A guide to Successful on Wafer Millimeter wave
Rf characterisation

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:: Agenda

- The need for on-wafer S-parameter Measurements
- Typical system components and station specifics
- Microwave Probes
- Probe Station Essentials
- Probe Tip Calibration
- How to Calibrate
- Device for testability
:: Why do we need on Wafer Characterisation
The need for on-wafer Characterisation?

- We want to know the true performance of the device and not the device plus package
  - De-embedding can be used but introduces additional errors and uncertainties
- We want to determine ‘known good die’ to reduce packaging cost and increase yields
  - Some RF packages can be very expensive and die yield can be low
- We want to automate the measurements
  - Being able to test wafers automatically can be cost effective and fast
Typical 110 GHz System

Vector Network Analyzer
Cables
Probes
Probe positioners
Probe station
Contact Substrate
Calibration Substrate
Calibration Software
Bias supply
Microscope
Large area linear lift positioner
:: 110 GHz Probes and Accessories

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220 GHz Probes / Waveguides
110 GHz Probe connection scheme
:: Semi-Automatic 220 GHz System
Manual 220 GHz System

- Quick release manual stage allows
- Evue microscope for rapid accurate probe set-up
- Deluxe anti-vibration table provides convenient monitor / keyboard mounts
220 GHz Probe connection scheme
Microwave Probes
:: Air Co-Planar Transition

- Probe transitions from coaxial to co-planar waveguide
- Fabricated probe tips
  - Uniform and compliant probe contacts
  - Tight Impedance control
ACP Series Probe

- Ideal for High Power
- Measurements up to 200degC
- Large 25um compliance between tips
- BeCu or W
- 15 W CW at 10 GHz
- 5 A DC current

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:: Infinity Series Probe

- Ultra Low Contact Resistance (30mΩ)
- Small Contact Area (12um)
- Improved Unsymmetrical Ground Performance
- Best Electrical Performing Probe

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Typical results: Contact resistance

Contact resistance on un-patterned aluminum averages about 30 mΩ over 5000 contact cycles at ambient.
:: New Infinity Waveguide Probe

Waveguide/flange
WR15 – 50-75GHz
WR12 – 67-90GHz
WR10 – 75-110GHz
WR8 – 90-140GHz
WR6 – 110-170GHz
WR5 – 140-220GHz
WR3 - 220-325GHz (en 2005)

SSMC bias T connector
Membrane coupon
Standard probe mount
Contact Marks on Aluminum Pads

• Reduced pad damage
• Contact marks (15 x 40 um)
• Good Tip visibility
:: Non-symmetrical Grounds

GSG pads shield like CPW

Fields terminate on backside of wafer on one side

GS pads fringe to the ground plane or chuck
Effects of Non-symmetrical Grounds

Non-symmetrical grounds can cause resonance loops even at frequencies <10GHz
Infinity Probe Tip Shielding

Coplanar probe tips do not shield from the DUT

Microstrip structure shields signal line better
110GHz Cal - ACP versus Infinity

- Much lower uncertainty due to lower mode content in Infinity Probe

InfinityCal Response

ACP Cal Response
Probe Station Essentials
MicroChamber™ Technology

- Dry, Frost Free environment
- Auxiliary Chucks
- Roll-out chuck
- Stable repeatable platen
- Top-Hat

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Shielded Environment

Shielding Technology

- EMI Gaskets
- Silver loaded slits
- Steel lens cover
- Steel top hat cover
MicroChamber™ Technology

- Completely Integrated Measurement Environment
  - FULL access to Positioners, Stage and Microscope
  - Roll-out stage – Complete chuck, not just top layer
    - Easy, fast & safe wafer loading
RF & DC Cabling

- Triax connection panels
  - Easy power supply connections
  - Cable strain relief
- Gore\textsuperscript{tm} RF cables
  - Low Loss
  - Phase stable
  - Flexible
- N5250 110 GHz pna has in-built triaxial bias tees as option
- Waveguide Infinity probes has bias tee built in as an option
Evue Microscopy

- Alignment of probes for mmw work is extremely important.
- Accuracy better than 5 um required.
- Simultaneous view of high and low magnification helps ensure safety of valuable mmw probes.
- Auto z helps ensure that repeatable contact is maintained on warped thinned wafer.
:: Evue – three simultaneous views
:: Evue – Positioning assessment
:: Evue – device identification
Evue – Auto xyz

- Auto xyz assesses contact X/Y/Z changes die by die using evue
- Wafer profiling automatically profiles the whole wafer using evue in a single one time operation prior to test
Probe Tip Calibration
:: Principle Calibration Techniques

- SOLT  Short Open Load Thru
- SOLR  Short Open Load Reciprocal
- LRM   Line Reflect Match
- LRRM  Line Reflect Reflect Match
- TRL   Thru Reflect Line
Uncorrected VNA

**S11 Magnitude**

- **Average > -10dB**
  - 10db > $S_{11}$
  - Load

- **Similar to Open & $S_{21}$**

**S11 Magnitude**

- **Similar to $S_{11}$ & $S_{22}$ Open/Short**

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General PNA Recommendations

Signal-to-noise ratio degrades calibration

- Use $\leq 300\text{Hz}$ IF bandwidth with no averaging
  - Can be increased after calibration
- Use high RF Power
  - Stay within DUT linear output limits
- Use the least amount of necessary attention
  - Port 1 normally $\leq 10\text{dB}$ for SS gain devices
  - Port 2 normally Zero for SS gain devices
- Use shortest possible low loss cables
  - Gore is best

Maintain constant temperature
:: SOL 1-Port Calibration

Only calibration technique
Works on all PNAs
PNA front panel supported
  Requires PNA cal kit
WinCal supported
Requires rigorous definitions
SOLT 2-Port Calibration

Works on all PNAs
Oldest calibration technique
PNA front panel supported
  Requires PNA cal kit
WinCal supported
Requires rigorous definitions
Looks best after calibration
Less accurate than LRM & LRRM
SOLT Calibration

All standards must be perfectly known
- Available every vector network analyzer (CalKit required)
- Open has capacitance (often negative)
- Short and load have inductance

Sensitive to probe placement
Mathematically over-determined
Unpredictable behavior
:: SOLT Calibration Results

All standards match their cal kit definitions
Even bad standards will look good
Must verify with other devices

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:: SOLT Calibration Results

Open stub
- Not centered on the Smith chart
- Lines crossing

S21 always exhibits ripple
- Bad artifact of the SOLT cal
:: SOL-R 2-Port Calibration

Works on PNAs
Not PNA front panel supported
WinCal supported
Requires no THRU definition
Recommended for dual probes, right angle probes & probe cards
**SOL-R Calibration**

### Short-Open-Load-Reciprocal Thru

- Reciprocal Thru requires only $S_{12} = S_{21}$
- Tolerant to lossy or highly reactive insertion standard
- Convenient for use with fixed probe spacing in probe cards
- Does not require a custom Thru
- Convenient for use when DUT terminals are orientated at $90^\circ$
- Available in WinCal (not front panel)
SOL-R Calibration Results

Short, Open & Load match the SOL definitions
:: SOL-R Calibration Results

Open Stub
Not centered on the Smith chart
Lines are crossing

S11
A:\SOLRstub.s2p
10-25-2001 22:25:01
Thru is least accurate of all calibration types

Best method for right-angled probing and probe cards
Right Angle Measurements

Carefully constructed right angle ‘Thru’ standard
Thru is non-ideal, large dip at 20 GHz
Errors in standard cal’s
SOLR immune to Thru errors
:: TRL 2-Port Calibration

Preferred by engineers for on-wafer microstrip embedded devices

- Cannot realize 50 Ohm lines exactly

Most popular for mmW GaAs

Hard to get broadband standards

- Dispersive below 5 GHz
- Long lines require too much wafer real estate
**TRL/LRM Calibration**

**Thru-Reflect-Line**
- Requires least info about standards
- S-parameters referenced to line Zo
- Reference plane at center of Thru
- Requires multiple probe spacings
- Zo is inherently complex at low frequencies
- Not suitable for fixed spacing probes (e.g., probe card)

**Line-Reflect-Match**
- Referenced to Zmatch
:: TRL Calibration Results

All standards exhibit large anomalies
:: TRL Calibration Results

Open stub is well centered on the Smith chart
No lines are crossing
:: TRL Calibration Results

Thru line exhibits excessive loss
TRL Measurement Problems

Very poor below 5 GHz
Propagation not constant for thin film structures

Apparent dispersion of a lumped element
:: TRL Measurement Problems

Discontinuities at the delay line definitions

**: S11 Magnitude**

A:\TRL.40pS.s2p
10-25-2001 14:57:02

[Graph showing S11 Magnitude with dB vs GHz]
:: LRM 2-Port Calibration

Works on all PNAs
PNA front panel supported
  Requires VNA cal kit
WinCal supported
  Automatic load inductance enhanced
Better than SOLT
:: LRM Calibration Results

All standards have visibly small anomalies
Results approximate SOLT cal definitions
:: LRM Calibration Results

Opens from LRM (open – load) exhibit non-linear characteristics
Opens from LRM (short – load) introduce additional ripple
Recommend LRM (open – load)
Open Response After LRRM/LRM Calibration – ACP Probes
Open Response After LRRM/LRM Calibration – Infinity Probes

Almost ideal
2 to 10 X better than ACP or GGB
SOLT always yields perfect response
:: LRM Calibration Results

Open stub is well centered on the Smith chart
No lines are crossing
:: LRM Recommendations

Best PNA front panel cal
   Does not require WinCal
Gives better results than SOLT
   Less fine grain ripple artifacts
   Less sensitive to probe placement errors
WinCal LRM open-load with automatic load inductance
   Better than PNA front panel LRM
Cascade Microtech Calibration Research
Line-Reflect-Reflect-Match Calibration

- TRL only Match acts as infinitely high loss line
- One transmission line standard only allows fixed probe spacing calibration
- Thru (line) delay, Match resistance must be known
- Measurements referenced to trimmed resistor
- Required measurement of only one load standard
- Patented load inductance compensation
- Uses off-wafer standards (ISS)
  - Same standards as SOLT only no need for cal kit
- Available in WinCal only (not front panel)
LRRM Requires only 1 Load

Easier to put standards on the wafer

- Only the dc (kelvin) resistance required
- LRM requires two matched loads
NIST Verification

System drift baseline
LRRM compares with system drift limit
  best fixed probe position calibration
SOLT / LRM
growing error w/ freq
  possible CalKit error
  possible ref plane error
How repeatable is my calibration?

LRRM automatic calibration is VERY repeatable

10 LRRM calibration verifications using NIST Verify software

0.3% Spread
How does a manual calibration compare to an automatic calibration?

Worst Case Accuracy to 40GHz

Four Manual Calibrations

15% Error - 10% spread

Ten Semi-Auto Calibrations

5% Error - 0.3% spread

Semi-auto Prober is faster and far more repeatable!
How repeatable are the calibration standards?

10 Different LRRM calibration verifications using NIST Verify software

3% Spread

Impedance Standard Substrate Standards are very repeatable
:: Which Calibration Technique is Best?

SOLT
All Hi-Q measurements <20GHz
Most measurements requiring attenuation
Most measurement < -10dBm input power

SOLR
All probe card applications
All dual signal probe applications
Right angle probe applications
:: Which Calibration Technique is Best?

**LRM (with auto load inductance)**
- Most accurate attenuation measurements
- Some on-wafer standards

**LRRM (with auto load inductance)**
- Best for broadband mmW transistors
- On-wafer standards with a single load

**TRL**
- Microstrip mmW device characterization
- Waveguide banded measurements
- III-V on-wafer mmW microstrip standards
:: Impedance Standard Substrate

W-band Impedance Standard Substrate
(Pitch: 75 μm – 150 μm, Configurations: Ground-Signal-Ground)
P/N: 104-783 ; S/N: 832221 899054

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Absorbing ISS holder

- Measurements > 50 GHz, unwanted modes are excited
- Microwave absorbing ISS holder reduces unwanted modes (PN 116-344)
  - Ideal for LRRM, LRM & SOL-R calibrations
- ISS enhanced for CPW transmission mode – thinned to 10 mils (PN 104-783)
How to calibrate
How to calibrate

- Ensure that the probes are in place
- Clean and connect the cables and torque using relevant wrench
  - Use IPA and swab to clean connectors and allow to dry
- Visually inspect the probe tips and clean if contaminated
  - Use IPA and swab, brushing away from the probe body and allow to dry for ACP
  - Use probe clean for Infinity
- Planarize the probes on the Contact Substrate inspecting the probe marks for even GSG contacts
  - Adjust the positioner planarity until all tips make even contact
Planarizing the Probes

- **Contact Substrate**
  - PN 005-018
  - Dull gold finish
  - Bright contact marks

- **Adjust planarity until equal marks from all probe contacts**
ISS Alignment Marks

- **Sets probes overtravel & spacing for calibration**
- **Initial Contact (zero overtravel)**
  - Line the edges of the probes to edge of flags
  - Center the contacts with X & Y micrometers
- **Final Contact (2 –3 mils overtravel)**
  - Tips lined up with flag centers
  - Center the contacts with Z micrometer only

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WinCal XE

Tools for the novice
- Guided Wizards
- Multi-media Tutorials
- Intelligence in setups

Tools for expert
- Enhanced verification
- Real time measurement validation
- Enhanced reports
System Setup

- Measurement System Setup
  - Define the measurement system
    - VNA, prober, ISS and probes
  - VNA Qualification
    - Test that the VNA is functional and repeatable
  - Probe Qualification
    - Check that the probe is making contact
    - ISS management
    - What structures to use
    - Is a structure good?
:: Using Wincal XE to Prepare the calibration

- Important to initialise instrument settings paying attention to power, number of points, Start and stop and particularly IF bandwidth
:: Probe Set-up

- Probe characteristics are displayed both graphically and numerically. Probes can be identified by serialisation.
- Probe data required to check calibration compatibility and where necessary provide lumped element data.
ISS Set-up for Auto calibration

- Individually serialised iss data can be loaded
- This information is important to keep track of correct iss for calibration and determine location of alignment structure
ISS Alignment structure location

- ISS Reference location determines the correct orientation and alignment of the probes with respect to the entire ISS.
- A similar tool is used to inform the software of damaged or untrimmed locations.
:: Automatic Calibration
Calibration Procedure

- Automatic calibration will use the prober to automatically move from standard to standard
- On pressing autocal the procedure is as follows
  - Repeatability check measures raw open multiple times in order to check the system is repeatable (often picks up problems relating to cabling, system directivity, Excessively high If bandwidth)
  - Calibration moves though all standards for the calibration, computes calibration and sends to instrument
  - Verification will look at a verification standard to compare against known values (typically an open)
  - Monitoring measurement will store data for future checks against system stability (is cal still good)
:: Repeatability Check

Wincal measures open to check repeatability of measurement system
:: Calibration measurements for LRRM - Thru
Calibration measurements for LRRM – Open

- System re-measures open for the calibration. At times the open measurement uses substrate opens hence the need for re-measurement

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Calibration Measurements for LRRM - Short
Calibration Measurements - Load

- It is important that only 50 ohm loads are used for this part of the calibration

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:: Calibration – Computation and sending of error coefficients

- Wincal applies the selected calibration to the measured data (typically we recommend LRRM) and error set is sent to the instrument
:: Calibration - Validation

Following calibration a validation is carried out against a known standard. Typically this is an open whose capacitance is known by the probe pitch, but can be a golden dut whose characteristics are pre-measured and stored. For lrrm the open is the raw open measured during the cal and corrected by the calibration (post corrected)
:: Wincal – Advanced reporting
Wincal – Advanced reporting

- Wincal can carry out advanced reporting to carry out post process mathematics “on the fly” such as parasitic de-embedding, parameter conversion and subtraction, Masons gain etc.
- Multiple page views can be created for truly versatile reporting
Wincal - Sequencing

- Sequences allow the prober and external instrumentation to be controlled by Wincal for simple automated testing.

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:: Wincal - Sequencing

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:: Wincal runs native on pna

- No need for external laptop and gpib adaptor
- PNA Can be used to control external instrumentation with Sequencing
- Only 1 external monitor is required
What defines a good calibration?

- Ideally a reflection measurement after calibration should be 0.0dB
- LRRM type calibration is self-consistent and will never look perfect as it will show any errors as a magnitude on a reflection measurement
- A guide would be to ensure that the magnitude of the reflection error is less than 0.1dB for measurement to 67GHz and 0.2dB to 110GHz
- Note this does not apply to an SOLT or SOL calibration as these are not self consistent and will be forced to look like a perfect reflection standard
  - Independent standards will need to be measured for verification
Independent Verification

As well as re-measuring the calibration standards, other verification standards can be measured to determine successful calibration:

- These include open stubs and transmission lines
- Open stubs and lines of varying lengths are found on the calibration standards
Calibration Verification Standards

- Unity Gain
- Negative Capacitance

-Due to wave propagation being faster in air than on the Alumna substrate
Independent Verification Standards

Open stub

- Linear Phase Lag
- 50ohm to stub Z miss-match
- Fringing C at stub open end
:: Calibration Drift

- WinCal XE Calibration software has a feature called monitoring.
- Monitoring allows the user to capture calibrated reference data immediately after a calibration has been performed. At a later time, you can re-measure the previously-acquired references (by selecting Calibration>Monitor in the Calibration menu), compare the data to the reference data, and determine if any portion of the measurement system has changed. Measurements and structures used in calculating the monitoring data are listed in the Monitoring tab.
Design for testability
Design for Testability

- Do you want to test the device at wafer level?
  - If yes, you will need to have a pad layout which conforms with possible probe configurations.

- How much money do you want to spend on probes?
  - Complex designs may require an RF/Microwave probe card
  - Well designed circuits may be able to use existing probes

- Do you want to automate die-to-die testing?
  - Can a wafer map be generated to step across a wafer?
Think About Testing Before Design

- **RF Performance**
  - Pad configuration (GS Vs GSG)
  - Probe pitch
- **Ability to Physically Probe**
  - Pad size
  - Pad height
  - Distance between probes
  - Number of contacts per side
- **Calibration**
  - Paths
  - Best calibration methods
  - De-embedding devices
:: Pad Sizes

- Recommended minimum pad is 80um x 80um for ACP Probes
- Infinity Probe Allows 50um x 50um probing
- Passivation height must be considered
- Pad height variation must not exceed 25um for ACP or 0.5um for Infinity
Probe Configuration

- Whenever possible use GSG
  - Use GSG above 10GHz

- Probe pitch affects S-parameters
  - Use smallest practical pitch
    - \(1/50^{th}\) \(\lambda\) of highest frequency for GS
    - \(1/20^{th}\) \(\lambda\) of highest frequency for GSG
:: Device Pad Layout
:: Probe Pad Positioning

- RF probes should have more than 200um separation to avoid cross-talk
- All pads must be on top surface
- All grounds should be connected together
- Adjacent devices should be >500um away for mm-wave measurements (>250um for Infinity)
Maximum Probe Contacts

- The maximum number of RF & DC contacts per side depends on the type of probe used to test the DUT
  - Only 1 standard RF or DC series probe head can be mounted on each side
  - A dual signal RF probe allows a GSSG/GSGSG probe on each side
  - A multi contact RF probe allows up to 3 RF contacts, or mixed RF and DC on each side
  - RF probe cards allows many RF and DC contacts on any side (but expensive if not in production)
Calibration Repeatability

- LRRM automatic calibration is VERY repeatable

10 LRRM calibration verifications using NIST Verify software

Worst case deviation

Frequency (GHz)
Pad Parasitic Removal

- Conductive substrate increases parasitic reactance
  - Pad and interconnect capacitance and inductances become more significant during device measurement
    - De-embedding of pads and interconnects is required
- Limitations of Pad Parasitic Removal methods
  - The larger the pads and smaller the device, makes de-embedding more difficult to achieve
Measurement and De-embedding

After calibration, the measurement reference plane is at the probe tip.

What is measured is the response of the device and the parasitics associated with the pads.
De-embedding and Verification Test Structures

OPEN

SHORT

DUT

THRU
:: De-embedding dummy devices

De-embedding from OPEN and SHORT

The parasitics of the OPEN consists only of parallel elements to the DUT
- More importance for high impedance devices

The parasitics of the SHORT consists only of series elements to the DUT
- More importance for high impedance devices

Use of Z and Y correction also helps eliminate residual cal errors
De-embedding Techniques

- Open and Short ‘dummy’ devices need to be measured.
- S-parameters are transformed to Y, Z-parameters.
- The dummy devices can be subtracted from the actual device.
- The resulting Y, Z-parameters can be transformed and displayed.
- Thankyou for listening
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