Radiation-Hardened SiGe BiCMOS Technologies for Analogue and Mixed-Signal ICs

RHBD SGB25RH (250nm) and SG13RH (130nm) PDKs

Maurizio Cirillo

innovations
for high
performance
microelectronics

2016-06-13

AMICSA 13 – 16 July 2016 – Gothenburg (Sweden)

Member of
Leibniz Association

Outline

1. IHP GmbH – short introduction
2. SiGe HBT BiCMOS vs RF-CMOS and future outlook
3. Commercially available IHP SiGe BiCMOS Technologies, EDA & PDK Flow
4. Capability Domains
5. Evaluation of SGB25RH
6. Evaluation of SG13RH
7. Summary of Results

IHP GmbH in Germany


CERTIFICATE

This is to certify that

IHP GmbH - Innovations for
High Performance Microelectronics/
Leibniz-Institut für innovative Mikroelektronik
Im Technologiepark 25
15236 Frankfurt (Oder)

has implemented and maintains a **Quality Management System**

Scope
Silicon-based solutions, especially for wireless and broadband communication, including system design, circuit design, process development, Multi Project Wafer (MPW)-Service and prototyping/small series, design and characterization of devices and customer relations

Through an audit, documented in a report, it was verified that the management system fulfills the requirements of the following standard:

ISO 9001 : 2008

Certificate registration no.	435242 QM08
Date of certification	2012-11-21
Valid until	2015-11-20

DQS GmbH

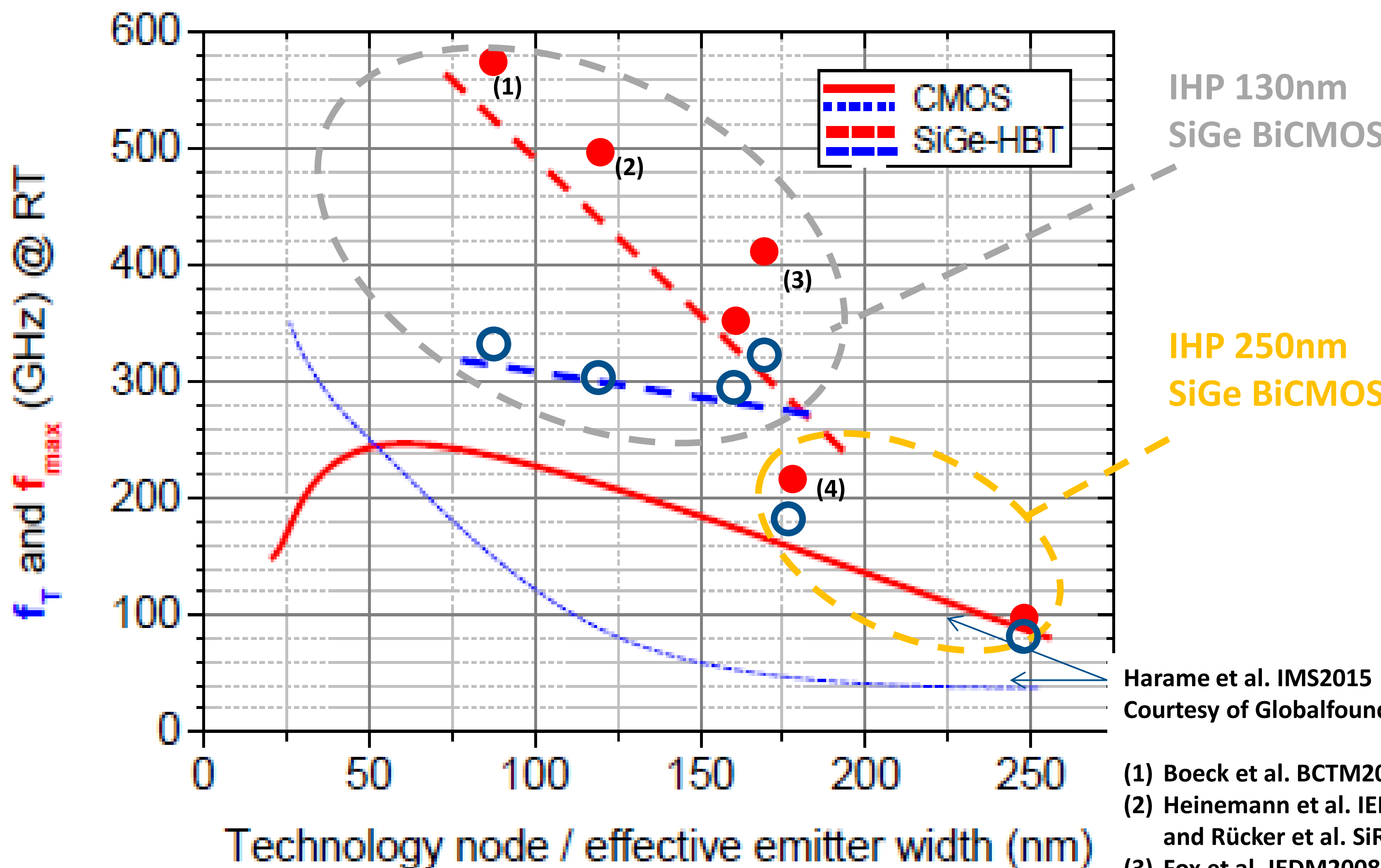
Michael Drechsel
Managing Director

Accredited Body: DQS GmbH, August-Schanz-Straße 21, 60433 Frankfurt am Main

DIN EN ISO 9001:2008 (Oct. 2015)

- Silicon-based solutions for wireless communications, including System Design, Circuit Design, Process Research, Prototyping and MPW-Service, Device Design and Characterization.
- MPW and LVP SiGe BiCMOS Process Technologies (250nm, 130nm)
  - 1000m² Class 1 Clean Room / 100WSPW
- Approx. 310 (scientists, engineers, technicians, administration staff, etc..)

SiGe HBT BiCMOS vs RF CMOS



Harame et al. IMS2015
Courtesy of Globalfoundries

(1) Boeck et al. BCTM2015
(2) Heinemann et al. IEDM2010 and Rücker et al. SiRF2012
(3) Fox et al. IEDM2008
(4) Heinemann et al. SST Journal 2007

Commercially available IHP SiGe BiCMOS Technologies

250nm CMOS (V_{DD}=+2.5V ; T_{OX} = 5.8nm)

130nm Dual Gate CMOS (V_{DD}=+1.2V, +3.3V ; T_{OX} = 2nm / 7nm)

BEOL : 3 thin + 2 thick metal layers (TM1:2µm, TM2:3µm) + MIM Capacitor Layer

BEOL : 5 thin + 2 thick metal layers (TM1:2µm, TM2:3µm) + MIM Capacitor Layer

SGB25V
npnVp 95/75/2.4
npnVs 90/40/4.0
npnVh 70/25/7.0

SG25H3
npnVp 180/110/2.3
npnVp 140/120/2.4
npnVs 140/45/5.0
npnVh 80/25/7.0

SG25H1
npnVp 190/190/1.9
npnVp 220/180/1.9
(REPLACED by SG25H4)

SG25H4
npnVp 190/190/1.9
npnVp 220/180/1.9

SG13S
npnVp 340/250/1.7
npnV1 220/180/3.7

SG13G2
npnVp 500/300/1.6

Speed-World-Record

EU-DotFive Project (2009-2012)

SGB25RH
npnVp 95/75/2.4
npnVs 90/40/4.0
npnVh 70/25/7.0

EPPL submission 2016

SG25H_EPIC
SG25H4 + Integrated Photonic

SG13RH
npnVp 340/250/1.7
npnVv 220/180/3.7

Under Development
Early Access for joint projects

MODULES

-GD
n-LDMOS 18/48/22
p-LDMOS 8/28/-17

-H3P
pnp 120/90/-2.5

-PIC
SI-Photonic Devices
Ge-PD, MZM, etc...

- RFMEMS
Capacitive Switches > 30GHz
IL < 1.0dB / Pull-in ~50V / C_{ON}/C_{OFF} > 10

TSV

LBE

Legend :

Stable | Early Access | In Development
Qualified based on JEDEC JP-001 | Phased-Out

Technology
device f_{MAX} / f_T / BV_{CEO}

Status : February 2016

Selected MPW and LVP Customers

Microsemi

ROHDE & SCHWARZ

CISCO

SILICON radar

EUROPRACTICE IC SERVICE

csr

KEYSIGHT TECHNOLOGIES

InnoSenT Innovative Sensor Technology

IMST

BOSCH

AIRBUS

SIVERSIMA

ARQUIMEA

OHB

space Asics

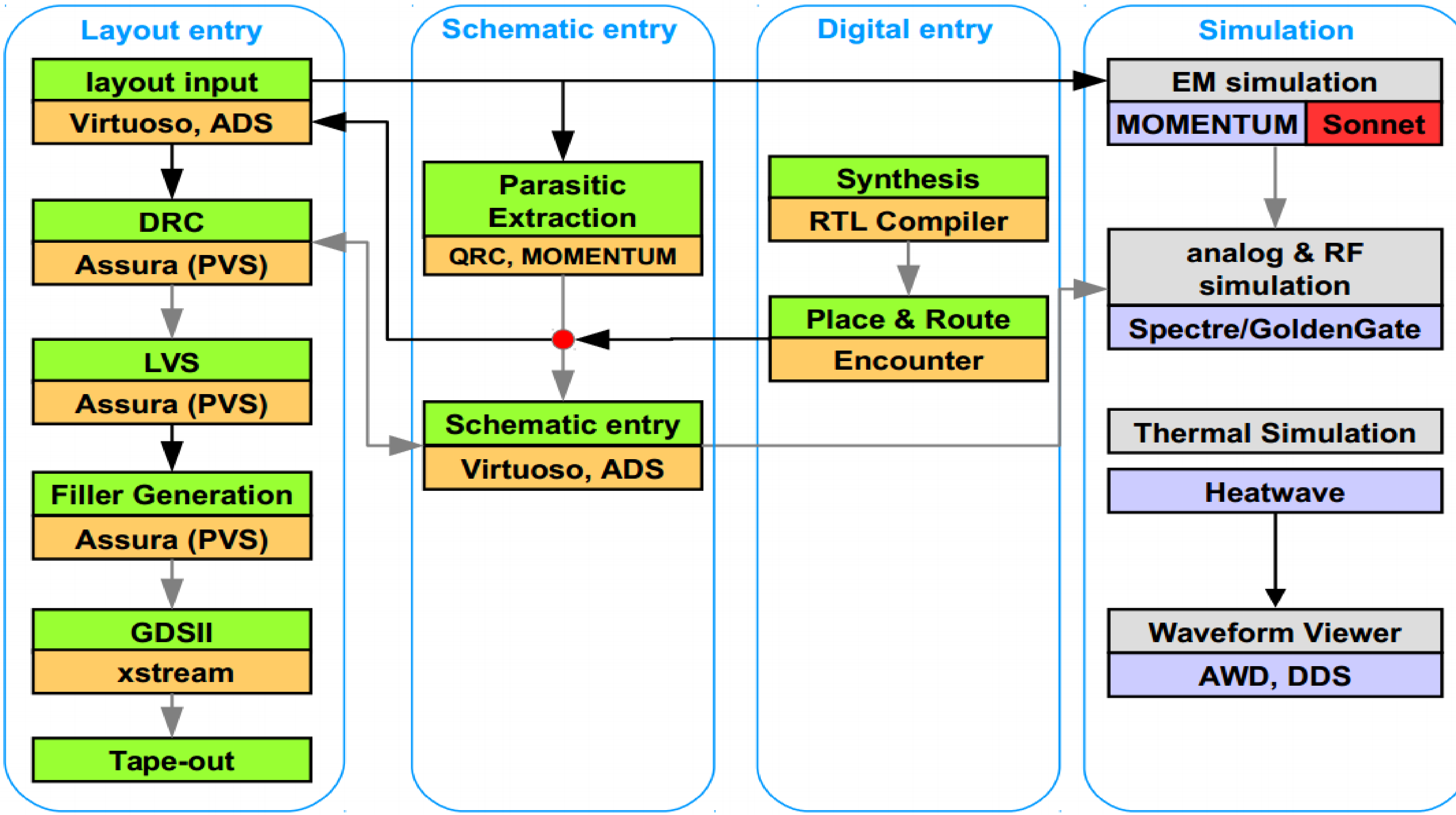
SPACE ENGINEERING

Supported EDA Tools

	cadence	KEYSIGHT TECHNOLOGIES	NI AWR Design Environment	TEXEDA DESIGN GMBH	SONNET
Schematic Capture	✓	✓	✓	✓	
Spice Simulation	✓	✓	✓	✓*	
Field Simulation	✓	✓	✓	✓*	✓
Layout	✓	✓	✓	✓	
Design Rule Check	✓	✓	✓	✓	
LVS Check	✓	✓	✓	✓	
Parasitic Extraction	✓	✓*	✓	✓	

* *Third-Party Vendor*

PDK Flow – Cadence, ADS Interoperability



Capability Domain for SGB25RH and SG13RH

Device	SGB25RH Key Parameters	SG13RH Key Parameters
HBT Devices	**Standard HBT** **npnVs** **β ~ 190** Peak f_T =45GHz, Peak f_{MAX} =90GHz, BV_{CEO}=4.0V	
	High Performance **npnVp** **β ~ 190** HBT - Peak f_T =75GHz, Peak f_{MAX} =95GHz, BV_{CEO}=2.4V	**High Performance** **npn13p /pl2** **β ~ 900** HBT - Peak f_T =250GHz, Peak f_{MAX} =340GHz, BV_{CEO}=1.7V
	High Voltage HBT **npnVh** **β ~ 190** Peak f_T =25GHz, Peak f_{MAX} =70GHz, BV_{CEO}=7.0V	**High Voltage HBT** **npn13v2** **β ~ 900** Peak f_T =50GHz, Peak f_{MAX} =165GHz, BV_{CEO}=3.7V
CMOS / MOS	**nmos** : Breakdown Voltage: typ. 4.8V	**nmosLV** : Breakdown Voltage : typ. 2.7V **nmosHV** : Breakdown Voltage : typ. 6.1V
	pmos : Breakdown Voltage: typ. -4.1V	**pmosLV** : Breakdown Voltage : typ. -3.1V **pmosHV** : Breakdown Voltage : typ. -5.6V
	Isolated_nmos : Breakdown Voltage: typ. 4.8V	**Isolated_nmos** : Breakdown Voltage: typ. 2.7V
Resistors	**4-Types** : Salicided N+ Poly, N+ Poly, P+ Poly, High Poly	**3-Types** : Salicided N+ Poly, P+ Poly, High Poly
C-MIM	typ. 1.0fF/μm^2, Breakdown Voltage typ. 30V	typ. 1.5fF/μm^2, Breakdown Voltage typ. 23V
MOS Varicap	typ. 2.7fF/μm^2 to 8.9fF/μm^2 (typ. from -2.5V to +2.5V, 1GHz)	
S-Varicap	typ. 2.7fF/μm^2 to 8.9fF/μm^2 (typ. from -2.5V to +2.5V, 1GHz)	typ. 23fF/μm^2 to 39fF/μm^2 Q>40 (typ. from -2.5V to +2.5V, 1GHz)

Evaluation of SGB25RH

PDK SGB25RH based on :

- Qualified SGB25V Standard Commercial Process based on JEDEC JP001.01
  - Process stable and running since 2005
- RHBD Libraries
  - RH Layout Rules and derating factors
  - Analog Devices (npn-HBT, MOS devices incl. ELT- RHBD version)
  - Digital Standard Cell and IO Libraries + RHBD (special layouts) core and IO cells.

Activity promoted by DLR and IHP

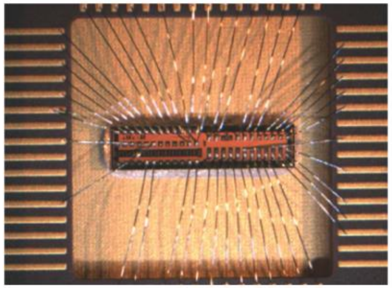
Project Partners : OHB (Prime), RHe-Cicor

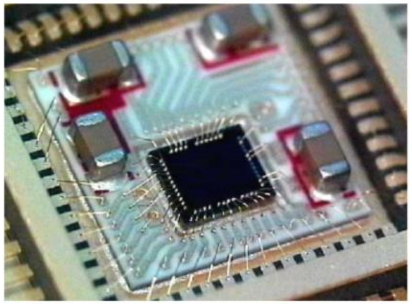
Goal :

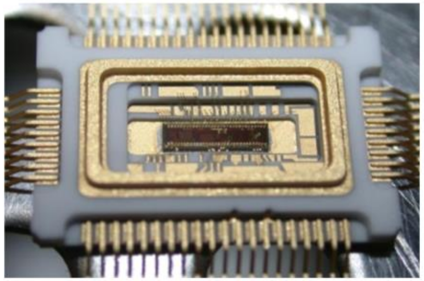
- Process Radiation Assessment
- Manufacturer Evaluation : IHP
  - Test Flow, Test Vehicles (TCV, DEC, RIC)
- Evaluation Testing based on ESCC 2269010 **Microwave MMIC Flow**
- Definition of Capability Domain

Test Vehicles as requested by ESCC Basic Specification 2269010

- TCV all devices, min. size MOS and npn-HBT devices
  - **Endurance Testing (4000h, 150°C)** **PASS**
    - with predicted degradations and failures during stress tests
- DEC-I : CMOS-, HBT- Shift Registers and Ring Oscillators
  - **Endurance Testing (3000h, 150°C)** **PASS**
    - Dynamic testing, aging. Some failures after 3000h
    - F/A confirms handling issues
- DEC-II CMOS- Ring Oscillators
  - **Endurance Testing (2x 2000h, RT)** **PASS**
    - CMOS ROs for HCI degradation leading to Lifetime estimation (>18y)
    - HBT no degradation
- RIC – VCO up to 24GHz, Divider, amplifier and SPI
  - **Endurance Testing (4000h, 150°C)** **PASS**
    - NO FAILURES
    - VCO very small drift f_{OUT} : +0.38ppm/h
    - VCO no measurable PN drift



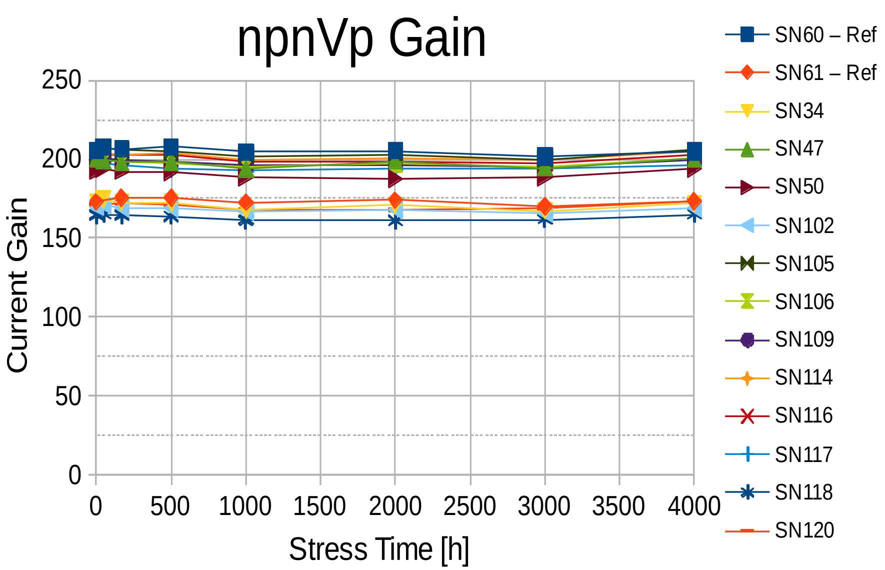


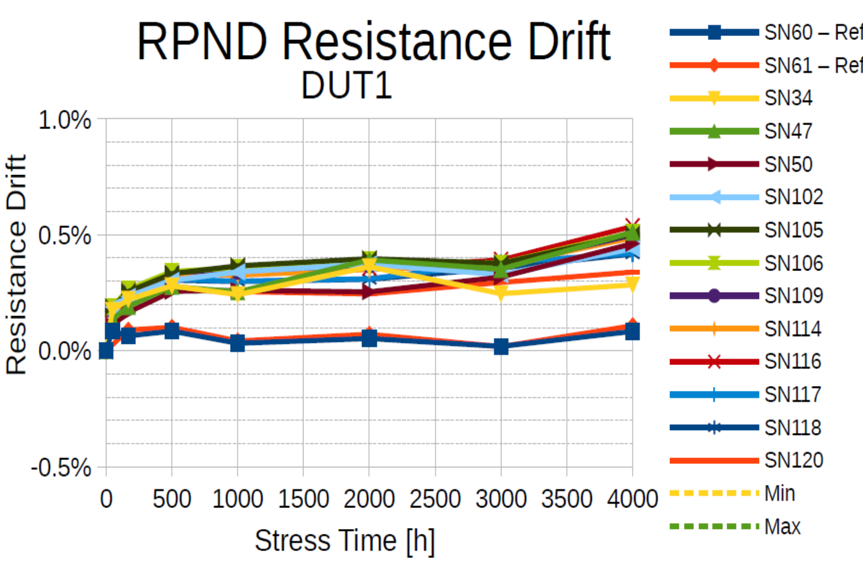


Evaluation of SGB25RH

TCV Endurance Testing (4000h, 150°C)

- MOS IDSAT drifts (NMOS ~ -2.0%, PMOS ~ -3.5%)
- HBT (npnVp, npnVs, npnVh) : No measurable Current Gain drift! Highly stable.
- Diode pn-nw : No measurable Reverse Current drift! Highly stable.
- Resistor drifts (RHIGH ~ +4%, RPPD < 1%, RPND < 0.5%)
- CMIM capacitor drifts @ V=25V < +/- 0.2%
- Varactor capacitor drifts @ V=4.5V < -2.0%

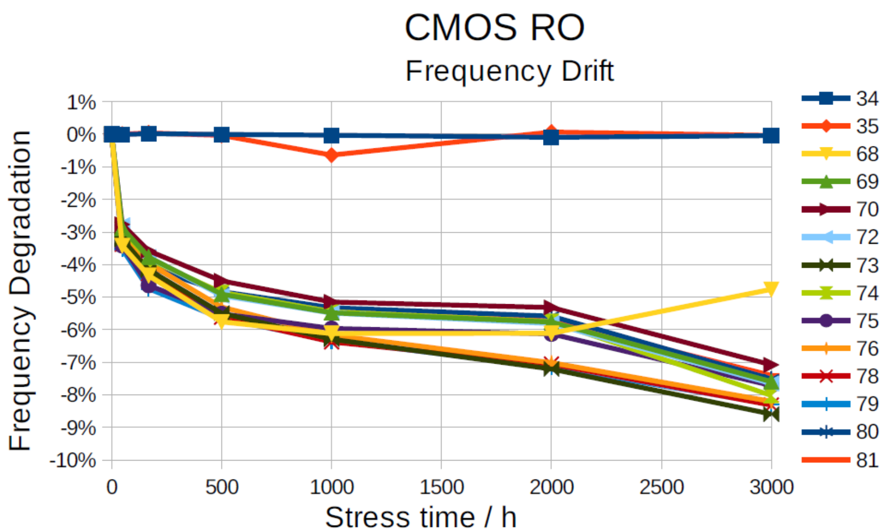


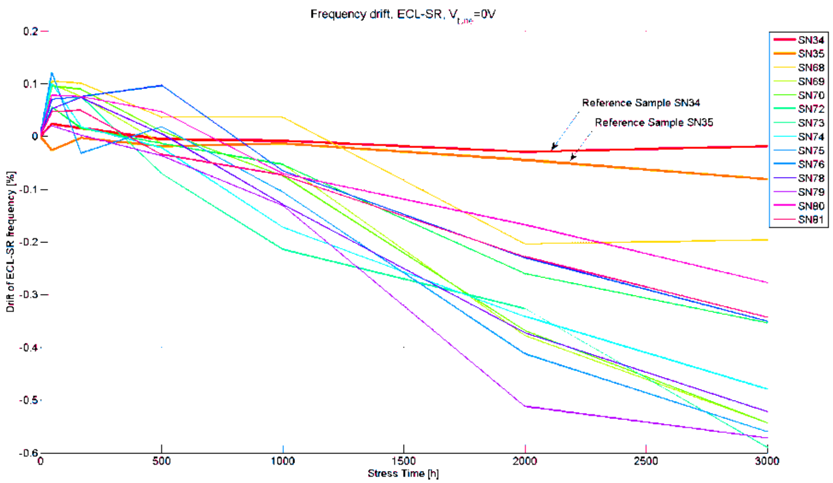


Evaluation of SGB25RH

DEC-I Endurance Testing (3000h, 150°C)

- CMOS Ring Oscillators (VDD=+3.7V) drift < -9.0%
- ECL Shift Register VCO (Clock) Frequency drift < -0.6% (0V); higher for higher VTUNE



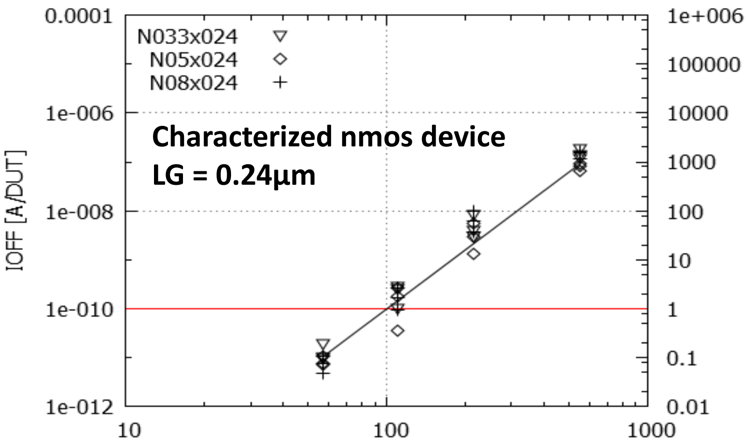


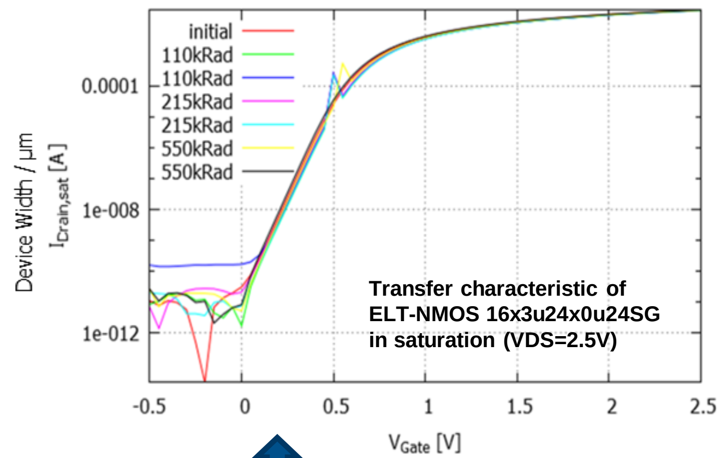
DEC-II Endurance Testing (2x2000h, 24°C)

- CMOS Ring Oscillators (VDD=+3.7V) drift < -16.0% (higher w.r.t. LLT @ 150°C) → HCI
  - CMOS Inverter (minimum size) – Lifetime of ~20 years @ 300MHz & VDD=+2.7V
- HBT Ring Oscillators – no drift evidenced

Evaluation of SGB25RH

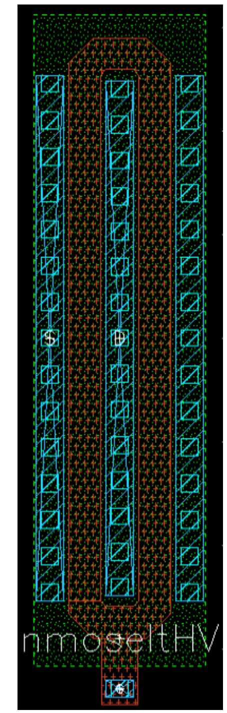
Radiation Assessment Results (Total Ionizing Dose)



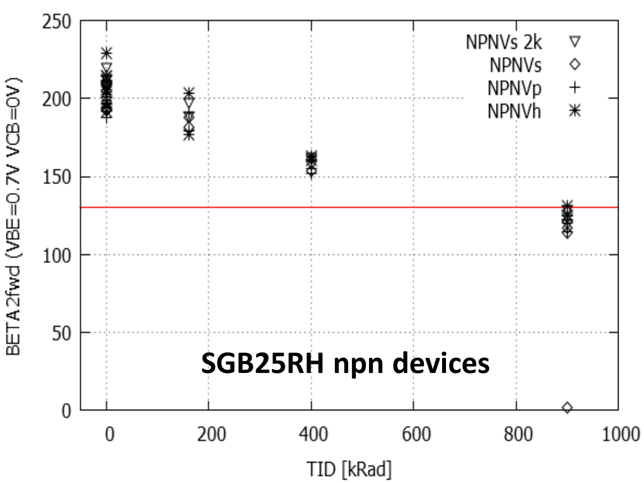


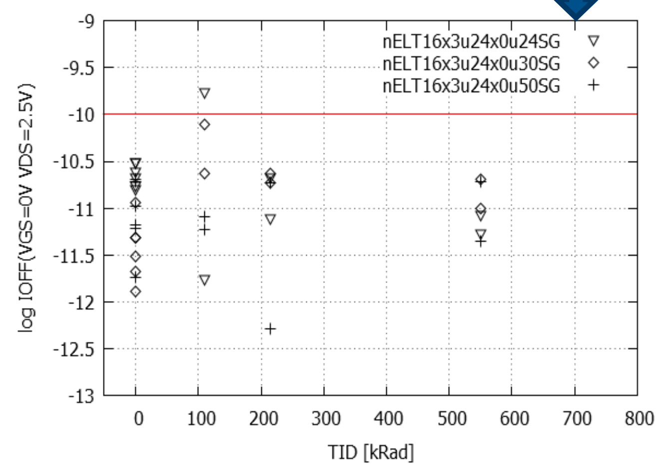
OHB

ELT-nmos
Edgeless transistor
RHBD



eltnmos device





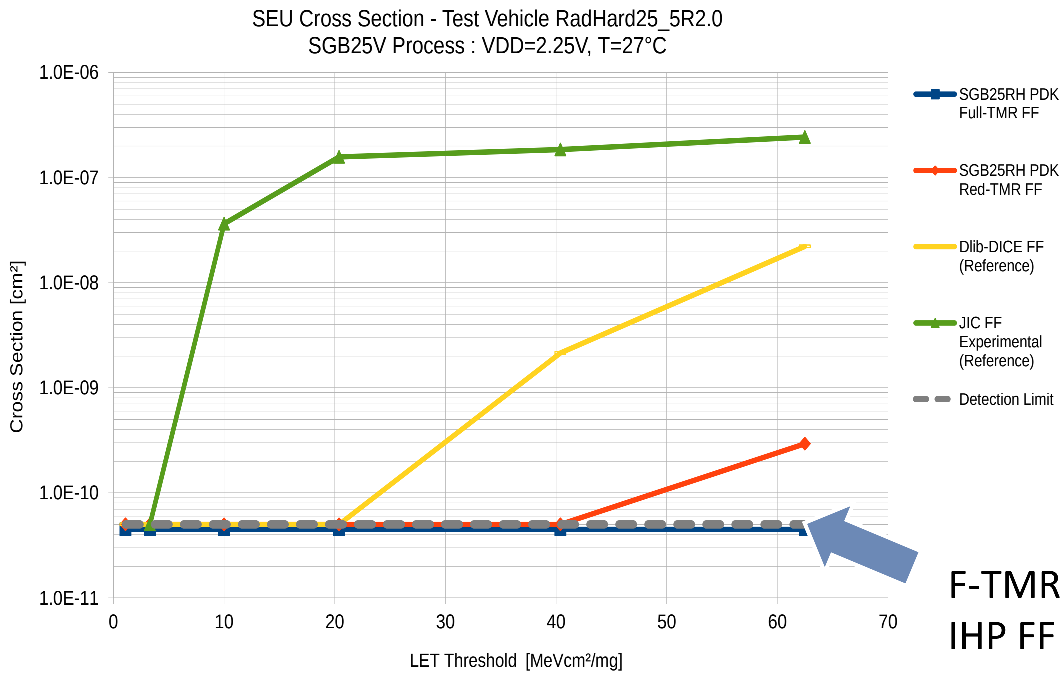
Radiation Source : Helmholtz-Zentrum Berlin für Materialien und Energie GmbH, Berlin. Gamma rays provided by Co^{60} source. Dosimetry performed by Farmer Ionization Chamber, nominal photon energy range from 60kV to 50MV.

Test Hardware : Keithley SCS-4200 Semiconductor Parameter Analyzer with Keithley 707B Switch Matrix Custom IHP Test Fixtures for measurements.

Evaluation of SGB25RH

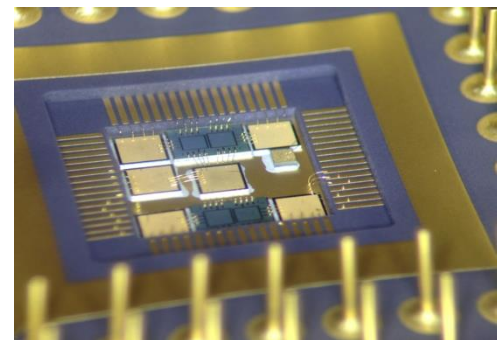
Radiation Assessment (SEU/SEL) on Digital CMOS Std Cell Library

- No SEL detected up to tested 65MeV/cm²/mg @ +105°C
- Standard Cell CMOS Libraries will cover all applications with TID rated up to 300krad(Si)

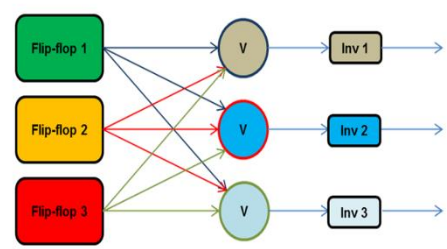


DEC Test Vehicle

4 Shift Registers based on different D-FFs



F-TMR
IHP FF



Radiation Source :
Heavy Ion Facility - UCL - Université de Louvain-la-Neuve (Belgium)
Test Hardware :
Custom IHP + ARQUIMEA FPGA based Test Board & Fixtures for measurements.

Evaluation of SG13RH

PDK SG13RH based on :

- Qualified SG13S Standard Commercial SiGe:C BiCMOS Dual Oxide
  - BEOL 5 thin + 2 thick (TM1:2µm TM2:3µm) Al metal layers + MIM Capacitor Layer
  - SiGe HBTs npnVp ($f_{MAX}/f_T/BV_{CEO}$) : 340GHz/250GHz/1.7V ; npnV1 : 220GHz/180GHz/3.7V
  - CMOS Library Core Voltage +1.2V; IO Library +3.3V
- RHBD Libraries
  - Analog Devices (npn-HBT, MOS devices incl. ELT- RHBD version)
  - Digital Standard Cell Core and IO Libraries RHBD special cells (80 cells)

Activity promoted by DLR and IHP – Radiation Assessment

Goal :

- Design of Test Vehicles TCV, DEC
- Process Radiation Assessment i.a.w. :
  - ESCC N°. 25100 (SEE Testing)
  - ESCC N°. 22900 (Total Dose Steady State Irradiation Test Method) & MIL-STD-750E TM1019, MIL-STD-883H TM1019 Condition A and/or ESCC 22900 Window1
- Draft Definition of Capability Domain i.a.w. ESCC 24300
- Process Identification Document (PID) i.a.w. ESCC 22700

Further activities : proceeding into Evaluation Testing i.a.w. 2269010 (Endurance)

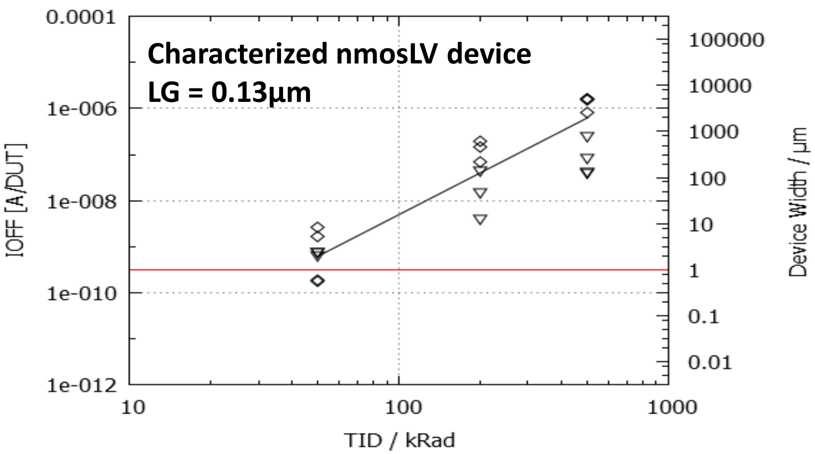
Evaluation of SG13RH

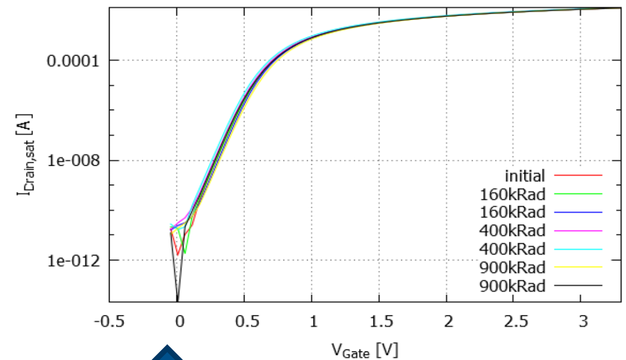
Test Vehicles as requested by ESCC Basic Specification 2269010

- TCV all single devices / elements of technology / min. size MOS and npn-HBT devices
  - TID, ELDRS Radiation Testing completed
- DECs – several defined comprising of analog and digital circuits
  - CMOS Test Structures (Shift Registers, Ring-Oscillators, Latch-Up)
    - Final Version currently in Manufacturing
    - Shift-Registers Test Structures based on IHP RHBD DFFs tested! Thresholds SEL/SEU > 40Mev/cm²/mg
    - Assembly and HI Testing – Fall 2016.
  - Bipolar HBT Test Structures (Ring-Oscillators, ECL Shift Register, BGR + PTAT Stable References)
    - Final Version design near completion - Manufacturing start planned for Sept. 2016
    - TID, SEE Testing early 2016
- RIC – Integrated Low Phase Noise Programmable RF Synthesizer (VCO+PLL)
  - Design ready – manufacturing not planned in present activity

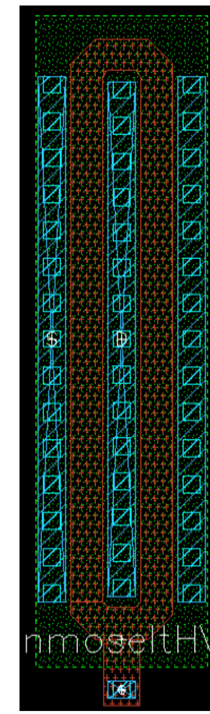
Evaluation of SG13RH

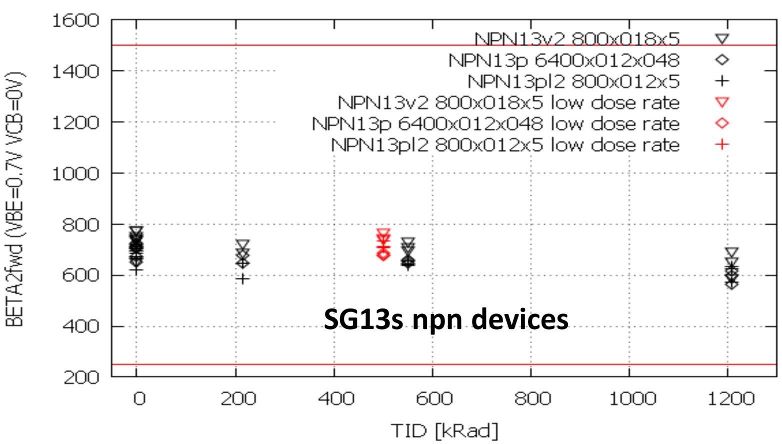
Radiation Assessment Results TCV (Total Ionizing Dose)



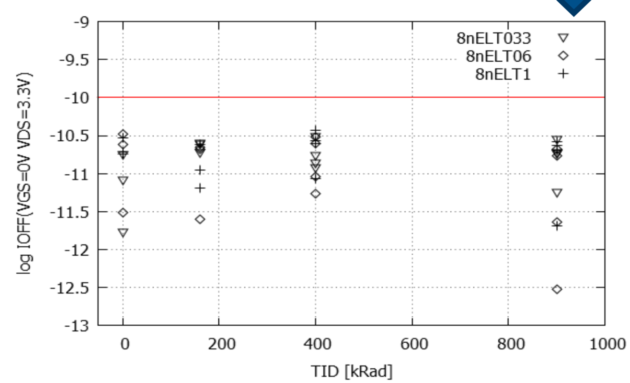


ELT-nmos
Edgeless transistor
RHBD





nmoseltHV device



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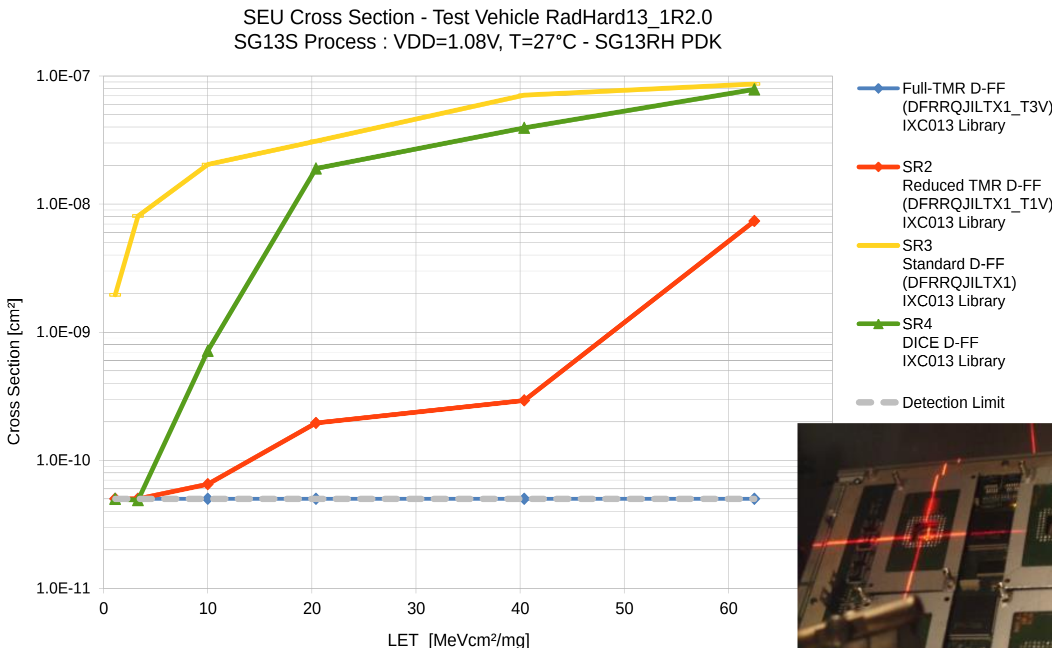
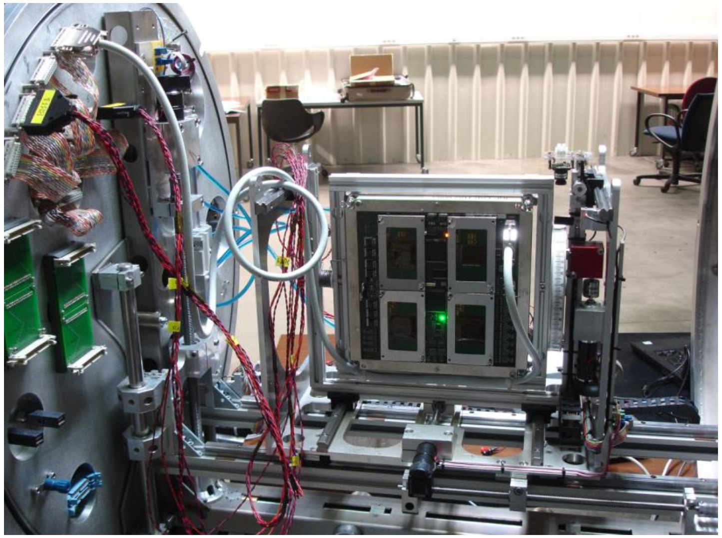
Test Hardware : Keithley SCS-4200 Semiconductor Parameter Analyzer with Keithley 707B Switch Matrix Custom IHP Test Fixtures for measurements.

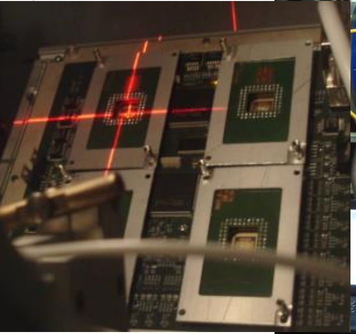
Evaluation of SG13RH

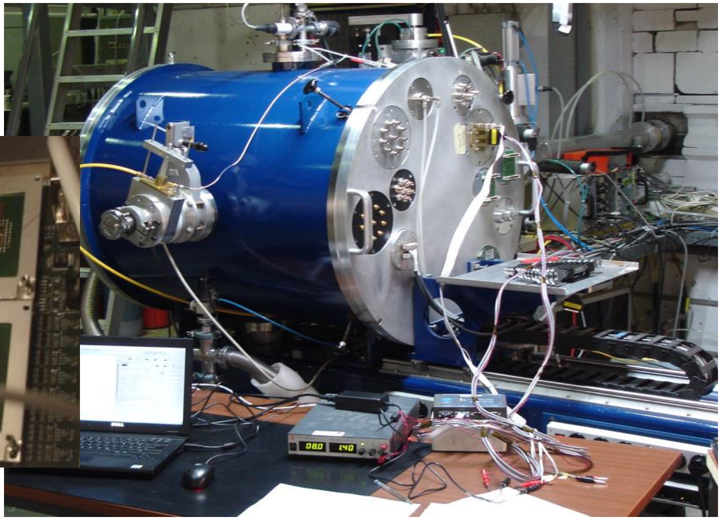
Radiation Assessment Results CMOS Test Structures

- IXC013RH CMOS Library and RHBD cells
- Intermediate Test Vehicle – RadHard13_1
  - 4 Shift Registers based on different D-FFs
  - Test Results (WK47 – 2015)









Radiation Source :
Heavy Ion Facility - UCL - Université de Louvain-la-Neuve (Belgium)
Test Hardware :
Custom IHP + ARQUIMEA FPGA based Test Board & Fixtures for measurements.

IHP Processes and PDKs for Space Applications

Summary I of II

Status : June 2016

	SGB25V/RH	SG13S/RH
■ Process Description	SiGe HBTs npn Peak f_T /f_{MAX} 75/95GHz 250nm CMOS (V_{DD}=+2.5V;T_{OX} = 5.8nm)	SiGe HBTs npn Peak f_T /f_{MAX} 220/340GHz 130nm Dual Gate –Oxide CMOS (V_{DD}=+1.2V, +3.3V ; T_{OX} = 2nm / 7nm)
■ Applications	Mixed-Signal MMIC/ASICs up to Ku Band	Mixed-Signal MMIC/ASICs up to W-Band
■ Commercial Qualification – Based on JEDEC Standard JP001.01 – QML/QPL (ESCC QPL, ESCC QML, MIL QPL, JAXA QPL)	**Re-Qualified 2010** **active & stable > 10 years (2005)** No QML/QPL	**completed 2014** No QML/QPL
■ Radiation Assessment (Analog) ■ HBT npn (all devices) ■ PMOS ■ NMOS (WG=1µm) ■ ELT-NMOS (RHBD Device)	**completed** PASS TID 800krad(Si) incl. ELDRS TID > 550krad(Si) PASS TID 100krad(Si) Characterized up to 500krad(Si) TID > 550krad(Si)	**completed** PASS TID >1210krad(Si) no ELDRS TID > 200 (HV) / 500 (LV) krad(Si) PASS TID 50krad(Si) (LV) Characterized up to 500krad(Si) TID > 900krad(Si)

IHP Processes and PDKs for Space Applications

Summary II of III

Status : June 2016

	SGB25V/RH	SG13S/RH
■ PDK Availability ■ Access Status	completed NDA – Unrestricted Royalties on Dolphin Library	In development NDA – Unrestricted (Early Access) NO ROYALTIES
■ CMOS Std Cell Core and IO Libraries	Dolphin SESAME2-LP core cells + special RHBD cells (IHP) (80 cells) Saphyrion SAGL (25 cells) (Tested for SEU/SEL only)	IHP IXC013RH (~ 90 cells)
■ Radiation Assessment (Digital) ■ TID ■ CMOS Libraries	100krad(Si) – 300krad(Si) SEU/SEL completed Threshold > 65MeV/cm²/mg (RHBD IHP cells) Threshold ~ 35MeV/cm²/mg (IHP DICE FF)	100krad(Si) – 300krad(Si) SEU/SEL partially completed Threshold > 65MeV/cm²/mg (RHBD IHP cells) Finalization during Fall 2016

IHP Processes and PDKs for Space Applications

Summary III of III

Status : June 2016

	SGB25V/RH	SG13S/RH
■ Evaluation Testing ■ in acc. ESCC No. 2269010	completed	not yet performed
■ Operation Temperature (max rated T_J)	-55°C to +125°C	-55°C to +125°C (TBC)
■ Test Vehicles ■ in acc. ESCC No. 2269010	TCV, DEC-I/-II, RIC	TCV, DEC –I (CMOS) DEC-II (Bipolar) update in progress RIC in progress
■ Radiation Tests ■ TCV (Devices, analog) ■ DECs (Digital, Analog BiCMOS) ■ RIC (Mixed-Signal IC)	completed „ DEC-I (SEU/SEL), Early structures TID + SEE LO RIC	partially completed completed partial planned
■ Endurance Testing HT & RT ■ HBT npns devices ■ HBT lifetime determination ■ CMOS devices ■ CMOS Core & IO Std Cell Library	passed very stable : no or low drifts characterization available drifts are mesured and defined lifetime determination ~ 20 years	not yet performed
■ Additional Tests (Reliability)	SiGe HBT HCI & Lifetime Estimation	SiGe HBT HCI & Lifetime Estimation

Thank you for your attention!

Cirillo, Maurizio

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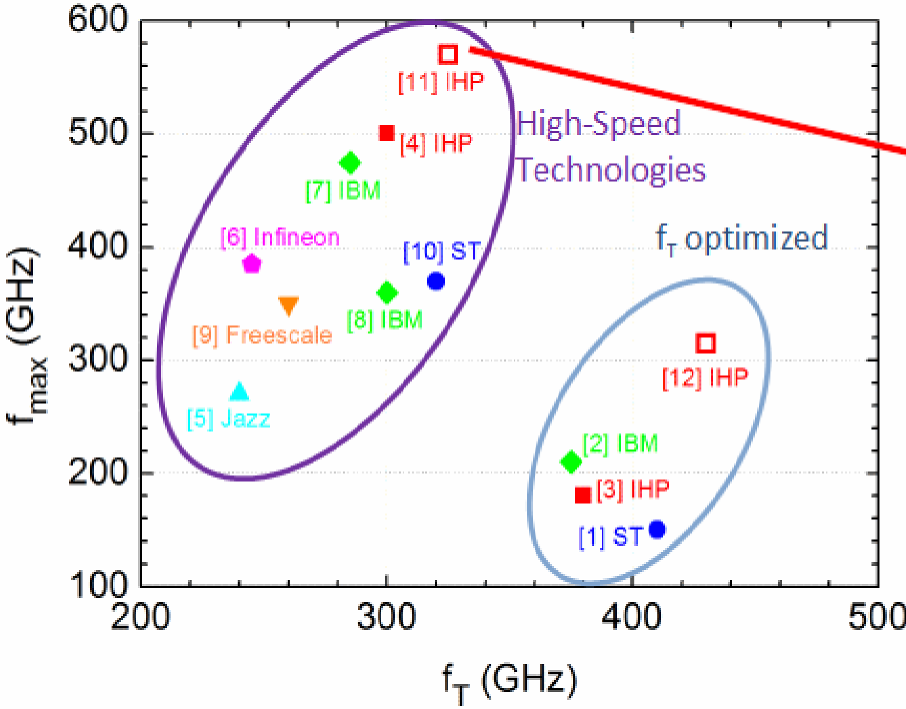
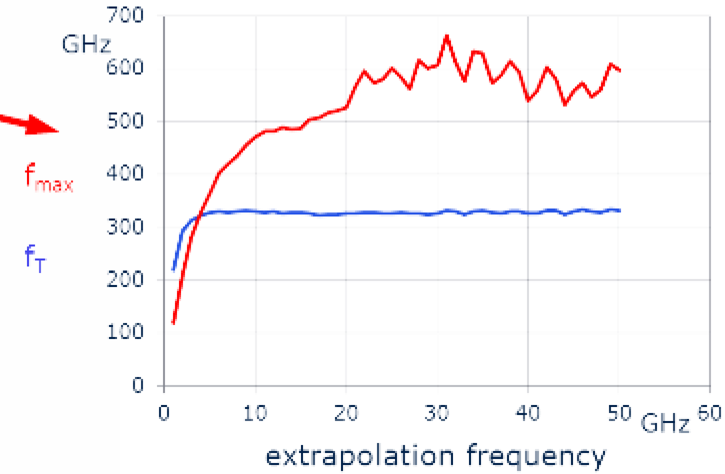
www.ihp-microelectronics.com

innovations for high performance microelectronics

Member of Leibniz Association

Outlook to possible Future fT/FMax Performance with SiGe





Böck et al. BCTM 2015

[1] Geynet et al. BCTM 2008
[2] Rieh et al. IPRM 2003
[3] Heinemann et al. IEDM 2004
[4] Heinemann et al. IEDM 2010
[5] Preisler et al. BCTM 2011
[6] Lachner et al. ECS 2014
[7] Liu et al. ECS 2014
[8] Pekarik et al. BCTM 2014
[9] John et al. BCTM 2014
[10] Chevalier et al. IEDM 2014
[11] Böck et al. BCTM 2015
[12] Korn et al. BCTM 2015

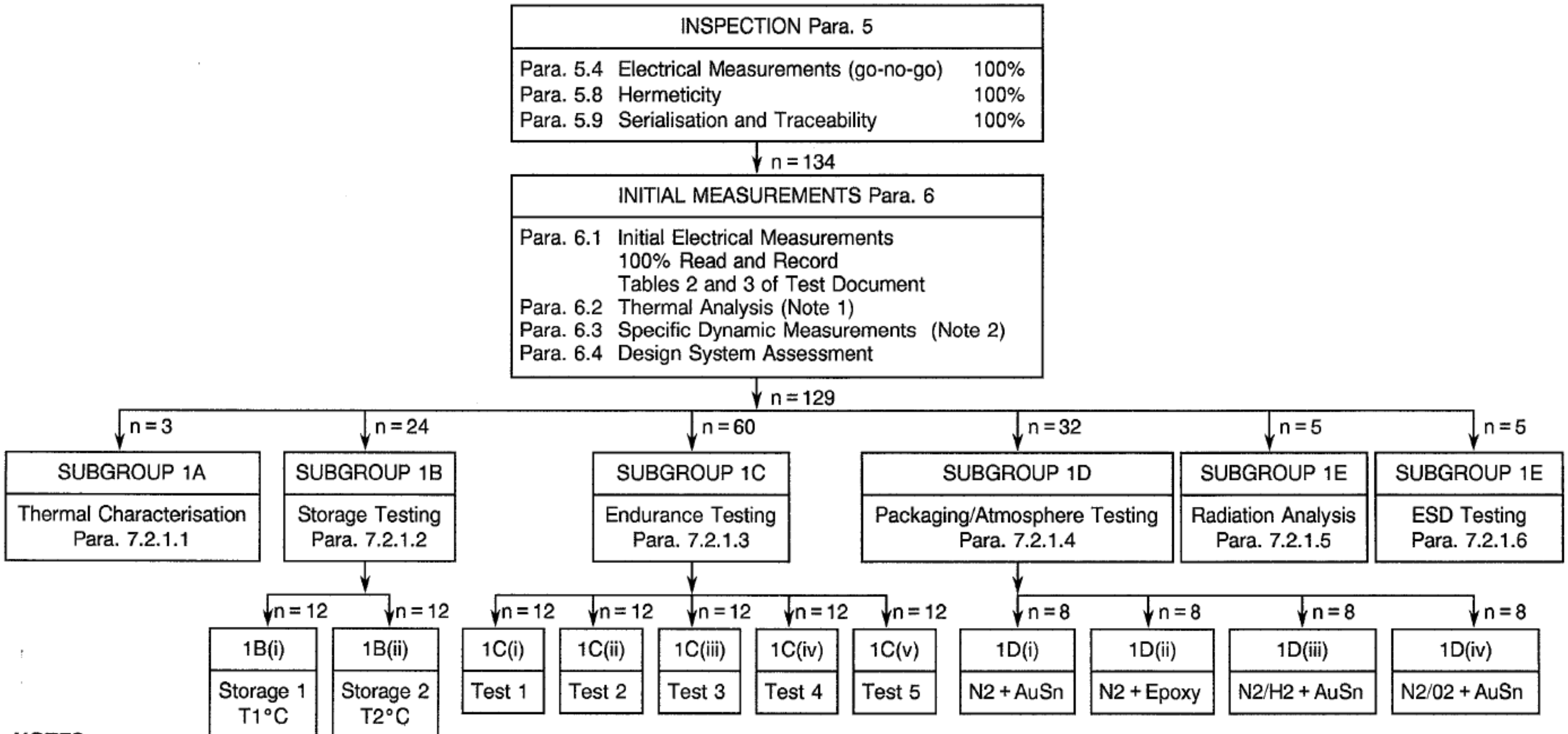
- Significant progress for fmax up to values ~ 600 GHz
- Only limited progress for fT over last years (often at the expense of fmax)
- Simulations shows that peak fT values close to 1 THz may be achievable [Schröter et al. TED 2011]

Evaluation Test Plan - ESCC 2269010 - MMIC Flow

Test Flow - TCV

CHART IB - EVALUATION TEST PROGRAMME FOR CAPABILITY APPROVAL

CHART IB1 - GROUP 1 TCV EVALUATION



NOTES

1. 5 devices out of the initial 134 devices could be destroyed in thermal analysis.
2. To be performed on either TCVs or DECs.

source: ESCC 2269010

Evaluation Test Plan - ESCC 2269010 - MMIC Flow

Test Flow – DEC, RIC

CHART IB2 - GROUP 2 DEC EVALUATION

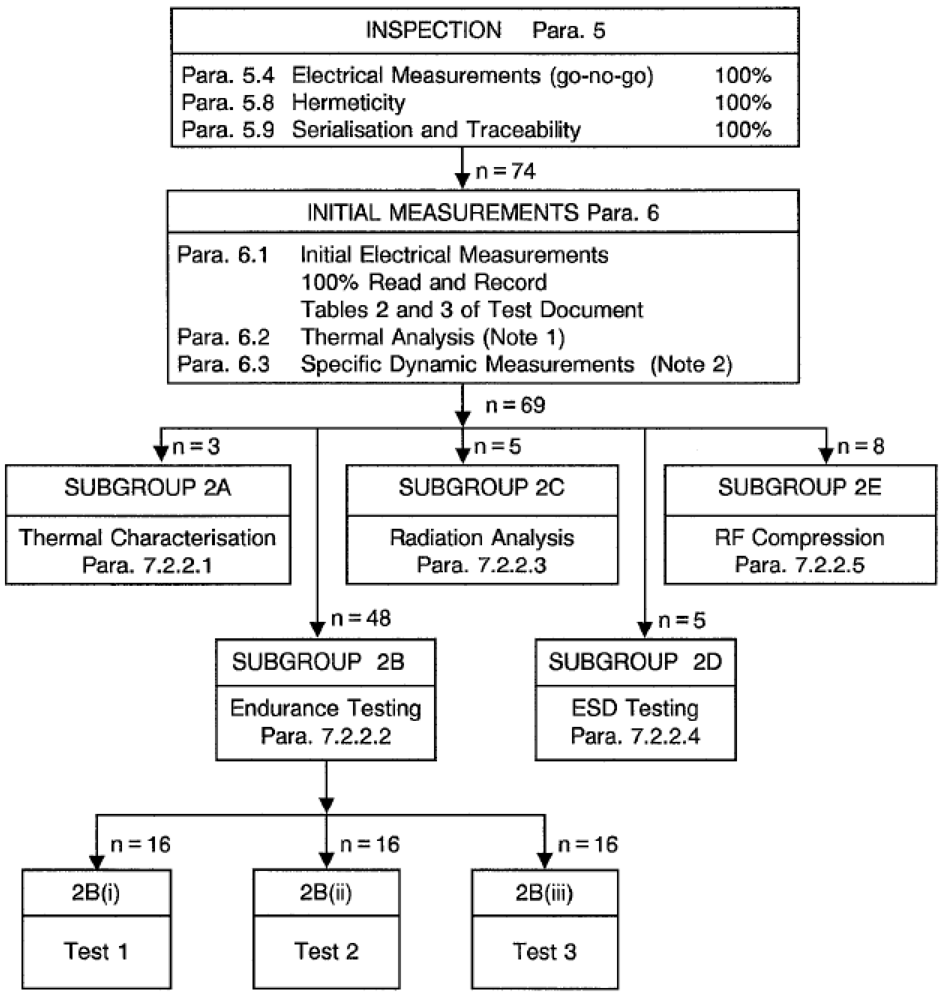
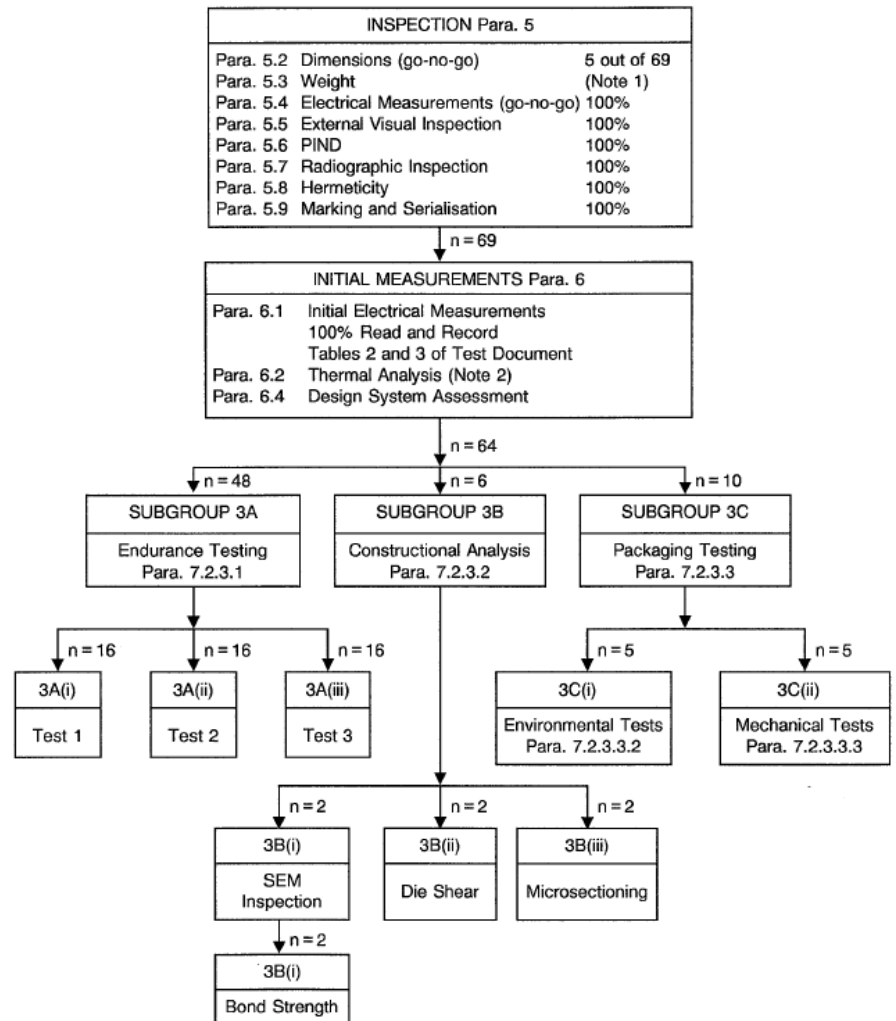


CHART IB3 - GROUP 3 RIC EVALUATION



source: ESCC 2269010

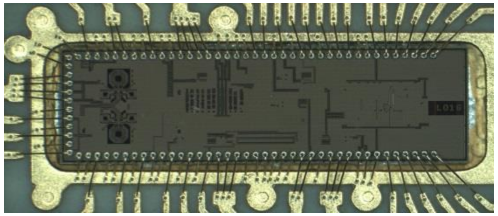
SGB25RH PDK Elements and Applications

Basic structure elements:

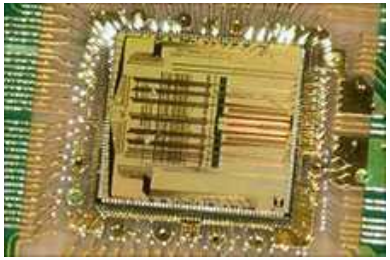
- PMOS
- NMOS
- I solated NMOS
- MOS Varactor
- RPND resistor
- RSIL resistor
- RPPD resistor
- RHIGH resistor
- MIM Capacitor
- npnVS bipolar HBT
- npnVH bipolar HBT
- npnVP bipolar HBT
- Inductor made by backend metal layer
- Antenna diode
- ESD clamp
- Digital standard cells
- Digital IO cells

Components in CMOS, bipolar and BiCMOS

- Maximal application frequency up to 20 GHz
- as chip or packaged
- Mixed Signal Technology
- fast counters
- fast shift register
- FlipFlops
- Dividers
- Frequency-/Phase comparator
- Charge pumps
- VCOs
- Linear amplifiers
- Current sources
- PLLs (integer and fractional)
- Digital Analog Converters
- etc.



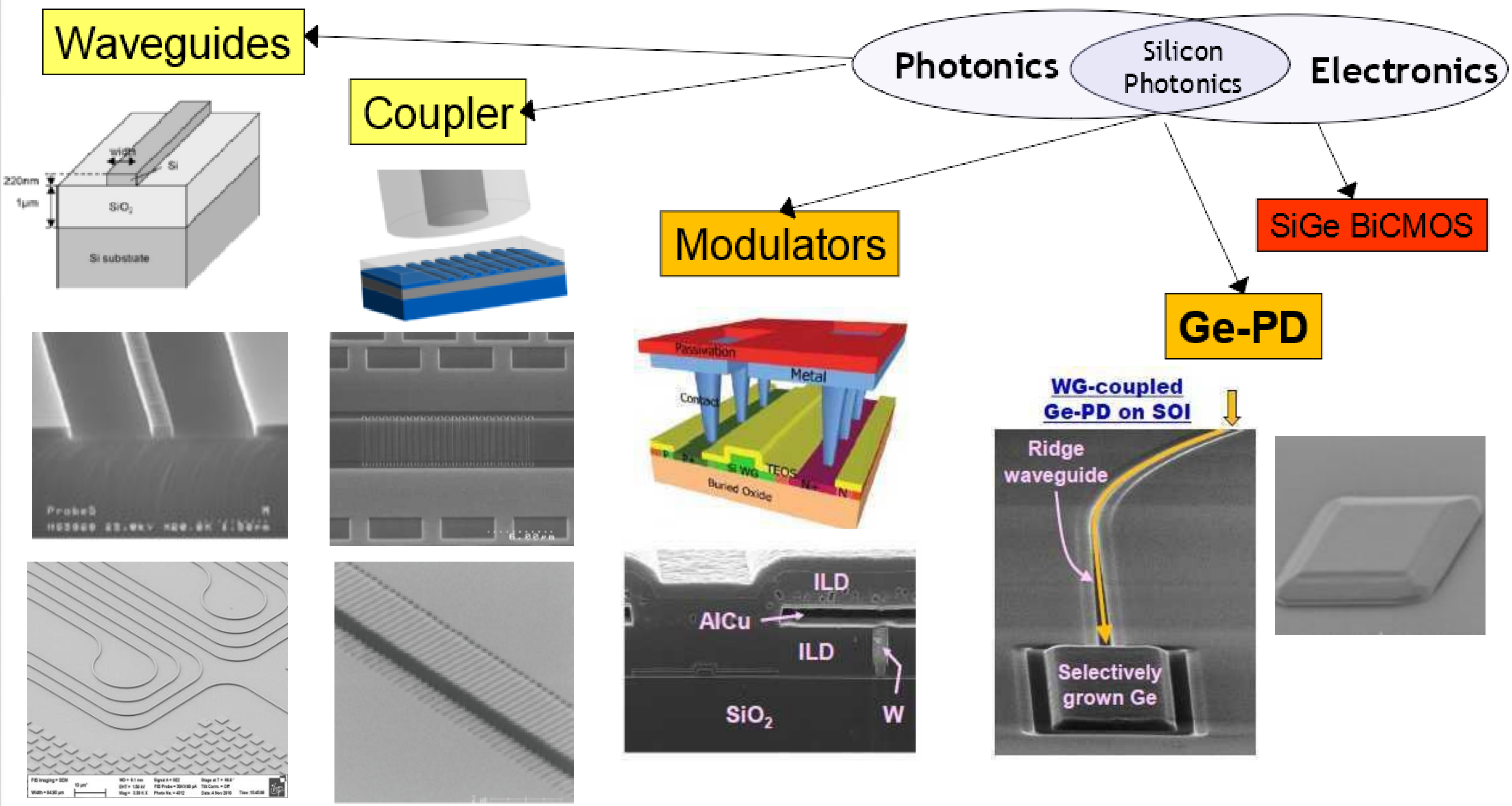
X-Band Local Oscillator Chip



12bit-1.5GSample DAC

Silicon Photonics @ IHP

PDK Offerings in SG25-EPIC and –PIC Module on 250nm Technology



New in 2016

- Extended possibilities – IHP Solutions
- New SG25H4 as replacement for SG25H1 MPW access
- SG25H4_EPIC Si-Photonic/BiCMOS technology
- SG25InP1 Heterointegratin of BiCMOS and InP HBTs (partnership FBH – IHP)
- TSV and RFMEMS module in SG13 technologies