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Practical Method for Modeling Conductor Surface Roughness Using Close Packing of Equal Spheres

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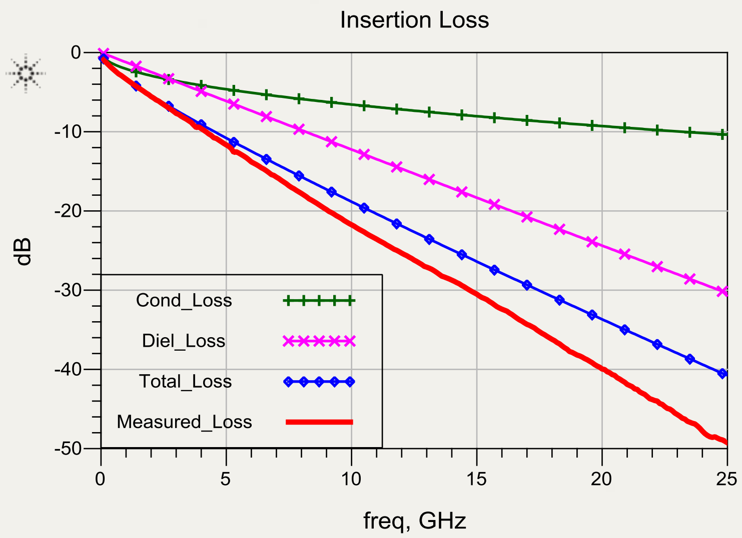
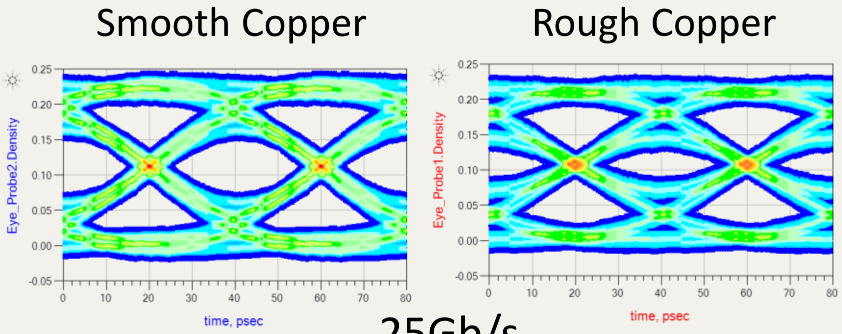
Outline

- Overview
- Conductor loss
- Copper foil fabrication
- Modeling roughness
- Hexagonal Close-packing of Equal Spheres Model
- Practical method to determine rough conductor loss
- Case study

Failure To Model Roughness Can Ruin You Day



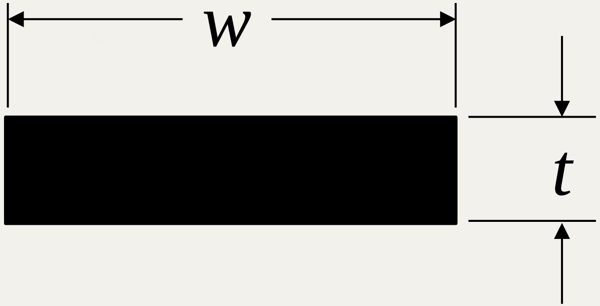
With just -3.5dB delta @12.5 GHz => ½ the eye height with rough copper



25Gb/s

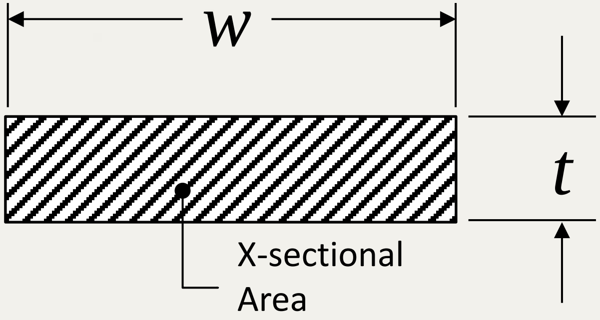
Simulated with Keysight ADS

DC Current Distribution Through a Rectangular Conductor



Current distribution at DC is uniform through cross-sectional area of conductor

DC Resistance



$$R_{DC\_cond} = \frac{\rho}{t \times w}\ \Omega / \mathrm{m}$$

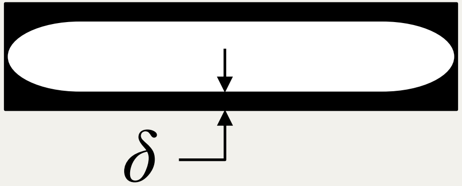
ρ = Bulk resistivity of the material in Ω-m

DC resistance is proportional resistivity and inversely proportional to the cross sectional area

Skin Effect

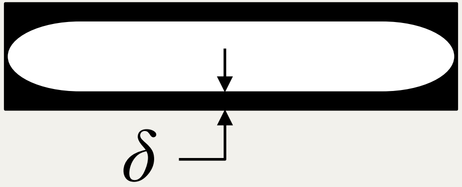
Above ~10MHz current flows mainly along “skin” of the conductor

Skin Depth



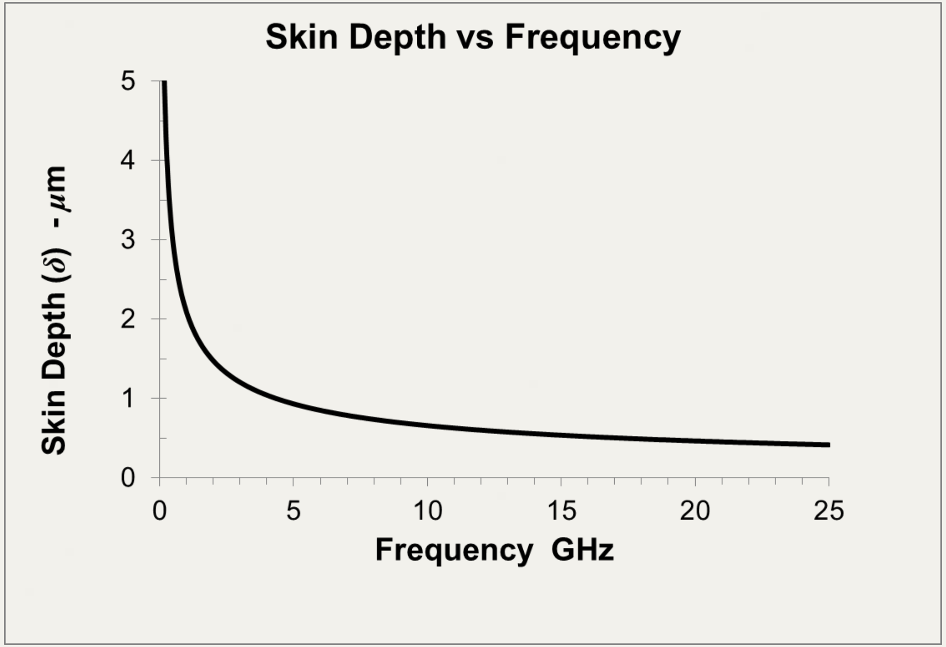
Skin depth (δ) is effective thickness where AC current flows

Skin Depth vs Frequency



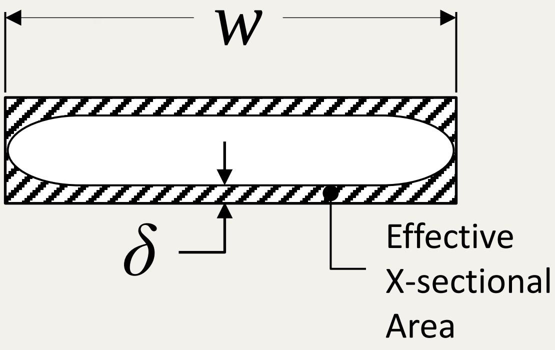
$$\delta = \sqrt{\frac{1}{\pi f \mu_0 \sigma}}$$

μ_0 = Permeability of free space in H/m
σ = Conductivity in S/m.

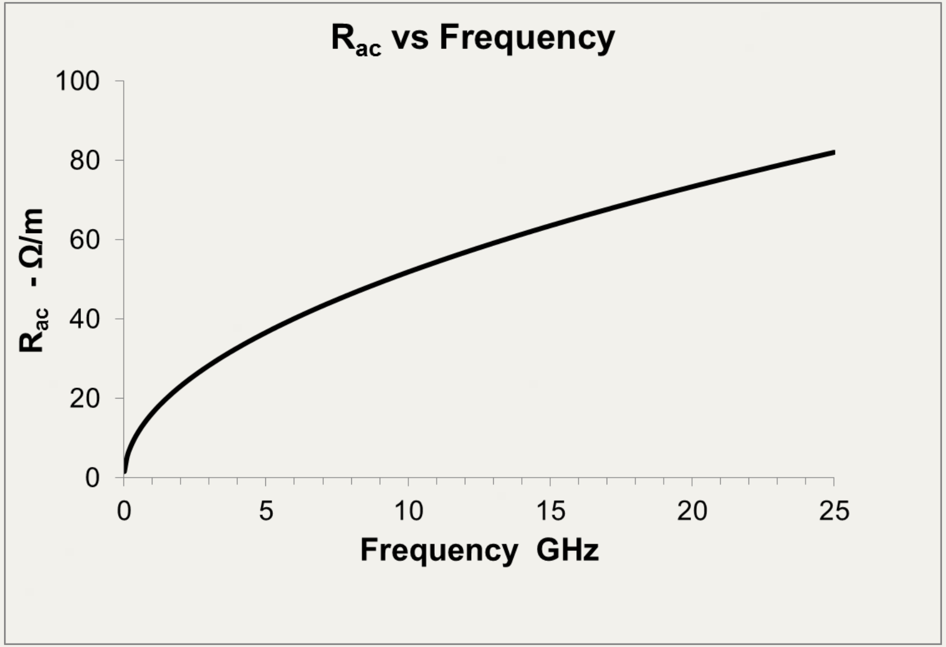


Skin depth inversely proportional to $\sqrt{f}$

AC Resistance

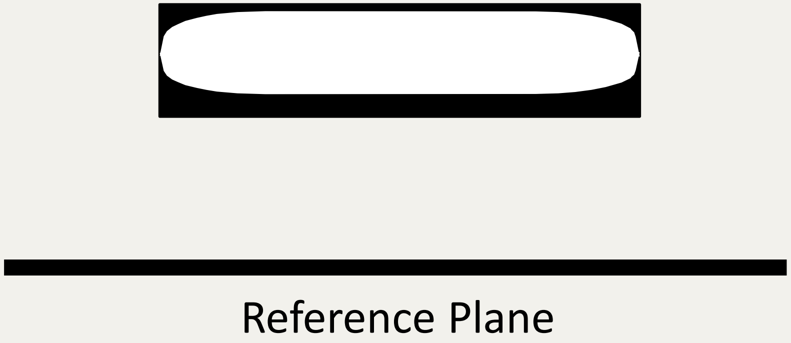


$$R_{AC\_cond} \approx \frac{\rho}{2\delta \times w} \Omega / \mathrm{m}$$



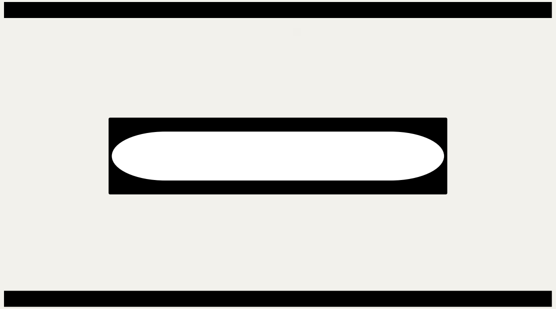
Reduced cross-sectional area causes AC resistance to increase proportional to $\sqrt{f}$

Current Distribution Microstrip



High frequency currents concentrated mostly along surface facing reference plane due to proximity effect

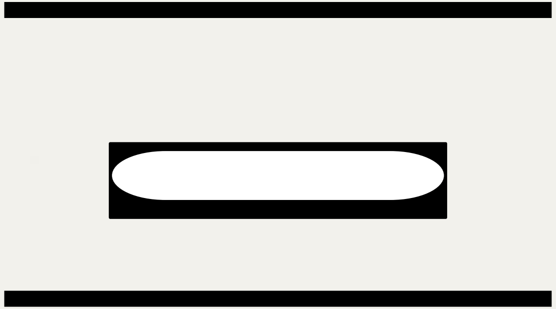
Current Distribution Stripline



Reference Plane

Reference Plane

Symmetrical

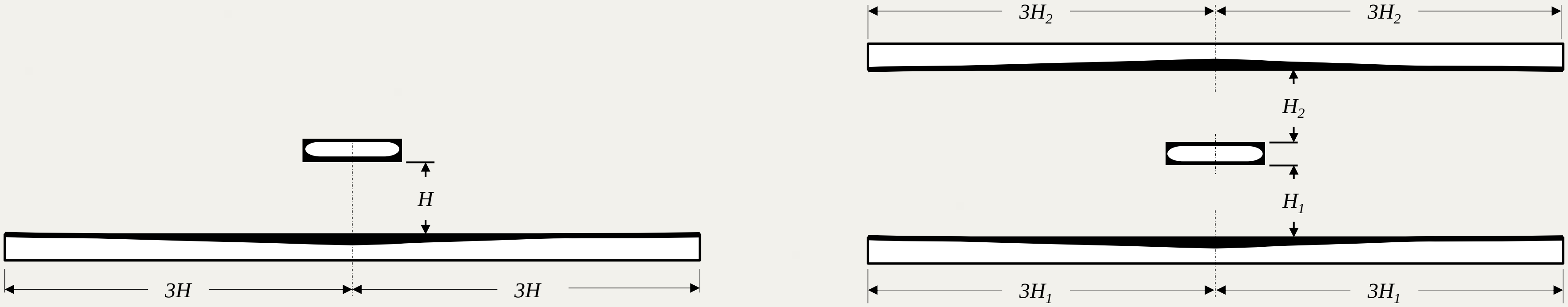


Reference Plane

Reference Plane

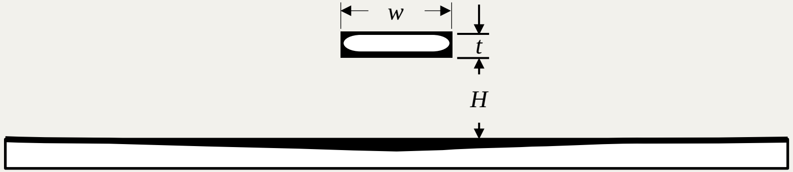
Asymmetrical

Return Current Distribution



Return current on respective reference plane ≈ +/-3*H* from signal conductor center

AC Resistance Microstrip

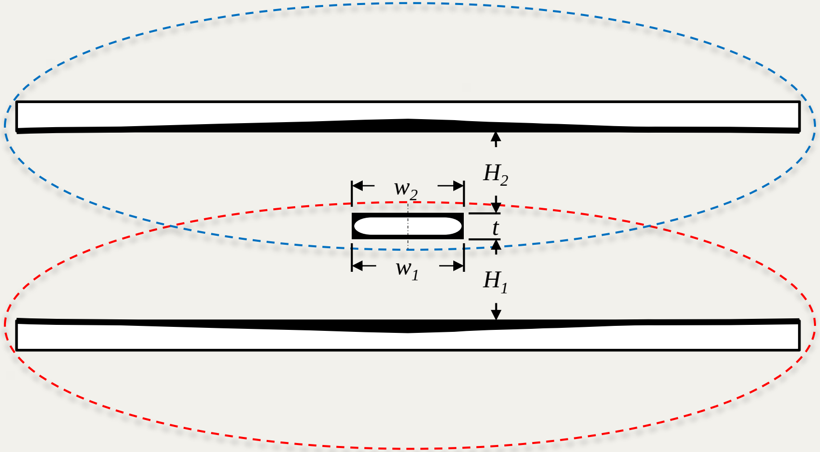


$$R_{AC\_microstrip} = R_{AC\_trace} + R_{AC\_ref}$$

$$\boxed{R_{AC\_microstrip}(f) = \frac{\sqrt{\pi\mu_0 f\rho}}{w}\left[\left(0.94+0.132\frac{w}{H}-0.0062\left(\frac{w}{H}\right)^2\right)\left(\frac{1}{\pi}+\frac{1}{\pi^2}\ln\frac{4\pi w}{t}\right)+\left(\frac{\frac{w}{H}}{\frac{w}{H}+5.8+0.03\left(\frac{H}{w}\right)}\right)\right]\ \Omega/\mathrm{m}\ ;\ \text{when } 0.5\le\frac{w}{H}\le 10}$$

Reference [1]

Stripline Conductor Loss



1. Determine $R_{AC\_microstrip1}$
2. Determine $R_{AC\_microstrip2}$
3. Combine both in parallel

$$R_{AC\_stripline}(f) = \frac{\left(R_{AC\_microstrip1}(f)\right)\left(R_{AC\_microstrip2}(f)\right)}{\left(R_{AC\_microstrip1}(f)\right)+\left(R_{AC\_microstrip2}(f)\right)} \ \Omega/\text{m}$$

4. Determine Insertion Loss:

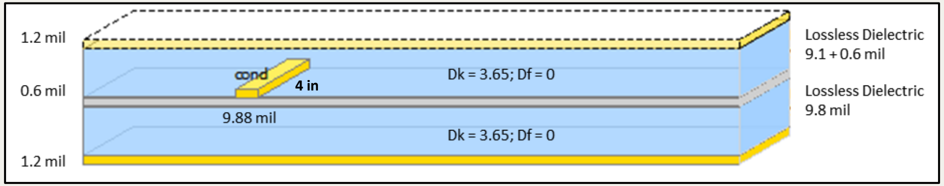
$$IL_{smooth}(f) = -20\log_{10} e\left(\frac{R_{AC\_stripline}(f)}{Zo(f)}\right) \ \text{dB/m}$$

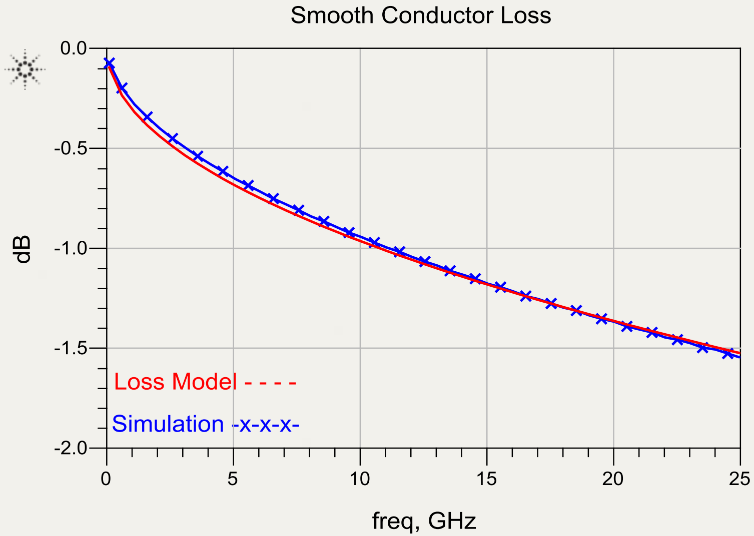
Conductor Loss Model Validation

$$IL_{smooth}(f) = -20\log_{10} e\left(\frac{R_{AC\_stripline}(f)}{Zo(f)}\right) \text{ dB/m}$$

VS

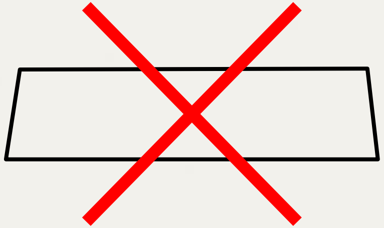
Keysight ADS Momentum



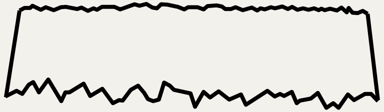


Excellent correlation!

Conductor Roughness



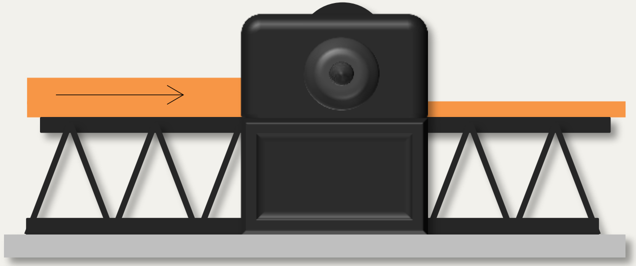
No such thing as a perfectly smooth PCB conductor surface



Roughness is always applied to promote adhesion to the dielectric material

Copper Foil Manufacturing Processes

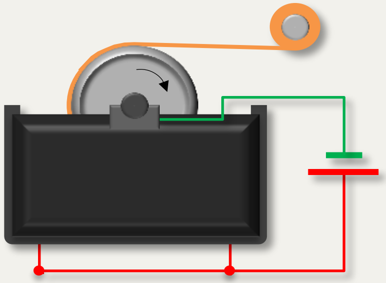
Rolled



Smoother

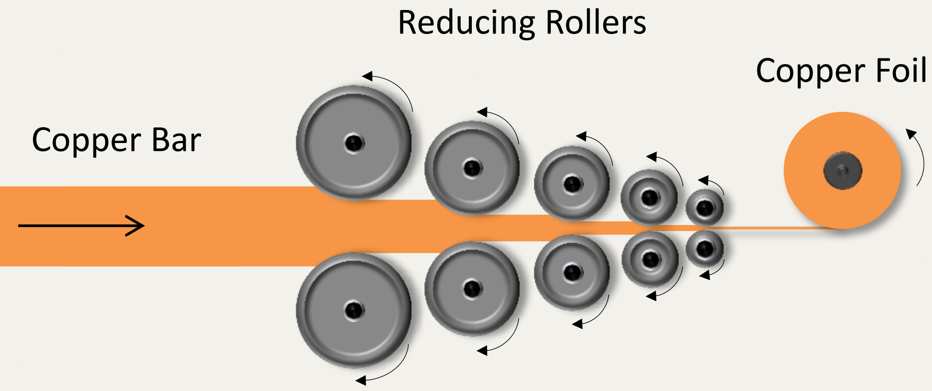
vs

Electro-deposited (ED)



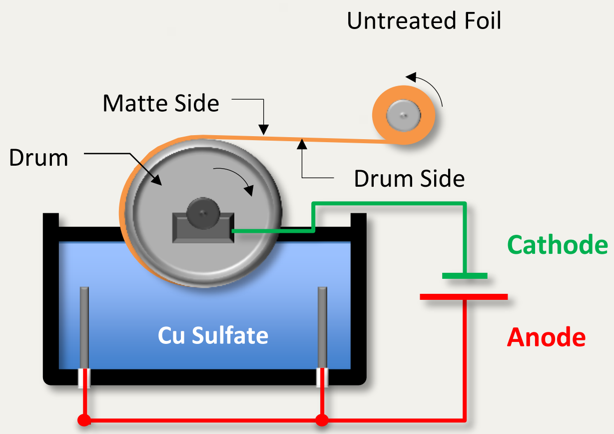
Lower Cost

Rolled Copper Foil Fabrication Process



- Copper bar fed through a series of progressively smaller rollers to achieve final thickness
- Roller smoothness determines final smoothness of foil

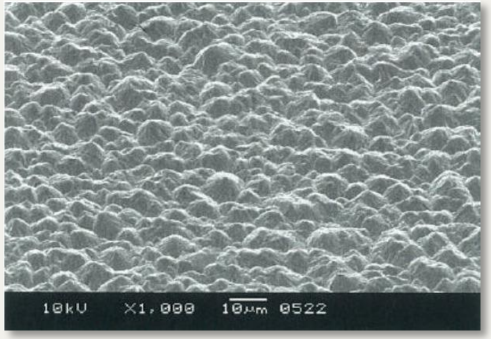
Electrodeposited Copper Foil Fabrication Process



- Drum speed controls foil thickness
- Matte side always rougher than drum side

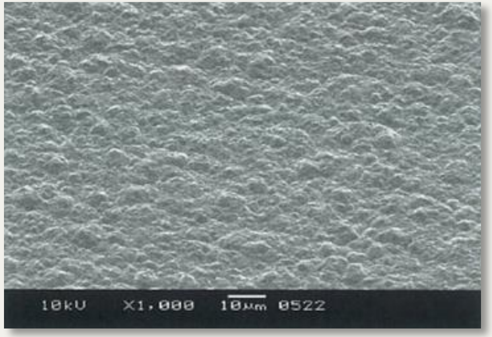
Common Roughness Profiles

IPC Standard Profile



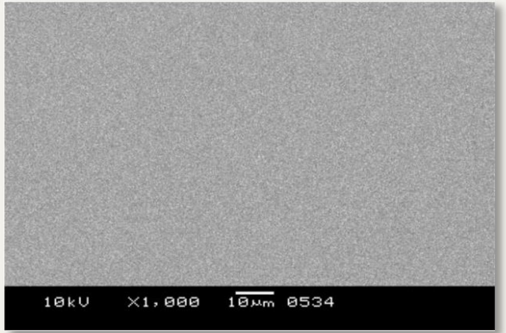
No min/max spec

IPC Very Low Profile(VLP)



< 5.2 μm max

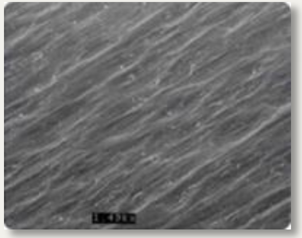
Ultra Low Profile (ULP)Class



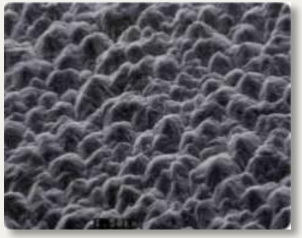
-*Other names: HVLP*, VSP
-No IPC spec
-Typically < 2 μm max

SEM Photos Courtesy [6]

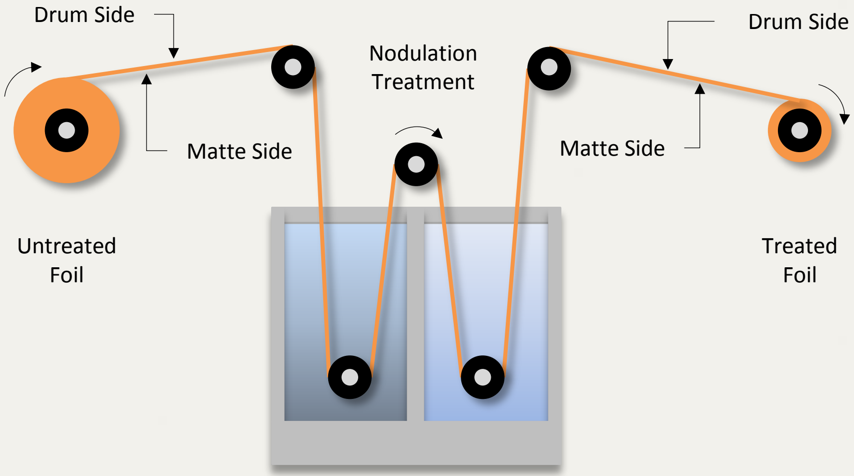
Electro-deposited Copper Foil Nodulation Treatment



Drum Side Untreated



Matte Side Untreated

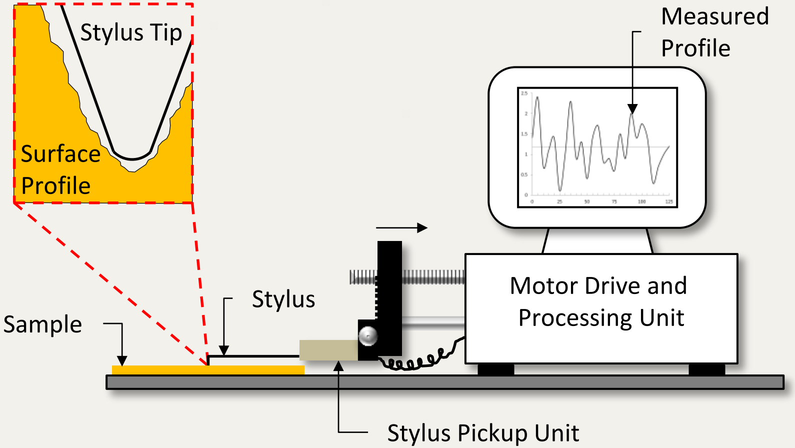


Drum Side Treated

Matte Side Treated

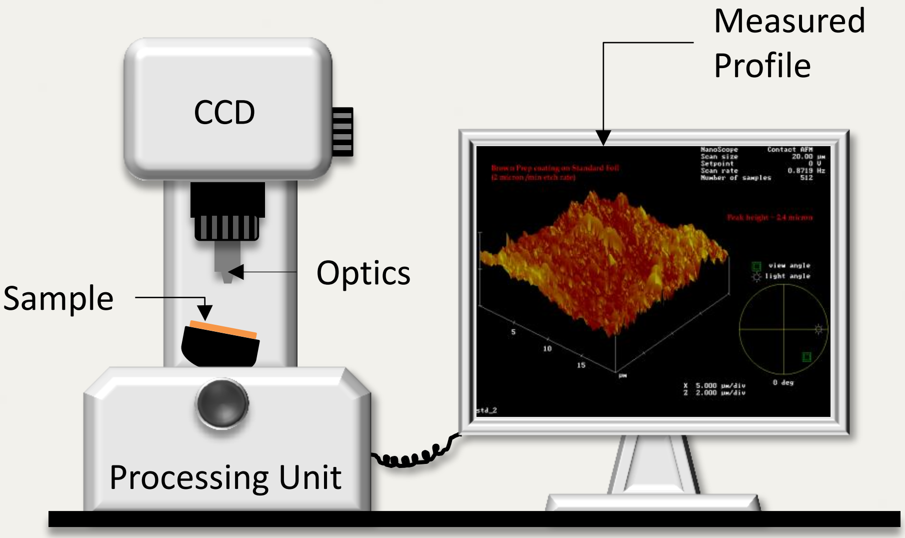
SEM Photos Courtesy [2]

Measuring Surface Roughness



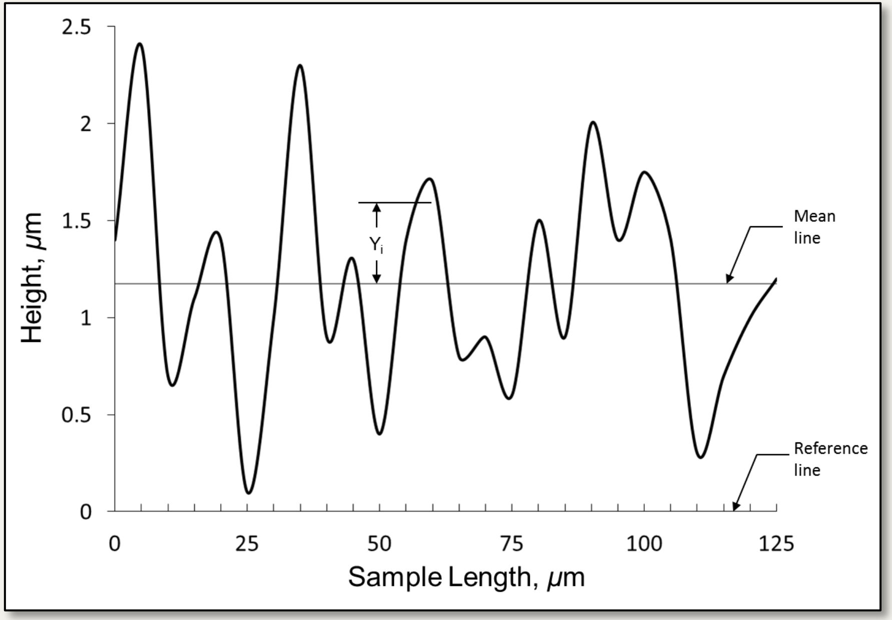
Profilometers are often used to measure surface roughness

Optical Profilometer



- ✓ 3D Scan Profile
- ✓ Faster
- ✓ More reliable
- ✓ More accurate

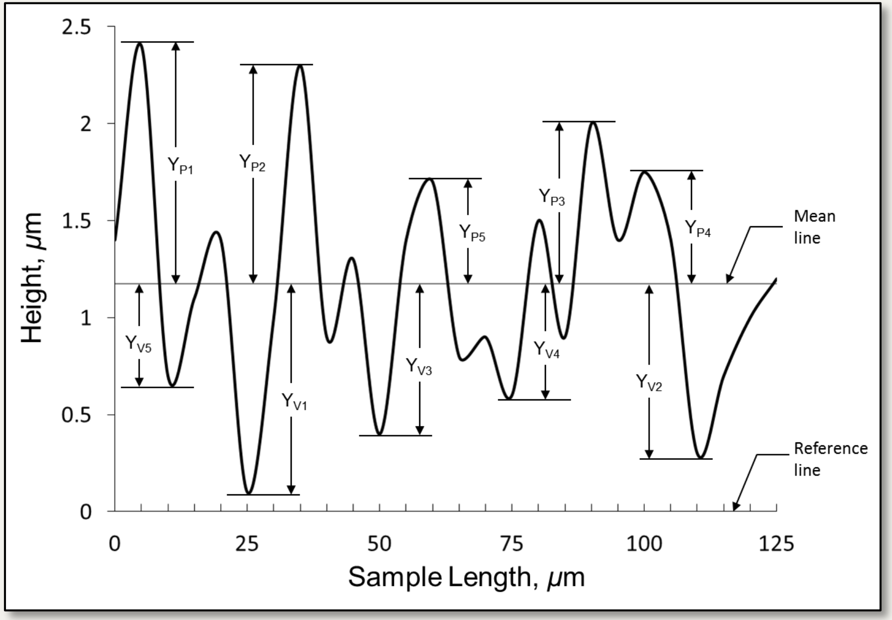
Average Roughness Parameter



- Average roughness (R_a) typically specified for drum side on data sheet
- R_a = Arithmetic average of the absolute values of deviations Y_i

$$R_a = \frac{1}{N}\sum_{i=1}^{N}|Y_i|$$

Ten-point Mean Roughness Parameter

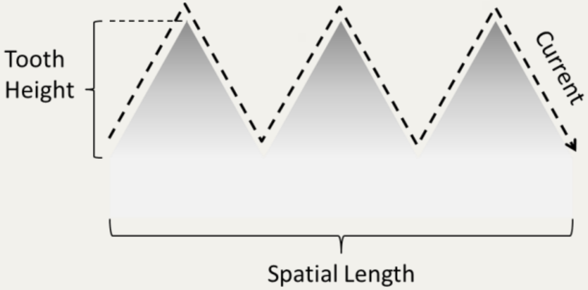


- Ten-point mean roughness (R_z) typically specified for matte side on data sheet
- R_z= Sum of the average of the five highest peaks and the five lowest valleys over the sample length

$$R_z = \frac{1}{5}\sum_{i=1}^{5}\left|Y_{Pi}\right| + \frac{1}{5}\sum_{i=1}^{5}\left|Y_{Vi}\right|$$

Modeling Copper Roughness

Hamerstad & Jenson Model

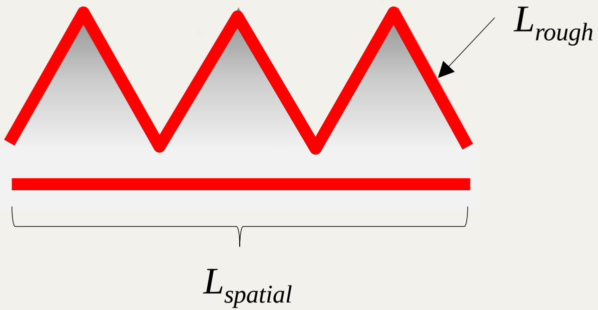


$$\boxed{K_{HJ} = \frac{P_{rough}}{P_{flat}} = 1 + \frac{2}{\pi}\arctan\left(1.4\left(\frac{\Delta}{\delta}\right)^2\right)}$$

$\Delta =$ RMS tooth height in meters

- Assumes 2D corrugated surface
- Based on mathematical fit to S.P. Morgan Power Loss Data (1948)
- Lose accuracy above 5GHz for rough copper

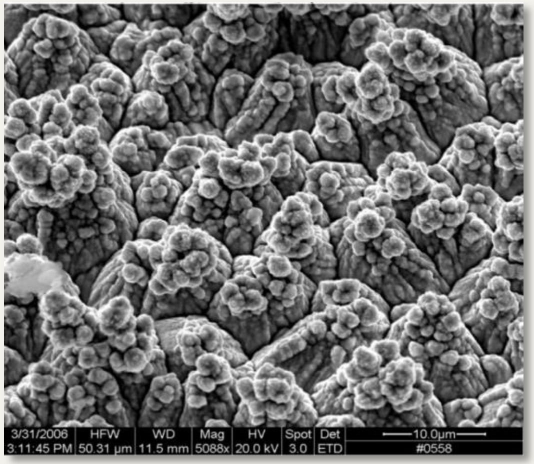
Modified Hamerstad & Jenson Model



$$\boxed{K_{HJM} = \frac{P_{rough}}{P_{flat}} = 1 + \frac{2}{\pi}\arctan\left(1.4\left(\frac{\Delta}{\delta}\right)^2\right) \times (SF - 1)}$$

- SF = scaling factor representing the ratio of the length of the rough surface (L_{rough})to the spatial length ($L_{spatial}$) –Ref [2]
- Impractical from first principles perspective – L_{rough} not published in data sheets

Huray “*snowball*” Model



SEM Photo Courtesy [3]

$$K_{SRH}(f) = \frac{P_{rough}}{P_{flat}} = \frac{A_{matte}}{A_{flat}} + \frac{3}{2}\sum_{i=1}^{j}\left(\frac{N_i \times 4\pi a_i^2}{A_{flat}}\right)\left(1 + \frac{\delta(f)}{a_i} + \frac{\delta^2(f)}{2a_i^2}\right)^{-1}$$

$\frac{A_{matte}}{A_{flat}}$ = relative area of the matte base compared to a flat surface

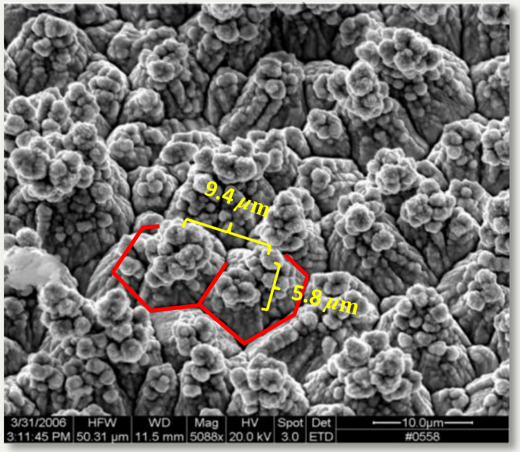
a_i = radius of the copper sphere (snowball) of the i^{th} size, in meters

$\frac{N_i}{A_{flat}}$ = number of copper spheres of the i^{th} size per unit flat area in sq. meters

$\delta(f)$ = skin-depth, as a function of frequency, in meters

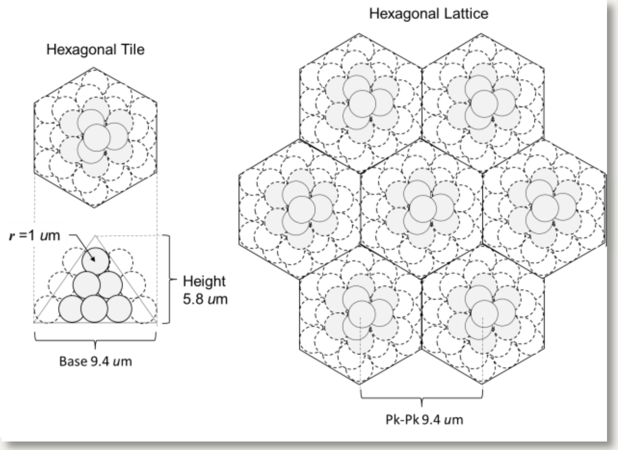
Reference [2]

Huray Model Prior Art

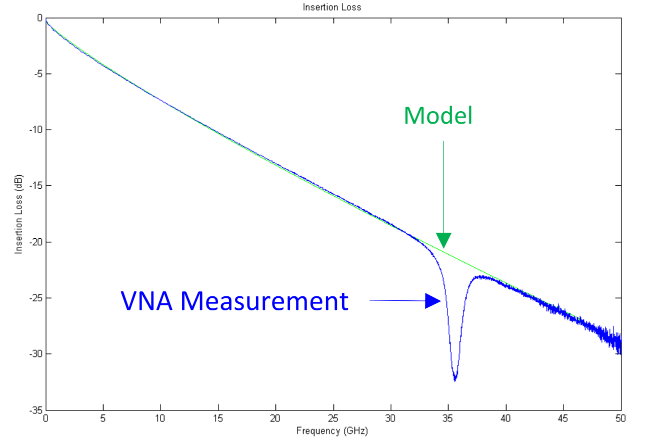


SEM Photo Courtesy [3]

Assumes stacked "snowballs" arranged in hexagonal lattice



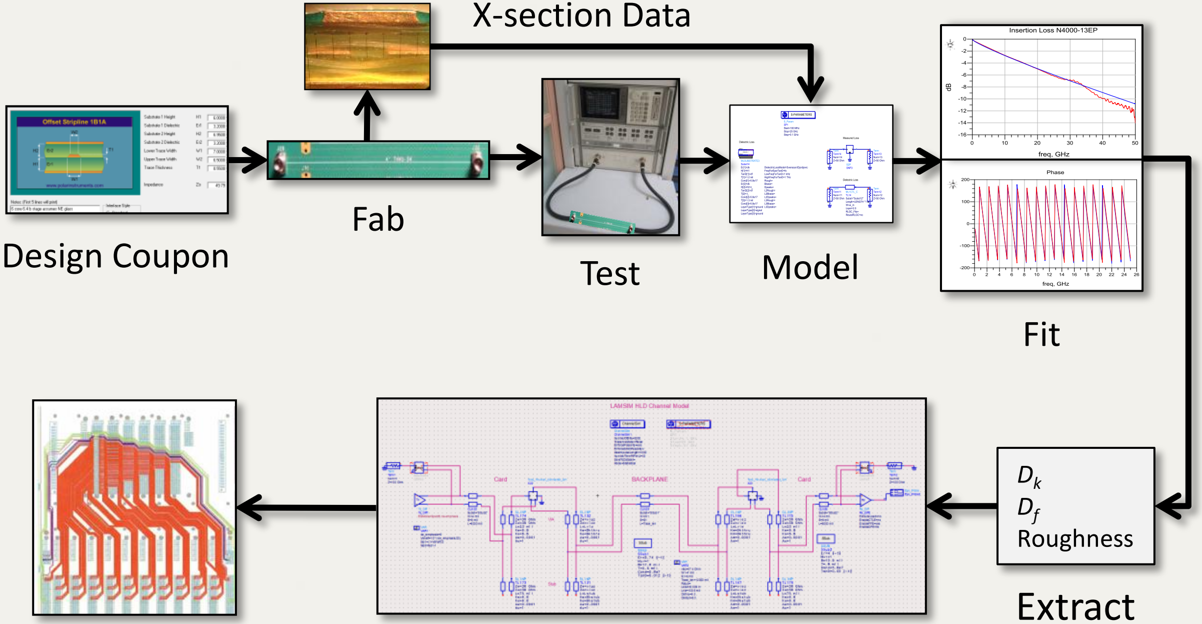
11 spheres min; 38 spheres max of radius 1μm to fit within hex tile area and height of 5.8μm



Plot Courtesy [2]

Fit equation parameters to measured data

Design Feedback Method*



X-section Data

Design Coupon

Fab

Test

Model

Fit

D_k
D_f
Roughness

Extract Parameters

Channel Simulation

Design Product

Benefits:

Practical

Accurate

Issues:

Expertise Required

Time

Money

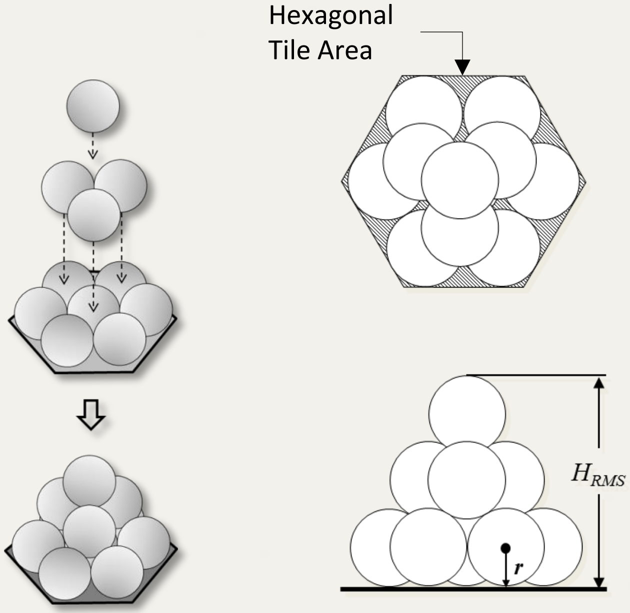
*Reference [2]

Hexagonal Close-packing of Equal Spheres (HCPES) Model

Why Bother?

- ✓ Helps make informed decision sooner - *“Sometimes an OK answer NOW! is more important than a good answer late”* – Eric Bogatin
- ✓ Fast simulation time - Practical for what-if spreadsheet analysis
- ✓ Minimal expertise required
- ✓ Useful to sanitize CAD tools
- ✓ Useful to gain intuition on what to expect with measurements and help determine root cause of differences

HCPES Model

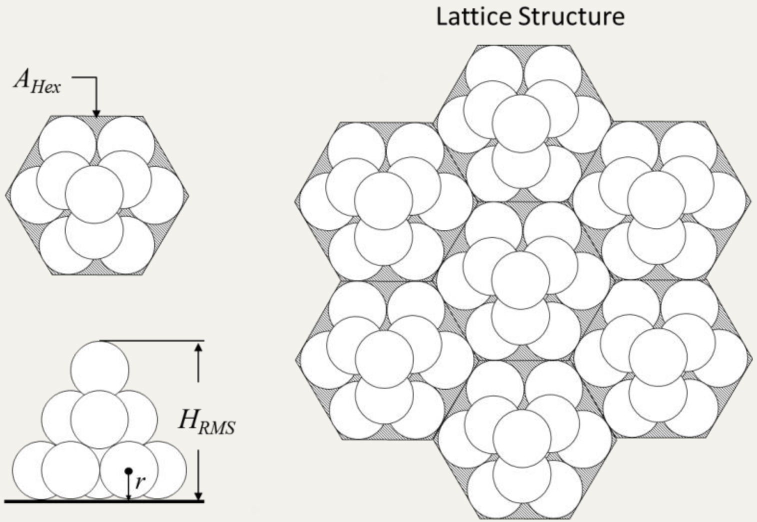


- Similar to Huray Model
- Based on close-packing of 11 equal sized spheres
- Does not require SEM analysis to determine stack height (H_{RMS}) or hexagonal tile area

Reference [5]

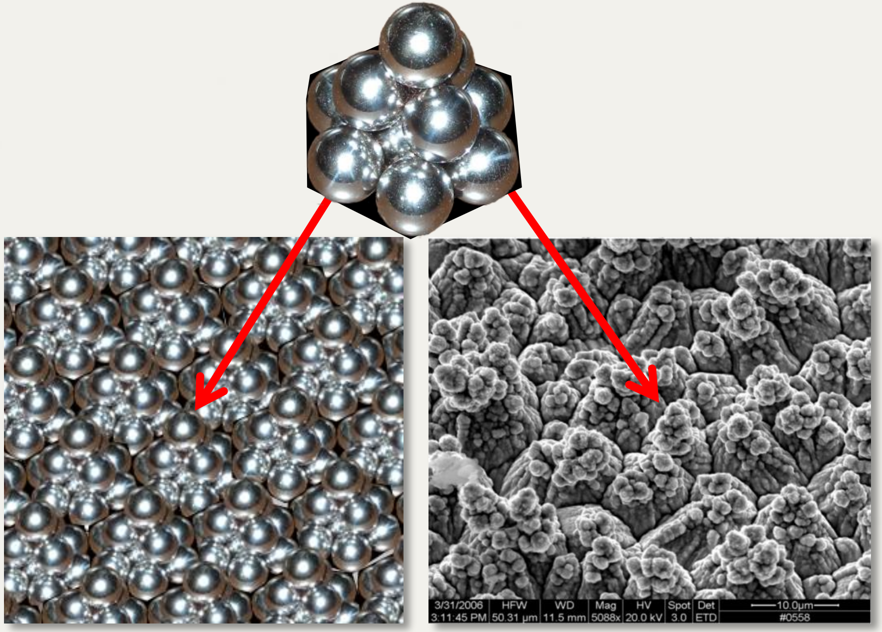
HCPES Correction Factor

$$K_{HCPES}(f) \approx \frac{P_{rough}}{P_{flat}} \approx 1 + 66\left(\frac{\left(\frac{\pi r^2}{A_{Hex}}\right)}{\left(1 + \frac{\delta(f)}{r} + \frac{\delta^2(f)}{2r^2}\right)}\right)$$



- Assumes nodule treatment applied to perfect flat surface
- Sphere radius and hex tile area determined solely on published roughness parameters from manufacturer’s data sheet

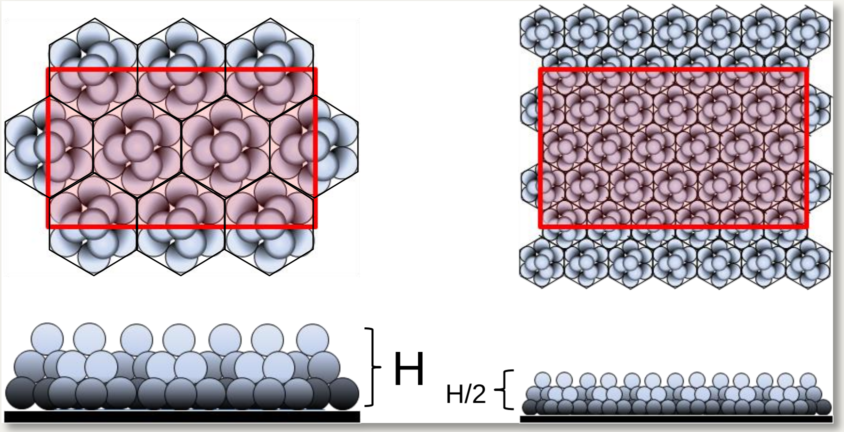
HCPES Model Lattice Structure



SEM Photo Courtesy [3]

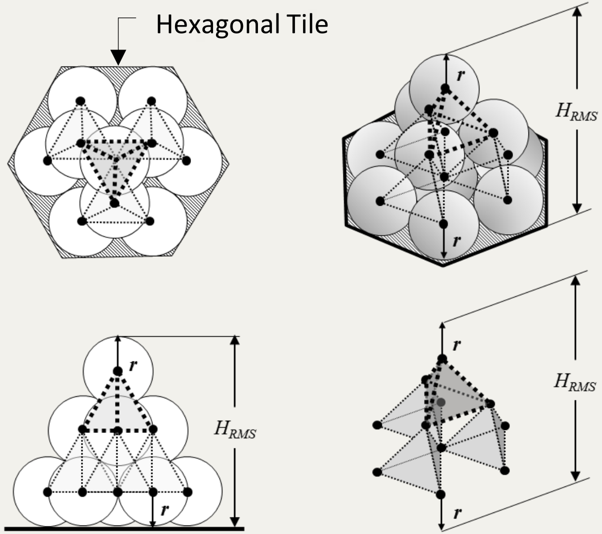
HCPES lattice structure loosely resembles the actual SEM photo

HCPES Model Scalability



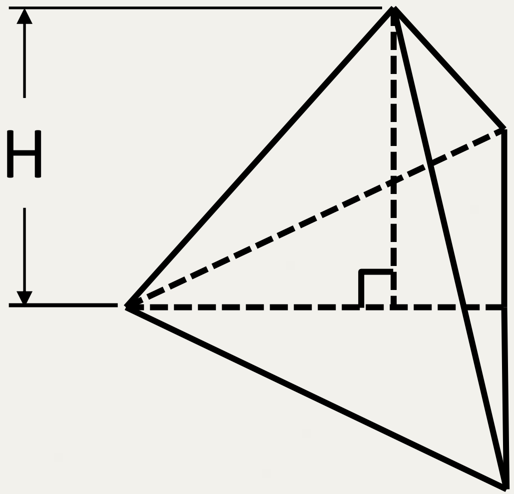
Lattice structure scales inversely to the square of the height

HCPES Model Anatomy

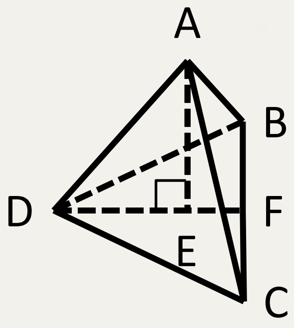


- Total of 11 equal sized spheres
- H_{RMS} = height of 2 tetrahedrons plus 2 sphere radii
- Hexagonal tile perimeter surrounds 7 base spheres exactly

Determine Height of Single Tetrahedron



1. Determine DE



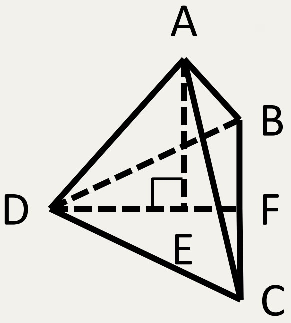
Given:

- ✓ Each side of the tetrahedron = 2*r*
- ✓ $DE = \frac{2}{3} DF$

Using Pythagorean theorem:

$$\begin{aligned} DE &= \frac{2}{3}\sqrt{DB^2 - BF^2} \\ &= \frac{2}{3}\sqrt{(2r)^2 - (r)^2} \\ &= \frac{2}{3} r\sqrt{3} \end{aligned}$$

2. Determine Height (AE)



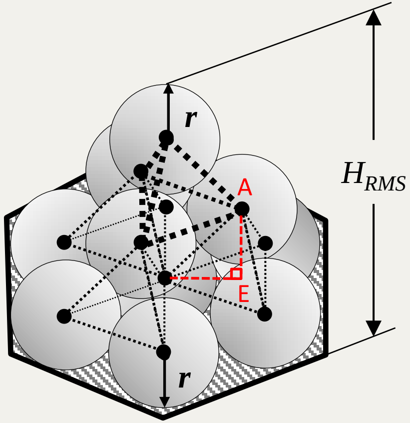
Therefore:

$$AE = \sqrt{AD^2 - DE^2}$$

$$= \sqrt{(2r)^2 - \left(\frac{2}{3} r\sqrt{3}\right)^2}$$

$$= \frac{2}{3} r\sqrt{6}$$

Determine HCPES Sphere Radius



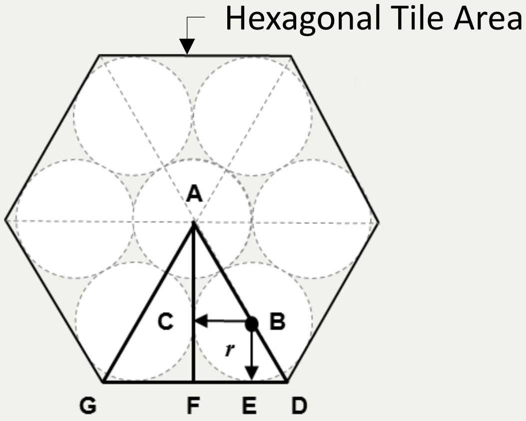
Since H_{RMS} = height of 2 tetrahedrons + sphere dia.

$$\begin{aligned} H_{RMS} &= 2AE + 2r \\ &= 2r\left(\frac{2}{3}\sqrt{6}+1\right) \end{aligned}$$

Therefore sphere radius is:

$$\boxed{r = \frac{H_{RMS}}{2\left(\frac{2}{3}\sqrt{6}+1\right)}}$$

Determine Hexagonal Tile Area

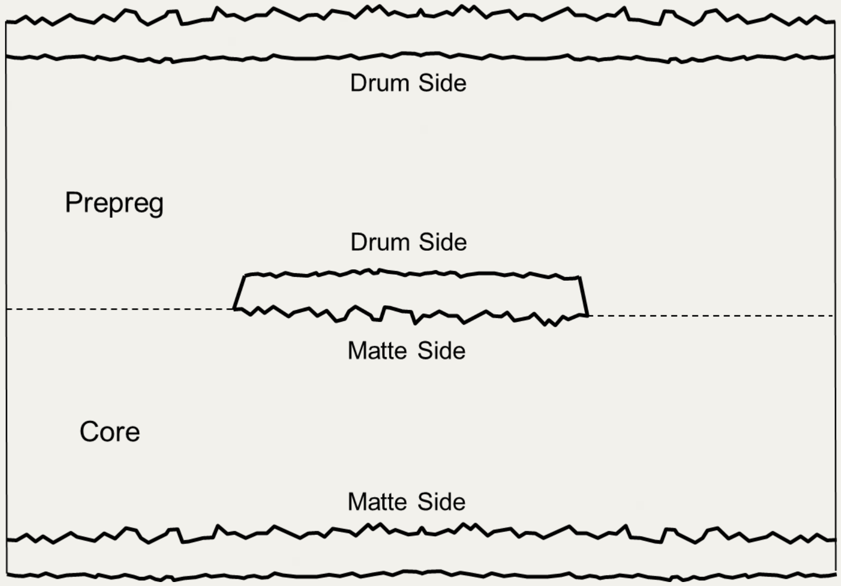


A_{Hex} = 6 x area of equilateral triangle ADG

$$\begin{aligned}
A_{Hex} &= 6\left(DF \times AF\right)\\
&= 6\left(r\left(\frac{1}{\sqrt{3}}+1\right)\times r\sqrt{3}\left(\frac{1}{\sqrt{3}}+1\right)\right)\\
&= 6r^2\sqrt{3}\left(\frac{1}{\sqrt{3}}+1\right)^2
\end{aligned}$$

Method to Determine Rough Conductor Loss

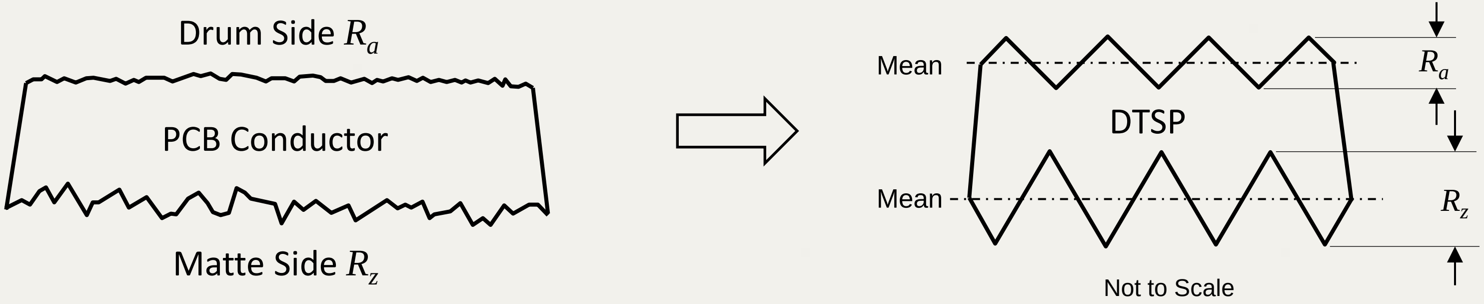
Stripline Geometry with Surface Roughness Example



Typically:

- Must consider roughness of each side when determining AC resistance
- Matte sides bonded to core
- Drum sides bonded to prepreg
- Drum sides roughened with oxide or etch treatment prior to lamination

Dual Triangular Sawtooth Profile (DTSP) Model

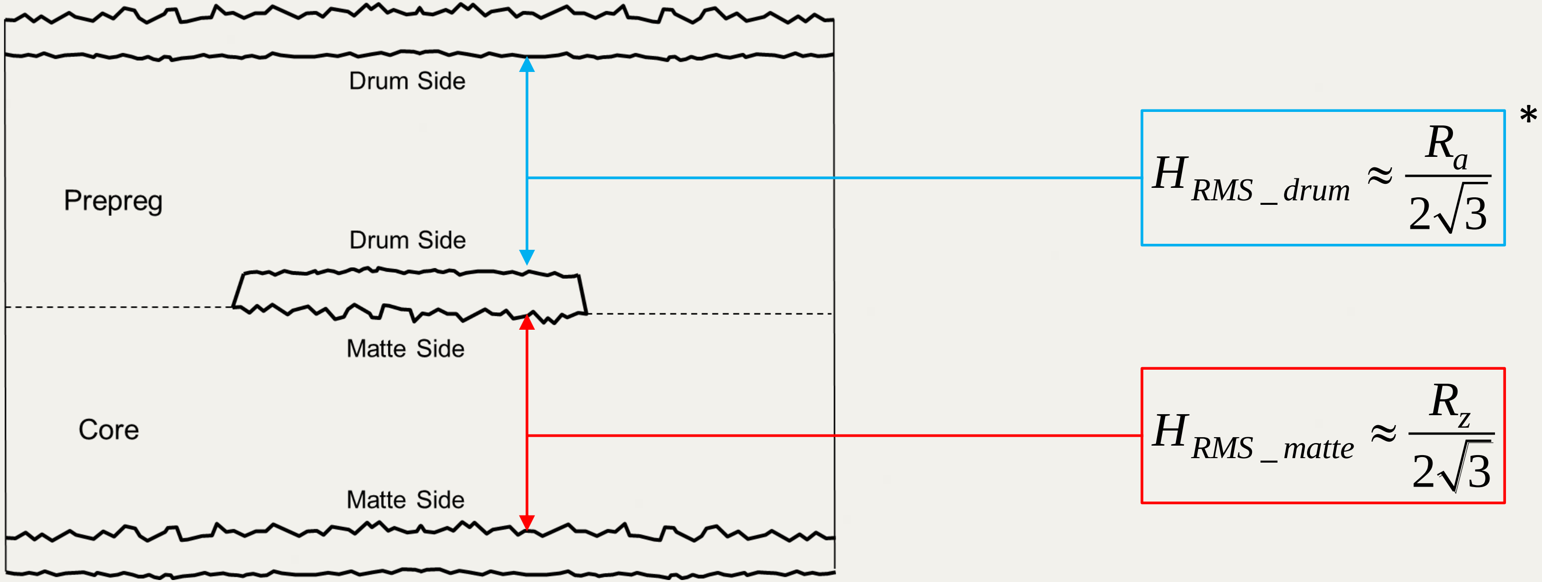


$$H_{RMSa} \approx \frac{R_a}{2\sqrt{3}}$$

$$H_{RMSz} \approx \frac{R_z}{2\sqrt{3}}$$

Used to approximate RMS height of matte and drum side

1. Determine RMS Tooth Height of Matte and Drum Sides

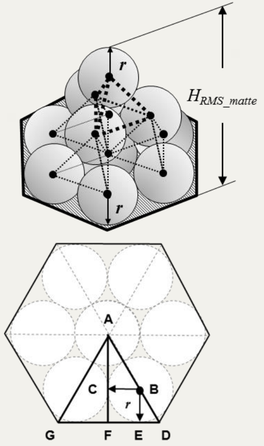


$$H_{RMS\_drum} \approx \frac{R_a}{2\sqrt{3}}$$ *

$$H_{RMS\_matte} \approx \frac{R_z}{2\sqrt{3}}$$

*Use Micro-etch Roughness for Drum Side

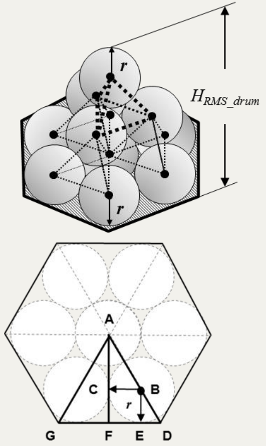
2. Determine HCPES Matte & Drum Correction Factors



$$r_{matte} = \frac{H_{RMS\_matte}}{2\left(\frac{2}{3}\sqrt{6}+1\right)}$$

$$A_{Hex\_matte} = 6\left(r_{matte}\right)^2\sqrt{3}\left(\frac{1}{\sqrt{3}}+1\right)^2$$

$$K_{HCPES\_matte}\left(f\right) \approx 1+66\left(\frac{\left(\frac{\pi\left(r_{matte}\right)^2}{A_{Hex\_matte}}\right)}{\left(1+\frac{\delta(f)}{r_{matte}}+\frac{\delta^2(f)}{2\left(r_{matte}\right)^2}\right)}\right)$$

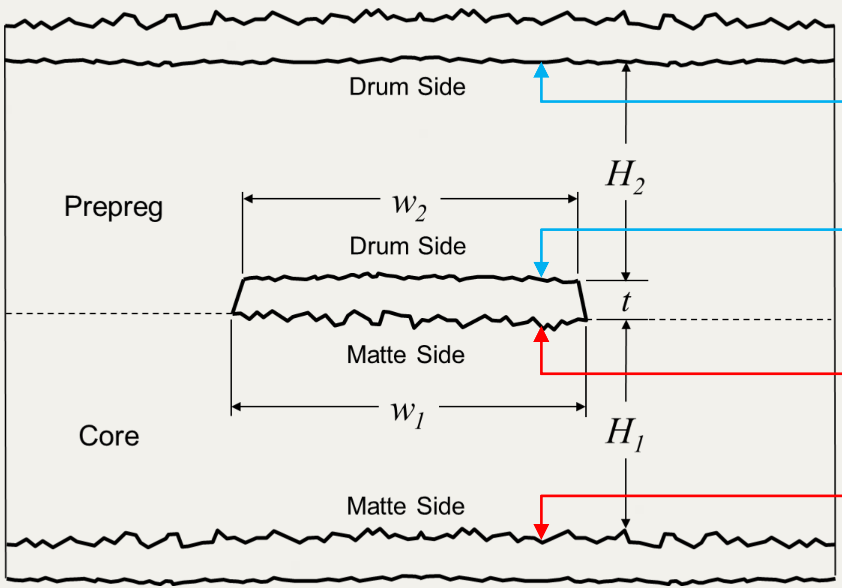


$$r_{drum} = \frac{H_{RMS\_drum}}{2\left(\frac{2}{3}\sqrt{6}+1\right)}$$

$$A_{Hex\_drum} = 6\left(r_{drum}\right)^2\sqrt{3}\left(\frac{1}{\sqrt{3}}+1\right)^2$$

$$K_{HCPES\_drum}\left(f\right) \approx 1+66\left(\frac{\left(\frac{\pi\left(r_{drum}\right)^2}{A_{Hex\_drum}}\right)}{\left(1+\frac{\delta(f)}{r_{drum}}+\frac{\delta^2(f)}{2\left(r_{drum}\right)^2}\right)}\right)$$

3. Determine AC Resistances of Each Surface



$$R_{AC\_ret\_2}(f)=\frac{\sqrt{\pi\mu_0 f\rho}}{w_2}\left(\frac{\frac{w_2}{H_2}}{\frac{w_2}{H_2}+5.8+0.03\left(\frac{H_2}{w_2}\right)}\right)\ \Omega/\text{m}$$

$$R_{AC\_w_2}(f)=\frac{\sqrt{\pi\mu_0 f\rho}}{w_2}\left(\frac{1}{\pi}+\frac{1}{\pi^2}\ln\frac{4\pi w_2}{t}\right)\left(0.94+0.132\frac{w_2}{H_2}-0.0062\left(\frac{w_2}{H_2}\right)^2\right)\ \Omega/\text{m}\quad *$$

$$R_{AC\_w_1}(f)=\frac{\sqrt{\pi\mu_0 f\rho}}{w_1}\left(\frac{1}{\pi}+\frac{1}{\pi^2}\ln\frac{4\pi w_1}{t}\right)\left(0.94+0.132\frac{w_1}{H_1}-0.0062\left(\frac{w_1}{H_1}\right)^2\right)\ \Omega/\text{m}\quad *$$

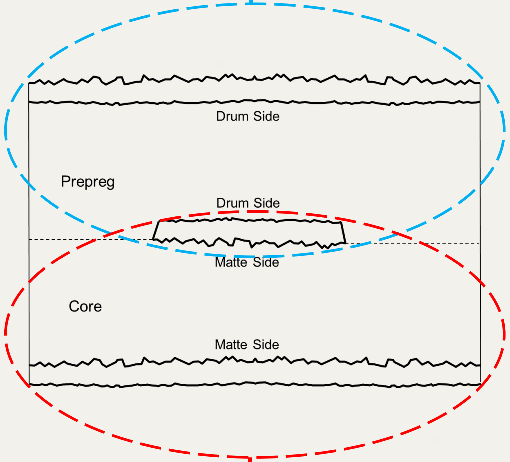
$$R_{AC\_ret\_1}(f)=\frac{\sqrt{\pi\mu_0 f\rho}}{w_1}\left(\frac{\frac{w_1}{H_1}}{\frac{w_1}{H_1}+5.8+0.03\left(\frac{H_1}{w_1}\right)}\right)\ \Omega/\text{m}$$

* when $0.5\le\frac{w_n}{H_n}\le 10$

Reference [1]

4. Determine Stripline Rough Conductor Loss

$$R_{AC\_drum}(f) = K_{HCPES\_drum}(f)\left[R_{AC\_w_2}(f) + R_{AC\_ret_2}(f)\right] \quad \Omega/\mathrm{m}$$



$$R_{AC\_matte}(f) = K_{HCPES\_matte}(f)\left[R_{AC\_w_1}(f) + R_{AC\_ret_1}(f)\right] \quad \Omega/\mathrm{m}$$

$$R_{AC\_stripline\_rough}(f) = \frac{\left(R_{AC\_matte}(f)\right)\left(R_{AC\_drum}(f)\right)}{\left(R_{AC\_matte}(f)\right) + \left(R_{AC\_drum}(f)\right)} \quad \Omega/\mathrm{m}$$

$$IL_{rough}(f) = -20\log_{10} e\left(\frac{R_{AC\_stripline\_rough}(f)}{Z_o(f)}\right) \quad \mathrm{dB/m}$$

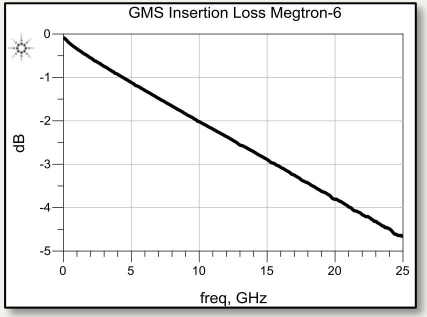
Case Study

Test Platform

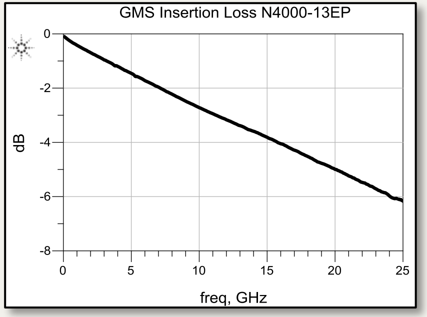
Case 1
Megtron-6
HVLP Cu

Case 2
N4000-13EP
VLP Cu

12 Layer test boards designed, built and tested by Molex Inc., courtesy of David Dunham



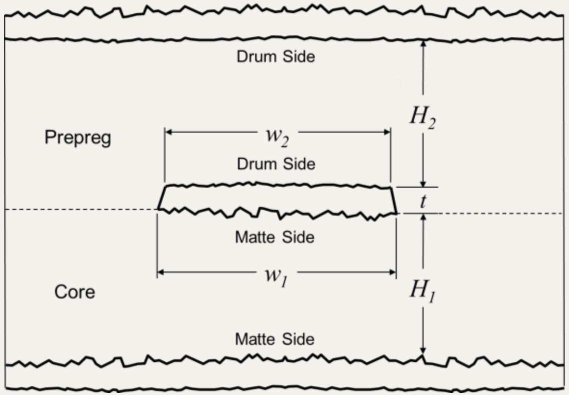
Generalized Modal S-parameters (GMS) data courtesy Scott McMorrow, Teraspeed Consulting Group



Generalized Modal S-parameters (GMS) data courtesy Yuriy Shlepnev, Simberian Software Corp

Photos courtesy [2]

Board Parameters From Data Sheets and Design



Stripline Geometry Reference

Parameter	Case 1 Megtron-6	Case 2 N4000-13EP
Dk	3.62 @50GHz	3.6-3.7 @10GHz[i]
Df	0.006 @ 50GHz	0.008-0.009 @ 10GHz[ii]
R_z HVLP	1.50 μm	-
R_z VLP	-	2.50 μm
R_a w/Micro-etch [iii]	1.44 μm	1.44 μm
Trace Thickness, t	15.23 μm	15.23 μm
Trace Widths w_1, w_2	251 μm, 236 μm	251 μm, 236 μm
Dielectric Heights, H_1,H_2	249 μm, 231 μm	249 μm, 231 μm
GMS trace length	10.15 cm (4.00 in)	10.15 cm (4.00 in)
$Zo(fo)$ ohms [iv]	52.29 @ 50GHz	52.07 @ 10GHz

[i] Dk = 3.65 used

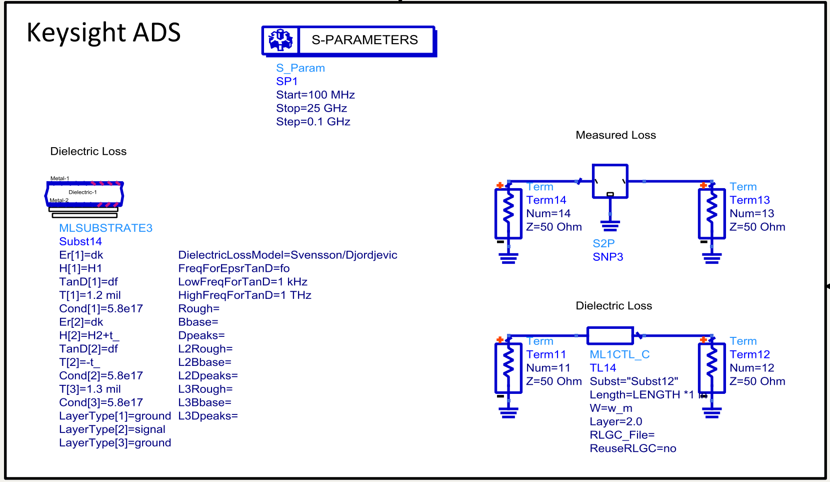
[ii] Df = 0.0085 used

[iii] CO-BRA BOND® SM is an example of a hydrogen peroxide/sulfuric acid micro-etch treatment often used by PCB fabricators to improve the adhesion of copper surface to dielectric materials.

[iv] $Zo(fo)$ = Characteristic impedance determined by 2D field solver at frequency *fo*

Determining Total Insertion Loss

$$IL_{Total}(f) = \underbrace{IL_{diel}(f)}_{} + \underbrace{IL_{cond\_rough}(f)}_{}$$



Keysight ADS

S-PARAMETERS
S_Param
SP1
Start=100 MHz
Stop=25 GHz
Step=0.1 GHz

Dielectric Loss

MLSUBSTRATE3
Subst14
Er[1]=dk
H[1]=H1
TanD[1]=df
T[1]=1.2 mil
Cond[1]=5.8e17
Er[2]=dk
H[2]=H2+t_
TanD[2]=df
T[2]=-t_
Cond[2]=5.8e17
T[3]=1.3 mil
Cond[3]=5.8e17
LayerType[1]=ground
LayerType[2]=signal
LayerType[3]=ground

DielectricLossModel=Svensson/Djordjevic
FreqForEpsrTanD=fo
LowFreqForTanD=1 kHz
HighFreqForTanD=1 THz
Rough=
Bbase=
Dpeaks=
L2Rough=
L2Bbase=
L2Dpeaks=
L3Rough=
L3Bbase=
L3Dpeaks=

Measured Loss

Term
Term14
Num=14
Z=50 Ohm

S2P
SNP3

Term
Term13
Num=13
Z=50 Ohm

Dielectric Loss

Term
Term11
Num=11
Z=50 Ohm

ML1CTL_C
TL14
Subst="Subst12"
Length=LENGTH *1 in
W=w_m
Layer=2.0
RLGC_File=
ReuseRLGC=no

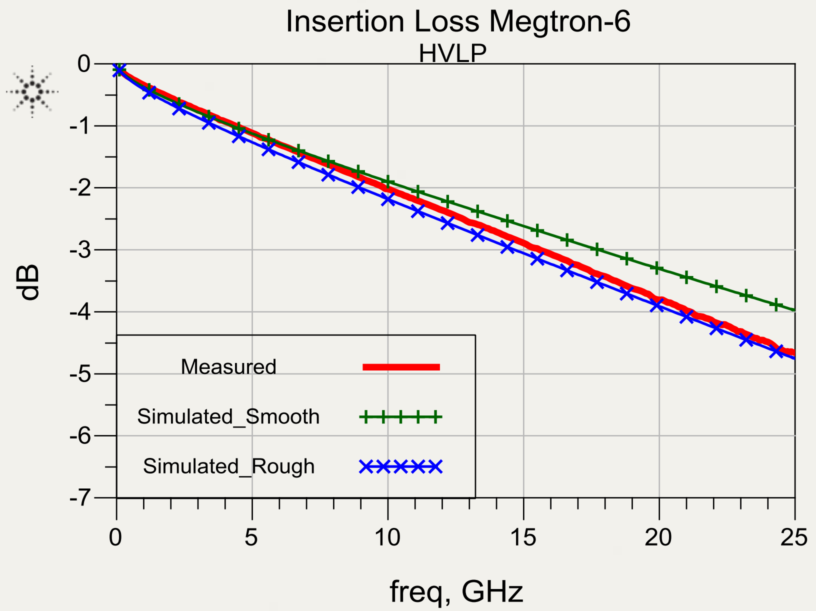
Term
Term12
Num=12
Z=50 Ohm

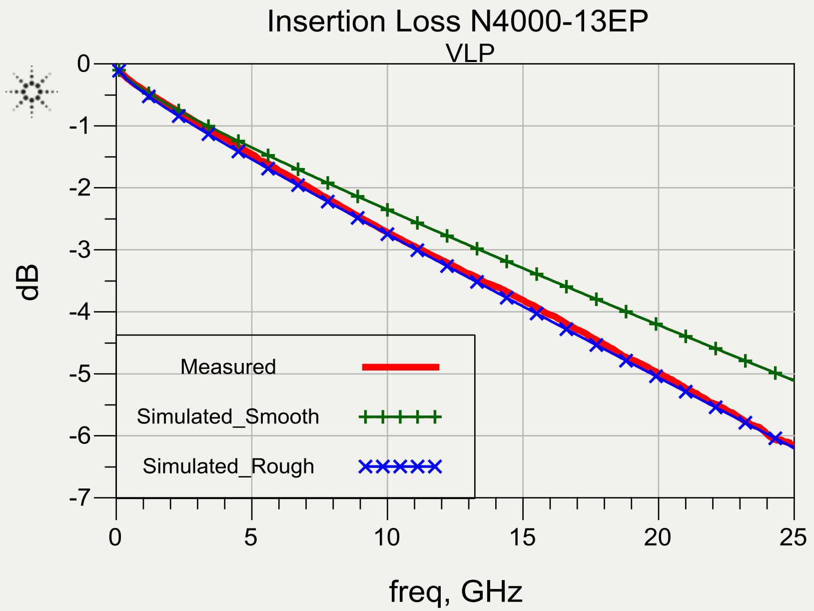
+

$$IL_{rough}(f) = -20\log_{10} e\left(\frac{R_{AC\_stripline\_rough}(f)}{Z_o(f)}\right) \text{ dB/m}$$

- Svensson/Djordjevic wideband Debye model used to ensure causality for dielectric loss
- Conductivity parameter set to a value much-much greater than the normal conductivity of copper ensures the conductor is lossless for the simulation

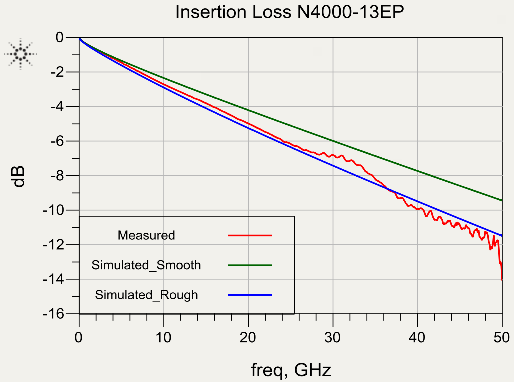
Simulation Correlation Results



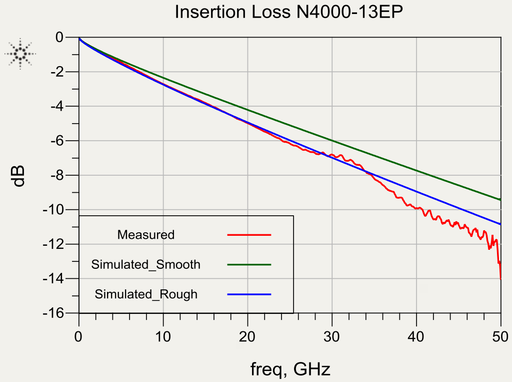


Excellent correlation!

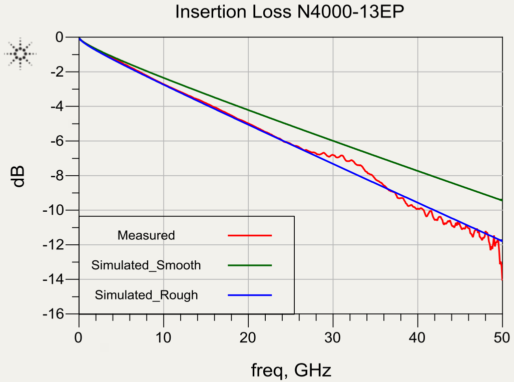
Model Comparisons



HJ



HJM



HCPES

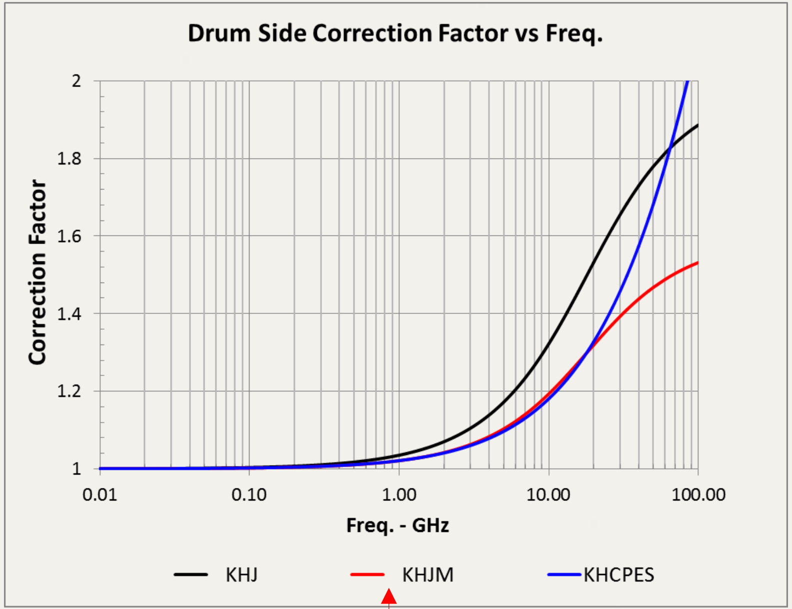
$$\boxed{K_{HJ} = \frac{P_{rough}}{P_{flat}} = 1 + \frac{2}{\pi}\arctan\left(1.4\left(\frac{\Delta}{\delta}\right)^2\right)}$$

$$\boxed{K_{HJM} = \frac{P_{rough}}{P_{flat}} = 1 + \frac{2}{\pi}\arctan\left(1.4\left(\frac{\Delta}{\delta}\right)^2\right) \times (SF - 1)}$$

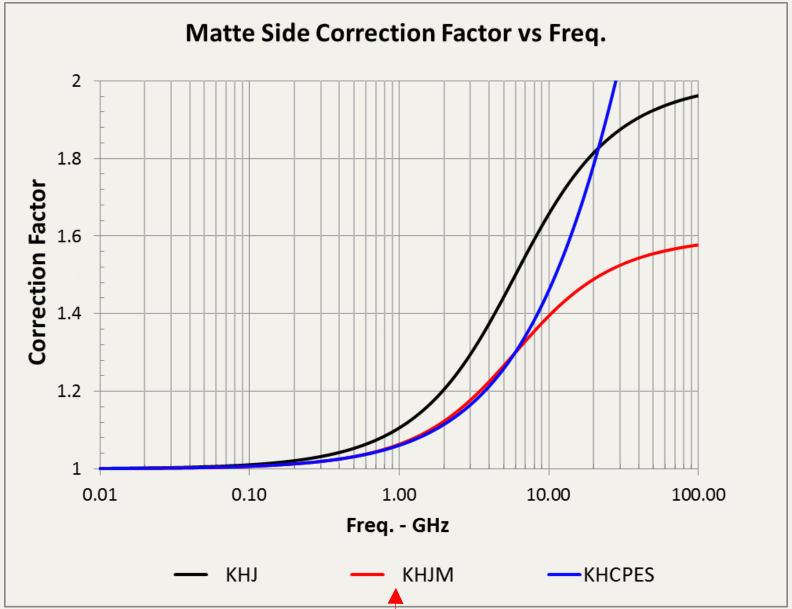
Tuned SF=1.65

$$\boxed{K_{HCPES}(f) \approx \frac{P_{rough}}{P_{flat}} \approx 1 + 66\left(\frac{\left(\frac{\pi r^2}{A_{Hex}}\right)}{\left(1 + \frac{\delta(f)}{r} + \frac{\delta^2(f)}{2r^2}\right)}\right)}$$

Correction Factor Comparisons (R_a = 1.44μm; R_z =2.5 μm)



K_{HJM} SF = 1.65



K_{HJM} SF = 1.65

Summary and Conclusions

1. Using the concept of hexagonal close-packing of equal spheres, a novel method to accurately calculate sphere size and hexagonal tile area was devised for use in the Huray model.
2. By using published roughness parameters and dielectric properties from manufacturers' data sheets, we show the need for further SEM analysis or experimental curve fitting, may no longer be required for preliminary design and analysis.
3. HCPES model looks promising as a practical alternative to previous modeling methods.

Ongoing Research

Test the HCPES model to see how well this method applies to other material and copper roughness

References

[1] S. Hall, H. Heck, “Advanced Signal Integrity for High-Speed Digital Design”, John Wiley & Sons, Inc., Hoboken, NJ, USA., 2009.

[2] E. Bogatin, D. DeGroot, P. G. Huray, Y. Shlepnev, “Which one is better? Comparing Options to Describe Frequency Dependent Losses”, DesignCon2013 Proceedings, Santa Clara, CA, 2013.

[3] Huray, P.G.; Hall, S.; Pytel, S.; Oluwafemi, F.; Mellitz, R.; Hua, D.; Peng Ye, "Fundamentals of a 3-D “snowball” model for surface roughness power losses," Signal Propagation on Interconnects, 2007. SPI 2007. IEEE Workshop on , vol., no., pp.121,124, 13-16 May 2007 doi: 10.1109/SPI.2007.4512227.

[4] Huray, P. G. (2009) “The Foundations of Signal Integrity”, Chapter 6, John Wiley & Sons, Inc., Hoboken, NJ, USA., 2009

[5] L. Simonovich, “Method for Modeling Conductor Surface Roughness”, Provisional Patent Application # US 61/977,138

[6] ISOLA-Group, “Copper Foil 102 Presentation”, 2012

Thank You!

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