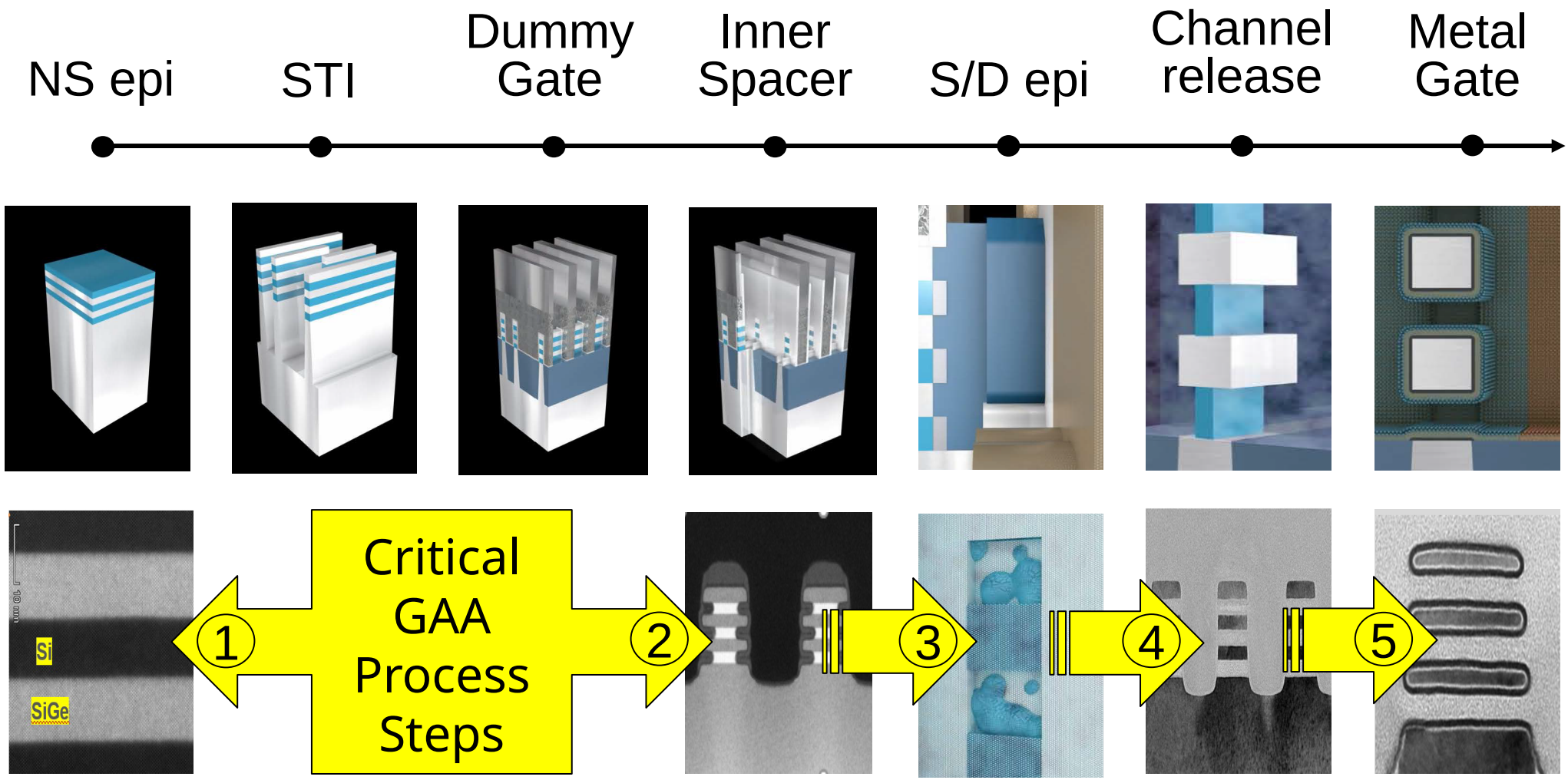
Photo-Modulated Reflectance for Gate-All-Around Metrology

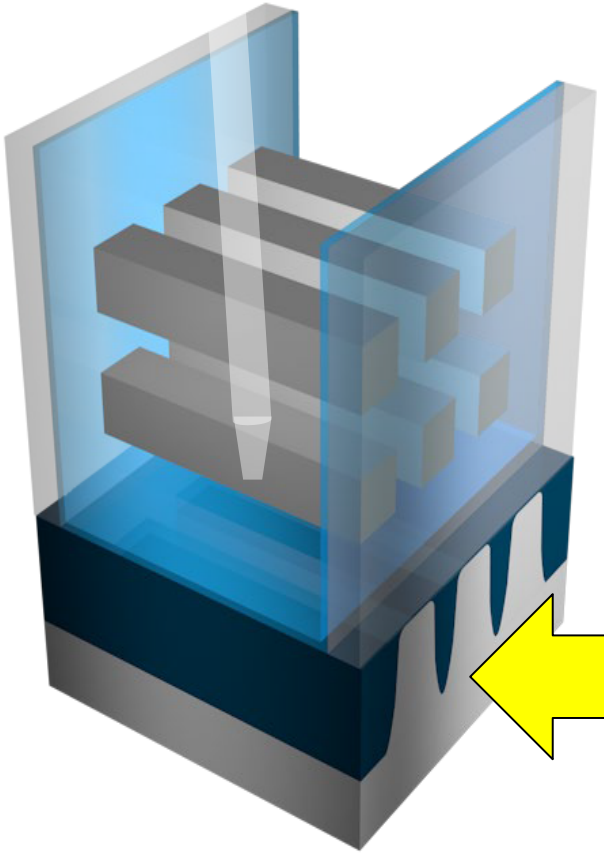
Gate-All-Around (GAA) Process Flow:



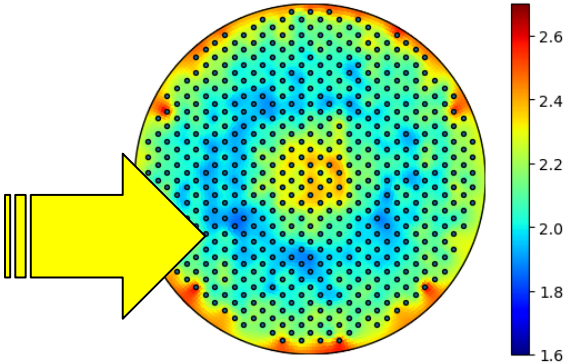
Images courtesy APPLIED MATERIALS®

eBeam Metrology/Inspection for GAA:

eBeam addresses 2 of the 5 Critical GAA Steps:
Inner Spacer & Channel Release



Challenges with 3D structures & Need for Massive Sampling (local & wafer scale)…



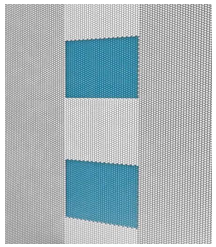
Images courtesy APPLIED MATERIALS®

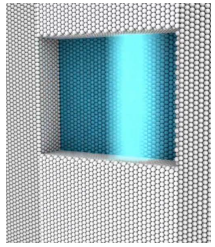
Metrology Missing for 3 Critical GAA Steps:

NS epi

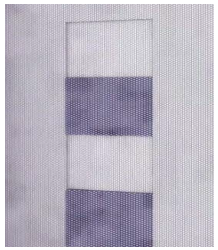
Metrology for SiGe/Si Superlattice??

Inner Spacer



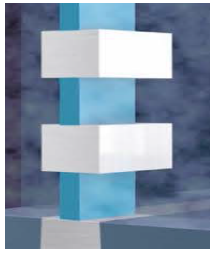


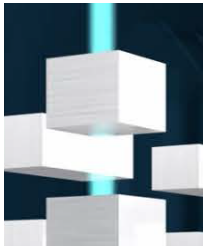
S/D epi



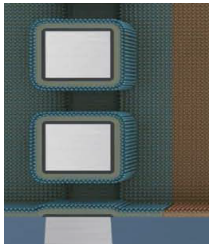
Metrology for SiGe, Doping Profile??

Channel release





Metal Gate

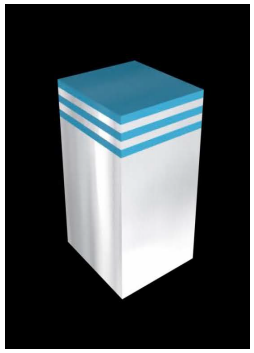


Metrology for Work Function (V_t adjust)??

Images courtesy APPLIED MATERIALS®

Case of the Missing Metrologies: GAA

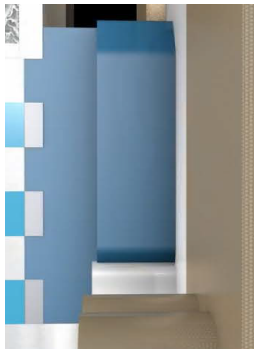
NS epi



- Ellipsometry for SL thicknesses, Ge% ⇒ unstable fits
- HR-XRD for SL thicknesses, Ge% ⇒ slow & analytical

KPM is mobility of Si channel: no metrology

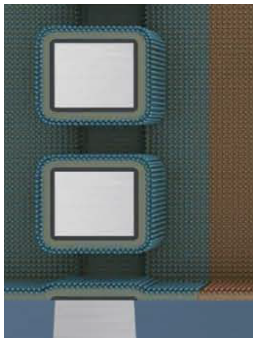
S/D epi



- μ-4PP ⇒ ~120μm spot size, contact…
- Hall Effect ⇒ accurate but destructive…

KPM is S/D doping profile: no metrology

Metal Gate



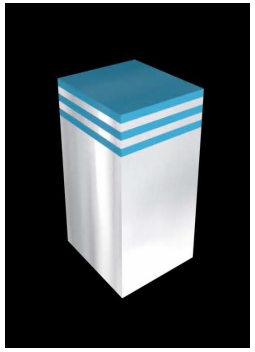
- UV-PES ⇒ large spot size, complex interpretation
- KPFM ⇒ should work in principle…

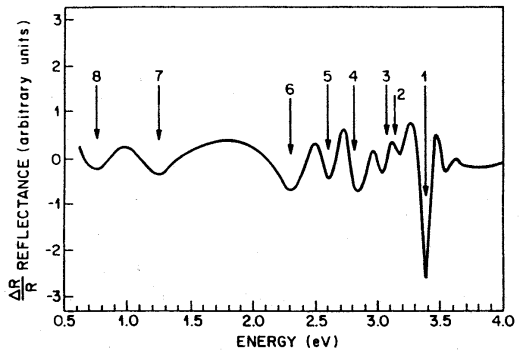
KPM is V_t: no metrology

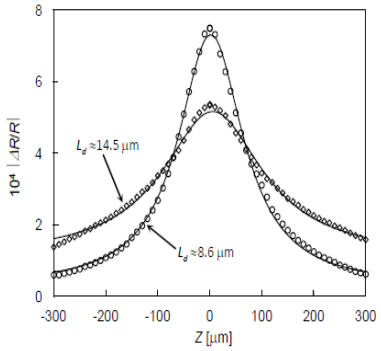
Images courtesy APPLIED MATERIALS®

Photo-Modulated Reflectance (PMR) for GAA:

NS epi

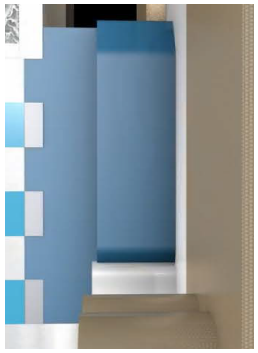


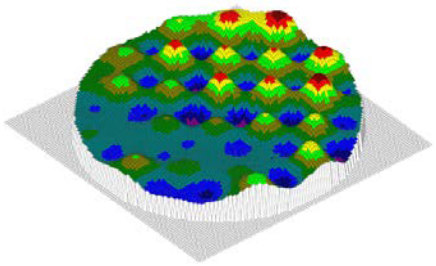


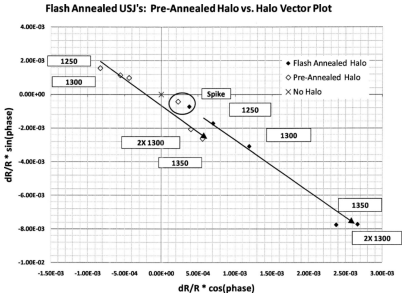


PMR for band-structure analysis & carrier diffusion: SL & μ metrology

S/D epi

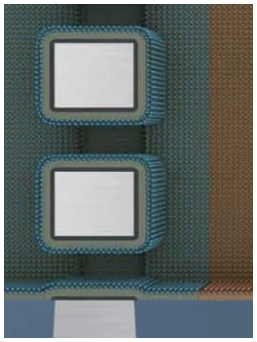


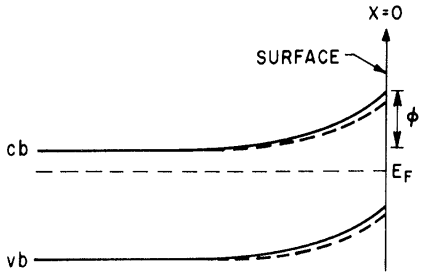




PMR signal directly proportional to N_e: doping metrology

Metal Gate





PMR very sensitive to surface capacitance (dipole): V_t metrology

Images courtesy APPLIED MATERIALS®

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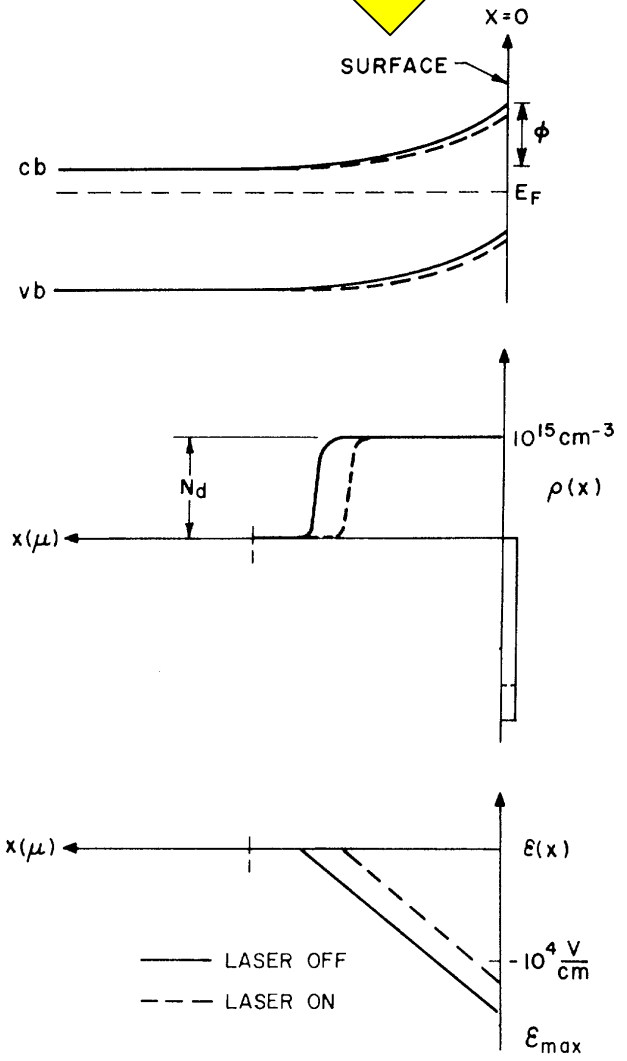
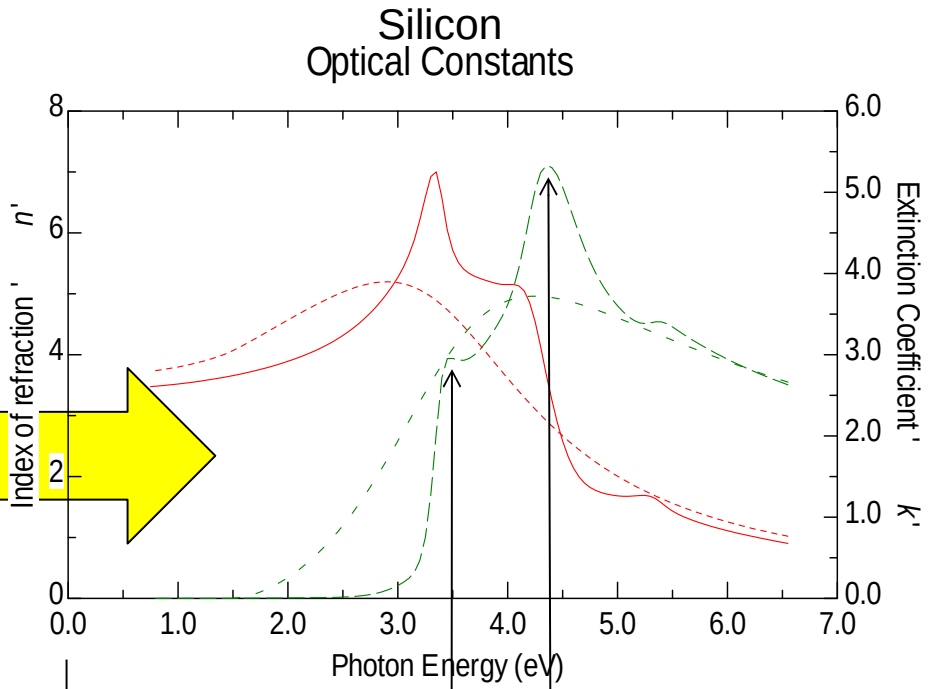
PMR Principles:

1. Pump beam modulates the sample charge/E-field/voltage

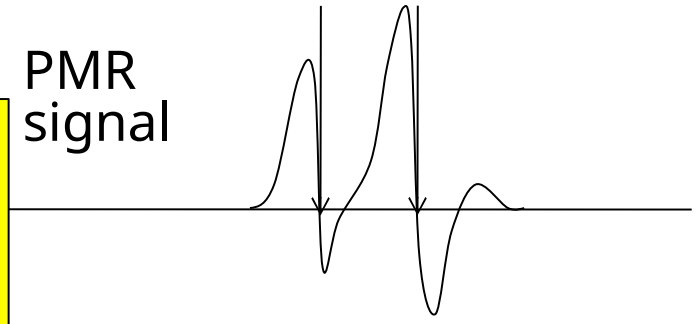


2. Modulated E-field causes reflectivity modulation



Interband transitions

PMR signal



3. Probe beam measures the modulated reflectance

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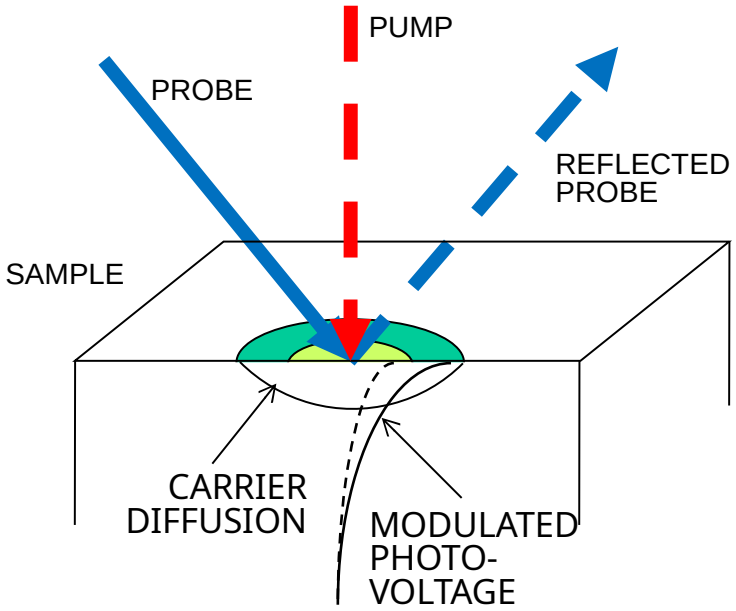
PMR Capabilities:



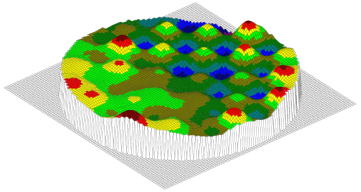
Measurement Signal:

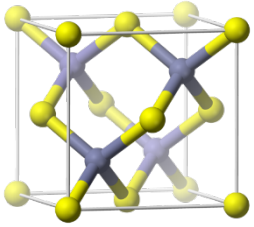
$$\frac{\Delta R}{R} = \frac{2qN_e\Delta V}{\varepsilon_s} \times L(\lambda)$$

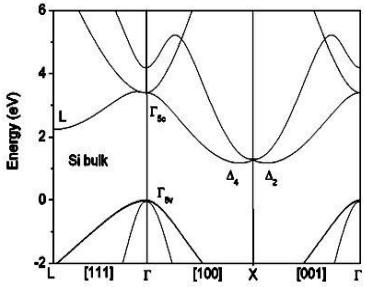
Carrier Density

Modulated Photo-Voltage

Band-structure







In-line Criteria:

- Non-contact
- High Sensitivity
- High Speed
- Local

PMR:

- Non-contact (optical)
- Direct sensitivity to Material Properties
- Measurement time ~seconds
- Micron resolution

PMR Ideal for GAA Metrology

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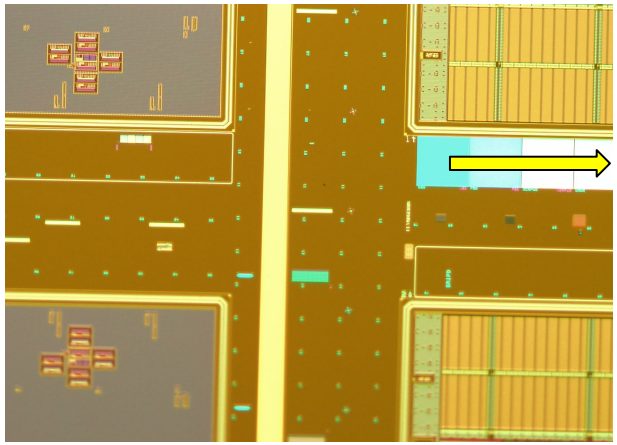
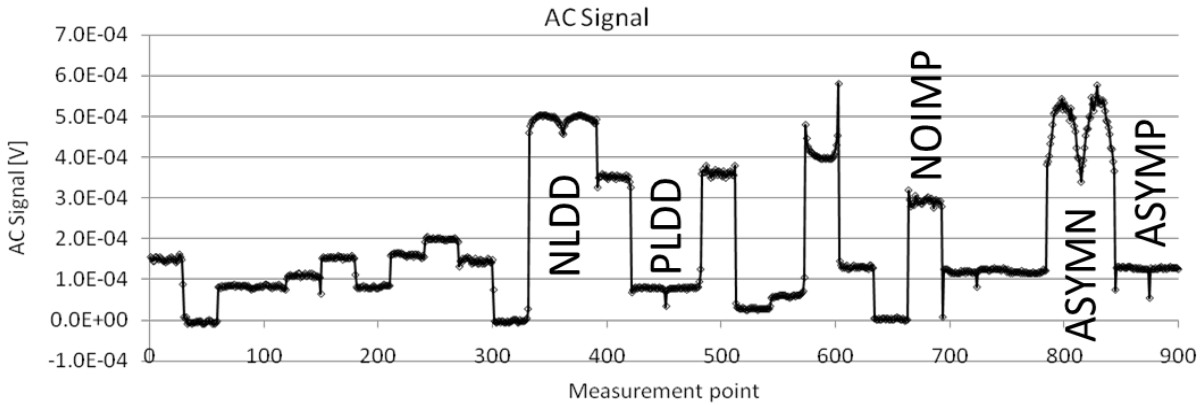
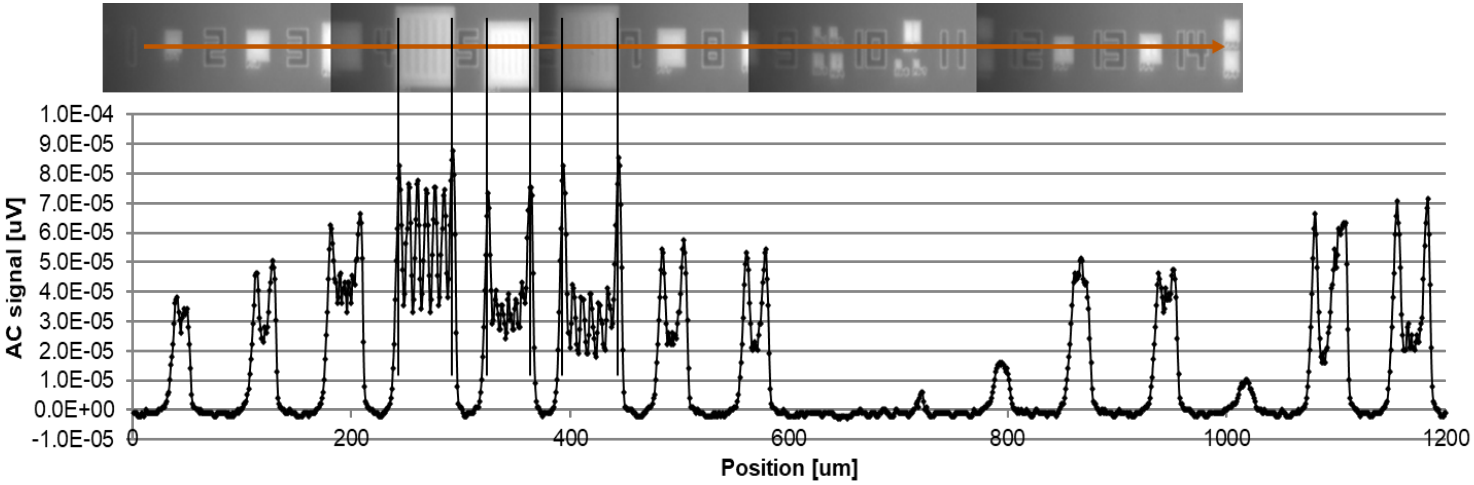
Example: PMR Carrier Activation



- SIMS boxes on SOI at “Major Foundries”
- MAM time ~4 sec; Spatial res ~ µm



- Epitaxial SiGe test structures at Taiwan foundry…



- Background free
- 1-2% Precision
- PR signal ideal for SPC/APC
- <R> provides filmstack info

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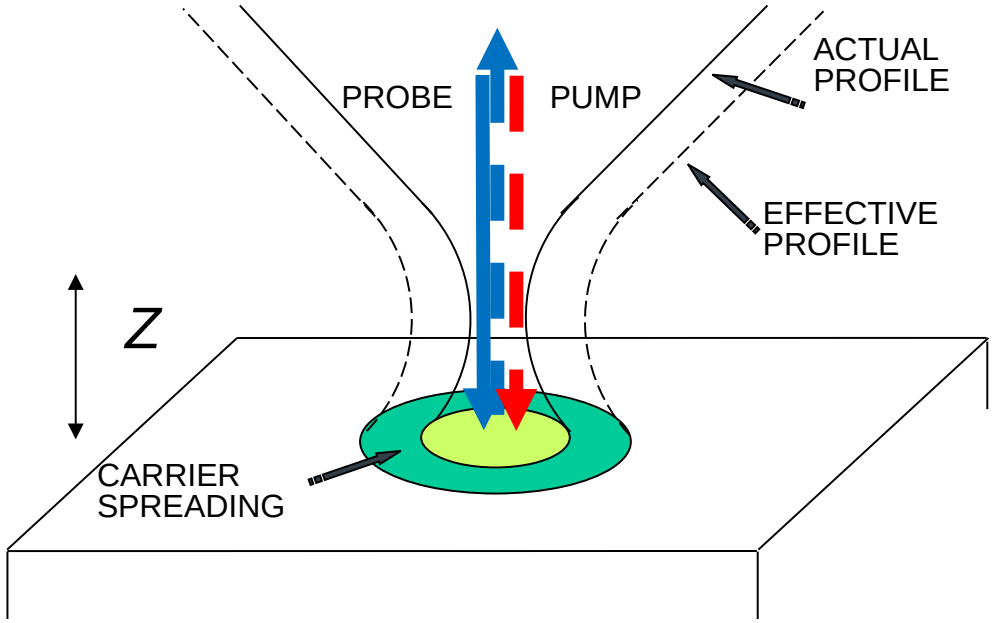
Example: *Z*-Scan PMR for Carrier Transport

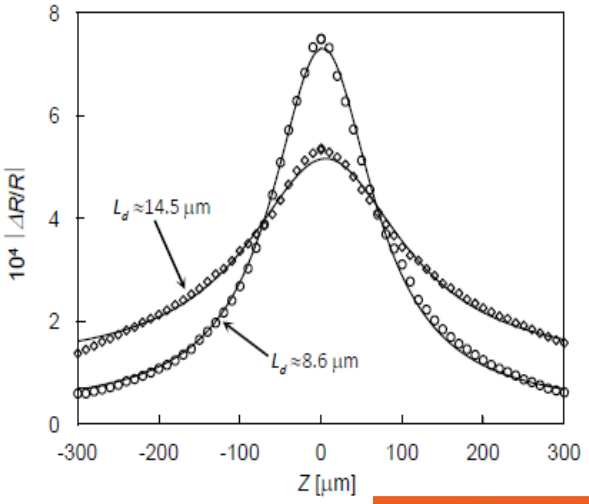
Measurement Signal:

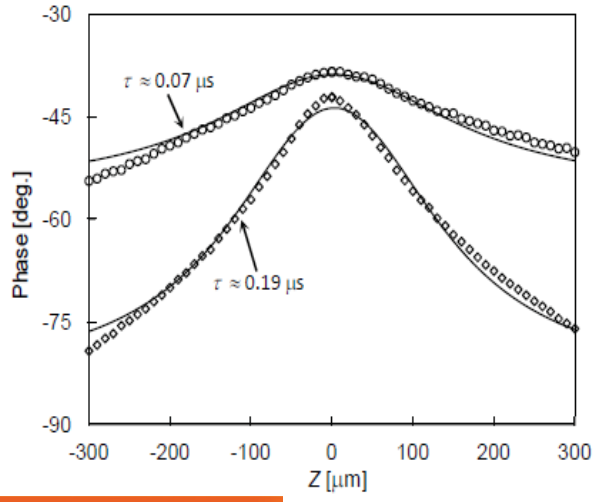
$$\frac{\Delta R}{R} = \frac{A \exp i\phi_o}{\omega^2(Z) + \omega_p^2(Z) + \tilde{L}_d^2}$$

Diffusion Length



Z-Scan PMR data & fit:





Z-scanning PMR yields All-Optical Carrier Transport Metrology!!

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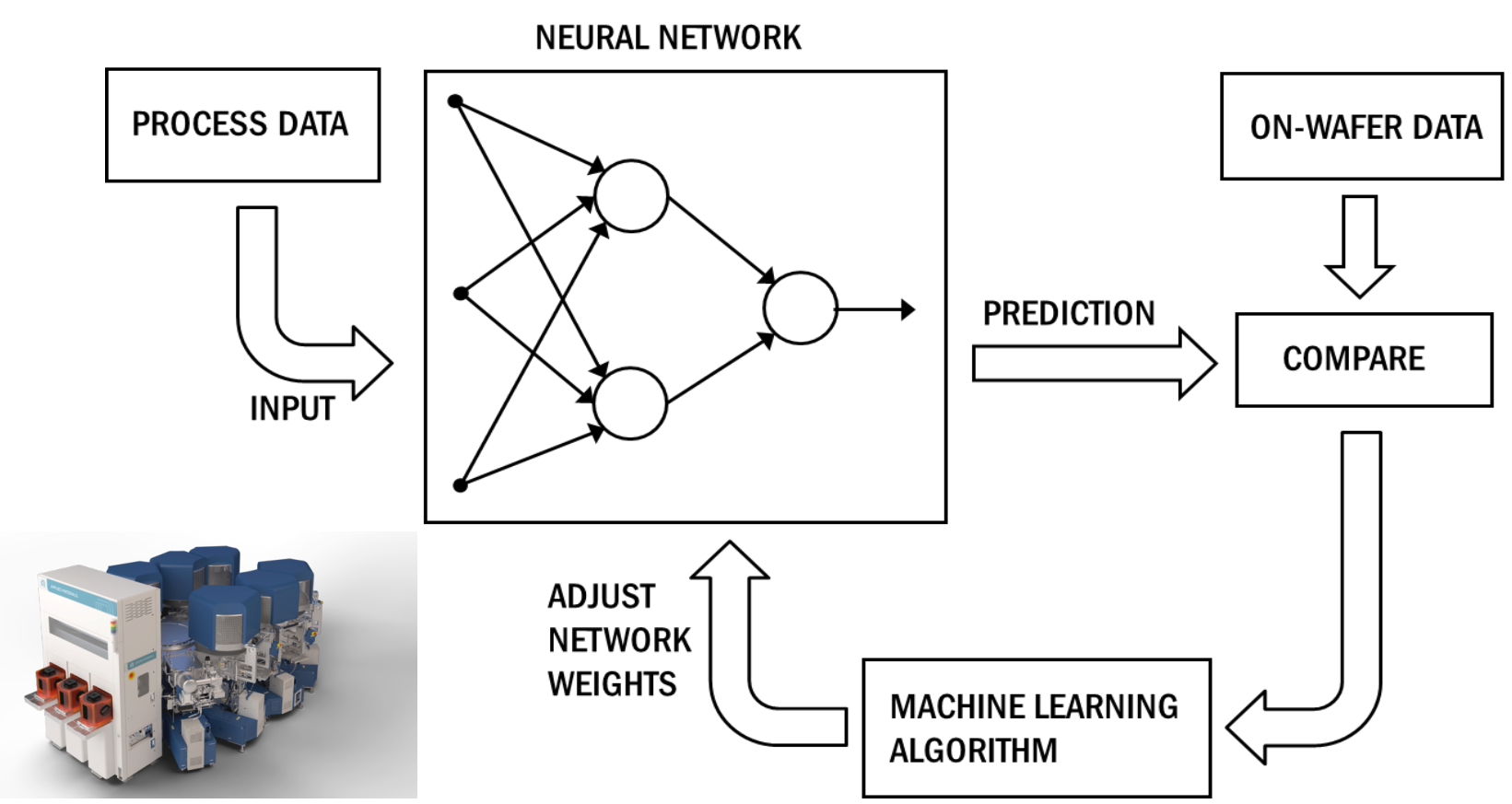
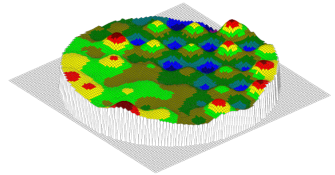
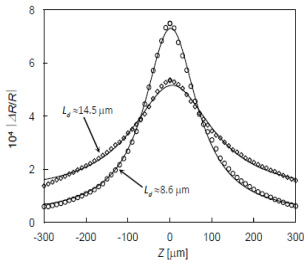
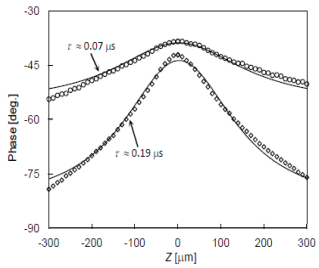
Process Tool Control Using PMR Data:

Process parameters + ML engine + metrology tool:









PMR provides ground truth for prediction from tool/sensor data…

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