ULSI Applications of Rapid X-Ray Reflectometry (XRR)

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7/1/00

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Outline

- ULSI metrology challenges
- Introduction to the Meta-Probe X and XRR
- Applications
  - Cu seed/Ta barrier stacks for Cu metallization
  - Ultra-thin MOCVD barrier development
  - Low-K dielectric materials
- Summary and future applications

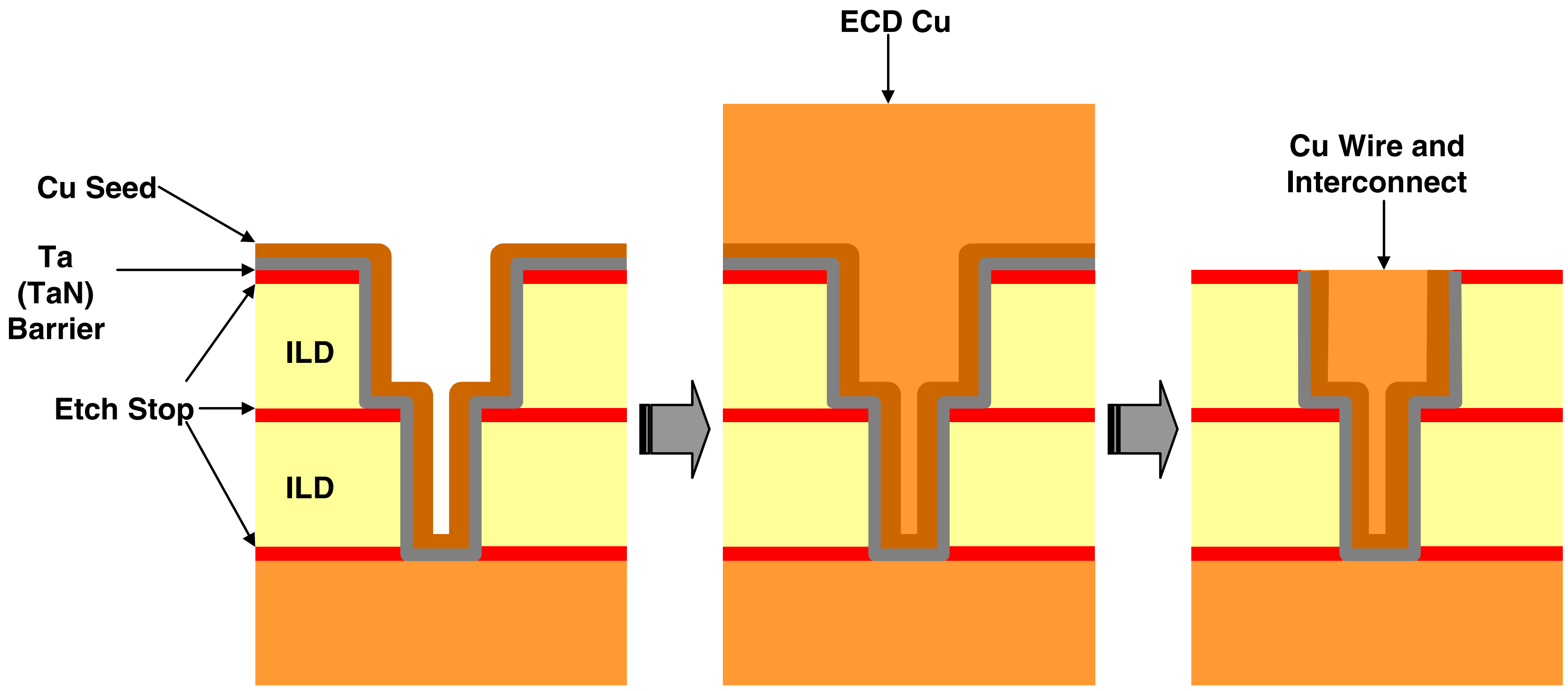
Interconnect Metrology Challenges

- Cu Damascene production process
  - Thin metal film stacks for seed/barrier
- Process development
  - Ultra-thin MOCVD barriers
  - CVD Cu
  - Low-K dielectric materials
  - Hybrid (CVD/PVD) metal stacks
  - Thin metal stacks for silicide formation

Production Cu Metallization Metrology

- Current Cu production (Damascene process)
  - Cu seed (1,000Å-1,500Å) on Ta or TaN barrier (200Å-400Å) deposited by advanced PVD techniques
  - Cu filled with ECD process (1µm-1.5µm)
  - Cu removed by CMP
- Cu production metrology requirements
  - Cu seed/barrier thickness and uniformity
  - ECD-Cu thickness
  - CMP dishing & erosion control

The Dual-Damascene Process



Deposit Barrier and Seed (PVD Cluster Tool)

Deposit Thick ECD Cu (Electro-Chemical Deposition)

Remove Cu to Etch Stop (CMP Tool)

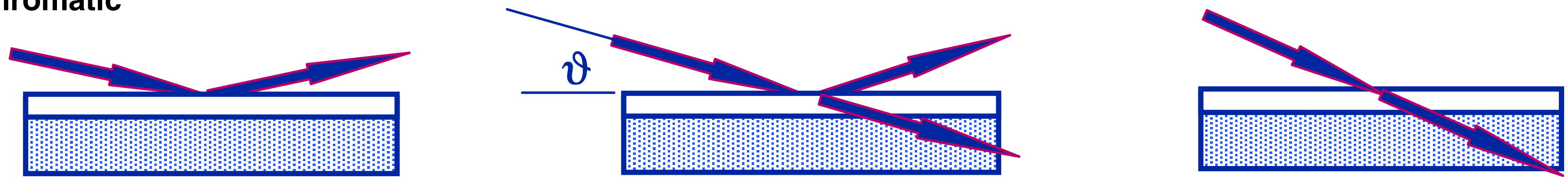
The Meta-Probe *X*

The Meta-Probe *X* is a fab-compatible metrology tool based on X-ray reflectometry (XRR):

- XRR measures the intensity of reflected monochromatic X-rays incident on a surface at near grazing incidence as a function of angle
- XRR analysis of a surface provides independent measurements of thin film thickness, density, and surface/interface roughness
- Value of XRR has been well recognized for R&D, but conventional technique is too slow for metrology

Basis of the XRR Technique

Monochromatic X-rays



$\vartheta < \vartheta_C$
Below the Critical Angle:
Total External Reflection

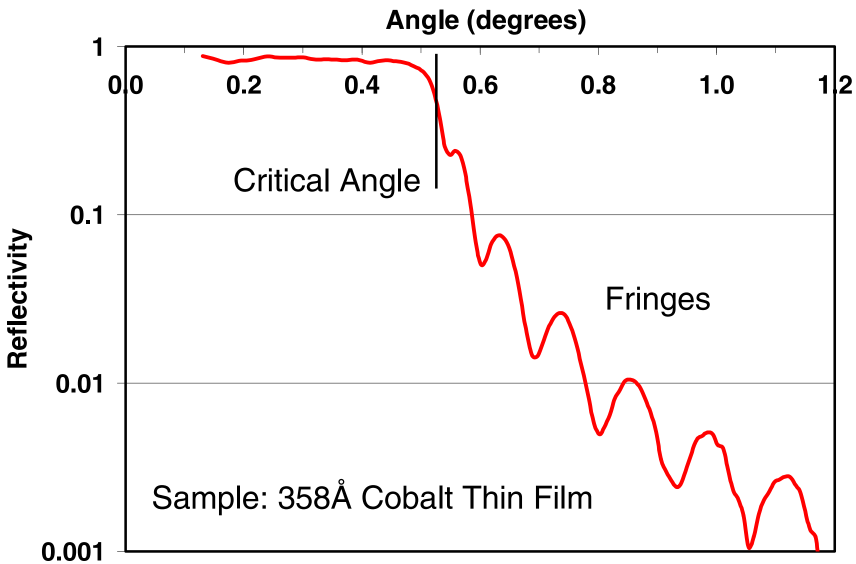
$\vartheta > \vartheta_C$
Above the Critical Angle:
Reflection & Transmission

$\vartheta >> \vartheta_C$
Much Greater than the Critical Angle:
Transmission Only

The critical angle ϑ_C is a function of $\lambda \cdot (\rho)^{1/2}$
… use critical angle to determine density

$\sin^2 \vartheta_{max} = \sin^2 \vartheta_C + [i + 1/2]^2 \cdot [\lambda/2 \cdot T]^2$ for $i = 1, 2, \ldots$
… use fringe spacing to determine thickness

$R = R_{ideal} \times \exp(-[4\pi \sin \varphi\, \sigma/\lambda]^2)$
… use slope of curve and attenuation of fringes to determine interface roughness



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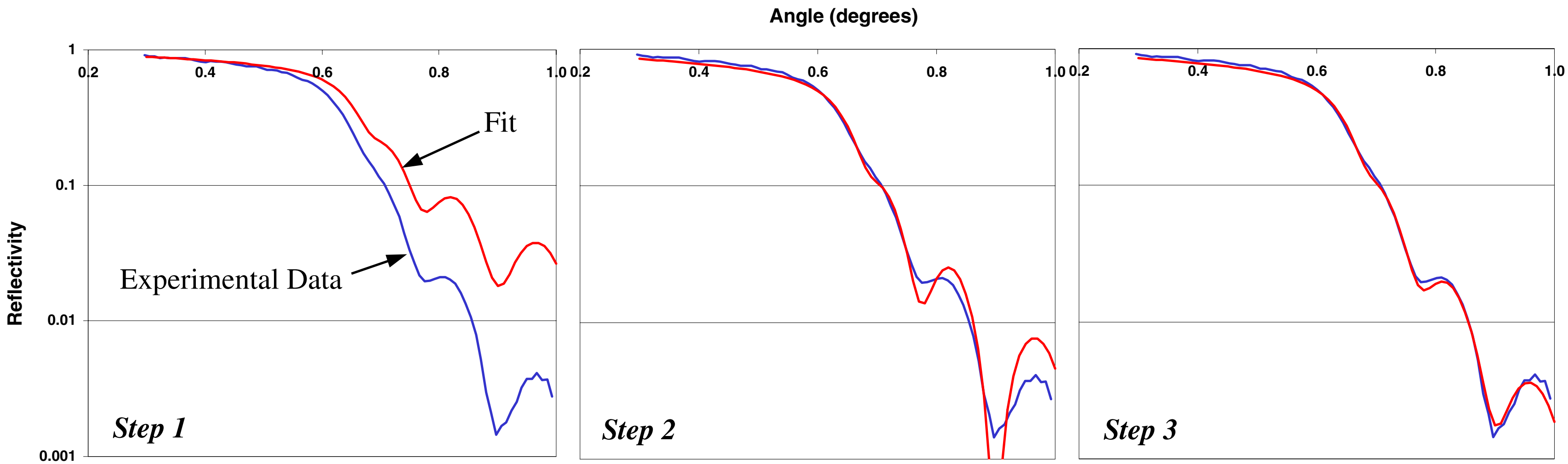
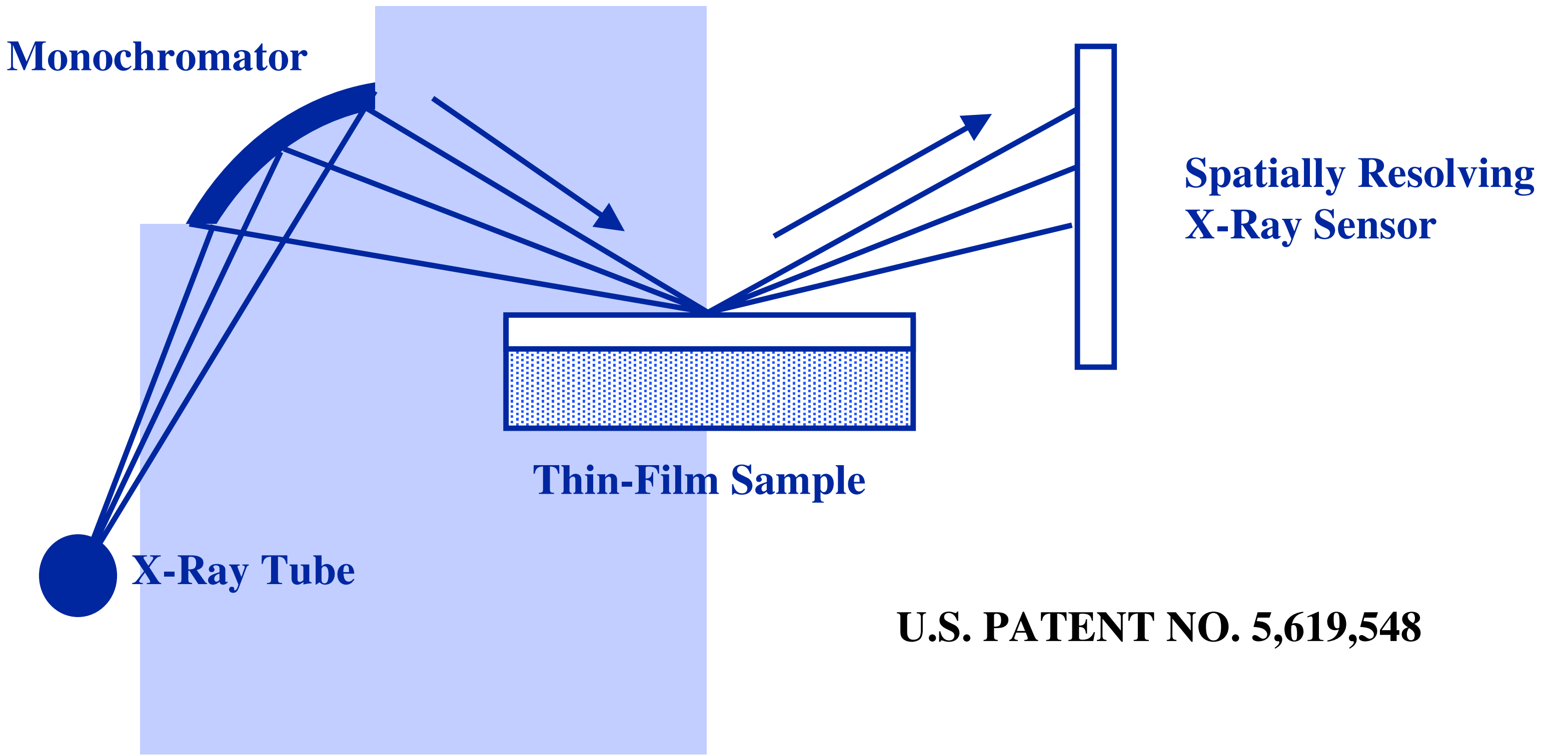
How to Fit Data for Thin-Film Properties



Ta on SiO_2	*Step 1: Fit Thickness and Density*	*Step 2: Fit Surface Roughness*	*Step 3: Fit Interface Roughness*
Thickness	268Å	268Å	268Å
Density	16.6 gm/cm^3	16.6 gm/cm^3	16.6 gm/cm^3
Surface Roughness	0	17Å-rms	17Å-rms
Interface Roughness	0	0	15Å-rms

Meta-Probe *X* Method for Rapid XRR



U.S. PATENT NO. 5,619,548

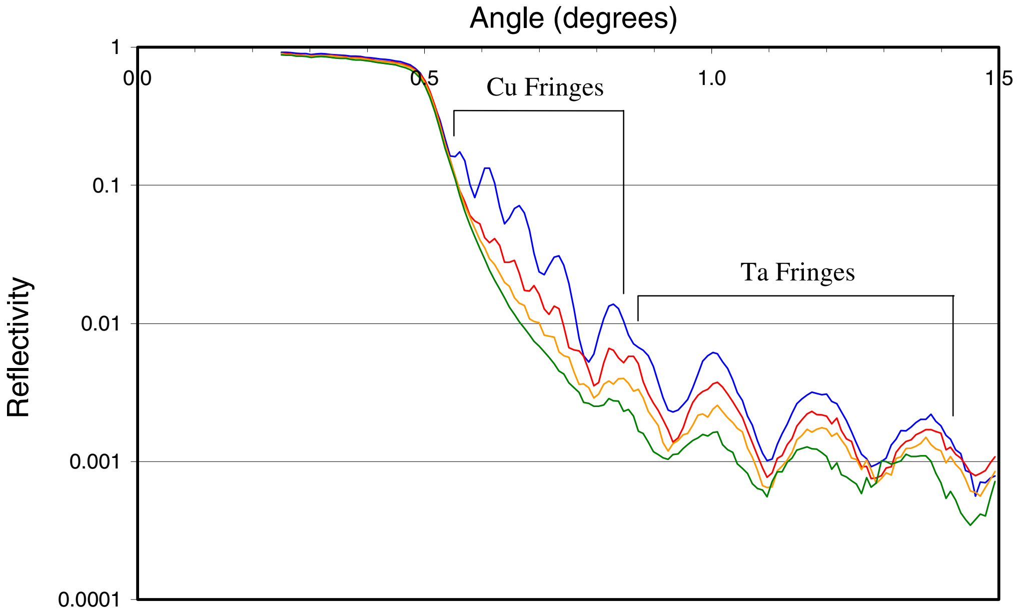
- Rapid Data Collection ...*measurements in seconds*
- No Moving Parts or Complex Lasers …*simple and robust*

Meta-Probe X

Cu-Seed/Ta-Barrier Stacks

- Measure Cu-seed/Ta barrier stack
- Typical Uniformity
- Repeatability measurements
- Measurement accuracy
  - Correlation with RBS
  - Sematech standard wafer set

Cu/Ta Thin Film Stacks



	Target		RXRR			
Cu/Ta Film	*Cu*	*Ta*	*Cu*	*Ta*	*Cu-σ*	*Cu/Ta-σ*
CuTa-1	500Å	250Å	524Å	250Å	14Å-rms	4Å-rms
CuTa-2	1,000Å	250Å	969Å	250Å	16Å-rms	5Å-rms
CuTa-3	1,500Å	250Å	1,734Å	249Å	14Å-rms	0Å-rms
CuTa-5	2,000Å	250Å	1,874Å	255Å	15Å-rms	0Å-rms

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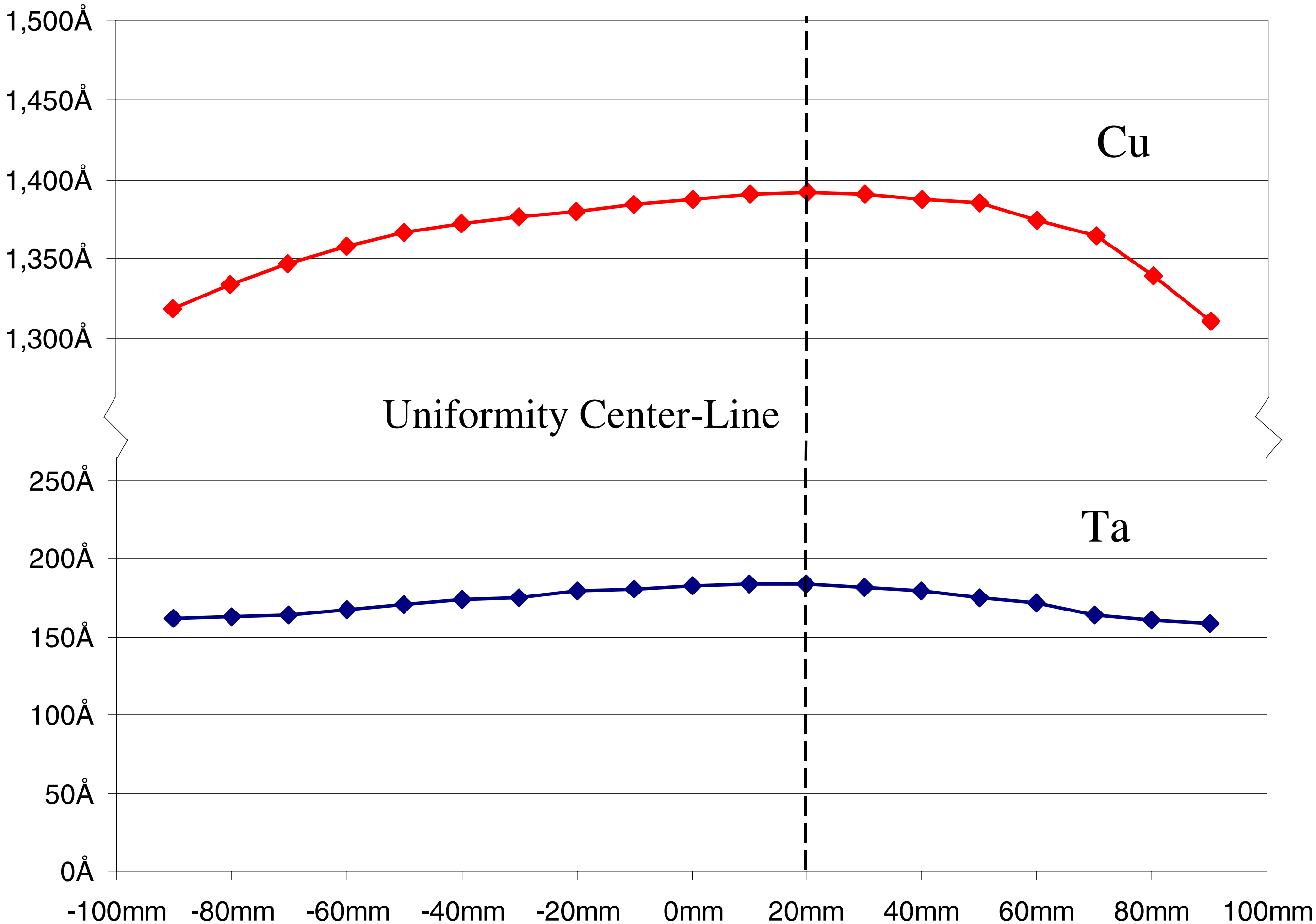
Cu Seed/Barrier Uniformity Control



$Average_{Cu}$ = 1,367Å

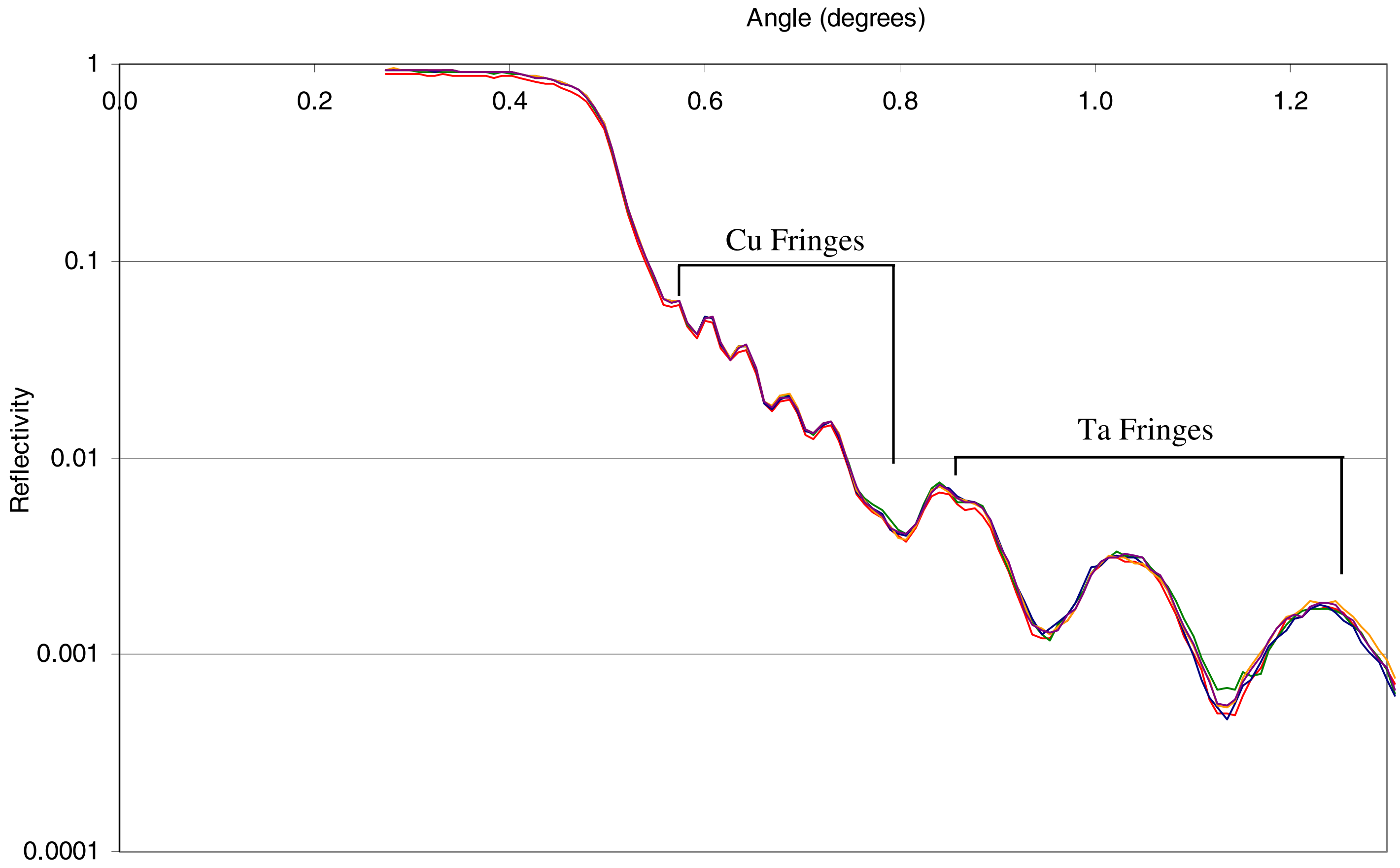
$\frac{Max_{Cu} - Min_{Cu}}{(Average_{Cu})} = 6.0\%$

$Average_{Ta}$ = 172Å

$\frac{Max_{Ta} - Min_{Ta}}{(Average_{Ta})} = 15.2\%$

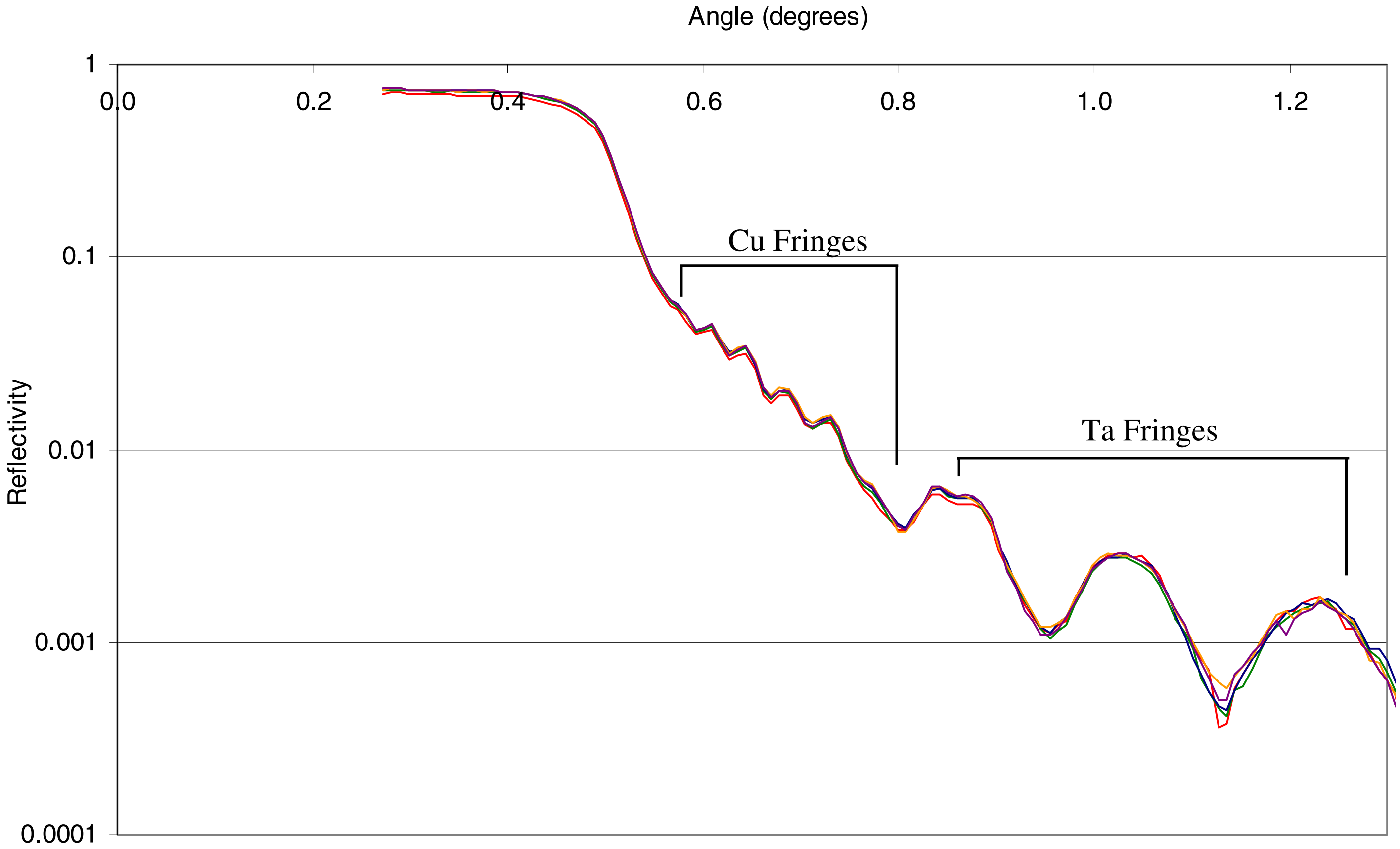
Repeatability on Blanket Wafers

5 Measurements Over Same Area on Blanket Wafer (Cu Seed/Ta Barrier)



Repeatability on Patterned Wafers

5 Measurements Over Same Area on Patterned Wafer (Cu Seed/Ta Barrier)



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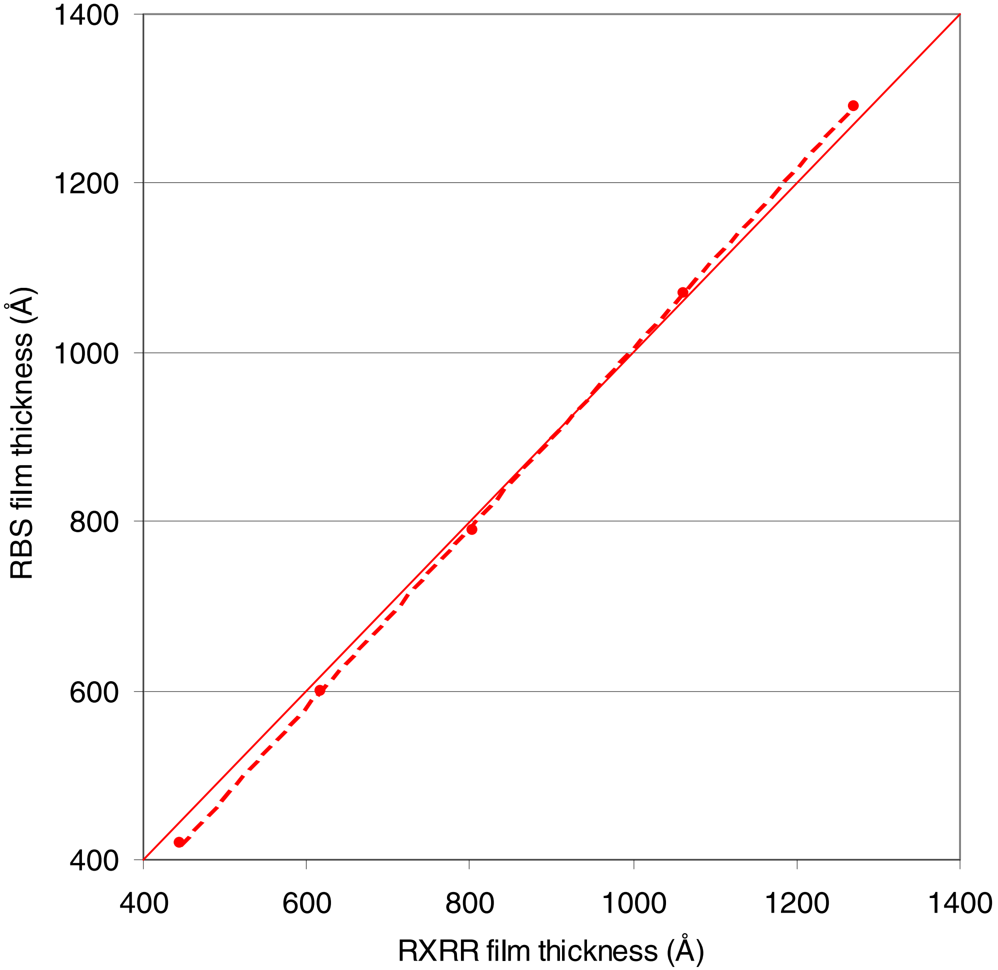
Repeatability Summary

5 Measurements on a Blanket Wafer and 5 Measurements on a Product Wafer
(Sister Wafers with PVD Cu Seed/Ta Barrier)

	Patterned Wafer		Blanket Wafer	
	Cu Seed	**Ta Barrier**	**Cu Seed**	**Ta Barrier**
Mean	829.4Å	233.2Å	826.0Å	232.8Å
Range	2Å	1Å	3Å	1Å
1σ	0.80Å	0.40Å	1.10Å	0.40Å
1σ(%)	0.10%	0.17%	0.13%	0.17%

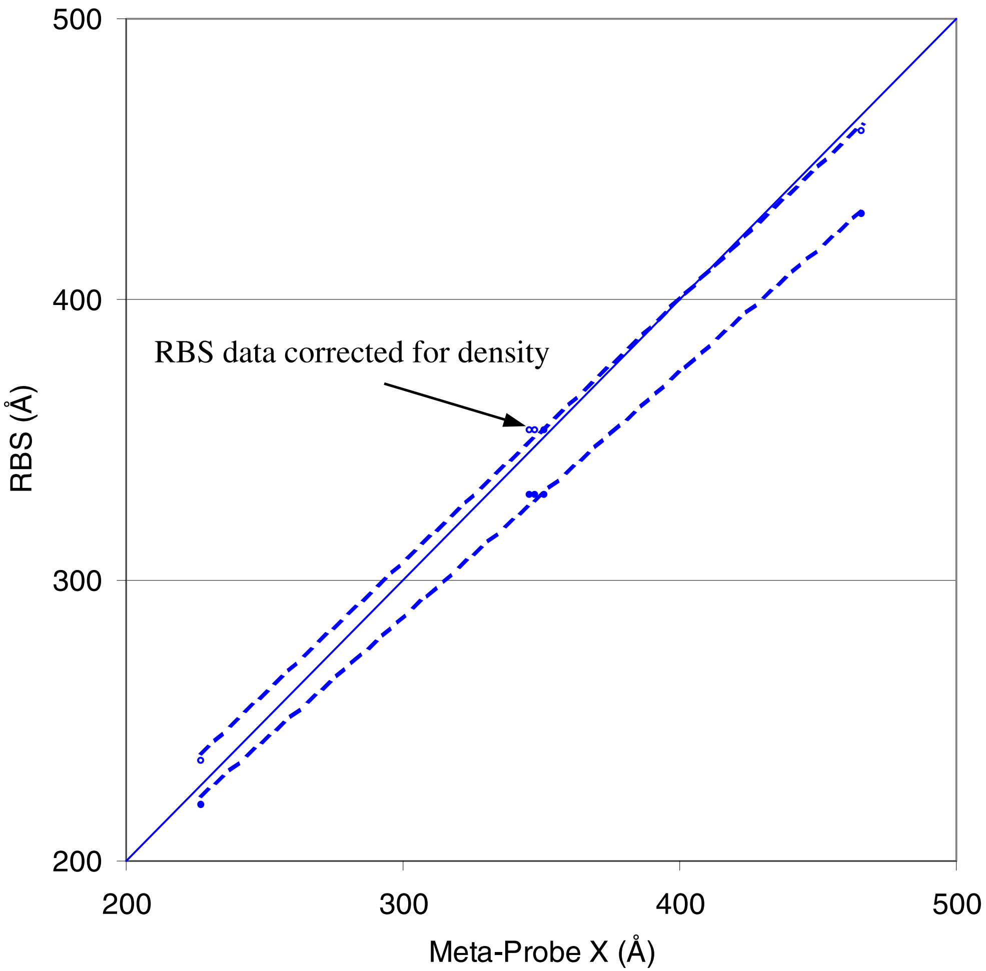
Cu/Ta Stack RBS Accuracy Correlation



Cu Thickness Measurements

Wafer	MPX	RBS
104-03	617Å	600Å
104-04	1,063Å	1,070Å
104-05	1,271Å	1,290Å
104-06	804Å	790Å
104-07	446Å	420Å

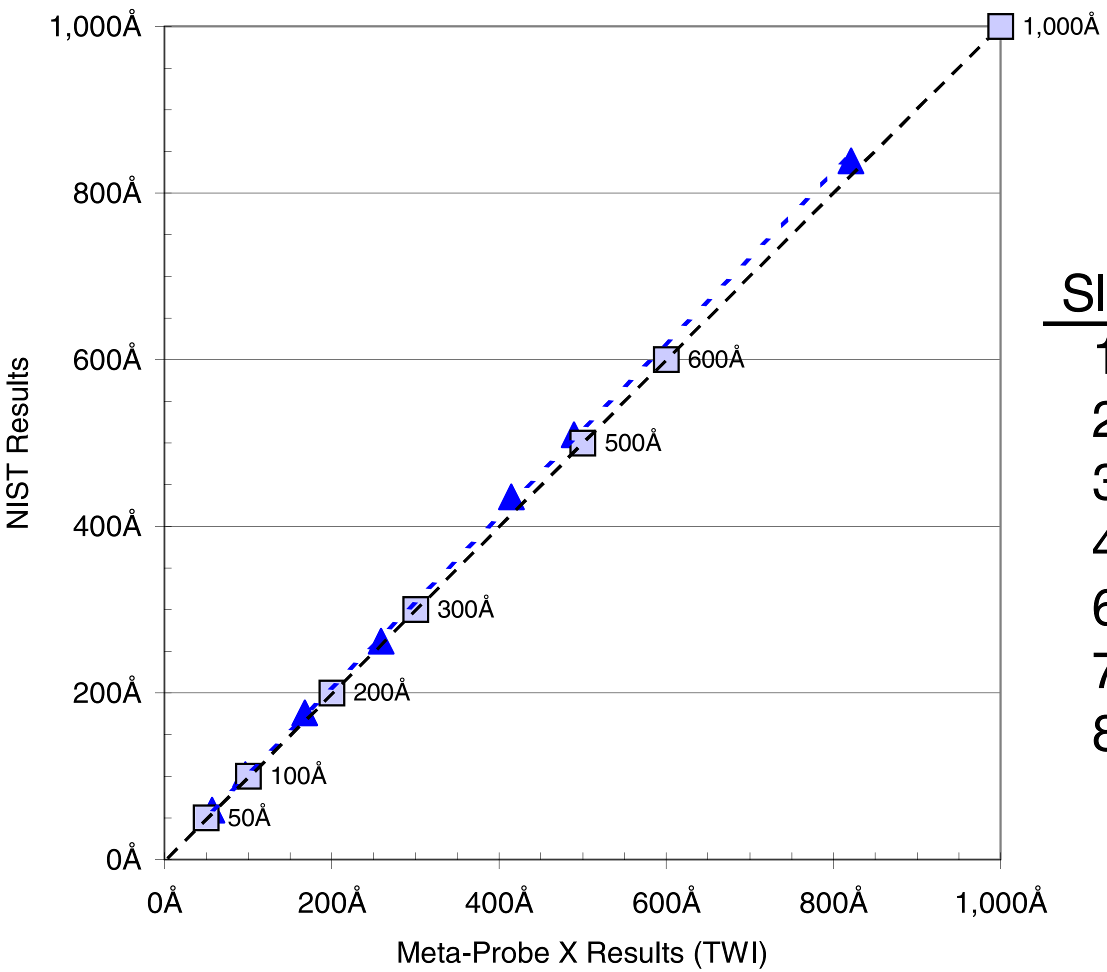
Cu/Ta Stack RBS Accuracy Correlation *(continued)*



Ta Thickness Measurements (corrected)

Wafer	MPX	RBS
104-03	346Å	353Å
104-04	348Å	353Å
104-05	351Å	353Å
104-06	227Å	235Å
104-07	466Å	460Å

SEMATECH Standard Cu/Ta Correlation



Ta Thickness Measurements (Ta Only Wafers)

Slot	Target	TWI	NIST
1	50Å	57Å	59Å
2	100Å	97Å	102Å
3	200Å	168Å	176Å
4	300Å	259Å	262Å
6	400Å	415Å	435Å
7	500Å	490Å	510Å
8	1,000Å	821Å	839Å

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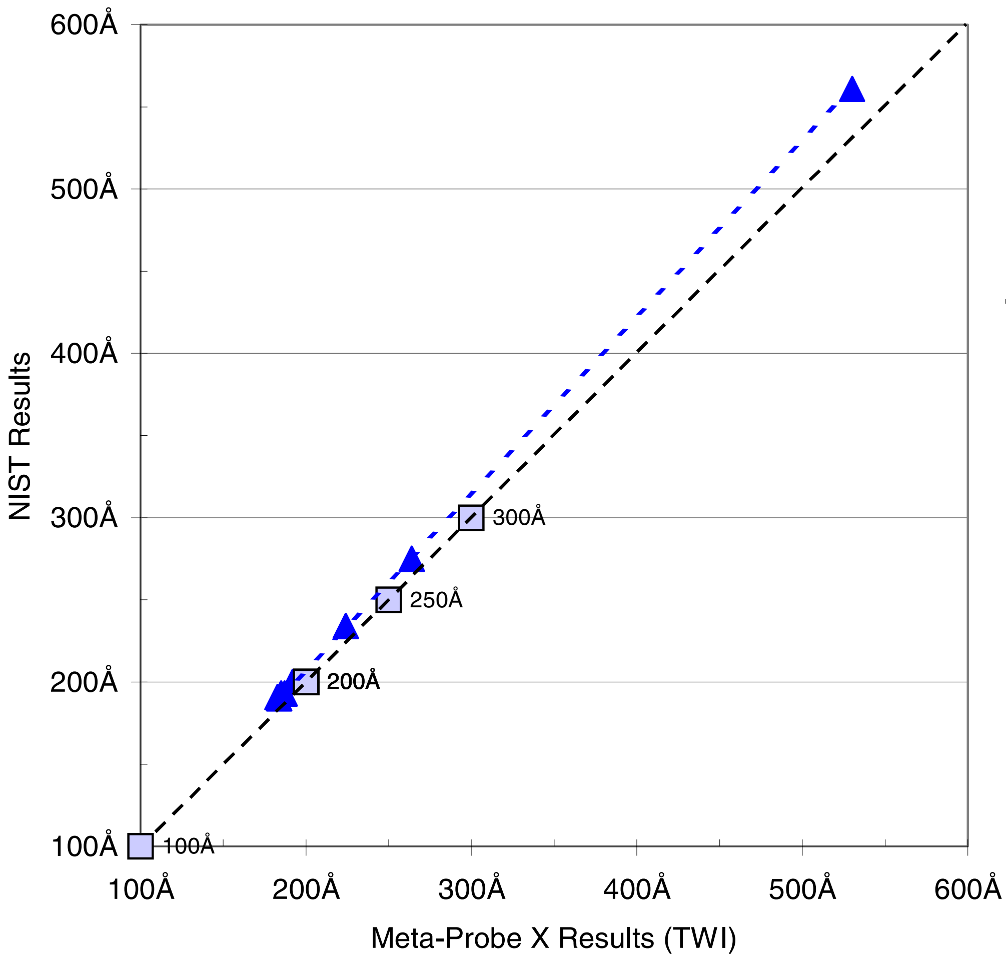
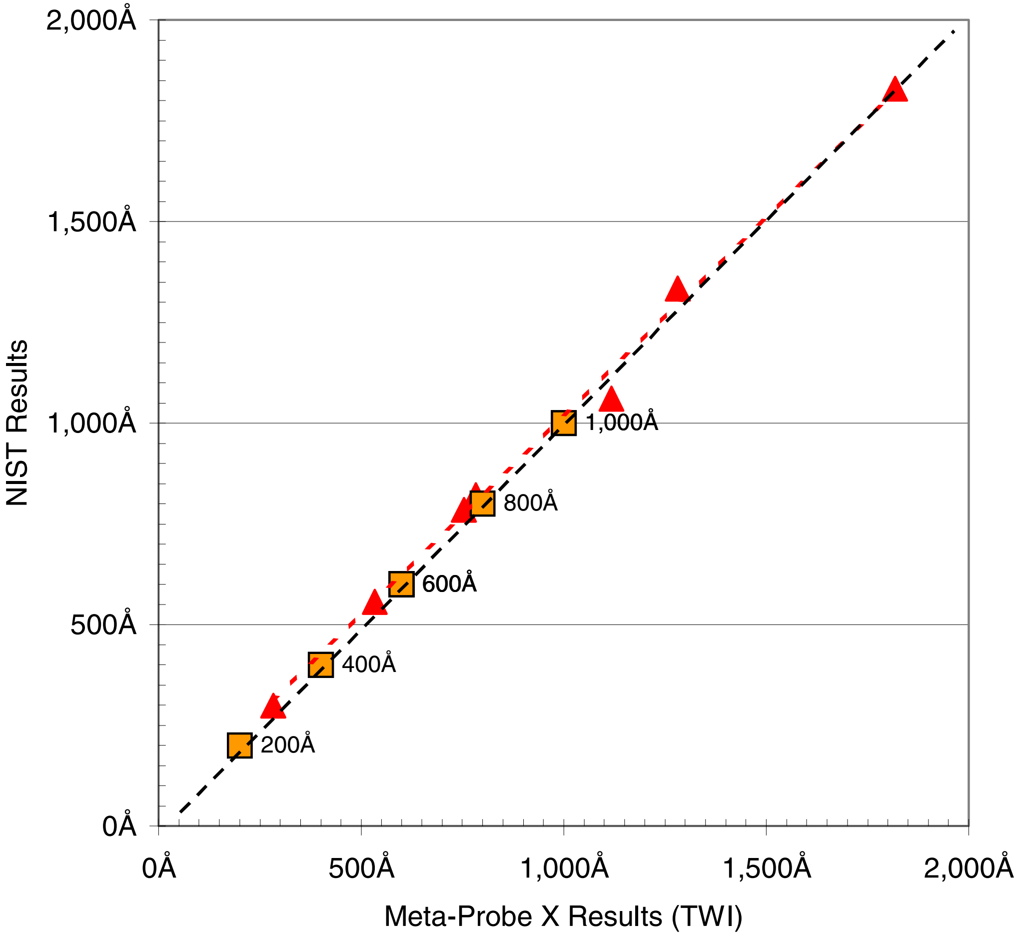
SEMATECH Standard Cu/Ta Correlation *(continued)*



Ta Thickness Measurements (Cu/Ta Wafers)

Slot	Target	TWI	NIST
9	200Å	183Å	191Å
10	200Å	185Å	193Å
11	200Å	187Å	193Å
12	200Å	183Å	191Å
13	200Å	184Å	190Å
14	100Å	530Å	561Å
16	250Å	224Å	234Å
17	300Å	264Å	275Å
18	200Å	192Å	200Å

SEMATECH Standard Cu/Ta Correlation *(continued)*

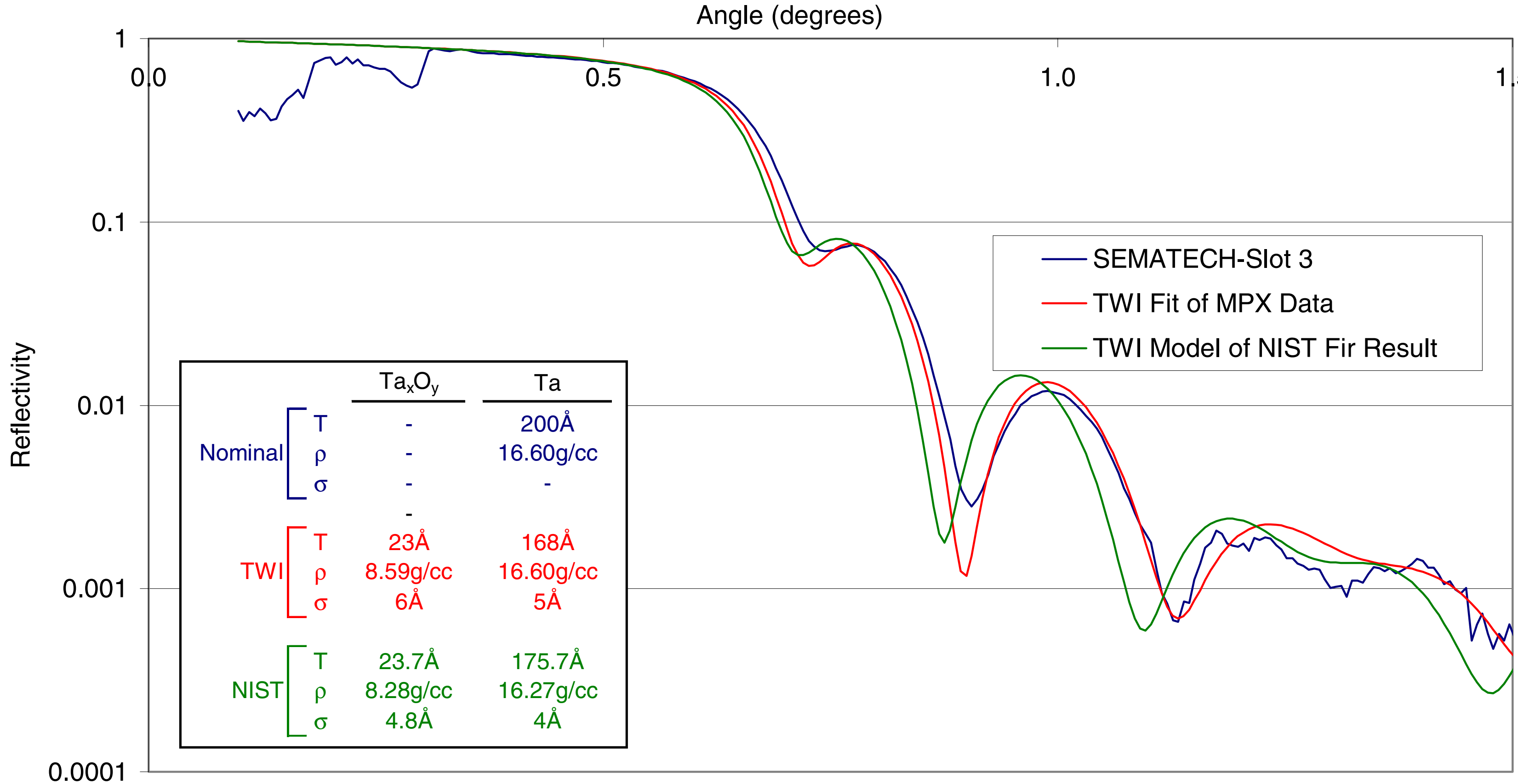


Cu Thickness Measurements (Cu/Ta Wafers)

Slot	Target	TWI	NIST
9	200Å	283Å	299Å
10	400Å	533Å	556Å
11	600Å	783Å	821Å
12	800Å	1,118Å	1,060Å
13	1,000Å	1,281Å	1,334Å
14	600Å	754Å	784Å
16	600Å	786Å	809Å
17	600Å	778Å	809Å
18	1,000Å	1,818Å	1,830Å

SEMATECH Standard Cu/Ta Correlation *(continued)*

Comparison of NIST and TWI Results for Sematech Slot-3



		Ta_xO_y	Ta
Nominal	T	-	200Å
	ρ	-	16.60g/cc
	σ	-	-
		-	
TWI	T	23Å	168Å
	ρ	8.59g/cc	16.60g/cc
	σ	6Å	5Å
NIST	T	23.7Å	175.7Å
	ρ	8.28g/cc	16.27g/cc
	σ	4.8Å	4Å

Seed/Barrier Production Monitoring

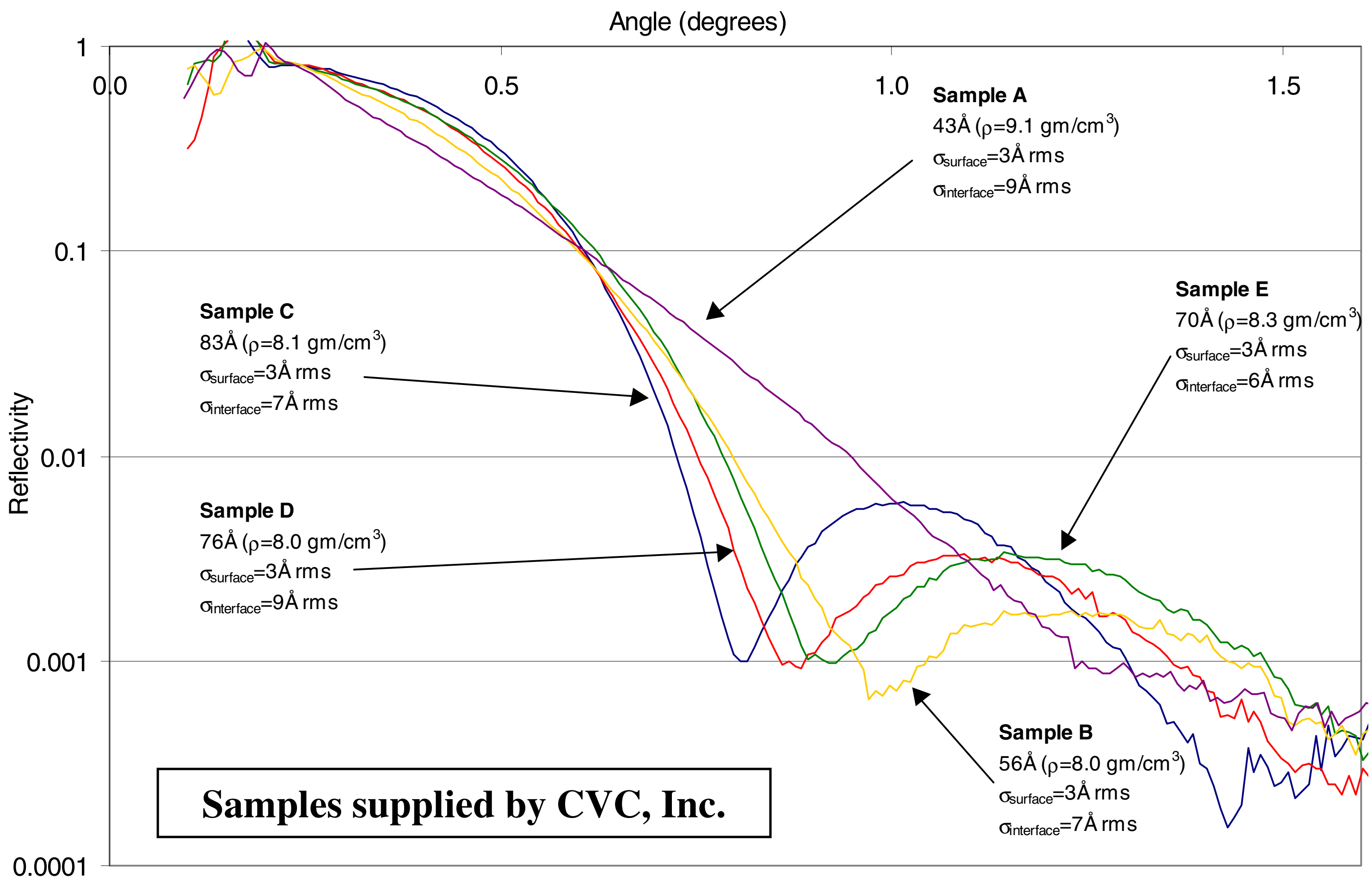
Use rapid XRR in Meta-Probe *X* to monitor Cu seed and Ta barrier thickness in production stacks on test or product wafers

- Cu seed thickness from <50Å to >1,500Å with repeatability <0.5% (1σ)
- Ta/TaN barrier thickness from <30Å to >500Å under Cu seed with repeatability <0.5% (1σ)
- Insignificant (<1 rad) gate oxide radiation exposure from 1st Cu measurement (no exposure for metal>2)

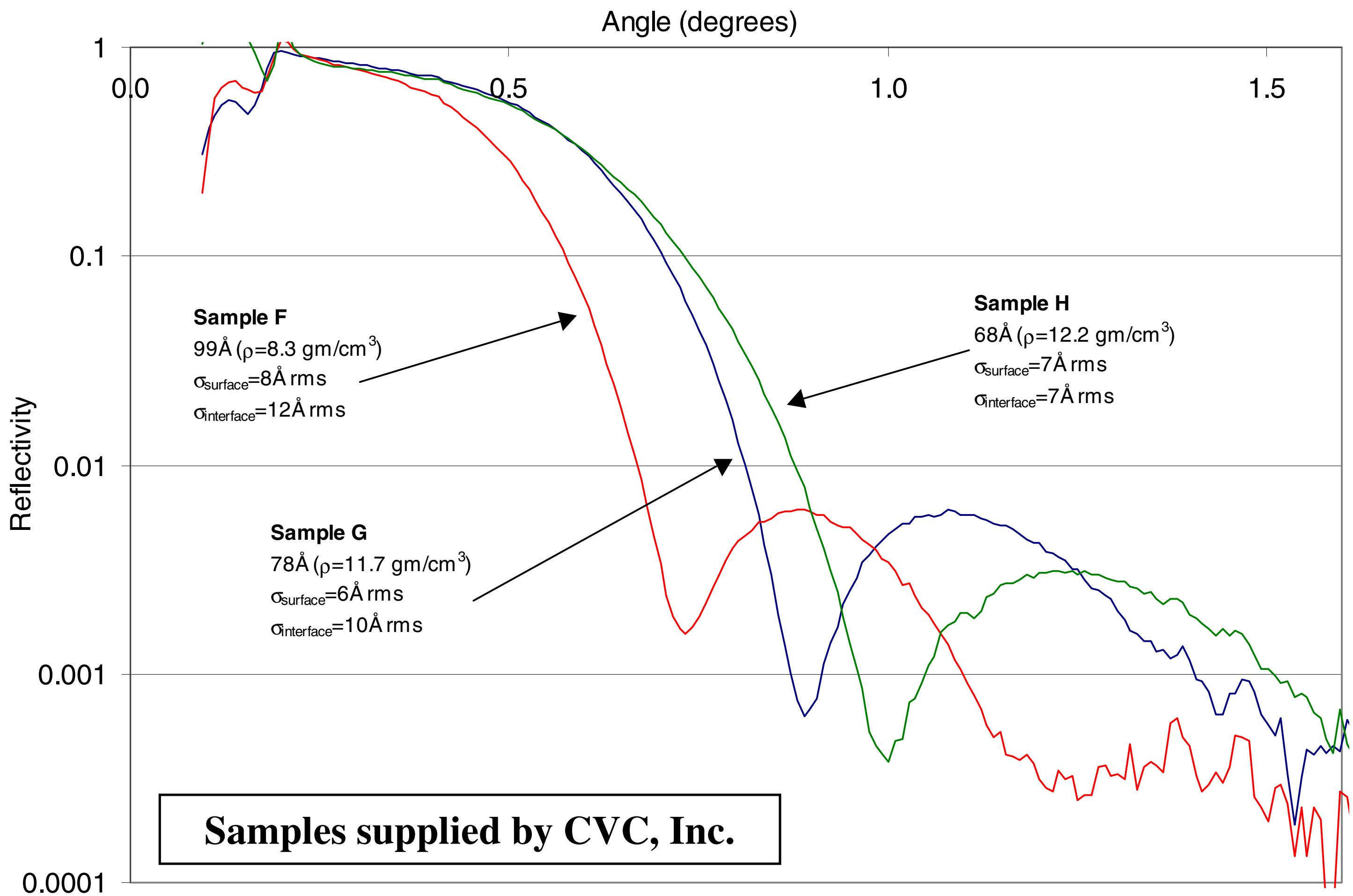
Critical Process Development Challenges

- Thin CVD Cu seed and compound barriers
  - Thickness of <100Å films in stacks
  - Stoichiometry and purity of MOCVD films
  - Surface and interface roughness of CVD films
- Low-k dielectric density and thickness
- RTP-processed silicides from thin film stacks
  - Ti/Co, Ti/Ni, etc.
  - Thickness and roughness and density
- Rapid measurement turn-around for rapid process iteration - *no time for metrology R&D*

Ultra-Thin CVD TaN Barrier Films



Ultra-Thin CVD TaN Barrier Films



Samples supplied by CVC, Inc.

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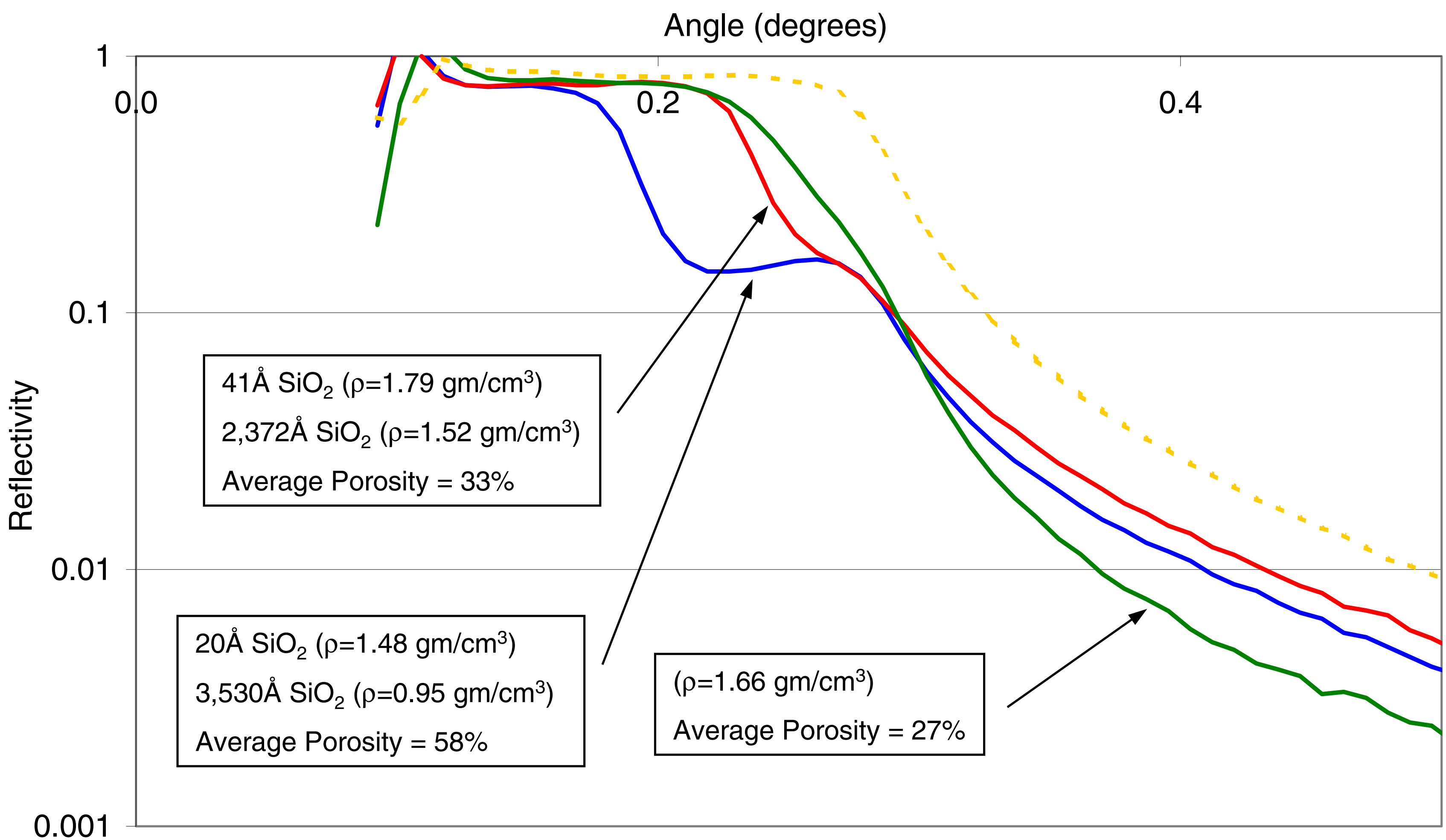
Low-K Dielectric Films



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Summary

- Rapid XRR in the Meta-Probe *X* is a promising metal metrology tool
- Can be used to monitor Cu-seed/Ta-barrier stack thickness in production
- Thickness, density, and roughness capability promising for process development
  - Ultra-thin MOCVD film stacks
  - Low-K dielectric density
  - Other thin film applications