Laser Physics &
Nonlinear Optics

Real-Time Ellipsometry for Studying Cesium-Telluride Photocathodes

Peter van der Slot
Rolf Loch
Mark Luttikhof
Liviu Prodan

Mesa^{+} Institute for
Nanotechnology

Content

- Introduction
- Setup and previous results
- Improvements
- Verification of setup

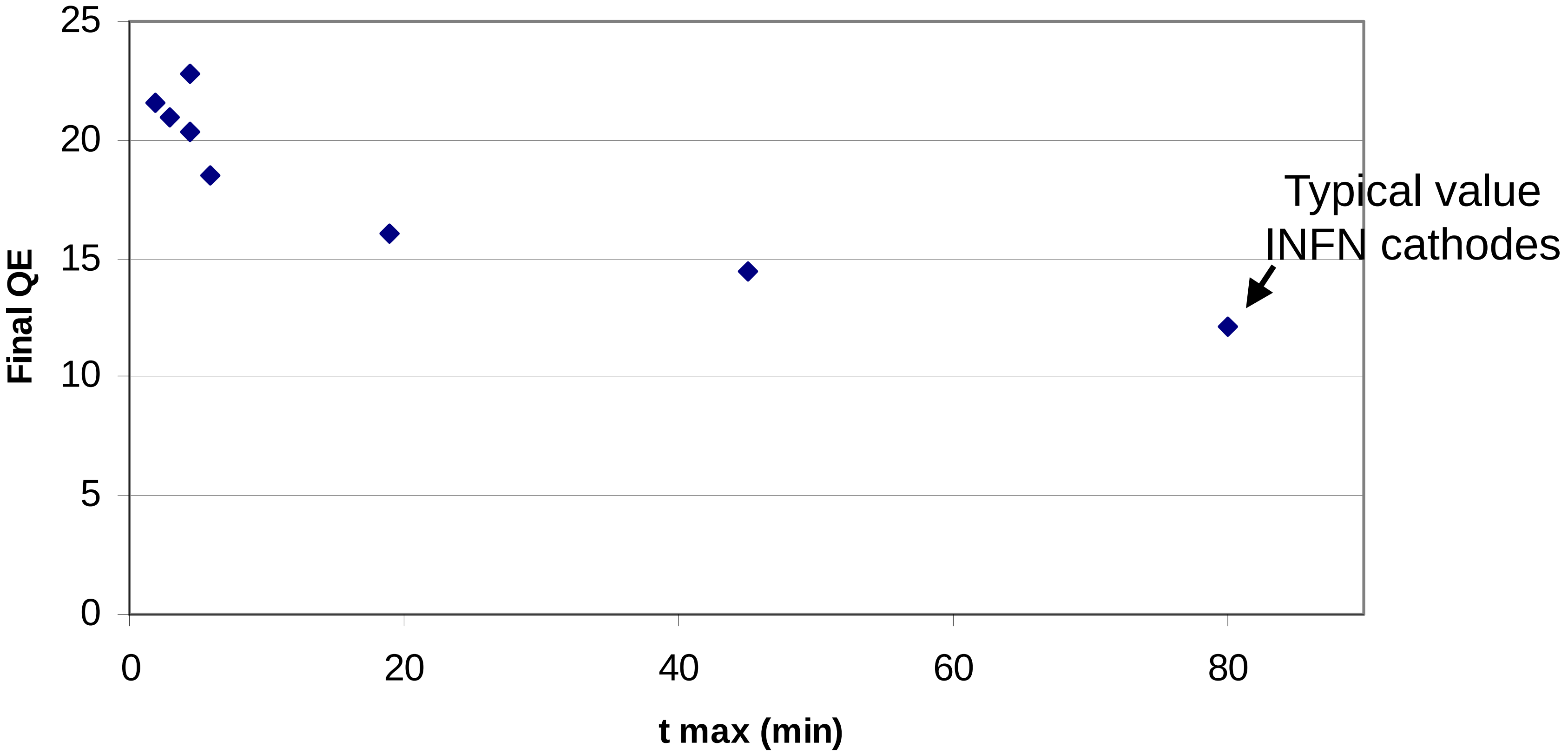
Introduction

- Real time ellipsometry seems viable to deliver inline information about
  - Layer thickness
  - Composition
- Knowledge about these is important for
  - Cathode production
  - Cathode performance monitoring
- Initial measurements performed by us shows
  - Variation in the ellipsometric variables
  - Complete characterisation of measurement setup required

Introduction

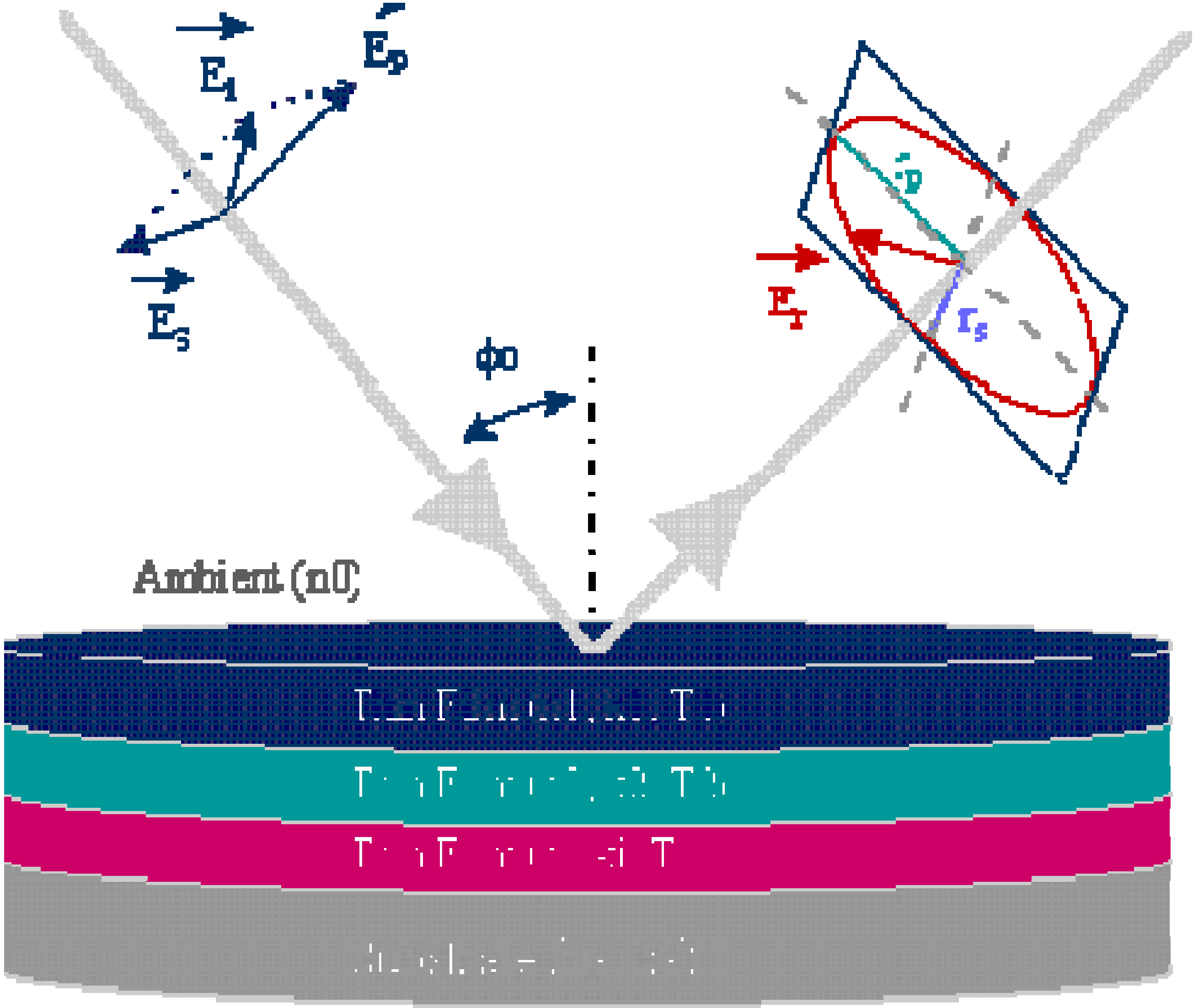
- From previous measurements we had insufficient information to retrieve the ellipsometric variables Ψ and Δ
  - Window preparation chamber was not stress-free
  - We did not characterize window of preparation chamber
  - Angles of various optical components could not be measured with sufficient accuracy

QE versus preparation time

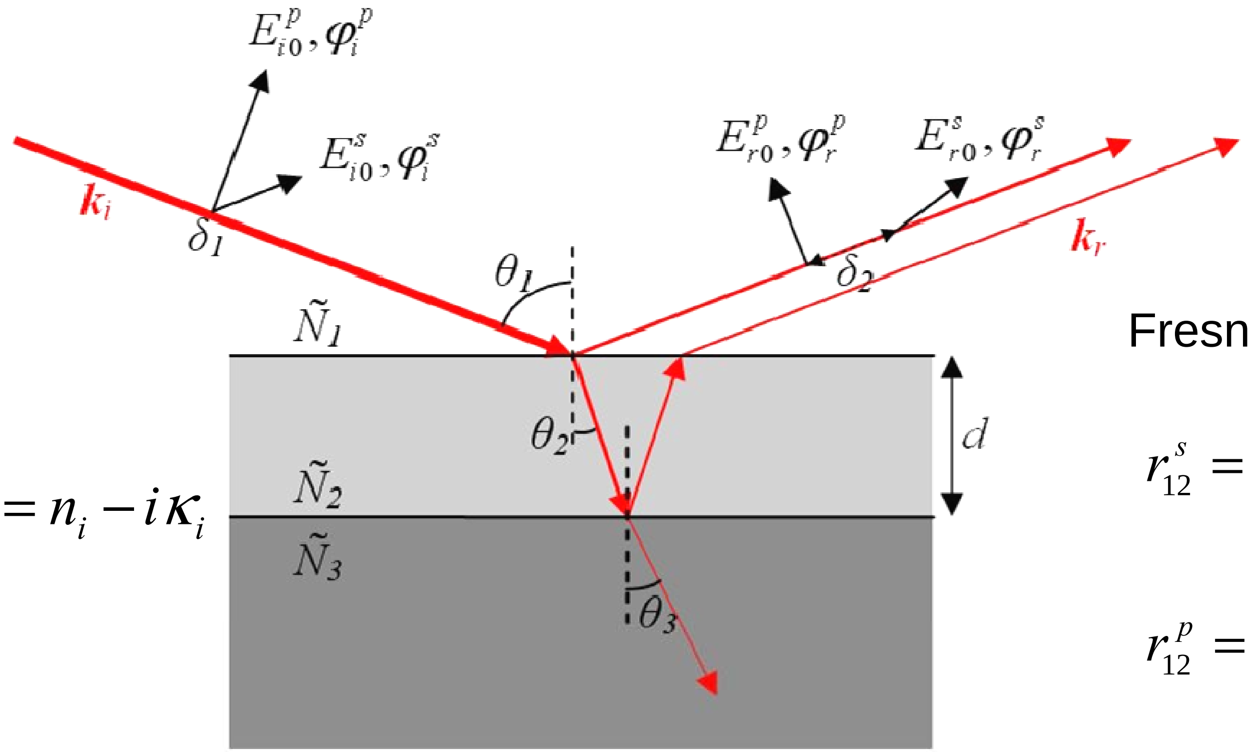


Longer preparation times results in lower quantum efficiencies and lead to more robust cathodes (also reported by other groups)

Ellipsometry (1)



Ellipsometry (2)



$$\tilde{N}_i = n_i - i\kappa_i$$

Fresnel reflection coefficient:

$$r_{12}^{s} = \frac{\tilde{N}_1\cos\theta_1 - \tilde{N}_2\cos\theta_2}{\tilde{N}_1\cos\theta_1 + \tilde{N}_2\cos\theta_2}$$

$$r_{12}^{p} = \frac{\tilde{N}_2\cos\theta_1 - \tilde{N}_1\cos\theta_2}{\tilde{N}_2\cos\theta_1 + \tilde{N}_1\cos\theta_2}$$

Total amplitude reflection for s and p polarisaton:

$$R^{s(p)} = \frac{r_{12}^{s(p)} + r_{23}^{s(p)}e^{-i\beta}}{1 + r_{12}^{s(p)}r_{23}^{s(p)}e^{-i\beta}}$$

$$\beta = 4\pi\left(\frac{d}{\lambda}\right)\tilde{N}_2\cos\theta_2$$

$$\boxed{\rho = \tan\Psi e^{i\Delta} = \frac{R^{p}}{R^{s}}}$$

Ellipsometry (3)

$$\boxed{\rho = \tan\Psi e^{i\Delta} = \frac{R^p}{R^s}}$$

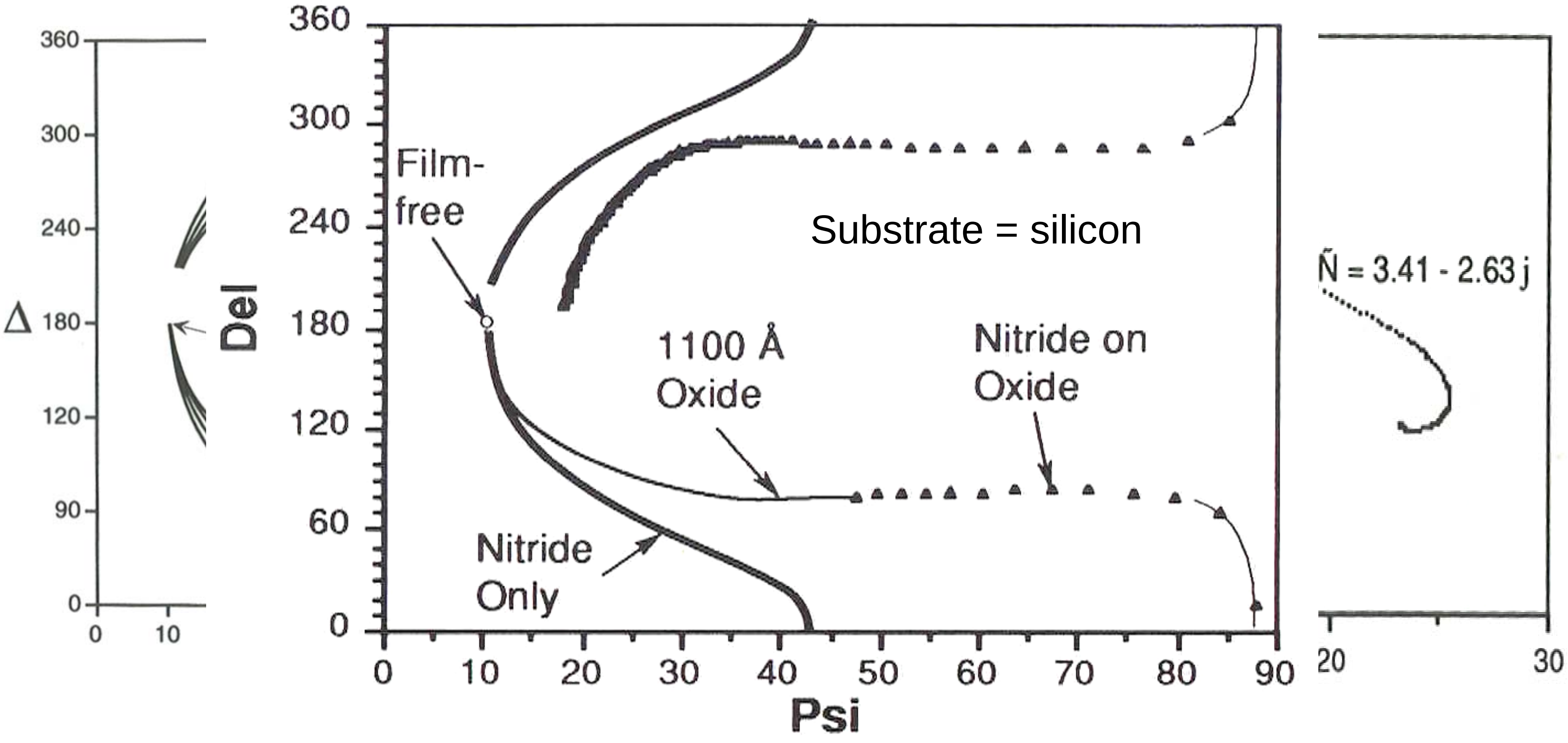
- This ratio is complex
- $\tan\Psi$ measures the modulus of the amplitude reflection ratio
- The phase difference between p- and s-polarised reflected light is given by Δ

Advantages

- It measures the ratio of two values so is highly accurate and reproducible, does not need a reference sample, and is not so susceptible to light source fluctuation
- Since it measures phase, it is highly sensitive to the presence of ultrathin films (down to submonolayer coverage).
- It provides two pieces of data at each wavelength. More film properties can be determined.

Delta-Psi trajectories

Starting point (no film): $\tilde{N}_3 = \tilde{N}_1 \tan\theta_1 \sqrt{1-\frac{4\rho\sin^2\theta_1}{(\rho+1)^2}}$



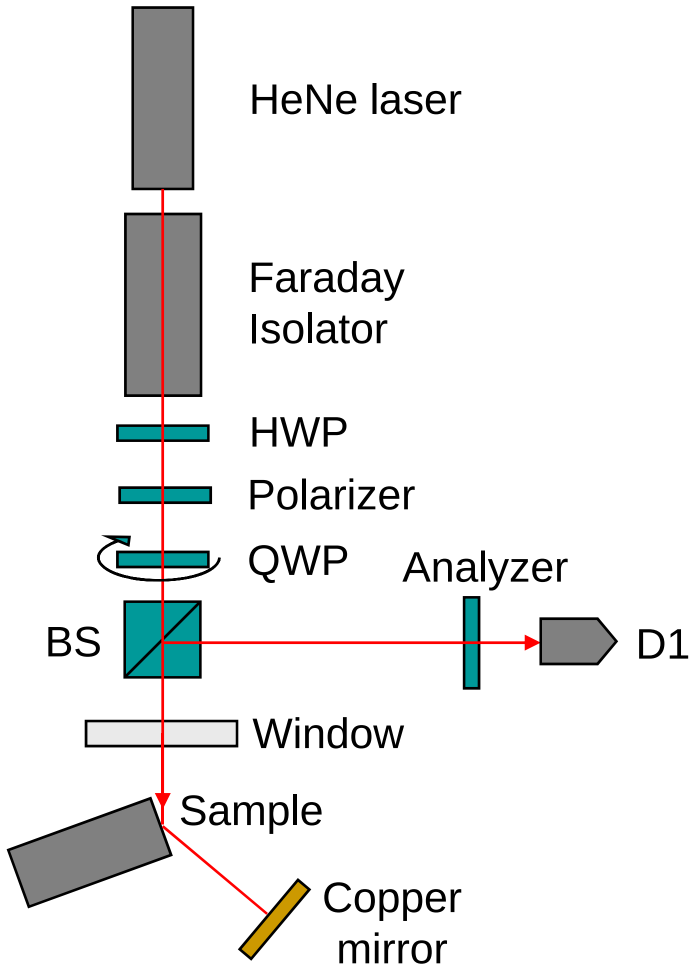
Substrate = silicon

Data analysis

- Regression Analysis
  - The measured data are compared with the data generated from a theoretical model.
  - Unknown parameters in the optical model, such as film thickness or optical constants, are varied to try to produce a “best fit” to experimental data.
  - Regression algorithms, such as Levenberg-Marquadt, are used to vary unknown parameters and minimize the difference between experimental and model-generated data.
  - Physical parameters are obtained once a good fit is achieved.

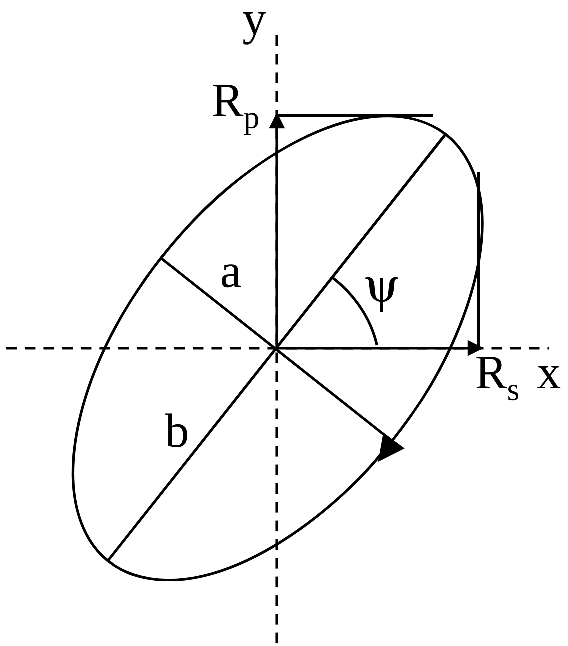
Rotating Compensator Ellipsometry

- Compensator (QWP) rotates continuously
- Sample properties influence reflected beam characteristics
- Reflected beam characteristics influence intensity after analyzer
- Correlation between compensator angle and detector signal gives information about sample properties



Stokes vector & Mueller matrix

- Intentsity $I=(R_p^2 + R_s^2)I_0^2$
- Polarization angle ψ
- Polarization ellipticity $\chi=a/b$
- Rotation direction

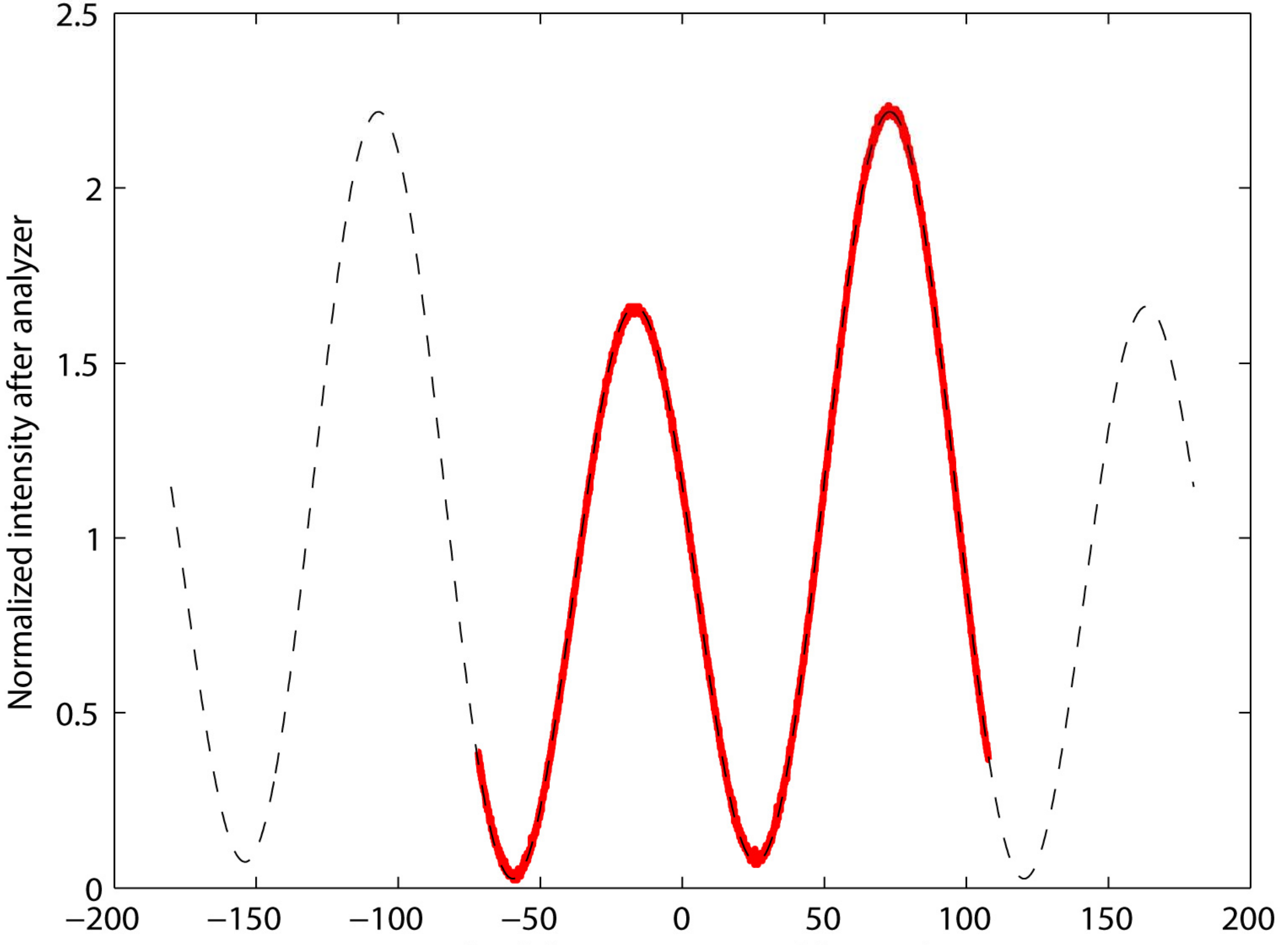


Component / light $\Downarrow$ Stokes vector / Mueller matrix

$$\vec{S}=\begin{pmatrix}S_1\\S_2\\S_3\\S_4\end{pmatrix}=\begin{pmatrix}I\\I\cos(2\psi)\cos(2\chi)\\I\sin(2\psi)\cos(2\chi)\\I\sin(2\chi)\end{pmatrix}$$

$$M_S=\begin{bmatrix}1&-\cos2\Psi&0&0\\-\cos2\Psi&1&0&0\\0&0&\sin2\Psi\cos\Delta&\sin2\Psi\sin\Delta\\0&0&-\sin2\Psi\sin\Delta&\sin2\Psi\cos\Delta\end{bmatrix}$$

Rotating Compensator



Tc

er:

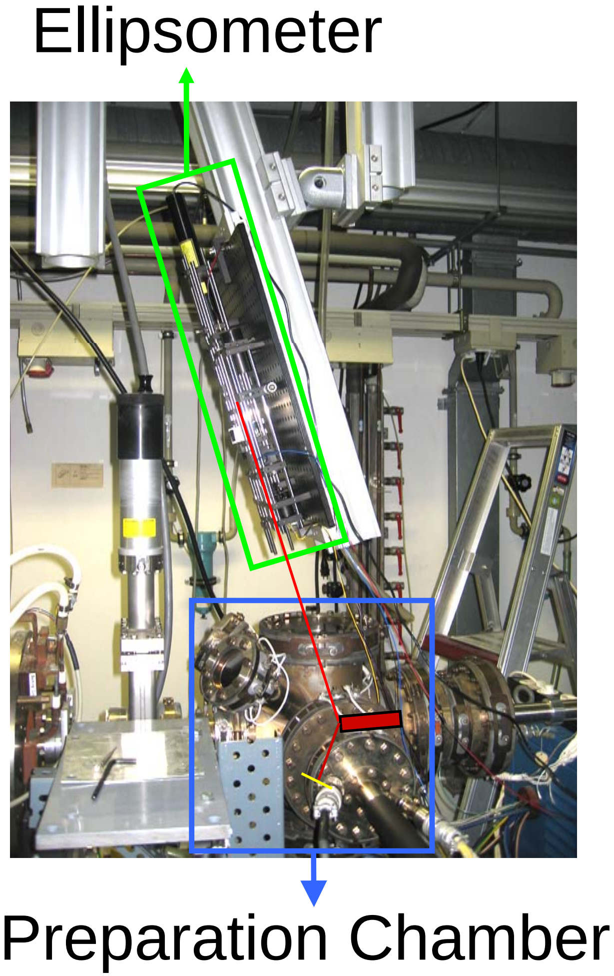
Sc

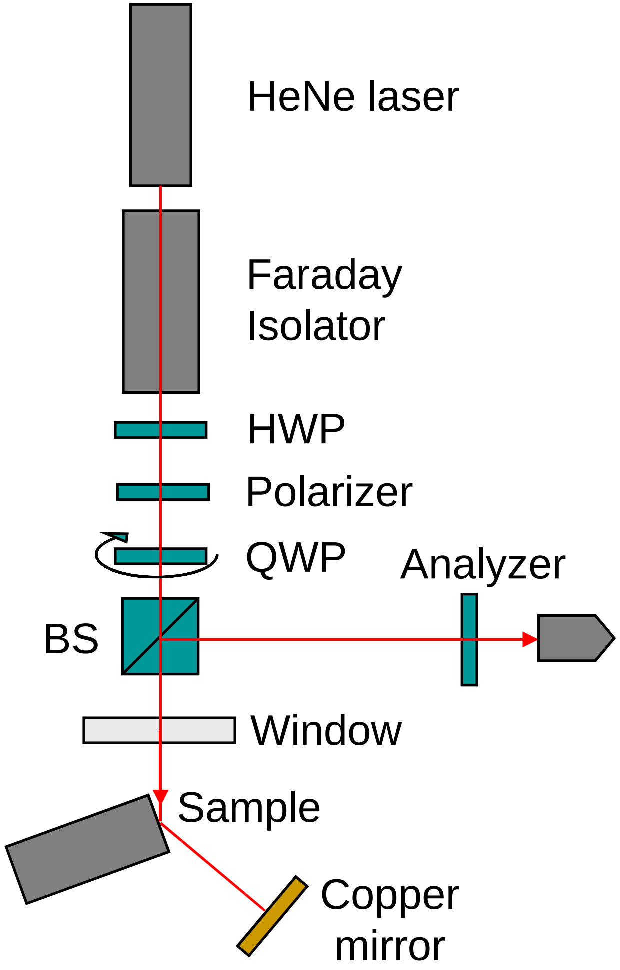
)

Fc

pc

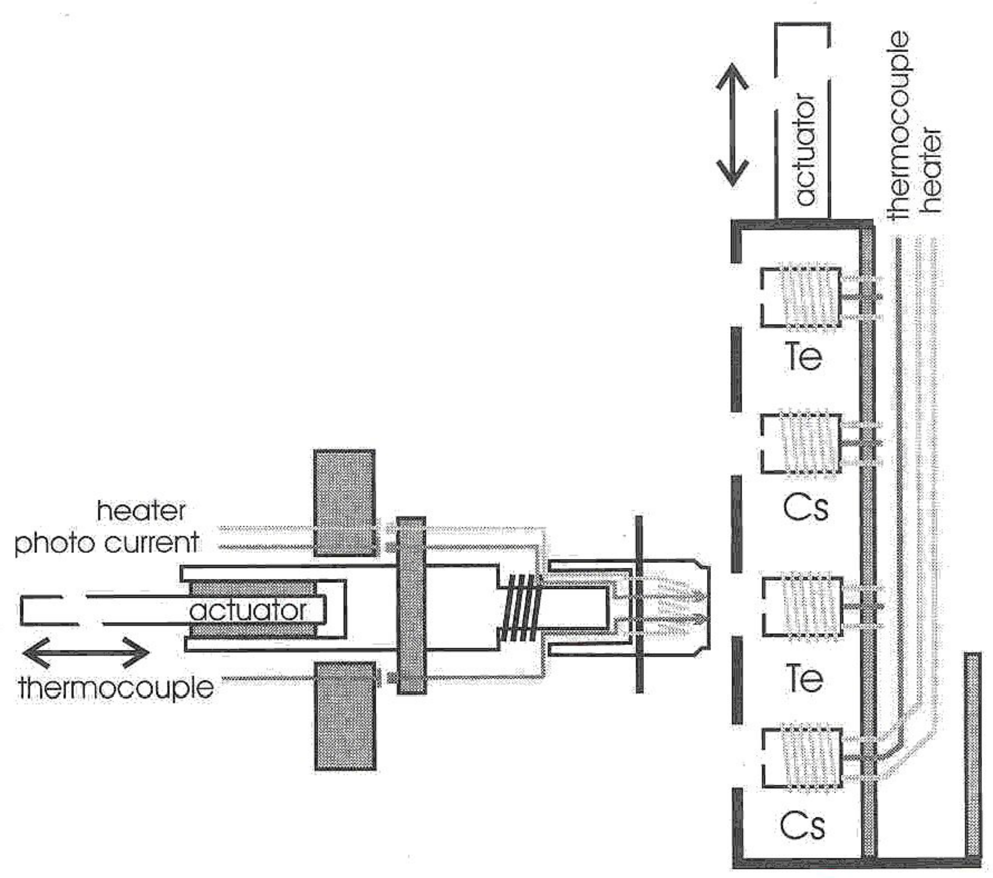
Experimental setup



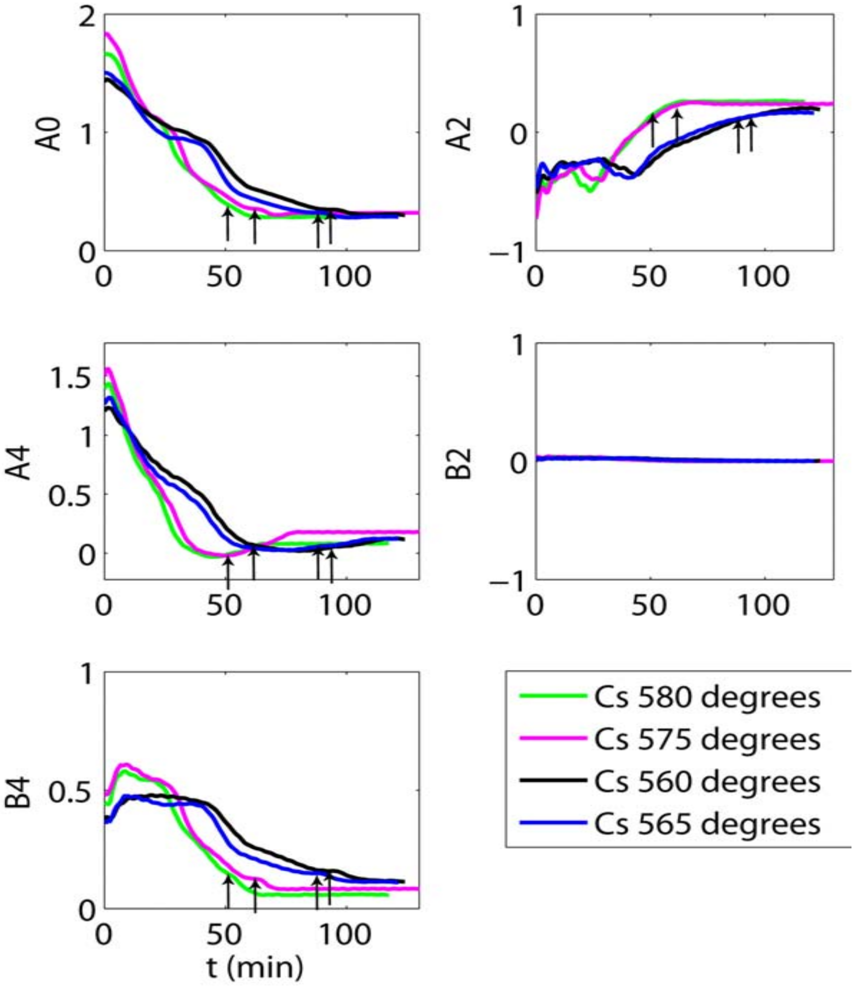


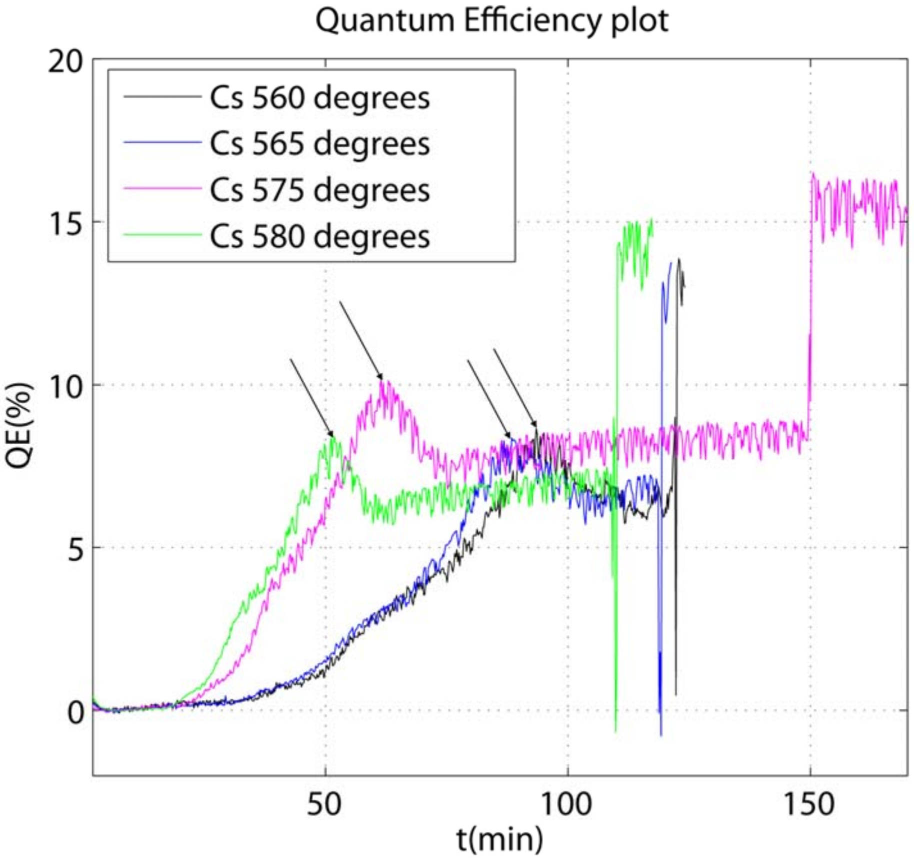
Cs:Te Photocathode Preparation

- Substrate at 120°C
- Deposit Tellurium by Physical Vapor Deposition (PVD) for about 30 minutes
- Deposit Cesium by PVD until cathode is completed
- Cs and Te mixing produces multiple Cs_xTe_y layers

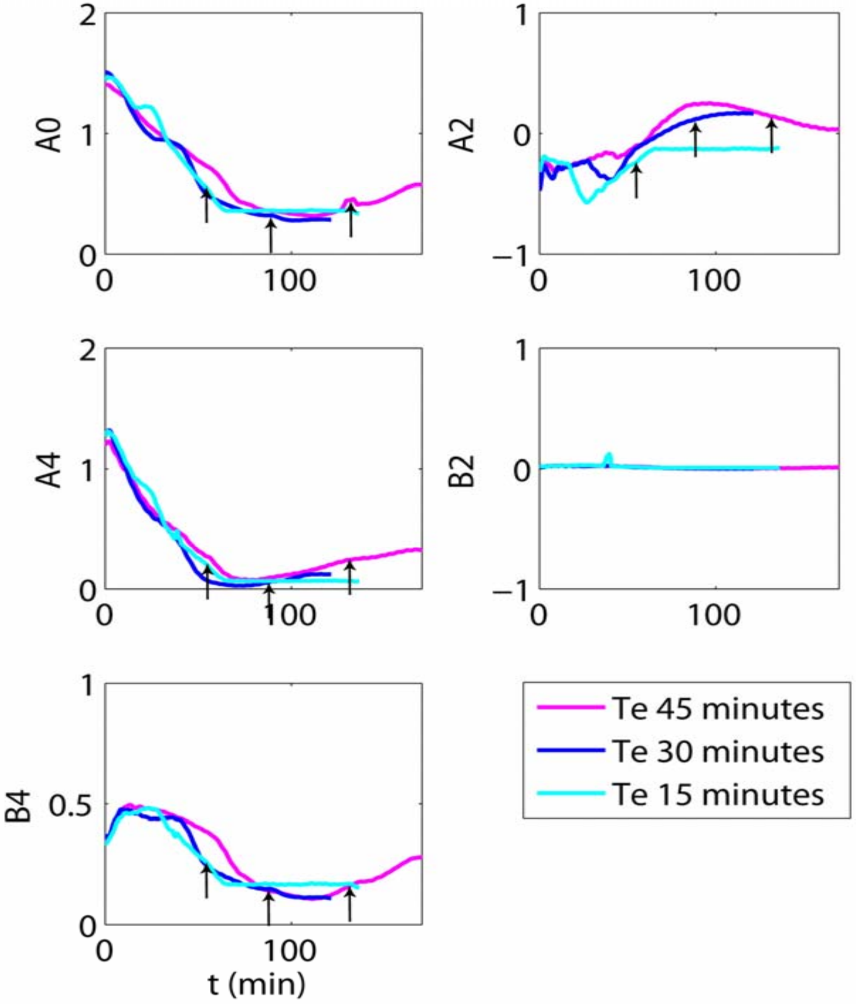


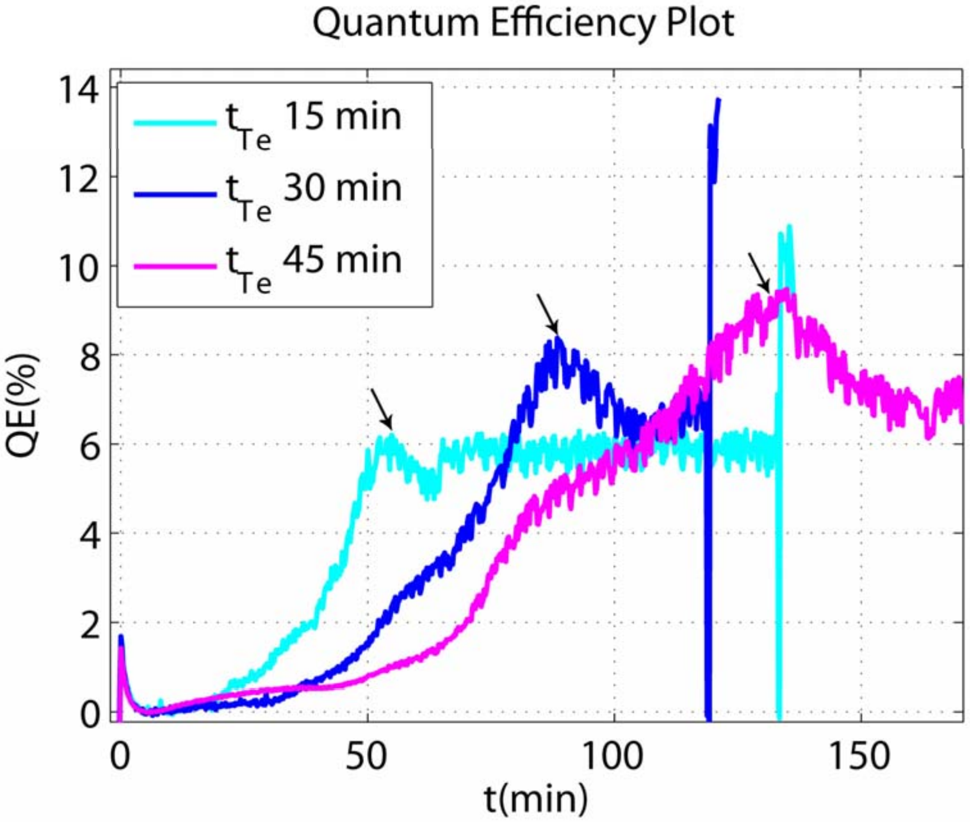
Different Cs deposition rates



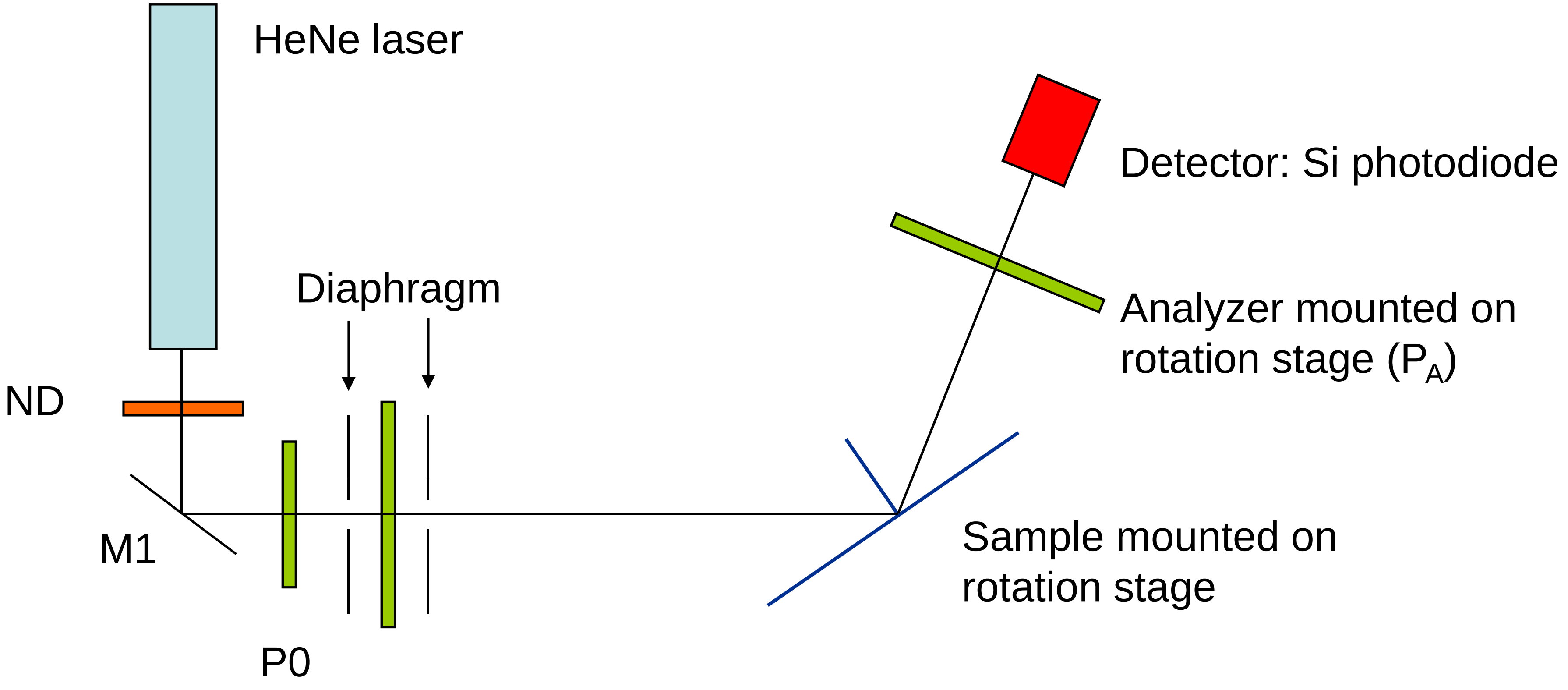


Different Te layers





New setup: Rotating Analyzer Ellipsometer



HeNe laser

Detector: Si photodiode

Diaphragm

Analyzer mounted on rotation stage (P_A)

ND

M1

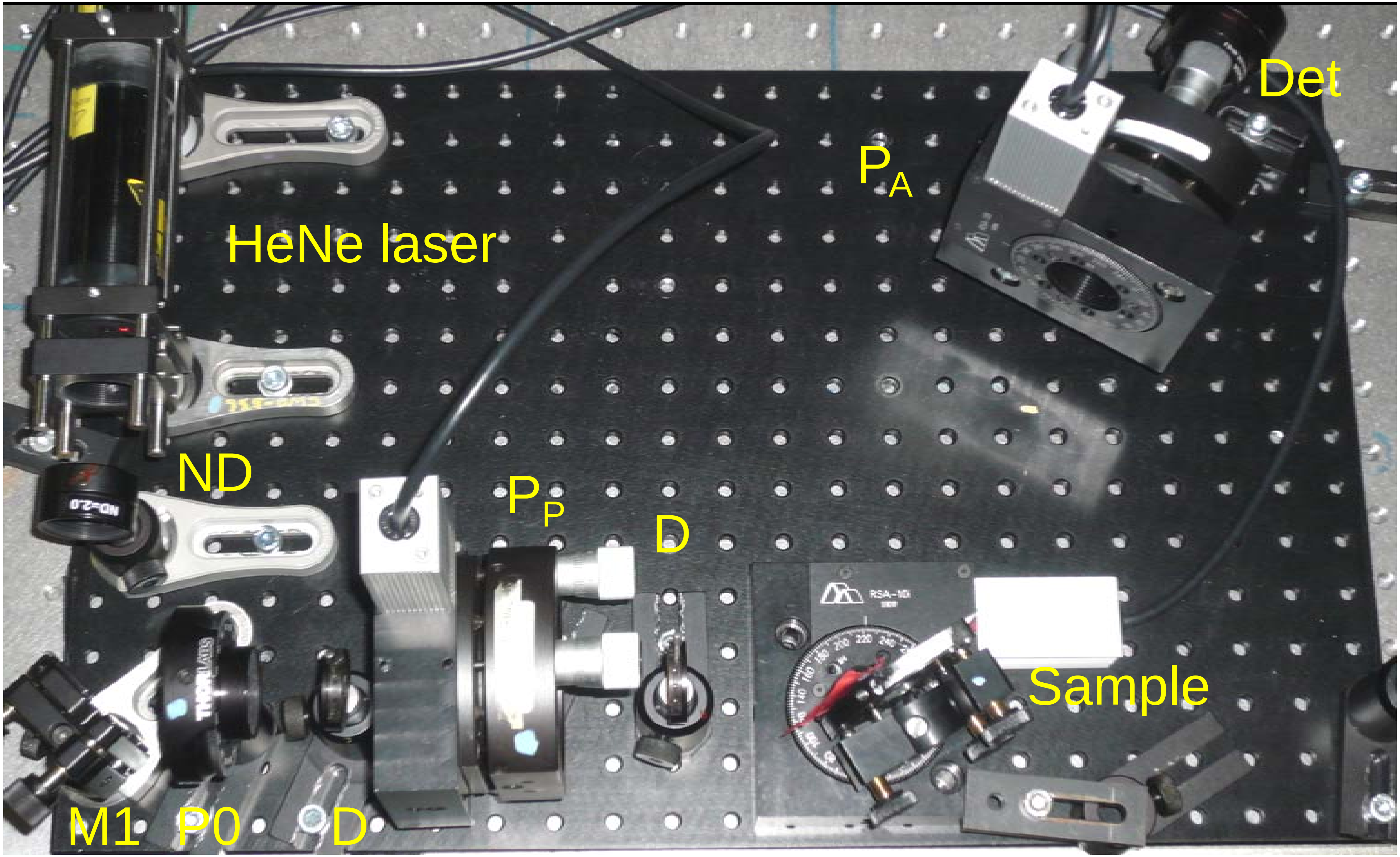
Sample mounted on rotation stage

P0

Polarizer mounted on rotation stage (P_p) set at 45°

P0 is used to set the input polarization equal to the p-polarization for the sample

Rotating Analyzer Ellipsometer



Improvements on setup

- Rotating Analyzer Ellipsometer (RAE)
- Motorized rotation stages
  - Constant rotation velocity
  - Accurate positioning through build-in encoders
  - Accurate determination of relative angles
- Alignment procedure for optical elements
  - Focused on accurate determinations of relative angles

Improvements (continued)

- Build additional electronics to synchronize angle measurement with detector signal
  - Requires two-channel oscilloscope
  - Trigger pulse & sample rate determine angle resolution

Alignment

- First use glass plate (n=1.5225) under Brewster angle to set P0 to p-polarization
- Then align P_P and P_A with respect to the p-polarization (determine angle of fast axis with respect to p-polarization)
- Insert P_P and set angle P_P to 45°
- Mount sample and determine 0°.
- Set sample to desired angle
- Place P_A and align, place detector
- Perform measurement

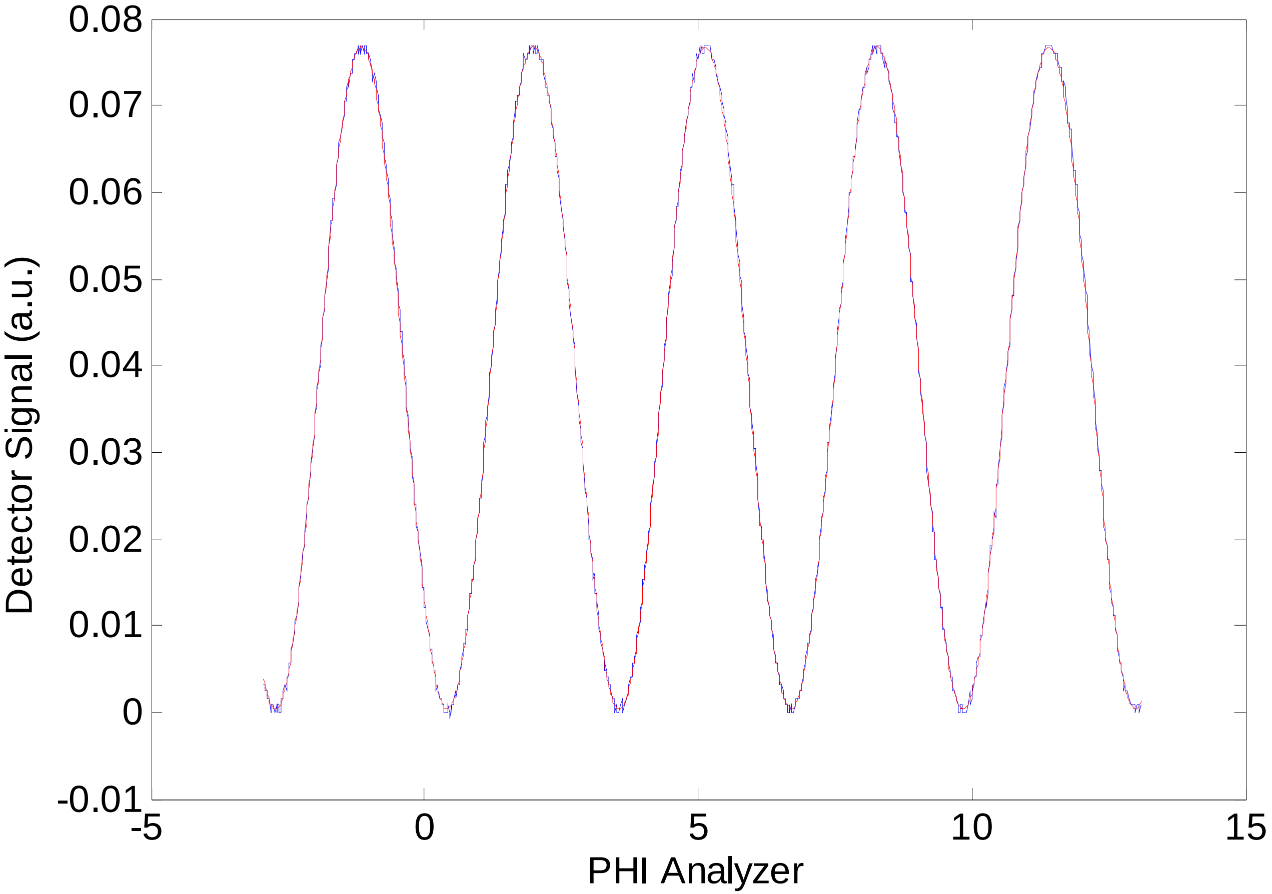
Results

- Measurement of relative angles with resolution better than 0.05°
- Absolute angle measurement is
  - 0.15° for angle of incidence for polarizer and analyzer
  - ~ 0.5° for angle of incidence on sample
- Sample = SOI wafer
  - $n_{Si} = 3.87732537 + i\,0.0213285228$ (632 nm)
  - $n_{SiO2} = 1.45707806$

Results (continued)

- SOI wafer
  - 1.5 µm Si top layer
  - 3 µm SiO_2 insulation layer
  - 522 µm Si substrate
- From these values we expect
  - $\Psi = 24.7°$ and $\Delta = 163.2°$ (632 nm, $\theta_i = 60°$)

Measurement on SOI wafer



Curve fit to measured data: fit coefficients are used to calculated Ψ and Δ

Results for SOI wafer

- Fit to function

$$I(\varphi) = a_0 + a_2 \cos(2\varphi) + b_2 \sin(2\varphi)$$

  - $a_0 = 0.0386$, $a_2 = -0.0256$, $b_2 = -0.0284$

- This results in
  - $\Psi = 24.25°$ and $\Delta = 168.4°$
- Theoretical
  - $\Psi = 24.7°$ and $\Delta = 163.2°$

Conclusions

- Rotating Analyzer Ellipsometer build and tested
- Obtained ellipsometric parameters agree well with theoretical values
- Obtained ellipsometric parameters compare well with commercial ellipsometer
- Still required:
  - Modification to preparation chamber
    - Stress free input/output windows
    - Mechanical setup for accurate alignment/ measurement of angle of incidence (highly sensitive)

Acknowledgement

This work is supported by
European Community – FP6

Research Infrastructure Activity
“Structuring the European Research Area” programme

CARE, contract number RII3-CT-2003-506395