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Plasmon Rulers for 3D IC Alignment

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Outline

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- 3D IC
  - Heterogeneous integration
  - Alignment
- Surface plasmons
  - Metal nanoplasmonic structures
  - Plasmon rulers

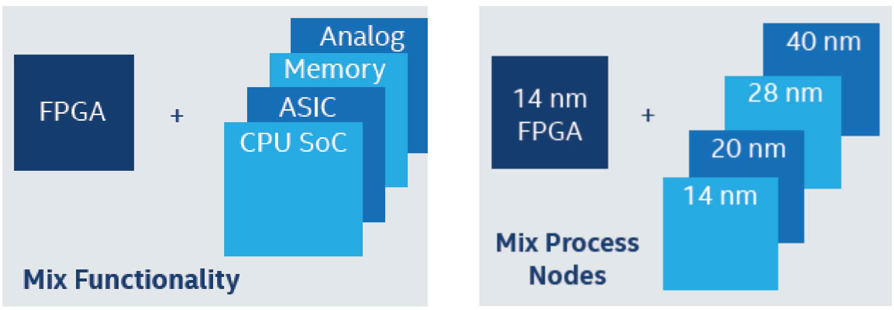
Plasmon rulers for packaging

- Concept of plasmon rulers for alignment
  - Configuration and design
- Simulations
  - Face-to-face grating ruler
  - Interdigiting grating ruler
- Fabrication

Summary

- Key characteristics
- Future work

Heterogeneous integration



Stratix 10 FPGA using Intel's Heterogeneous 3D SiP Technology [1]

Ever-increasing demands in:

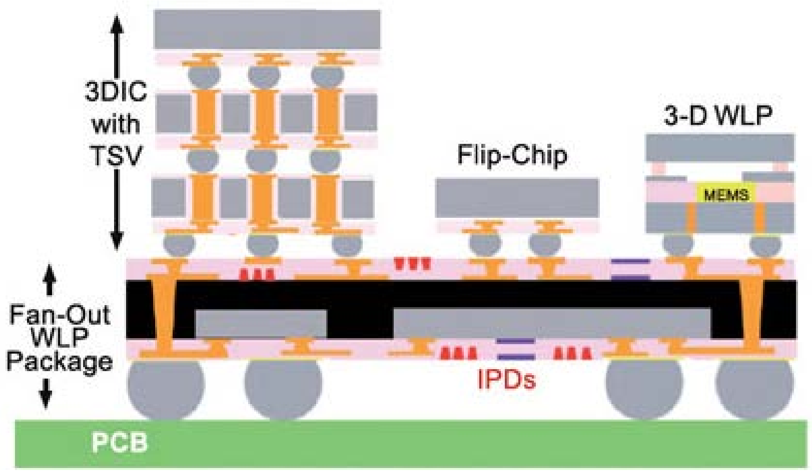
- Higher bandwidth
- Lower power consumption
- Smaller footprint or form factor
- More functionality
- More flexibility
- IoT, cloud computing, data center, 5G, etc.

Heterogeneous integration can:

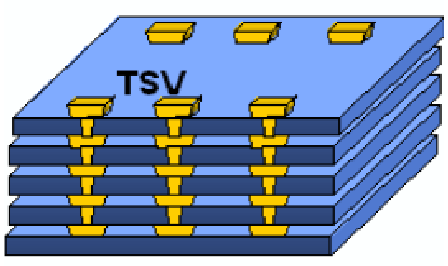
- Mix functionality: sensors, RF, Analog, memory, optical, etc.
- Combine components fabricated from different process nodes

[1]Manish Deo, "Enabling Next-Generation Platforms Using Intel's 3D System-in-Package Technology", (white paper) @ 2017 Intel Corp.

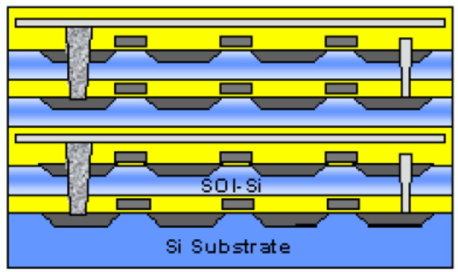
3D IC



Fan-out wafer level package[1]



3D Stacked ICs



Monolithic 3D IC

<u>3D IC manufacturing:</u>

- 3D packaging
- 3D stacked ICs
- Monolithic 3D IC

<u>Packaging strategies:</u>

- Die to wafer
- Die to die
- Wafer to wafer

<u>Techniques:</u>

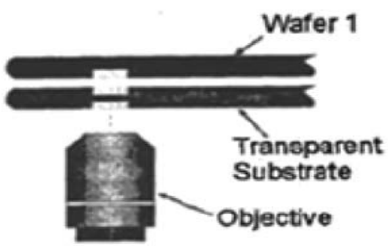
- Fan-out wafer level package (FOWLP)
- through-silicon via (TSV)
- through-encapsulant via (TEV)

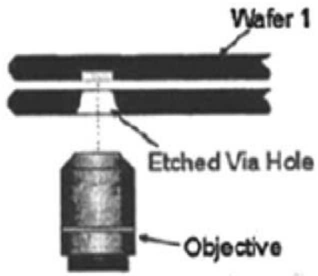
Alignment between dies, wafers or layers is a key step

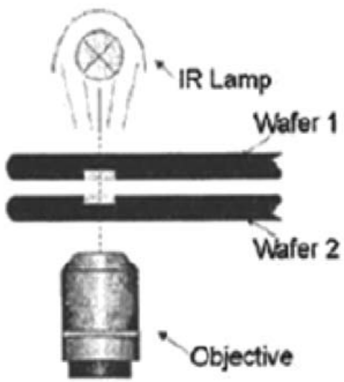
[1]image source: https://www.pddnet.com/article/2010/06/embedded-wafer-level-packages-%E2%80%93-2010-report

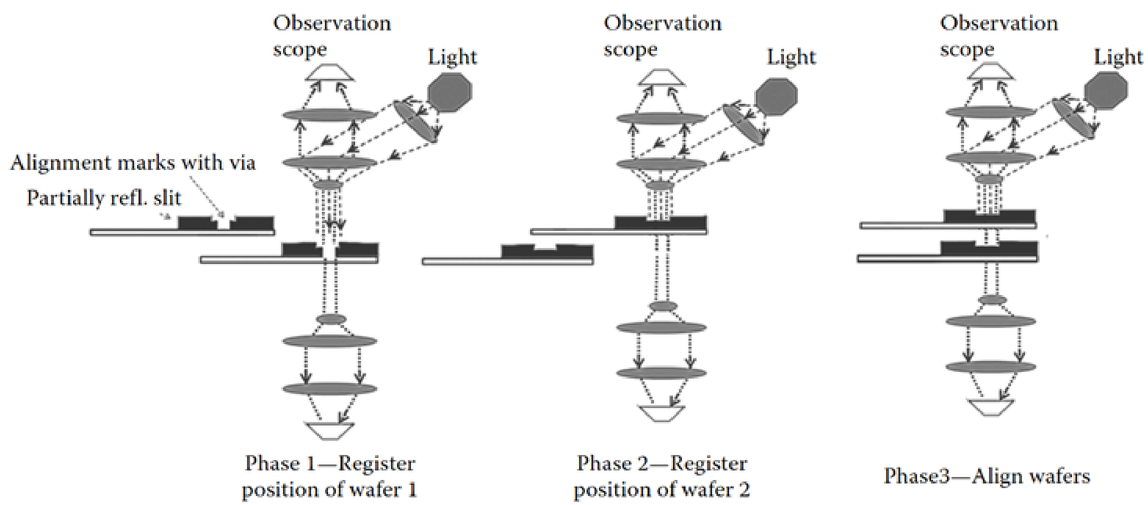
Traditional alignment techniques

- Based on alignment marks
- Optically "image" the marks
- Current commercial tools: 0.25 um accuracy
- Face to face
- Face to back





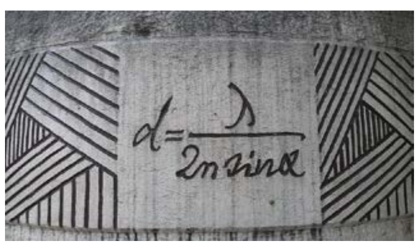


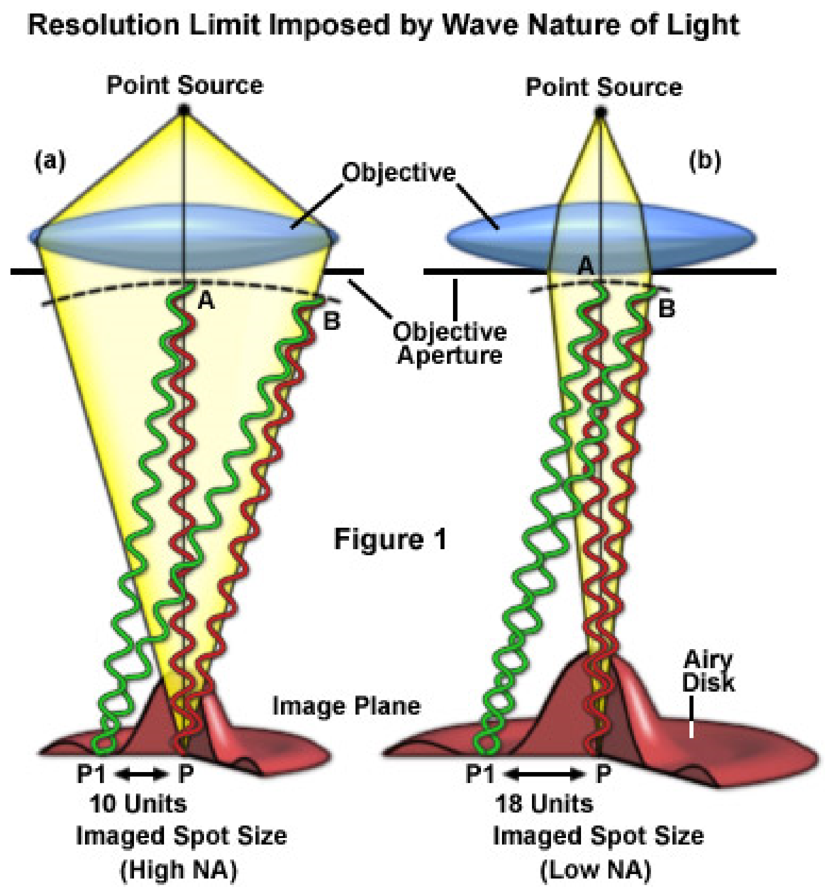


Lee et al., "Wafer-to-wafer alignment for three-dimensional integration: a review." Journal of Microelectromechanical Systems 20.4 (2011): 885-898.

Diffraction limit of conventional optics

Ernst Abbe
(1840-1905)

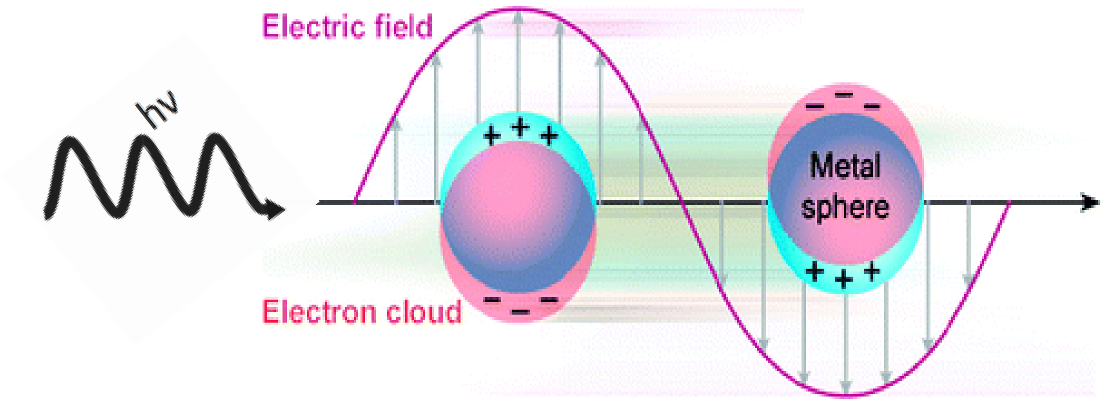


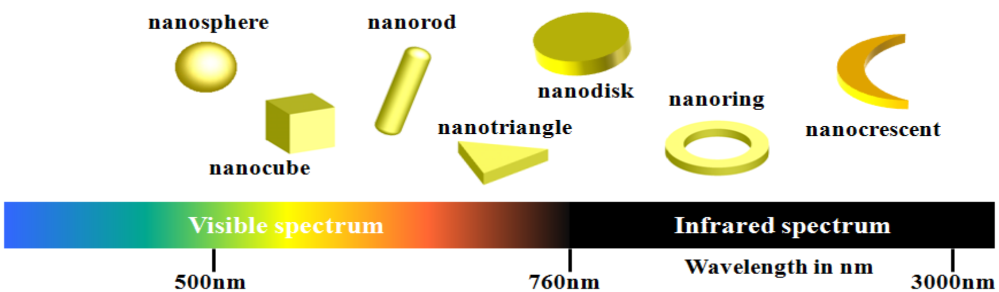


λ=1000nm
NA=1
Diffraction limit=500 nm

Can we “optically” align two wafers with accuracy beyond “diffraction limit”?

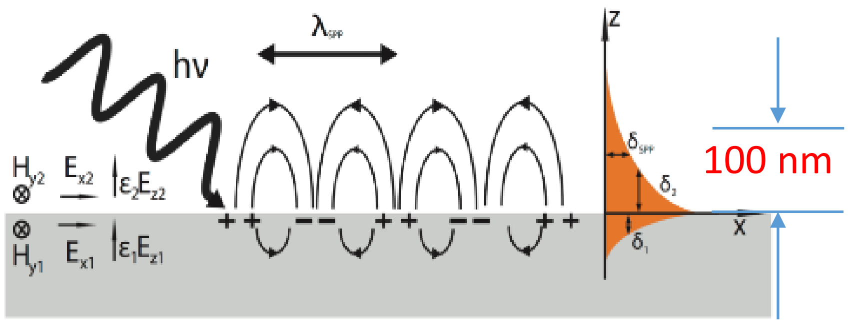
Surface plasmons



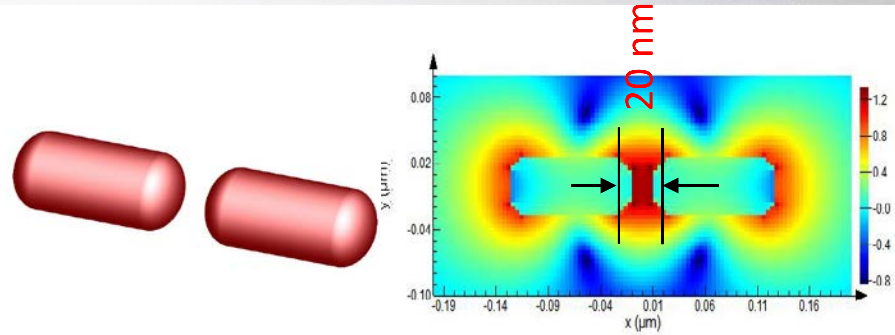


- Surface plasmons: surface electrons of metal coupled with light
- Available metal: gold, silver, aluminum, copper, etc.
- Tunable across wide spectral range
- Local surface plasmon (LSP)
- Propagating surface plasmon polariton (SPP)
- Nanoplasmonics --- shaping metal nanostructures for manipulating light-matter interaction.

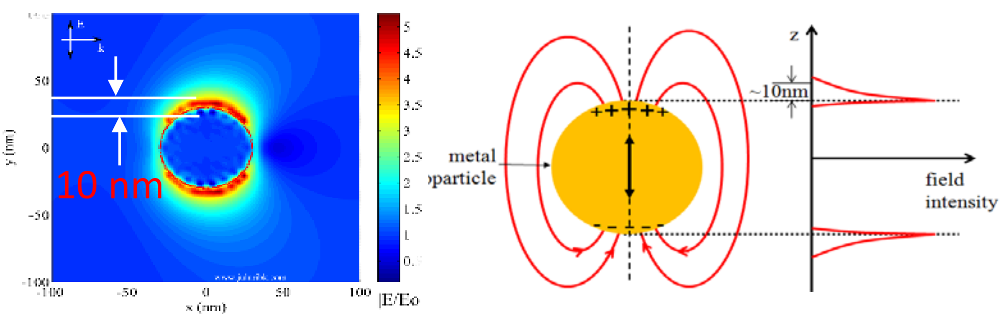
Nanoplasmonic 'hot spot' break through diffraction limit



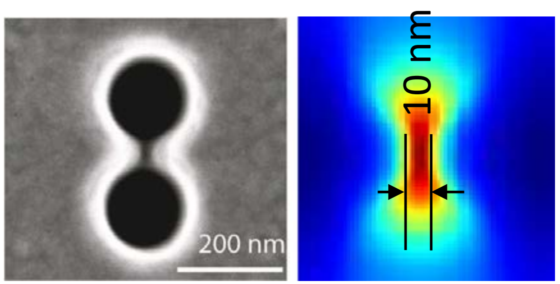
hot surface



hot spot in a nano-antenna



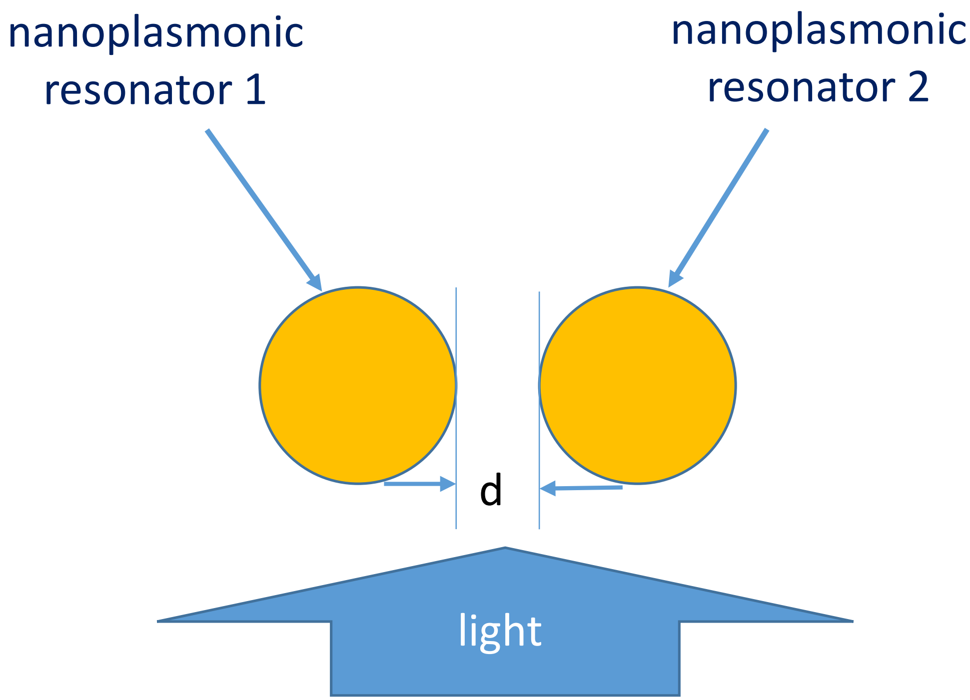
hot spot in a metal nanoparticle

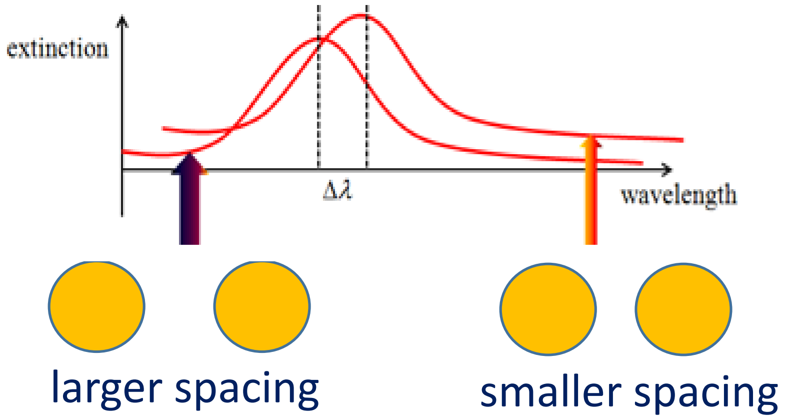


hot spot in a nano-aperture

- Nanoplasmonic structures: focus light onto a very tight spot to enhance light-matter interactions
- Applications: sensing, surface-enhanced Raman scattering (SERS), optical trapping, display, structural colors, photothermal treatment, non-linear optics, light source, nanolens, solar cells, optical transistor, terahertz optics, **plasmon ruler**

Plasmon ruler

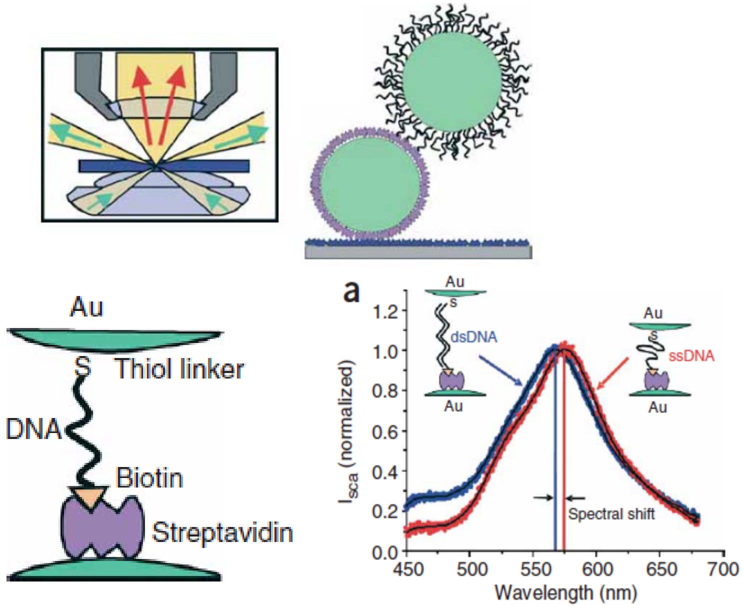




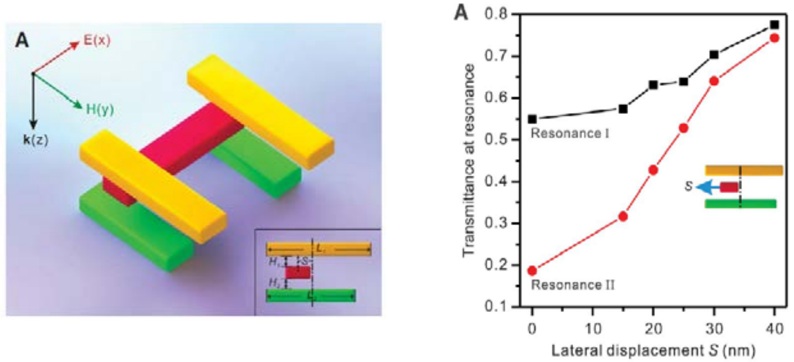
Probe *inter-resonator distance* from *shift in wavelength*

- *Plasmon ruler*: based on coupling nano-plasmonic resonators, each resonator is composed of one nanoplasmonic structure
- Two resonators must be within the near-field distance, typically <200nm
- Distance and spacing between resonators is probed with a beam of light
- Spectral feature extremely sensitive to their spacing
- Sub-nanometer resolution!!!
- Primarily used for studying biomolecular interaction
- 3D orthogonal detection in special design

Plasmon ruler



Plasmon rulers for detecting DNA [1]

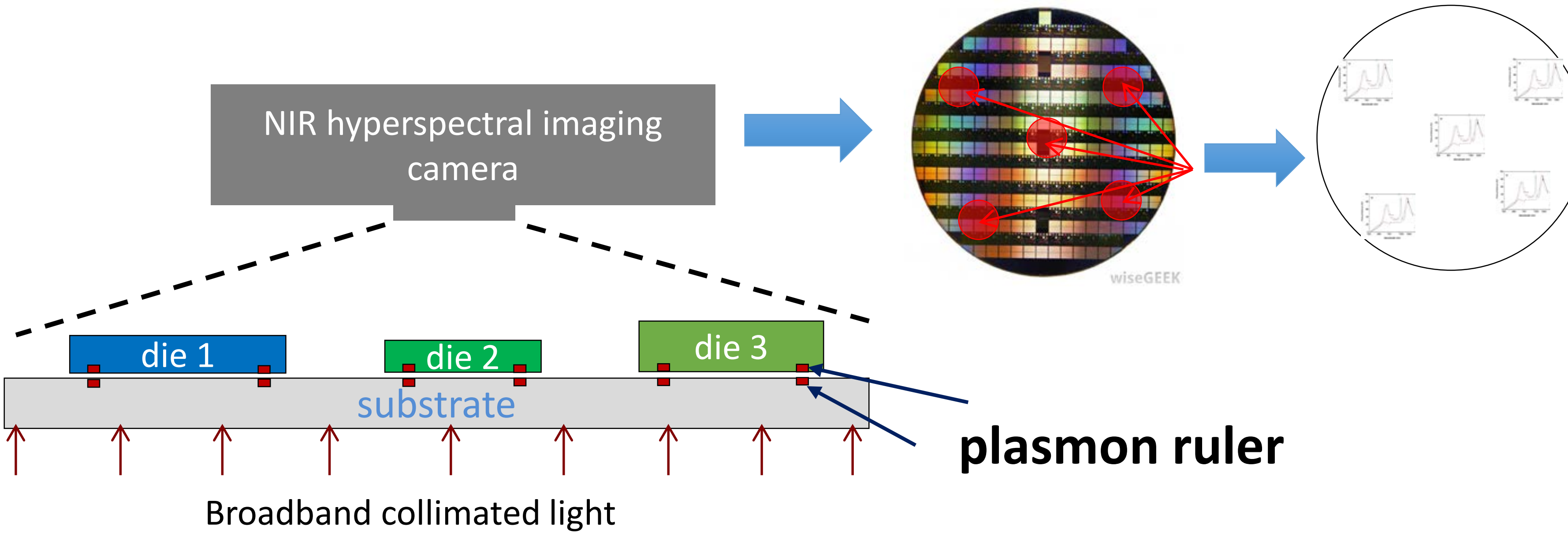


3D plasmon ruler[2]

How do we apply the sub-nanometer resolution of plasmon rulers for aligning wafers?

[1] Sönnichsen et al., Nature Biotechnology 23(6):741-745, 2005;
[2] Liu et al., Science 332(6036):1407-1410, 2011.

Plasmon ruler for 3DIC alignment



Proposed plasmon rulers for die to wafer integration

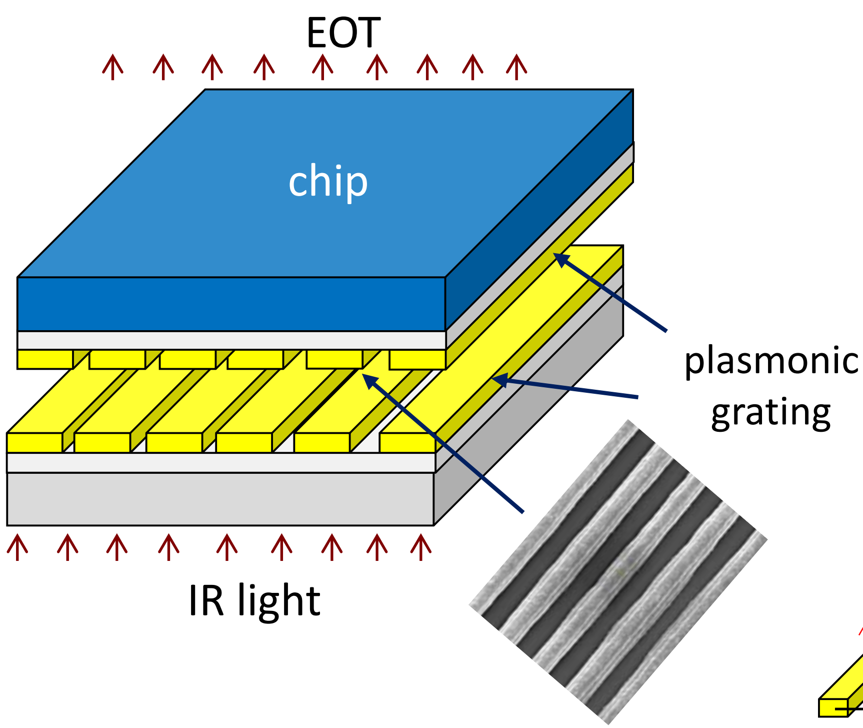
- Plasmon rulers pre-fabricated on dies and substrate
- A pair of coupling rulers tells the relative alignment between two rulers from transmission peak
- Broadband collimated light illuminates all rulers
- Hyper-spectral camera acquires a map of transmission spectra across the entire wafer
- Spectra shift → location shift between two rulers

Advantages:

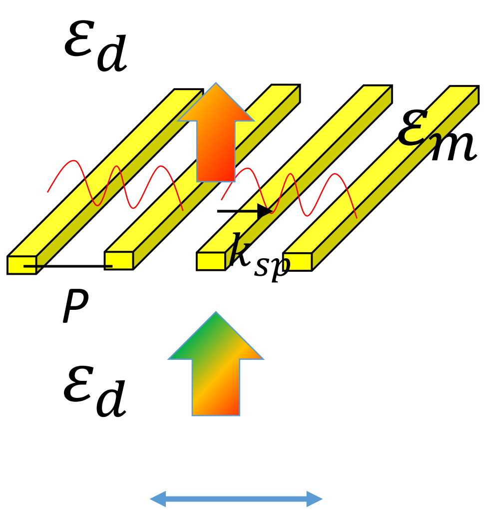
- Fully optical, non-invasive probing of status of alignment
- Don't need microscopes!!!
- Fast quantification of mis-alignment from spectral shift

Plasmon ruler based on metal grating

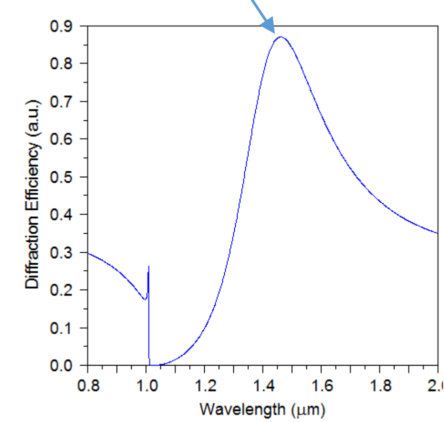
- Plasmon ruler design based on metal grating
- Available metal: copper, gold, aluminum
- Extraordinary optical transmission (EOT) of p-polarized light: light couples to the surface plasmons of metal grating from back side; and couples out from the top side
- Transmission peak mainly determined by: period, width and position-dependent coupling.
- Near infrared (NIR) spectral range for compatibility with silicon



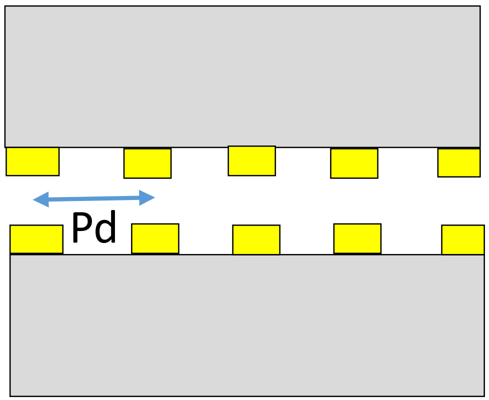
Plasmon ruler design based on 1-D metal grating



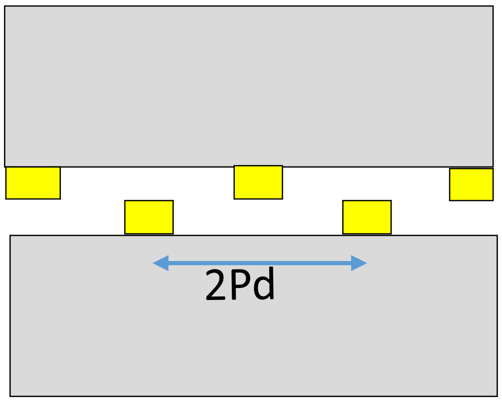
$$\lambda = \frac{P}{i}\sqrt{\frac{\varepsilon_m \varepsilon_d}{\varepsilon_m + \varepsilon_d}}$$



Alignment schemes using metal gratings



Face-to-face grating

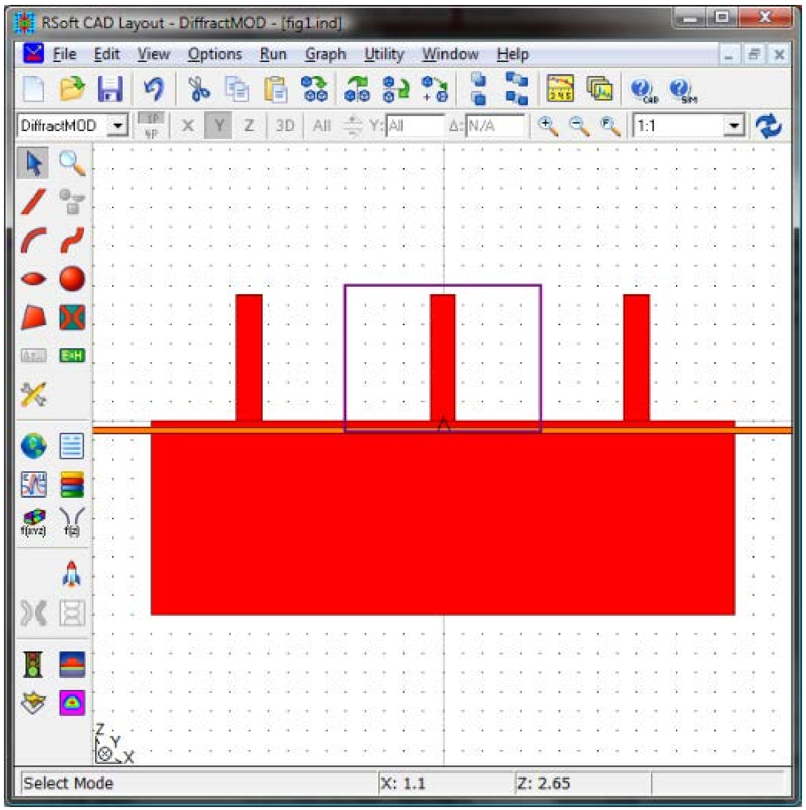


Interdigiting grating

Two schemes:

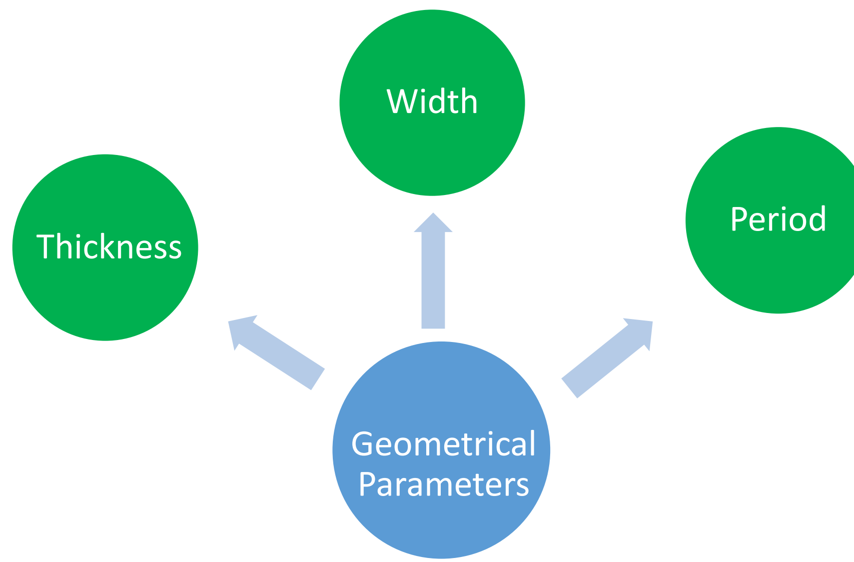
- Face-to-face grating rulers
- Interdigiting grating rulers

RCWA Simulation configuration

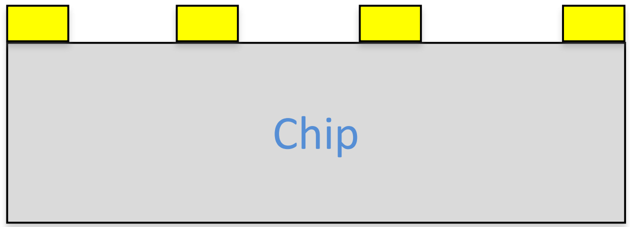


Rsoft RCWA simulation configuration

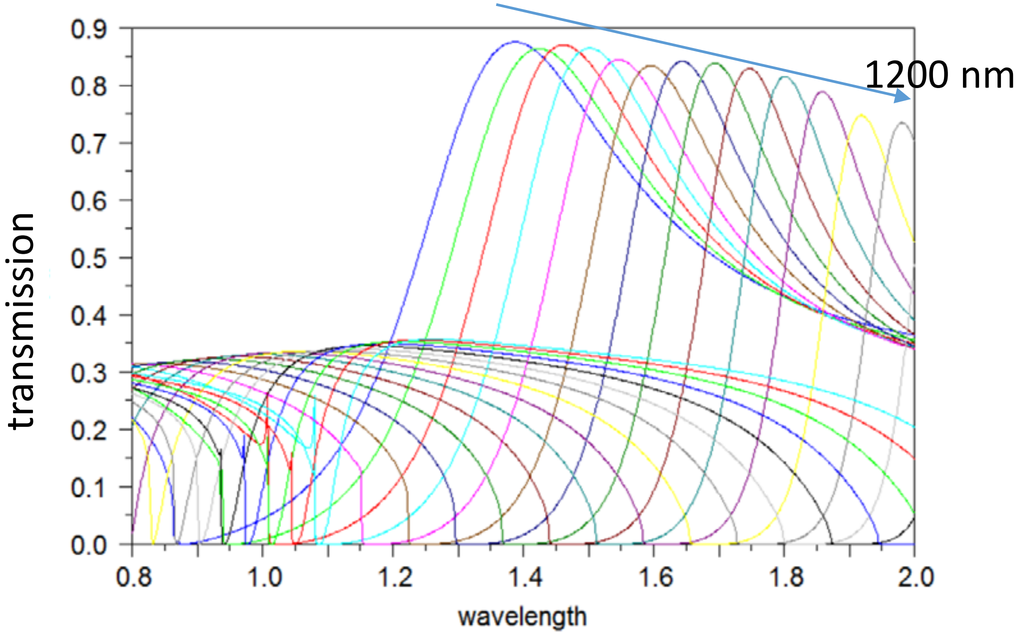
- RCWA: rigorous coupled wave analysis
- Plane-wave expansion of electromagnetic (EM) waves
- Periodic boundary in x direction
- Light polarized along x direction
- Simulate transmission spectra for near-infrared range



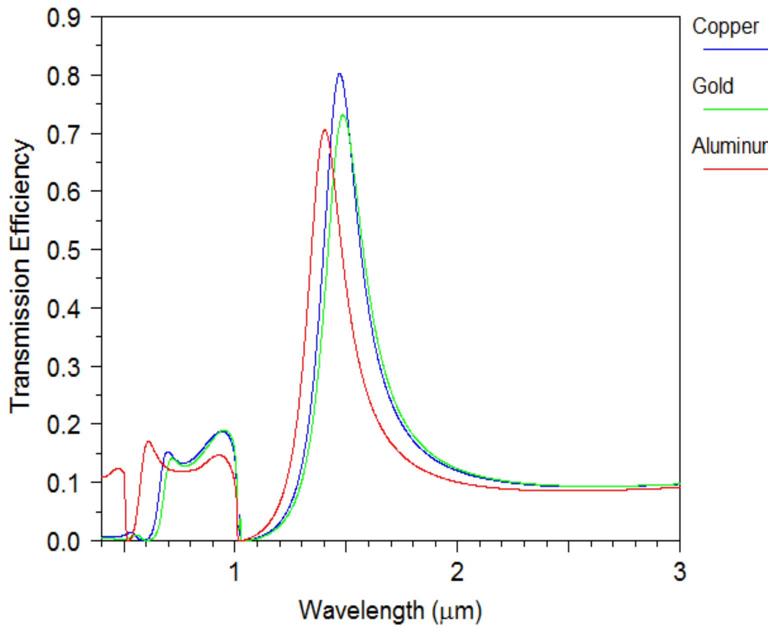
Face-to-face grating:
Simulation of stand-alone ruler



Period	Grating Width	Grating Thickness
700 nm	600 nm	300 nm

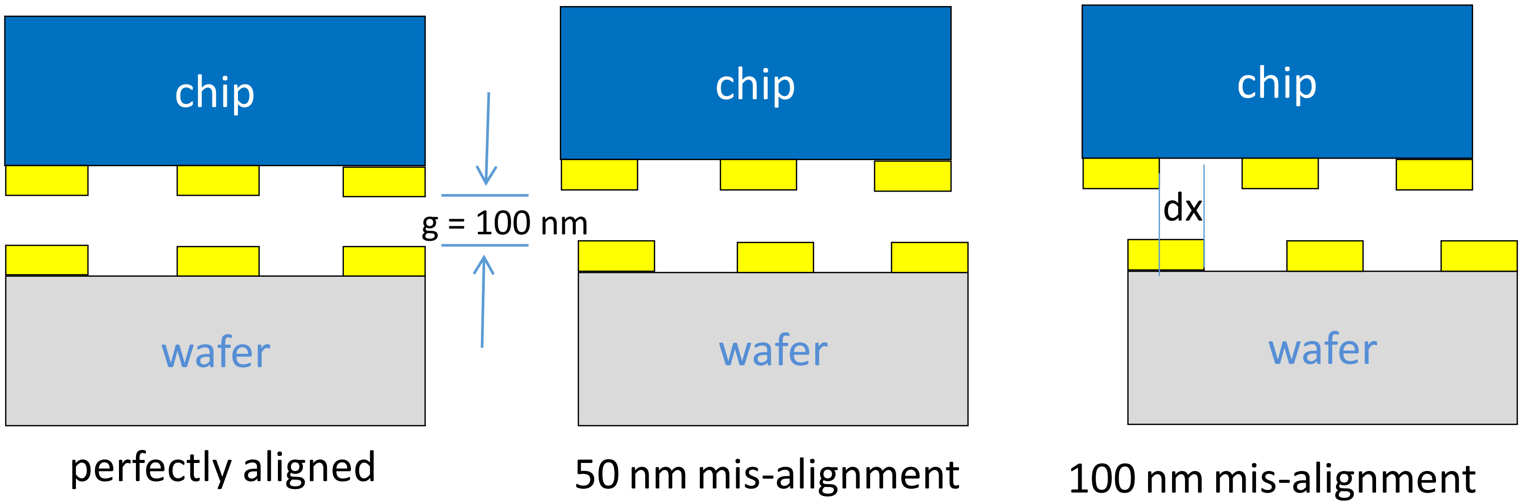


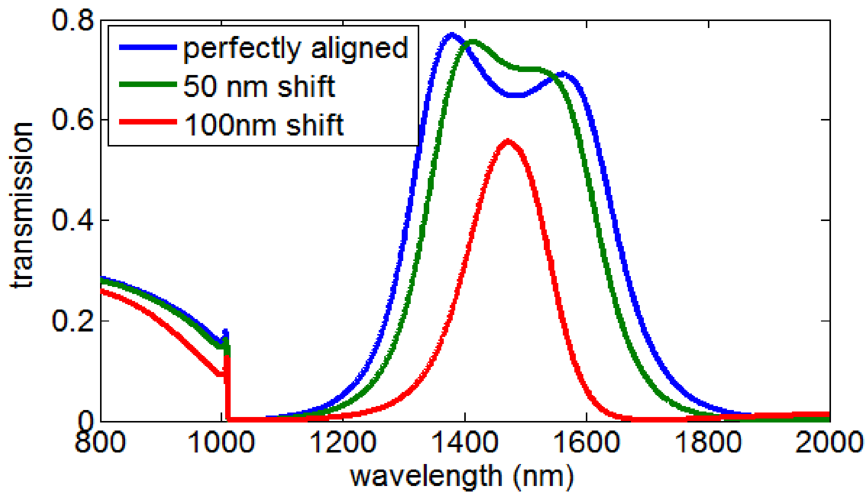
Transmission spectra vs. period



Transmission spectra for different metals

Simulated spectra vs. lateral shift



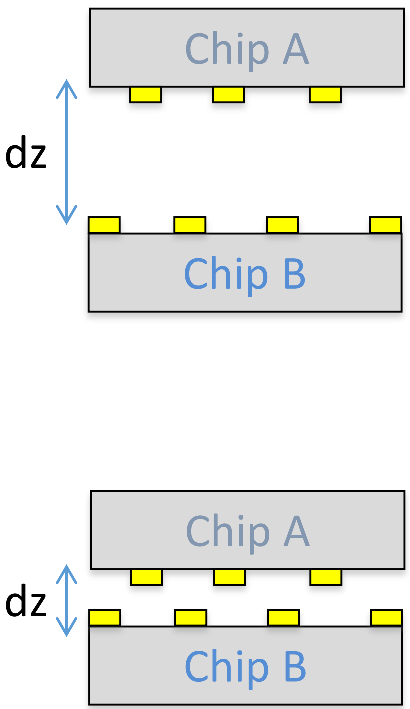


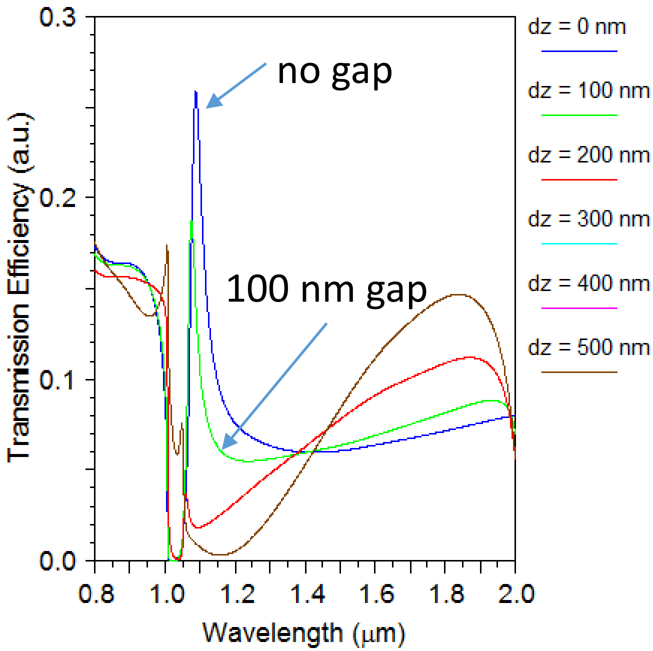
<u>Spectral features to detect:</u>

- peak wavelength
- rate of transmission

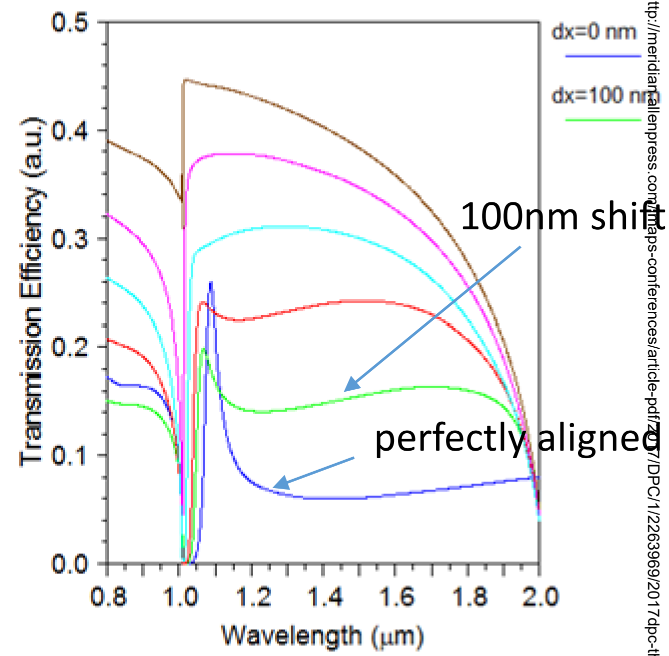
- Perfectly aligned rulers give two widely separated peaks
- Two peaks gradually merge into one peak with increasing lateral shift
- 100 nm shift changes transmission by more than 10%
- Estimated detection sensitivity at least 100 nm

Interdigiting grating: Simulation of vertical gap





Transmission spectra vs. vertical shift

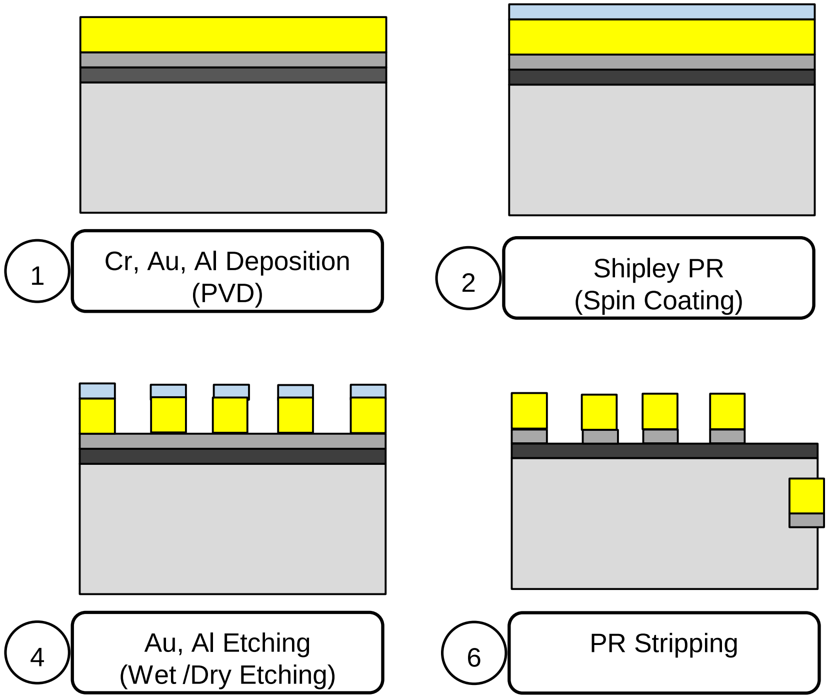


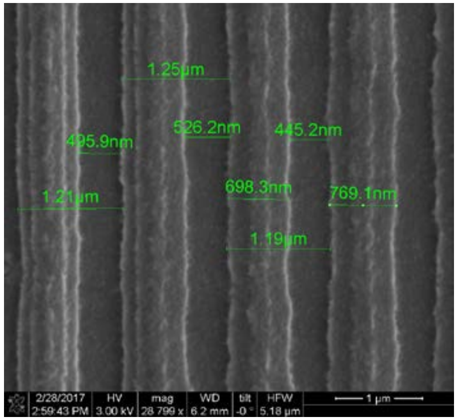
Transmission spectra vs. lateral shift

Period	**1300 nm**
Width	500 nm
Thickness	150 nm

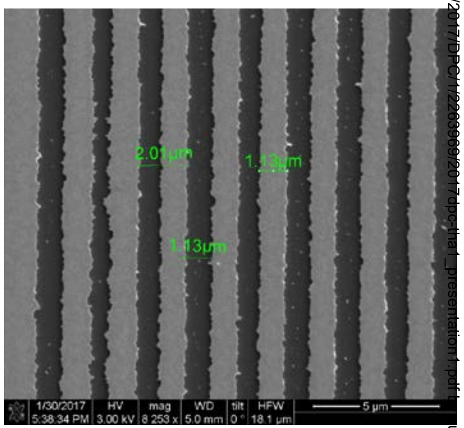
- Increasing vertical gap strongly decrease transmission around 1100nm wavelength → *bring two wafers very close to each other*
- Increasing lateral shift strongly increases transmission in the band 1300nm to 1600nm → *bring two wafers into aligned position*

Fabrication Process - Summary





P = 1.2 um
Patterned
photoresist film



P = 2 um
Gold grating

Summary

New alignment method based on plasmon rulers:

- Optically probe the position (transmission spectrum), rather than seeing the position (image processing)
- Use light beam (not necessarily focused beam) to detect position shift smaller than diffraction limit
- For both guiding alignment process and inspecting alignment quality
- 1-D grating design based on face-to-face grating and interdigiting grating schemes
- Proof of concept simulations show that at least sub-100 nm accuracy is likely achievable

Challenges and questions:

- Where to put the ruler structures? Which layer? How thick metal?
- How to integrate the optical detection system with the mechanical system?

On-going development:

- Test optical properties of coupled plasmon rulers
- Design 3D ruler for comprehensive information of mis-alignment in all three dimensions
- Study lateral shift and rotational shift
- Integrate the plasmon rulers in real systematic tests

Questions?