Sandia National Laboratories

National Nuclear Security Administration

SAND2018-12109PE

Power Spectrum Analysis (PSA)

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Outline

Introduction

- PSA characteristics
- Off-normal biasing
- Principal component analysis (PCA)

PSA application examples

- Counterfeit detection
- Aging detection
- Monitor processing changes
- Detect changes that originate from packaging
- Detect changes due to radiation (gamma ray) exposure

Focus of recent PSA work

- Correlate PSA signals with physical analysis

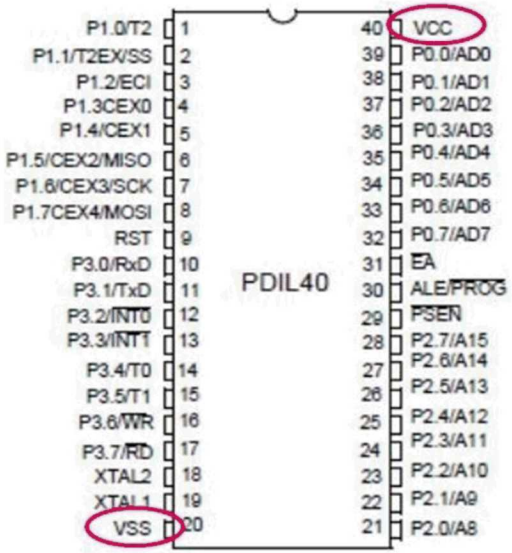
PSA Characteristics

- Non-intrusive electrical technique
  - Off-normal biasing
- Requires minimal electrical knowledge of a test device
  - Package pin layout and normal operating voltage
- Identify subtle device differences (dynamic impedance)
- Comparative
  - Standard or control sample
- Versatile
  - Can monitor die and package
- Applicable to a wide range of devices
  - Discrete, digital, analog, and mixed-signal devices
  - Capacitors, diodes, transistors, op-amps, temperature sensors, voltage regulators, microcontrollers, ASICs, FPGAs, and memory devices (e.g. SRAM, EEPROM, flash)

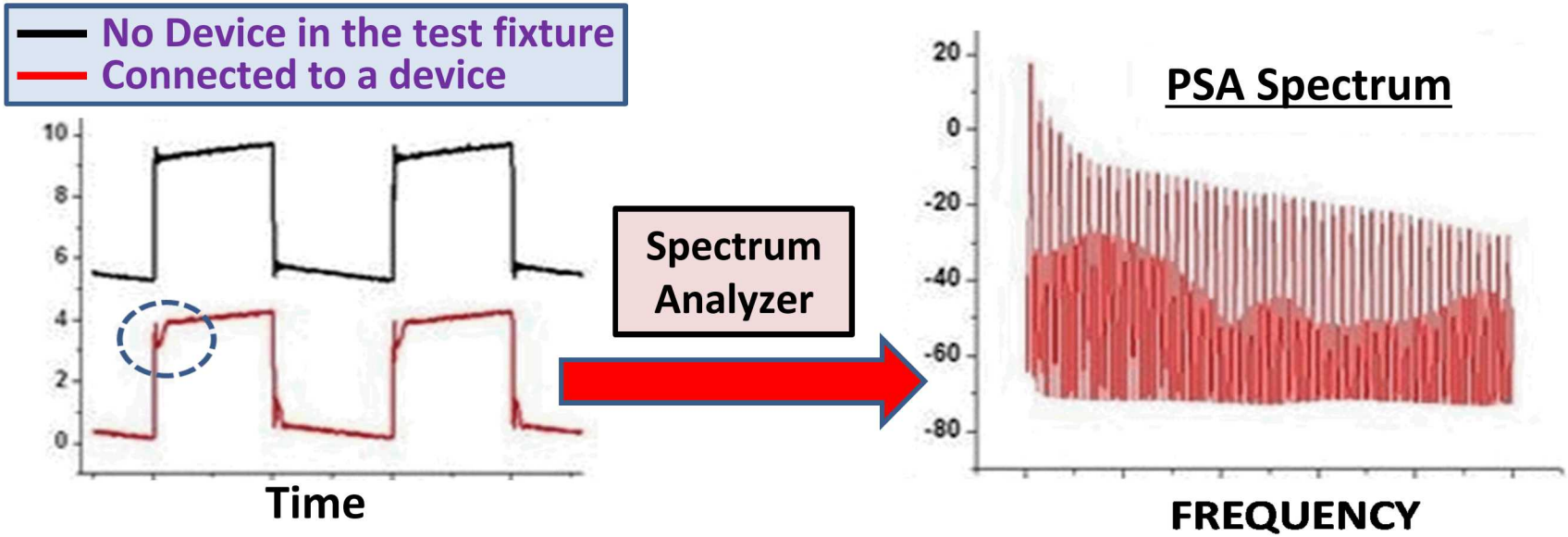
Off-normal Biasing

- Unconventional device biasing
- High sensitivity in detecting differences between devices
  - In many cases, not detectable with conventional testing
- Fast acquisition times (< 10 seconds)
- Pulse device with a periodic-waveform voltage (square wave)
  - Bias power and ground pins; all other pins floating
  - Stable frequency-domain signatures (PSA spectra)
  - Frequencies : 1 kHz to 1 MHz

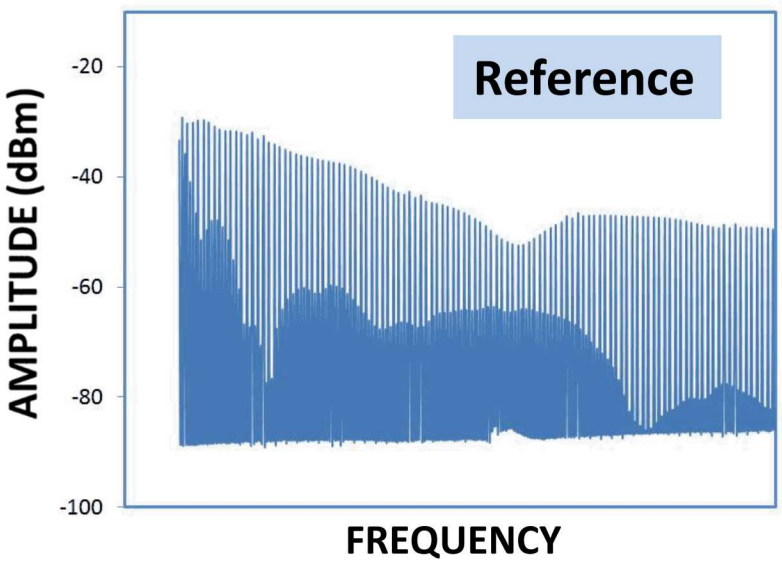
Example of Off-normal Biasing: Microcontroller

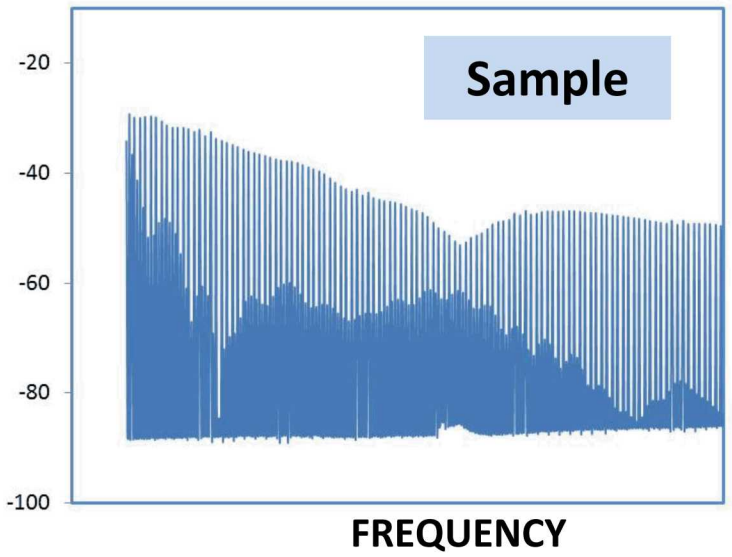


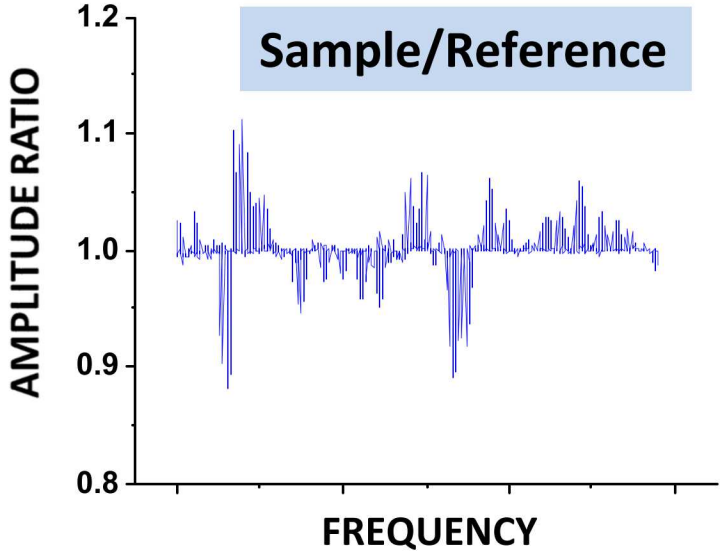
- **Pulse device with a square-wave voltage**
  - **Between V_{CC} and V_{SS}**
  - **All other pins floating**
  - **Pulse amplitude : 0 to 4.5 V**
  - **Below the normal operating voltage of 5 V**
- **A slight distortion in the voltage waveform**
  - **When connected to the device**
  - **Distinct signatures in frequency-domain PSA spectrum (measured by a spectrum analyzer)**



Normalized PSA Spectrum (Ratio Plot)



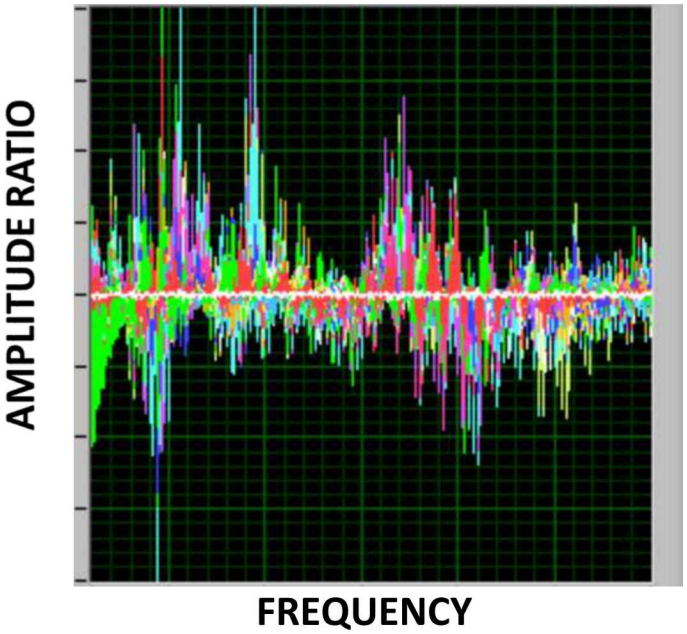




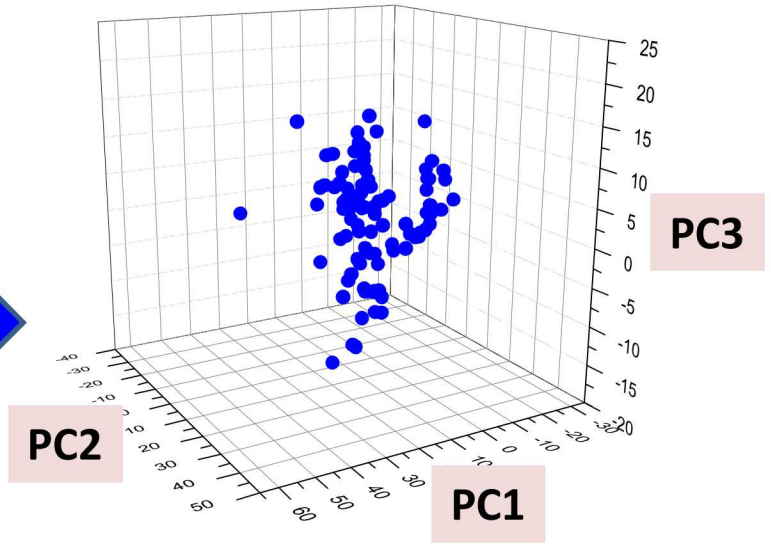
- Minimizes experimental variation effects
  - Allows comparison of data taken at different times
- Normalized spectra highlight differences

Principal Component Analysis (PCA)

- Statistical method of reorganizing information
  - A well-known technique used in spectroscopy
  - Find new variables, Principal Components (PCs)
  - Account for variability with a few Principal Components (PC1, PC2, PC3)
  - Facilitates visualization of variability in 3-D plots



PCA



- Spectra from 100 samples superimposed
- 800 points (frequencies)/spectrum
- 80,000 data points total

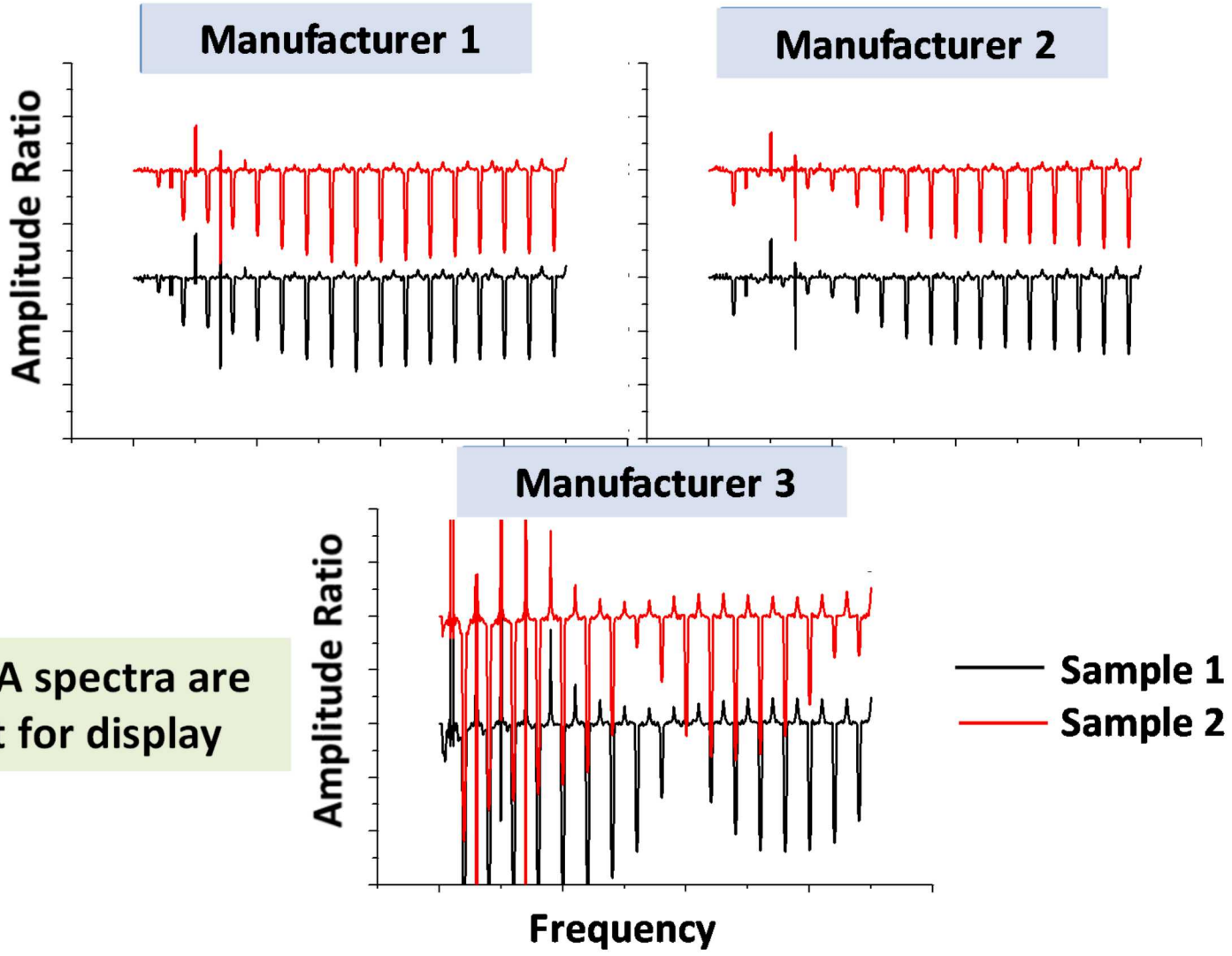
- Each PC a linear frequency combination
- Each frequency weighted differently

PSA Application Examples: Counterfeit Detection

Example 1: Differences in Manufacturers

Normalized PSA Spectra: LM20 Temperature Sensors

Normalized to the experimental setup (no device in the fixture)

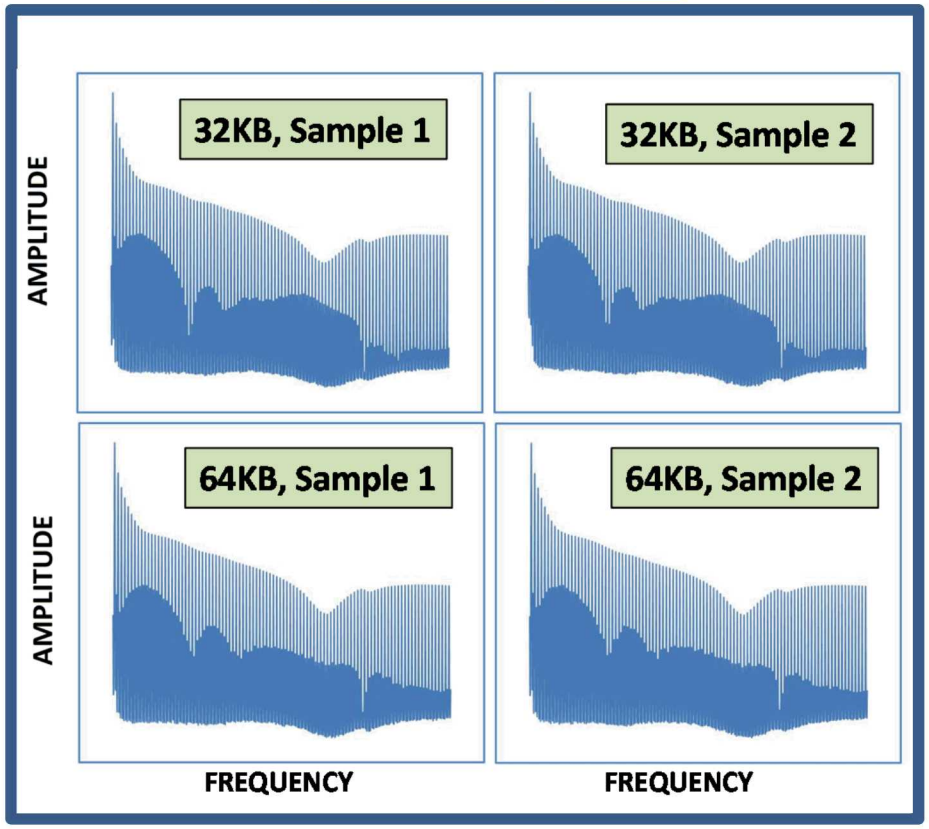


The PSA spectra are offset for display

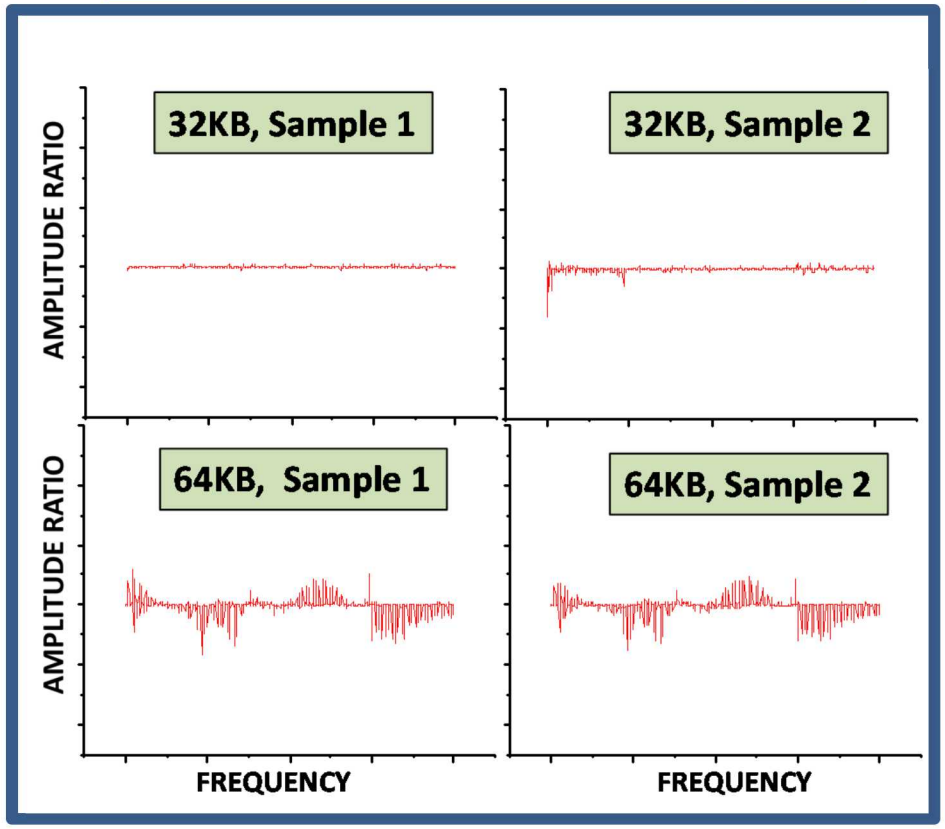
Example 2: Different Memory Sizes

PSA Spectra: NXP Microcontrollers

Raw PSA spectra

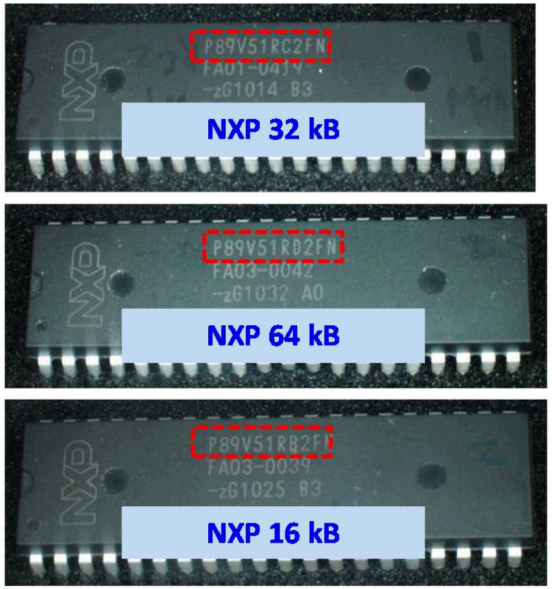


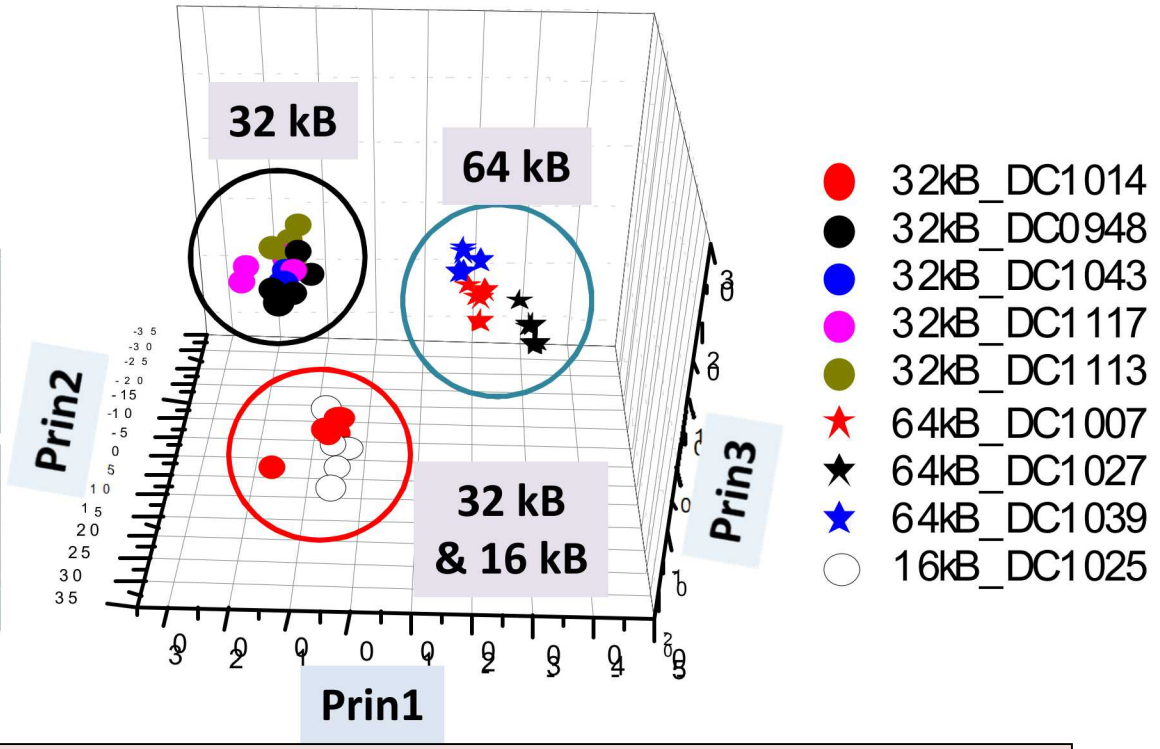
Normalized to the 32 kB sample 1



Example 3: Different Memory Sizes and Date Codes

NXP Microcontroller PCA Analysis





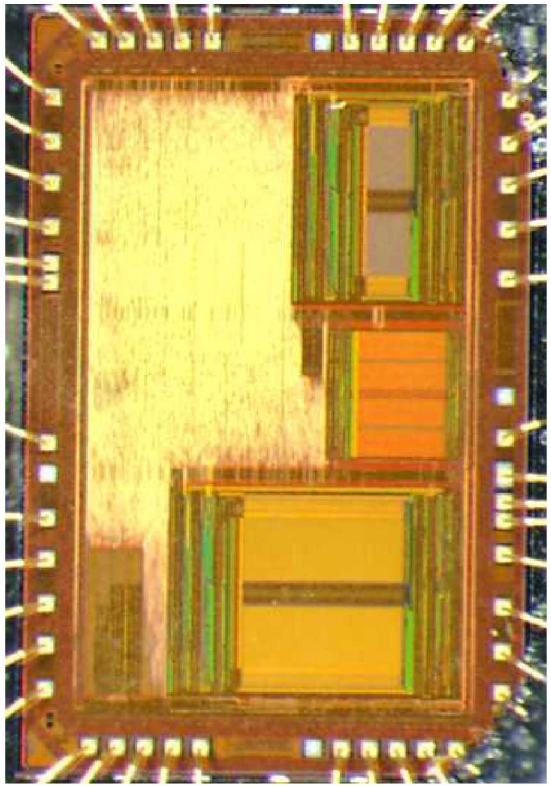
- 32 kB samples show a bi-modal distribution with samples from date code 1014 appearing in a separate cluster
- 16 kB samples lie in the same cluster as 32 kB samples with date code 1014

Example 3: Different Memory Size (32 kB versus 16 kB)

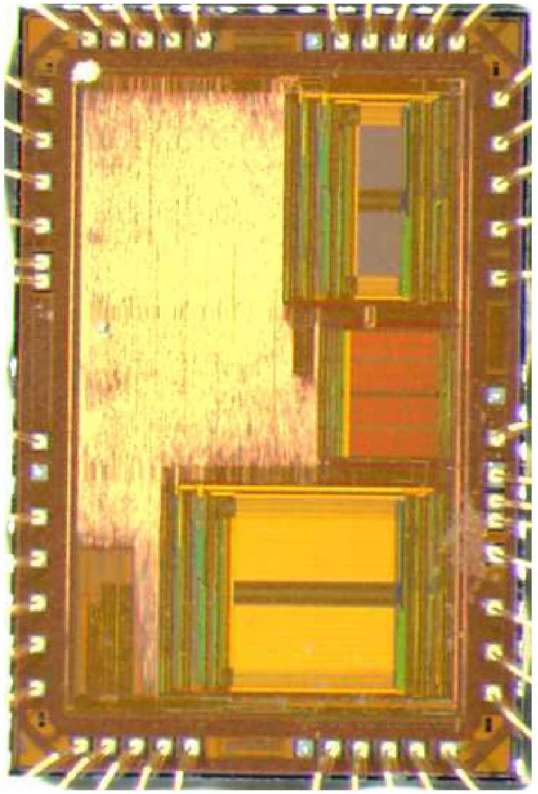
Optical Images of NXP Microcontrollers

- Same die type used for 32 kB and 16 kB
- Devices have different ID codes
- 16 kB devices can be used as 32 kB devices by ignoring the ID code

32 kB memory



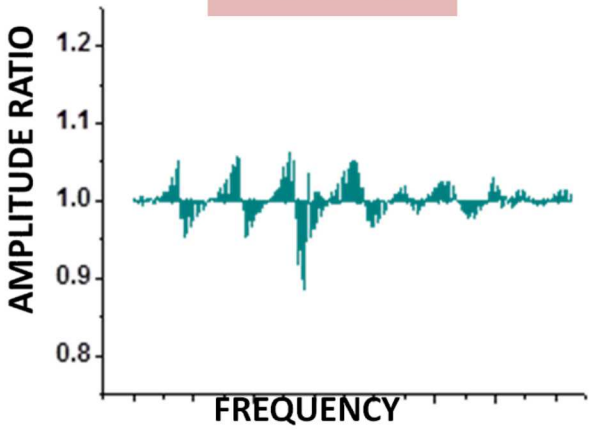
16 kB memory



Example 4: Differentiating between "Genuine" and "Suspect" XC4008E FPGAs

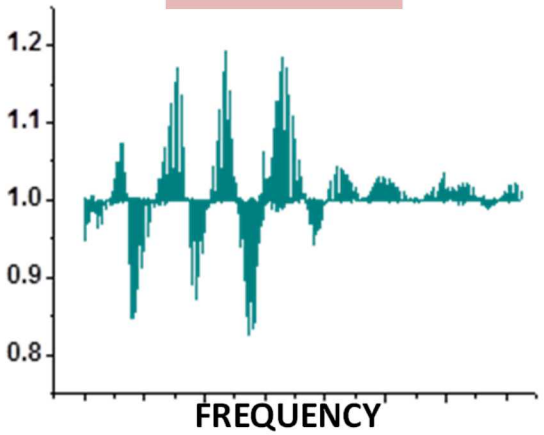
Distributor A

"Genuine"



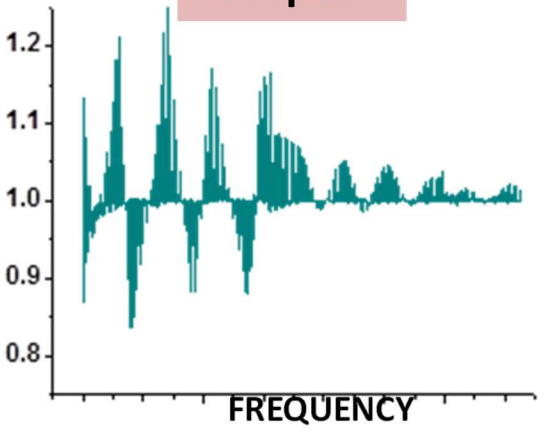
Distributor B

"Suspect"



Distributor C

"Suspect'

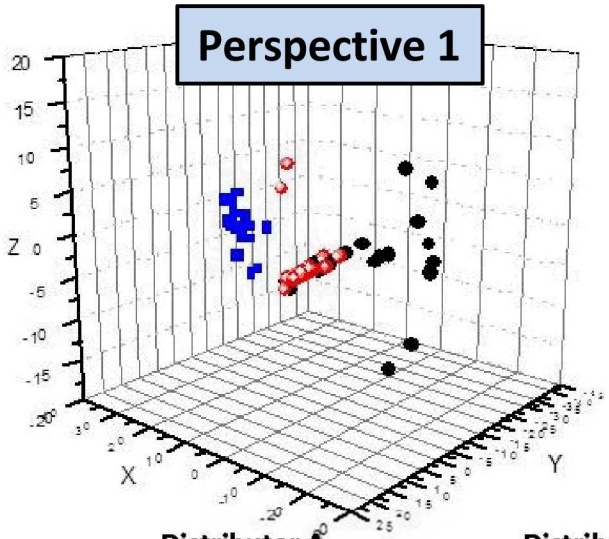


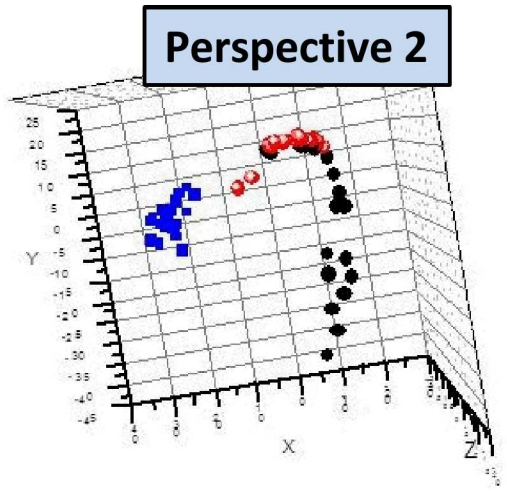
Example 4: Differentiating between "Genuine" and "Suspect" XC4008E FPGAs

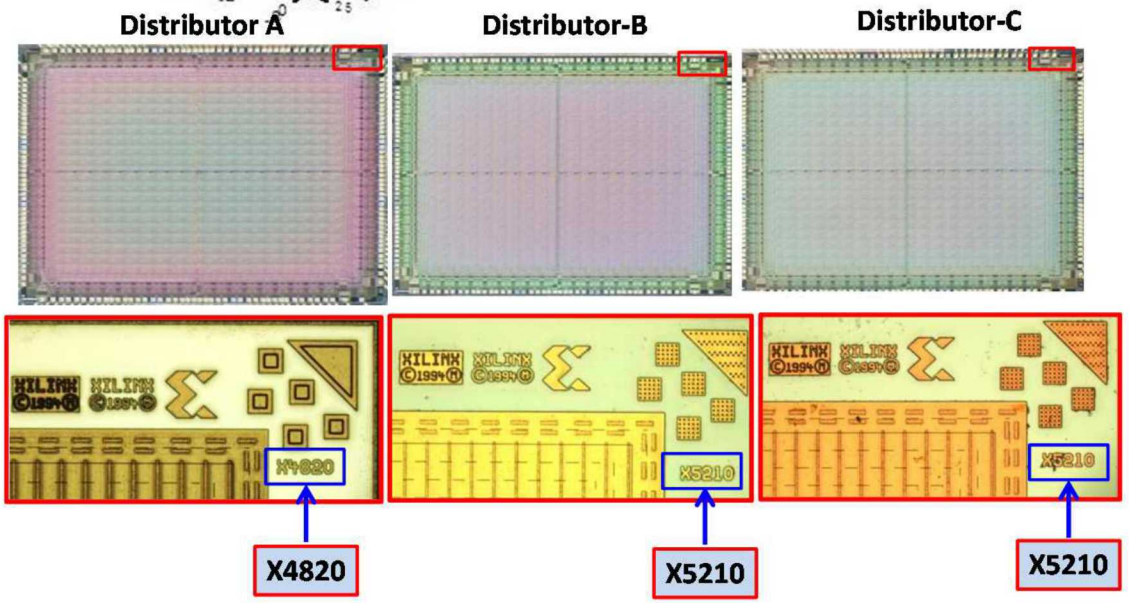
Distributor A population is separate from those of Distributor B/Distributor C

Distributor A samples have a more localized distribution

More scattering in Distributor C population



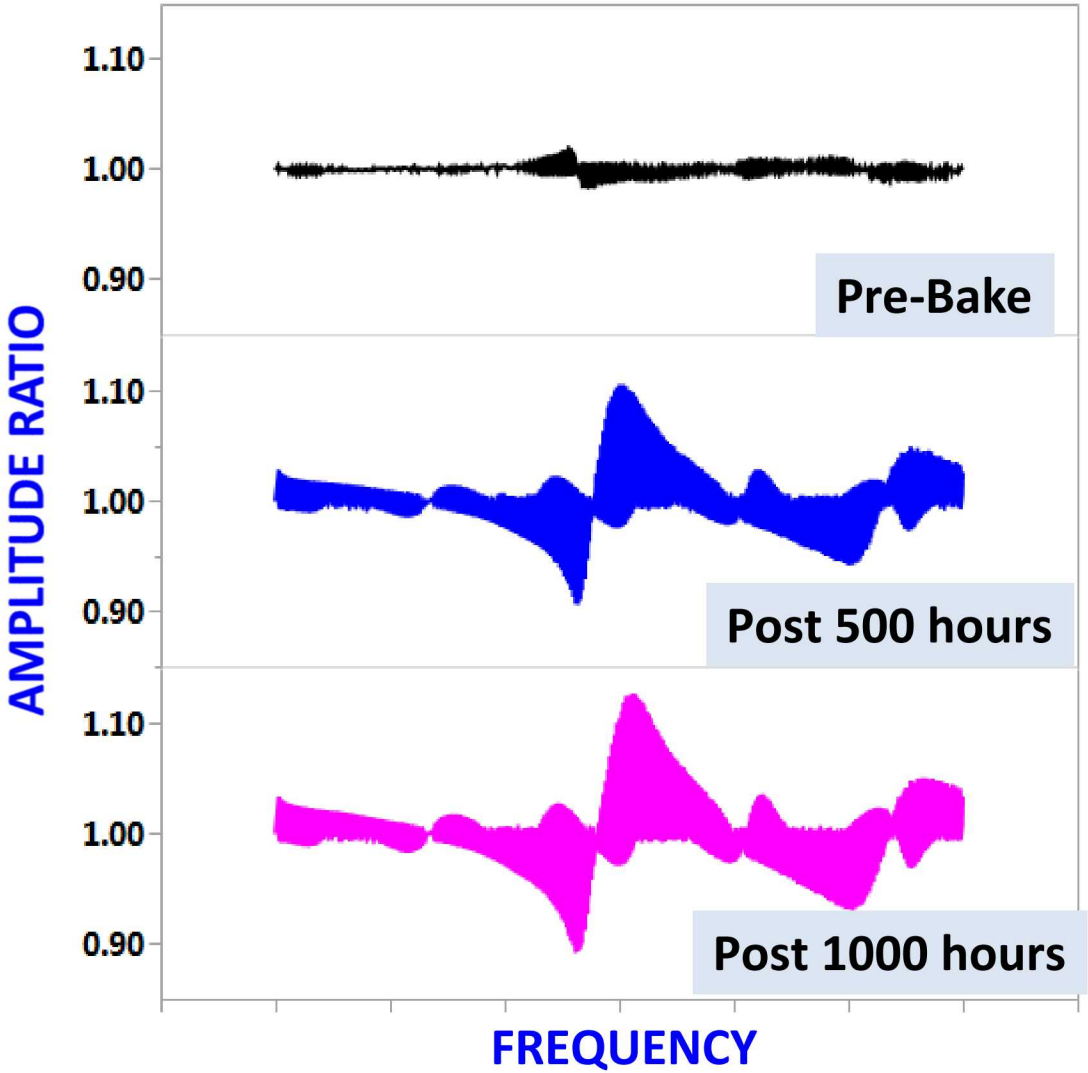




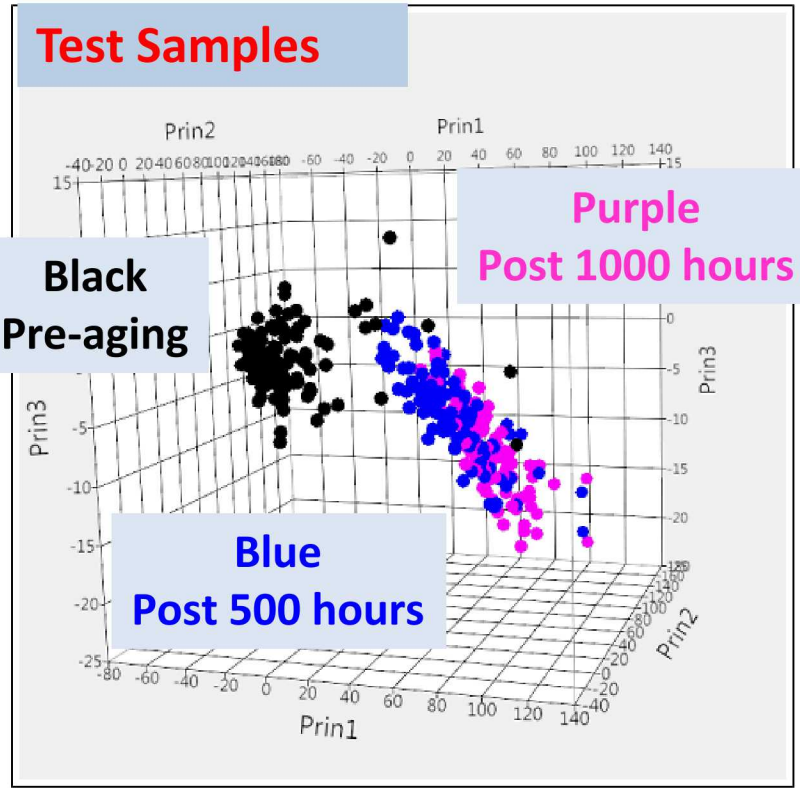
- Distributor A "Genuine"
- Distributor B "Suspect"
- Distributor C "Suspect"

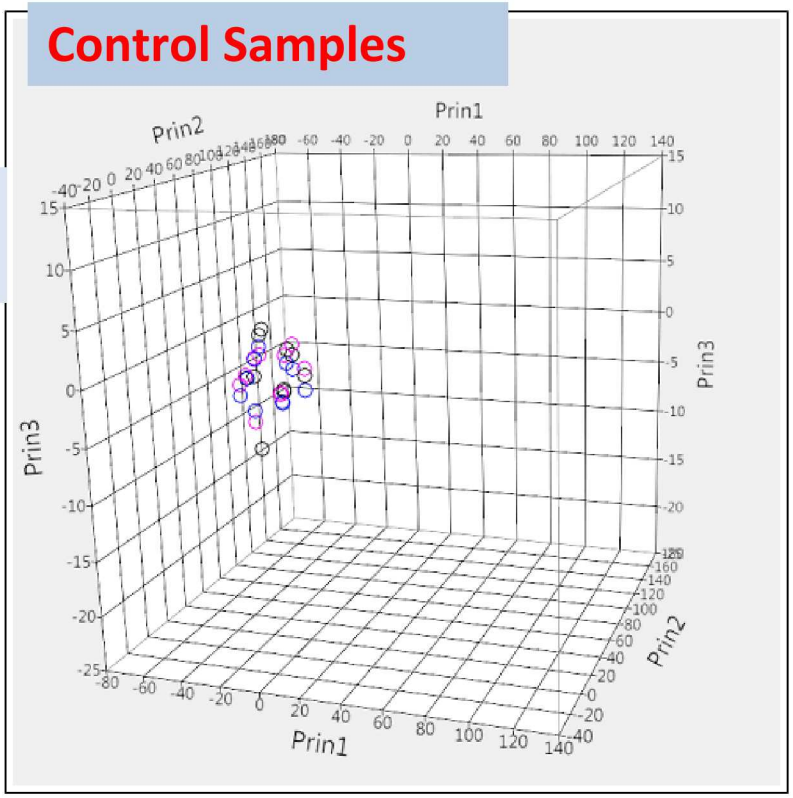
PSA Application Examples: Aging Detection

Normalized PSA Spectra of a Representative Zener Diode Before Aging and After Two Successive Unbiased 500-hour Bakes at 140 C



Aging Effects : Zener Diodes
PCA Distributions Before and After Aging



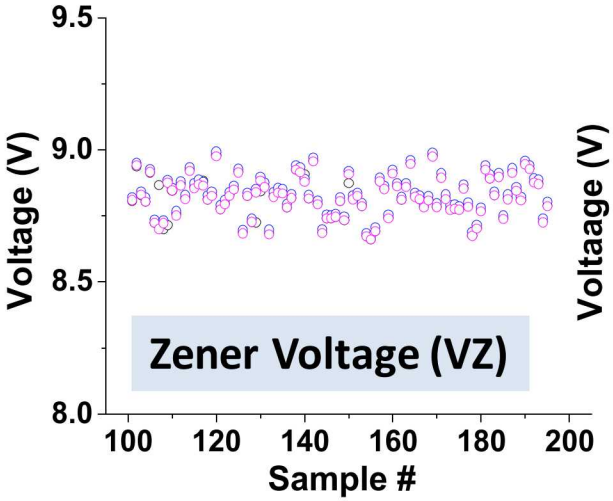


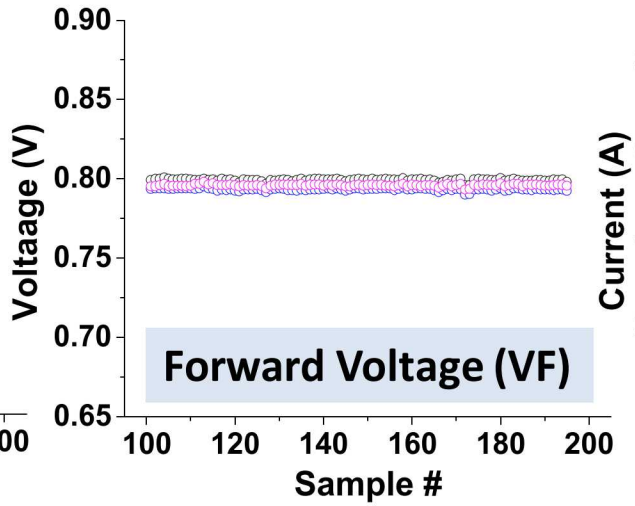
Black: Pre_Aging
Blue : Post 500 hours
Purple : Post 1000 hours
Filled Circles : Test Samples
Open Circles : Control Samples

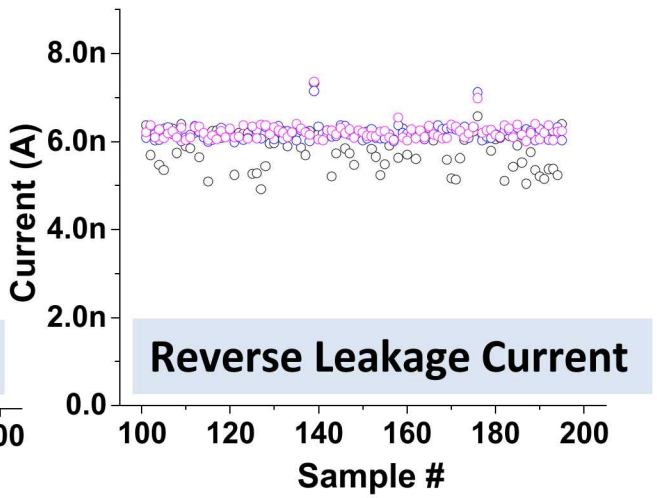
- Control samples not aged
- PSA spectra taken concurrently with the test samples before and after aging
- Demonstrates PSA system stability

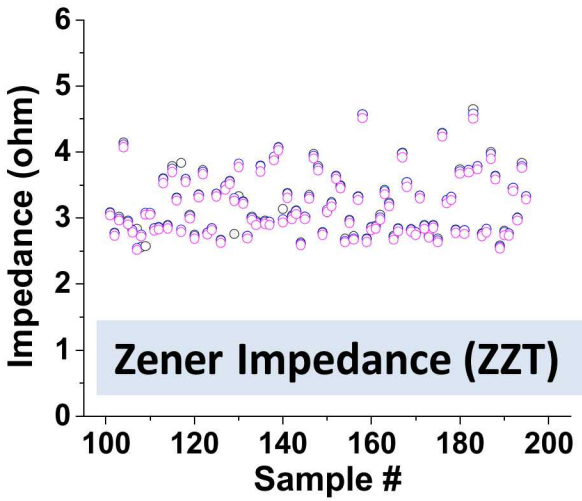
Zener Diode Electrical Test Data Before and After Aging

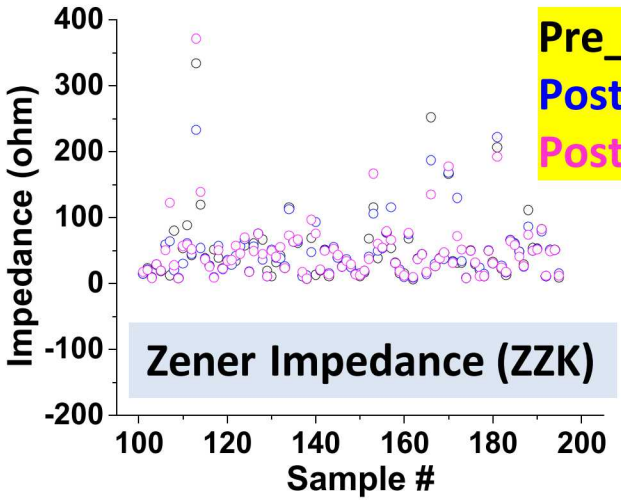
Essentially No Differences Observed









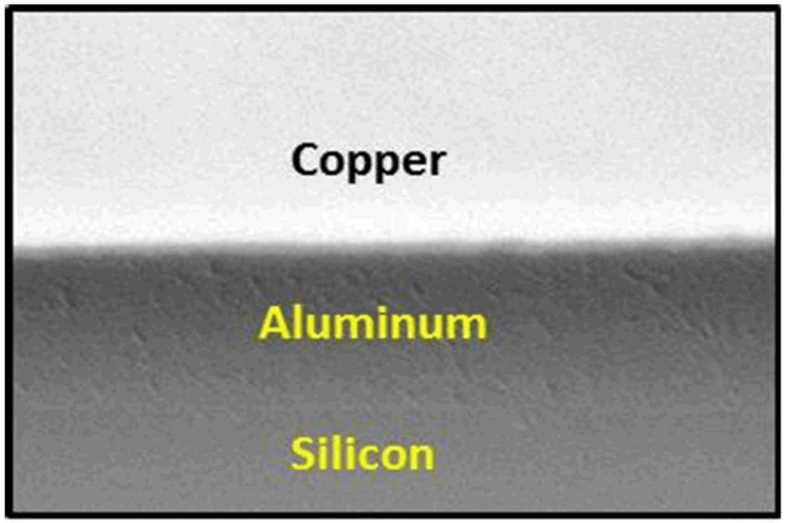


Pre_Aging (black)
Post 500 hours (blue)
Post 1000 hours (pink)

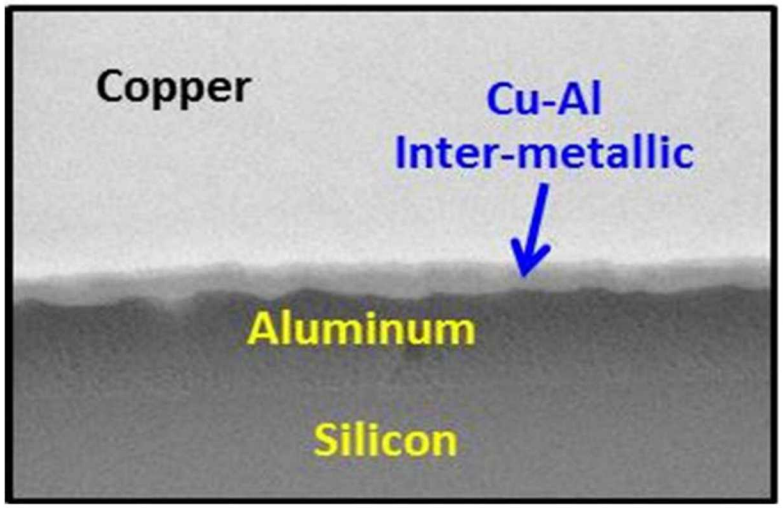
SEM Cross Sections of Bond-pad Areas
Zener Diodes

Growth of a Cu-Al Inter-metallic Layer at the bond pad after aging

Good Correlation between PSA and physical analysis results



Unaged

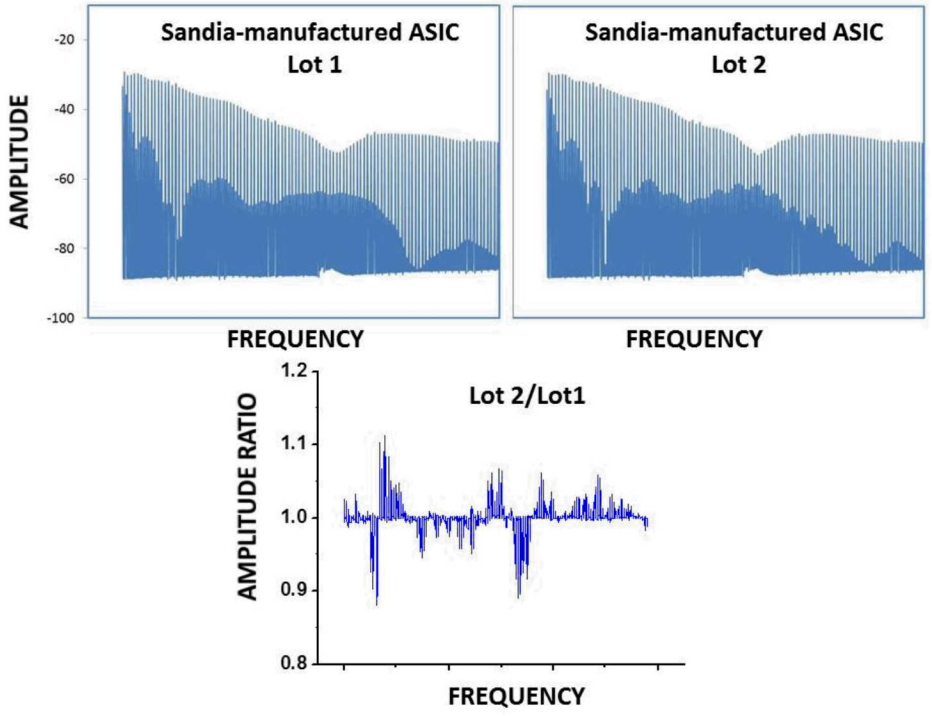


Post 1000-hour Bake

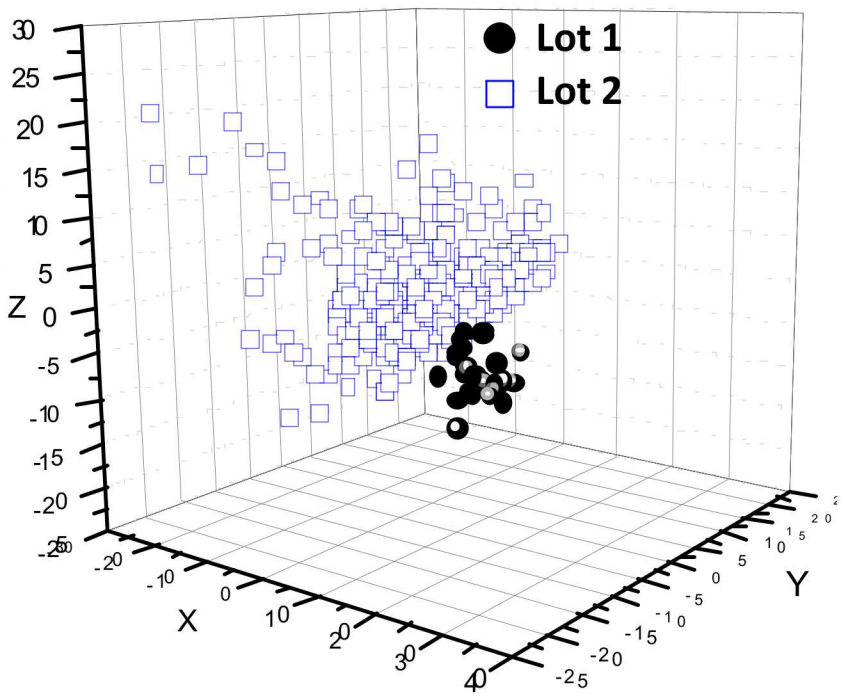
PSA Application Examples: Process Monitoring

Process Monitoring : Sandia Manufactured ASICs From Two Different Wafer Lots

Representative PSA from Each Lot



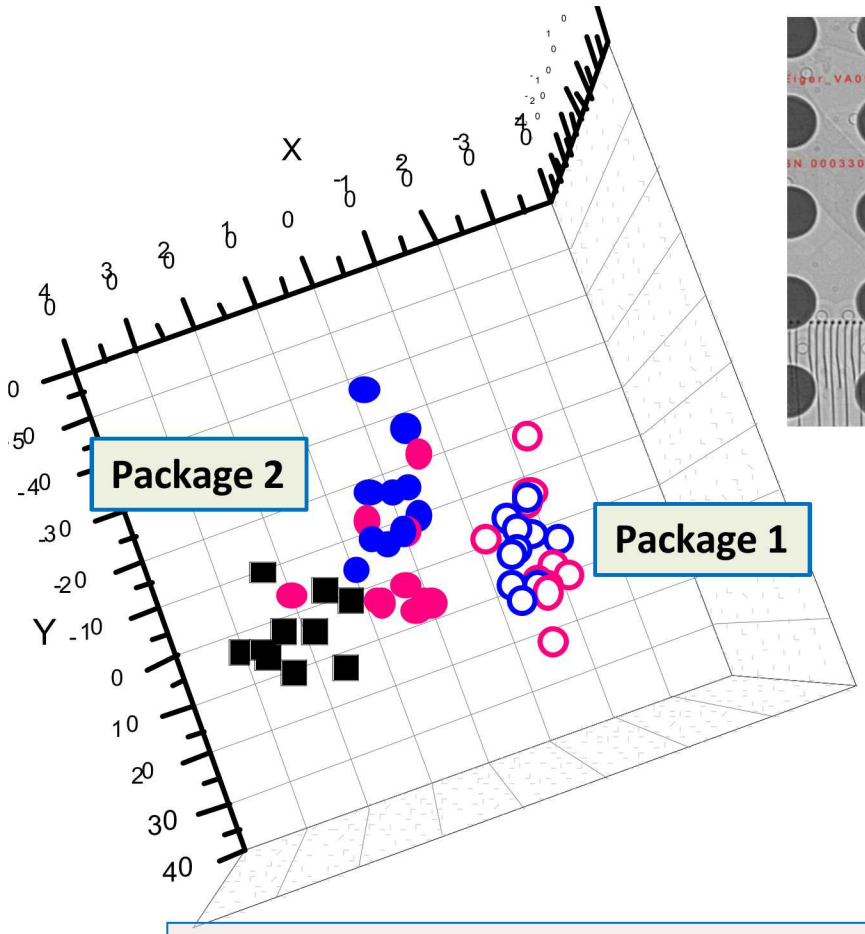
PCA Distributions



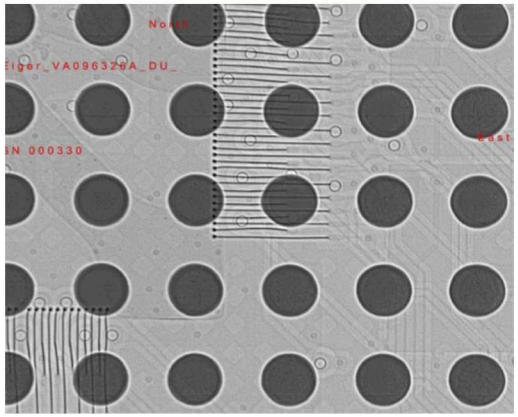
- **Differences observed in PSA**
  - Most likely the result of the differences in contact etch
  - No in-situ clean in Lot 1 versus in-situ clean in Lot 2
  - Resulting in differences in contact resistance

PSA Application Examples: Package Differentiation

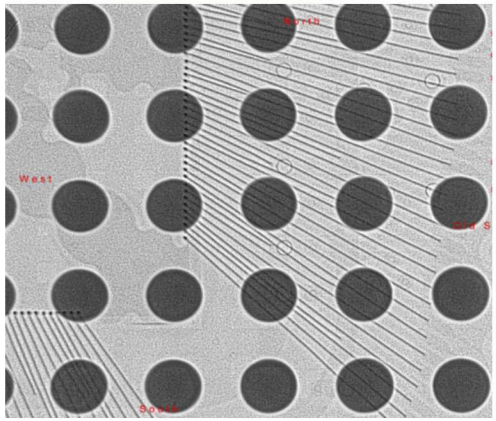
Package Differentiation
PSA Data from Sandia-manufactured ASICs



Package 2



Package 1



- Lot 1, Package 2
- Lot 2, Wafer 1, Package 2
- Lot 2, Wafer 8, Package 2
- Lot 2, Wafer 1, Package 1
- Lot 2, Wafer 8, Package 1

- Specific PSA biasing detects differences in packaging
- The parts performed identically under normal electrical testing.

PSA Application Examples: Detecting Radiation Effects

Effects of Gamma-ray Exposure

Sandia-manufactured ASICs

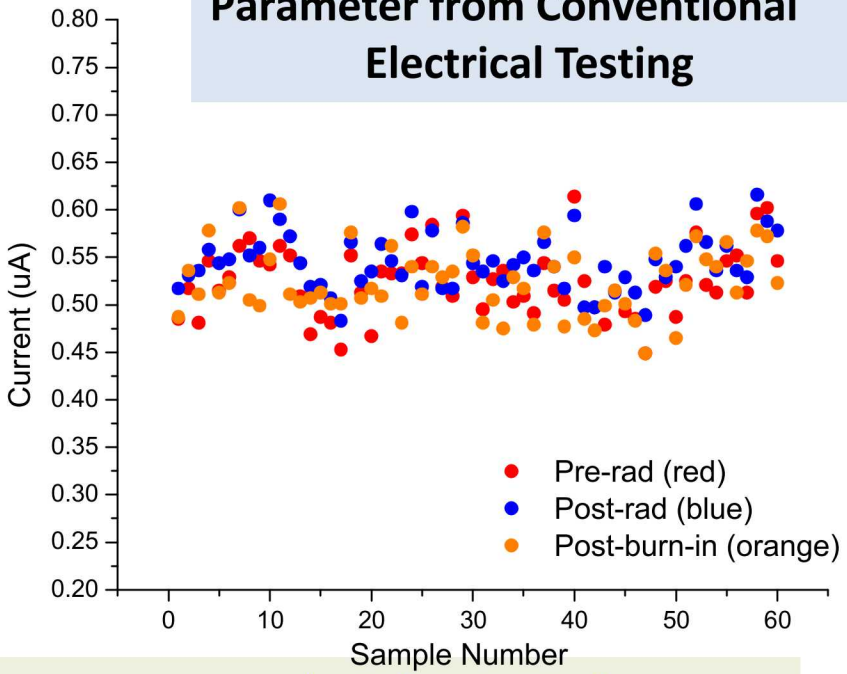
PSA Distributions of the Die

Post-rad (blue)

Pre-rad (red)

Post-burn-in (orange)

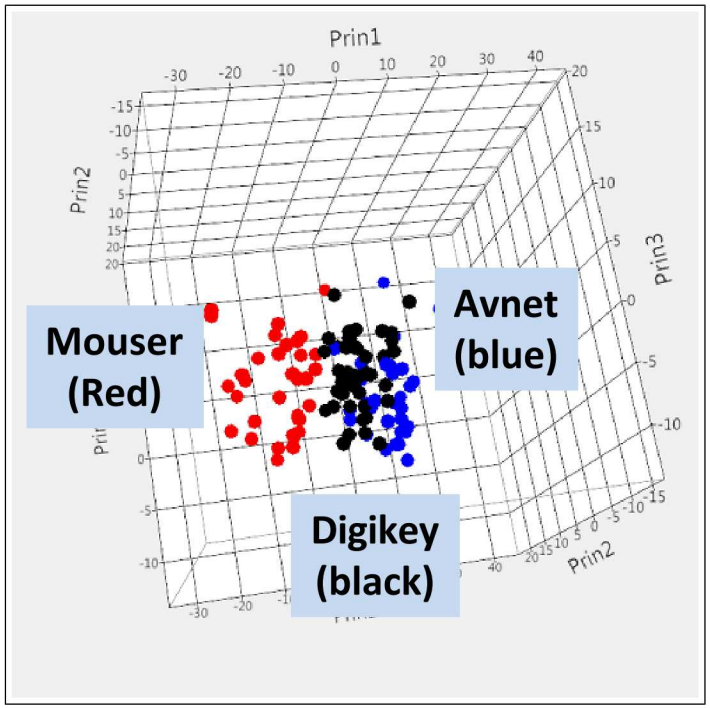
Distribution of a Representative Parameter from Conventional Electrical Testing



- PSA detects a large shift between pre-rad and post-rad populations and a small shift between post-rad and post-burn-in populations in the die of the samples.
- Virtually no shift in distributions is observed with conventional electrical testing

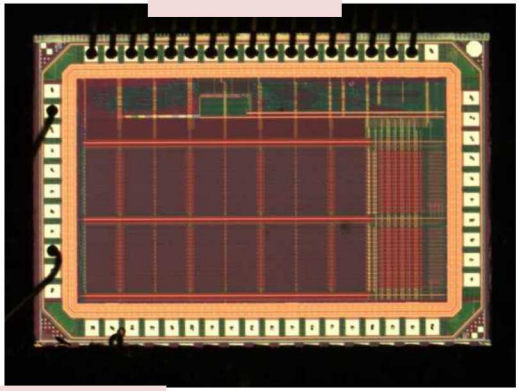
Focus of Recent Work:
Correlation with Physical Analysis Data

Example 1 : Ferroelectric Random Access Memory (FRAM)
Correlations between PSA and Optical Inspection



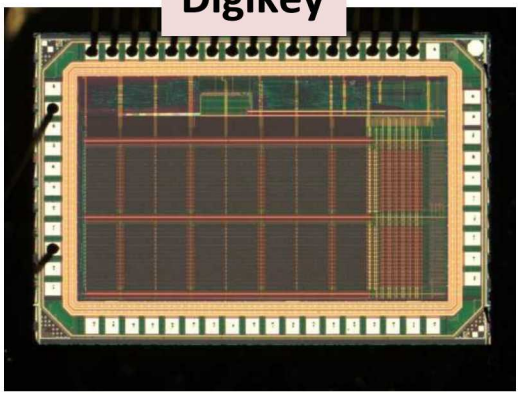
Correlation between
PSA data and optical imaging
(different colors in the arrays of the die)

Mouser



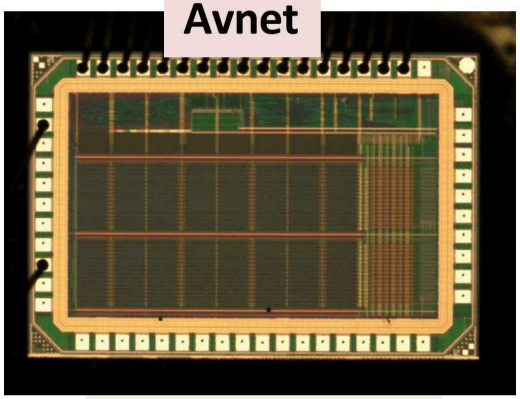
Mouser
"Reddish"
Date Code 1537

Digikey



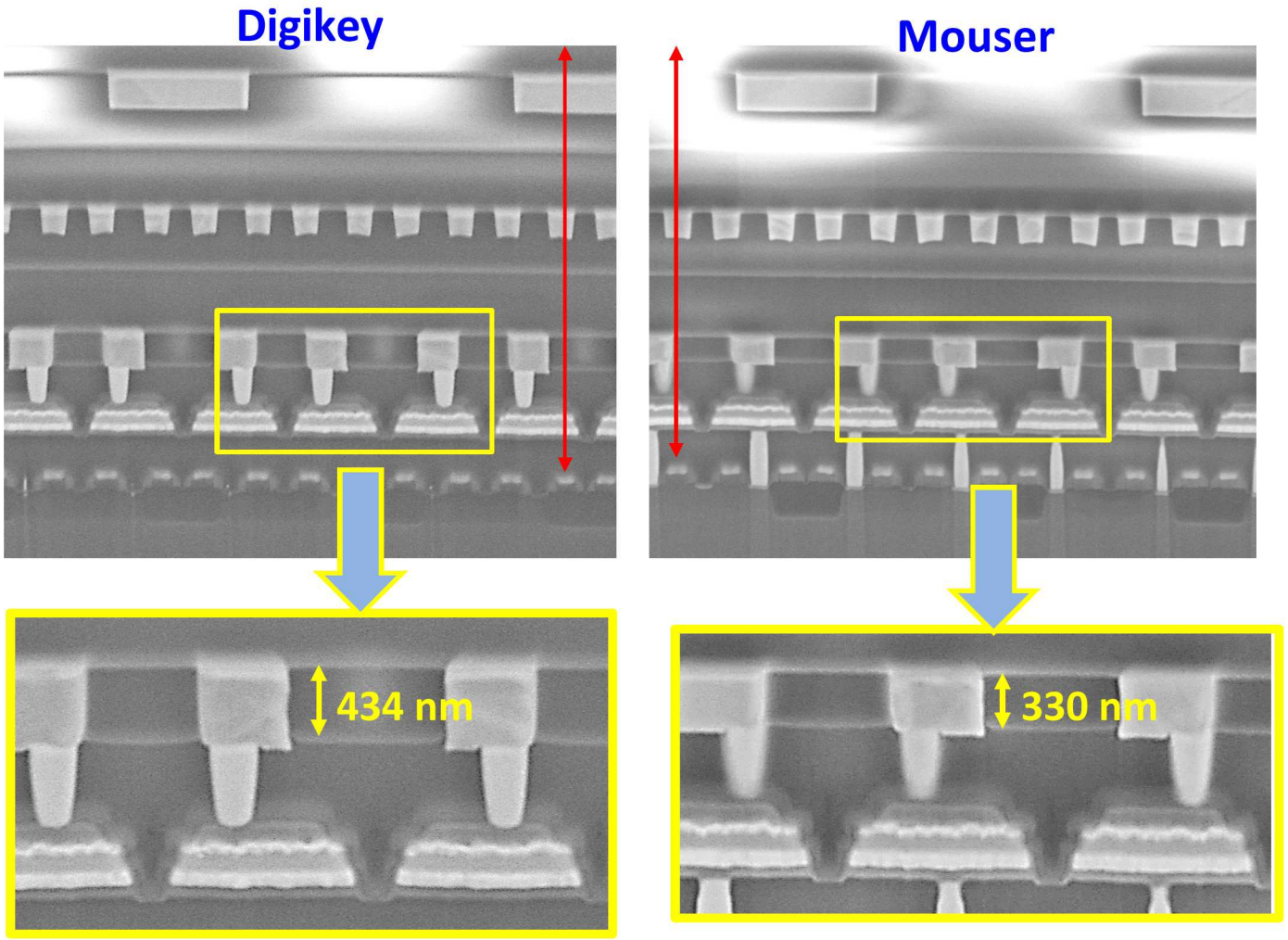
Digikey
"Greenish"
Date Code: 1607

Avnet



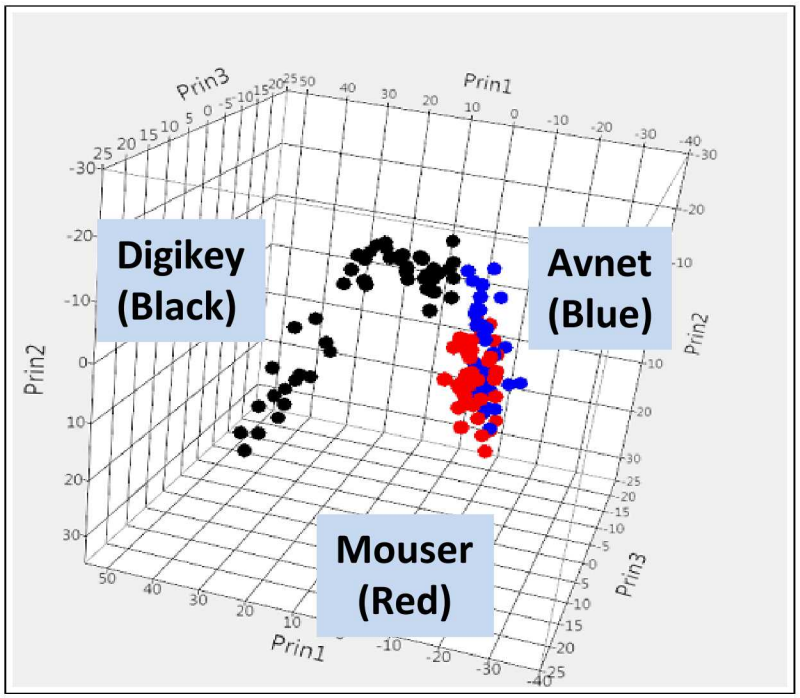
Avnet
"Greenish"
Date Code 1625

Example 1: FRAM Ferroelectric Die
SEM images of FIB Cross Sections of

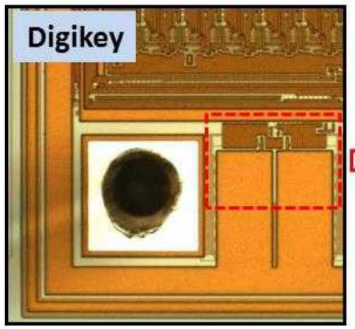


Correlation between PSA data SEM imaging of FIB cross sections
(Different metal and dielectric thickness (denoted by red arrows)

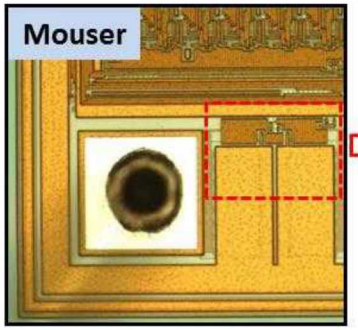
Example 2 : Electrically Erasable Programmable Read-only Memory (EEPROM) Correlations between PSA and Optical Inspection



Correlation between PSA data and optical imaging (different colors in the metal lines)

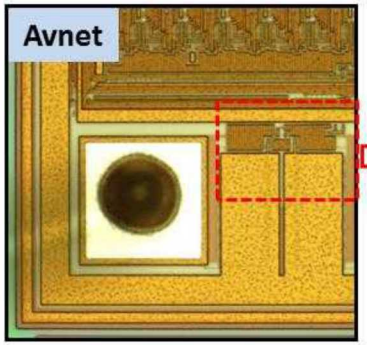


Date Code: 1625



Date Code: 1636

"Grainy" Metal Lines

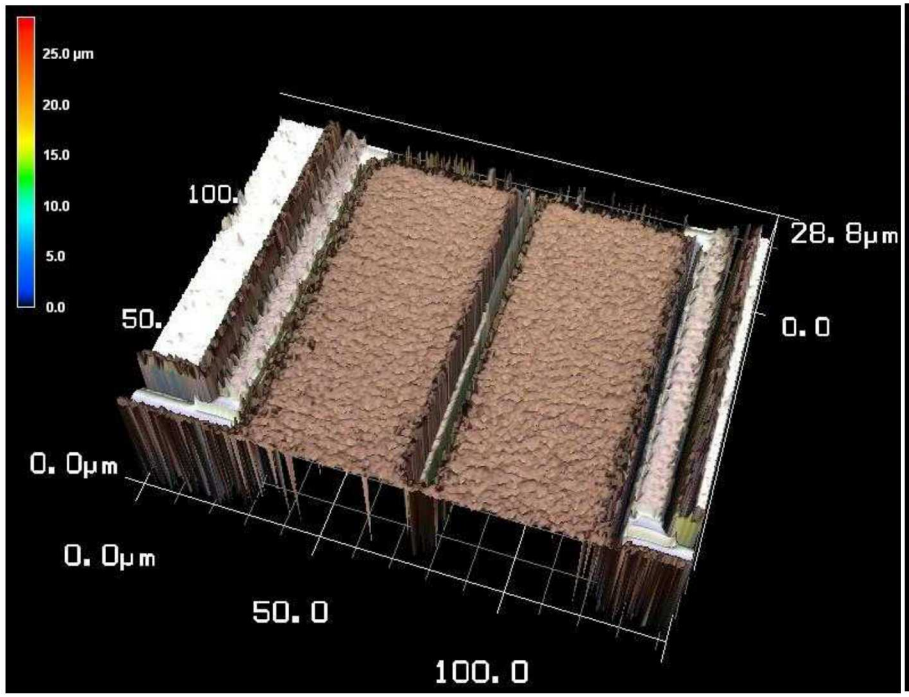


Date Code: 1429

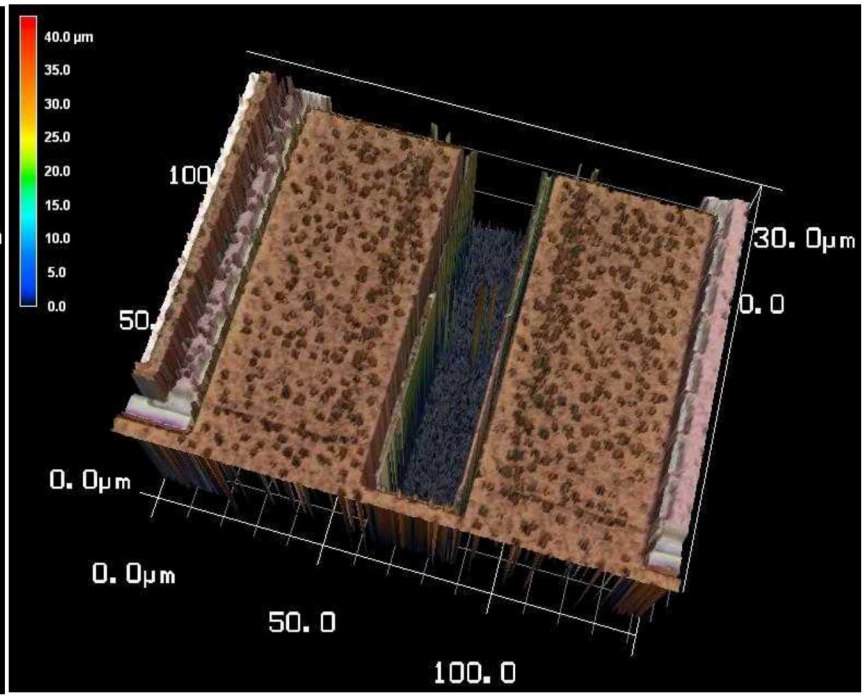
"Grainy" Metal Lines

Example 2 : EEPROMs
(Correlation between PSA and Data and Confocal Laser Imaging

Digikey



Mouser



Correlation between PSA data and confocal laser imaging
(Different textures of the metal-line)

Summary

- PSA identifies subtle device differences
  - Not detectable with conventional testing in many cases
- PSA uses off-normal biasing
  - Requires minimal test device electrical knowledge
  - Fast acquisition times (< 10 sec)
- Various applications presented
- Good correlation between PSA data and results from physical analysis

Future Work

- **Apply machine learning to PSA data**
  - **PSA spectrum (800 data points) contains a lot of information**
  - **Principal component analysis is not adequate**
  - **Machine learning can potentially extract more information**
  - **Improve predictive capability of PSA**
    - **Identify failure precursor**
    - **Estimate aging**
    - **Require accelerated aging experiments**
    - **Incorporate other data (e.g. conventional electrical test data)**