Optical-alignment Si μ-strip sensors

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Supported by the FP6-Infrastructure I3 European Project EuDET

ILC-ECFA08 Workshop (Warsaw) – 10th June 2008

Outline

1) The concept of an optical (Si) tracking alignment system for the ILC

2) Realistic optical simulation of Si strip sensors

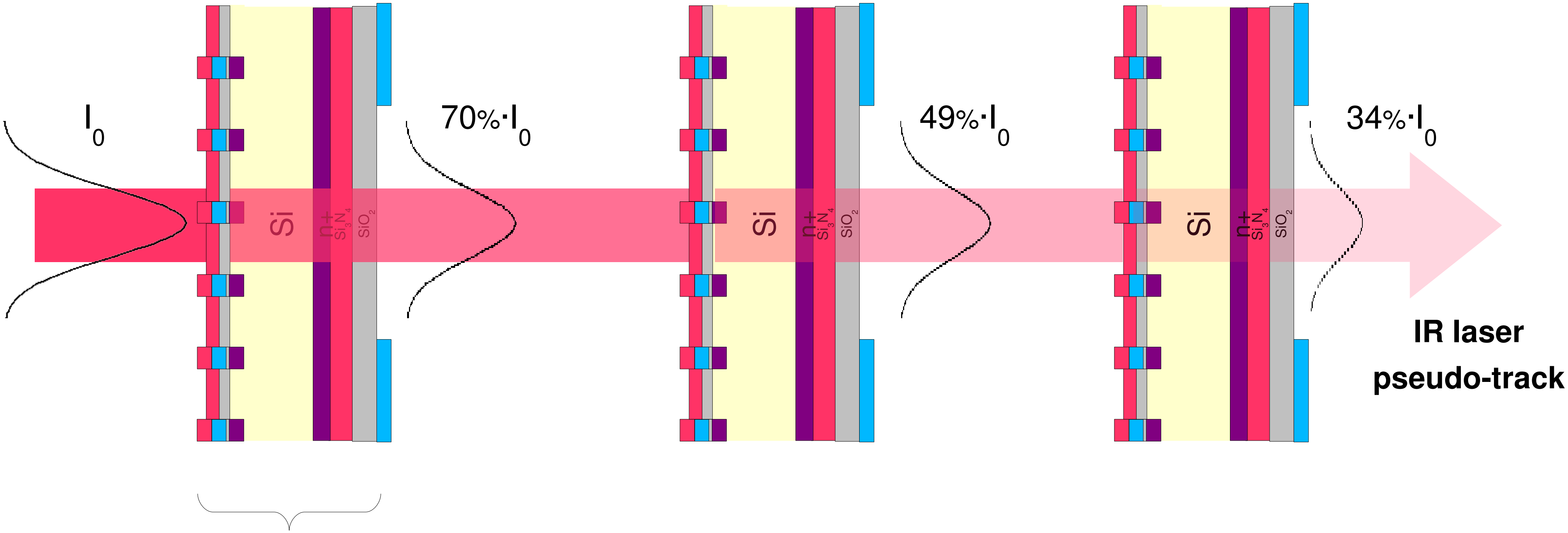
3) Optical characterization of:

    3.1) TopSiL Si wafers: optical properties of Si

    3.2) New HPK (à la CMS) Si μ-strip sensors

4) Summary and Next Steps

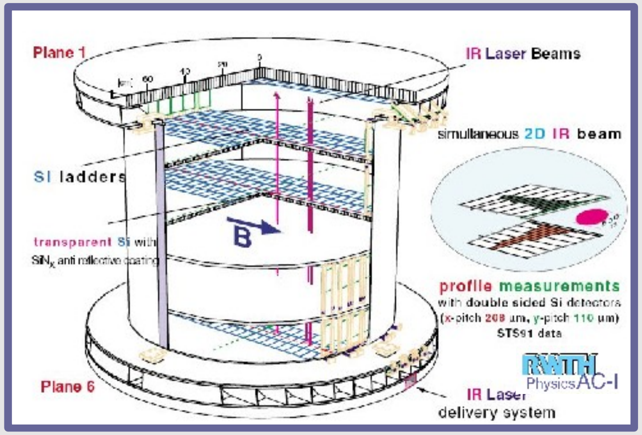
Si optical alignment in 1 pic



Si µstrip detector

Currently: T<54% (AMS) → Our design goal:
T=70% with Al strips
T=75-80% with ITO strips

An idea that works …



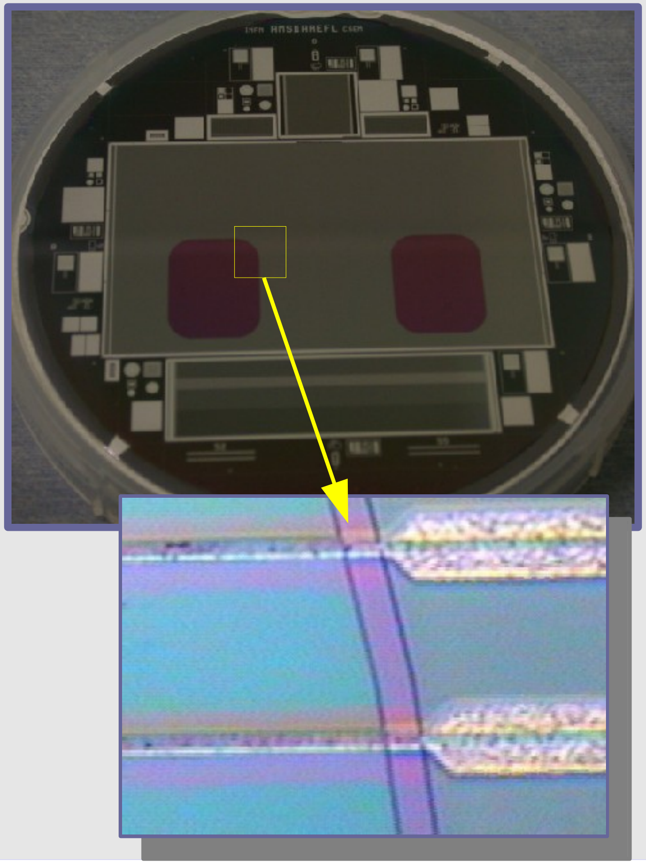
AMS-01 innovation (W. Wallraff)

λ = 1082 nm

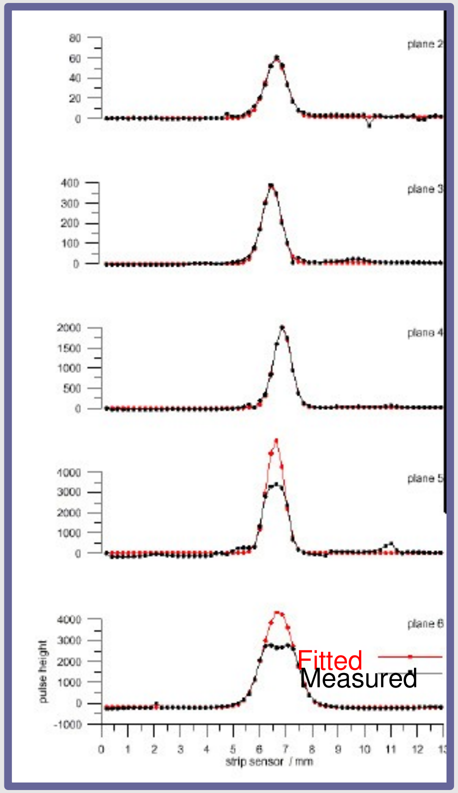
IR "pseudotracks"

1-2 µm accuracy obtained

Transmittance~ 50%

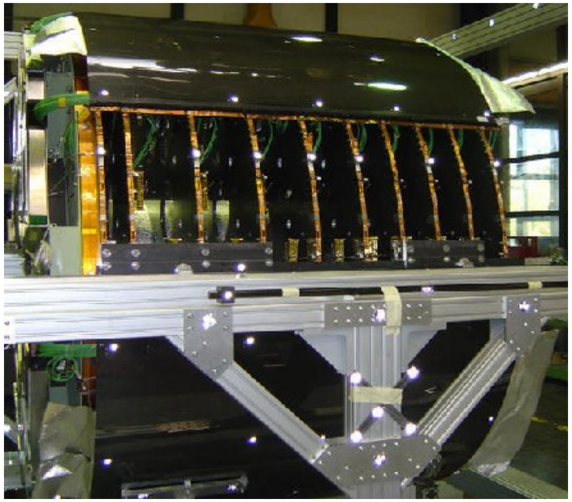


Up to 4 ladders traversed



CMS

TEC



λ = 1075 nm

- Optimization of sensors not included from beginning of sensor design ⇒ **lower transmittance** achieved~20%
- 180 deg **beam splitters** in the middle of the tracker produce back to back beams measured by modules
- Laser spot reconstructed with **10 µm resolution** (1st sensor)

9 TEC disks (18 petals) reconstructed using 2 beams with 50 µm accuracy (100 µm required in CMS)

Si μ-strip “photosensors”? Advantages

Advantages of this approach:

— Sensors under study are their own alignment system ⇒ **No** mechanical **transfer errors** between fiducial marks and the modules

— IR beam read out using Si DAQ ⇒ **Straightforward integration into DAQ**

— Minimum impact on system integration, **no cost in extra material budget**

— Alignment system does not compromise tracker design.
Example: changes in geometry of the modules have no impact in system precision

Si is almost transparent to IR light. Still, ~200 MIPs can be produced with standard laser diodes

— Beam position across several sensors can thus be measured.
— Remaining sensors are reconstructed using tracks in overlap region.
(**track alignment** improves precision 1 order of magnitude).

Requirements of this approach:

— Alignment system must be taken into account from the design phase of the sensor
— Modifications of the sensor needed in a ~10 mm (*) diameter optical window: **removal of aluminum backelectrode locally**

(*) This number can be optimized

SiLC: 2-fold approach

R&D on transparent Silicon µstrip sensors:

- Together with **IMB-CNM (Barcelona)** design, build and test new IR-transparent Silicon microstrip detectors.
- Consider option of aluminum electrodes or transparent electrodes

AMS-like approach:

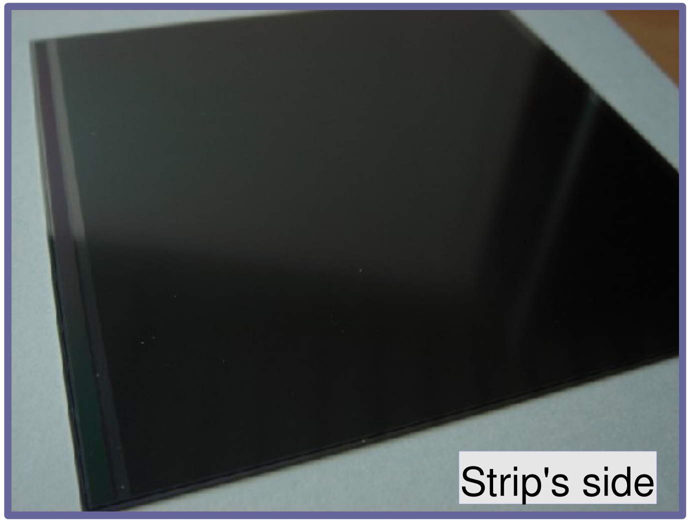
Baseline version: Minimum set of changes for any SiLC sensors. For instance, for the new HPK sensors

Implemented:

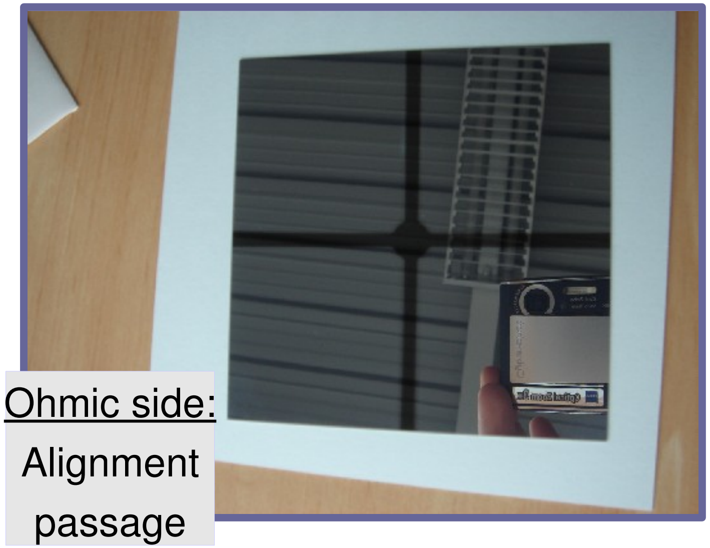
- ∅~10 mm window where Al back-metalization has been removed

Suggested (not cost effective for small batches):

- Strip width reduction (in alignment window)
- Alternate strip removal (in alignment window)



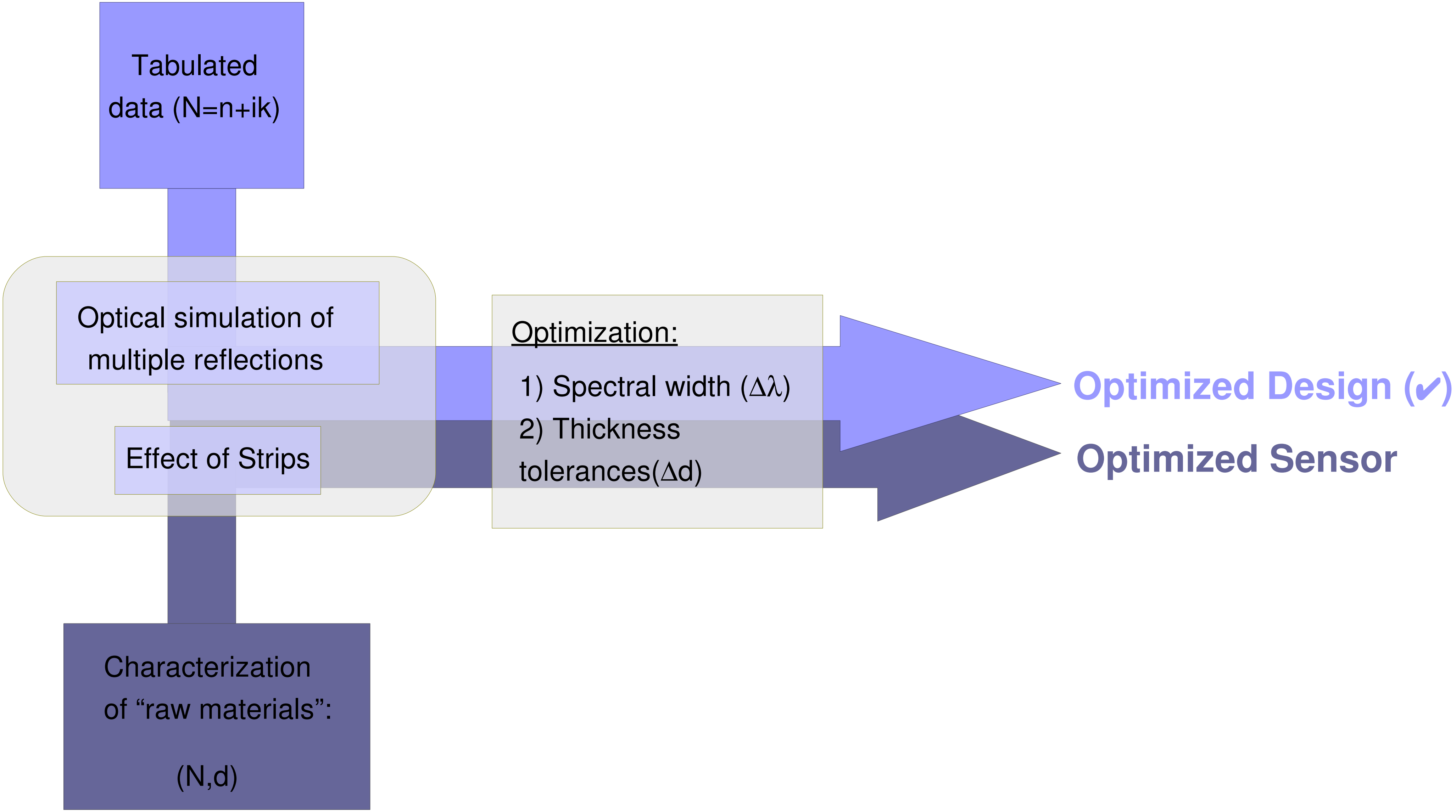
Strip's side



Ohmic side:
Alignment passage

R&D on transparent Silicon µstrip sensors:

Transparent sensors HOWTO



Tabulated data (N=n+ik)

Optical simulation of multiple reflections

Effect of Strips

Characterization of “raw materials”:

(N,d)

Optimization:

1) Spectral width ($\Delta\lambda$)

2) Thickness tolerances(Δd)

Optimized Design (✔)

Optimized Sensor

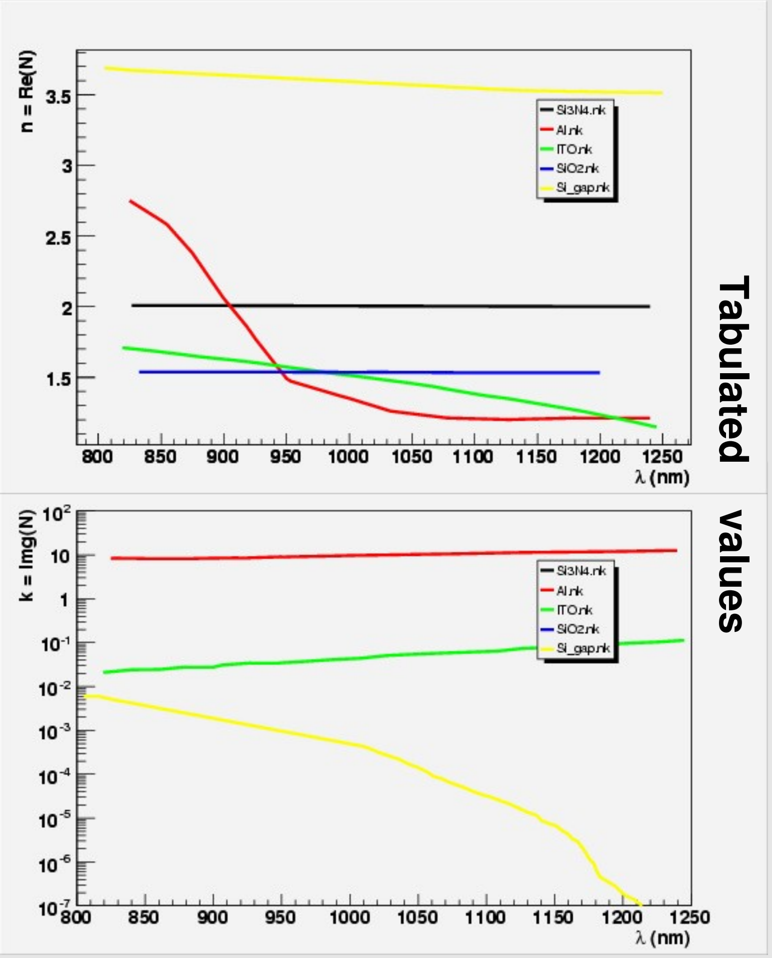
Optical simulation in a nutshell

- Refraction index characterizes materials.

Function of wavelength: N=n(λ)+iκ(λ)

n=speed of light in the medium

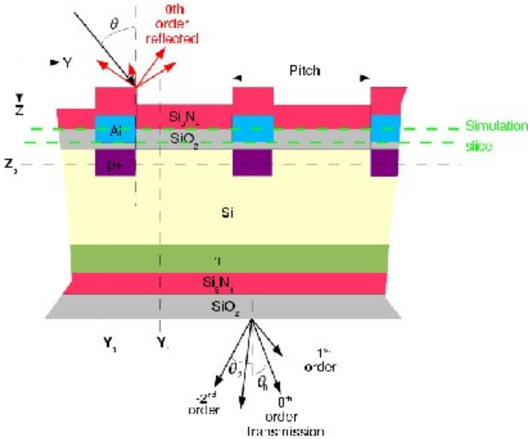
κ=related to optical absorption $\frac{1}{\alpha} = \frac{\lambda}{4\pi k}$



Tabulated values

- Typical absorption for Silicon [200-320] µm thick for λ in IR: A~5-10% ⇔ 40-2000 MIPs

- Si µstrip sensors are **multilayer** structures.



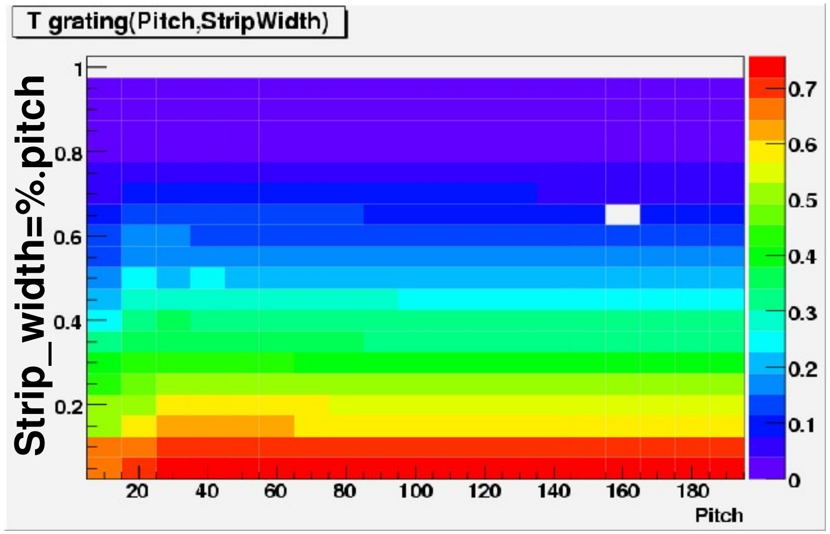
Multiple reflections inside the stack ⇒ **interferences**

Periodic strips = grating ⇒**diffraction**

Both effects included in the simulation

See our report under: [Eudet-memo-2007-32]

- Since strips are considered we could optimize pitch/width ratio for maximum transmittance:



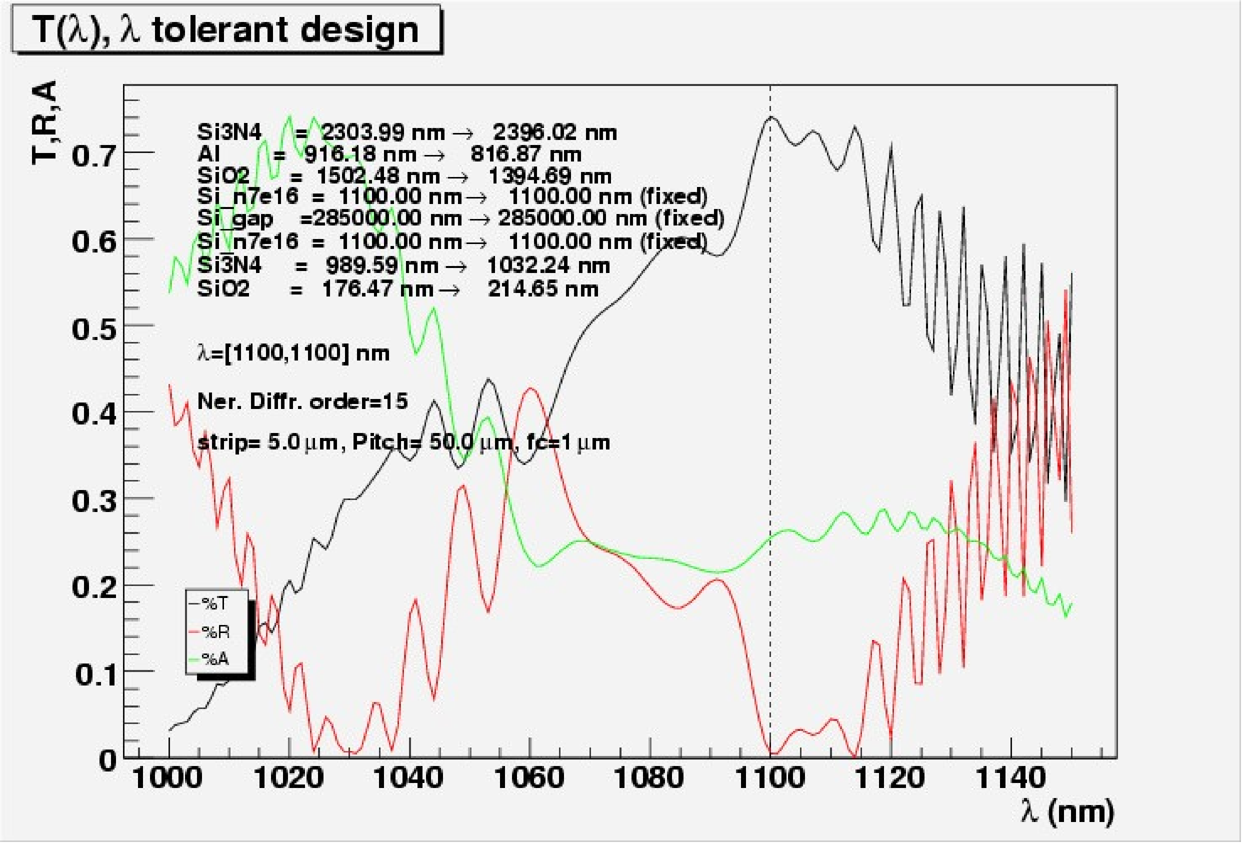
→ The less Al, the more %T

→ Good compromise: **stripwidth = 10% · Pitch**

Design optimization

- Once strip_width/pitch is optimum, we modify material thicknesses to get maximum transmittance **(constructive interference)** using the following χ^2:

$$\chi^2 = \underbrace{\sum_{\lambda=1098}^{1102} \left[\; (T(N,d) - T_{MAX})^2 + R^2 + \underbrace{\sum (T_{MC} - T_{MAX})^2}_{\text{Thickness Tolerance: MonteCarlo}} \; \right]}_{\text{Laser spectral width}}$$



- ✓ Al strips
- ✓ Pitch=50 μm
- ✓ Strip Width=5 μm
- ✓ p,n implants 7×10^{16} cm^{-3}
- ✓ Spectral width included
- ✓ Using tabulated N=n+ik

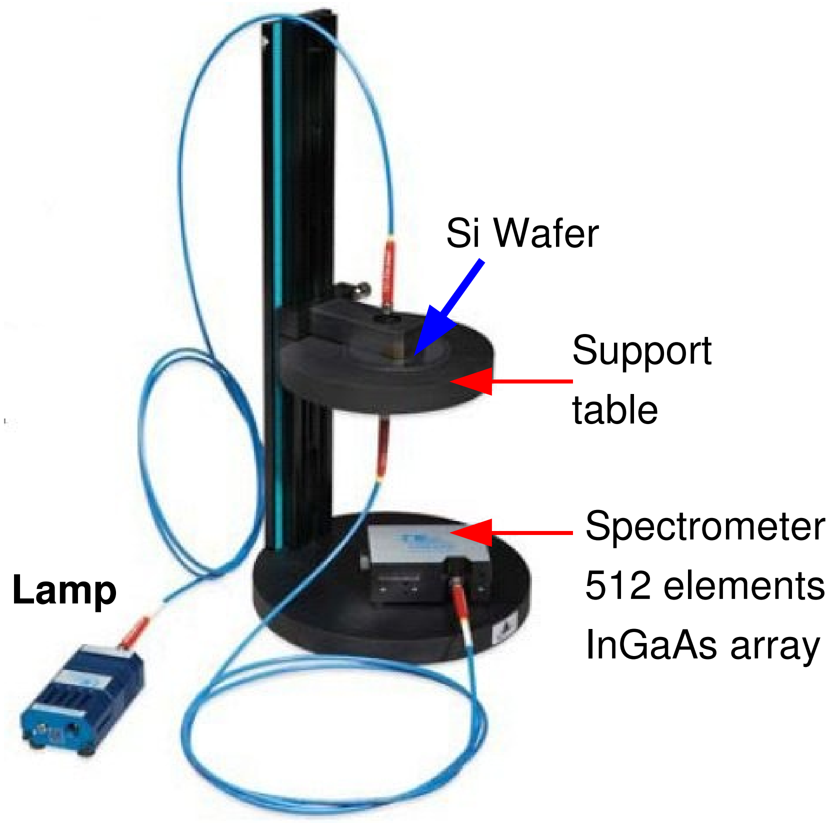
Measuring %T and %R

- A spectro(photo)meter provides Transmittance (T) and Reflectance (R) as a function of wavelength (λ).

- Jan 08: Custom designed grating in a spectrometer (SPM): λ=[950,1150] nm ; σ_λ=1.2 nm spectral resolution %T and %R accessories

- Measurements of T and R can be used to characterize the materials optically: find the refraction indexes that produced the measured (T,R).

$$\left.\begin{array}{l} T[n(\lambda), k(\lambda), d] \\ R[n(\lambda), k(\lambda), d] \end{array}\right\} \Rightarrow n(\lambda), k(\lambda), d$$



- We compared the output of our SPM with a high end SPM: both agree at 2% level

Available material samples

- **IMB-CNM** Barcelona provides us with **samples** of each of the materials.

Manufacturing and processing granted by Spanish Program to Access Large Research Facilities (ICTS).

Shown to the right wafers from **TOPSIL**, (high resistivity, double polished, 300±20 µm thick).

— Different wafers have different doping levels
— Wafers divided into quadrants.
— In each quadrant only one new material has been deposited.
— We also have one wafer with pad sensors and no backmetal to study the effect of diffraction at strips
— Also available a raw wafer (unprocessed)

- The **goals** of these **measurements** are:

—**Characterize** each material as produced by the manufacturer
— Study **thickness tolerances** of the materials and, if needed, establish upper limits
— Study of transparent electrodes as a solution for the strips of the sensor

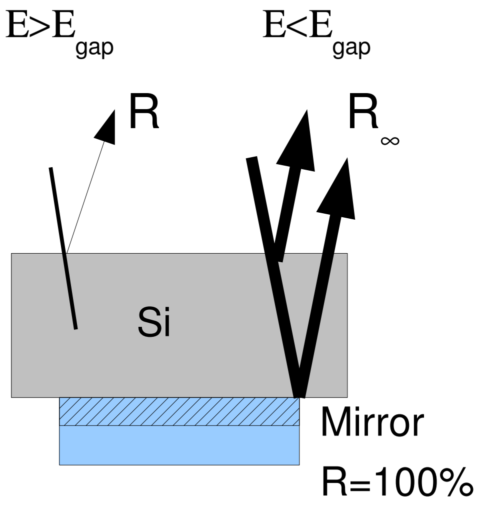
- The ultimate goal in the project:

— Using our simulation produce alignment sensors
— If needed, know-how transfer to larger manufacturer

Calculating n

- Considered Si wafer here

- The real part of the refractive index can be calculated easily. Due to Si high absorption for E>E$_{gap}$, the photons do not reach the bottom surface ⇒ Checked with a **mirror** on the Si wafer

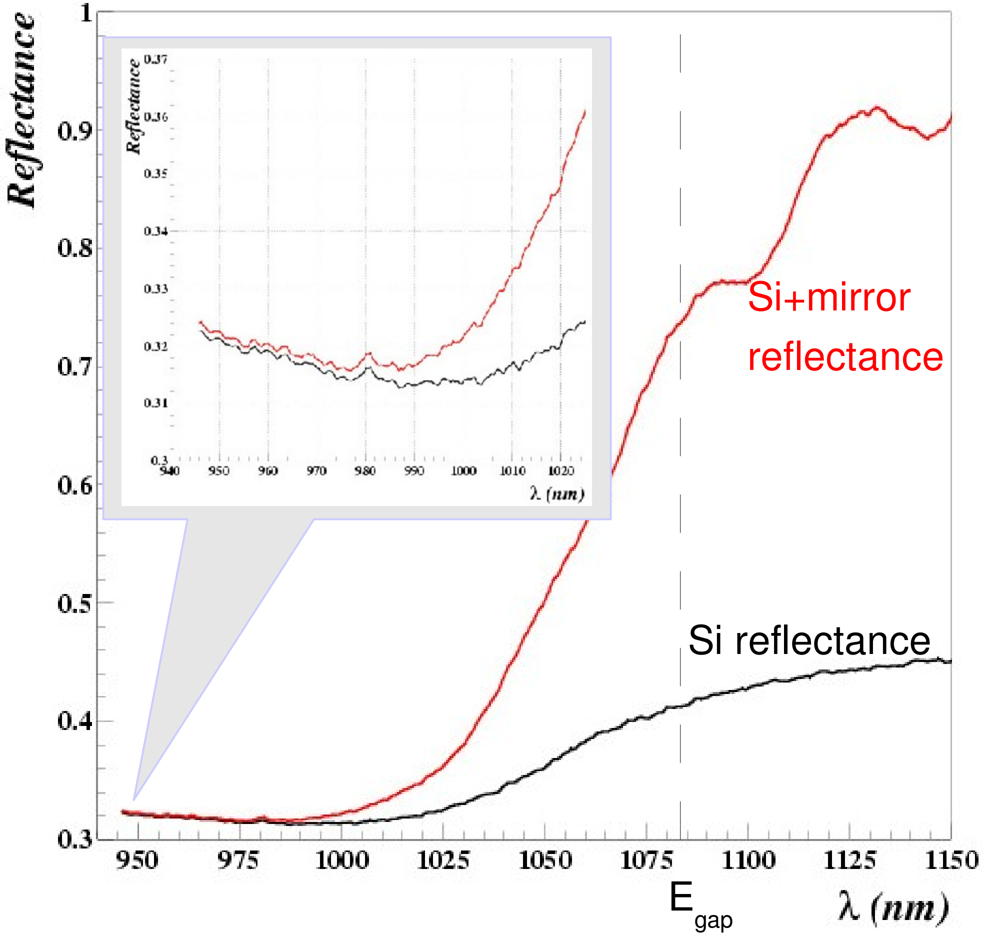


$$R=\frac{(n-1)^2+k^2}{(n+1)^2+k^2}\approx\frac{(n-1)^2}{(n+1)^2}$$

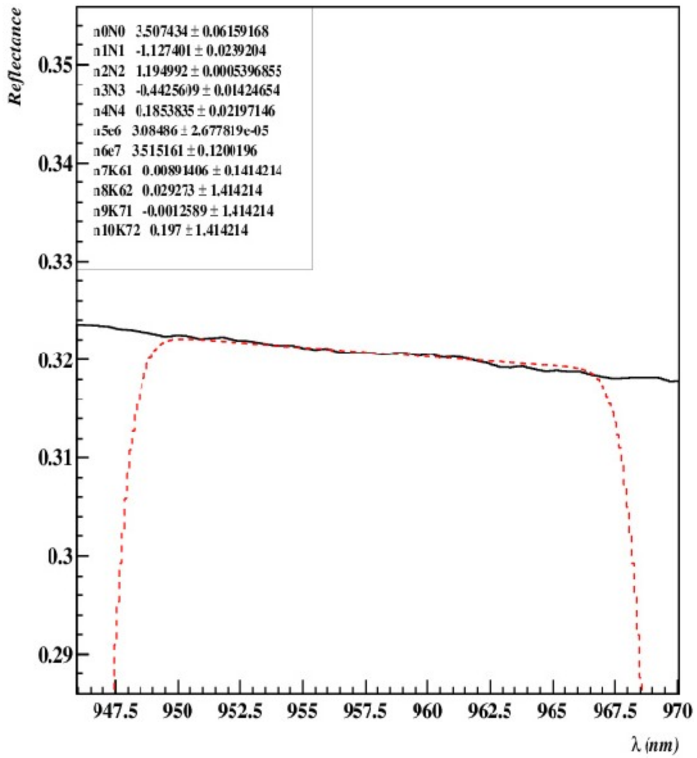
(n~3.5,k~10^{-3})

Independent of thickness and k

$$\sigma_n=\frac{\sigma_R}{\frac{\delta R}{\delta n}}=\sigma_R\frac{(n+1)^3}{4(n-1)}\approx 10\,\sigma_R$$

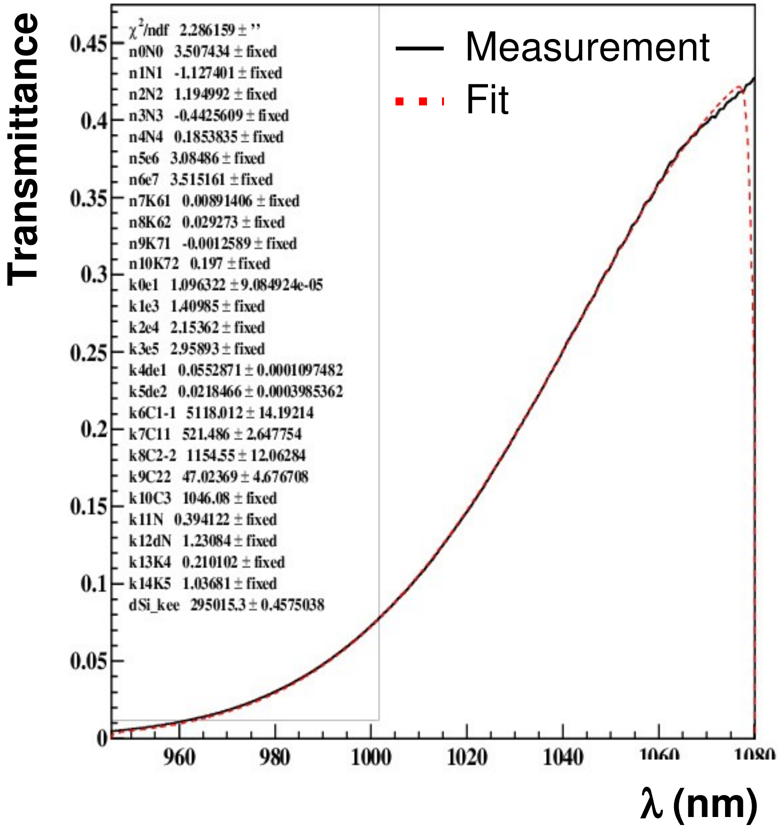


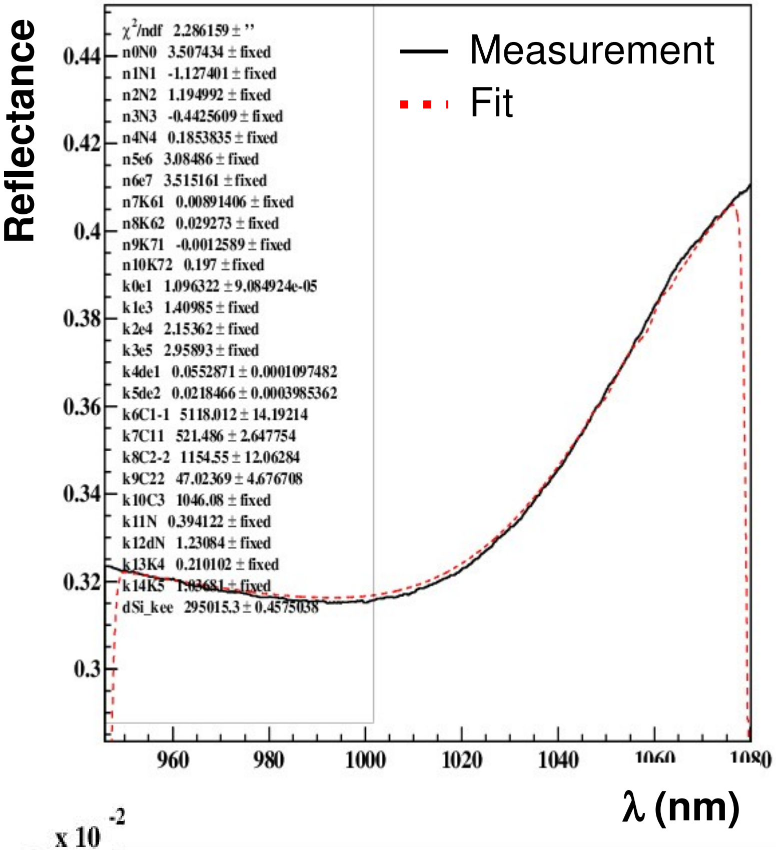
Example of a fit using above formula:

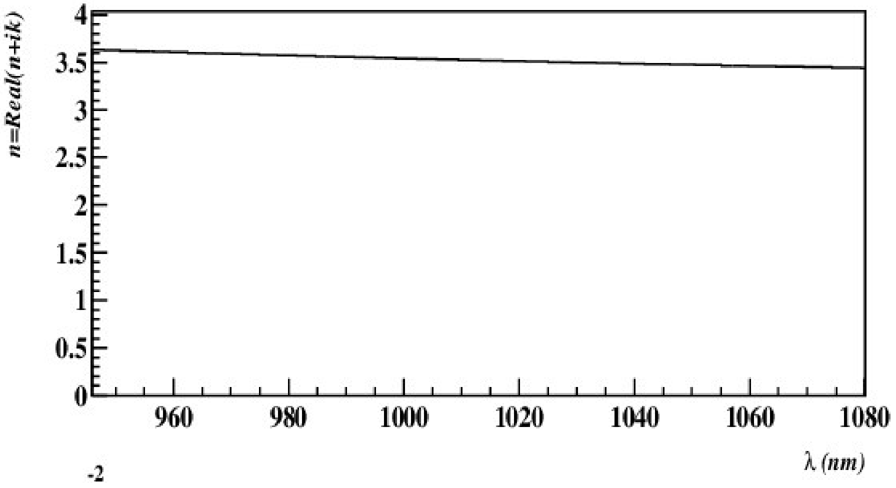


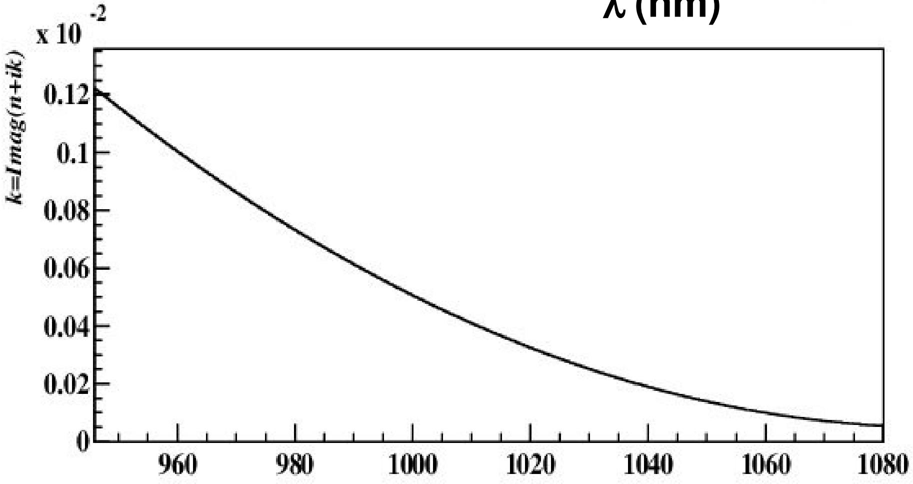
Backengineered wafer

- We can fix “n” using the former method. T and R are then fitted simultaneously varying (k,d).









Measurements of HPK alignment sensors

(Almost there... 2 more slides before conclusions)

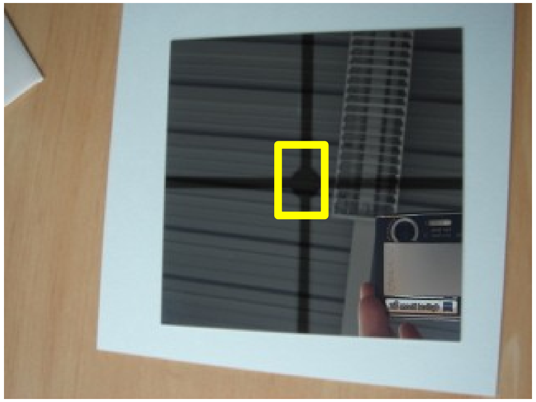
Measurements of HPK sensors (I)

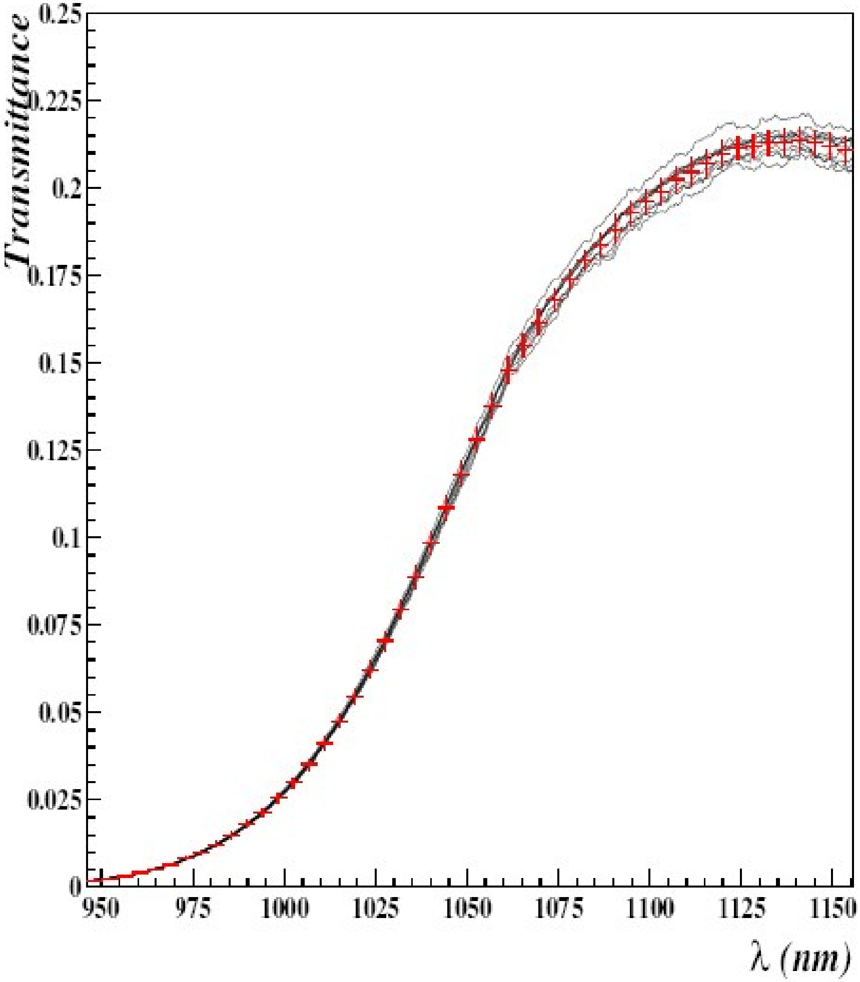
- These are standard CMS sensors:

50 µm pitch, 12.5 µm strip width, 312 µm thick

- They are alignment friendly, but not optimized for transmittance: no Anti-Reflection Coating (ARC).

- Plot shows the Transmittance measured at 9 different spots within the alignment passage:

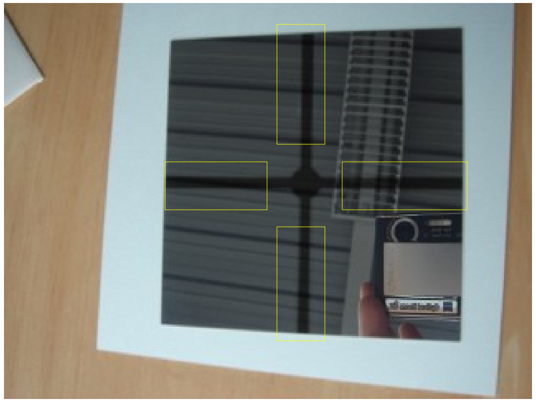


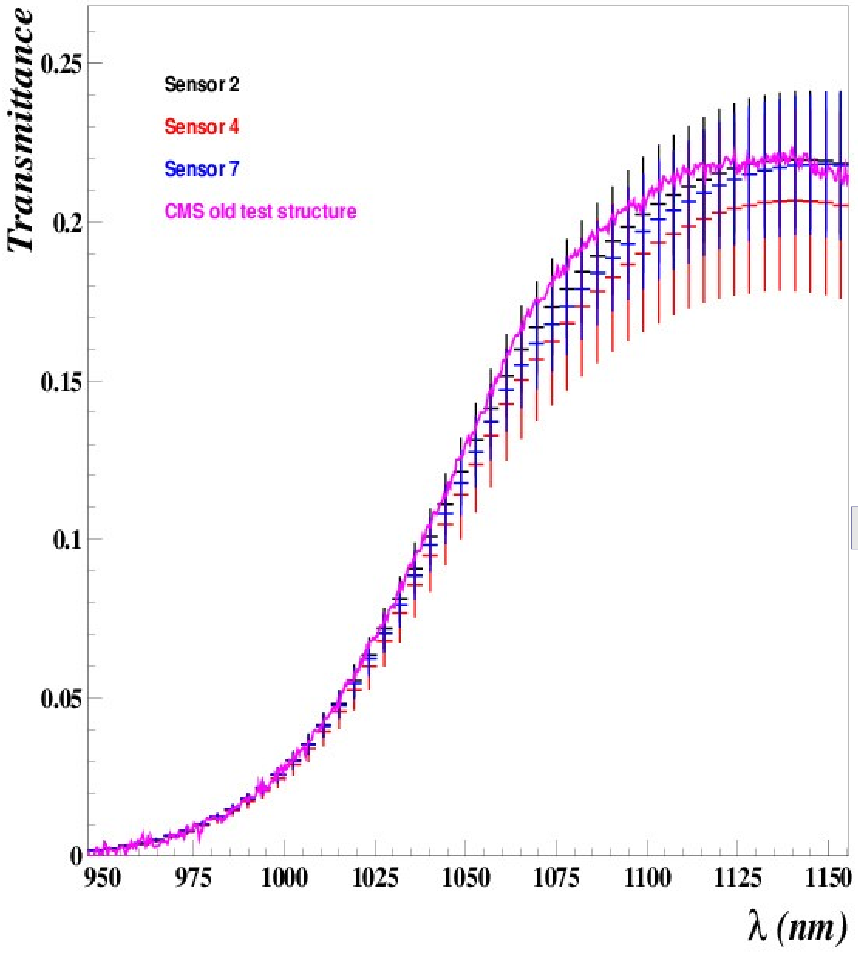


- Transmittance value is the same as measured by CMS in the uncoated areas

Measurements of HPK sensors (II)

- For completeness, we also measured the transmittance along the cross for 3 different sensors:





- Shown here are the mean values (points) and RMS (error bars) of 20 measurements/sensor at each λ. We can see that there are sensible differences in %T. We are investigating where they might come from

- Also shown the %T (pink line) of a CMS test structure without ARC [p=130 µm, stripw=32.5 µm]

Thanks to Th. Bergauer
(HEPHY-Vienna) for the CMS test structure.

- These sensors (5) are going to be tested in a dedicated test beam in October 08 at CERN.

ToDo & Summary

- Presented R&D activity developed within SiLC Collaboration and EuDET project
- We proposed to align the tracker using IR laser beams (pseudotracks), as in AMS and CMS
  - We are improving Si sensor layout (strip width/pitch) and layer depths to obtain maximum Transmittance
  - New sensor simulation developed. It accounts for interferences and diffraction effects in the strips
  - Design is optimized wrt laser spectral resolution and manufacturer's thickness tolerances

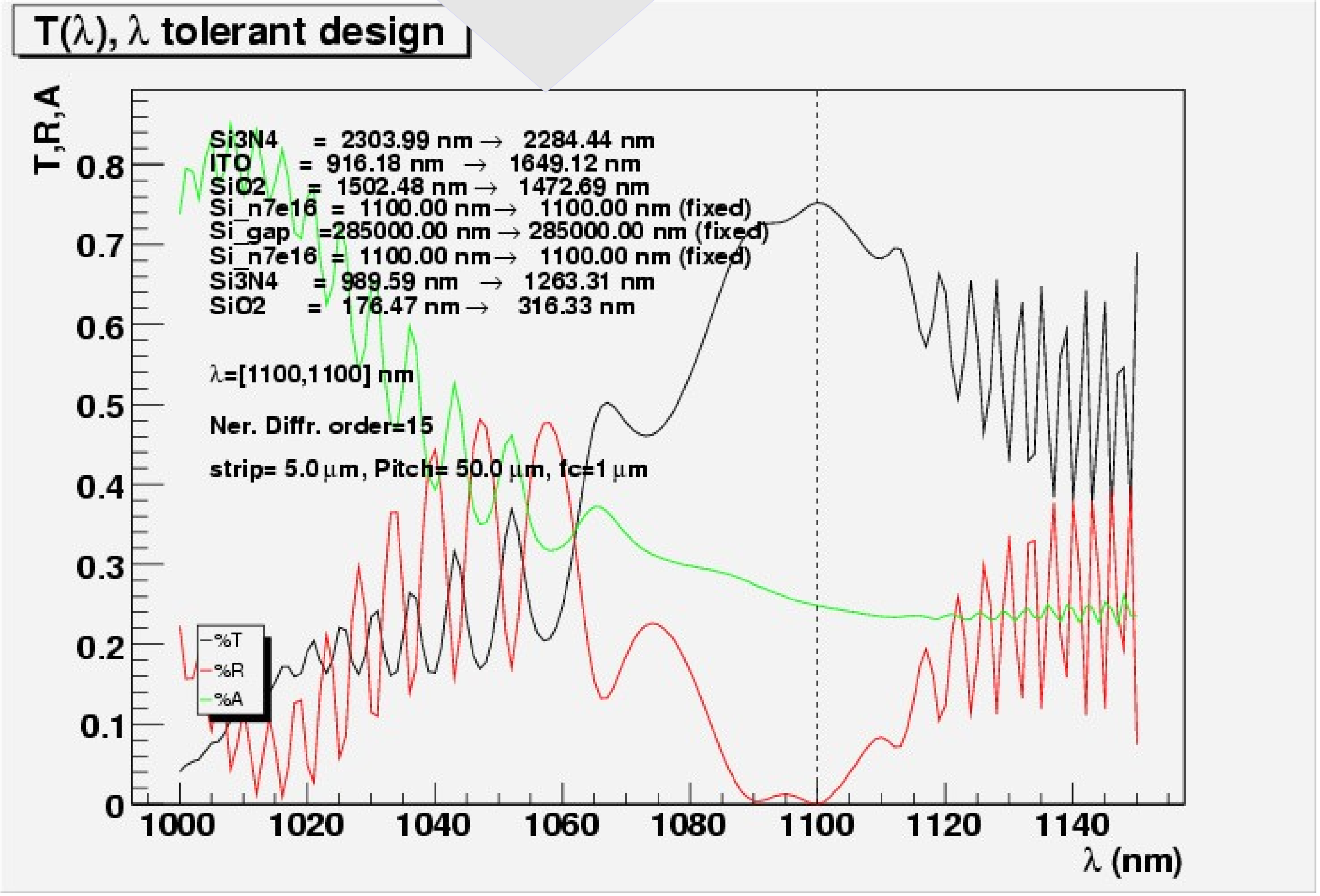
- It is fundamental to obtain refraction indexes of the real materials. CNM prepared samples of each layer in the sensor. Each layer is measured using a new spectrometer. Analysis is ongoing.

- 5 new HPK sensors modified (not optimized) for IR alignment have been received, after electrical tests
  - Transmittance within the alignment passage is uniform within 2% (max difference)
  - Transmittance across the full sensor wafer shows bigger variations (8-10 %)
  - We will test them optically in IFCA labs (Spain) and with particles in test beam at CERN

Backup

Transparent electrodes

- 5% increase (T~75%) if thick ITO layers (>500 nm) are used.



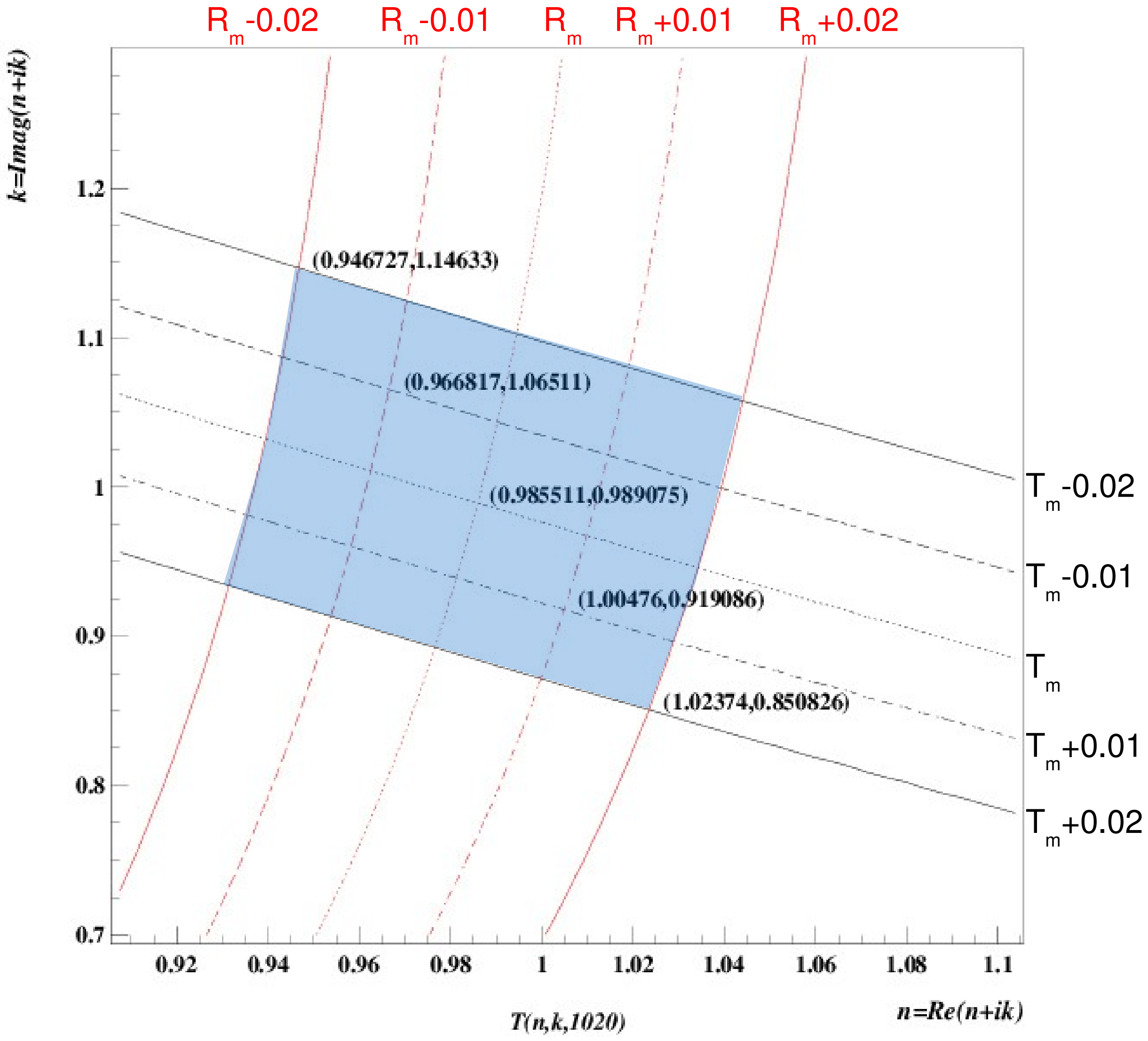
- Note: There is a 10% increase (T~80%) if thin layers ITO layers (≤100 nm) are used (technologically challenging)

Further details on the results shown can be found at Eudet-memo-2007-32

Unicity of solution

- Let's suppose we know the layer thickness. One can try to solve the system: $\begin{cases} T_{meas}(\lambda) - T_{th}(n,k,\lambda)=0 \\ R_{meas}(\lambda) - R_{th}(n,k,\lambda)=0 \end{cases}$ graphically.

- Solutions can be determined by the intersections of $R_{meas}=R(n,k)$ with $T_{meas}=T(n,k)$ in the (n,k) plane



- Experimental errors can be also displayed as $T_{meas}+\sigma_T=T(n,k)$; $R_{meas}+\sigma_R=R(n,k)$

- Blue area displays range of possible solutions compatible with 2% error in measurement.

- The displayed window does not change much for changes in thickness ~10-20 µm.

- The experimental error is reponsible for many possible solutions.

- To reduce the allowed area, we can:
  - i) reduce experimental error
  - ii) use a 3rd measurement
  - (T under angle?) [being considered]

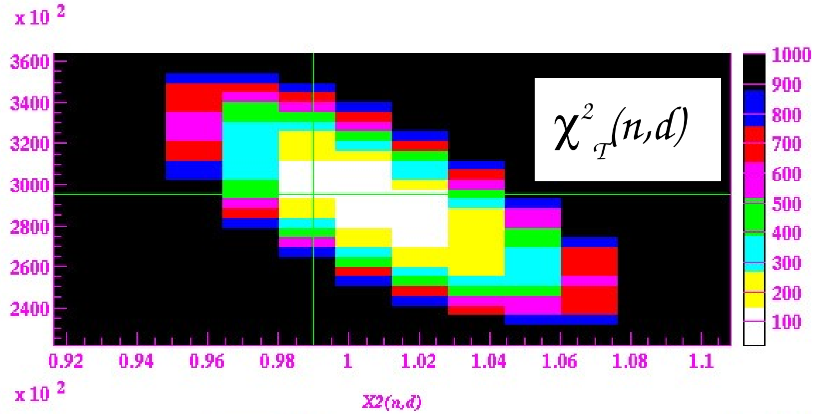
χ^2 scans

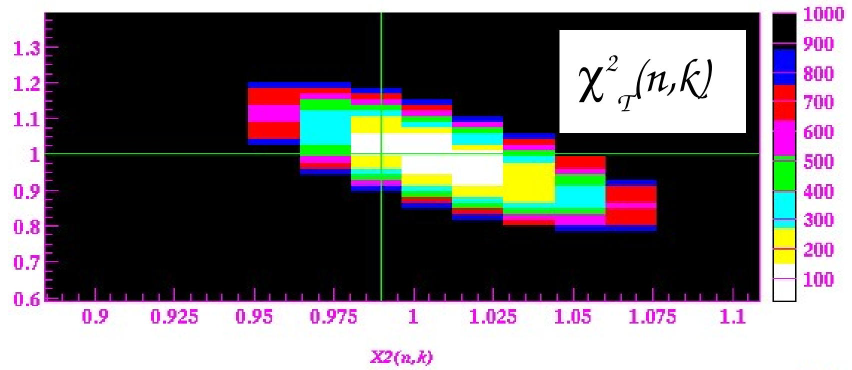
- We have taken measurements of R and T in different points of the wafer.
- Both sets can be fitted separately: (k,d) averages possible within each set.

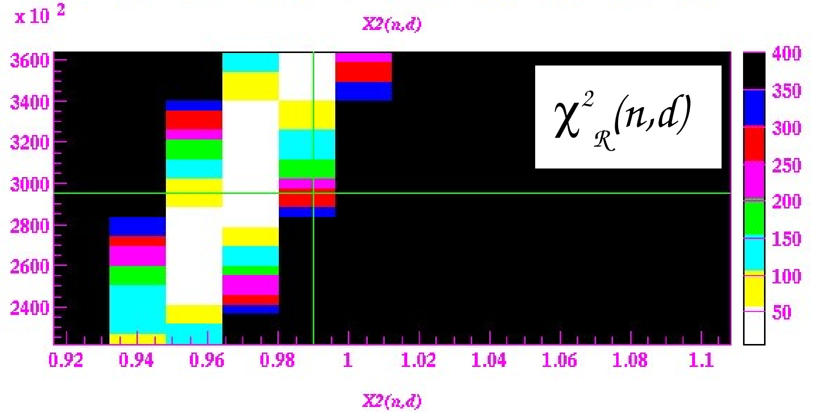
  Example: <n>=0.988389 ⇒ (k_T,d_T)=(1.00,295.00 µm) ; (k_R,d_R)=(1.22,295.01 µm)

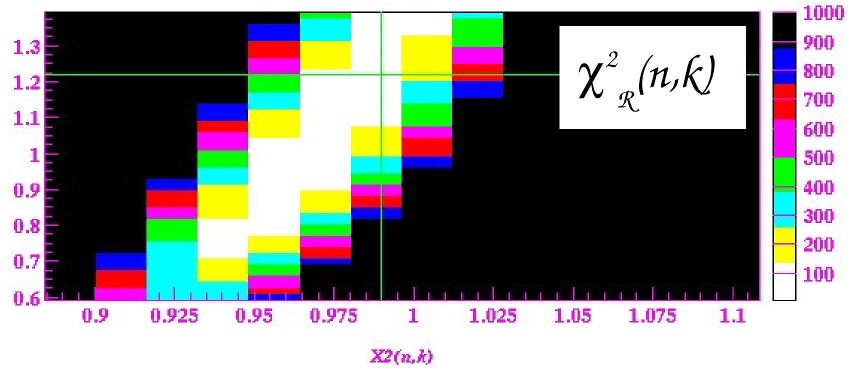
  But $(k_T,d_T)\neq(k_R,d_R)$

- Inspecting χ^2 minima around region of interest: $\chi^2_{\mathcal{T}}=\Sigma_\lambda\,[\,T_{meas}(n_{sc},k_{sc},d;\lambda) - T(n_{sc},k_{sc},d;\lambda)\,]^2$ (same way for R)



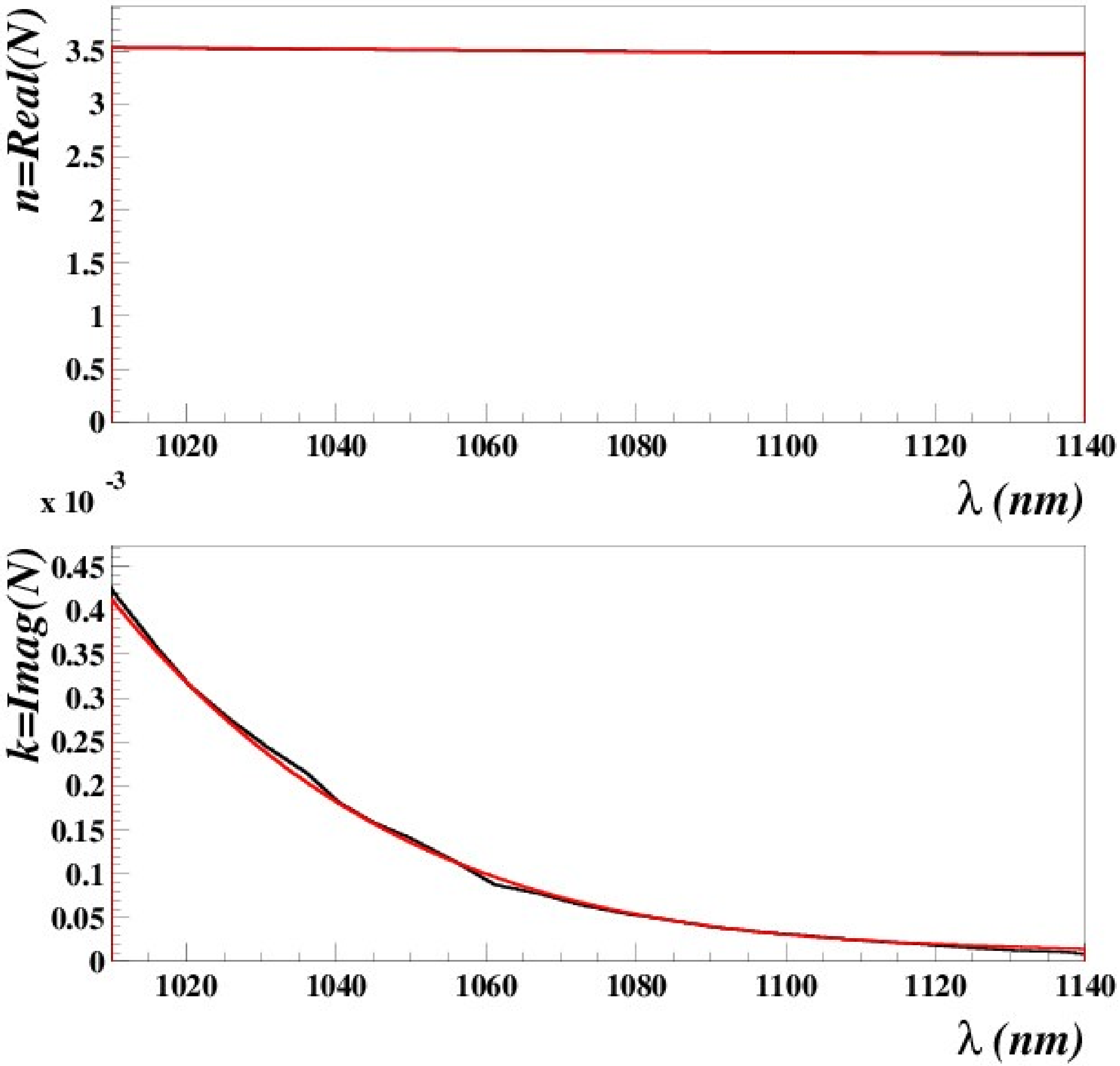






- There are multiple solutions, and χ^2 tests do not solve the degeneracy

(n,k) comparison



Error propagation

- Questions we would like to answer:

1) How much are (T_{calc},R_{calc}) affected by errors in $n_{tabulated}$,$k_{tabulated}$?

2) What is error on n_{fit},k_{fit},d_{fit} obtained from the comparison of (T_{calc},R_{calc}) with (T_{meas},R_{meas})?

1) How much are (T_{calc},R_{calc}) affected by errors in $n_{tabulated}$,$k_{tabulated}$,d_{meas}?

° $\sigma_n \sim 1\text{-}5\times10^{-4}$ (Palik HOC, pg. 549): $\sigma_k \sim 10^{-8}$ (Guessed from Keevers&Green) $\sigma_d \sim 2\ \mu\text{m}$ (Micrometer)

T=T(n,k,d) ⇒ $$\sigma_T^2=\left(\frac{\delta T}{\delta n}\right)^2\sigma_n^2+\left(\frac{\delta T}{\delta k}\right)^2\sigma_k^2+\left(\frac{\delta T}{\delta d}\right)^2\sigma_d^2+2\left(\frac{\delta T}{\delta n}\right)\left(\frac{\delta T}{\delta k}\right)\rho\sigma_n\sigma_k+2\left(\frac{\delta T}{\delta n}\right)\left(\frac{\delta T}{\delta d}\right)\rho\sigma_n\sigma_d+2\left(\frac{\delta T}{\delta k}\right)\left(\frac{\delta T}{\delta d}\right)\rho\sigma_k\sigma_d$$

- But we do not measure T but: $\tau(n,k,d;\lambda)=\int T(n,k,d;x)G(\lambda-x,\sigma)\,dx$

$$\sigma_\tau^2=\sigma_n^2\left(\int\frac{\partial T(x)}{\partial n}G(\lambda-x,\sigma)\,dx\right)^2+\sigma_k^2\left(\int\frac{\partial T(x)}{\partial k}G(\lambda-x,\sigma)\,dx\right)^2+\sigma_d^2\left(\int\frac{\partial T(x)}{\partial d}G(\lambda-x,\sigma)\,dx\right)^2+\ldots$$

Still work in progress.