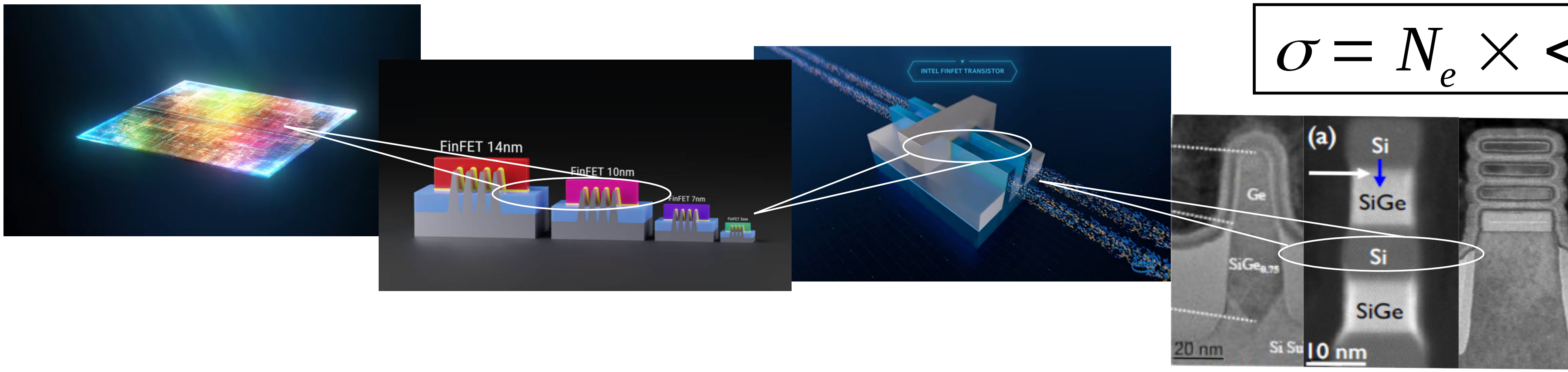
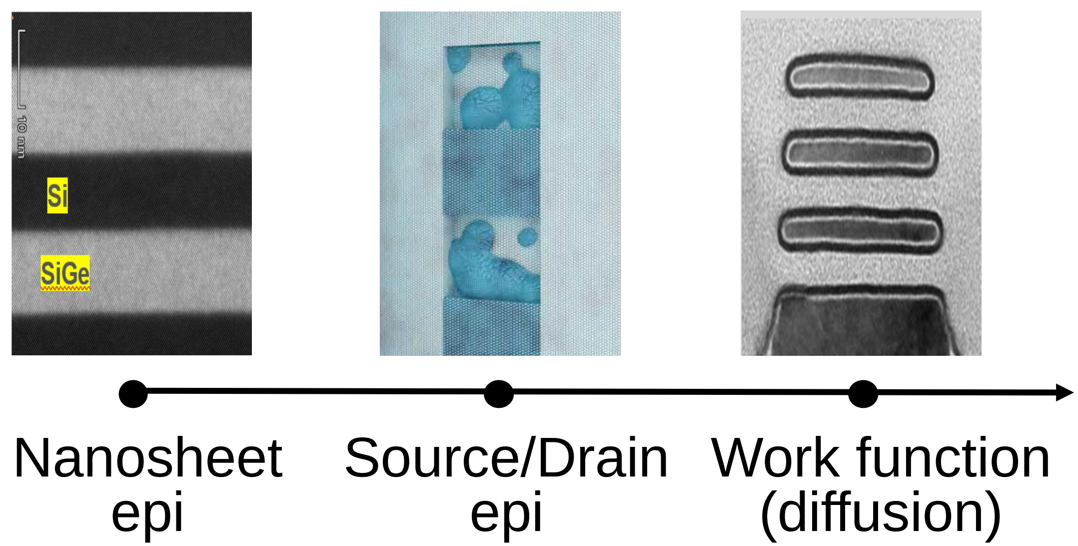
Z-scanning Laser PMR for Carrier Transport Metrology

Carrier Transport is Fundamental to Device Performance



$$\sigma = N_e \times \langle v \rangle$$

Ex: Transport-critical GAA process steps:

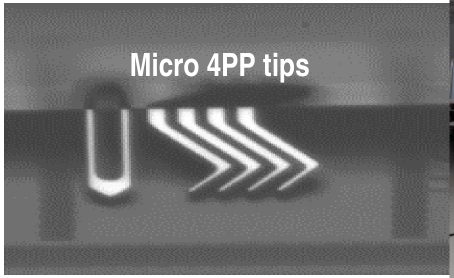


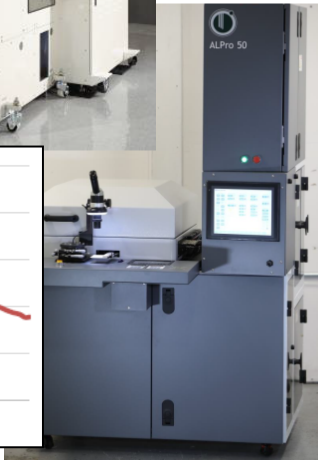
⇒ Carrier Transport Metrology needed in Advanced Mfg

Measuring Carrier Transport is Not Easy:

Micro-4PP:

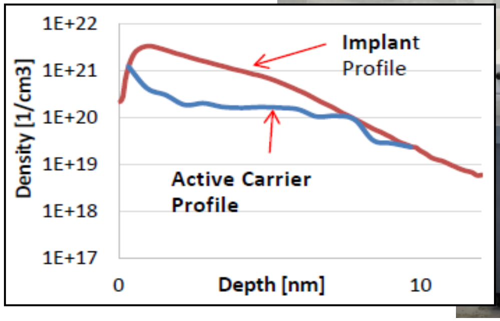
- Requires wafer contact (contamination)
- Geometrical limitations (>120 um spot)
- Sensitive to contact placement & force
- Consumables (costs)





Differential Hall Effect (DHE):

- Accurate reference technique
- Requires contacts/etch (destructive)



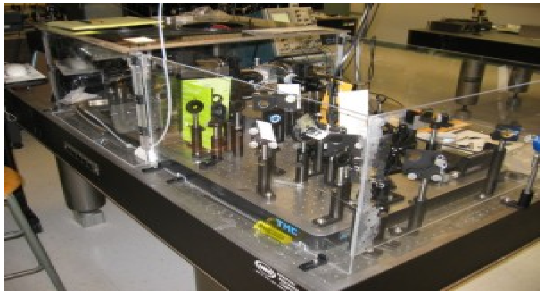
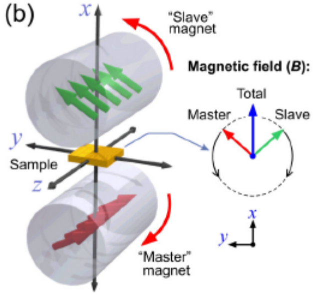


Photo-Hall Effect:

- Carrier-resolved technique pioneered by IBM
- Requires contacts (destructive)



THz Spectroscopy:

- Non-contact technique developed by NIST
- Requires expensive femtosecond lasers

⇒ Industry efforts illustrate need (& degree of difficulty)

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Is there a way to measure Carrier Transport in-line w/o contact?

- Photo-Modulated Reflectance (PMR) provides direct sensitivity to Electronic Properties
- PMR meets In-Line criteria
- *Z*-scanning PMR provides high precision evaluation of Electronic Transport

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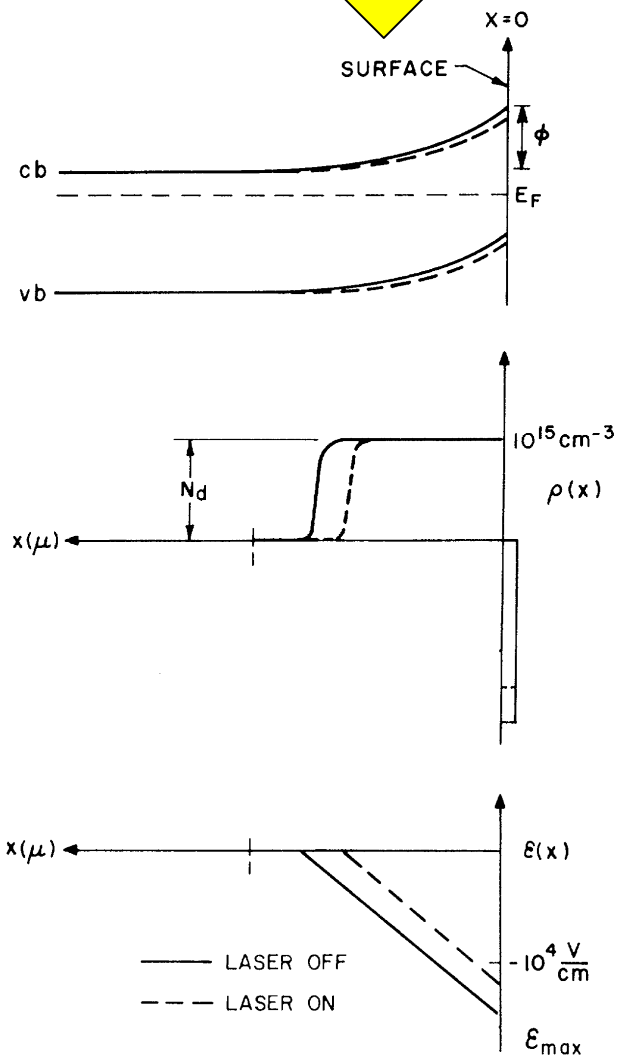
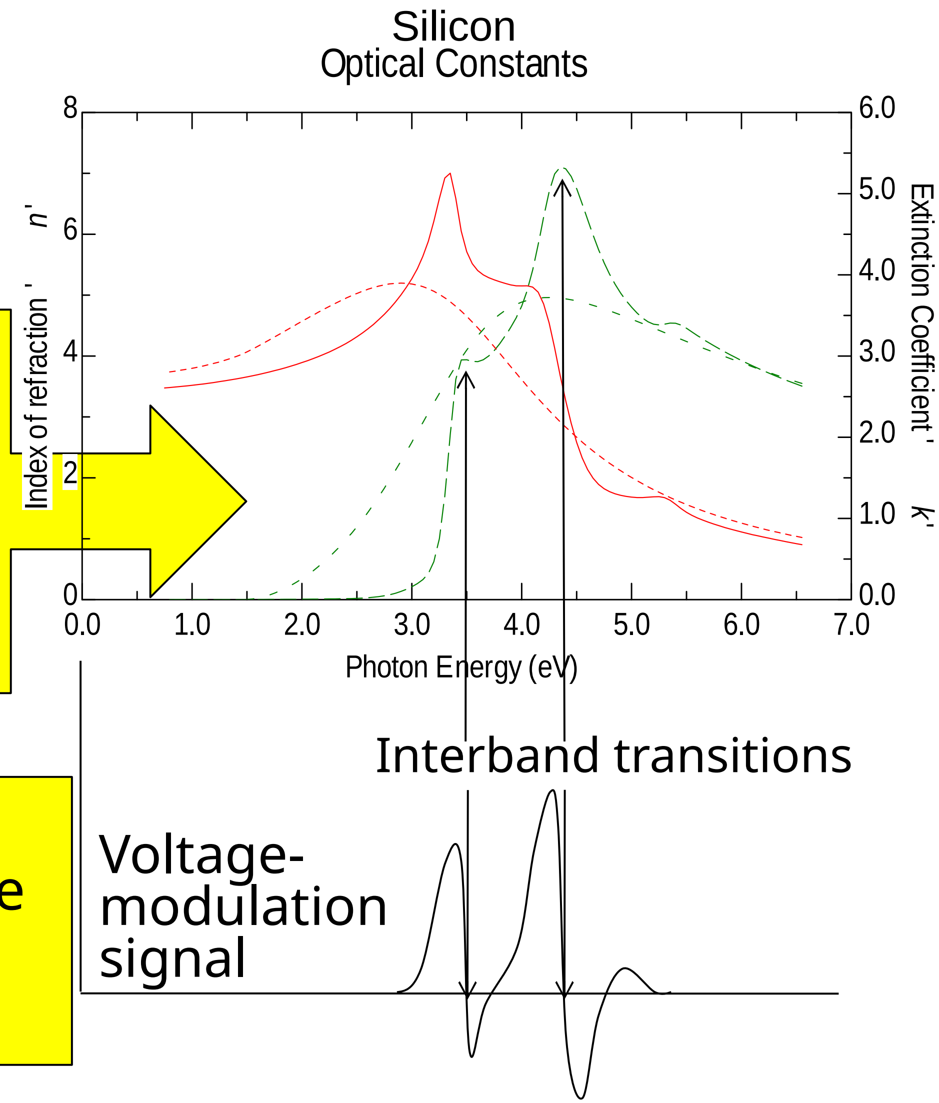
PMR: Basic Principles

1. Pump beam modulates the sample charge/voltage/temp

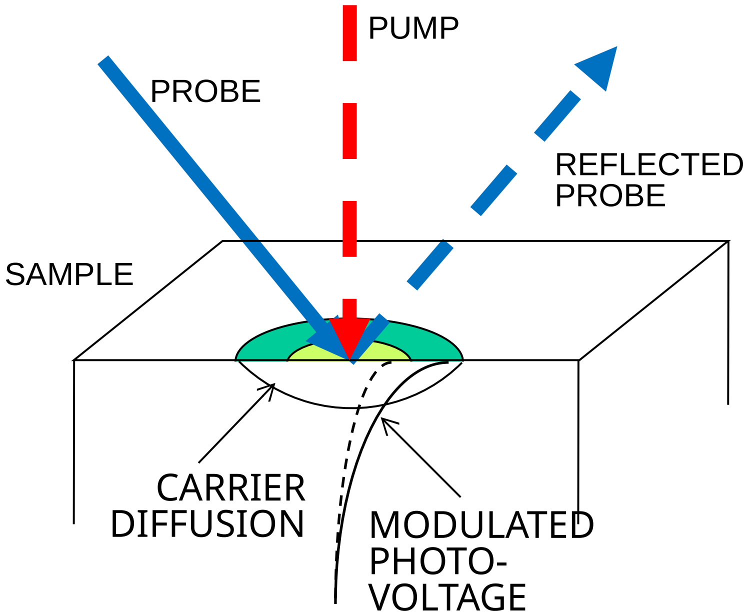


2. Modulated charge/temp causes reflectivity modulation



3. Probe beam measures the modulated reflectance

PMR: Capabilities



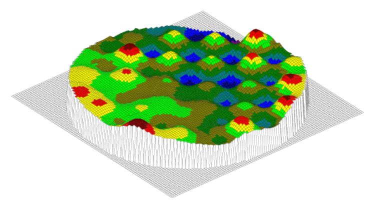
Voltage Modulation Signal:

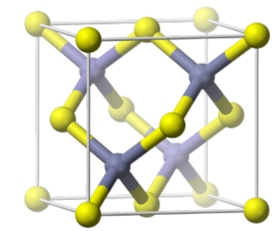
$$\frac{\Delta R}{R} = \frac{2qN_e\Delta V}{\varepsilon_s} \times L(\lambda)$$

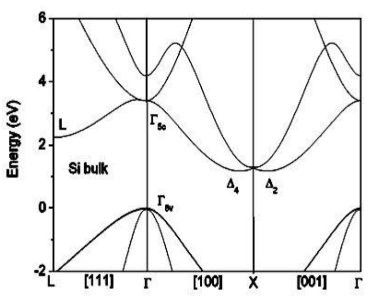
Carrier Density

Modulated Photo-Voltage

Band-structure







In-line Criteria:

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

Photo-Reflectance:

- Non-contact (optical)
- Direct sensitivity to Material Properties
- Measurement time ~seconds
- Resolution ~microns

⇒ PMR provides direct sensitivity to Electronic Properties & meets In-Line Criteria

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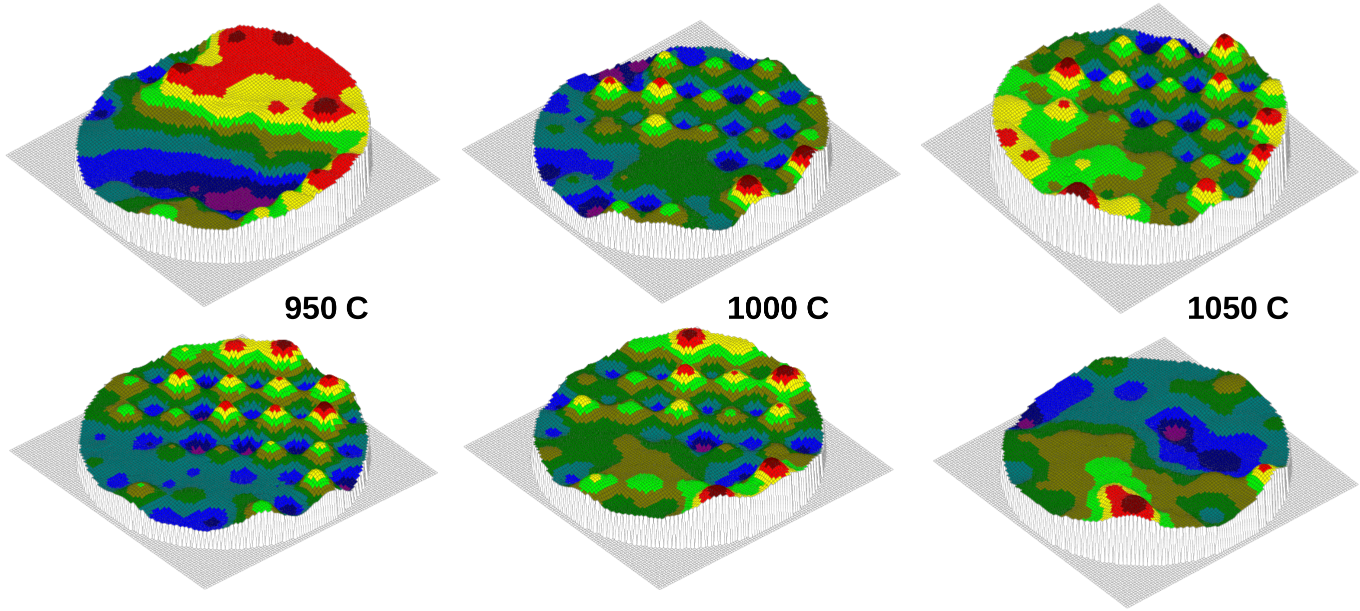
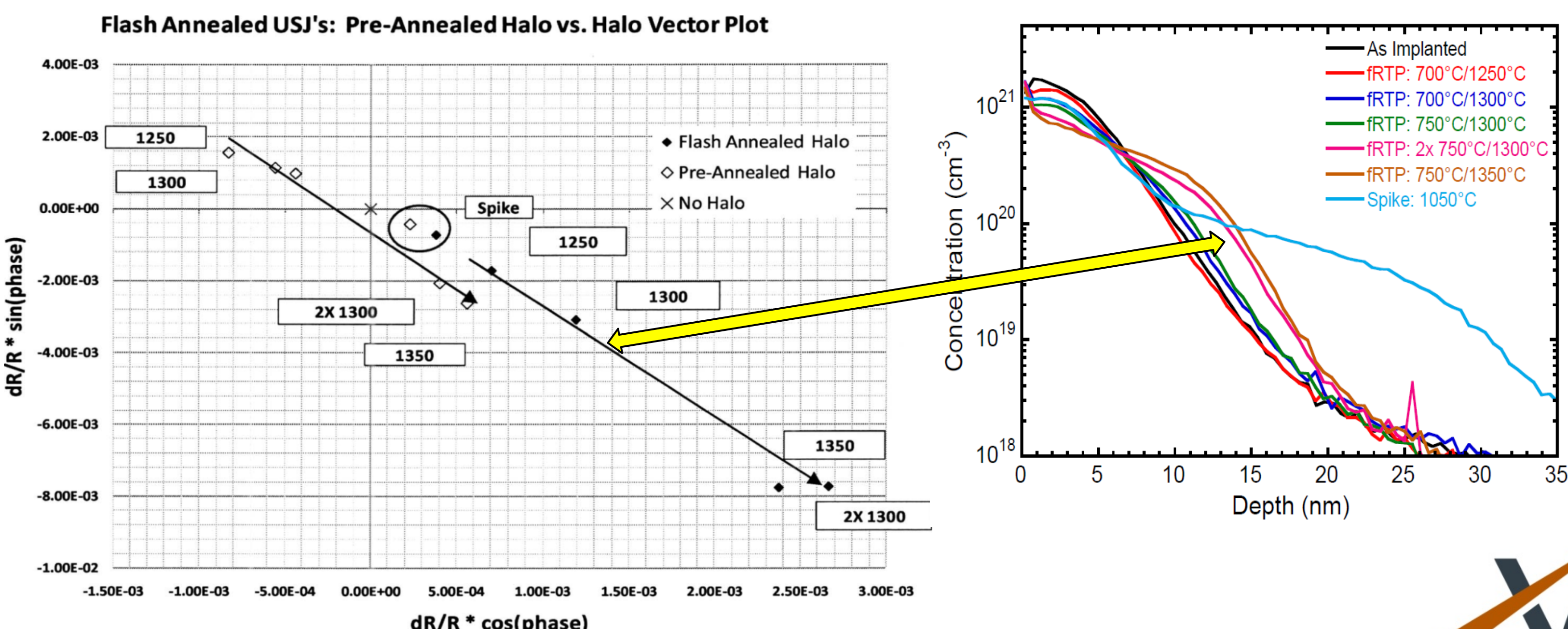
Ex: USJ Activation Measurement

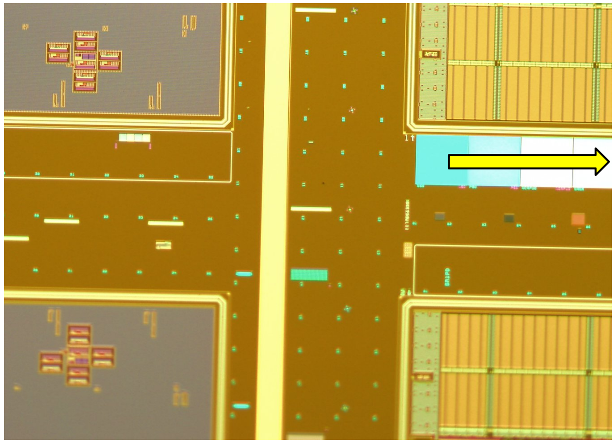


Phosphorous activation increasing with anneal temp

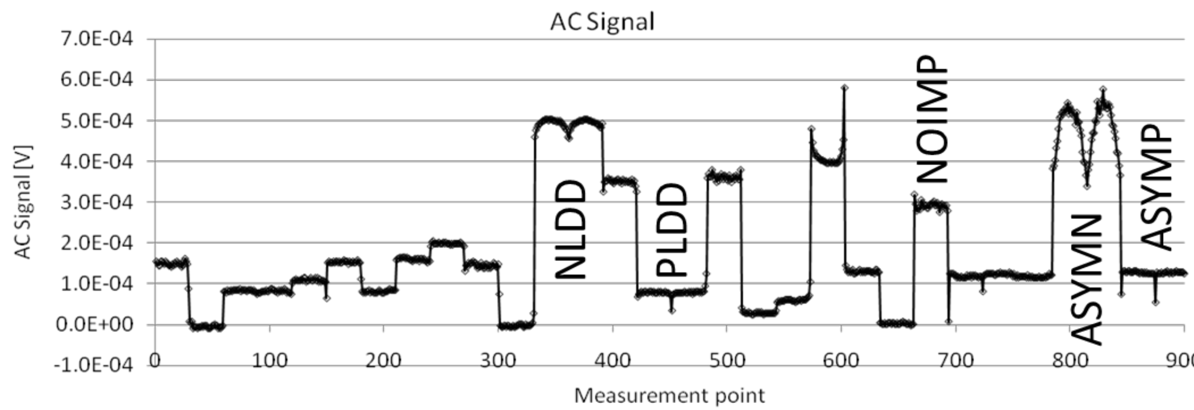
Boron activation decreasing with anneal temp (diffusion)



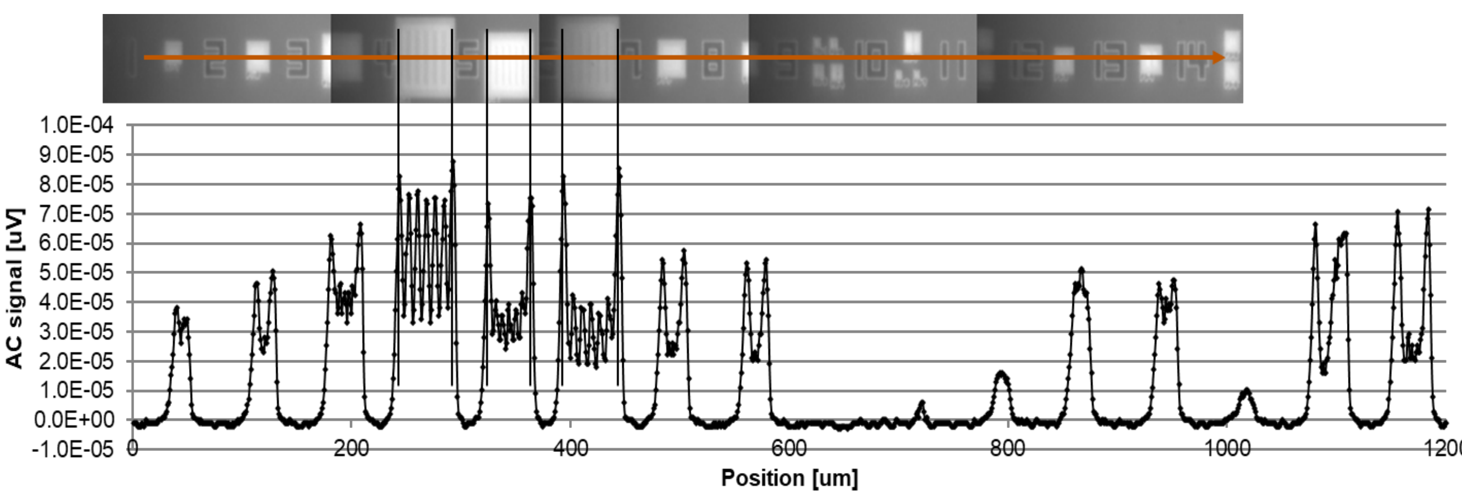
Ex: PMR Line Scans



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



- Epitaxial SiGe test structures at Taiwan foundry…



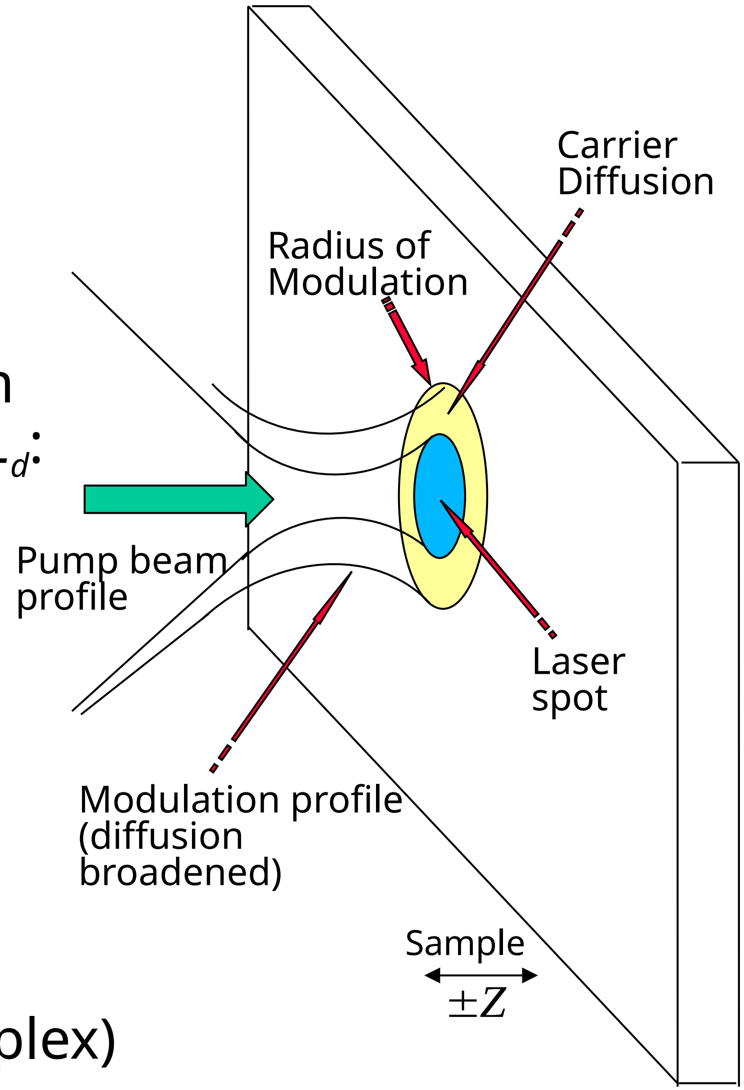
- Background free
- 1-2% Precision
- PMR signal ideal for SPC/APC
- <R> provides filmstack info

Z-scanning PMR: Basic Principles

PMR Signal:

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

Signal depends on focus offset (Z) & L_d:



<u>*Z*-dependence of PMR Signal:</u>

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

Laser spots

Diffusion Length (complex)

⇒ Carrier diffusion modifies *Z*-profile of PMR Signal

Carrier Transport Measurement:

A. Measure PMR signal (Amp & Phase) w.r.t. *Z*

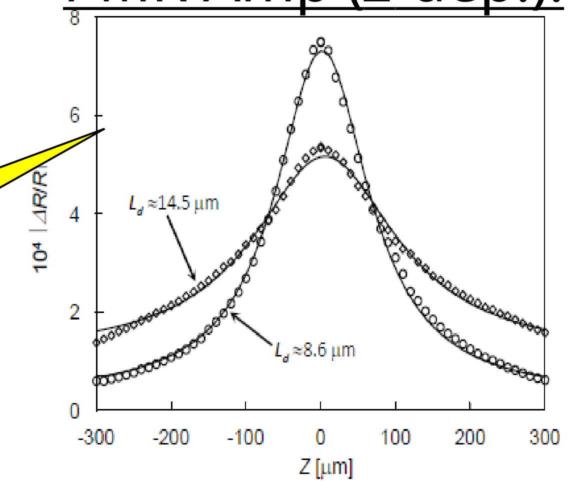
B. Perform nonlinear regression to extract diffusion length & recombination lifetime

C. Calculate *D* (or mobility)

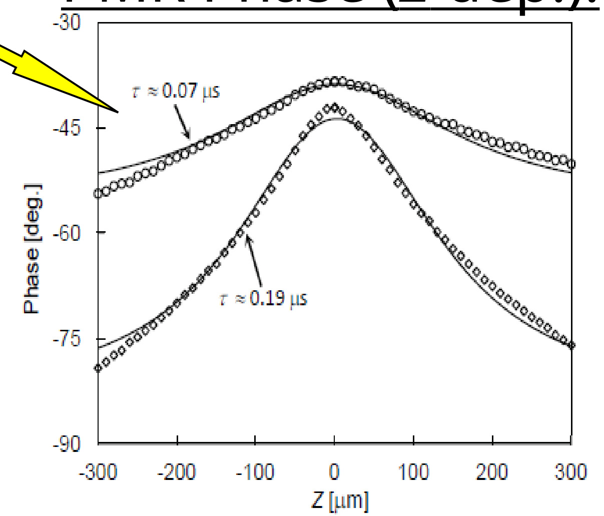
D. Other electronic transport parameters follow

⇒ Protocol enables high-precision optical characterization of carrier transport properties

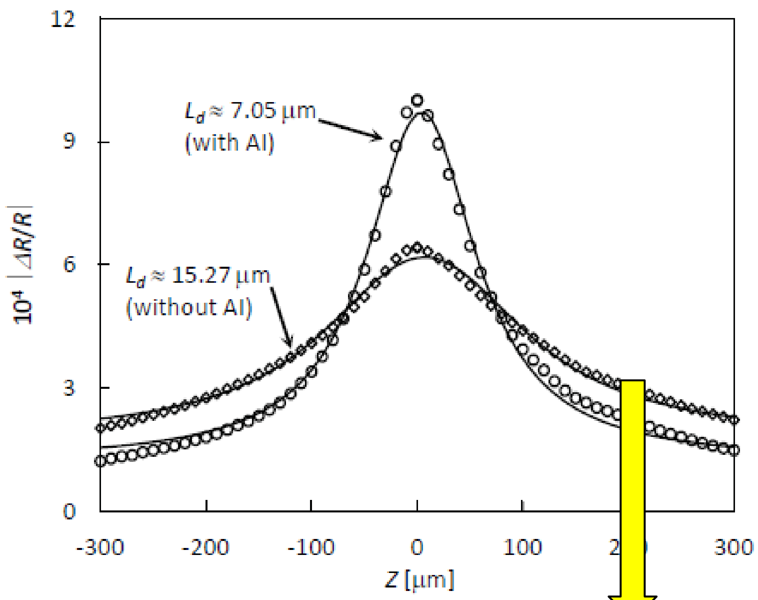
PMR Amp (*Z* dep.):

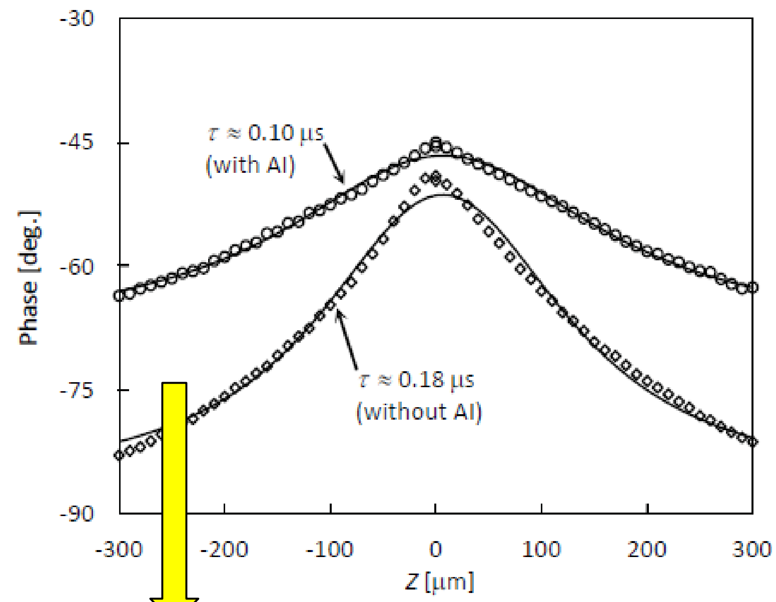


PMR Phase (*Z* dep.):



Ex: Carrier Mobility at *p*-type USJs





with amorphization implant:

	L_d [μm]		τ [ns]		μ [cm^2/V · s]	
Flash temp [°C]	Flash only	As pre-soak	Flash only	As pre-soak	Flash only	As pre-soak
1250/550	7.84 ± 0.03	9.09 ± 0.03	151.9 ± 0.5	165.1 ± 0.6	155 ± 2	192 ± 2
1300/550	5.47 ± 0.01	5.36 ± 0.01	122.5 ± 0.7	131.8 ± 0.7	94 ± 1	84 ± 1
1300/550(2X)	6.54 ± 0.01	7.05 ± 0.01	99.9 ± 0.3	99.5 ± 0.6	165 ± 1	192 ± 1
1300/600	8.41 ± 0.02	9.81 ± 0.02	165.2 ± 0.5	168.5 ± 0.5	165 ± 1	220 ± 1
1350/600	8.87 ± 0.01	10.99 ± 0.01	163.4 ± 0.5	168.9 ± 0.5	185 ± 1	275 ± 1

w/o amorphization implant:

	L_d [μm]		τ [ns]		μ [cm^2/V · s]	
Flash temp [°C]	Flash only	As pre-soak	Flash only	As pre-soak	Flash only	As pre-soak
1250/550	15.17 ± 0.04	21.97 ± 0.05	197.7 ± 0.6	269.4 ± 0.6	447 ± 3	689 ± 5
1300/550	15.44 ± 0.02	–	203.6 ± 0.5	–	450 ± 3	–
1300/550(2X)	20.04 ± 0.01	19.09 ± 0.02	285.2 ± 0.9	207.0 ± 0.7	542 ± 2	677 ± 3
1350/600	14.09 ± 0.01	15.27 ± 0.02	180.8 ± 0.5	179.8 ± 0.5	422 ± 2	499 ± 2

⇒ Excellent agreement with Hall effect measurements

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Current PMR IP Landscape

<u>Carrier Transport PMR (XCALIPR):</u>

US Pat. Nos. 11,940,488, 11,402,429 & 10,921,369 – in force

<u>Voltage-modulation PMR (XCALIPR):</u>

US Pat. No. 7,391,507 – expires Nov. 1, 2026

<u>Thermo-modulation PMR (KLA):</u>

US Pat. Nos. 8,817,260, 7,646,486, 7,362,441, 7126,690 – all invalid, disclaimed, or expired (courtesy XCALIPR)

<u>Carrier-modulation PMR (Semilab):</u>

US Pat. Nos. {...} – expired

⇒ All core PMR IP effectively "off-patent"
⇒ *Z*-scanning PMR for Carrier Transport provides basis for superior product

PMR for Carrier Transport Metrology: Status

- Strong Industry Need for Carrier Transport Metrology
- Z-scanning PMR proven for high-precision Carrier Transport Metrology
- Z-scanning PMR for Non-Contact Carrier Transport Metrology patented by XCALIPR
- XCALIPR accepting orders for 300mm Fab Tool!