CIC nanoGUNE
nanoscience cooperative research center

Generalized Magneto-Optical Ellipsometry (GME) for Magnetic Materials Characterization

- basic considerations
  - Light Polarization and Reflection
  - Jones Calculus and Ellipsometry
- Fundamentals of Magneto-Optics
  - dielectric tensor
  - Nomenclature of Magneto-Optical effects
  - size of the Magneto-Optical effect
- Generalized Magneto-Optical Ellipsometry
  - experimental set-up and capabilities
  - detection and analysis scheme
  - applications
  - recent developments

Andreas Berger

a.berger@nanogune.eu | www.nanogune.eu

CIC nanoGUNE
nanoscience cooperative research center

Generalized Magneto-Optical Ellipsometry (GME) for Magnetic Materials Characterization

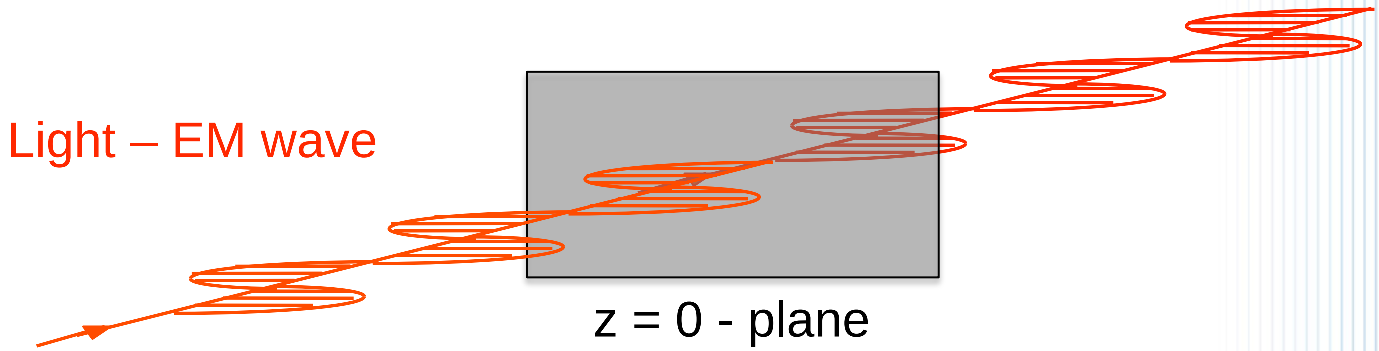
- **basic considerations**
    - **Light Polarization and Reflection**
    - **Jones Calculus and Ellipsometry**
- Fundamentals of Magneto-Optics
    - dielectric tensor
    - Nomenclature of Magneto-Optical effects
    - size of the Magneto-Optical effect
- Generalized Magneto-Optical Ellipsometry
    - experimental set-up and capabilities
    - detection and analysis scheme
    - applications
    - recent developments

Andreas Berger

a.berger@nanogune.eu | www.nanogune.eu

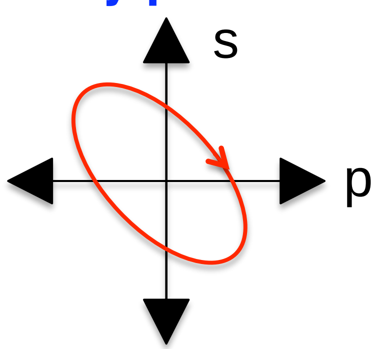
Light and Polarization

Polarized light



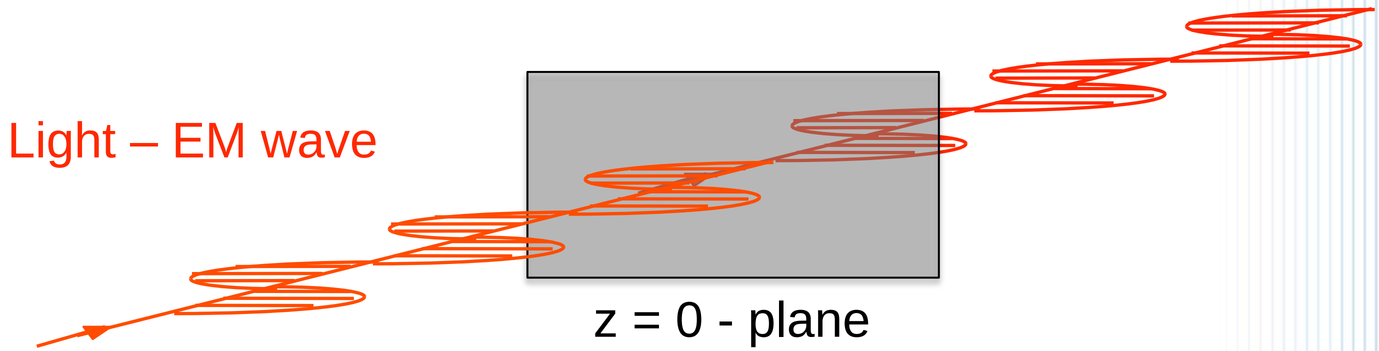
time evolution of the electromagnetic field in the z = 0 – plane

stable → fully polarized: P = 1



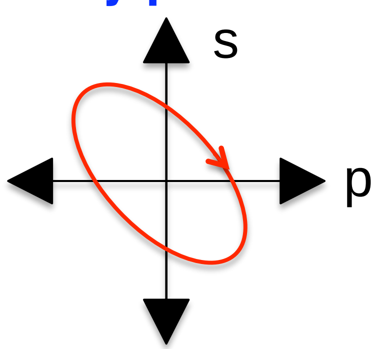
Light and Polarization

Polarized light



time evolution of the electromagnetic field in the z = 0 – plane

stable → fully polarized: P = 1



Jones Calculus

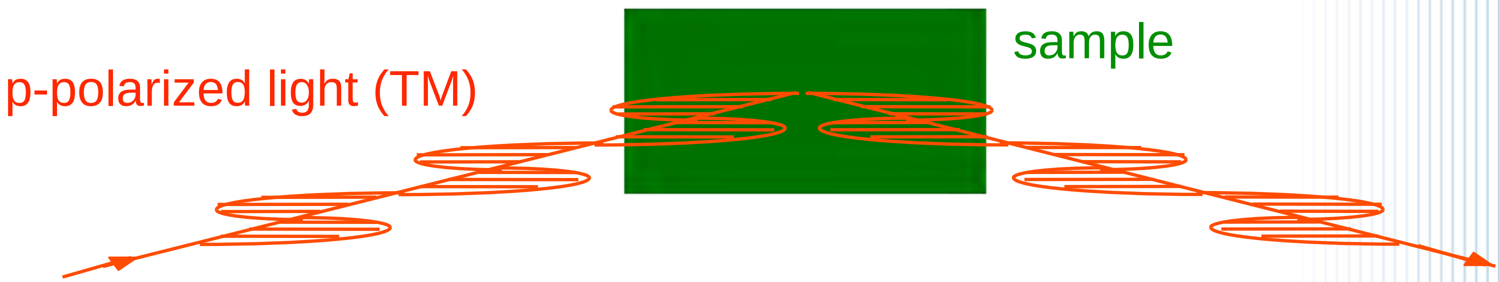
fixed $\underline{k}$, P = 1

$$\underline{E} = \begin{bmatrix} E_s \\ E_p \end{bmatrix} \exp(i(\underline{k}\bullet\underline{r}-\omega t))$$

$\underline{E}$ = 2x1 vector, E_s and E_p complex

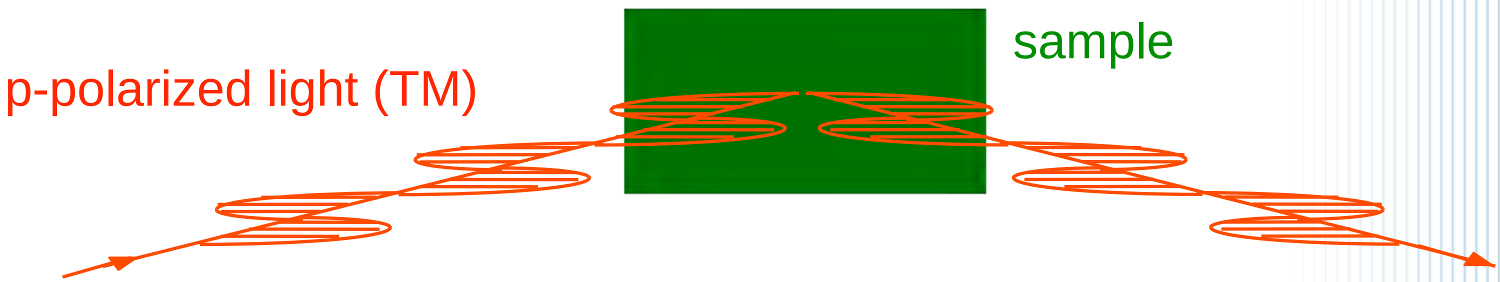
Light Reflection

Reflection from a flat surface



Light Reflection

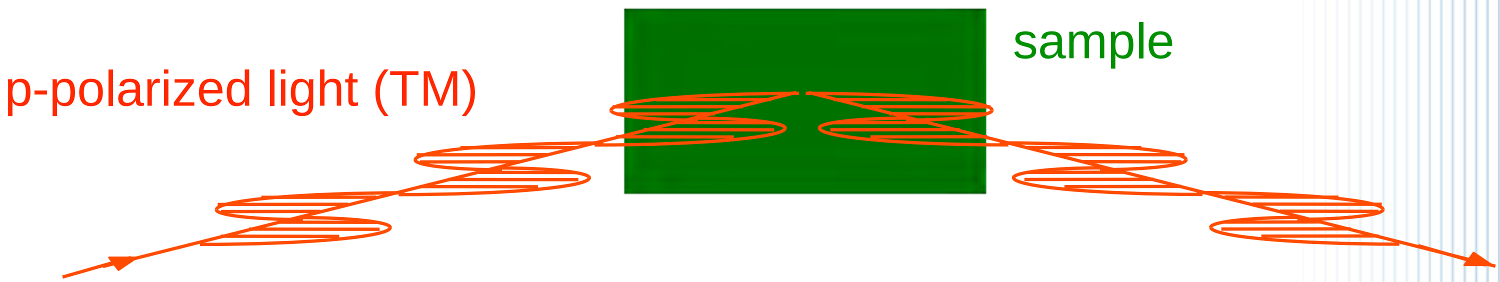
Reflection from a flat surface



$$P_{in} = \begin{bmatrix} E_s \\ E_p \end{bmatrix}_{in}$$

Light Reflection

Reflection from a flat surface

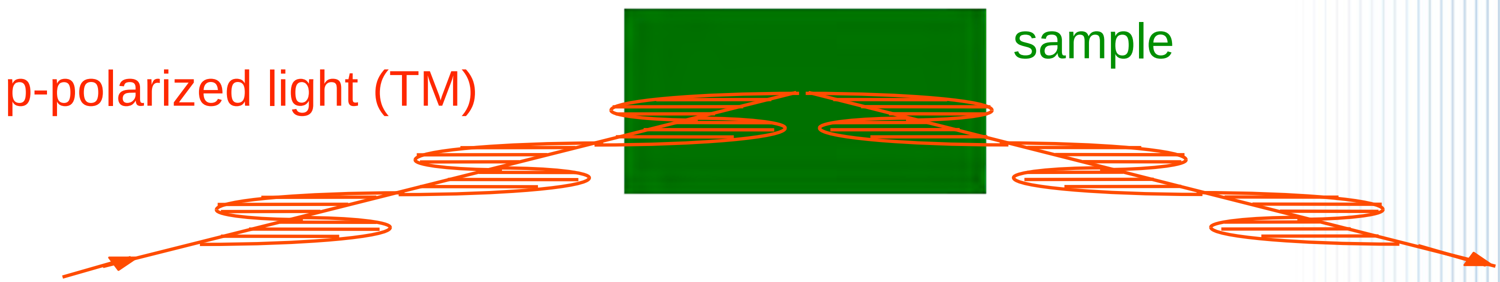


$$P_{in} = \begin{bmatrix} E_s \\ E_p \end{bmatrix}_{in}$$

$$P_{out} = \begin{bmatrix} E_s \\ E_p \end{bmatrix}_{out}$$

Light Reflection

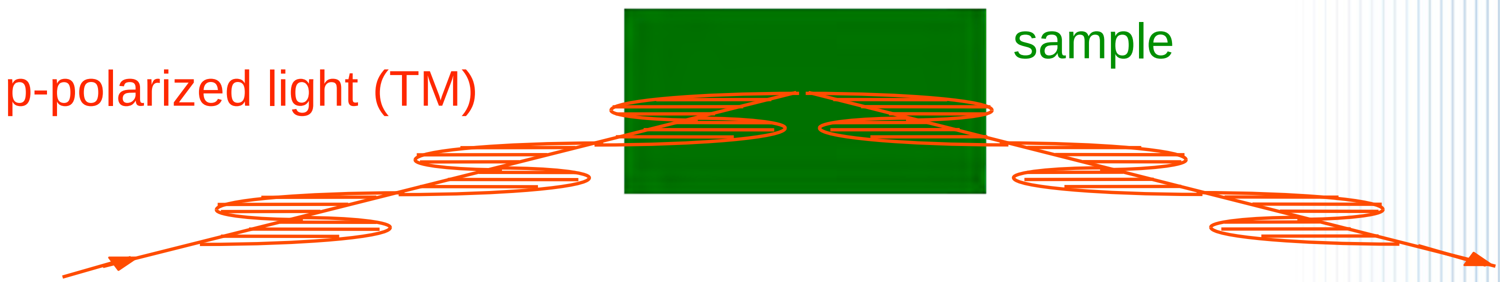
Reflection from a flat surface



$$P_{in} = \begin{bmatrix} E_s \\ E_p \end{bmatrix}_{in} \qquad R = \begin{bmatrix} r_{ss} & r_{sp} \\ r_{ps} & r_{pp} \end{bmatrix} \qquad P_{out} = \begin{bmatrix} E_s \\ E_p \end{bmatrix}_{out}$$

Light Reflection

Reflection from a flat surface



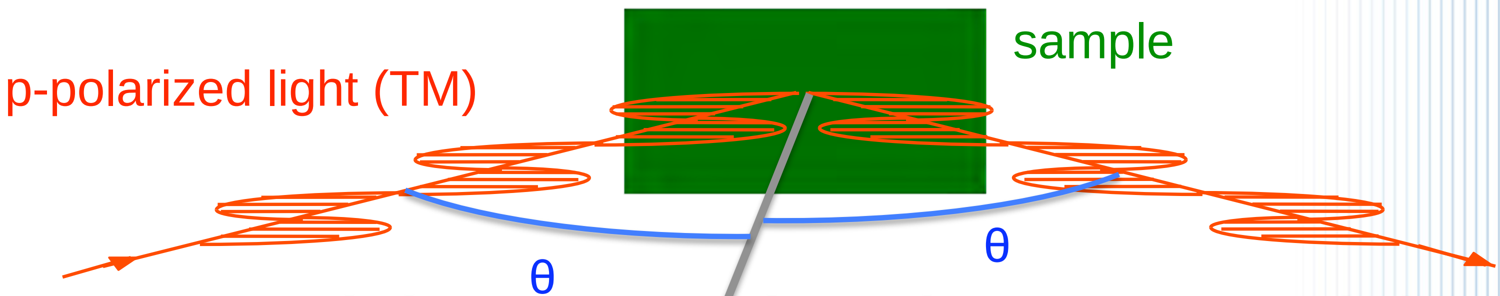
$$P_{in} = \begin{bmatrix} E_s \\ E_p \end{bmatrix}_{in} \qquad R = \begin{bmatrix} r_{ss} & r_{sp} \\ r_{ps} & r_{pp} \end{bmatrix} \qquad P_{out} = \begin{bmatrix} E_s \\ E_p \end{bmatrix}_{out}$$

Plane-Wave Reflection from flat surface is fully described by a

2x2 reflection matrix **R** (applies to any optical element)

Light Reflection

Reflection from a flat surface



$$P_{in} = \begin{bmatrix} E_s \\ E_p \end{bmatrix}_{in} \qquad R = \begin{bmatrix} r_{ss} & r_{sp} \\ r_{ps} & r_{pp} \end{bmatrix} \qquad P_{out} = \begin{bmatrix} E_s \\ E_p \end{bmatrix}_{out}$$

Plane-Wave Reflection from flat surface is fully described by a

R depends on geometry (θ) and material **ε** or **ε**(z)

Ellipsometry: methodology to measure R to determine **ε** or **ε**(z)

CIC nanoGUNE
nanoscience cooperative research center

Generalized Magneto-Optical Ellipsometry (GME) for Magnetic Materials Characterization

- basic considerations
    - Light Polarization and Reflection
    - Jones Calculus and Ellipsometry
- **Fundamentals of Magneto-Optics**
    - **dielectric tensor**
    - **Nomenclature of Magneto-Optical effects**
    - **size of the Magneto-Optical effect**
- Generalized Magneto-Optical Ellipsometry
    - experimental set-up and capabilities
    - detection and analysis scheme
    - applications
    - recent developments

Andreas Berger

a.berger@nanogune.eu | www.nanogune.eu

CIC nanoGUNE nanoscience cooperative research center

Fundamentals of Magneto-Optics

Materials Optics: EM-wave propagation in the presence of matter

- Maxwell's equations: contain E, D, H, B

- linear materials relation: D = **ε** E; B = ***μ*** H → **ε**, ***μ*** are 3x3 tensors

- Optics: ***μ*** = **1**

- Materials Optics (incl. Magneto-Optics): **ε**

- non-magnetic material: isotropic, cubic → reflection matrix

$$\hat{\varepsilon} = \begin{bmatrix} \varepsilon & 0 & 0 \\ 0 & \varepsilon & 0 \\ 0 & 0 & \varepsilon \end{bmatrix}$$

$$\begin{bmatrix} r_{ss} & 0 \\ 0 & r_{pp} \end{bmatrix}$$

CIC nanoGUNE nanoscience cooperative research center

Fundamentals of Magneto-Optics

Materials Optics: EM-wave propagation in the presence of matter

- magnetic material: (1st order terms)

$$\hat{\varepsilon} = \varepsilon \begin{bmatrix} 1 & iQm_z & -iQm_y \\ -iQm_z & 1 & iQm_x \\ iQm_y & -iQm_x & 1 \end{bmatrix}$$

- Q is the magneto-optical coupling constant (λ)

- m_x, m_y, m_z are the components of **M**

Fundamentals of Magneto-Optics

Materials Optics: EM-wave propagation in the presence of matter

- magnetic material:
  (1st order terms)

$$\hat{\varepsilon} = \varepsilon \begin{bmatrix} 1 & iQm_z & -iQm_y \\ -iQm_z & 1 & iQm_x \\ iQm_y & -iQm_x & 1 \end{bmatrix}$$

- Q is the magneto-optical coupling constant (λ)

- m_x, m_y, m_z are the components of **M**

- **Q is of the order of 10^{-4} - 10^{-3} for ferromagnets**

CIC nanoGUNE nanoscience cooperative research center

Fundamentals of Magneto-Optics

Materials Optics: EM-wave propagation in the presence of matter

- magnetic material:
  (1st order terms)

$$\hat{\varepsilon} = \varepsilon \begin{bmatrix} 1 & iQm_z & -iQm_y \\ -iQm_z & 1 & iQm_x \\ iQm_y & -iQm_x & 1 \end{bmatrix}$$

- Q is the magneto-optical coupling constant (λ)

- m_x, m_y, m_z are the components of **M**

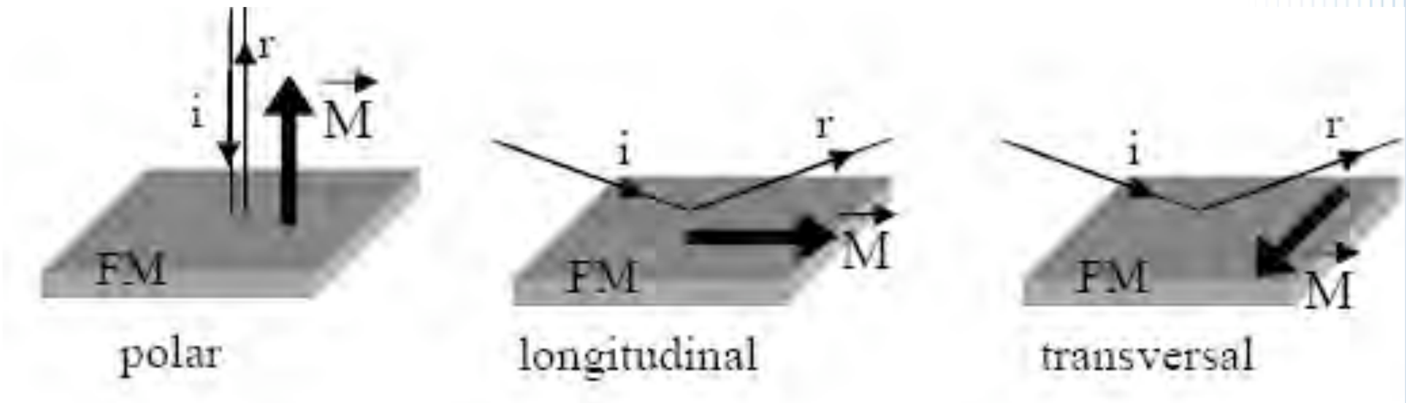
- **Q is of the order of 10^{-4} - 10^{-3} for ferromagnets**

→ **Optical Activity: M orientation dependence**

CIC nanoGUNE
nanoscience cooperative research center

Fundamentals of Magneto-Optics

Nomenclature of Magneto-Optical effects



polar configuration

Dielectric Tensor

$$\begin{pmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \\ \varepsilon_{yx} & \varepsilon_{yy} & \\ & & \varepsilon_{zz} \end{pmatrix}$$

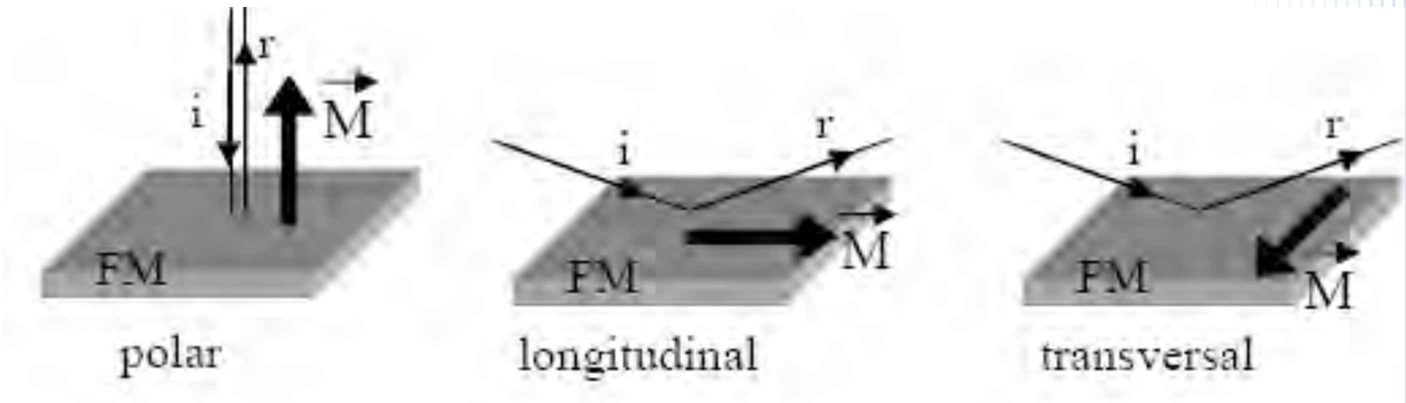
Reflectivity matrix

$$R = \begin{pmatrix} r_{s\to s} & r_{p\to s} \\ r_{s\to p} & r_{p\to p} \end{pmatrix}$$

CIC nanoGUNE nanoscience cooperative research center

Fundamentals of Magneto-Optics

Nomenclature of Magneto-Optical effects



longitudinal configuration

Dielectric Tensor

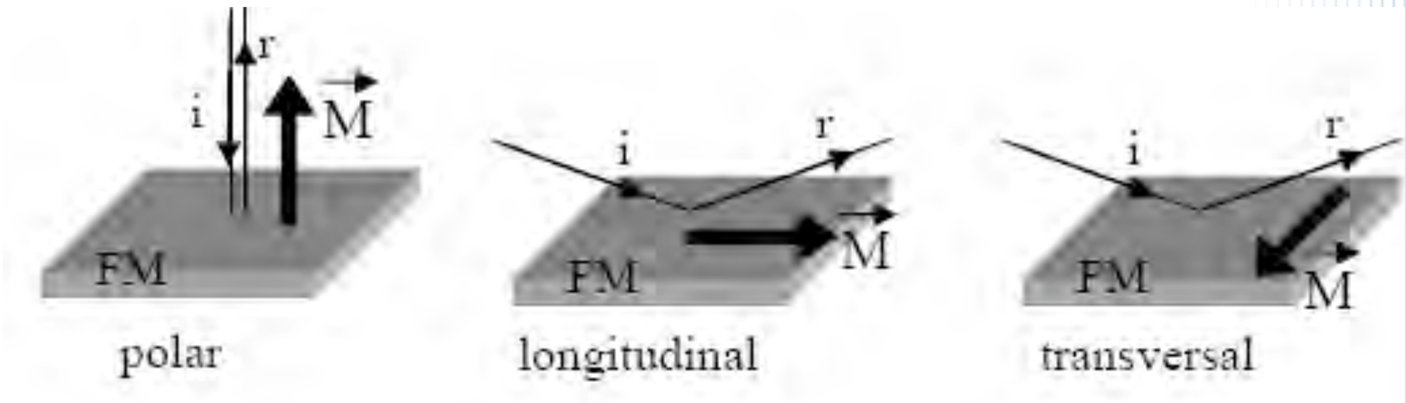
$$\begin{pmatrix} \varepsilon_{xx} & & \\ & \varepsilon_{yy} & \varepsilon_{yz} \\ & \varepsilon_{zy} & \varepsilon_{zz} \end{pmatrix}$$

Reflectivity matrix

$$R = \begin{pmatrix} r_{s\to s} & r_{p\to s} \\ r_{s\to p} & r_{p\to p} \end{pmatrix}$$

Fundamentals of Magneto-Optics

Nomenclature of Magneto-Optical effects



transverse configuration

Dielectric Tensor

$$\begin{pmatrix} \varepsilon_{xx} & & \varepsilon_{xz} \\ & \varepsilon_{yy} & \\ \varepsilon_{zx} & & \varepsilon_{zz} \end{pmatrix}$$

Reflectivity matrix

$$R = \begin{pmatrix} r_{s\to s} & 0 \\ 0 & r_{p\to p} + \delta_p \end{pmatrix}$$

CIC nanoGUNE
nanoscience cooperative research center

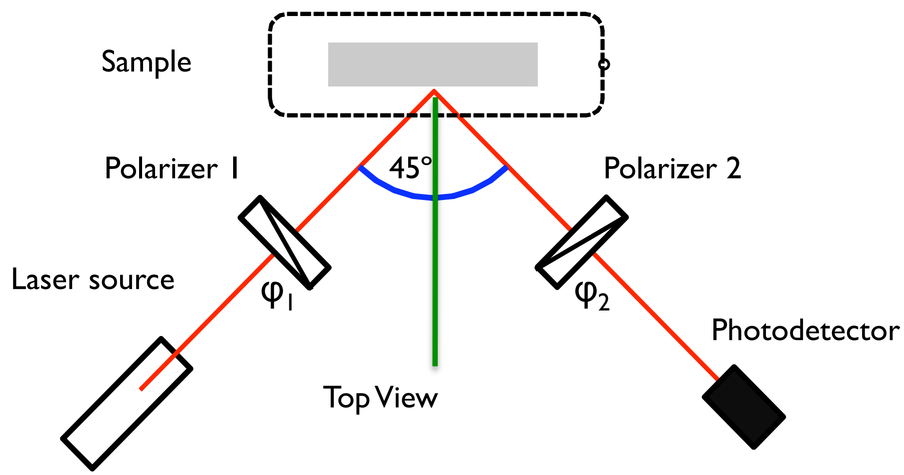
Generalized Magneto-Optical Ellipsometry (GME) for Magnetic Materials Characterization

- basic considerations
    - Light Polarization and Reflection
    - Jones Calculus and Ellipsometry
- Fundamentals of Magneto-Optics
    - dielectric tensor
    - Nomenclature of Magneto-Optical effects
    - size of the Magneto-Optical effect
- **Generalized Magneto-Optical Ellipsometry**
    - **experimental set-up and capabilities**
    - **detection and analysis scheme**
    - **applications**
    - **recent developments**

Andreas Berger

Experimental Magneto-Optics

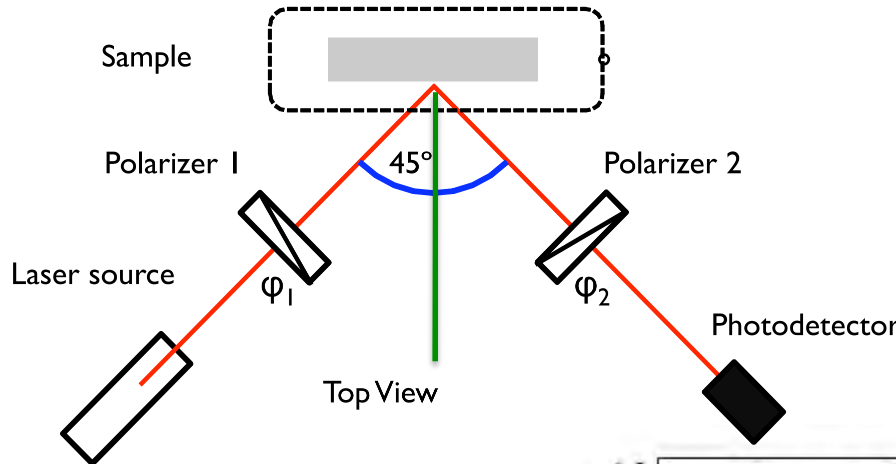
crossed Polarizer set-up



CIC nanoGUNE
nanoscience cooperative research center

Experimental Magneto-Optics

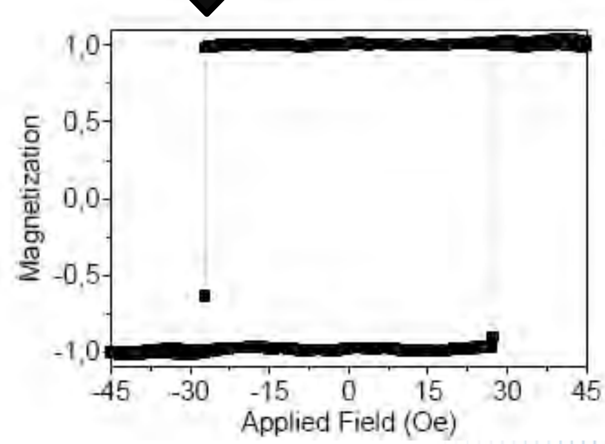
crossed Polarizer set-up



Performance: 30 nm Co-film

- complete hysteresis loop in 10 ms
- S/N-ratio = 48.2 (30 μs)

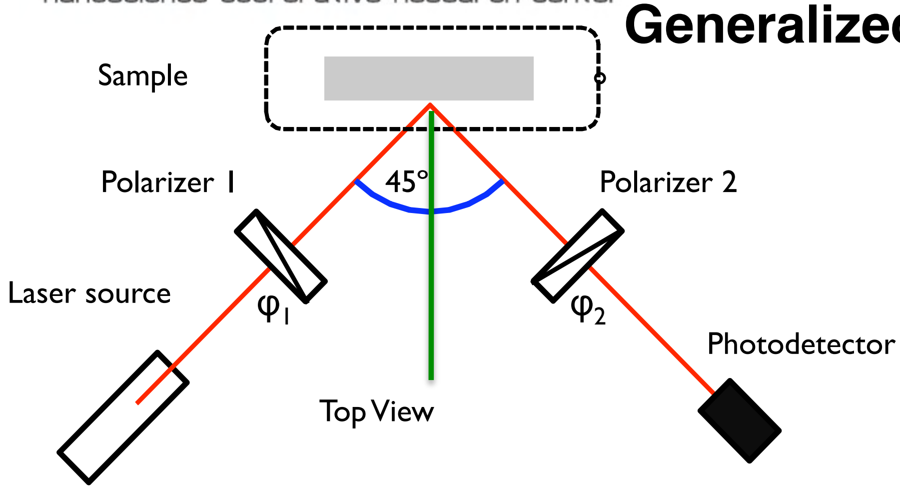
- optical noise level 1μrad/√Hz (DC)
  (1/30 monolayer signal)



a.berger@nanogune.eu | www.nanogune.eu

Experimental Magneto-Optics

Generalized Magneto-Optical Ellipsometry (GME)



maximum information from any reflection experiment

see A. Berger et al., APL **71**, 965 (1997)

Jones Matrices Analysis

$$E_D = r_p \begin{pmatrix} \cos^2\varphi_2 & \sin\varphi_2\cos\varphi_2 \\ \sin\varphi_2\cos\varphi_2 & \sin^2\varphi_2 \end{pmatrix} \begin{pmatrix} \tilde{r}_s & \tilde{r}_{ps} \\ -\tilde{r}_{ps} & 1+\tilde{\delta}_p \end{pmatrix} \begin{pmatrix} \cos^2\varphi_1 & \sin\varphi_1\cos\varphi_1 \\ \sin\varphi_1\cos\varphi_1 & \sin^2\varphi_1 \end{pmatrix} \rightarrow I = |E_D|^2$$

$$\frac{dI}{I} = \frac{I^+ - I^-}{I^+ + I^-} = 4\frac{B_1 f_1 + B_2 f_2 + B_3 f_3 + B_4 f_4}{f_3 + P_4 f_4 + P_5 f_5}$$

$$f_i = f(\varphi_1, \varphi_2)$$

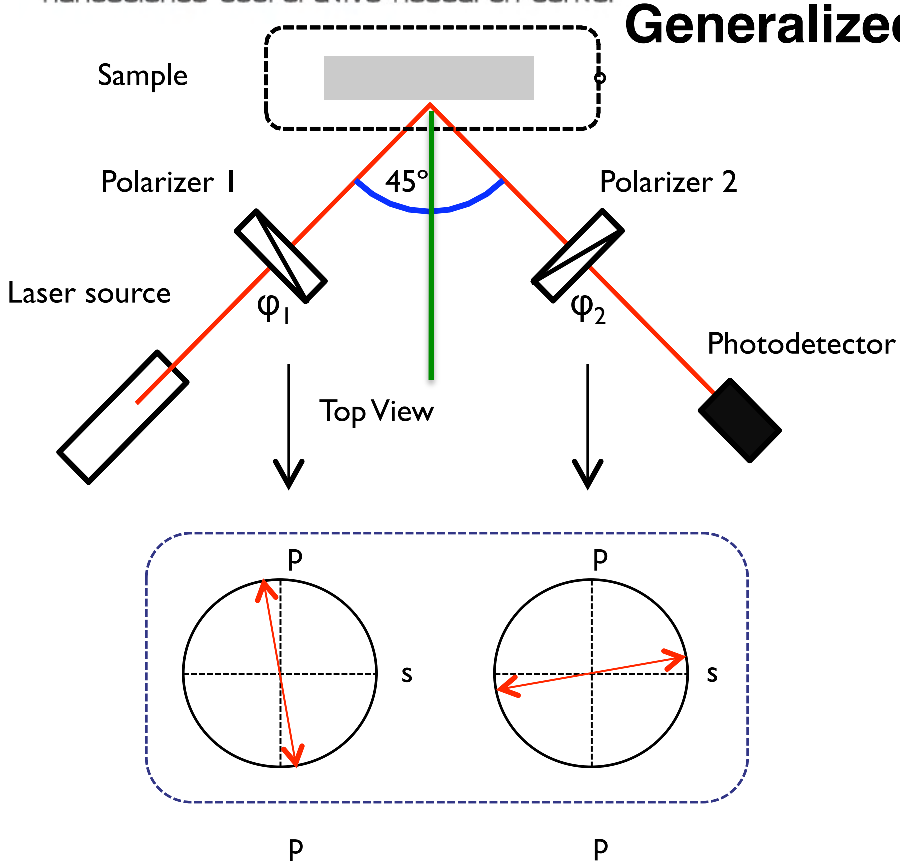
$B_1 = \mathrm{Re}(\tilde{r}_{ps})$ $\quad B_2 = \mathrm{Re}(\tilde{r}_s \tilde{r}^*_{ps})$ MO Longitudinal

$B_3 = \mathrm{Re}(\tilde{\delta}_p)$ $\quad B_4 = \mathrm{Re}(\tilde{r}_s \tilde{\delta}^*_p)$ MO Transverse

$P_4 = 2\,\mathrm{Re}(\tilde{r}_s)$ $\quad P_5 = |\tilde{r}_s|^2$ Pure Optical

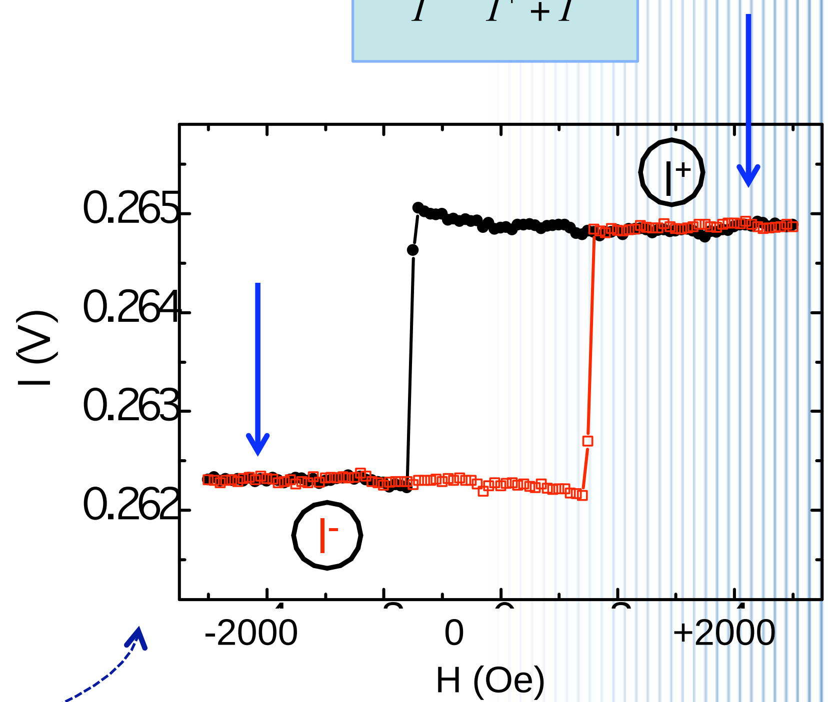
Experimental Magneto-Optics

Generalized Magneto-Optical Ellipsometry (GME)



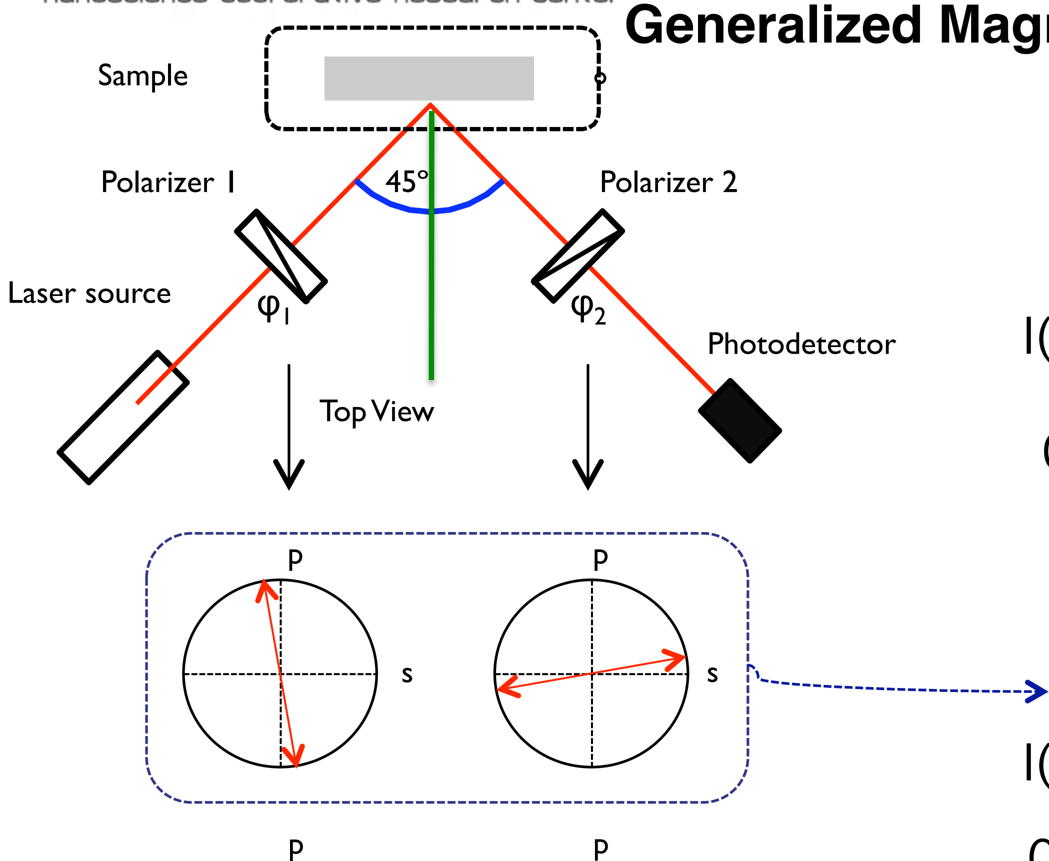
$\Phi_1 = 91°$ $\varphi_2 = 0.5°$

$$\frac{dI}{I} = \frac{I^+ - I^-}{I^+ + I^-}$$

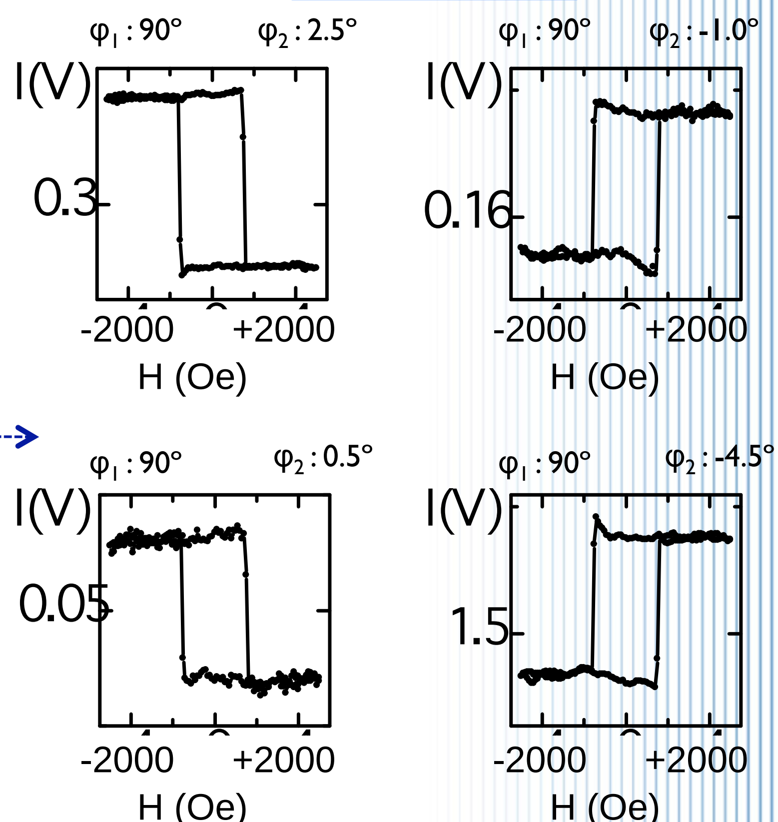


Experimental Magneto-Optics

Generalized Magneto-Optical Ellipsometry (GME)



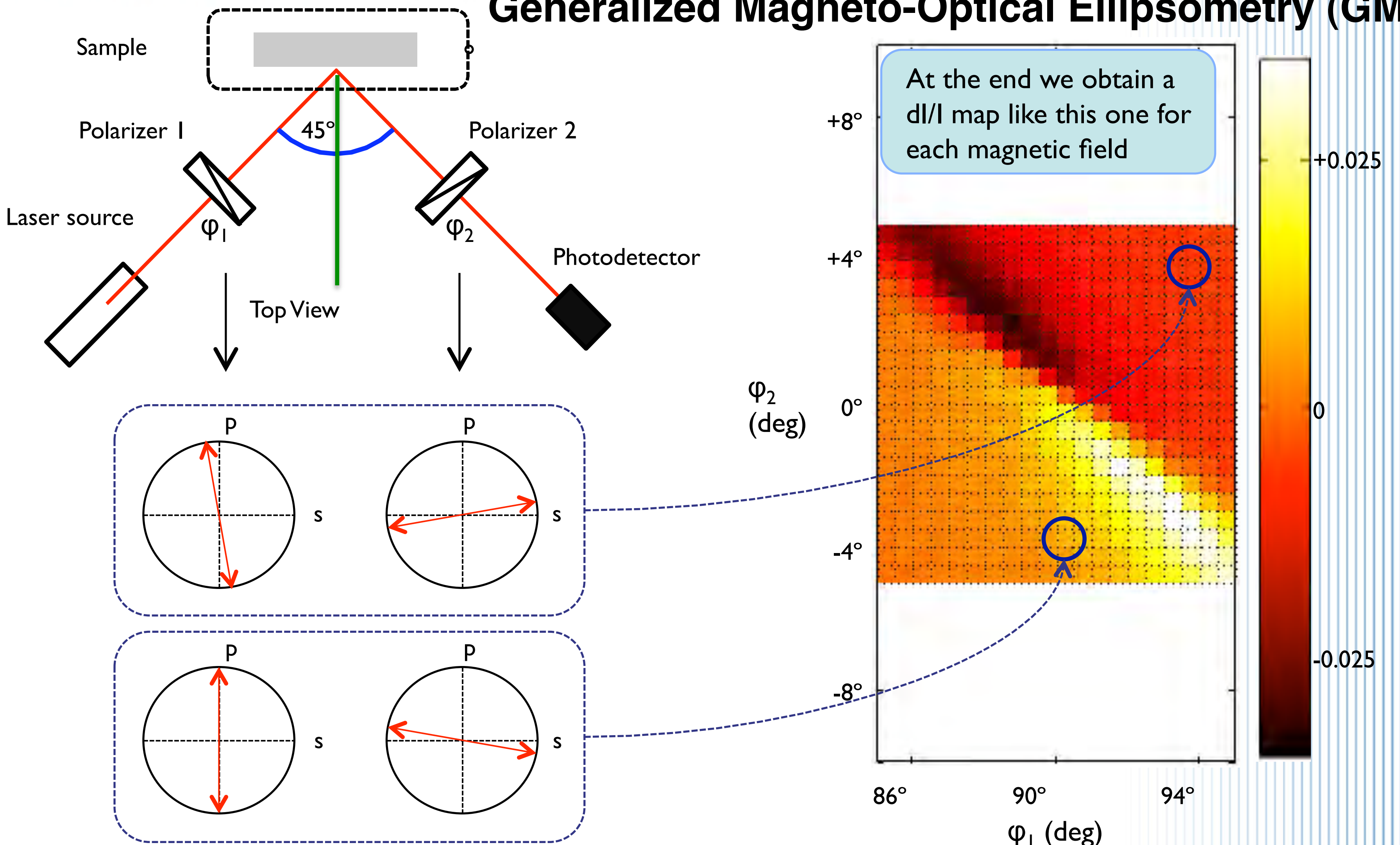
$$\frac{dI}{I} = \frac{I^{+} - I^{-}}{I^{+} + I^{-}}$$



a.berger@nanogune.eu | www.nanogune.eu

Experimental Magneto-Optics

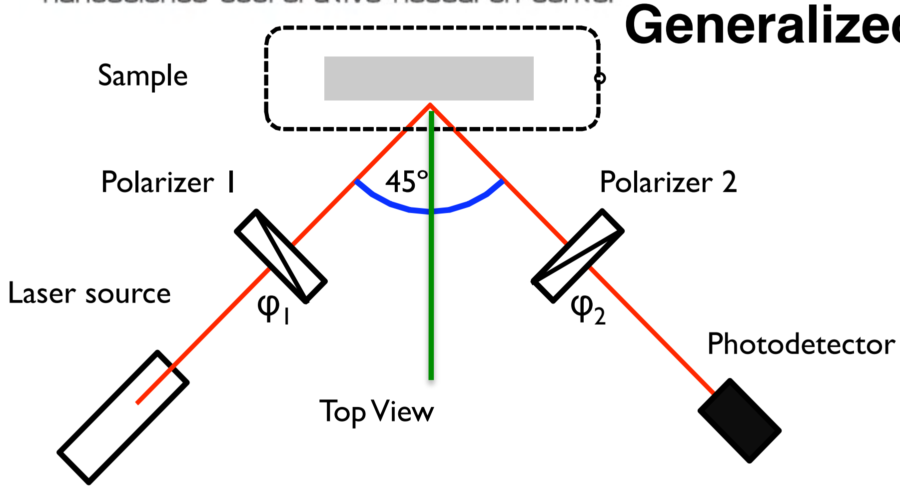
Generalized Magneto-Optical Ellipsometry (GME)



a.berger@nanogune.eu | www.nanogune.eu

Experimental Magneto-Optics

Generalized Magneto-Optical Ellipsometry (GME)



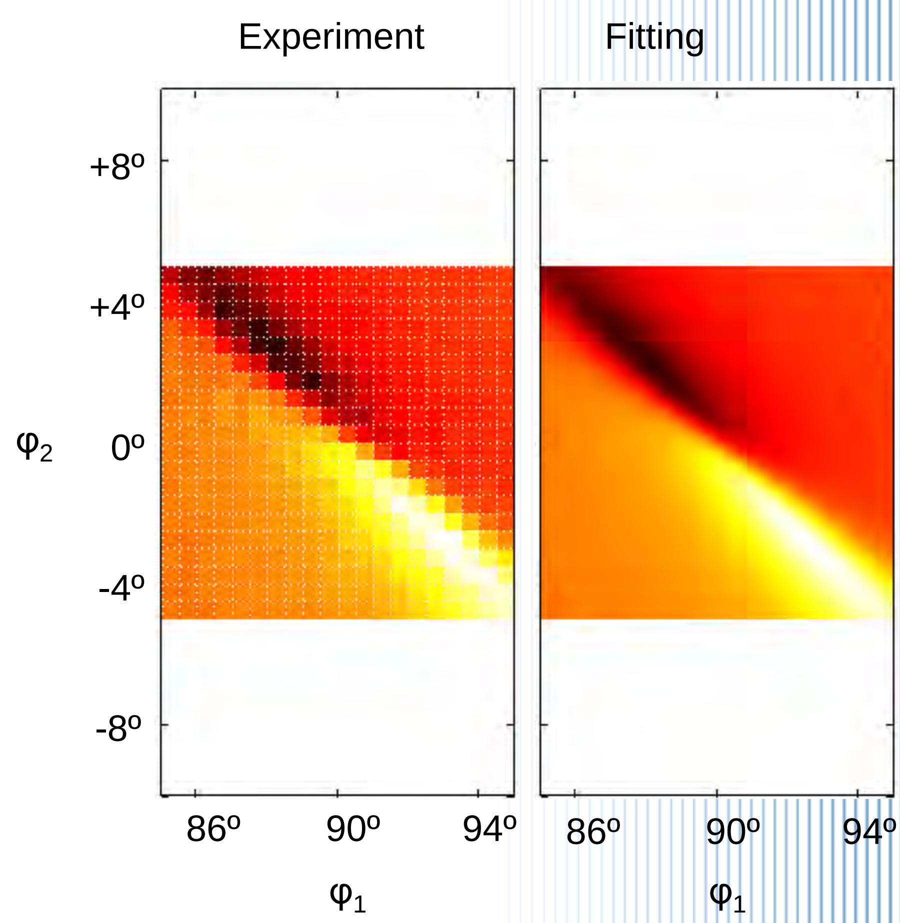
Non-linear Fitting

$$\frac{dI}{I} = 4\frac{B_1 f_1 + B_2 f_2 + B_3 f_3 + B_4 f_4}{f_3 + P_4 f_4 + P_5 f_5}$$

Independent Variable: dI/I

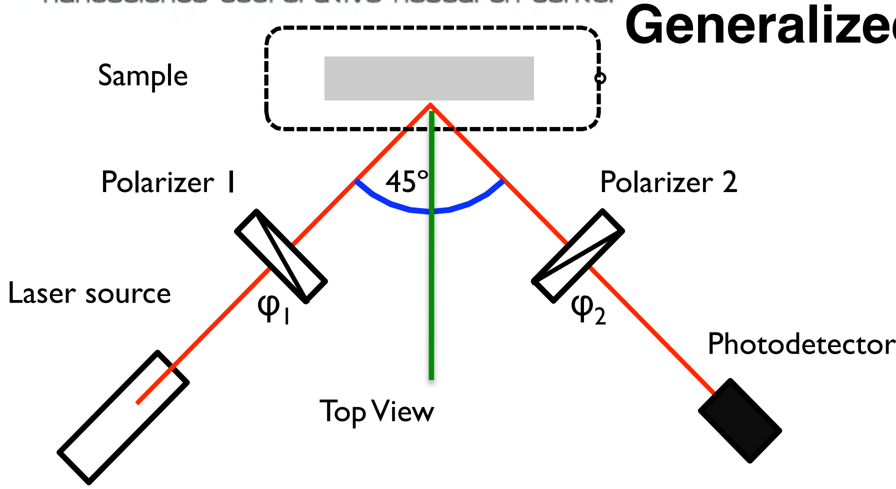
Dependent Variables: φ_1, φ_2

Fitting Parameters: $B_1, B_2, B_3, B_4, P_4, P_5$



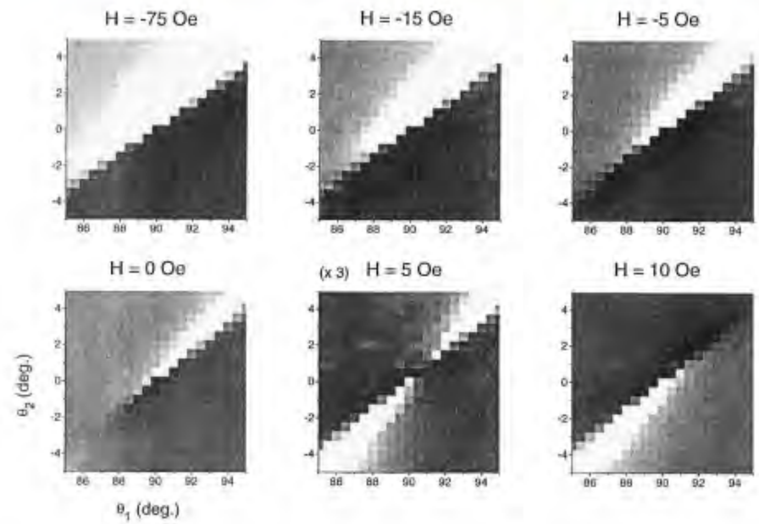
Experimental Magneto-Optics

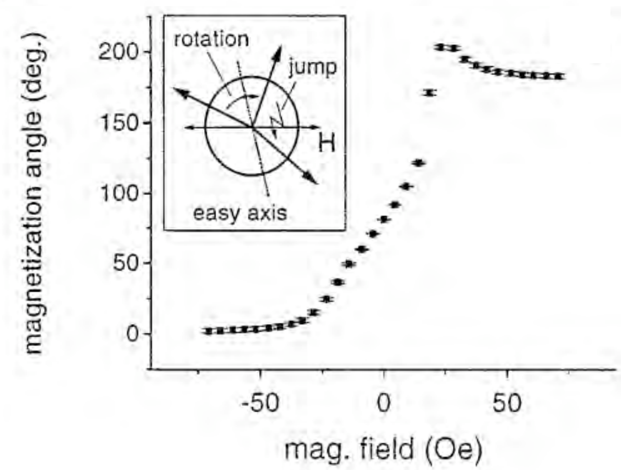
Generalized Magneto-Optical Ellipsometry (GME)



Full Vector magnetometry

φ2





Non-linear Fitting

$$\frac{dI}{I} = 4\frac{B_1 f_1 + B_2 f_2 + B_3 f_3 + B_4 f_4}{f_3 + P_4 f_4 + P_5 f_5}$$

Independent Variable: dI/I

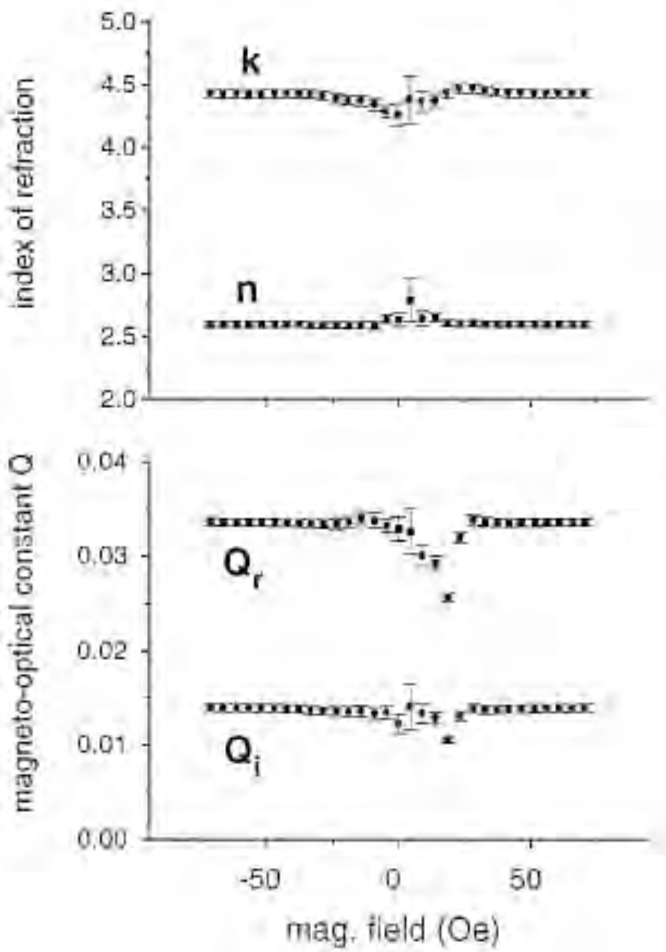
Dependent Variables: φ_1, φ_2

Fitting Parameters: $B_1, B_2, B_3, B_4, P_4, P_5$

Experimental Magneto-Optics

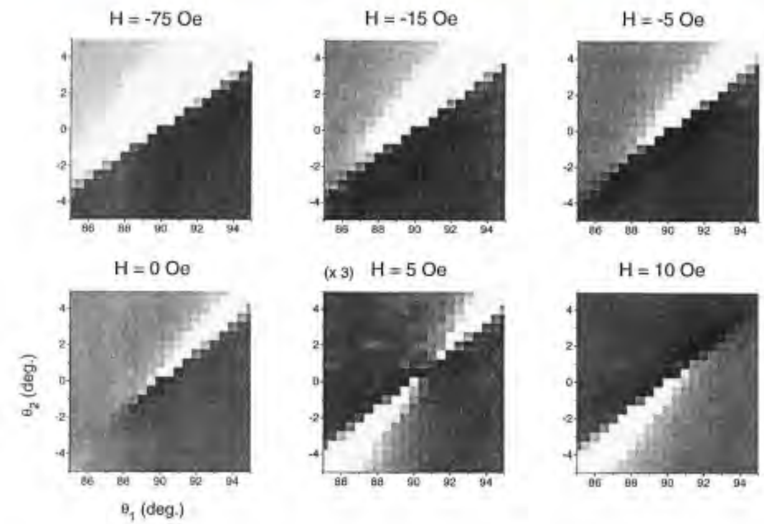
Generalized Magneto-Optical Ellipsometry (GME)

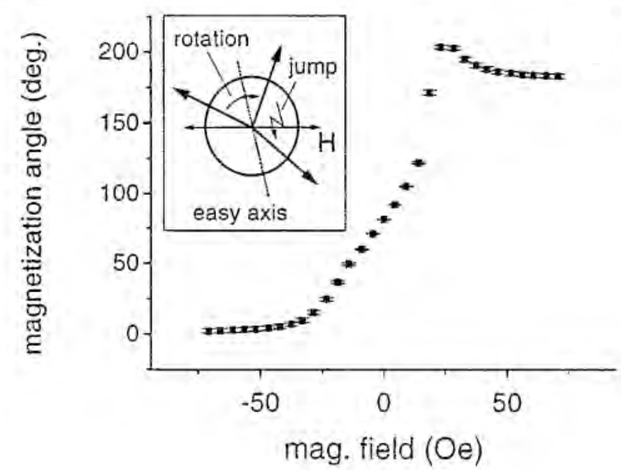
CIC nanoGUNE
nanoscience cooperative research center



Full Vector magnetometry

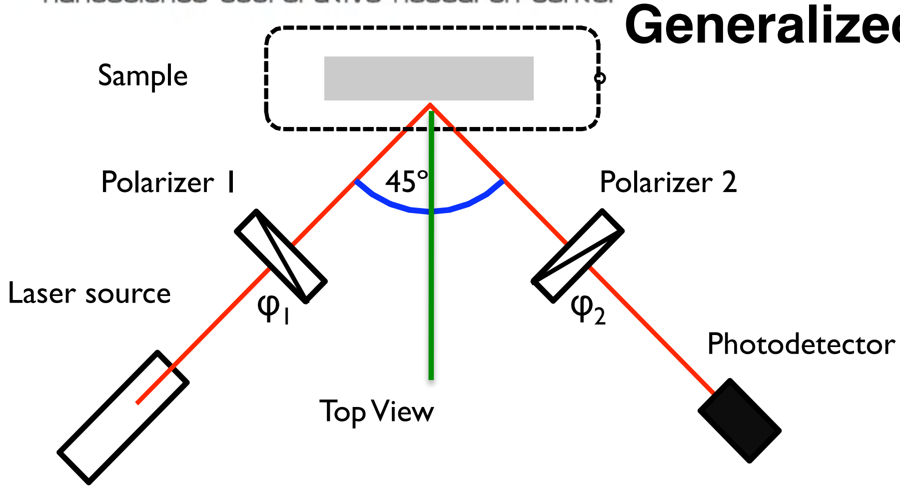
φ_2



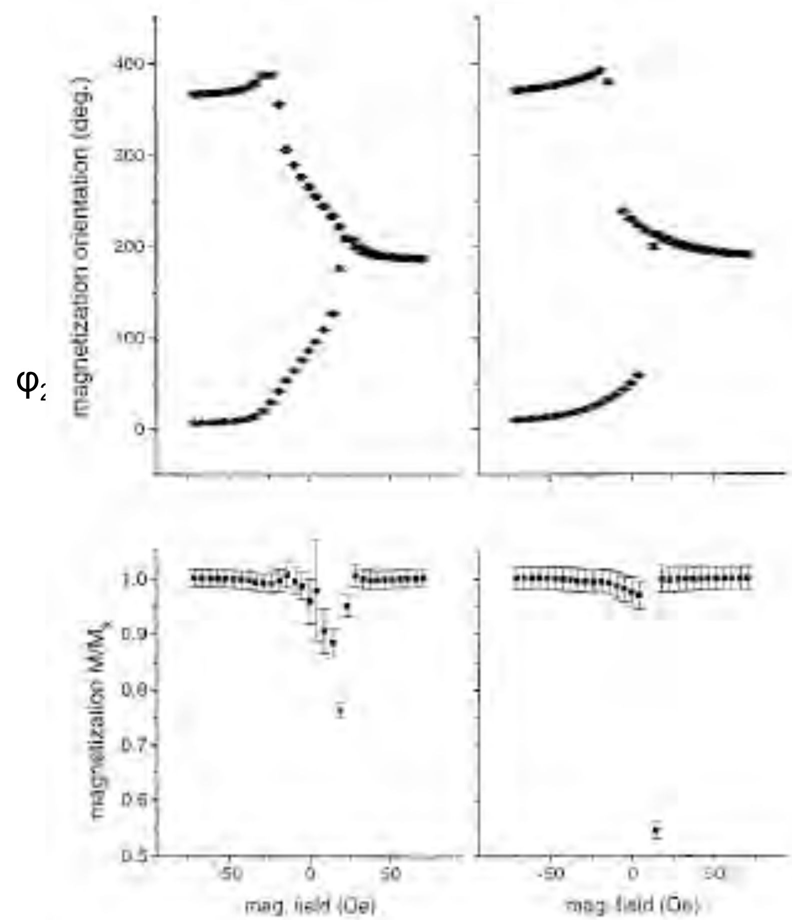


Experimental Magneto-Optics

Generalized Magneto-Optical Ellipsometry (GME)



Full Vector magnetometry



Non-linear Fitting

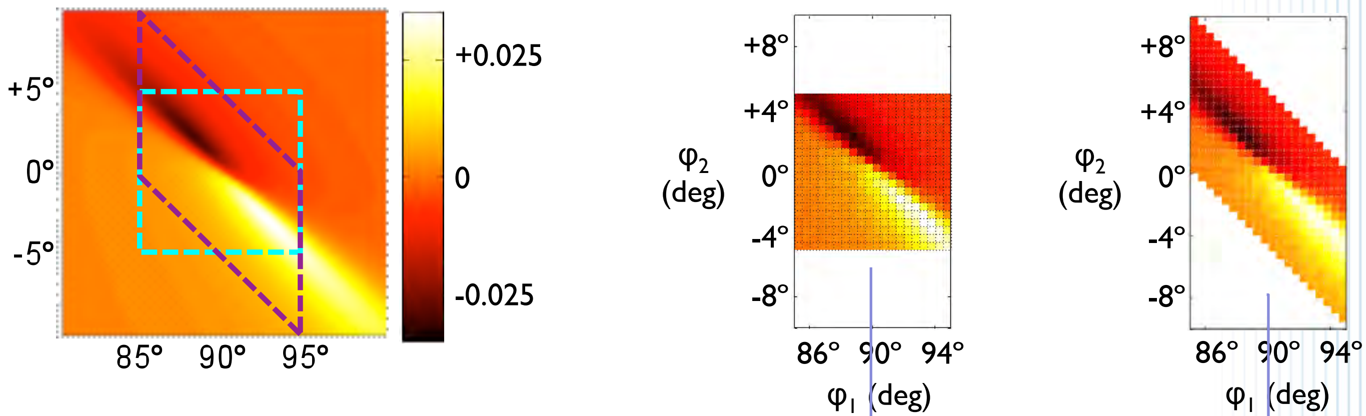
$$\frac{dI}{I} = 4\frac{B_1 f_1 + B_2 f_2 + B_3 f_3 + B_4 f_4}{f_3 + P_4 f_4 + P_5 f_5}$$

Independent Variable: dI/I

Dependent Variables: φ_1, φ_2

Fitting Parameters: $B_1, B_2, B_3, B_4, P_4, P_5$

GME efficiency: data map

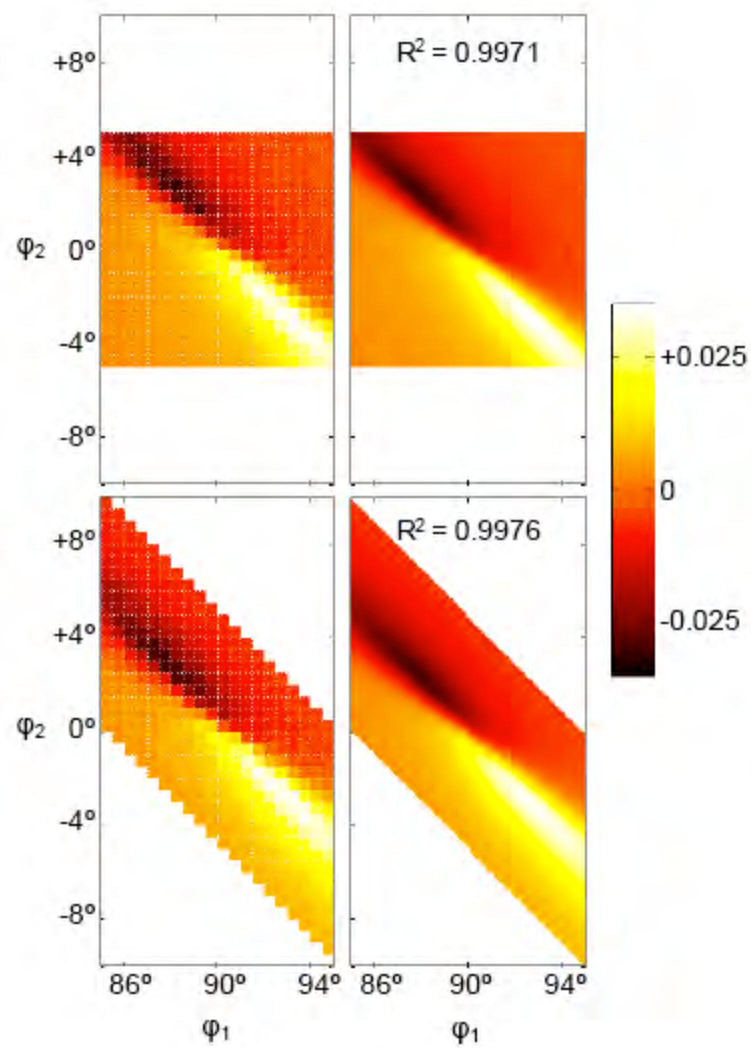


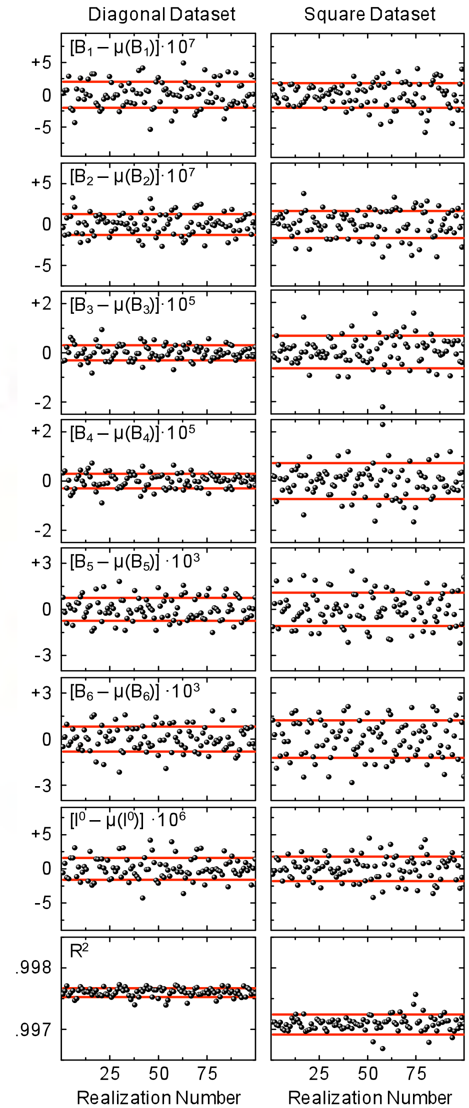
x 1000 times

		Diagonal DataSet		Square DataSet	
Parameter	Exact Value	μ	σ	μ	σ
B_1	-1,39E-04	-1,390118E-04	9,684631E-07	-1,390971E-04	1,220211E-06
B_2	7,88E-05	7,879426E-05	8,083828E-07	7,886012E-05	9,363473E-07
B_3	1,65E-04	1,647655E-04	9,708091E-06	1,653061E-04	1,208305E-05
B_4	-5,00E-05	-4,959715E-05	1,432071E-05	-4,985288E-05	1,549608E-05
P_4	-1,824E+00	-1,823819E+00	6,823377E-03	-1,824084E+00	9,962343E-03
P_5	9,070E-01	9,067618E-01	6,976650E-03	9,066683E-01	9,052316E-03
I_0	2,00E-04	2,005070E-04	1,159999E-05	2,022689E-04	1,618046E-05

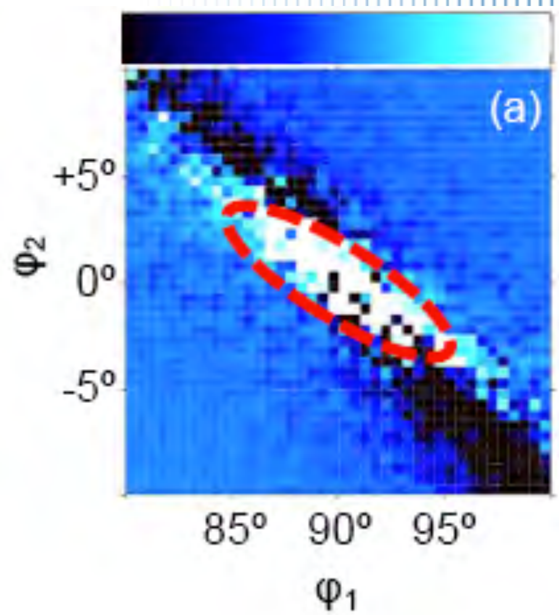
CIC nanoGUNE
nanoscience cooperative research center

GME efficiency: data map





data point impact



Results:

- SQ-lattice not optimal
- DIA-lattice clear better
- reliability improved
- efficiency improved

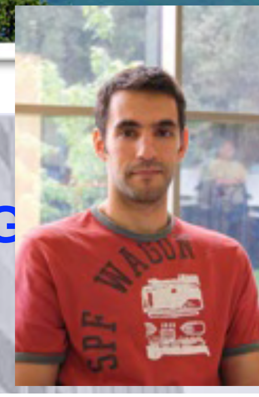
Generalized Magneto-Optical Ellipsometry (GME) for Magnetic Materials Characterization

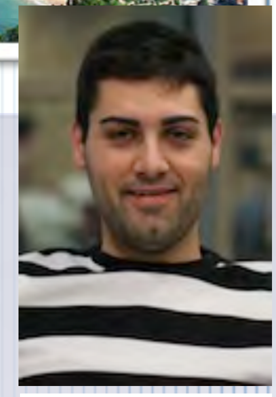
- basic considerations
    - Light Polarization and Reflection
    - Jones Calculus and Ellipsometry
- Fundamentals of Magneto-Optics
    - dielectric tensor
    - Nomenclature of Magneto-Optical effects
    - size of the Magneto-Optical effect
- Generalized Magneto-Optical Ellipsometry
    - experimental set-up and capabilities
    - detection and analysis scheme
    - applications
    - recent developments

Andreas Berger

a.berger@nanogune.eu | www.nanogune.eu

CIC nanoGUNE





Paolo Vavassori
Jon Ander Arregi
Olatz Ididgoras
Juan Gonzalez
Cesar Rufo

ed M … tical … try (G
etic M … harac

- Light Polarization and Reflection
- Jones Calculus and Ellipsometry

- Fundamentals of Magneto-Optics
  - dielectric tensor
  - Nomenclature of Magneto-Optica
  - size of the Magneto-Optical effec
- Generalized Magneto-Optical Ellipsor
  - experimental set-up and capabilities
  - detection and analysis scheme
  - applications
  - recent developments

Department of Industry, Trade and Tourism of the Basque Government, Provincial Council of Gipuzkoa
ETORTEK Program: Project IE06-172

Spanish Ministry of Science and Education:
Consolider-Ingenio 2010 Program, Project CSD2006-53

EU-FP7-Project IEF 220166

Andreas Berger

a.berger@nanogune.eu | www.nanogune.eu