Optical Contrast: a Review and Application of Chi-Square Analysis

Ultrafast Laser Lab

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Background

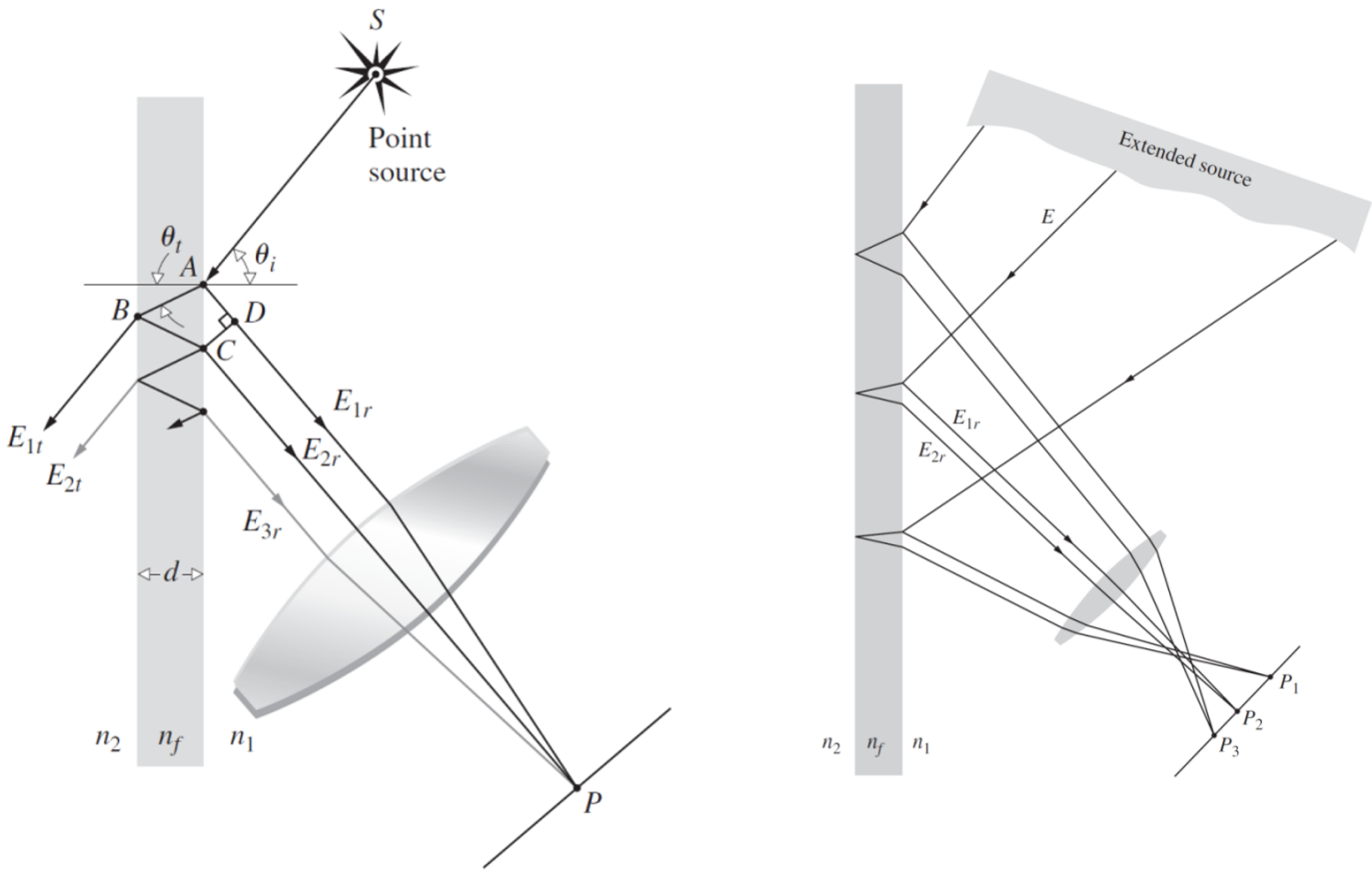

Figure 1: Optical path of light reflected off thin film.[1]

[1] Hecht, E. (2002). *Optics* (4th ed.). San Francisco, CA: Addison-Wesley.

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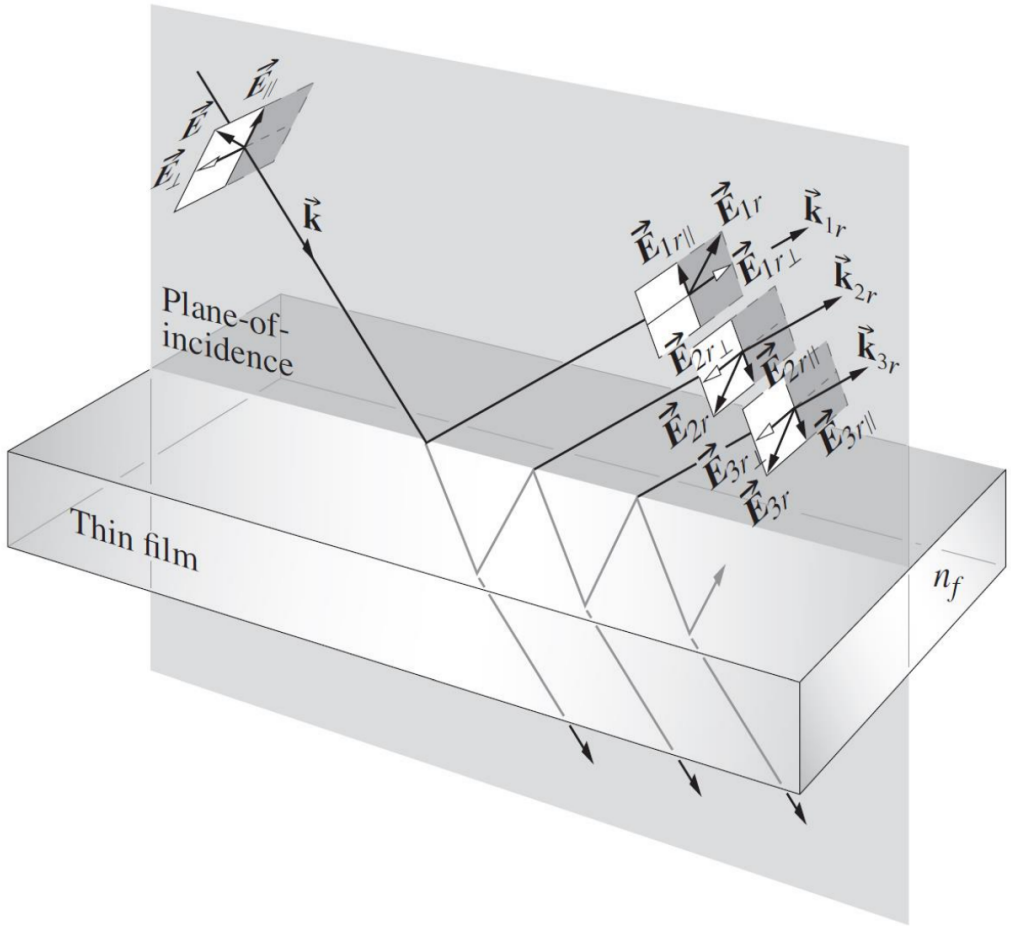

Figure 2: Phase shift of light reflected off thin film.[2]

[2]Hecht, E. (2002). *Optics* (4th ed.). San Francisco, CA: Addison-Wesley.

Background

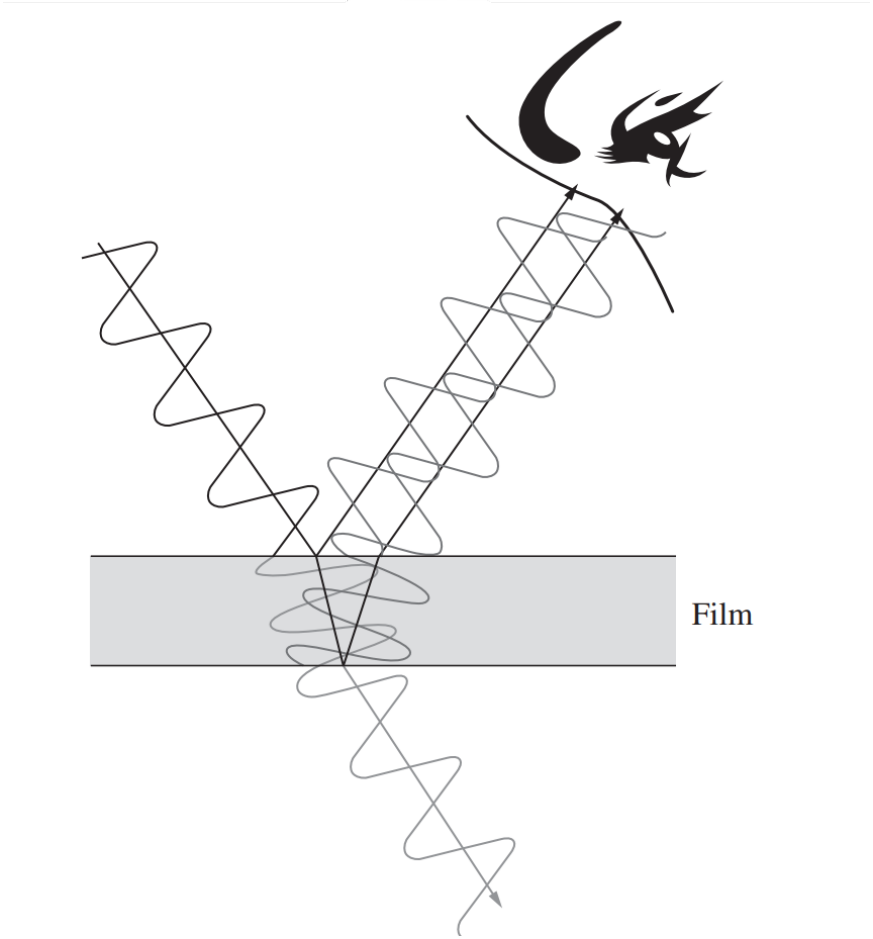

Figure 3: Overall representation of thin-film interference.[3]

[3]Hecht, E. (2002). *Optics* (4th ed.). San Francisco, CA: Addison-Wesley.

Oil Spills

Figure 4: Oil spill of the Japanese bulk carrier *MV Wakashio*. [4]

[4] Field, Rebecca. "Oil Is Leaking All over the World." Greenpeace International, 9 Apr. 2021.

Oil Spills

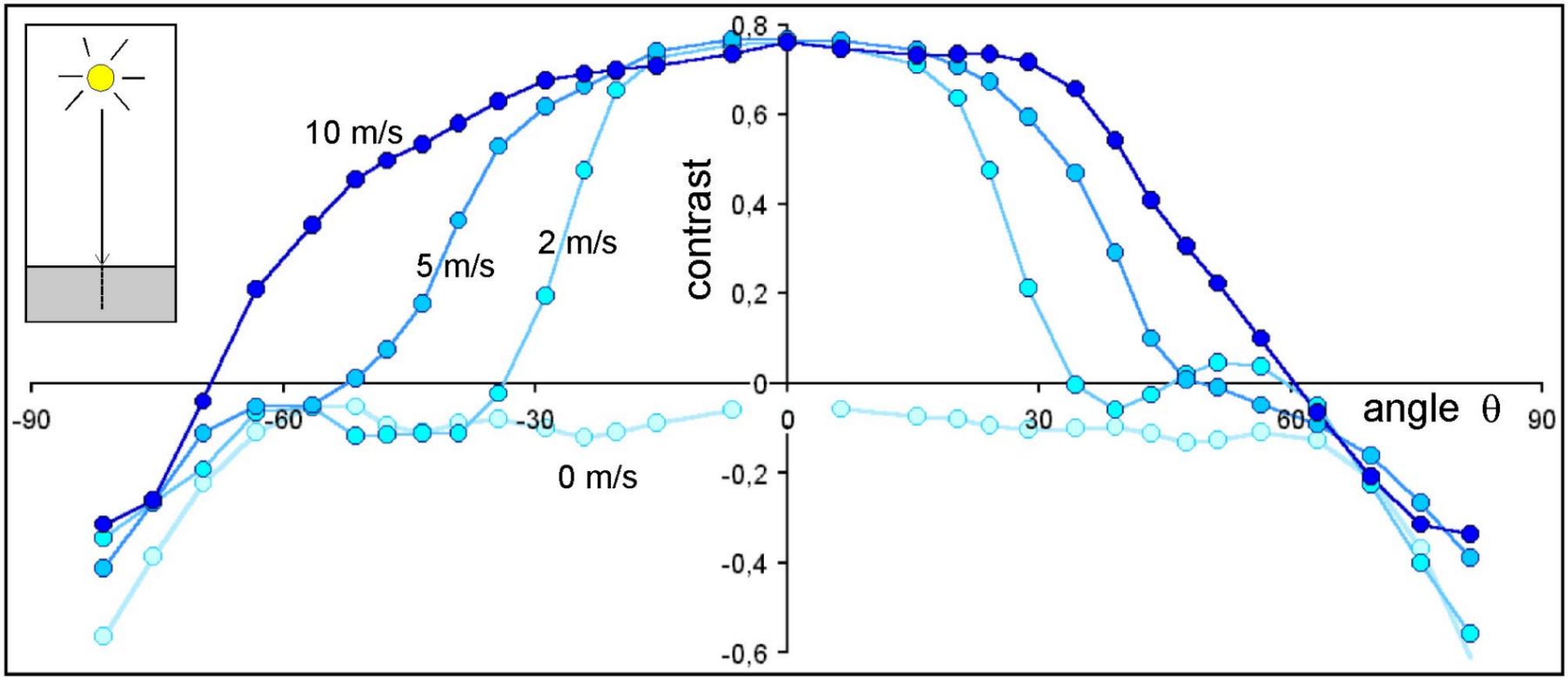

Figure 5: Contrast of an oil film using 550 nm incident light. [5]

[5] Z. Otremba and J. Piskozub, "Modelling of the optical contrast of an oil film on a sea surface," Opt. Express **9**, 411-416 (2001).

Thin Films Under Microscope

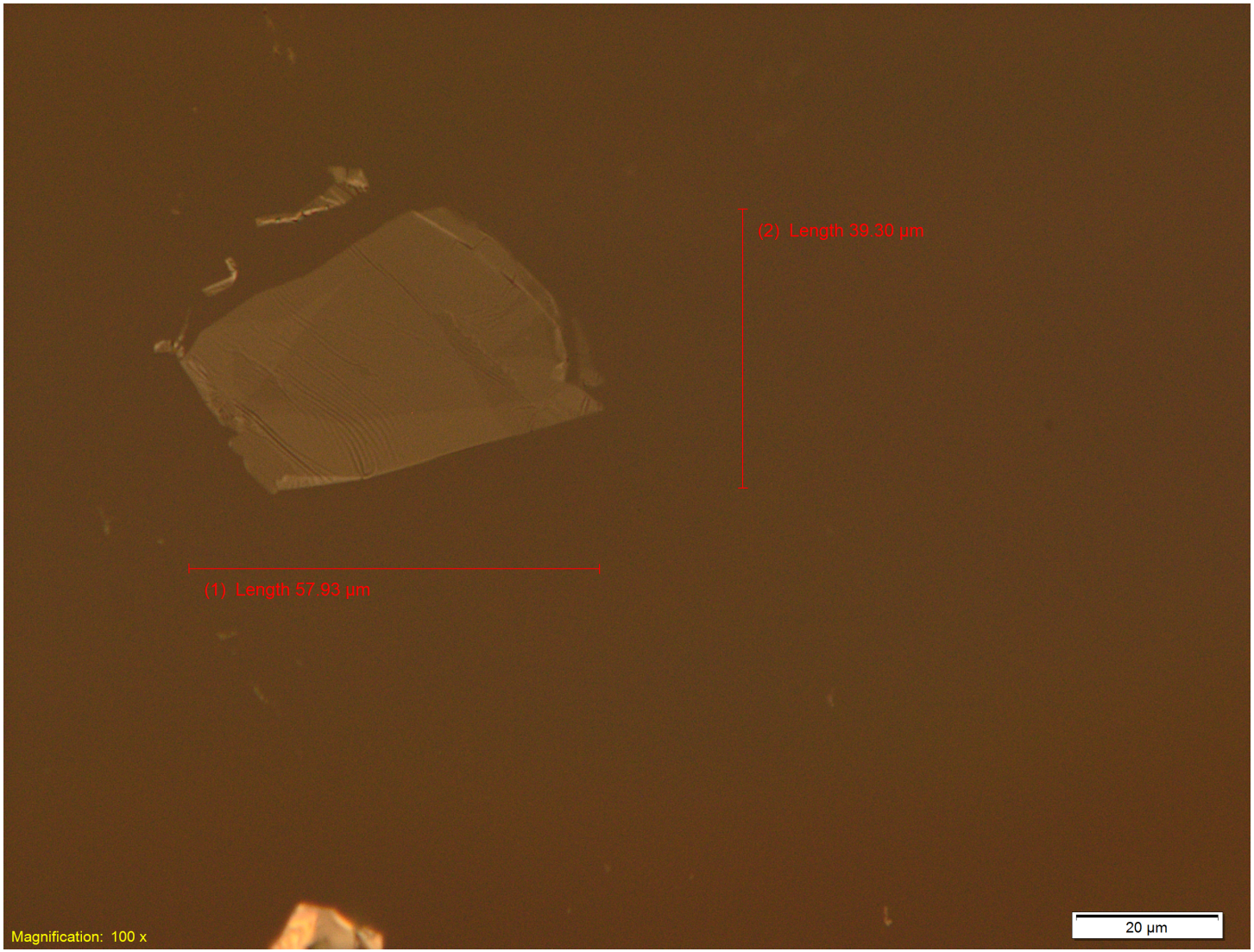

Figure 6: Example of graphene under optical microscope.

Making Graphene Visible

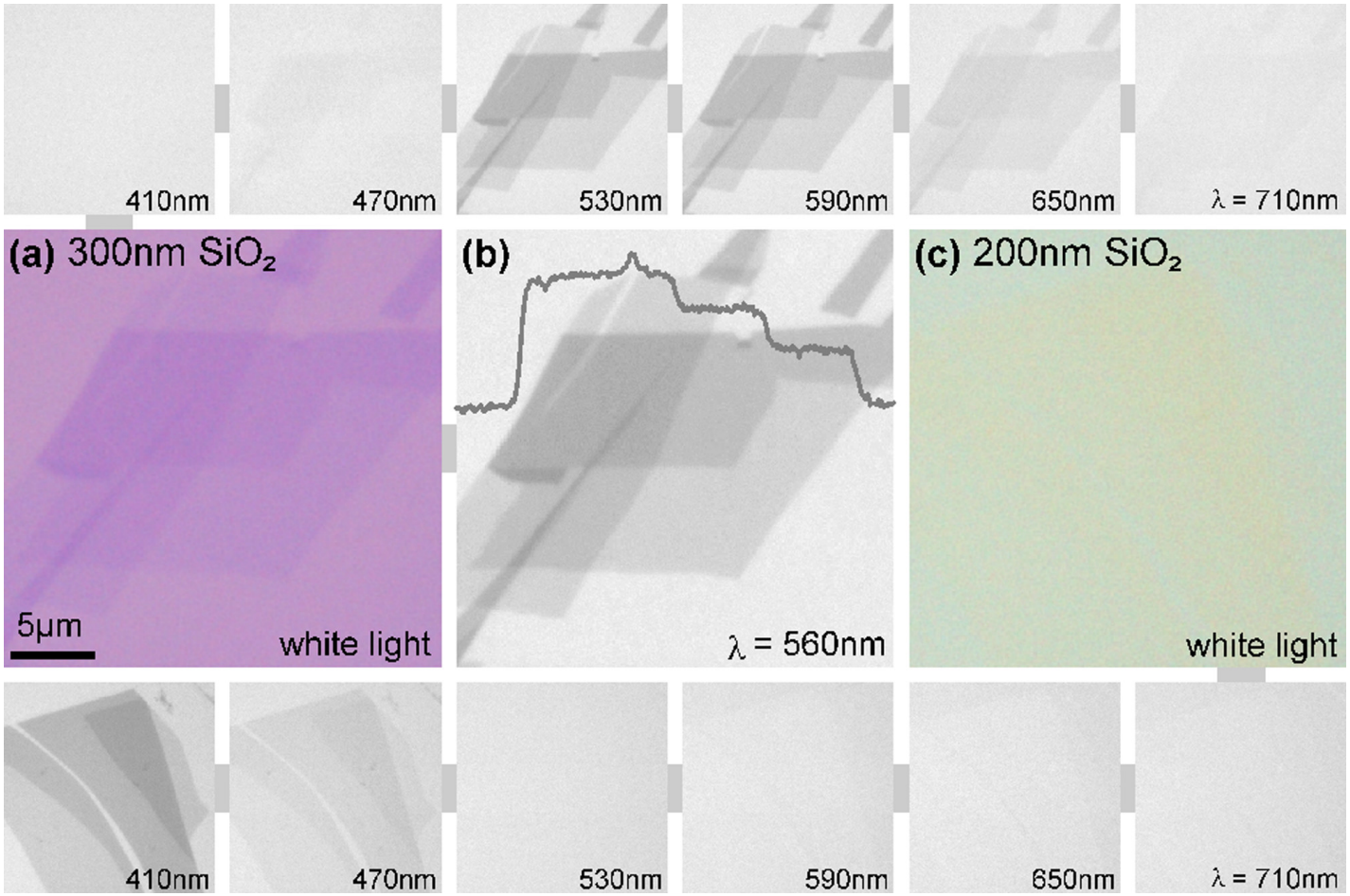

Figure 7: Optical contrast of few-layer graphene. [6]

[6] Blake, P, et al. "Making Graphene Visible." *Applied Physics Letters* **91**, no. 6, 2007, pp. 063124–063124-3.

Thin Films Under Microscope

This is great because . . .

- no complicated sample preparation,
- can calculate the index of refraction of the thin material,
- can calculate the thickness of the thin material.

However, there is one problem.

What if I don't know the contrast of a monolayer of my material?

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What Does Chi-Square Represent?

The standard equation for Chi-Square is given by,

General Chi-Square Equation

$$\chi^2 = \sum_{i=1}^{N} \frac{(O_i - E_i)^2}{E_i}$$

where O_i are the measured experimental values and E_i are the expected values from the applied fit.

Through this process, a chi-square test essentially measures how well experimentally measured results compare to an applied fit.

What Does Chi-Square Represent?

General Chi-Square Equation

$$\chi^2 = \sum_{i=1}^{N} \frac{(O_i - E_i)^2}{E_i}$$

Now, our specific analysis replaces the variables as,

Contrast-Specific Chi-Square Equation

$$\chi^2 = \sum_{i=1}^{N} \frac{(c_{i,\text{sample}} - n_i c_{i,1\text{L}})^2}{n_i c_{i,1\text{L}}} \quad \text{where} \quad n_i = \text{nint}\left(\frac{c_{i,\text{sample}}}{c_{i,1\text{L}}}\right)$$

Our unknowns are the chi-square and the monolayer contrast.

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Calculation of a Single Potential Value

Example of a Single Chi-Square Calculation

Let us use the set,

$$[8, 15, 16]$$

and see how well the integer 5 fits as their common multiple:

$$\begin{aligned}
\chi^2 &= \sum_{i=1}^{3} \frac{(O_i - E_i)^2}{E_i} \\
&= \frac{(8-10)^2}{10} + \frac{(15-15)^2}{15} + \frac{(16-15)^2}{15} \\
&\approx 0.5
\end{aligned}$$

which demonstrates 5 may not be the best fit for this set of data.

Calculation of a Spread of Potential Values

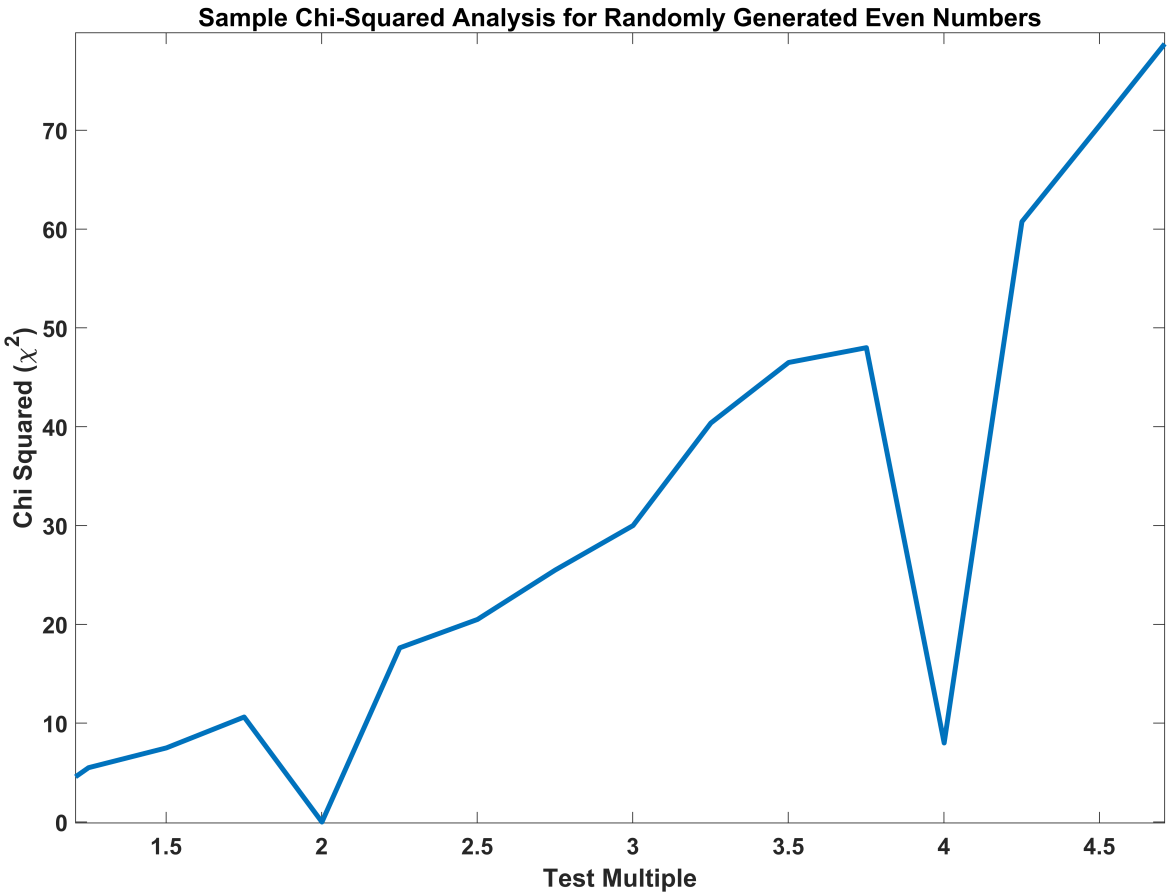

Figure 8: The graph here shows 2 as a much better fit for the integer multiple as the chi-squared value reaches 0, while the value for 4 is non-zero.

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Measuring a Contrast for $PtSe_2$

Figure 9: Example of one of the $PtSe_2$ flakes used to calculate contrast.

Analyzing Chi-Square for $PtSe_2$

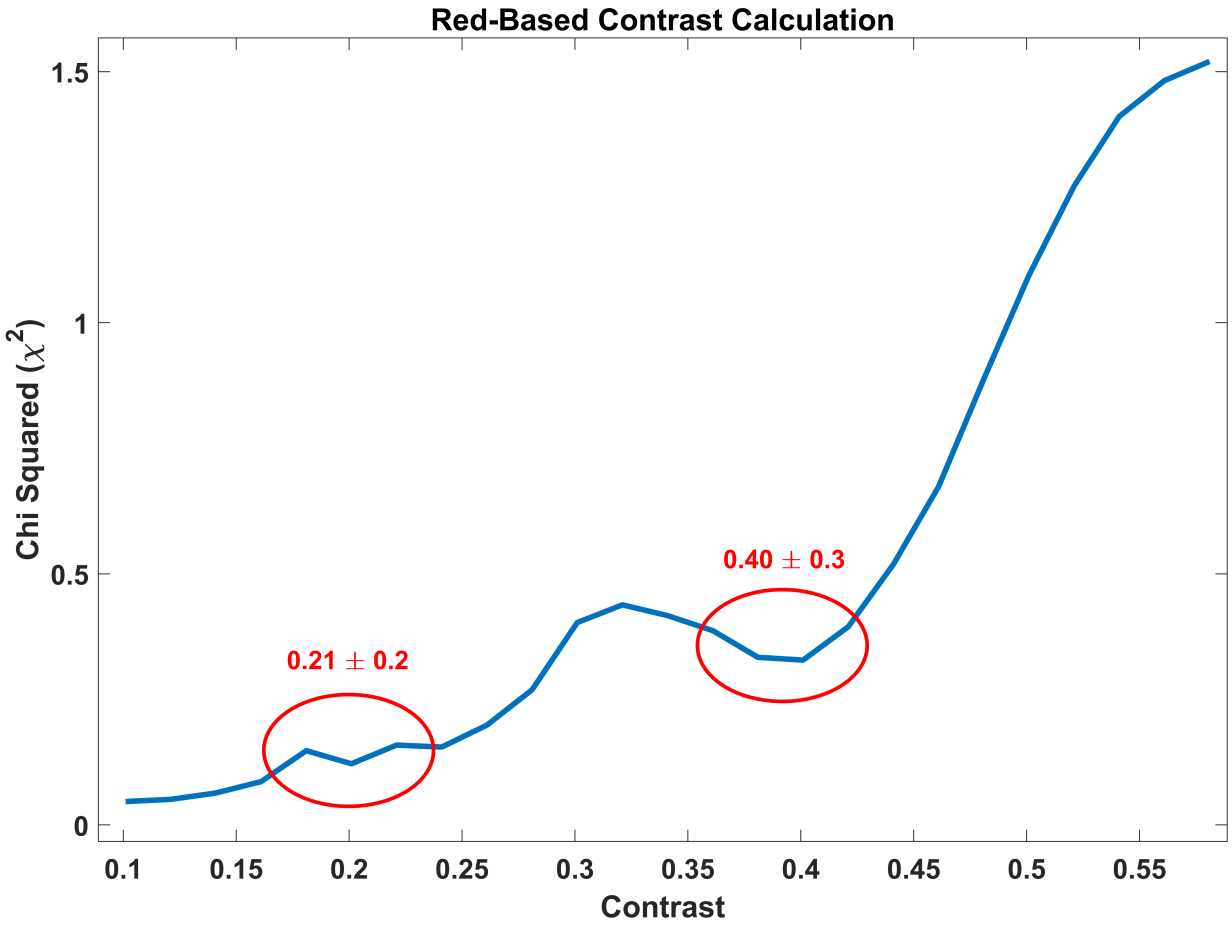

Figure 10: Chi-Square analysis of contrast data from roughly 40 flakes results in a conclusion of the monolayer having a contrast of 0.21 ± 0.2.

Monolayer Found!

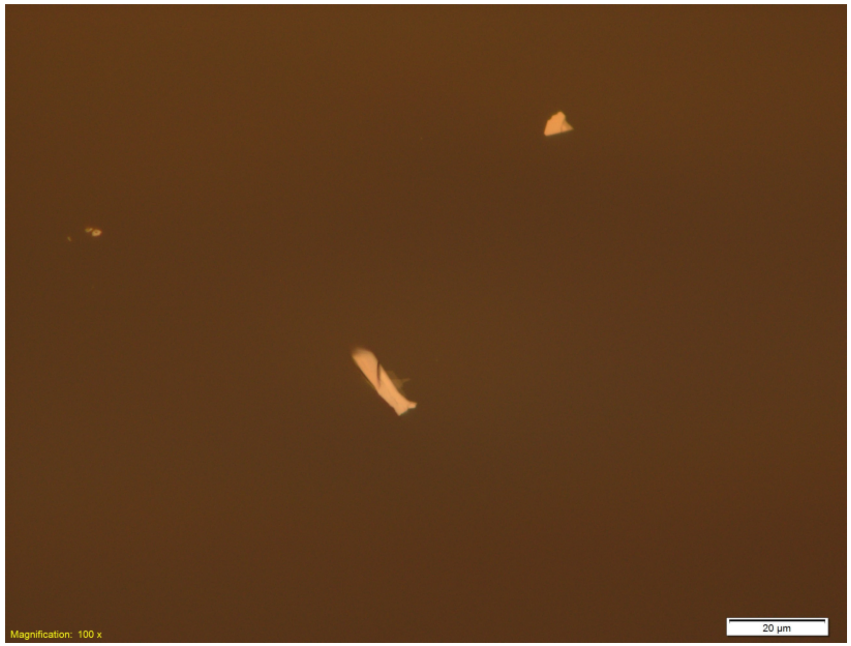

Figure 11: Monolayer found after calculating the chi-square predicted value, falls within reasonable contrast uncertainty from prediction.

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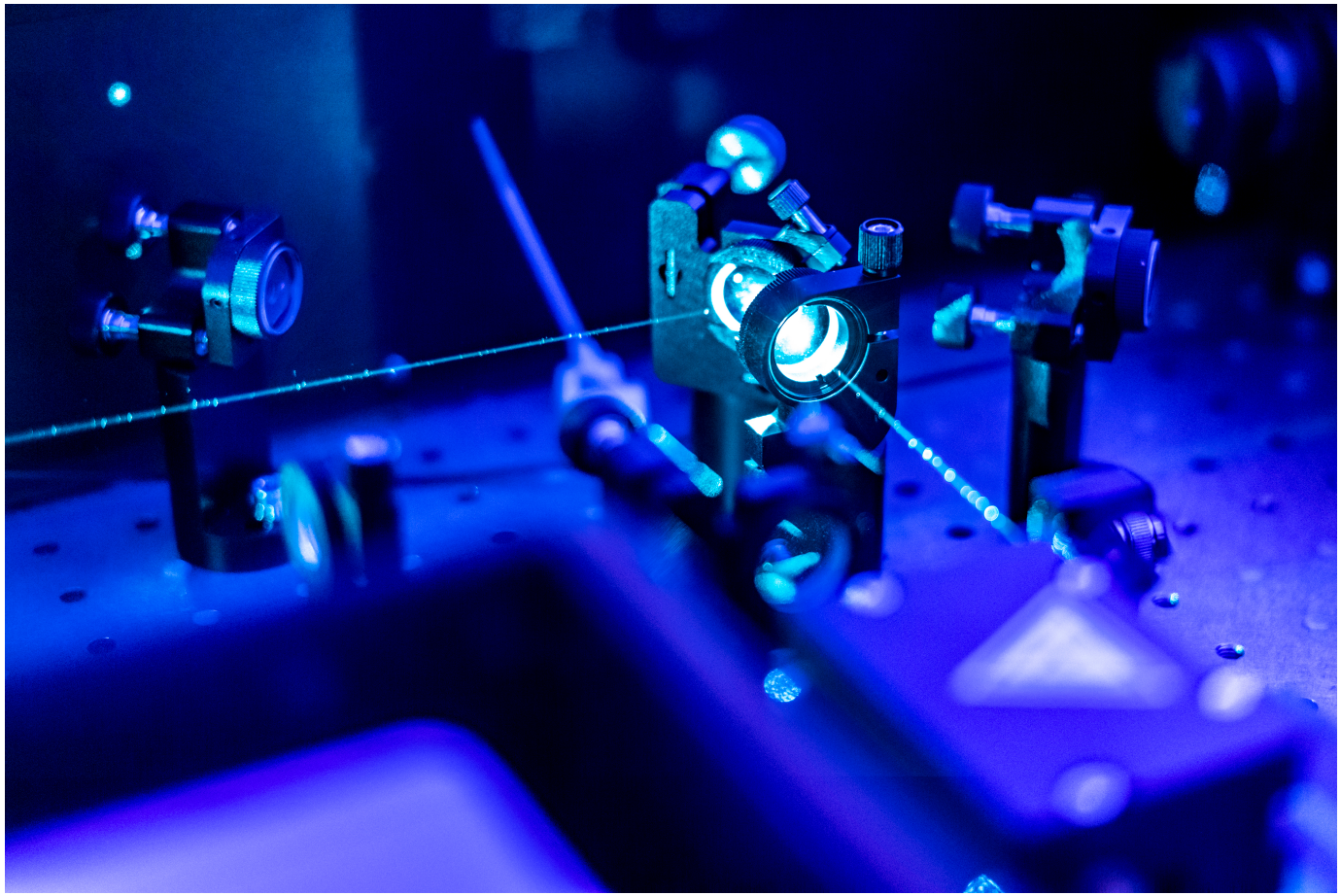
Future Plans

Future plans include:

- preparing an AFM-ready sample to verify calculated thickness.
- design a setup to verify calculated refractive index.



Fin.