machine. The sun spur gear (fig. no. 1) is driven by the magnetic rotor (fig. no. 11) via the axis of sun (fig. no. 4). The magnetic force of the magnet in the fork (fig. no. 26) shaped structure on the atmosphere side rotates the magnetic rotor on the vacuum side. The fork is driven by the motor (fig. no. 21) By keeping the annulus spur gear fixed and driving the sun spur gear, the planet spur gears (fig. no. 18) rotate around their axis (fig. no. 5) and revolve around the axis of the sun spur gear along the inner circumference of the annular spur gear. Consequently, the carrier (fig. no. 7), which support the axis of planets, also rotate, but slower then the input (axis of sun). It is decided to attach sample holder plates (fig. no. 17) to the planet spur gears. The sample holder plates are detachable by using the thin nut (fig. no. 18).

In the bill of materials (Table 5) can be seen that the planetary system model consist of sub-assemblies and parts. It is decided to place sub-assemblies in the planetary system model to obtain a clearer overview. There are two type of parts in the planetary system, namely, parts that will be purchased and parts that will be manufactured within CTI. The sub-assemblies will be briefly described.

Fig. no.	**Part number**	**Part description**	**QTY**
1	ISO - Spur gear 2M 25T 20PA 3FW	Sun spur gear (25 teeth)	1
2	ISO - Spur gear 2M 50T 20PA 3FW	Planet spur gear (50 teeth)	3
3	ISO - Internal spur gear 2M 125T 20PA	Annulus spur gear (125 teeth)	1
4	axis_sun	Axis of the sun	1
5	axis_planet	Axis of the planet	3
6	ISO 10642 - M3 x 12 - 12C	Countersunk head screw M3 x 12	3
7	carrier_assem	Carrier assembly	1
8	B27.7M - 3AM1-5	Basic external retaining clip ref diameter 5	1
9	Hexagon Thin Nut M5 - C	Hexagon Thin Nut M5	6
10	feedthrough_inner_assem	Inner piece feedthrough assembly	1
11	rotor_magnetic	Rotor inside feedthrough	1
12	ISO 4762 M2 x 10 - 10C	Socket head cap screw M2 x 10	1
13	Hexagon Thin Nut ISO - 4035 - M2 - C	Hexagon Thin Nut M2	1
14	feedthrough_outer_assem	Outer piece feedthrough assembly	1
15	annulus_fixture_bracket	Fixture bracket of annulus spur gear	1
16	ISO 4762 M5 x 12 - 12C	Socket head cap screw M5 x 12	3
17	sample_holder_assem	Sample holder assembly	3
18	Hexagon Thin Nut ISO - 4035 - M3 - C	Hexagon thin nut M3	6
19	ISO 10642 - M5 x 10 - 10C	Countersunk head screw M5 x 10	2
20	ISO 4762 M6 x 30 - 30C	Socket head cap screw M6 x 30	3
21	magnetic_feedthrough_upper_assem	Magnetic feedthrough upper assembly	1
22	magnetic_feedthrough_lower_assem	Magnetic feedthrough lower assembly	1
23	ISO 4762 M5 x 16 - 16C	Socket head cap screw M5 x 16	6
24	ISO 4026 - M3 x 5 - C	Socket set screw flat point M3 x 5	4
25	fork_assem	Fork assembly	1

Table 5: Bill Of Materials of planetary system (Figure 39)

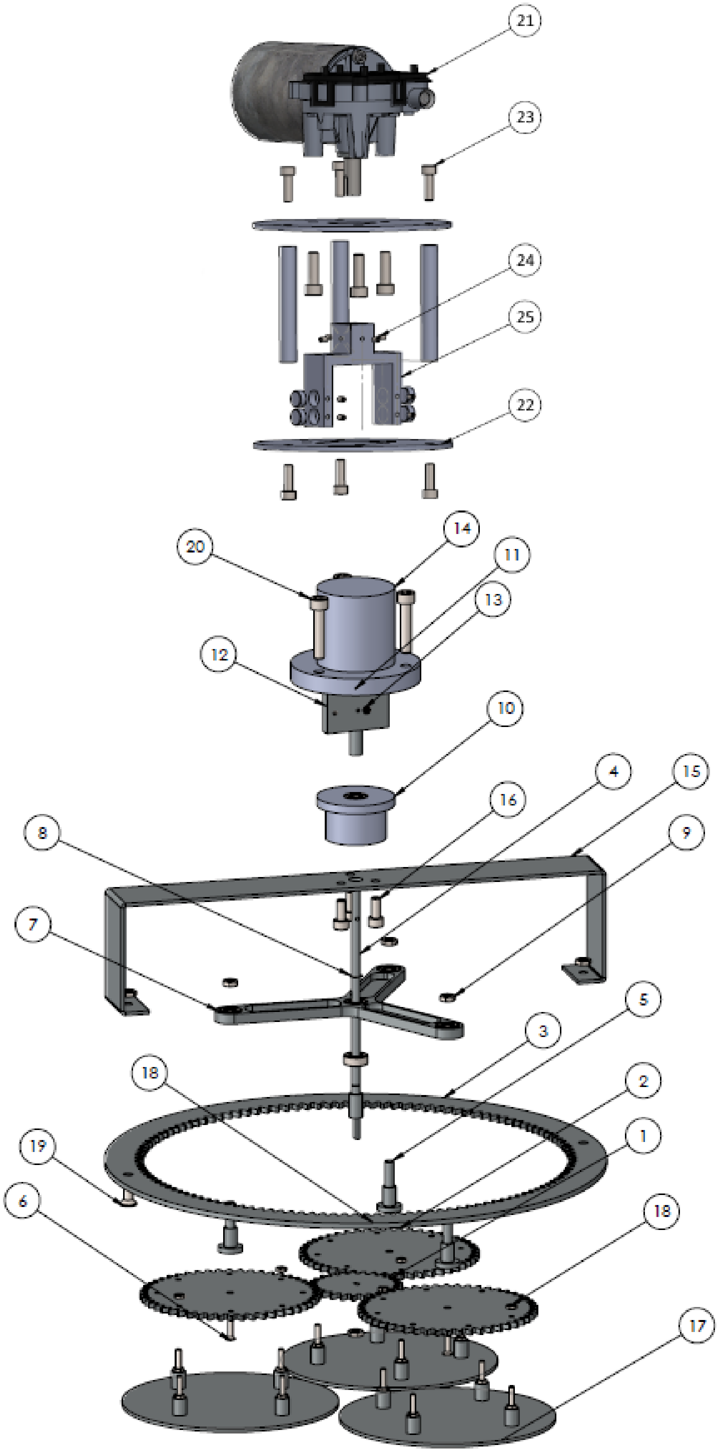

Figure 39: Components of the planetary system

An exploded view of the carrier and sample holder assembly are given in figure 40 and figure 41, respectively. The related bill of materials can be found in table 6 and table 7. In figure 41 can be seen that four bearings (fig. no. 2) are mounted in the carrier (fig. no. 1). The bearings will reduce the friction by making the moving surface, in this case the axis of the sun and planet spur gears, roll rather then slide. In figure 41 can be seen that four mounting stubs (fig. no. 2) are bolted on the sample holder plate (fig. no. 1). The mounting stubs function as spacers and fixing point on the planet spur gears.

Fig. no.	Part number	Part description	QTY
1	carrier_fram	Frame of carrier	1
2	ISO 15 RBB - 105 - 8,DE,AC,8_68	SKF 605ZZ bearing	4

Table 6: Bill Of Materials of carrier assembly (Figure 40)

Fig. no.	Part number	Part description	QTY
1	sample_holder_plate	Sample holder plate	1
2	sample_stub	Sample stub	4
3	ISO 10642 - M3 x 25 - 25C	Countersunk head screw M3 x 25	4
4	Hexagon Thin Nut ISO - 4035 - M3 - C	Hexagon thin nut M3	4

Table 7: Bill Of Materials of sample holder assembly (Figure 41)

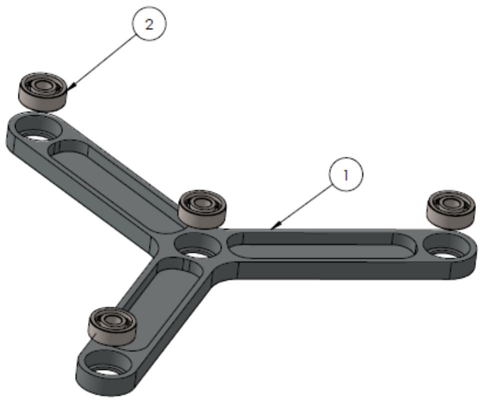

Figure 40: Components of carrier assembly

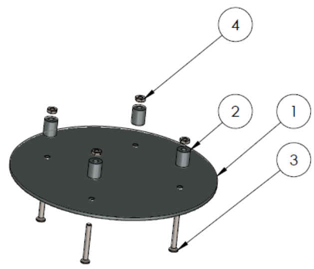

Figure 41: Components of sample holder assembly

An exploded view of the inner piece of feedthrough and outer piece of feedthrough assembly are given in figure figure 42 and figure 43, respectively. The related bill of materials can be found in table table 8 and table 9. It can be seen that in both piece of the feedthrough a bearing is added. This bearing arrangement support and locate the axis of the sun radially and axially. The (locating) bearing is fixed in the outer piece of the feedthrough and provides radial support and at the same time locates the shaft axially in both directions. The (non-locating) bearing in the inner piece of the feedthrough provides radial support but allows axial displacement in both directions.

Fig. no.	Part number	Part description	QTY
1	feed_through_inner_housing	Inner piece feedthrough housing	1
2	ISO 15 RBB - 105 - 8,DE,AC,8_68	SKF 605ZZ bearing	1

Table 8: Bill Of Materials of inner piece feedthrough assembly (Figure 42)

Fig. no.	Part number	Part description	QTY
1	feed_through_outer_housing	Outer piece feedthrough housing	1
2	ISO 15 RBB - 105 - 8,DE,AC,8_68	SKF 605ZZ bearing	1

Table 9: Bill Of Materials of inner piece feedthrough assembly (Figure 43)

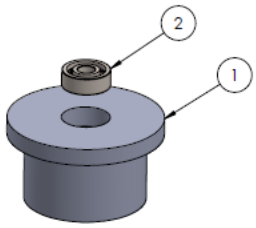

Figure 42: Components of inner piece of feedthrough assembly

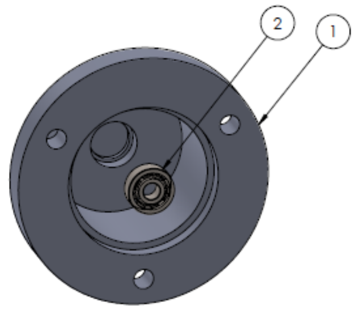

Figure 43: Components of outer piece of feedthrough assembly

An exploded view of the fork, magnetic feedthrough lower and magnetic feedthrough upper assembly are given in figure 44, figure 45 and figure 46, respectively. The related bill of materials can be found in table 10, table 11 and table 12. In figure 44 can be seen that the magnets (fig. no. 2) are attached in the fork (fig. no. 1) by using socket set screws (fig. no. 3). The lower magnetic decoupling assembly (Figure 45) and upper magnetic decoupling assembly (Figure 46 are used to set the fork at a certain height around the feedthrough.

Fig. no.	Part number	Part description	QTY
1	fork	Fork assembly	1
2	magnetic	Magnetic	4
3	ISO 4026 - M3 X 5 - C	Socket set screw flat point M3 x 5	4

Table 10: Bill Of Materials of fork assembly (Figure 44)

Fig. no.	Part number	Part description	QTY
1	sub_frame_base_plate_lower	Sub frame base plate lower	1
2	spacers_motor	Spacers motor	3
3	ISO 4762 M5 x 16 - 20C	Socket head cap screw M5 x 16	3

Table 11: Bill Of Materials of lower magnetic decoupling assembly (Figure 45)

Fig. no.	Part number	Part description	QTY
1	F006WM0310	Motor Bosch F006WM0310 DC 24V	1
2	sub_frame_base_plate_upper	Sub frame base plate upper	1
3	ISO 4762 M6 x 20 - 20C	Socket head cap screw M6 x 20	3

Table 12: Bill Of Materials of upper magnetic decoupling assembly (Figure 46)

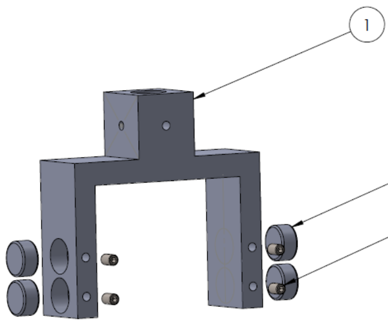

Figure 44: Components of fork assembly

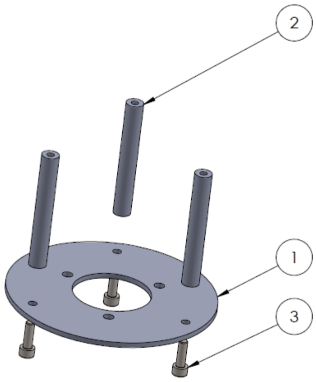

Figure 45: Components of lower magnetic decoupling assembly

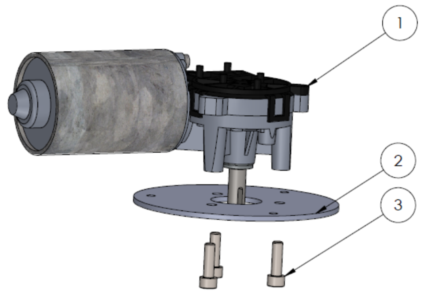

Figure 46: Components of upper magnetic decoupling assembly

9.2 Epicyclic gearing

In this subsection concept 1 of the epicyclic gearing, discussed in section 7 and chosen in section 8, will be further designed and developed. Firstly, the gear ratios and thus the number of teeth of the spur gears will be determined. As mentioned in the design guidelines (Table 4), the goal is to maximize the sample plate holder area. This implies that the area of the spur gears and thus the annulus spur gear should be maximized, which is geometrical constraint by the diameter of the vacuum chamber. The ISO Toolbox of SolidWorks is used to design the annulus spur gear with a outer diameter of 290mm and a pitch diameter of 250mm. In this case the play between the annulus spur gear and the vacuum chamber will be $1cm$ and the number of teeth will be 125. After some iteration in SolidWorks it is decided to design the planet gears with a pitch diameter of 100mm and number of teeth of 50. When using the planet spur gears as sample holder the diameter is not sufficient. As stated in section 5, the diameter of the sample holder plate should be at least 120mm. A solution will be sought later in this subsection. Equation 22 is used to calculate the number of teeth of the sun spur gear. Filling in leads to a pitch diameter of 50mm and the number of teeth of 25. In this configuration there is no gear tooth interference. With this information it is possible to calculate the angular velocity of carrier and planet spur gears. Filling in equation 4, with a rotational speed of the sun spur gear of 45RPM (maximum speed of motor), leads to an angular velocity of the carrier of 0.7854 rad per second or a rational speed of 7.5RPM. Filling in equation 25, with a rotational speed of the sun spur gear of 45RPM (maximum speed of motor), leads to an angular velocity of the planet spur gears of $-1.1781\frac{rad}{s}$ or a rotational speed of the planet spur gears of -11.25RPM. Figure

47 and figure 48 illustrate the detail design of the epicyclic gearing. And table 13 and table 14 summarize the specifications and rotational speeds of the epicyclic gearing, respectively.

Parameter	**Value**
Pitch diameter annulus spur gear	250
Number of teeth annulus spur gear	125
Pitch diameter planet spur gears	100
Number of teeth planet spur gears	50
Pitch diameter sun spur gear	50
Number of teeth sun spur gear	25

Table 13: Design specifications of epicyclic gearing

Parameter	**Value**
Rot. speed of annulus spur gear	0RPM
Rot. speed of planet spur gears	-11.25RPM
Rot. speed of sun spur gears	45RPM
Rot. speed of carrier	7.5RPM

Table 14: Rotational speeds of epicyclic gearing

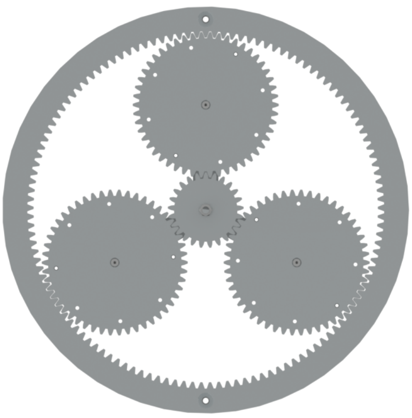

Figure 47: Detail design of epicyclic gearing

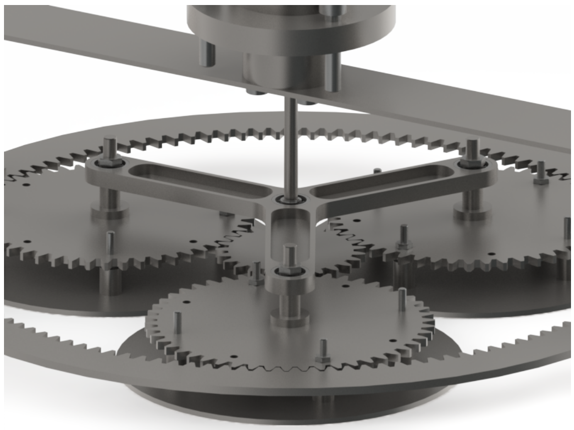

Figure 48: Close up of the carrier

To satisfy the requirements, a solution is sought to obtain a minimum size of 120mm for the sample holder plate. Also, the sample plate holder area should be maximized. It is decided to design a so-called sample holder assembly, consisting of four sample stubs and a sample holder plate. By mounting the sample holder plate assemblies on the planet spur gears the sample holder plate is raised and can overlap the annulus spur gear and sun spur gear. The result is a diameter of exactly 120mm. Figure 49 shows a bottom view of the planetary system where the sample plate holders clearly can be seen.

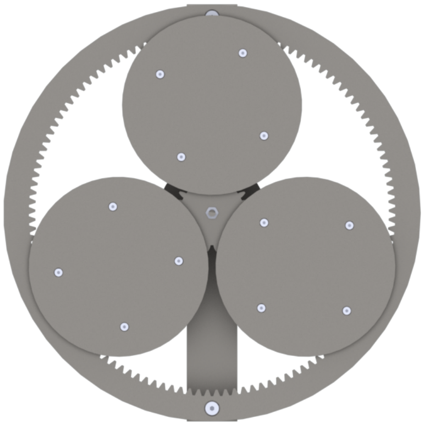

Figure 49: Bottom view planetary system

As mentioned before, it is decided to use bearings in the carrier. The bearings will reduce the friction in the system by making the moving surface, in this case the axis of the sun and planet spur gears, roll rather then slide. As mentioned in section 5, the SKF 605ZZ bearings are provided by CTI. To ensure long bearing life a proper shaft and housing fits need to be determined. The fit, or amount of interference that exists between mating components (such as the shaft and bearing bore), can be devised into three categories: loose (slip), transition, and press (tight). A loose fit allows for easy installation, but too loose of a fit may allow the bearing ring to slip or creep on the shaft or in the housing. A (slight) press fit will generally help prevent creep, but an excessive press fit will eliminate the bearing internal clearance and cause a rise in operating temperature that can lead to early failure. Firstly, the load case of the epicyclic gearing will be determined. And secondly, the type of fit of the various bearings will be determined. Figure 50 shows the free body diagram of the epicyclic gearing. Input torque is applied to the sun spur gear which results into tangential forces and radial forces. The tangential forces and radial forces causes bending stresses and compressive stresses on the spur gears, respectively. The planet spur gears meshes with the sun spur gear and annulus spur gear which produces two tangential forces. Therefore, twice the tangential force is required to hold a planet spur gear. In this configuration, the sun bearing encounter fluctuating loads. Applying torque to the sun spur gear involves a rotating inner ring and static outer ring. The load is in a constant direction in relation to the bearing, as the inner ring turns all parts of it are subjected to the load. The outer ring does not rotate, the load acts on only one point on the outer ring. This application requires an interference shaft fit and a clearance housing fit. As mentioned before, by keeping the annulus spur gear fixed and driving the sun spur gear, the planet spur gears revolve around the axis of the sun spur gear along the inner circumference of the annular spur gear. Therefore, the carrier rotates around its axis. Rotating the carrier around its axis involves a static inner ring and rotating outer ring. The load is in a constant direction in relation to the bearing, as the outer ring turns, all parts of it are subjected to the load. The inner ring does not rotate so the load acts on only one point of the inner ring. This application requires an clearance shaft fit and a interference housing fit. Due to the fluctuating load direction, the bearing of the sun require a interference fit for both shaft and housing. In this configuration, the planet bearings encounter fluctuating loads. Rotating the planet spur gears around their axis involves a rotating inner ring and static outer ring. The load is in a constant direction in relation to the bearing, as the inner ring turns all parts of it are subjected to the load. The outer ring does not rotate, the load acts on only one point of the outer ring. This application requires an interference shaft fit and a clearance housing fit. Revolving the planet spur gears around the axis of the sun spur gear involves a static inner ring and roting outer ring. The load is in a constant direction in relation to the bearing, as the outer ring turns, all parts of it are subjected to the load. The inner ring does not rotate so the load acts on only one point of the inner ring. This application requires an clearance shaft fit and a interference housing fit. Due to the fluctuating load direction, the bearings of the planets require a interference fits for both shaft and housing. Interference fits should not reduce the radial play of the bearing to an unacceptable level. The provided bearings by CTI have unknown specifications. Therefore, no tolerances are calculated.

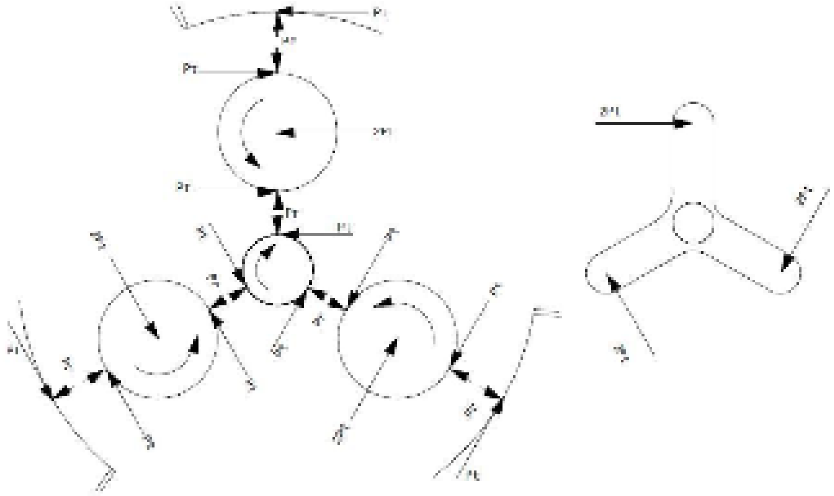

Figure 50: Load case epicyclic gearing

9.3 Feedthrough

In this subsection concept 1 of the feedthrough, discussed in section 7 and chosen in section 8, will be further designed and developed. The transfer of mechanical energy between the motor and the epicyclic gearing is based on the method of magnetic coupling. In this method the atmosphere side and the vacuum side are separated by a barrier wall or housing. The magnetic force of the magnet on the atmosphere side rotates the rotor, and thus the axis of the sun, on the vacuum side. A cross section of the feedthrough is made to illustrate the inner side of the feedthrough, see figure 51. It can be seen that four permanent magnetics, provided by CTI, are placed inside the fork. The permanent magnets create their own persistent magnetic field and pulls on other ferromagnetic materials, such as iron, and attracts or repels other magnetics. Therefore, the feedthrough outer housing and fork (number 14 and number 25 in figure 39, respectively) should be made out of non ferromagnetic material. On the other hand, the rotor (number 11 in figure 39) should be made out of ferromagnetic material.

As can be seen in figure 51, the inner piece of the feedthrough fits into the existing feedthrough hole of the EV400. The outer piece of the feedthrough geometrical constraint the inner piece of the feedthrough and is attached on the the mounting thread hole of the EV400. By tightening the bolts the outer piece of the feedthrough will be pressed against the inner piece of the feedthrough to ensure the inner piece of the feedthrough is properly secured. The bolts are also used to compress the O-ring between the two surfaces, which result in a seal at the interface.

The fork is mounted on the axis of the electric motor through four socket set screws and is adjustable in height.

As mentioned in section 7, the bearing arrangement of a shaft requires two bearings to support and locate it radially and axially. As mentioned in section 5, the SKF 605ZZ bearings are provided by CTI. The locating bearing, in the inner piece of feedthrough housing, provides radial support and at the same time locates the shaft axially in both directions. This application requires an interference shaft fit and a clearance housing fit. The bearing is hold in place by the rotor. The non-locating bearing, in the outer piece of the feedthrough housing, provides radial support but allows axial displacement in both directions. This application requires a interference shaft fit and an clearance housing fit. As can be seen in figure 51 the outer piece of the feedthrough and rotor allow axial displacement of the bearing.

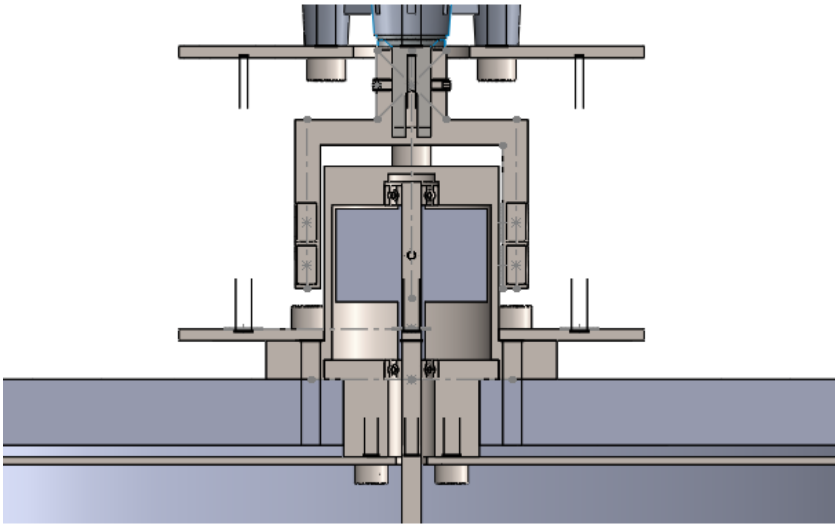

Figure 51: Cross section of the feedthrough

9.4 Interconnection

The parts responsible for the interconnecting between the epicyclic gearing and feedthrough consist of a fixture bracket and various socket head cap screws and hexagon thin nuts. The annulus spur gear is held stationary by connecting the annulus spur gear through the fixture bracket to the inner piece of the feedthrough. Figure 52 and figure 53 show two different side views of the planetary system to obtain a better understanding of the structure.

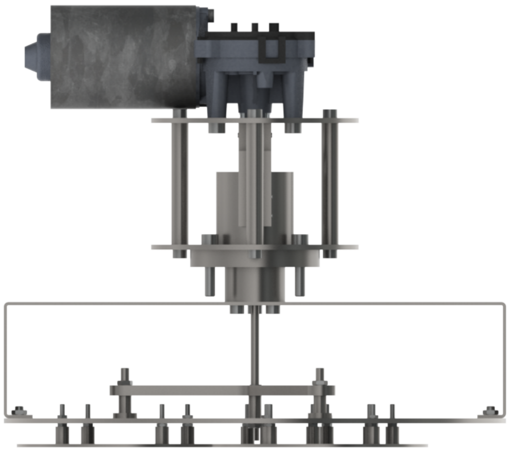

Figure 52: Side view of planetary system

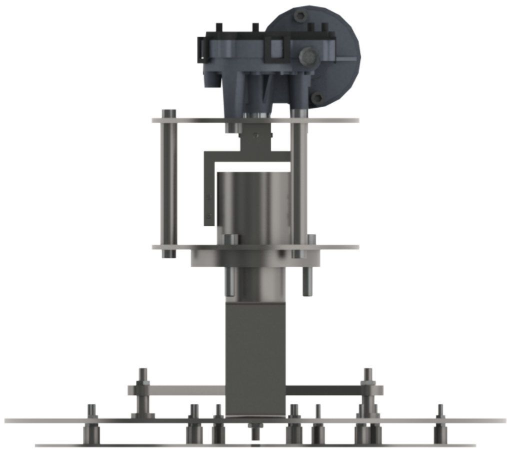

Figure 53: Side view of planetary system

10 Production

In this section the material and production method of the various parts which will be produced at CTI will be discussed. As mentioned in section 5, the production facilities within CTI are limited to lathes, milling machines and laser cutting machines. Also, due to the tight budget, material choice is mainly based on availability of material within CTI. Table 15 shows an overview of all the parts that will be produced at CTI with the material and production method choice. The table is established through interaction between DMI and the technicians of the workshop of CTI. Contamination inside the vacuum chamber should be minimized because it influence the vacuum and thus disastrous for film deposition. Therefore, due to the corrosion characteristics, Stainless Steel is the main choice of material for parts within the vacuum chamber. Stainless steels are stainless because a protective layer spontaneously forms on their surfaces and reduces the rate of corrosion to almost negligible levels. As can be seen in table 15 also aluminum and steel materials will be used. This is due to the lack of availability of Stainless Steel.

Part number	QTY	**Material**	**Production**
ISO - Spur gear 2M 25T 20PA 3FW	1	Stainless Steel plate 3mm	Laser cutting + Milling machine
ISO - Spur gear 2M 50T 20PA 3FW	3	Stainless Steel plate 3mm	Laser cutting + Milling machine
ISO - Internal spur gear 2M 125T 20PA	1	Stainless Steel Plate 3mm	Laser cutting + Milling machine
axis_sun	1	Stainless Steel round tube	Lathe
axis_planet	3	Stainless Steel round tube	Lathe
rotor_magnetic	1	Steel rectangular bar	Milling machine + Lathe
annulus_fixture_bracket	1	Stainless Steel plate 2mm	Laser cutting + Bending
carrier_fram	1	Aluminum plate 6mm	Laser cutting + Milling machine
sample_holder_plate	1	Stainless Steel plate 2mm	Laser cutting
sample_stub	4	Stainless Steel tube	Lathe
feed_through_inner_housing	1	Stainless Steel	Milling machine
feed_through_outer_housing	1	Stainless Steel	Milling machine
fork	1	Steel	Milling machine
sub_frame_base_plate_lower	1	Steel plate 3mm	Laser cutting
spacers_motor	3	Steel	Lathe
sub_frame_base_plate_upper	1	Steel plate 3mm	Laser cutting

Table 15: Overview of the parts that will be produced at CTI

11 Conclusion

The project described in this report was set out to resolve film thickness variation of film deposited workpiece samples in the EV400 evaporation deposition machine. Film thickness variation is analyzed by constructing multiple theoretical mathematical models to signify the problem in section 6. One of the main conclusions of this analysis is that by using a planetary system in the EV400 evaporation deposition machine film thickness variation reduces, in theory, by 80 percent. The detailed design, described in section 9, will satisfy all the requirements. Firstly, the overview of requirements (Table 2) will be discussed. And secondly, the overview of design guidelines (Table 4) will be discussed. The proposed detailed design consist of three sample holders with a diameter of 120mm. The desired motion of workpiece samples is created by using a simple epicyclic gearing system whereby the sample holder assemblies are mounted on the planet spur gears. By keeping the annulus spur gear fixed and driving the sun spur gear by using the Bosch F006WM0310, the workpiece samples rotate around their axis and revolve around the sun gear axis along the inner circumference of the annular spur gear. The design specifications of the epicyclic gearing (Table 13) resulted in the desired rotational speeds of the epicyclic gearing (Table 14). The planetary system is designed as a separate system and mounted on the existing feedthrough of the EV400 evaporation deposition machine. Throughout the project the interaction between DMI and the technicians of the workshop of CTI was crucial for the producibility of the planetary system. Interaction consist, among others, of giving advise on production methods and materials. Cost is minimized by using available parts and materials within CTI. It can be concluded that the planetary system is producible within CTI.

12 Recommendations

Recommendation can be made regarding the planetary system. Firstly, it can be recommended to calculate the proper tolerances of housing and shaft fits for the bearings in the carrier. As discussed in section 9, due to the fluctuating load direction interference fits are required. Interference fits should not reduce the radial play of the bearing to an unacceptable level. In other words, a high tolerance is needed. The provided bearings by CTI have unknown specifications, therefore, no tolerances were calculated. Secondly, it can be recommended to calculate the required magnetic force required for the magnetic coupling mechanism. If the force isn't sufficient the mechanism will not work and parts need to be changed. Thirdly, it is recommended to calculate the wear of the bearing of the lower piece of the feedthrough. The weight of the rotor, axis of the sun, carrier, sun spur gear, planet spur gears, three sample holder assemblies and various other parts are supported by the inner ring of the bearing. Due to the relative high weight wear can be an issue.

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