Impact of process variation on the circuit performance (RO / LNA)

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Overview

1. Introduction
2. Process Parameters
3. RO Investigations
4. LNA Investigations
5. Conclusion
6. Future Prospects
1. Introduction

Further device scaling increases the impact of process variations on the circuit performance.
1. Introduction

• Methodology: The impact of 11 process parameters on 2 RF Designs is investigated
• Technology provided by ST Microelectronics → SiGe:C BiCMOS (B9MW)
• 1) Ring oscillator (RO) for 3.1GHz
   – Propagation delay 3.15ps
• 2) Low noise amplifier (LNA) for 94GHz
## 2. Process Parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Determination</th>
</tr>
</thead>
<tbody>
<tr>
<td>rsbx</td>
<td>Extrinsic base sheet resistance</td>
<td>PCM based parameter</td>
</tr>
</tbody>
</table>
| rea  | Emitter sheet resistance  
→ Variation of emitter resistance | PCM based parameter |
| rsbl | Buried layer sheet resistance  
→ Variation of buried layer resistance | PCM based parameter |
| rsbp | Pinch base sheet resistance  
→ Variation of pinched base resistance | PCM based parameter |
| nepi | Epi layer doping parameter  
→ Variation of SIC doping for BC capacitance variation | Fitting parameter |
## 2. Process Parameters

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
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</tr>
</thead>
</table>
| nsub  | Substrate doping level parameter  
→ Variation of substrate doping level for CS capacitance variation | Fitting parameter      |
| wepi  | Thickness of epi layer  
→ Variation of BC capacitance                                                               | Fitting parameter      |
| rec   | BE saturation current parameter  
→ Base current is monitored and rec is fitted                                                   | Fitting parameter      |
| deg   | Impact of bandgap variation on Ic  
→ Collector current is monitored and deg is fitted                                              | Fitting parameter      |
| irec  | BE recombination saturation current parameter  
→ Base current is monitored and irec is fitted                                                  | Fitting parameter      |
| wctf  | Tuning parameter for transit time  
→ Monitoring of ft and wctf is fitted                                                           | Fitting parameter      |
3. RO Investigations

- CML differential inverter with a current mirror
- Biasing through $V_{CC}$ and $V_{POL}$

**Diagram:**
- 53 Stages
- RO Oscillation Frequency: $f_0 \approx 3.1$GHz

**Components:**
- $T_1$, $T_2$, $T_3$, $T_4$
- $R_M$, $R_E$, $R_L$
- $V_{CC}$, $V_{EE}$, $V_{POL}$

**Values:**
- $R_M = 90 \Omega$
- $R_E = 30 \Omega$
- $R_L = 30 \Omega$
- $I_{En} = 5 \mu m$
3.2. RO: Measurements

![Graph](image1)

![Graph](image2)

- **V<sub>CC</sub>**
- **V<sub>EE</sub>**
- **V<sub>POL</sub>**
- **V<sub>EE</sub>**
- **V<sub>CC</sub>**

**Inverter Stage**

**RF<sub>out</sub>**
### 3.3. RO: Impact of Process Parameters

**Process Control Monitoring (PCM) of Extrinsic base sheet resistance**

- **External Base Resistance:** \( r_{bx} = \pm 10\% \)
- **RO Oscillation Frequency:** \( f_{o} = \pm 3\% \)

**Typical Value**

- **\( \text{nsigma}_{rsbx} \)**
  - Variation between \(-3\sigma\) and \(3\sigma\)
  - \( = 50 \) simulations

**Graphs:**

- Plot of \( V_{\text{swing}} \) vs. \( \Delta rsbx \)
- Plot of \( f_{o} \) vs. \( \Delta rsbx \)
3.3. RO: Impact of Process Parameters

Optimized parameters:
- $\text{nsigma}_{\text{rsbx}} = -3$
- $\text{nsigma}_{\text{nepi}} = -3$
- $\text{nsigma}_{\text{rsbp}} = 3$
- $\text{nsigma}_{\text{wctf}} = -3$

For 99.7% of all devices, the oscillation frequency can be differ:
- $f_0 = \pm 11\%$

TYP:
- $f_0 = 3.24\, \text{GHz}$

BEST CASE:
- $f_0 = 3.62\, \text{GHz}$

Biasing @ $V_{cc} = 3\, \text{V}$ and $V_{pol} = 1.9\, \text{V}$
3.3 RO: Wafer Map: Propagation Delay

Biasing @ $V_{cc}=3\text{V}$ and $V_{pol}=1.9\text{V}$

On one measured wafer the oscillation frequency differ: $f_o=\pm3\%$

$$t_p = \frac{1}{2 \cdot 53 \cdot f_o}$$

Crosses indicate measured devices
4. LNA Investigations

- Single cascode stage for 94.7 GHz

- Performance optimized through inter-stage matching inductor

- 1µm emitter length in order to achieve current density for minimum noise figure (NF)

- Transistors Q1 and Q2 with five emitter fingers

4. LNA Investigations

![Graph showing S parameters versus frequency]

- S11
- S12
- S21
- S22
- Simulation

- RF in
- RF out
- V bias
- V cc
4.3. LNA: Figures of Merit

Maximum small signal gain
\[ S_{21\text{max}} = 8.625 \text{dB} \]

Working Frequency
\[ f_{\text{LNA}} = 94.7 \text{GHz} \]

Noise Figure
\[ NF = 9.265 \text{dB} \]
4.3. LNA: Figures of Merit

1dB Compression Point
- $P_{in\_1dB} = -13$ dBm
- $P_{out\_1dB} = -5.43$ dBm

3$^{rd}$ Order Interception Point
- $IIP3 = 19.86$ dBm
- $OIP3 = 24.78$ dBm
4.3. LNA: Impact of Process Parameters

nsigma_wctf

→ Fitting parameter for the transit time
→ Changes the low-current forward transit time at $V_{BC}=0V \rightarrow t_0=\pm 10\%$

![Noise Figure](image1)
![Maximum small signal gain](image2)
4.3. LNA: Impact of Process Parameters

1dB Compression Point

3rd Order Interception Point

\[ S_{21_{\text{max}}} = \pm 2.94\% \]
\[ \text{NF} = \pm 2.62\% \]
\[ P_{\text{out1db}} = \pm 2.36\% \]
\[ I_{\text{IP3}} = \pm 2.09\% \]
\[ O_{\text{IP3}} = \pm 3.08\% \]
5. Discussion

**Optimized parameters RO**
- nsigma_rsbx=-3
- nsigma_nepi=-3
- nsigma_rsbp=3
- nsigma_wctf=-3

Can be influenced by the process engineers!

**Optimized parameters LNA**
- nsigma_rsbx=-3
- nsigma_rsbp=3
- nsigma_wctf=-3

**Changed HICUM Parameters**
- nsigma_rsbx → rbx
- nsigma_nepi → vdcx, rci0, cjci0, tr, vdc1, cjcx0
- nsigma_rsbp → qp0, vdei, cjep0, vdep, t0, tr, rbi0, cjei0
- nsigma_wctf → t0
5. Conclusions

• Only 4 out of 11 process variation parameters affect Figures of Merit of the presented RO and LNA
• These 4 parameters enhance RO as well the LNA performance (in the same direction)
• nsigma_rsbx and nsigma_rsbp are PCM based parameters
6. Future Prospects

- Measurement of FOM variations of the LNA
- Apply the same methodology for Mixer and PA designed for B9MW technology
- Process optimization in order to increase circuit performance
- Improve robustness of circuit design due to process variations
Thank you for your attention!

Acknowledgements: DOTFIVE, SIAM, Nano2012
Questions?

• E.g. What are the most important HiCuM parameters?
# Process Parameter -> HICUM

<table>
<thead>
<tr>
<th>Process Par.</th>
<th>Range</th>
<th>HICUM Par.</th>
<th>Rel. Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>nsigma_rsbx</td>
<td>[-3,3]</td>
<td>rbx</td>
<td>±10.33%</td>
</tr>
<tr>
<td>nsigma_rea</td>
<td>[-3,3]</td>
<td>re</td>
<td>±11.40%</td>
</tr>
<tr>
<td>nsigma_rsbl</td>
<td>[-3,3]</td>
<td>rcx</td>
<td>±9.25%</td>
</tr>
<tr>
<td>nsigma_rsbp</td>
<td>[-3,3]</td>
<td>qp0, vdei, cjep0, vdep, t0, tr, rbi0, cjei0</td>
<td>±25.96%, ±0.83%, ±5.06%, ±0.80%, ±8.48%, ±25.96%, ±25.96%, ±21.17%</td>
</tr>
<tr>
<td>nsigma_nepi</td>
<td>[-3,3]</td>
<td>vdcx, rci0, cjci0, tr, vdc, cjcx0</td>
<td>±0.25%, ±9.9%, ±3.39%, ±9.9%, ±0.37%, ±6.87%</td>
</tr>
<tr>
<td>Process Par.</td>
<td>Range</td>
<td>HICUM Par.</td>
<td>Rel. Change</td>
</tr>
<tr>
<td>-----------------</td>
<td>---------</td>
<td>------------</td>
<td>---------------</td>
</tr>
<tr>
<td>nsigma_nsub</td>
<td>[-3,3]</td>
<td>cjs0</td>
<td>±7.15e-6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>vds</td>
<td>±2.31e-6%</td>
</tr>
<tr>
<td>nsigma_wepi</td>
<td>[-3,3]</td>
<td>rci0</td>
<td>±9.9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>tr</td>
<td>±9.9%</td>
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<tr>
<td>nsigma_rec</td>
<td>[-3,3]</td>
<td>ibeis</td>
<td>±8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ibeps</td>
<td>±8%</td>
</tr>
<tr>
<td>nsigma_deg</td>
<td>[-3,3]</td>
<td>qp0</td>
<td>±24.99%</td>
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<td></td>
<td></td>
<td>tr</td>
<td>±24.99%</td>
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<tr>
<td>nsigma_irec</td>
<td>[-3,3]</td>
<td>ireis</td>
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<td></td>
<td></td>
<td>ireps</td>
<td>±51%</td>
</tr>
<tr>
<td>nsigma_wctf</td>
<td>[-3,3]</td>
<td>t0</td>
<td>±10.5%</td>
</tr>
</tbody>
</table>

These values are valid for a device with CBEBC configuration, emitter length $l_E=5 \mu m$ and emitter width $w_E=0.27\mu m$. 