RF Characterization – The approach and the advantages

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MOS-AK Tutorial Day – Shanghai
www.incize.com/mos-ak_RF_tutorial.pdf
Mobile Data Usage Exploding

**General Mobile Data Traffic Growth/Top Line**

- **2014**: 2.5 B Exabytes
- **2015**: 4.2 EB Exabytes
- **2016**: 6.8 EB Exabytes
- **2017**: 10.7 EB Exabytes
- **2018**: 16.1 EB Exabytes
- **2019**: 24.3 EB Exabytes

- **CAGR 57%**

**Device Data Consumption**

- **M2M Module** = 3 X
- **Wearable Device** = 6 X
- **Smartphone** = 37 X
- **Tablet** = 94 X
- **Laptop** = 119 X

**CAGR 16.7%**


Source: Peter A. Rabbeni, Director RF Product Marketing and Business Development, GLOBALFOUNDRIES SOI Consortium RF SOI Workshop – Shanghai, September 2015
Mobile Data Usage Exploding

General Mobile Data Traffic Growth/Top Line

Device Data Consumption

<table>
<thead>
<tr>
<th>Device Type</th>
<th>Multiplier</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2M Module</td>
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</tr>
</tbody>
</table>


1 EB = 10^{18} \text{ bytes} = 1 \text{ billion gigabytes}

7 Billion people (Earth’s population) Each downloading 1 gigabyte / month in 2016!!!
Mobile Data Usage Exploding

Source: Peter A. Rabbeni, Director RF Product Marketing and Business Development, GLOBALFOUNDRIES
SOI Consortium RF SOI Workshop – Shanghai, September 2015
wireless
Radio Frequency
RF is a powerful tool to intelligently measure many effects.
RF Characterization – All you need to know ...

- On-Wafer
- Packaged
- System
RF Equipment – DC Bias, cables, bias-T, etc…
RF Equipment – Vector Network Analyzer (VNA)
Air Co-Planar Transition

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

Source: Gavin Fisher, Cascade Microtech Europe Ltd
“A guide to Successful on Wafer RF characterisation”
RF Equipment – Probes and accessories

- Probe
  - Probe tips
  - Contact substrate
  - Impedance standard substrate

Step 1. Planarity
Step 2. Alignment

Step 3. Measuring standards and calibration
- Short (L)
- Thru (td)
- Load (R + L)
- Open (C): Probes are in the air
- **SOLT**  |  Short Open Load Thru
- **SOLR**  |  Short Open Load Reciprocal
- **LRM**   |  Line Reflect Match
- **LRRM**  |  Line Reflect Reflect Match
- **TRL**   |  Thru Reflect Line
RF Equipment – Calibration

Systematic Measurement Errors

Frequency response:
- reflection tracking (A/R)
- transmission tracking (B/R)

Six forward and six reverse error terms yields 12 error terms for two-port devices.
RF Equipment – Calibration

- Pad configuration (GS Vs GSG)
- Probe pitch
- Ability to physically probe
- Pad size
- Pad height
- Distance between probes
- Number of contacts per side
- De-embedding devices
- Paths
- Best calibration methods

Reference plane

Reference plane

Eliminate parasitic effects through De-embedding

Source + Substrate

Gate

Drain

Ground

Signal

Ground

Source + Substrate
See it. Touch it. Measure it.

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

Reference plane of port 1 of the NWA after calibration

Reference plane of port 2 of the NWA after calibration

Reference planes of the device
RF Equipment – De-embedding

- **Y_{11i}.raw**
- **Y_{11i}.d1**
- **Y_{11i}.d2**

Finger number = 10

\[ W_f = 6 \mu m \]
\[ L_f = 0.18 \mu m \]

- **Raw data**
- **After de-embedding with open**
- **After de-embedding with open/short**

\[ V_{GS} = 1 \text{ V} \]
\[ V_{DS} = 1 \text{ V} \]
RF Equipment – De-embedding

\[ S_{\text{Total}} \]

\[ Y_{\text{Total}} = Y(S_{\text{Total}}) \]

\[ Y_{\text{DUT-OPEN}} = Y_{\text{TOTAL}} - Y_{\text{OPEN}} \]

\[ Z_{\text{DUT-OPEN}} = Z(Y_{\text{DUT-OPEN}}) \]

\[ Z_{\text{DUT}} = Z_{\text{DUT-OPEN}} - Z_{\text{SHORT}} \]

Ewout P. Vandamme et al., IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 48, NO. 4, APRIL 2001

Mattias Ferndahl et al., IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 56, NO. 12, DECEMBER 2008
RF Representation – The Smith Chart

Smith, P. H.; Transmission Line Calculator; Electronics, Vol. 12, No. 1, pp 29-31, January 1939

Phillip Hagar Smith
(1905 – 1987)
While working for Bell Telephone Laboratories, he invented his eponymous Smith chart.
Smith Chart Review

Smith Chart maps rectilinear impedance plane onto polar plane.

- Rectilinear impedance plane
- Polar plane
- Smith chart

Network Analyzer Basics

Agilent Technologies

www.agilent.com/find/basics
RF Representation – The Smith Chart
RF Representation – The Smith Chart

\[ z = \frac{Z_L}{Z_0} \]

\[ \Gamma = \frac{V_{\text{reflected}}}{V_{\text{incident}}} \]

https://en.wikipedia.org/wiki/Smith_chart
**RF Characterization – 2-port network**

DuT: Device under test

- Transmission line, crosstak structure, inductor, transistor, PA, …
RF Characterization – Equivalent circuit of a quadripole

\[ V_1 = Z_{11} I_1 + Z_{12} I_2 \]
\[ V_2 = Z_{21} I_1 + Z_{22} I_2 \]

\[ Z = \begin{pmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{pmatrix} \]

\[ Y = \text{inv}(Z) = \begin{pmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{pmatrix} \]

\[ Z_{11} = V_1 / I_1 \text{ with } I_2 = 0 \text{ (OPEN circuit)} \]
\[ Z_{12} = V_1 / I_2 \text{ with } I_1 = 0 \text{ (OPEN circuit)} \]
\[ Y_{11} = I_1 / V_1 \text{ with } V_2 = 0 \text{ (SHORT circuit)} \]
\[ Y_{12} = I_1 / V_2 \text{ with } V_1 = 0 \text{ (SHORT circuit)} \]
RF Characterization – Boundary conditions at DC and LF

DC and low frequency (< MHz):
- Equipotential for the feed lines
- Lumped elements
- Boundary conditions:
  SHORT (Z = 0) and OPEN (Z = ∞)

1 MHz ≡ 300 m

Equipotential (DC & LF)

Waves

OPEN Or SHORT

DuT

D

G

S

Connections

Connections

Waves

Equipotential (DC & LF)
RF Characterization – Boundary conditions at HF

At high frequency:  
- Propagation of waves  
- Distributed elements  
- Boundary conditions: SHORT ($Z \neq 0$) and OPEN ($Z \neq \infty$)

Length of the elements are often of the same order of magnitude as the electrical wavelength $\Rightarrow$ transmission line theory $\Rightarrow$ wave forms for current and voltage:

$$V = V_0 \cos (\omega t - \beta z) = \text{Re} \{V_0 \exp j(\omega t - \beta z)\}$$
RF Characterization – S-parameters definition

\[ v = z \cdot i \]

\[ i = y \cdot v \]

\[ b = s \cdot a \]

\[ a_i = \frac{v_i + Z_{ni}i_i}{2\sqrt{R_{ni}}} \]

\[ b_i = \frac{v_i - Z_{ni}^*i_i}{2\sqrt{R_{ni}}} \]

where \( R_{ni} = \text{real}(Z_{ni}) \)

- \( a_i \) and \( b_i \) are linear combinations of \( v_i \) and \( i_i \)
- dimensions \( \sqrt{\text{W}} \)
- normalization impedance \( Z_{ni} \) (generally 50 \( \Omega \))

1948
V. Belevitch
Transmission losses in 2n-terminals
RF Characterization – Incident and reflected power waves

Physical meaning of

\[ a_i = \frac{v_i + Z_{ni} i_i}{2\sqrt{R_{ni}}} \]

\[ b_i = \frac{v_i \frac{Z_{ni}^* i_i}{2\sqrt{R_{ni}}}} \]

If matching: \( Z_{ii} = Z_{ni}^* \) → \[ |a_i|^2 = \frac{|e_i|^2}{4R_{ni}} = P_{ai} \] available power

\[ |a_i|^2 - |b_i|^2 = \text{real} \left( v_i \cdot i_i^* \right) = P_i \] power entering port \( i \)

thus \[ |b_i|^2 = P_{ai} - P_i \] reflected power
RF Characterization – Available and reflected powers

Available power

\[ |a_i|^2 \]

Reflected power

\[ |b_i|^2 \]
**RF Characterization – S-parameters meaning**

- **$S_{11}$**: mismatch at the device input
- **$S_{22}$**: mismatch at the device output
- **$S_{21}$**: transmitted power from the input to the output
  - insertion loss for a line ($S_{21} < 1$, $S_{21} < 0$ dB)
  - power gain for a transistor ($S_{21} > 1$, $S_{21} > 0$ dB)
RF Characterization – S-to-Z and S-to-Y conversions

\[
\begin{align*}
 z_{11} &= \frac{(1 + s_{11})(1 - s_{22}) + s_{12}s_{21}}{(1 - s_{11})(1 - s_{22}) - s_{12}s_{21}} \\
 z_{12} &= \frac{2s_{12}}{(1 - s_{11})(1 - s_{22}) - s_{12}s_{21}} \\
 z_{21} &= \frac{2s_{21}}{(1 - s_{11})(1 - s_{22}) - s_{12}s_{21}} \\
 z_{22} &= \frac{(1 + s_{22})(1 - s_{11}) + s_{12}s_{21}}{(1 - s_{11})(1 - s_{22}) - s_{12}s_{21}} \\
 y_{11} &= \frac{(1 + s_{22})(1 - s_{11}) + s_{12}s_{21}}{(1 + s_{11})(1 + s_{22}) - s_{12}s_{21}} \\
 y_{12} &= \frac{-2s_{12}}{(1 + s_{11})(1 + s_{22}) - s_{12}s_{21}} \\
 y_{21} &= \frac{-2s_{21}}{(1 + s_{11})(1 + s_{22}) - s_{12}s_{21}} \\
 y_{22} &= \frac{(1 + s_{11})(1 - s_{22}) + s_{12}s_{21}}{(1 + s_{11})(1 + s_{22}) - s_{12}s_{21}}
\end{align*}
\]
MOSFET RF Characterization – Test Structures

- Active zone
- Ground
- Signal
- Contact pads
- Measurements reference planes
- Pad configuration (GS Vs GSG)
- Probe pitch
- Pad size
- Pad height
- Distance between probes
- Number of contacts per side
- Calibration
- Paths
- Best calibration methods
- De-embedding devices

Think About Testing Before Design!

RF Performance

See it. Touch it. Measure it.

Company Confidential
MOSFET RF Characterization – Figures of Merit

Key-factors:

MOSFET-level

- $f_T = \frac{g_m}{(2 \cdot \pi \cdot C_{gg})}$
- $f_{\text{max}}$
- $A_{v0} = \frac{g_m}{g_d} = \left(\frac{g_m}{I_d}\right) \cdot V_{EA} \neq \text{const} (f)$

IC (amplifier)-level

- $\text{GBW} = \frac{g_m}{(2 \cdot \pi \cdot C_L)} = \left(\frac{g_m}{I_d}\right) \cdot \left(\frac{I_d}{2 \cdot \pi \cdot C_L}\right)$

$$f_T \approx \frac{g_m}{2 \cdot \pi \cdot C_{gs}} \left[ \frac{1}{1 + \frac{C_{gd}}{C_{gs}}} \right] + \left(\frac{R_s + R_d}{R_s}\right) \cdot \left(\frac{C_{gd}}{C_{gs}}\right) \cdot \left(\frac{g_m + g_d}{g_d}\right)$$

$$f_{\text{max}} \approx \frac{g_m}{4 \cdot \pi \cdot C_{gs}} \left[ \frac{1}{1 + \frac{C_{gd}}{C_{gs}}} \right] \sqrt{\frac{g_d}{R_s + R_d}} \cdot \left(\frac{R_s + R_d}{2 R_s}\right) + \frac{1}{2} \cdot \frac{C_{gd}}{C_{gs}} \cdot \left(\frac{R_s \cdot g_m + C_{gd}}{C_{gs}}\right)$$

- Transconductance $g_m$
- Drive current, $I_d$
- Output conductance, $g_d$
- Early voltage, $V_{EA}$ ($V_{EA} = \frac{I_d}{g_d}$)
- $g_m/I_d$ ratio
- Gate capacitance, $C_{gg}$
- Parasitics (C, R)
MOSFET RF Characterization – Figures of Merit

HF small-signal equivalent circuit

Cutoff frequency when Gain = 1 = 0 dB

\[ f_T \approx \frac{g_m}{2 \cdot \pi \cdot C_{gs}} \left\{ 1 + \frac{C_{gd}}{C_{gs}} \right\} \frac{1}{R_s + R_d + \left( \frac{C_{gd}}{C_{gs}} \cdot g_m + g_d \right) + g_d} \]

\[ f_{\text{max}} \approx \frac{g_m}{4 \cdot \pi \cdot C_{gs}} \left( 1 + \frac{C_{gd}}{C_{gs}} \right) \frac{1}{\sqrt{g_d \cdot \left( R_g + R_s \right) + \frac{1}{2} \cdot \frac{C_{gd}}{C_{gs}} \cdot R_s \cdot g_m + \frac{C_{gd}}{C_{gs}}} \]
MOSFET RF Characterization – Gains & Cutoff frequencies

**Voltage gain**

\[ A_V = \frac{V_2}{V_1} \quad I_2 = 0 \quad \text{(OPEN circuit)} \]

\[ A_V = \frac{G_m}{G_d} \]

**Current gain**

\[ H_{21} = \frac{I_2}{I_1} \quad V_2 = 0 \quad \text{(SHORT circuit)} \]

\[ H_{21} = \frac{G_m}{\omega C_{gg}} \]
MOSFET RF Characterization – Gains & Cutoff frequencies

Cutoff frequency when Gain = 1 = 0 dB

Current gain

\[ H_{21} = \frac{I_2}{I_1} \quad V_2 = 0 \]  (SHORT circuit)

\[ H_{21} = \frac{G_m}{\omega C_{gg}} \]
**Maximum available power gain (MAG)**

\[
\Gamma_{in} = S_{11} + \frac{S_{12} S_{21} \Gamma_L}{1 - S_{22} \Gamma_L} \quad \Gamma_{out} = S_{22} + \frac{S_{12} S_{21} \Gamma_S}{1 - S_{11} \Gamma_S}
\]

\[
MAG = \left| \frac{S_{21}}{S_{12}} \right| \cdot \left( k - \sqrt{k^2 - 1} \right) \quad k > 1: \text{unconditionally stable}
\]

\[
\Gamma_S = \Gamma^*_{in} \quad \Gamma_L = \Gamma^*_{out} \quad k = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2|S_{12} S_{21}|}
\]

\[
\Delta = S_{12} S_{21} - S_{11} S_{22}
\]

\[
k < 1: \text{potentially unstable}
\]
IBM: record RF performance of sub-45 nm SOI CMOS (2007)  
Peak $f_T$ of 485 GHz and 345 GHz measured in floating-body nFET and pFET  

[R. Valentin, IEMN, PhD thesis, 2008]
MOSFET RF Characterization – Cutoff frequencies

HF small-signal equivalent circuit

\[ f_T \approx \frac{g_m}{2 \cdot \pi \cdot C_{gs}} \left( \frac{1}{1 + \frac{C_{gd}}{C_{gs}}} \right) + \left( R_s + R_d \right) \cdot \left( \frac{C_{gd}}{C_{gs}} \right) \cdot \left( g_m + g_d \right) \]

\[ f_{\text{max}} \approx \frac{g_m}{4 \cdot \pi \cdot C_{gs}} \left( \frac{1}{1 + \frac{C_{gd}}{C_{gs}}} \right) \left( \frac{g_d}{R_s} \right) \left( R_g + R_s \right) + \frac{1}{2} \cdot \frac{C_{gd}}{C_{gs}} \cdot \left( R_s \cdot g_m + \frac{C_{gd}}{C_{gs}} \right) \]
MOSFET RF Characterization – Cutoff frequencies

FinFET: Unfortunately, lower cutoff frequency

[IMEC, IEEE TED’06]
MOSFET RF Characterization – Role of parasitics

Extrinsic

Intrinsic

f_T (GHz)

100

10

L_g (nm)

100

Planar bulk

Planar

FinFET

f_Te

f_Ti

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MOSFET RF Characterization – Role of parasitics

- $f_T$ decreases by 60% from intrinsic value due to $C_{\text{inner}}$
- Further 15% due to $C_{\text{outer}} + R_S, R_D$

- $f_{\text{max}}$ decreases 40% from intrinsic value due to $R_g$
- Further 30% due to $C_{\text{inner}}$

Inner capacitance is a big bottleneck to FinFET’s RF performance
The capacitance $C_3$ accounts for a big fraction of FinFET inner parasitic capacitance.

Relatively high value is due to tight coupling and proximity of the plates.

Specific and inherent to FinFET architecture.

[Wu et al., TED 2007]
**Adjacent elements**: do not depend on transistor dimensions and bias conditions

**Extrinsic elements**: depend on transistor dimensions but independent of bias conditions

**Intrinsic elements**: depend on transistor dimensions and bias conditions
Adjacent elements: do not depend on transistor dimensions and bias conditions

Extrinsic elements: depend on transistor dimensions but independent of bias conditions

Intrinsic elements: depend on transistor dimensions and bias conditions
Direct extraction techniques of extrinsic resistances and capacitances are based on the simplification of the intrinsic parameters under certain bias conditions and the knowledge of the extrinsic parameters dependences versus transistor dimensions.
**MOSFET – Extraction of Extrinsic Resistances**

**Strong inversion and V_DS = 0 V**

- $\text{Re}(Z_{11}) = R_{ge} + R_{se} + \frac{1}{4G_{dsi}}$
- $\text{Re}(Z_{12}) = \text{Re}(Z_{21}) = R_{se} + \frac{1}{2G_{dsi}}$
- $\text{Re}(Z_{22}) = R_{de} + R_{se} + \frac{1}{3G_{dsi}}$

**Use of geometric dependence of $G_{dsi}$**

$G_{dsi} \Rightarrow \infty$ for $L = 0$

**Use of bias dependence of $G_{dsi}$**

$G_{dsi} \Rightarrow \infty$ for $1/(V_{GS} - V_{th}) = 0 V$
Self-heating in MOSFETS – RF technique

![Graph showing Intel CPU power density vs. year]

- **1960**
- **1970**
- **1980**
- **1990**
- **2000**
- **2010**
- **2020**
- **2030**

- **10000**
- **1000**
- **100**
- **10**
- **1**

- **Hot plate**
- **Rocket nozzle**
- **Sun surface**
- **Nuclear reactor**

Intel CPU power density, W/cm²
- Dynamic self-heating is frequency-dependent
- $g_m = \text{Re}(Y_{21})$; $g_d = \text{Re}(Y_{22})$
- $R_{th} \propto \Delta g_d$
- $T_{device} \propto \Delta g_d$
Self-heating in MOSFETS – RF technique

UTBB: $T_{si} = 7$ nm and $T_{BOX} = 10$ nm

Conductance, $mS$

$V_g = V_d = 1V$

$V_g = 0.6$ V; $V_d = 1V$

$g_d (DC)$ is up to 3 times smaller than $g_d (HF)$

[S. Makovejev et al., 2011]
HR-SOI suffers from Parasitic Surface Conduction (PSC) effect at the SiO₂/Si interface.

Parasitic Surface Conduction (PSC)

- Mobile & Interface trapped charges
- Highly conductive layer
- Accumulation layer
- Fixed charges

10 kΩ.cm + PSC ≈ 200 Ω.cm
## Substrates – Small Signal RF Characterization

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<tr>
<th>Substrate</th>
<th>$\rho_{\text{nom}}$ [Ω·cm]</th>
<th>$\rho_{\text{eff}}$ [Ω·cm]</th>
<th>$Q_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>std-Si</td>
<td>10</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>HR-Si</td>
<td>$&gt; 5$ k</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td>-</td>
<td>$&gt; 5$ k</td>
<td></td>
</tr>
<tr>
<td>trap-rich HR-Si</td>
<td>$&gt; 5$ k</td>
<td>$&gt; 5$ k</td>
<td>$3 \times 10^{11}$</td>
</tr>
</tbody>
</table>
Substrates – Crosstalk on HR and TR-SOI

[C. Ben Ali et al., TED’11]
Substrates – Crosstalk on HR and TR-SOI

Crosstalk in HR-Si and TR-SOI substrates is shown in the diagram. The test structure is illustrated with dimensions of 150 x 50 µm². The frequency response of S21 [dB] is plotted on a logarithmic scale, showing a trend of 20 dB/dec and a crosstalk level of -35 dB.

[K. Ben Ali et al., TED’11]
Substrates – Crosstalk on HR and TR-SOI

Test structure

- Trap-rich layer
- SiO₂
- CROSSTALK
- HR-Si

SiO₂

150 x 50 µm

d = 50µm

Inversion layer

20dB/dec

\[ S_{21}(\text{dB}) \]

Frequency (Hz)

100kHz, 1MHz, 10MHz, 100MHz, 1GHz
Substrates – Digital Substrate Noise

[Image of a schematic diagram showing substrate coupling and an SOI FD MOSFET]

NOISE SOURCE (digital) → VICTIM (analog)

SUBSTRATE COUPLING
Bulk Si / SOI HR-Si

NOISE SOURCE (digital) → VICTIM (analog)

Limited DSN reduction due to PSC

[D. Bol et al., SOI'07]

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Substrates – Digital Substrate Noise

Without Noise

Noise: square signal @ 500 kHz

Almost 25 dB reduction of the coupled noise.

[K. Ben Ali, SOI Conf. 2012]
Substrates Characterization for nonlinearities
Spreading Resistance Profiling (SRP)

- Destructive.
- Difficult to get detailed wafer mapping.
- Does not capture interface conduction.
- Difficult to relate to final processed RF and Non-linear wafer behavior.
- Expensive
Substrates – HD Characterization

CPW 2146 µm-long

![Graphs showing HD2 and HD3 vs. P_out for Standard, HR, and Trap-Rich substrates.](image)
Substrates – HD Characterization

CPW 2146 µm-long

![Graphs showing HD2 and HD3 vs. P_{out} for different substrates](image)

- Standard
- HR
- Trap–Rich
- Glass1
- Glass2
- Sapphire

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Substrates – HD Characterization (Two-tone)

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thank you!

TAKE AWAY
RF is a powerful tool
Thank you!
谢谢
we innovatively characterize
Exclusive License

10 years

Background
Semiconductor Activity

Technology Enablement

Training
WELCOME – Characterization Facility

Frequency DC - 220 GHz

RF power -25 to 40 dBm

Load-pull 0.8 – 50 GHz

Temperature 4K – 600K

Noise RF and 1/f

Packaged, co-axial and on-wafer
Technology Enablement

TCAD Simulations
Design and Fabrication of Test Structures
Characterization and measurements
Compact and Macro Modelling
PDK Support
Design of Demonstrator Circuits
CRC – Cyclotron Resource Centre

Facilities

- Heavy Ion Irradiation
- Proton Beam Line
- Neutron and Gamma Irradiation

One of the most powerful cyclotrons in Europe

Co-located with WELCOME in Louvain-La-Neuve
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Upcoming Event: 2016-09-09

“A Practical Guide to SOI

www.incize.com