Spectroscopic Ellipsometry and Cryogenic Capability

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by

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Abstract

This project focused on ellipsometry, using it to find optical properties of sapphire, and designing a vacuum chamber to expand the temperature range in which we can perform ellipsometry. First, we obtained the anisotropic optical constants of an m-plane sapphire substrate using reflectance ellipsometry and transmission intensity measurements between 0.6 eV and 6.0 eV with a Woollam Inc. variable-angle spectroscopic ellipsometer. These anisotropic optical constants of m-plane sapphire could be used in the future to aid in modeling layered systems where the sapphire is used as a substrate for growing thin film samples of transition metal oxides.

Second, we designed and tested an ultra-high vacuum chamber to enable us to perform variable angle cryogenic ellipsometry measurements. The vacuum chamber was designed for reflection and transmission ellipsometry, as well as near-normal incidence reflection measurements at cryogenic temperatures down to 4K. This will give us new experimental capabilities allowing us to obtain data in temperature ranges that have rarely been probed with ellipsometry. We also designed and constructed a vertical translation stage, as well as a combination horizontal translation and tilt stage to allow us to align the sample for ellipsometry measurements.
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Introduction

Ellipsometry is a powerful optical spectroscopy technique that allows us to gather valuable information about the optical properties of a sample. It is an extremely accurate and reproducible technique that leads to very reliable data. Our lab is interested in studying phase transitions where the properties of a material, in particular the electronic, magnetic or structural properties change as a function of temperature. For example, a superconducting material undergoes a phase transition when it is cooled below its critical temperature and its resistance rapidly drops to zero. Understanding the mechanisms that drive phase transitions to happen will allow us to make progress towards controlling them for a number of practical applications. Ellipsometry allows us to study how these materials change as they undergo these phase transitions and potentially uncover the reasons why and how they happen.

Spectroscopic ellipsometry is useful because it allows us to perform ellipsometric measurements across a wide range of frequencies which increases our experimental access to many of the interesting frequency-dependent optical properties of materials. Similarly, a large temperature range is important because many materials have phase transitions significantly above or below room temperature. Developing a cryogenic system that will allow us to perform measurements far below room temperature gives us the ability to further expand the number of materials we are able to study.
M-Plane Sapphire

We are interested in sapphire (Al₂O₃) because it is commonly used as a substrate for growing transition metal oxide films. Its optical properties are anisotropic but remain nearly constant over the range of wavelengths we are interested in (0.6 to 6eV). Sapphire is uniaxially anisotropic, which means that the optical properties for light polarized parallel to a particular axis called the optic axis (in this case the c-axis) differ from those for light polarized perpendicular to the optic axis. Therefore sapphire has two different sets of optical constants that we need to obtain.

When we take data on a composite system that is comprised of a film and a substrate, for example a vanadium dioxide (VO₂) film grown on a sapphire substrate, we need to be able to distinguish the optical properties of VO₂ from those of sapphire. Provided we have the optical constants of sapphire, we can obtain the optical constants of VO₂ alone from the ellipsometry data of the composite system. Sapphire also comes in several different orientations, such as c-plane and m-plane. These refer to different orientations of the unit cell within the sample. The unit cell of sapphire is shown in Figure 1, with the m-plane highlighted and the c-plane is the hexagonal face perpendicular to the green axis. In addition, the a-plane is the plane perpendicular to any of the 3 a-axes that also runs through 2 corners of the hexagon. The plane that makes up the surface of the sample defines the orientation of a particular sapphire sample. In m-plane sapphire, the m-plane makes up the surface of the sample. Ellipsometry data on m-plane sapphire has not been taken before. However, data on
a-plane sapphire exists and this is what we compared with our data\(^1\). If we compare functional transition metal oxide films grown on m-plane sapphire with films grown on a-plane or c-plane sapphire, we see that the films are strained in different ways. There is interest in examining the effect this strain has on the optical properties of oxide films grown on different orientations of sapphire.

**Experimental Methods**

**X-Ray Diffraction**

Before the optical properties of sapphire could be found, we first had to determine the exact orientation of the optical axis of sapphire within our sample. To this end, we needed to perform single crystal x-ray diffraction, which would allow us to find the orientation of the crystallographic axes within the unit cell, specifically the c-axis, which we need for our ellipsometry experiment. X-Ray diffraction is a crystallographic technique that uses x-rays to determine the dimensions of a crystal’s unit cell, as well as the locations of the atoms within the cell. This works by shining an x-ray beam of known wavelength at the sample and rotating the sample, which gives us an interference pattern based on the orientation of the crystal. A crystal is defined as a solid whose atoms, molecules or ions are arranged into a pattern, the unit cell, which repeats periodically throughout the solid. This regular, periodic structure is the crystal lattice. The vectors that join these lattice points are called lattice vectors. The position of a lattice point with respect to the origin can be described by a linear combination of the three lattice vectors \((\mathbf{a}, \mathbf{b}, \mathbf{c})\) that span the lattice. The coefficients of the linear combination are reduced to their simplest form, after taking the reciprocal and are referred to as the Miller Indices. These Miller indices also tell us where the plane intersects each crystallographic axis. We take the reciprocal because if a plane is parallel to a particular axis, we would need to use infinity to describe the intersection, so instead we take the
reciprocal and use zero. For example the indices $[2\ 2\ 2]$ intersects half way along each axis that defines the unit cell, and would be written $[1\ 1\ 1]$. The $[2\ 2\ 2]$ plane and the $[1\ 1\ 1]$ plane are equivalent from a crystallographic perspective because they are parallel and described by the same axes. A bar over the index number indicates a negative index. The Miller Indices also refer to any lattice point that lies along an axis parallel to the line between the origin and the given point. Therefore the lattice point $[4\ 4\ 4]$ and $[9\ 9\ 9]$ are both represented by the indices $[1\ 1\ 1]$. For a hexagonal geometry, the system is a little different. There are 4 indices, three in the hexagonal plane, the three a-axes, and the c-axis, which is perpendicular to the plane that contains the a-axes (see Figure 1). These indices define a particular axis within the crystal structure, and we can determine its orientation with x-ray diffraction. Each axis also names the lattice plane it is perpendicular to. Our sample is m-plane which is given by the indices $[1\ 0\ 0\ 1]^2$. Depending on how the a-axes are defined any of the 6 faces of the hexagonal unit cell can be m-plane. Our objective is to find the c-plane, which is perpendicular to the c-axis which comes out of the page in Figure 2 and is given by the indices $[0\ 0\ 0\ 1]$. The a-plane from the literature is given by either $[1\ 0\ 0\ 0]$, $[0\ 1\ 0\ 0]$, or $[0\ 0\ 1\ 0]$, which are equivalent due to the $\pi/6$ rotational symmetry of the hexagonal unit cell.

If the lattice vectors are the same regardless of the lattice point they start from, the lattice is a Bravais lattice. The Bravais lattice describes the geometry of the crystal, so if we can use x-rays to determine the location of the Bravais lattice points we can find the orientation of the unit cell within our crystal. Shown in Figure 2 is

![Figure 2: 2D Hexagonal Bravais lattice with example hexagonal structure. The dashed lines represent the lattice vectors, and each circle represents a lattice point.](image)
an example of a two dimensional hexagonal Bravais lattice. For demonstrative purposes I have drawn in the hexagonal unit cell, and examples of the two lattice vectors. However, these lattice vectors can be drawn from any lattice point in the crystal. In 3 dimensions, the third lattice vector would be pointing out of the page in the direction of the extrusion of the hexagonal prism. It is often useful to define the reciprocal lattice. The wave vectors that describe plane waves that have the same periodicity as the Bravais lattice for that crystal define the reciprocal lattice of a crystal. In other words, a reciprocal lattice vector drawn to any reciprocal lattice point with indices \([h j k l]\) is perpendicular to the plane in the real space lattice that is described by those same indices. Every Bravais lattice has a corresponding reciprocal lattice that determines the interference pattern we get when doing x-ray diffraction. Reflected x-rays will only constructively interfere when the vector that describes the difference between the incoming and reflected wave vectors is a reciprocal lattice vector\(^2\). So once we find an interference peak, we know the orientation of a reciprocal lattice vector and therefore a real space lattice plane\(^3\). Finding the \([0 0 0 1]\) reciprocal lattice vector will give us the orientation of the c-plane in real space.

**Reflection Ellipsometry**

Ellipsometry is a broadband optical experiment that measures the change in polarization state of a beam of light after it is reflected off of (or transmitted through) a sample. The polarization state is defined by the orientation of the electric field of the light wave with respect to the plane of incidence. The plane of incidence is defined by the incident light wave and the normal to the sample surface. If a beam of light is polarized parallel to the plane of incidence, it is p-polarized. S-polarized light is polarized perpendicular to the plane of incidence. A beam of light comprised of p- and s-polarized light with equal amplitudes and in phase results in light linearly at 45° to the plane of incidence. If the amplitudes or
phases of the light are not the same, the light is elliptically polarized. The ellipsometer first emits a beam of light of known polarization, and detects the polarization state of the beam after reflection off the sample. If the incident beam is linearly polarized in general, the reflected beam is elliptically polarized. The parameters that are measured are Ψ and Δ, the ellipsometric coefficients (Figure 3). When the light hits the detector, it is measured as an intensity function that oscillates in time and can be expressed as:

$$I(t) = I_0[1 + \alpha \cos(2A(t)) + \beta \sin(2A(t))]$$  \hspace{1cm} (1)

$I_0$ is a DC offset, while $A(t)$ gives the angle of the rotating polarizer on the detector side. The Fourier coefficients $\alpha$ and $\beta$ characterize the intensity function and we can calculate $\psi$ and $\Delta$ directly from them with the following equations\(^5\):

$$\alpha = -\cos(2\psi)$$  \hspace{1cm} (2)

$$\beta = \sin(2\psi) \cos(\Delta)$$  \hspace{1cm} (3)
\( \Delta \) is the phase shift between the p- and s-polarized component of the incident beam and the p- and s-component of the reflected (or transmitted) beam\(^4\).

\( \Psi \) measures the inclination of the ellipse traced out by the polarization state of the reflected beam. These coefficients give the ratio of the Fresnel coefficients for the p-polarized light \( (R_p) \) to s-polarized light \( (R_s) \):

\[
\tan(\psi) e^{i\Delta} = \frac{\tilde{R}_p}{\tilde{R}_s}
\]

The Fresnel coefficients depend upon the optical constants of the sample.

\[
\tilde{R}_p = \frac{\tilde{n}_2 \cos(\phi_0) - \tilde{n}_1 \cos(\phi_0)}{\tilde{n}_2 \cos(\phi_0) + \tilde{n}_1 \cos(\phi_0)}
\]

\[
\tilde{R}_s = \frac{\tilde{n}_1 \cos(\phi_0) - \tilde{n}_2 \cos(\phi_0)}{\tilde{n}_1 \cos(\phi_0) + \tilde{n}_2 \cos(\phi_0)}
\]

Note here that the optical constants are given by the complex number \( \tilde{n} \) defined as \( \tilde{n} = n + ik \). The properties of the background medium are given by \( \tilde{n}_1 \), while the properties of the sample are given by \( \tilde{n}_2 \). The other parameter \( \phi_0 \) is the angle of incidence of the measurement\(^5\). The index of refraction \( n \) describes the angle at which light bends when it hits the sample at an angle, while the extinction coefficient \( k \) describes the amount of light that is absorbed by the material. We can use this technique to calculate the optical constants of the sample over a broad range of wavelengths. Ellipsometry is a powerful technique because it gives extremely accurate and reproducible data. In the case of our ellipsometer, we measure from 0.6 to 6.5 eV, which is from the long wavelengths in the infrared all the way up to the ultraviolet range.

Because we determined the orientation of the optical axis of our sample from x-ray diffraction, we were able to use standard ellipsometry as opposed to generalized
ellipsometry. Data analysis for standard ellipsometry is much less complicated than it is for generalized ellipsometry because the Jones matrix has no off diagonal elements. The Jones matrix is a two dimensional matrix that characterizes the reflective behavior of a sample. An incident beam of light is characterized by a two dimensional Jones vector, where one value is the incident p-polarized light, and the second is the incident s-polarized light. A Jones matrix will transform this Jones vector into another vector that describes the p- and s-polarized components of the reflected beam. A standard Jones Matrix equation is shown below.

\[
\begin{bmatrix}
E_{p, out} \\
E_{s, out}
\end{bmatrix} =
\begin{bmatrix}
R_{pp} & R_{ps} \\
R_{sp} & R_{ss}
\end{bmatrix}
\begin{bmatrix}
E_{p, in} \\
E_{s, in}
\end{bmatrix}
\] (7)

\(R_{pp}\) and \(R_{ss}\) are the Fresnel coefficients that describe how much of the incident p- or s-polarized light is reflected as p-polarized or s-polarized light respectively. \(R_{ps}\) defines how much p-polarized light is transformed to s-polarized light by reflection, and \(R_{sp}\) defines the amount transformed from s- to p-polarized light. In standard ellipsometry, the Jones matrix is as follows:

\[
J = \begin{bmatrix}
R_p & 0 \\
0 & R_s
\end{bmatrix}
\] (8)

When the optic axis is aligned either parallel or perpendicular to the plane of incidence, the off-diagonal elements \(R_{ps}\) and \(R_{sp}\) are zero, and we can refer to \(R_{pp}\) and \(R_{ss}\) as \(R_p\) and \(R_s\) respectively because all the p-polarized light is reflected as p-polarized light and the same is true for the s-polarized light\(^5\). This means that we can obtain the Jones Matrix of a material from one set of \(\Psi\) and \(\Delta\). Because sapphire is anisotropic, we need to take two sets of data, one with the optic axis parallel to the plane of incidence, and the other with the optic axis perpendicular to the plane of incidence. There will be two different Jones Matrices, one each for the optic axis parallel and perpendicular to the plane of incidence both with zero off-
diagonal elements. However, if the orientation of the optic axis is unknown or not in either of
the alignments mentioned above, we must use generalized ellipsometry where there is cross-
conversion between p- and s-polarized light. Generalized ellipsometry involves taking three
sets of $\Psi$ and $\Delta$ to determine all the elements of the Jones matrix needed to completely
describe the sample. In addition to the regular $\Psi$ and $\Delta$ values noted above, we also need the
cross conversion elements:

$$\tan(\psi_{ps}) e^{i\Delta_{ps}} = \frac{R_{ps}}{R_{pp}} $$ \tag{9}

$$\tan(\psi_{sp}) e^{i\Delta_{sp}} = \frac{R_{sp}}{R_{ss}} $$ \tag{10}

To find these terms, we need three complete sets of $\Psi$ and $\Delta$ for each angle of incidence$^5$.

The additional data is needed so that the orientation of the optical axis can be found, however
it also introduces greater error because more fitting parameters need to be taken account to
define the location of the optic axis. Therefore, locating the optic axis with x-ray diffraction
and orienting it so that we can do standard ellipsometry gives us an advantage in the data
analysis process, making our data acquisition easier, and the data analysis more accurate$^6$.

**Transmission Intensity**

We also did a transmission intensity measurement with our ellipsometer. This is a
measurement that sends a beam of light through the sample and measures the intensity of the
light that is transmitted. This is then normalized to a baseline intensity measurement to give a
percentage of light transmitted for each wavelength. This is important because our sapphire
sample was only 0.42mm thick and transparent, the absorption is nearly zero, which means
we could not calculate an accurate value of $k$ with just a reflection ellipsometry
measurement. We needed to roughen the backside of the sample for reflectance ellipsometry
measurements to avoid back side reflections in the data, and therefore we used another piece with both sides smooth from the same crystal wafer for our transmission measurements.

**Experimental Data and Results**

**X-Ray Diffraction**

We used the rotating crystal method of single crystal x-ray diffraction to determine the orientation of our optic axis. This is a single wavelength, fixed beam method where the sample crystal is rotated, perpendicular to the surface of the sample in our case. We first marked our sapphire sample with stripes as shown to ensure that we knew exactly how the sample was orientated when the optic axis was identified. We filmed the sample on edge as it rotated to record the interference peaks that occurred at different angles. Each interference pattern represents a reflection from a particular lattice plane or combination of lattice planes. After a full rotation, the x-ray diffractometer software interpreted the interference peaks and revealed the orientation of the c-plane. Because the c-axis is perpendicular to the c-plane, we could then identify the direction of the c-axis in Figure 4.

**Reflection Ellipsometry**

![Figure 4: Sapphire sample used in X-Ray diffraction measurement.](image)

![Figure 5: Ψ data (degrees) for the optical axis parallel to plane of incidence (left) and perpendicular to plane of incidence (right).](image)
We did reflection ellipsometry with angles of incidence of 55°, 65°, and 75° shown in Figure 5. We chose these angles because they were far enough away from the Brewster angle (almost exactly 60° for sapphire). The Brewster angle is a unique angle of incidence that polarizes any incident light by reflecting only s-polarized light. This would render our data meaningless because we would get no intensity for the p-polarized component. We took three different angles because each new data set gives us a new set of constraints to make sure that our modeling is accurate. Once we were sure that we had avoided the Brewster angle, we needed to investigate how to determine the anisotropy of the sample. Because the optical constants are different along the a- and c- axes of the unit cell, we decided to take two sets of data at each angle. One set would be with the c-axis of the unit cell parallel to the plane of incidence, and the other with the c-axis perpendicular to the plane of incidence. This would give us the anisotropic optical constants. This anisotropy is seen in Figure 6 by the difference between the extraordinary ray optical constants and the ordinary ray optical constants. The extraordinary ray optical constants are for a beam of light polarized parallel to the optical axis, while the ordinary ray optical constants are for light polarized perpendicular to the optical axis. Fitting primarily the $\Psi$ values in these two data sets with anisotropic substrate model in WVASE software from Woollam Inc. gave us the values of $n$. The difference between these two curves shows the anisotropy of the sample that agrees with the work done by Yao and Yan. There is a difference

![Figure 6: Measured values of $n$ for the ordinary and extraordinary ray.](image)
between the ordinary and extraordinary ray optical constants of about .008 throughout the entire spectral range.

Figure 7: Normalized transmission intensity data for optical axis polarized parallel (left) and perpendicular (right) to plane of incidence.

**Transmission Intensity**

Reflectance ellipsometry data gives a value of $\Delta$ that is close to zero, which for a transparent sample implies a vanishingly small extinction coefficient. The extinction coefficient describes the loss of intensity of an incident light ray transmitted through the sample. To obtain the small but finite value of $k$, the extinction coefficient, we performed transmission intensity measurements. The absolute transmitted intensity is given by dividing the intensity transmitted through the sample by an intensity without the sample in the beam path. The absolute transmission data is modeled to extract the extinction coefficient. We took transmission data with the angle of polarization parallel (extraordinary ray) and perpendicular (ordinary ray) to the optical axis or c-axis to match with our data and model for reflectance ellipsometry. The transmission data itself (Figure 7) is featureless for sapphire, remaining nearly constant across the entire spectral range at about 85%. This is good for a substrate because we know that any optical features we see in these wavelength ranges will be due to the film or crystal grown on the sapphire rather than the sapphire itself. This makes
modeling the substrate-film composite system much more straightforward. A more complicated sample would have a more complex transmission curve, with significant peaks or troughs in the curve in this spectral range. Also, the fact that sapphire is highly transmissive throughout the spectral range means that we can do transmission measurements on samples grown on sapphire. When we calculate values for $k$, as shown in Figure 8, $k$ is nearly zero for almost the entire range, which is expected because the sample is transparent in the visible and only 0.42 mm thick, so not much light is absorbed. Only at the higher frequencies (or photon energies) do we start to see the extinction coefficient start to rise as the sample becomes more absorbing.

Data Analysis

Once we obtained ellipsometry and transmission data for a wavelength range of 0.6 eV to 6.5 eV, the next step was to model the data to give us a curve that defines the value of $n$ as a function of wavelength. We created a model with two general oscillators, which we set as Cauchy functions. We use one oscillator for the extraordinary ray, and one for the ordinary ray optical constants. The Cauchy function we used for fitting is given by the following:

$$n(\lambda) = A_n + \left(\frac{B_n}{\lambda^2}\right) + \left(\frac{C_n}{\lambda^4}\right)$$  \hspace{1cm} (11)

where $A_n$, $B_n$, and $C_n$ are fitting parameters that were adjusted for our data, and $\lambda$ is the wavelength of the beam. This Cauchy model is a commonly used dispersion relation for
transparent metal oxides. It is frequently used to reduce the number of variables needed to describe a material. However, sapphire is only transparent in the visible. As we approach the UV region, it becomes much more absorbent and the transmission drops. To model this, we use an Urbach absorption function to model the absorption behavior at short wavelengths. The Urbach function is an exponential given by:

\[ k(\lambda) = A_k e^{B_k(1.24\left(\frac{1}{\lambda} - \frac{1}{C_k}\right))} \] (12)

where \( k \) is the extinction coefficient, \( A_k \) is the amplitude of the absorption band, \( B_k \) is the broadening, and \( C_k \) is the edge of the absorption band. The Cauchy and Urbach dispersion functions combined give the nearly flat transmission across the visible range, and increased absorption in the UV range.

**Cryogenic Vacuum Chamber Design**

After completing the ellipsometry work on sapphire, I moved on to the vacuum chamber design (Figure 9). The purpose of this chamber is to allow us to do ellipsometry at temperatures down to 4K. The vacuum chamber is necessary because at cryogenic temperatures the air around the sample would freeze if it was kept in air, forming layers of ice on the sample. Because ellipsometry uses light with short wavelengths (200-2000nm), it is very sensitive to even thin layers of ice. Therefore we need to keep the sample in ultra-high vacuum to prevent any ice forming on the sample. This will allow us to perform ellipsometry on samples that have phase transitions significantly below room temperature in order to gain insight into why these phase transitions happen. For example, we are interested in various superconductors, as well as a few doped samples of vanadium and manganese oxides that undergo phase transitions at cryogenic temperatures. The vacuum chamber itself was designed for maximum experimental flexibility. In our case, this meant being able to operate
in transmission, do reflection ellipsometry at many angles of incidence, and do near normal reflectance. In addition, to perform ellipsometry on very small samples, we needed to be able to accommodate a focusing apparatus with an angular spread of +/- 15 degrees. In order to accomplish these goals, we decided to use a custom made UV quartz tube that is fused to a stainless steel conflat flange. This allows us to use almost any angle of incidence without needing to worry about the location of optical ports. However, the glass needed to be specifically chosen so that it has high transmission across the spectral range of the ellipsometer. Most types of glass transmit light in the visible wavelengths, but the transmission drops dramatically in the ultraviolet spectrum. We needed a glass that is highly transmissive throughout the UV and visible spectral regions because we need as much light
as possible to reach our detector. We selected GE 214 quartz, which is ideal for our purposes because it is specifically engineered to have high UV and visible transmission. We performed transmission intensity and ellipsometry measurements on the quartz to confirm that it was spectrally flat and that the index of refraction and the extinction coefficient of the quartz did not vary wildly over small distances. During the fusing process, strains will be induced in the structure of the quartz that will slightly affect the index of refraction and extinction coefficient, and may not be uniform over the surface of the tube. Especially if this induced strain is anisotropic, this will make it much more difficult to perform ellipsometry, because we will see this anisotropy in the data for any sample that we test. Also, the anisotropy created by the strain in the quartz produces a retardation effect. This means that there is a phase difference imparted to the beam by the fact that the p- and s- polarized components of the incident beam will be transmitted at different speeds through the quartz, and there will be contributions to Δ data due to the tube. Accounting for the retardation effects from the tube is critical because the walls of the tube are significantly thicker than the wavelength of the incident beam, so even a small anisotropy can create a significant retardation. If the strain in the tube varied over a distance as small as our beam diameter, it would introduce anisotropies in the quartz that we would be unable to account for when we calibrate our system for window effects. Therefore, when we perform a measurement, we will need to calibrate the system with a reference material with known optical properties then measure the sample at the same position and orientation as the reference. In our case, this test sample is silicon dioxide (SiO₂). The calibration is critical to ensure that we are getting the correct data for the sample from our experiment. This procedure will be performed by assembling the entire vacuum chamber and placing a SiO₂ reference wafer inside the chamber and running a script.
provided by Woollam Inc. that will compare that data to the known properties of the reference and thereby provide a measure of the retardance due to the quartz tube.

This quartz tube will be attached to a custom 4-way conflat adapter that will attach to the quartz tube on the bottom, the vertical translation stage, the turbo pump on one side, and the vacuum gauge on the other side. The flange that attaches to the turbo pump will be welded to a support stand that the entire system will rest on (see Figure 9). This support stand will bolt into the top plate of the combination tilt translation stage.

Because of the geometry of our ellipsometer, and the weight limit on the installed automatic rotation stage, we needed to design our own custom translation stages in order to align our sample. One main concern was the presence of the turbomolecular vacuum pump, which would be attached to the side of the chamber with a conflat flange and therefore place an off-axis load on the stages. We therefore needed to ensure that whatever stages we used are capable of carrying this weight. Fortunately, there was a commercially available rotation stage from Newport that we were able to order. Another serious concern is that the low beam height limited the thickness of the alignment stages that could be placed below the chamber. We solved this geometric constraint by designing a vertical translation stage that would be operated above the chamber and move just the cryostat instead of the
entire chamber. The vertical translation, as well as the horizontal translation and tilt needed to be custom made. Our vertical translation stage (Figure 10) consists of a custom Ultra-high-vacuum bellows with conflat flanges on either end attached to plates on the top and bottom. The bellows is extended or contracted by turning a drive screw that allows the top plate to move up and down on a dovetail railing that is attached to the bottom plate. Once the sample is in position, a locking screw is turned that fixes the translator in place.

We also needed to design a horizontal translation stage and a tilt stage because none of the commercially available stages that could support the weight of the chamber would fit underneath the chamber due to the low beam height. We decided to combine the two into a single combination stage with a stainless steel load bearing plate resting on steel bearings rather than aluminum, which was used in the commercial stages (Figure 11). These stages have been fabricated by the machine shop (Figure 12). The linear translation stage is used to make sure that the sample is in the beam path. It is composed of a top plate that moves as a drive screw is adjusted, and a bottom plate that is fixed to the rotation stage below. The two stages are connected by bearings that are attached to each plate, which allow the top plate to slide with respect to the...
fixed bottom plate. The linear stage is kept in place with a combination of a $\frac{1}{4}"$-80 lead screw and a spring that provides a restoring force for moving the stage back. This stage is designed to give us +/- 0.5 inches of motion, and is supported on crossed roller bearings, which use cylindrical bearings instead of spherical ones to give more stability. The reason we used this bearing is because of the torque created by the turbo pump. Traditional ball bearings would be much less stable under this off-centered load. The tilt stage is made up of a single plate that rests on 2 ball bearings and a $\frac{1}{4}"$-80 screw that provides the motion. It is held to the top plate of the linear translator by 4 extension springs kept under tension.

**Conclusion**

For this project, we have taken room temperature reflectance ellipsometry and transmission intensity measurements on m-plane sapphire and successfully obtained the anisotropic optical constants. These will help to model compound systems in future experiments, for example, thin films grown on a sapphire substrate.

In addition, we have designed and manufactured a vacuum chamber for cryogenic ellipsometry as well as a system of translation stages to align the sample. The vacuum chamber itself, a vertical translation stage, a tilt and horizontal translation stage, as well as the stand to support the entire assembly were all custom designed and made for this specific set up. All of the translation stages and the vacuum chamber have been successfully built and tested. The vacuum chamber was tested down to a pressure of $1.2 \times 10^{-7}$ mbar. This could be improved by baking the vacuum chamber. The next step is to run the calibration procedure on the SiO$_2$ sample and then test the low temperature capabilities.
References:


