Low-Cost Ellipsometer

3EF - The Tune Squad
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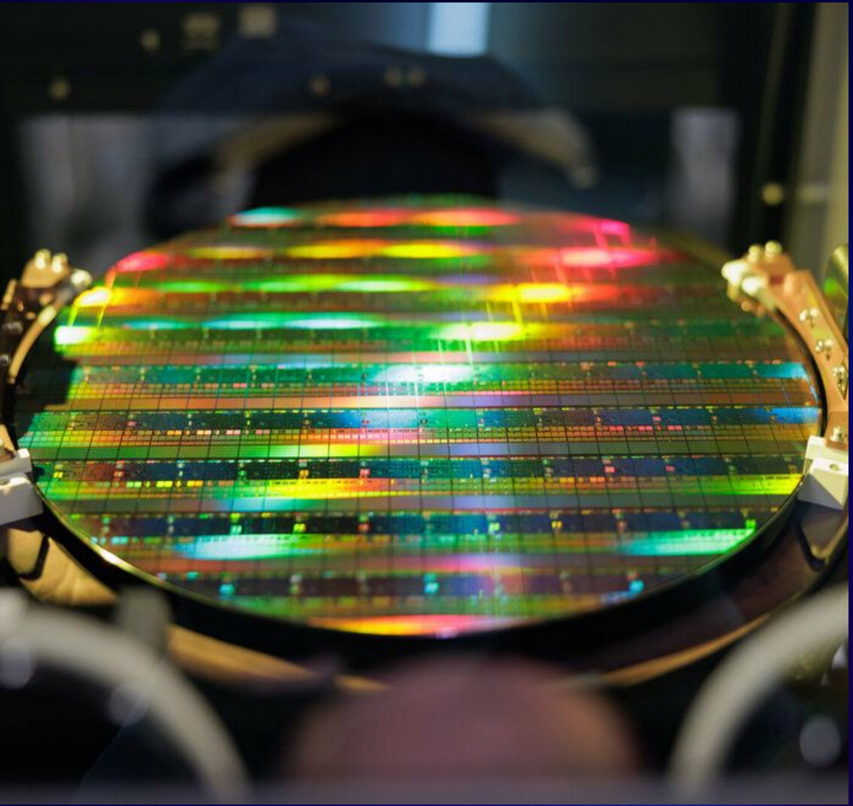
Presenting April 30th at 11:15 a.m.



Silicon Wafer, image from “Martin van den brink’s secret is collaboration” by van Overveld, 2024.

01 – Introduction

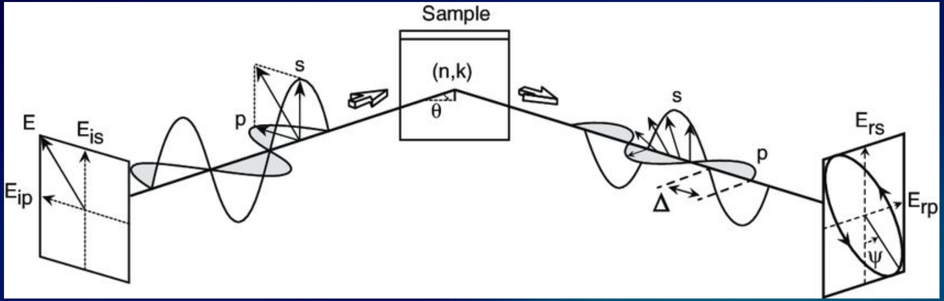
Background - Ellipsometry

- Used to study thin films
- Can measure thickness, complex refractive index, other characteristics
- Often used in semiconductors, solar panels, materials science

Professional Ellipsometer, image from “M-2000 Ellipsometer” by J.A. Woolam, 2024.

Ellipsometry - Theory

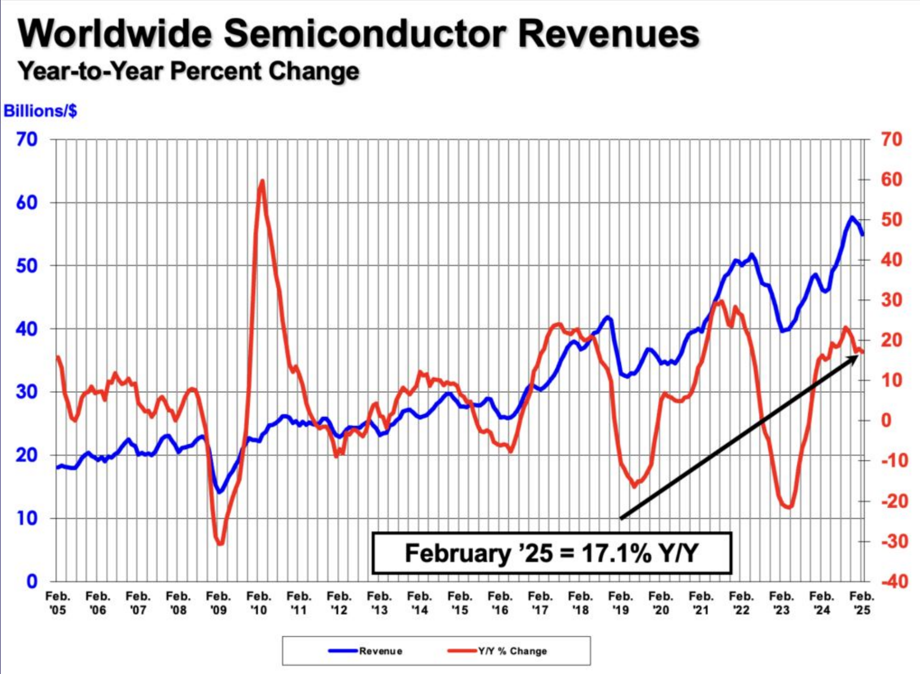
- Analyze electric fields that oscillate parallel (p) and perpendicular (s) to plane of incidence
- Incident light is linearly polarized



https://www.researchgate.net/figure/Measurement-principle-of-spectroscopic-ellipsometry-59_fig14_331023989

- After reflecting off the film, the light is elliptically polarized
- Delta is the phase difference between the p and s electric fields
- The angle Psi tells us the ratio of the amplitudes of the p and s components

Necessity



Semiconductor's growth in terms of capital since 2005 by *Semiconductor Industry Association* (2025).

Cost Prohibitive

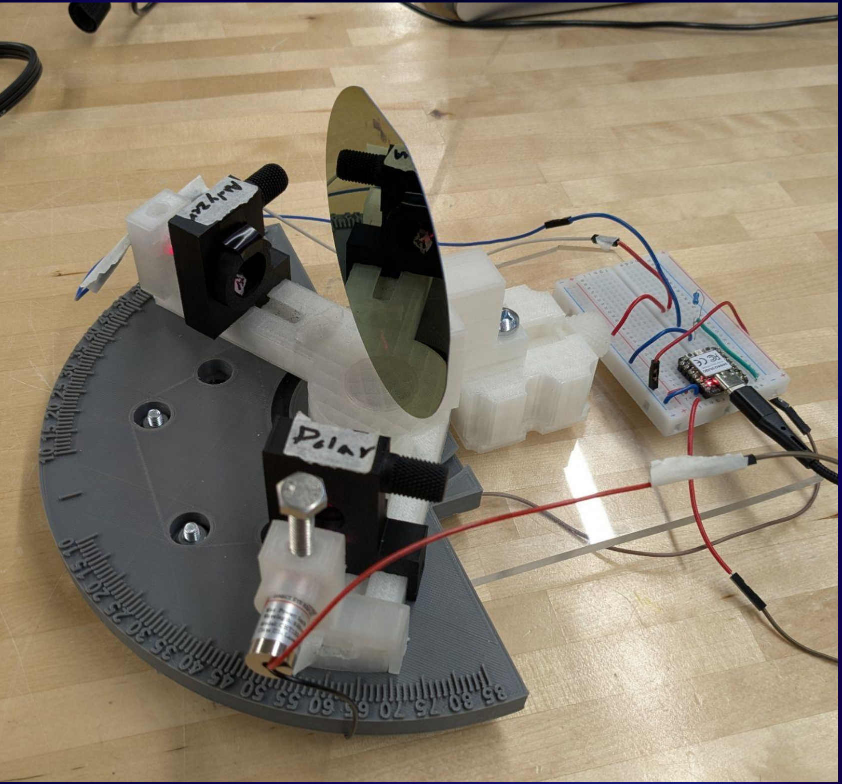
- Professional ellipsometry can cost from $2,000 to $50,000

Departmental Need

- Many students are interested in the semiconductor industry.
  - Industry has doubled since 2016
- Opens doors to research and familiarizes students with the semiconductor industry.

Project Targets

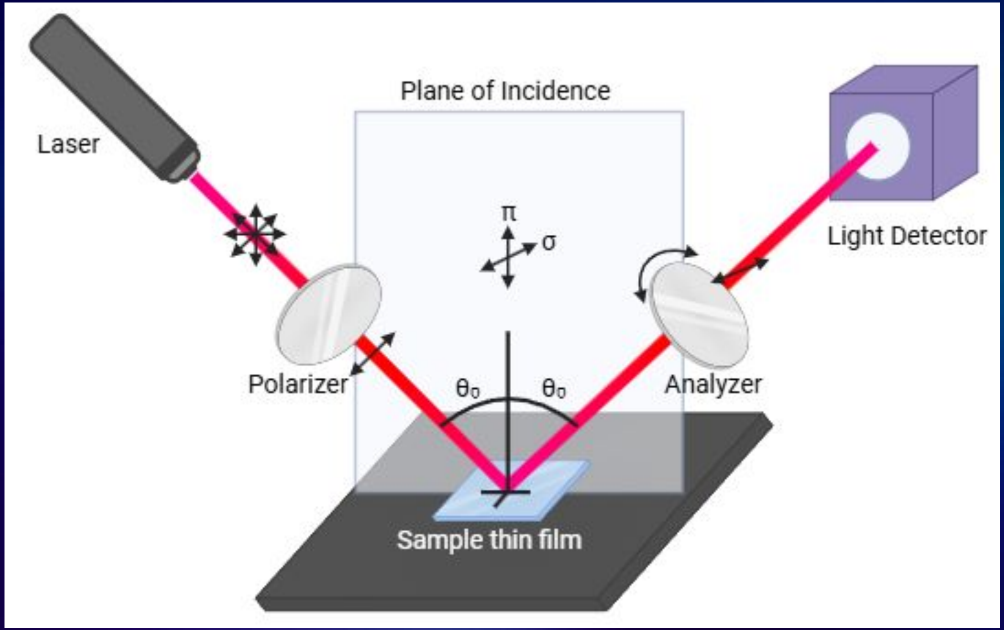
- Cost under $50, 1/40th the cost of commercial
- Calculate film thickness within 10% error
  - Within 30 nm for the 300 nm wafer
- Be robust enough to handle repeated tests without losing accuracy



02 – Apparatus & Procedure

Overall Design

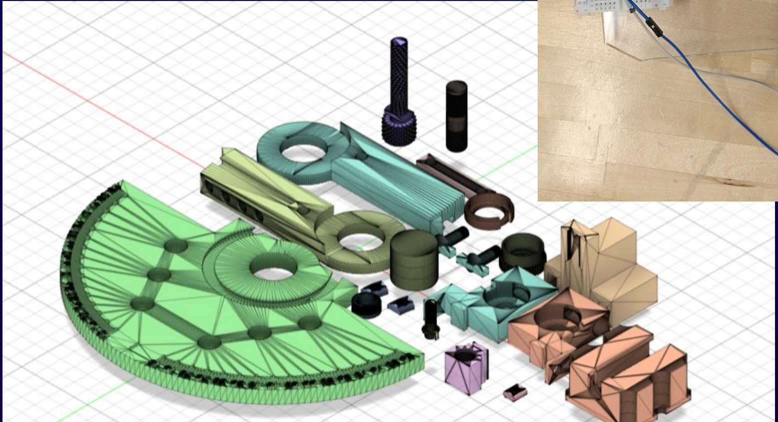
- Simple rotating analyzer ellipsometer
- Design based on the supplemental materials in a 2022 paper by Mantia and Bixby



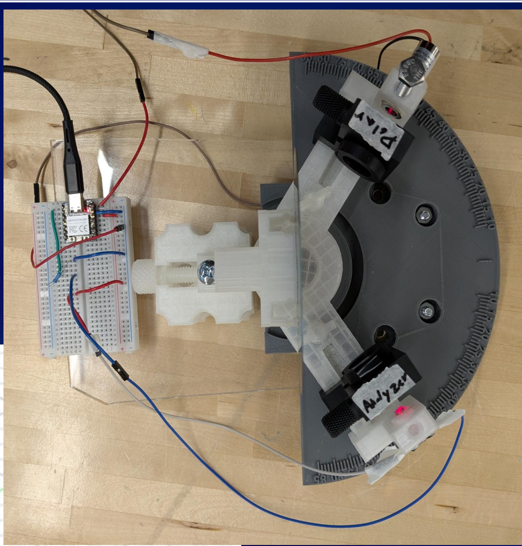
Rotating Analyzer Ellipsometer (created with BioRender)

3D Printing and Assembly

- 3D printed parts were borrowed from a 2022 paper (Mantia & Bixby, 2022)
- Follow instructions to construct ellipsometer on a build plate
- Parts include:
    - 32 printed parts
    - 1 laser (650nm)
    - 1 seeeduino & electronics
    - 1 polarizing sheet
    - 1 GL5549 photoresistor
    - 11 screws (1/4"-20 x 3/8")



3D render of all the parts done in fusion 360



Assembled ellipsometer

Costs

Device Cost

Component	Cost ($)
Laser 653 nm, 3-5V, 5mW	2
Polarizing Film, Linear	12
Seeeduino	10
Glass slide	0
x11 1/4" x 3/8" cap head machine screw	2
~350g PLA filament	10
GL5549 photoresistor	0.30
Total Cost:	**$36.30**

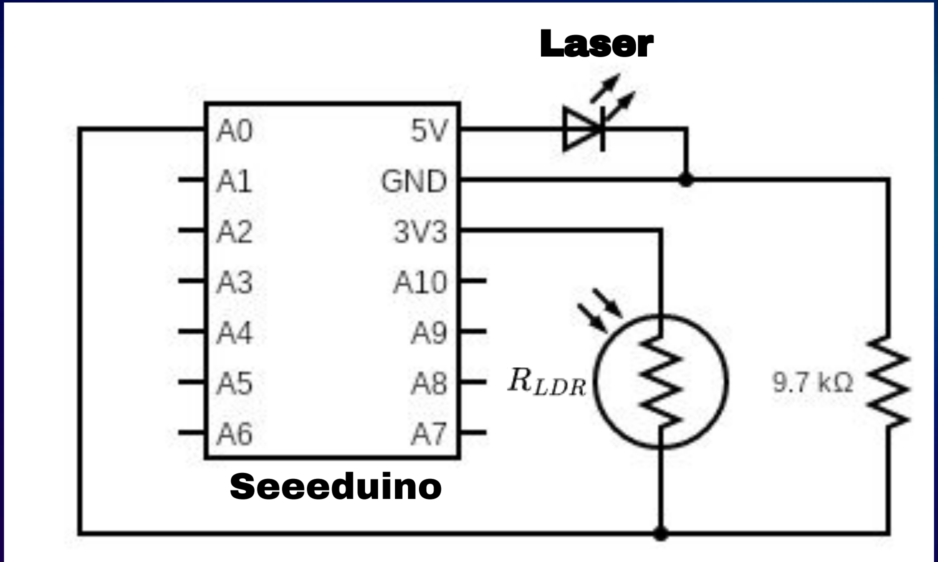
Total Project Cost

Component	Cost ($)
Device (left table)	36.30
Unused Components	
Hamamatsu s1227-66BR	15.85
Testing Materials	
300 nm SiO_2 film & Case	45
Total Cost:	**$97.15**

Circuit Design

Components:

- Seeeduino microcontroller
- Breadboard & wires
- Laser (650nm, 5mW, 3-5V)
- Photoresistor (GL5549)
- Resistor (9.7kΩ)



Our Ellipsometer Circuit

LDR Resistance Calculation

Given:

$$\Delta V_{in} = V_{in}$$
$$|\Delta V_R| = V_{A0}$$

Find I

$$\Delta V_{in} = I(R_{LDR} + R)$$
$$\Rightarrow I = \frac{\Delta V_{in}}{R_{LDR} + R} = \frac{V_{in}}{R_{LDR} + R}$$

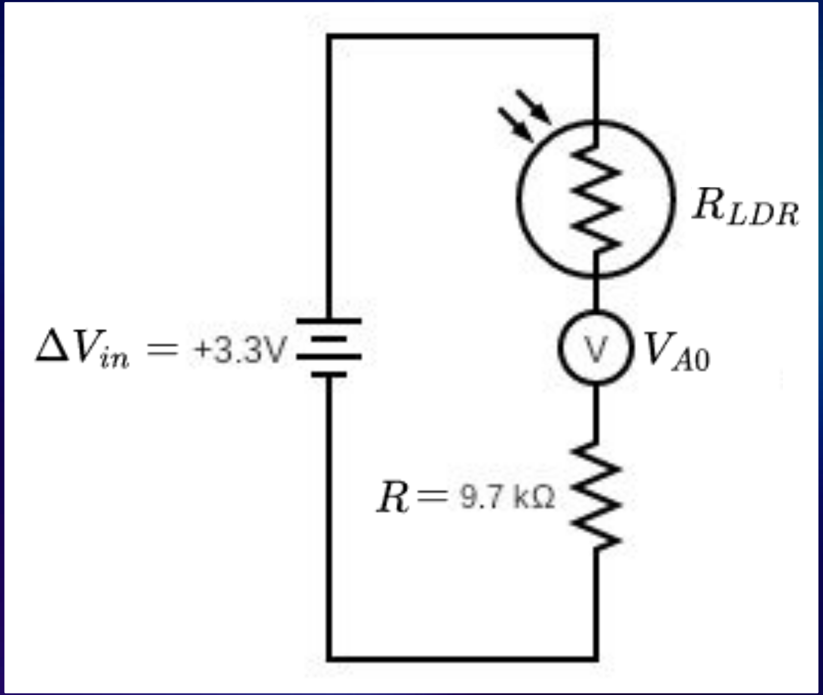
Substitute into Kirchhoff's Loop Law

$$|\Delta V_{LDR}| = IR_{LDR}$$
$$\Rightarrow |\Delta V_{LDR}| = \frac{V_{in}R_{LDR}}{R_{LDR} + R}$$
$$\Delta V_{in} - |\Delta V_{LDR}| - |\Delta V_R| = 0$$
$$\Rightarrow V_{in} - \frac{V_{in}R_{LDR}}{R_{LDR} + R} - V_{A0} = 0$$

Solve Algebraically

...

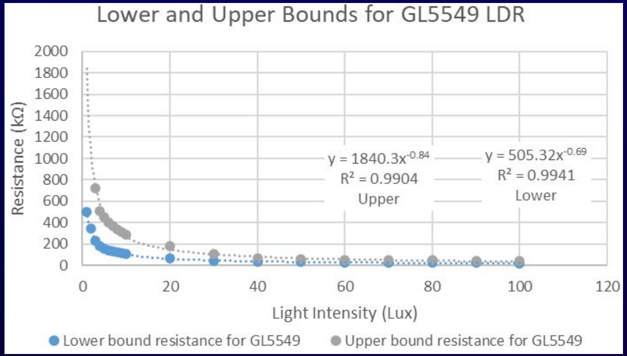
$$\therefore R_{LDR} = \frac{R(V_{in} - V_{A0})}{V_{A0}}$$

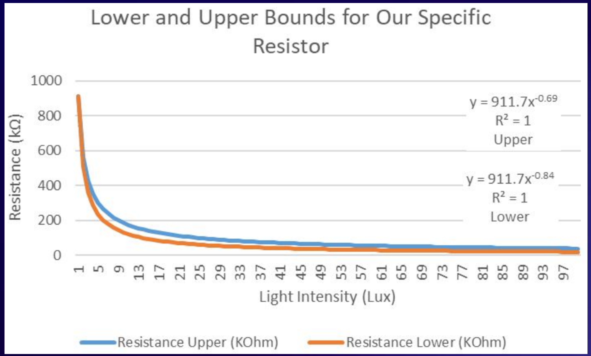


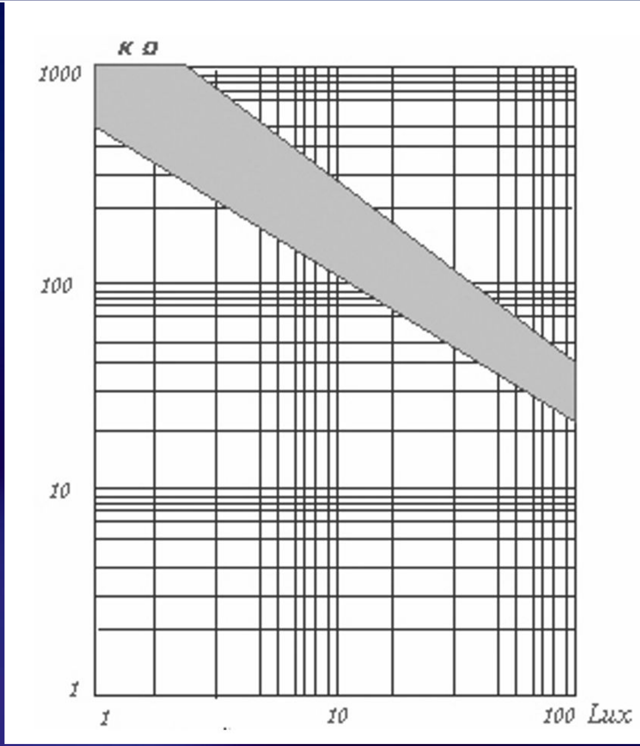
Simplified LDR Voltage Circuit

Estimating Light Intensity

- Dark Resistance (~1 lux) = 911.7 kΩ
- Re-plotted the GL5549 curve to the right, found equations (Fig. A).
- Set equations to be 911.7 at 1 lux (Fig. B)
- Solve for lux (both estimates)
- Take average to estimate lux







GL5549 Intensity-Resistance Curve (provide source)

Testing Samples

- Tested with a 4-inch wafer from the Nanofab
  - 300 nm SiO_2 film
  - Silicon substrate

$$\arctan\left(\frac{n_{glass}}{n_{air}}\right) = \arctan\left(\frac{1.52}{1.003}\right)$$

Brewsters equation using the indices of reflection for glass and air.

Calibration

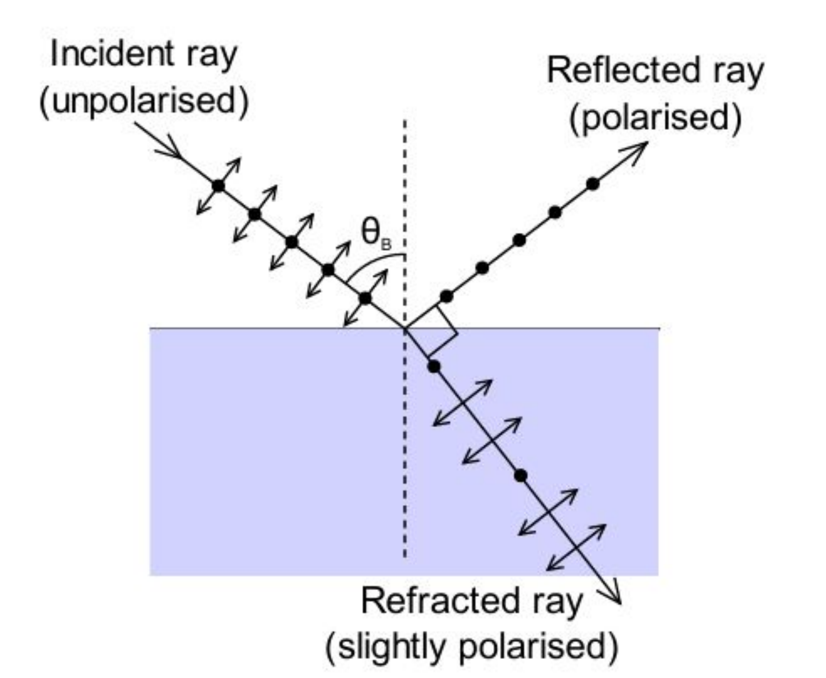


Diagram of Brewster effect. Image by *Ellipsometry.*

- Find Brewster angle using Brewsters equation (56.5°)
- Find Minimum brightness using photometer readings at 56.5°
  - Minimum is 90° (p)
- Reattach both polarizers and rotate one at a time to find 0°(s)
- ±45° from the 0° using protractor to get all azimuth angles
  (90°, 45°, 0°, -45°)

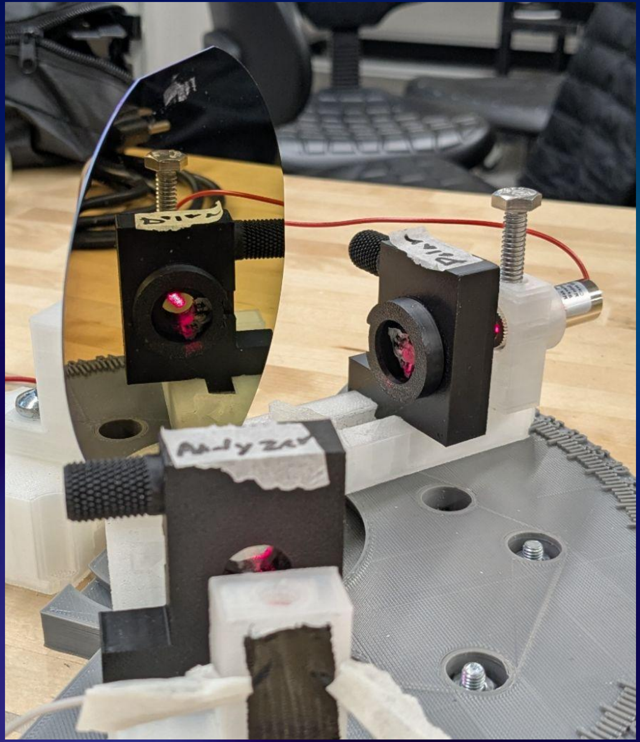
Testing

Procedure

- Rotate arms to desired angle of incidence
- Rotate analyzer lens to desired angle
- Measure LDR resistance for 60 seconds
- Calculate average LDR resistance

Calculations

- LDR resistance (kΩ) → light intensity (lux)
- Light intensities → Ψ and Δ (degrees)



The Math

$$\Psi = \frac{1}{2}\cos^{-1}\left(\frac{I(90^\circ) - I(0^\circ)}{I(90^\circ) + I(0^\circ)}\right) \quad \Delta = \cos^{-1}\left(\frac{I(45^\circ) - I(-45^\circ)}{I(45^\circ) + I(-45^\circ)} \times \frac{1}{\sin(2\Psi)}\right)$$

$$\theta_1 = \sin^{-1}\left(\frac{n_0 \sin(\theta_0)}{n_1}\right) \quad \theta_2 = \sin^{-1}\left(\frac{n_1 \sin(\theta_1)}{n_2}\right)$$

$$\rho_{01}^{\pi} = \frac{\tilde{n}_1 \cos(\theta_0) - \tilde{n}_0 \cos(\theta_1)}{\tilde{n}_1 \cos(\theta_0) + \tilde{n}_0 \cos(\theta_1)} \quad \rho_{12}^{\pi} = \frac{\tilde{n}_2 \cos(\theta_1) - \tilde{n}_1 \cos(\theta_2)}{\tilde{n}_2 \cos(\theta_1) + \tilde{n}_1 \cos(\theta_2)}$$

$$\rho_{01}^{\sigma} = \frac{\tilde{n}_0 \cos(\theta_0) - \tilde{n}_1 \cos(\theta_1)}{\tilde{n}_0 \cos(\theta_0) + \tilde{n}_1 \cos(\theta_1)} \quad \rho_{12}^{\sigma} = \frac{\tilde{n}_1 \cos(\theta_1) - \tilde{n}_2 \cos(\theta_2)}{\tilde{n}_1 \cos(\theta_1) + \tilde{n}_2 \cos(\theta_2)}$$

$$P^{\pi} = \frac{\rho_{01}^{\pi} + \rho_{12}^{\pi} e^{-i2\beta}}{1 + \rho_{01}^{\pi}\rho_{12}^{\pi} e^{-i2\beta}} \quad P^{\sigma} = \frac{\rho_{01}^{\sigma} + \rho_{12}^{\sigma} e^{-i2\beta}}{1 + \rho_{01}^{\sigma}\rho_{12}^{\sigma} e^{-i2\beta}}$$

$$P = \frac{P^{\pi}}{P^{\sigma}} = \tan(\Psi)e^{i\Delta} \quad \beta = 2\pi\frac{d}{\lambda}\tilde{n}_1 \cos(\theta_1)$$

MATLAB Says

$$\begin{pmatrix} 0.5000 \log\left(\frac{0.5000\ (-\rho_{12,\pi} + \sigma_1 - \rho_{01,\pi}\,\rho_{01,\sigma}\,\rho_{12,\sigma} + \sigma_4 + \sigma_3)}{\sigma_2}\right) \mathrm{i} \\ 0.5000 \log\left(-\frac{0.5000\ (\rho_{12,\pi} + \sigma_1 + \rho_{01,\pi}\,\rho_{01,\sigma}\,\rho_{12,\sigma} - \sigma_4 - \sigma_3)}{\sigma_2}\right) \mathrm{i} \end{pmatrix}$$

where

$$\sigma_1 = \sqrt{e^{4\,\Delta\,\mathrm{i}}\,{\rho_{01,\pi}}^2\,{\rho_{12,\pi}}^2\,{\rho_{01,\sigma}}^2\,\tan(\Psi)^2 - 2\,e^{2\,\Delta\,\mathrm{i}}\,{\rho_{01,\pi}}^2\,\rho_{12,\pi}\,{\rho_{01,\sigma}}^2\,\rho_{12,\sigma}\,\tan(\Psi) + 4\,e^{2\,\Delta\,\mathrm{i}}\,{\rho_{01,\pi}}^2\,\rho_{12,\pi}\,\rho_{12,\sigma}\,\tan(\Psi) + {\rho_{01,\pi}}^2\,{\rho_{01,\sigma}}^2\,{\rho_{12,\sigma}}^2 - 2\,e^{2\,\Delta\,\mathrm{i}}\,\rho_{01,\pi}\,{\rho_{12,\pi}}^2\,\rho_{01,\sigma}\,\tan(\Psi) - 2\,e^{4\,\Delta\,\mathrm{i}}}$$

$$\sigma_2 = \rho_{12,\pi}\,\rho_{01,\sigma}\,\rho_{12,\sigma} - \rho_{01,\pi}\,\rho_{12,\pi}\,\rho_{12,\sigma}\,e^{2\,\Delta\,\mathrm{i}}\,\tan(\Psi)$$

$$\sigma_3 = \rho_{01,\pi}\,\rho_{12,\pi}\,\rho_{01,\sigma}\,e^{2\,\Delta\,\mathrm{i}}\,\tan(\Psi)$$

$$\sigma_4 = \rho_{12,\sigma}\,e^{2\,\Delta\,\mathrm{i}}\,\tan(\Psi)$$

σ_1 calculation continued...

$$\rho_{01,\pi}\,\rho_{12,\pi}\,\rho_{01,\sigma}\,\rho_{12,\sigma}\,\tan(\Psi)^2 - 2\,\rho_{01,\pi}\,\rho_{12,\pi}\,\rho_{01,\sigma}\,\rho_{12,\sigma} - 2\,e^{2\,\Delta\,\mathrm{i}}\,\rho_{01,\pi}\,\rho_{01,\sigma}\,{\rho_{12,\sigma}}^2\,\tan(\Psi) + {\rho_{12,\pi}}^2 + 4\,e^{2\,\Delta\,\mathrm{i}}\,\rho_{12,\pi}\,{\rho_{01,\sigma}}^2\,\rho_{12,\sigma}\,\tan(\Psi) - 2\,e^{2\,\Delta\,\mathrm{i}}\,\rho_{12,\pi}\,\rho_{12,\sigma}\,\tan(\Psi) + e^{4\,\Delta\,\mathrm{i}}\,{\rho_{12,\sigma}}^2\,\tan(\Psi)^2$$

Psi and Delta

Experimental

$$\Psi = \frac{1}{2}\cos^{-1}\left(\frac{I(90^\circ) - I(0^\circ)}{I(90^\circ) + I(0^\circ)}\right)$$

+

$$\Delta = \cos^{-1}\left(\frac{I(45^\circ) - I(-45^\circ)}{I(45^\circ) + I(-45^\circ)} \times \frac{1}{\sin(2\Psi)}\right)$$

=

```
I0 = 5362.383; % Intensity at 0°
I45 = 12433.564; % Intensity at 45°
I90 = 16475.800; % Intensity at 90°
I315 = 2906.573; % Intensity at -45°

% Calculated ellipsometric parameters in degrees
Psi_ = .5*acosd((I90-I0)/(I90+I0))
Delta_ = acosd((I45-I315)/(I45+I315)/sind(2*Psi_))
```

Theoretical

```
theta_0 = deg2rad(20:0.1:70);
d = 300; % Thickness in nm
lambda = 650; % Wavelength of light in nm
n_0 = 1; % Index of refraction of ambient
n_1 = 1.4565; % Index of refraction of film
n_2 = 3.8435; % Index of refraction of substrate
cn_0 = 1 + 0i; % Complex index of refraction of ambient
cn_1 = 1.4565 + 0i; % Complex index of refraction of film
cn_2 = 3.8435 + 0.015793i; % Complex index of refraction of substrate

% Angles of refraction calculated using Snell's Law
theta_1 = asin(n_0*sin(theta_0)/n_1);
theta_2 = asin(n_1*sin(theta_1)/n_2);

% Fresnel coefficients
rho_01_pi = ((cn_1*cos(theta_0) - cn_0.*cos(theta_1))./(cn_1.*cos(theta_0) + cn_0.*cos(theta_1)));
rho_12_pi = ((cn_2*cos(theta_1) - cn_1.*cos(theta_2))./(cn_2.*cos(theta_1) + cn_1.*cos(theta_2)));
rho_01_sigma = ((cn_0*cos(theta_0) - cn_1*cos(theta_1))./(cn_0*cos(theta_0) + cn_1*cos(theta_1)));
rho_12_sigma = ((cn_1*cos(theta_1) - cn_2*cos(theta_2))./(cn_1*cos(theta_1) + cn_2*cos(theta_2)));

% Film phase thickness
Beta = 2*pi*d/lambda*cn_1*cos(theta_1);

% Complex reflection coefficients
Ppi = (rho_01_pi+rho_12_pi.*exp(-2i*Beta))./(1+rho_01_pi.*rho_12_pi.*exp(-2i*Beta));
Psigma = (rho_01_sigma+rho_12_sigma.*exp(-2i*Beta))./(1+rho_01_sigma.*rho_12_sigma.*exp(-2i*Beta));
```

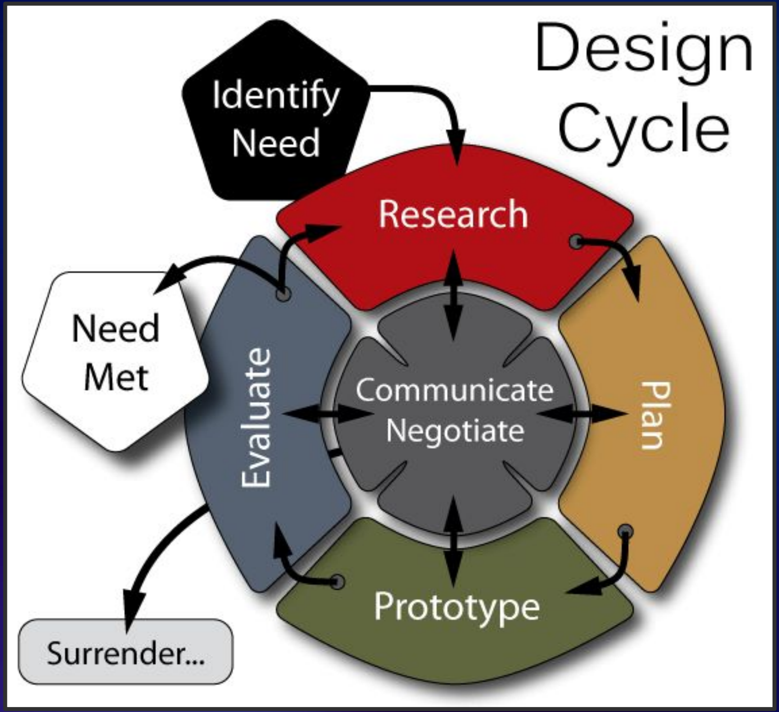
```
% Total complex reflection ratio
P = Ppi./Psigma;

% Theoretical ellipsometric parameters in radians
Psi = atan(abs(P));
Delta = abs(atan(imag(P)./real(P)));
```

03

– Results / Conclusions

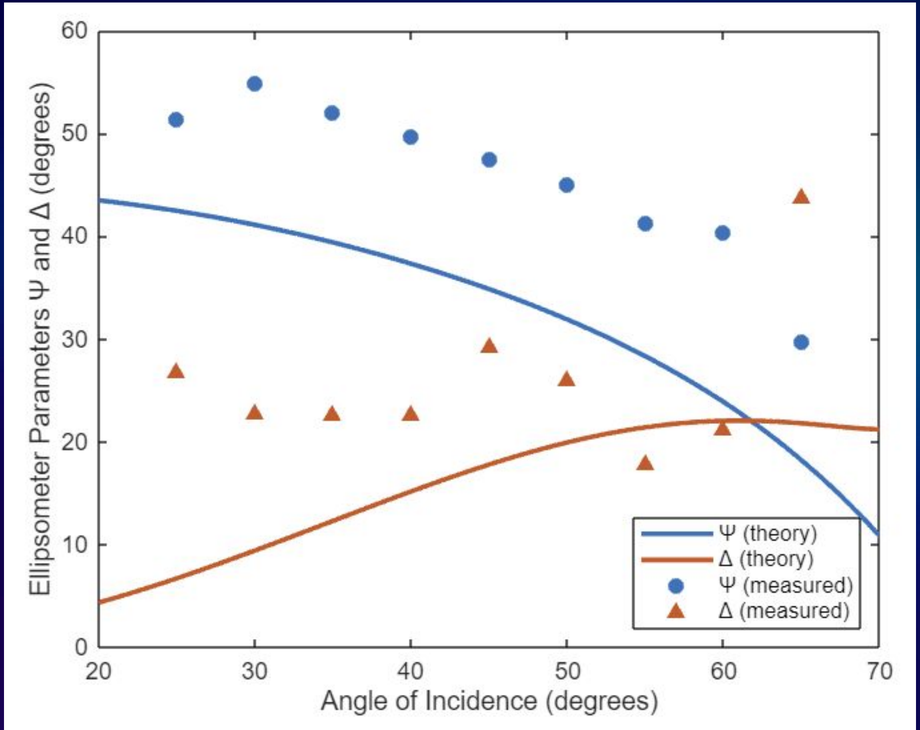
Cost and Durability

- Aimed to cost under $50, 1/40th the cost of commercial
    - Total Cost: $97
    - Cost for future production: $36
        - Not including 1 time purchases (wafers, wrong sensor, etc.)
- Be robust enough to handle repeated tests without losing accuracy
    - Held up to repeated testing; special care needed when handling silicon wafer



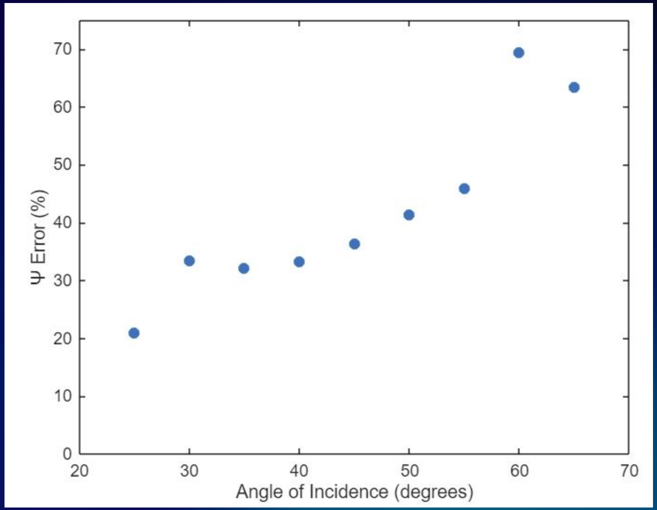
Numbers

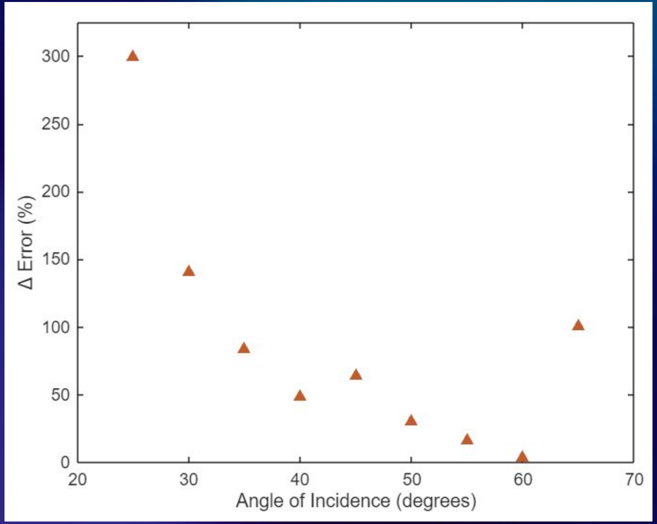
- Experimental values of Psi follow the theoretical trend, just shifted vertically
  - Unsure of cause of this discrepancy, but it isn't resistance to intensity conversion
- Experimental values for Delta are further from the theoretical values and don't follow the trend
  - Discrepancies are especially great at shallower angles



Results

- Psi has an average percent error of 41.857%
  - Increases somewhat linearly as angle of incidence increases
- Error is much greater for Δ, average percent error of 87.788%
  - Decreases exponentially as angle of incidence increases
- We didn't achieve our goal of having an average error of 10% (original paper had an average error of 0.7%)





Recommendations (realistic)

Image from *Space Jam* (1996).

- Use calibrated Photodiode instead of LDR
  - Easier to find light intensity (lux)
- Enlarge the analyzer lens apparatus
  - Hard to determine the polarization of the lens, especially after cutting
  - 45 degree rotations are non-exact
- Improve calibration
  - Rewrite instructions to make calibration clearer

Recommendations (ambitious)

Image from *Space Jam* (1996).

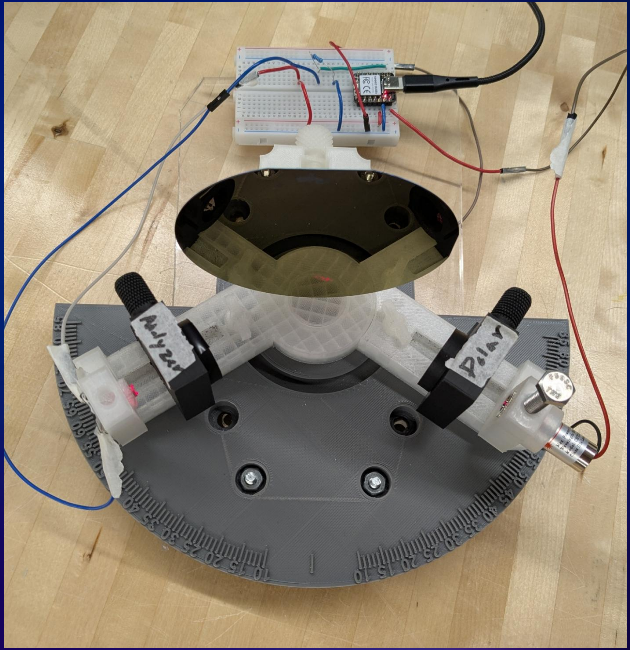
- Automate the analyzer lens angle rotation to ensure every angle is correct
- Detect at multiple wavelengths (spectroscopic ellipsometry) to obtain accurate data from irregular surfaces (bumpy, scratched, etc.)

Thanks!

Faculty Advisor
- Dr. Swomitra Mohanty

Technical Help
- Dr. Mike Scarpulla

Samples
- U of U Nanofab



References

J.A. Woollam. (2024, March 21). *M-2000 Ellipsometer*. https://www.jawoollam.com/products/m-2000-ellipsometer

Mantia, M., & Bixby, T. (2022, June 1). *Optical measurements on a budget: A 3D-printed ellipsometer*. American Journal of Physics. https://doi.org/10.1119/10.0009665

Semiconductor Industry Association. (2025, April 4). *Global Semiconductor sales increase 17.1% year-to-year in February*. https://www.semiconductors.org/global-semiconductor-sales-increase-17-1-year-to-year-in-february/

van Overveld, N. (2024, June 11). *Martin van den brink's secret is collaboration*. Eindhoven University of Technology. https://www.tue.nl/en/news-and-events/news-overview/11-06-2024-martin-van-den-brinks-secret-is-collaboration

https://www.youtube.com/watch?v=Fc48QDjaJgc