Polarimetry of Light scattered by Surface Roughness and Periodic Structures in Nanotechnologies: A new Challenge in instrumentation and Modeling.

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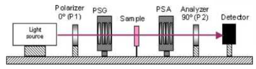
Abstract:

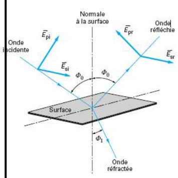
In the literature exhaustive studies detail the Mueller matrices properties through decomposition models, optical entropy and depolarization formalism. Mathematical basis for depolarizing systems, have been first applied in radar polarimetry. In the visible range optics, di-attenuation and retardance decomposition, are present tools today in turbid media analysis. The optical entropy concept provides a very powerful analysis technique yielding important surface parameters such as depolarization, correlation and roughness.

Complementary applications exist in scatterometry, for thin grating films. With high capability polarimeters, the next generation of the angle resolved polarimeters instruments opens new fields of investigation for nanotechnologies materials, lithography applications such as gratings and sophisticated photonics structures.

The theories for surface spectral power density (PSD) and the RCWA theories in periodic structures turn then in a major interest particularly with the recent the S matrix algorithms developments. Behind this instrumentation progress, simulation remains definitely a key point to overcome and will be a challenge between the instruments.

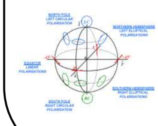
Attempt has been made here to describe the implementation of some of these available codes in applications for surface analysis and with the lithography, (grating overlay) structures.

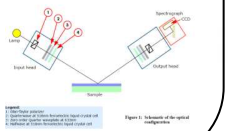




The Ellipsometric measurements Ψ,Δ are limited when the reflector surface roughness becomes significant or in case e.g. of incoherently reflecting samples. Non diagonal null matrix elements are detected.

$$M_{rf} = \begin{matrix} 1.028 & -0.015 & 0.004 & 0.078 \\ -0.013 & 0.603 & -0.157 & -0.111 \\ 0.004 & -0.156 & 0.637 & 0.044 \\ 0.077 & -0.112 & 0.043 & 0.685 \end{matrix} = M \begin{bmatrix} 1 & -\cos 2\psi & 0 & 0 \\ -\cos 2\psi & 1 & 0 & 0 \\ 0 & 0 & \sin 2\psi\cos\Delta & \sin 2\psi\sin\Delta \\ 0 & 0 & -\sin 2\psi\sin\Delta & \sin 2\psi\cos\Delta \end{bmatrix}$$





The Polarimetric Surface scattering model.

Thin Films surface Characterization

Case of a random media and the Stochastics hypothesis .

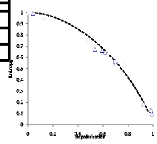
For a stochastics system with a mean measured Mueller matrix [M] turns written as <M>. Similarly, the model is built over the eigen values of the coherency <T>. For a stochastic system, each eigen vector, is representing one of the possible states associated to the normalized eigen values, and with the probabilities Pi, of the system to be found in this state. The randomness of the system is then characterized, defining the Neumann entropy E, within the interval [0,1].

$$E = -\sum_{i=1}^{N} p_i \log_N p_i \qquad p_i = \lambda_i / \sum_j^N \lambda_j$$

Within the Bernoulli model,, one has an evaluation of a parameter **α** taking the average of the form

$$\bar{\alpha} = \sum_i^N P_i \alpha_i \qquad (7)$$

Samples	Entropy	depolarization
Dielectric C	0.9902	0.0935523
Nylon	0.9842	0.125090
Dielectric S	0.0381	0.990365
polished Al 0.3microns 500 nm	0.5941	0.658
(exp errors correc)	0.6183	0.64199690

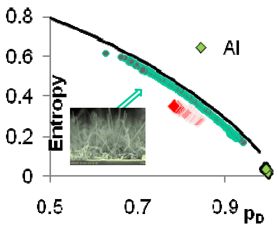


Within the special case of diagonal matrices, for an isotropic depolarizer, the Mueller matrix is diagonal. The corresponding coherency <H> is also diagonal: In the [S=Entropy,α] space , it will turn to

$$< \mathbf{H} > = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & m & 0 & 0 \\ 0 & 0 & m & 0 \\ 0 & 0 & 0 & m \end{bmatrix} \qquad S = -\frac{1}{1+3m}\left\{\log_4 \frac{m^{3m}}{(1+3m)^{3m-1}}\right\} \ (9$$

$$depol = [M]_{00} - \frac{1}{3}\sqrt{\{trace[M].[M]^T - [M]_{00}} \Rightarrow m = \lambda_1 = \lambda_2 = \lambda_3 = \frac{d}{2}$$

$$p_D = \left[1/3\sqrt{(4\sum_{i=0}^{3} p_i^2 - 1)}\right] = 1 - depol\ (11) \qquad S = -(3p_D+1)/4\log_4\left(\frac{3p_D+1}{4}\right) - \frac{3(1-p_D)}{4\log_4(\frac{1-p_D}{4})}) \qquad (14)$$

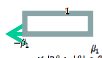


An alternative way to introduce surface disturbance roughness is by a reflection symmetric depolarizing rotation of the Bragg coherency matrix about un angle in a plane perpendicular to the scattering plane. A configurationally averaging has to be taken over a unit surface slopes distribution, S.R. Cloude[10] proposed a slopes distribution uniform of half width with when $b<b_1$, and zero T] appears as:

<[T>]=

$$\int_0^{2\pi} [T(\beta)]P(\beta)d\beta \qquad (15)$$

β_1 0 to 90°

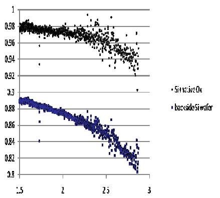


$$P(\beta) = \begin{cases} 1/2\beta_1 & |\beta| \le \beta_1 \\ 0 & otherwise \end{cases}$$

$$T = \begin{bmatrix} A & B\,sinc(2\beta_1) & 0 & 0 \\ B^*sinc(2\beta_1) & C(1+sinc(4\beta_1)) & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & C(1-sinc(4\beta_1)) \end{bmatrix}$$

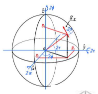
$$\gamma_{(HH+VV)(HH-VV)} = \frac{T_{12}}{\sqrt{T_{11}T_{22}}} = sinc(2\beta_1)/\sqrt{1+sinc(4\beta_1)} < 1.$$

Spectroscopic polarimetry, specifies surface properties and films textures. Nanotechnologies material are considered. From smooth samples like aluminum (Al), to low reflectivity thin films of plastic (PET), or silicon nano-wires (SiNW) deposited on a silicon substrate. Compared to the analytical equation (14), i) the aluminum film data remains in a very high reflectivity limit [S=0, p_D=1] ii) the SiNW film(it can be seen as distribution of various components, (needle and various shaped micro-crystal), the micron-sized light-scatterers),. Shows a spectroscopic distribution (blue dots), following surprisingly well, the universal character curve finally, iii), the plastic PET film having to a less extent micro impurities behave similarly (red diamonds), anisotropic since well below the isotropic case limit.



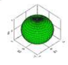
Within this model the polarimetric coherency$T_{12}/\sqrt{T_{11}T_{22}}$/ is only related to the surface roughness and not of the dielectric properties of the considered material. It can be verified in some cases, e.g., in the case of a 70° incidence measurement on both sides of a Silicon wafer(polished side with native oxide and rough backside of the wafer.

The Mueller matrix Decomposition: How to present experimental Data ?

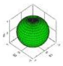


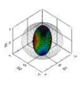
We adopted the classical representation of the state of polarized light, through the Poincaré sphere. Sample are studed such as one desire to know , the specific behaviour of the surface reflecting sample , or effect of the transmitted light coming from the samples . The Mueller matrix M will give this information through the analysis comparing the Stokes vectors of the light S,S' respectively before and after interaction with the sample. will be modified .such as $S' = [M].S$

$$S = S_0[1, \quad cos2\varepsilon cos2\theta, \quad cos2\varepsilon sin2\theta, \quad sin2\varepsilon]^T$$



$$M = \begin{bmatrix} 1/4 & 0 & 0 & 0 \\ 0 & 1/4 & 0 & 0 \\ 0 & 0 & 1/4 & 0 \\ 0 & 0 & 0 & 1/4 \end{bmatrix}$$





$$M_{rf} = \begin{matrix} 1.028 & -0.015 & 0.004 & 0.078 \\ -0.013 & 0.603 & -0.157 & -0.111 \\ 0.004 & -0.156 & 0.637 & 0.044 \\ 0.077 & -0.112 & 0.043 & 0.685 \end{matrix}$$

Normalized and P<1 (the dimmed sphere) and *Physically realizable* Mueller matrix

Homomorphism S[U]4-> [O6] enable to relate the Mueller matrix to the coherence matrix. (S.R.Cloud, E.Pottier)

$$[\mathbf{M}] = \begin{bmatrix} A_0+B_0 & C+N & H+L & I+F \\ C-N & A+B & E+J & K+G \\ H-L & E-J & A-B & M+D \\ I-F & K-G & M-D & A_0-B_0 \end{bmatrix} = [m_{ij}]$$

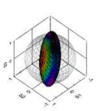
$$\mathbf{H} \equiv \mathbf{T}$$

$$T = H = T^{\dagger}\ is\ fullfilled \qquad = \begin{bmatrix} A_0+A & C-iD & H+iG & I-iJ \\ C+iD & B_0+B & E+iF & K-iL \\ H-iG & E-iF & B_0-B & M+iN \\ I+iJ & K+iL & M-iN & A_0-A \end{bmatrix} = [h_{ij}]$$

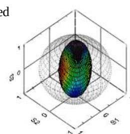
- Matrix Filtering
- Analysis of the experimental data following the coherence matrix

$$\mathbf{H} \equiv [\mathbf{T_c}] = \lambda_0[\mathbf{T_{c0}}] + \lambda_1[\mathbf{T_{c1}}] + \lambda_2[\mathbf{T_{c2}}] + \lambda_3[\mathbf{T_{c3}}] +$$

- Example : If l_3 turns to be a negative value:



take the resulting filtered Matrix as the best estimate



Spectroscopic polarimetry of light scattered by surface roughness and textured films in nanotechnologies. F.Ferrieu published in g FCMN09 Albany mars 2009 conference book.

s. Y. Lu, R. A. Chipman "*Interpretation of Mueller matrices based on polar decomposition*" J. of Opt. A,**13**,1106 (1996),

S.R. Cloude, E. Pottier,"*Concept of polarization Entropy in optical scattering*" Opt.Eng.,34,6,1599-1610(1995).

Ben Hatit , M. Foldyna, A. de Martino, and B. Drevillon *« Angle resolved Mueller Polarimeter using microscope objective »* phys. stat. sol. (a) **205**, No. 4 (2008)

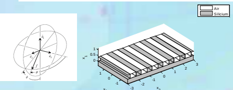
"*ANR-PNano2008 MUELLER FOURIER*" LPICM, JYH and LETI 2009-2011 research program.for overlay metrology.

See e.g., http://physics.nist.gov/Divisions/Div844/facilities/scatmech/html/. "Scatmech C++ Library" Th.. Germer., National Institute of Standard and Technology (NIST).USA

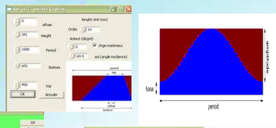
www.leti.fr

1-D structures

MUELLER Fourier Project
LPICM JYH LETI- ANR08 NANO-020-01

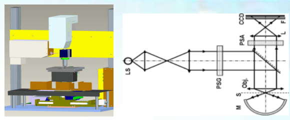


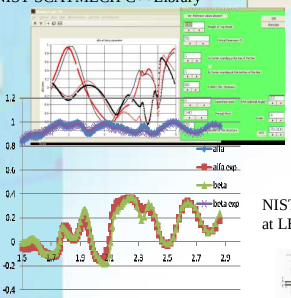
NIST SCATMECH C++Library

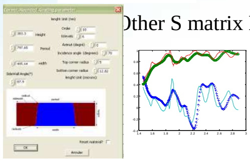


Scattero Mueller :One Incidence angle
Spectroscopic wide band large spot size

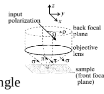
$$M = \begin{bmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{10} & m_{11} & m_{12} & m_{13} \\ m_{20} & m_{21} & m_{22} & m_{23} \\ m_{30} & m_{31} & m_{32} & m_{33} \end{bmatrix}$$







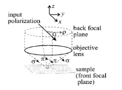
Other S matrix Matlab code



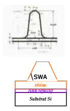
Mueller Fourier Multi Angle
Narrow band small spot size

86.5 SiO2on Si sample experimental data
Courtesy of LPICM A. De Martino and
Ben Hatit et al.: phys. stat. sol. (a) **205**, No. 4
(2008)

Examples



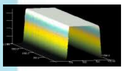
NIST SCATMECH C++Library script files used in optimisation software at LETI

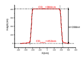


```
BOUNDARIES
v1  v2  oxide     medium_t
v3  v4  poly      oxide
v4  v5  nitride   oxide
v3  v6  nitride   poly
v6  v7  nitride   poly
v7  v4  nitride   poly
v8  v9  medium_i  nitride
v9  v10 resist    nitride
v10 v11 medium_i  nitride
v9  v12 medium_i  resist
v12 v13 medium_i  resist
v13 v10 medium_i  resist
END
```

```
WORKING
x1   -period/2
x2   period/2
x3   x1
x4   -period/2+CDs
x5   x2
x6   x3
x7   x4
x8   x6
x9   -period/2 + ovl
x10  -period/2+ovl+CDr
x11  x5
x12  x9
x13  x10
y1   -t
y2   -t
y3   0
y4   0
y5   0
y6   hs
y7   y6
y8   h-hr
y12  h
y13  h
END
```

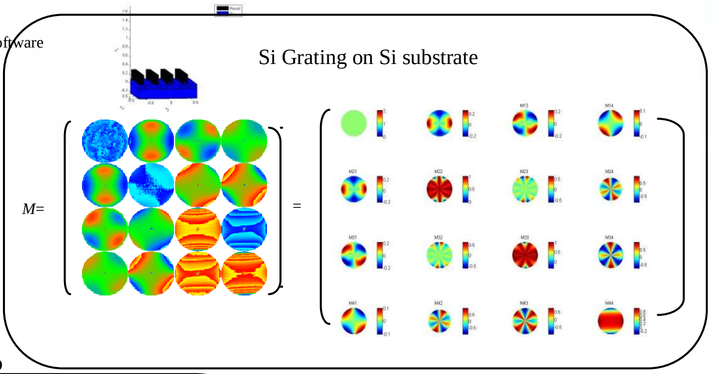
```
MATERIALS; FF STMicro
poly   f:\\SILICON.txt
oxide  f:\\SILICA.txt
nitride f:\\nitride.txt
resist f:\\PR248.txt
END
VERTICES
v1 (x1,y1)
v2 (x2,y2)
v3 (x3,y3)
v4 (x4,y4)
v5 (x5,y5)
v6 (x6,y6)
v7 (x7,y7)
v8 (x8,y8)
v9 (x9,y8)
v10 (x10,y8)
v11 (x11,y8)
v12 (x12,y12)
v13 (x13,y12)
END
```





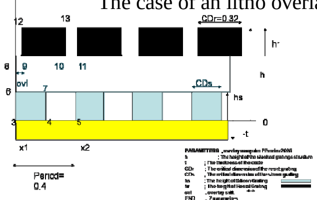
CD SEM and AFM 3D

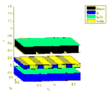
Si Grating on Si substrate



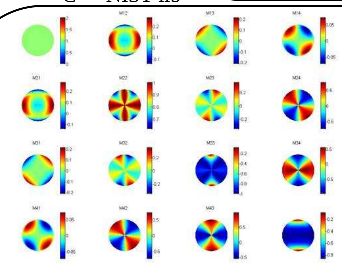
SCATMECH script

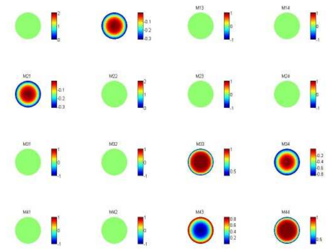
The case of an litho overlay

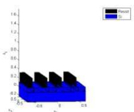




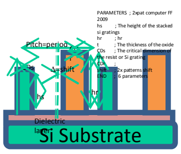
C++ NIST lib



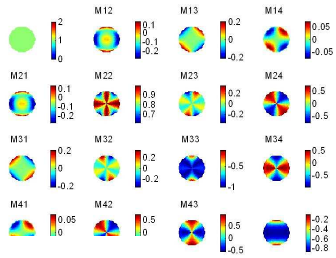


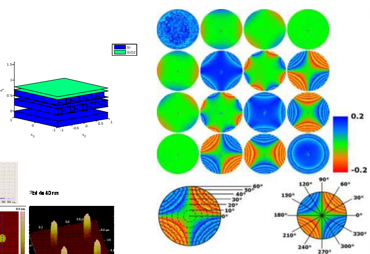


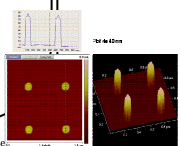
```
PARAMETERS  ; 2xpat computer FF 2009
hs        ; The height of the stacked  si gratings
hr        ; hr
t         ; The thickness of the oxide
CDs       ; The critical dimension of the resist or Si grating
CDr       ; PARAMETERS  ; overlay computer FF 2009
hs        ; The height of the stacked  si gratings
hr        ; hr
t         ; The thickness of the oxide
CDs       ; The critical dimension of the resist or Si grating
CDr       ;
shift     ; 2x patterns shift
END       ;  6 parametres   hs  hr   t   CDs   CDr  ovl
          ;
pstring=(STRING)"(0.2,0.1,0.145,0.1,0.12,0.025)";// parametres double patterning
WORKING
x1   -period/2
x2   period/2
x3   x1
x4   -period/2+CDs
x5   0
x6   shift
x7   shift+CDr
x8   x2
x9   x1
x10  x4
x11  shift
x12  x7
y1   -t
y2   -t
y3   0
y4   0
y5   0
y6   0
y7   0
y8   0
y9   hs
y10  hs
y11  hr
y12  hr
END
shift     ;
END
```



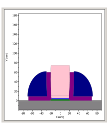
Matlab Software



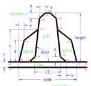




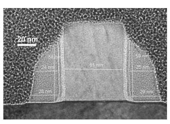
2-D structures



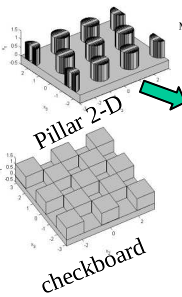
Kla description



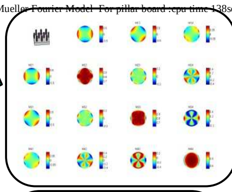
Nist Script

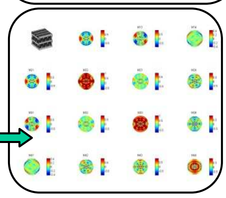


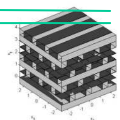
TEM picture

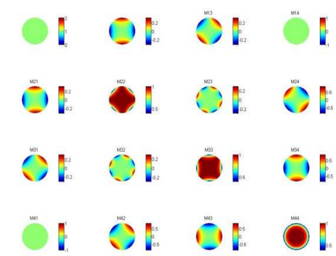


Mueller Fourier Model For pillar board cpu time 138se









3-D structures

Polarimetry....
What else?....

Light-scattering codes and open databases: see e.g.:
http://www.astro.ufl.edu/~elsnews/links.htm

www.leti.fr