An HCI-Healing 60GHz CMOS Transceiver

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Outline

• Motivation
• Hot-Carrier-Injection Issues, Prior Arts and Proposed Solution
• Proposed HCI-Healing 60GHz TRX
  • Detailed circuit implementation
• Measurement and Comparison
• Conclusion
60GHz-Band Capability

Wireless Standards

- LTE
- WiMAX
- PDC
- UMTS
- GSM
- WLAN
- DVB-T
- ISDB-T
- GPS
- Bluetooth
- UWB

9-GHz BW @60-GHz band

Frequency (GHz)

Channels of IEEE 802.11ad standard

- 1
- 2
- 3
- 4

7.04 Gbps/ch in 16QAM

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Hot-Carrier-Injection Issue in CMOS (1/2)

CMOS power amplifier

Drain efficiency: $\eta = \frac{P_{\text{out}}}{P_{\text{DC}}}$

Class-A
$\eta = 50\%$

Large $V_{\text{ds,peak}} = 2V_{\text{DD}}$

HCl damage

Class-A
$\eta = 12.5\%$

Small $V_{\text{ds,peak}} = 1.5V_{\text{DD}}$

Low efficiency
Hot-Carrier-Injection Issue in CMOS (2/2)

Lifetime: the time when $\Delta I_{DS} = 10\%$ @ saturation

Stress cond.
$V_D=2.4\,V$
$V_G=0.8\,V$
1 hour

$V_D=1.2\,V$

HCl damage

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Hot-Carrier-Injection Mechanism

Generated defects: Trapped charges & Interface states

Gate oxide

Silicon

High field

Impact ionization

P-Substrate

Degrade $V_t$, $\mu_n$, $g_m$, $I_D$, and lifetime

Trapped charges & Interface states

[*Y. Leblebici et al., JSSC 1993]
HCl Issue in Advanced CMOS

HCl aging $\propto E_{\text{lateral}} \propto V_{ds}/L_{\text{eff}}$

HCl issues more severe

$V_{ds,\text{peak}}$ for same $V_{ds,\text{peak}}/L_{\text{eff}}$

HCl limited

$V_{ds,\text{peak}} = 1.35V^*$

Nominal $V_{DD}^{**}$

Voltage (V)

Process node (nm)

$\boxed{[**\text{ITRS2013}]}$

$[\text{*D. Stephens et al., RFIC 2009}]$
HCl Issues for 60-GHz Applications

2.4-GHz power amplifier

2.5 V

Thick oxide

$L=250$ nm (I/O Tr.)

$f_{\text{max}}=40$ GHz

60-GHz power amplifier

1.0 V

Standard

$L=65$ nm (core Tr.)

$f_{\text{max}}=220$ GHz
Summary of Prior HCI Solutions@60GHz

- $V_{DD}=1.2V$
- $P_{1dB}=10$ dBm
- Better lifetime
- Degraded output power, linearity and efficiency

Low $V_{DD}$ or Stack Tr.

- $V_{DD}=0.7V$
- $P_{1dB}=5$ dBm

Low $V_{DD}$

- Stack Transistor

- $V_{DD}=1.2V$
- $P_{1dB}=6$ dBm

[*[M. Tanomura et al., ISSCC 2008]*]  
[**A. Siligaris et al., JSSC 2010]*
Power Combining Techniques

Individual: $\text{PAE} = \frac{P_{\text{out},n} - P_{\text{in},n}}{I_n V_{\text{DD}}}$

Combined: $\text{PAE} = \frac{n \times (P_{\text{out},n} - P_{\text{in},n})}{n \times I_n V_{\text{DD}}}$

- Compensate output power and linearity
- Deteriorated efficiency cannot be improved

[*J. Chen et al., ISSCC 2011*]
Proposed HCl-Healing Technique

Ultimate solution: Physically heal HCl damage

\[ V_D = 1.2 \text{ V} \]

HCl damage

HCl healing

How?
Proposed HCl Healing Mechanism (1/2)

Damaged gate oxide

Damage mechanism: trapped electrons

[Y. Leblebici et al., JSSC 1993]
Proposed HCI Healing Mechanism (2/2)

Possible solution: charge ejection
Measured HCl-Healing $I_D-V_G$ Curves

**First** HCl healing demonstration

<table>
<thead>
<tr>
<th>Condition</th>
<th>$V_D$</th>
<th>$V_G$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress</td>
<td>2.4V</td>
<td>0.8V</td>
</tr>
<tr>
<td>Heal</td>
<td>2.2V</td>
<td>$V_D=0V$</td>
</tr>
</tbody>
</table>

$$V_D=1.2\text{ V}$$

- **Fresh**
- **Damaged**
- **Healed**

Accelerated Meas. $V_G=V_D=0V$, 1 second
**HCI-Healing Function in Transistor**

**First HCI healing transistor**

Floating source* & low drain bias** assisting ejection (memory cells)

Ejection of the trapped electrons

*Ejection is assisted by floating source and low drain bias.*

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[*T. Endoh et al., IEDM 1989]*

[**K. Miyaji et al., JJAP 2012]**
HCl-Healing Transistor Module

Equivalent circuit for 60-GHz operation

Equivalent circuit for HCl healing

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HCl-Healing Power Amplifier (1/3)

Proposed HCl healing block

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HCI-Healing Power Amplifier (2/3)

Deep n-well

VH
High voltage

VH

High Z

HCI healing status

RF_{in}

MIM TL

TL

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19.5: An HCI-Healing 60-GHz CMOS Transceiver
HCl-Healing Power Amplifier (3/3)

60GHz operation status

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HCI-Healing TRX Block Diagram

Direct Conversion

20GHz PLL+
60GHz QILO

Integrated HCI-healing function

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Die Micrograph

<table>
<thead>
<tr>
<th>Block</th>
<th>Area (mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX</td>
<td>0.79</td>
</tr>
<tr>
<td>RX</td>
<td>1.01</td>
</tr>
<tr>
<td>PLL</td>
<td>0.27</td>
</tr>
<tr>
<td>Logic</td>
<td>0.21</td>
</tr>
</tbody>
</table>
Measurements

- Transistor TEG
  - DC stress lifetime
  - AC stress lifetime
- Stand-alone PA TEG
  - $P_{\text{in}}-P_{\text{out}}$ with healing
  - AC stress lifetime with healing
- TRX Board
  - EVM versus $P_{\text{out}}$ with healing
65 nm NMOSFET DC Stress Lifetime

Lifetime = 63 years
@ $V_{DS}=1.2\, \text{V}$

\[ \tau = K \cdot e^{\frac{b}{V_{DS}}} \]

Stress condition

$V_{GS} = 0.8 \, \text{V}$

$V_{DS} = \ldots$

$V_{GS} = 0.8 \, \text{V}$

[*E. Takeda et al., EDL 1983]
65 nm NMOSFET RF Stress Lifetime

Lifetime = 2 hours

Freq. = 100 MHz
P_{out} = 11 \text{ dBm}

\Delta I_{DSat} = A \cdot t^{n*}

Stress condition

\[ \begin{align*}
V_{gs} & \uparrow & V_{ds} & \downarrow \\
0.8 \text{ V} & \uparrow & 1.2 \text{ V} & \downarrow \\
1 \text{ V} & \uparrow & 1.2 \text{ V} & \downarrow \\
\end{align*} \]

[*L. Negre et al., JSSC 2012]
Measured $P_{\text{in}} - P_{\text{out}}$ of the PA

DC Stress-AC Meas.

Freq.=60 GHz
$V_{G6}=0.7$ V

Symbols: $P_{1\text{dB}}$

Accelerated Meas.

Fresh
Damaged
Healed
Measured Lifetime of the PA

AC Stress-DC Meas.

- Fresh Tr. Stress $P_{out} = 7$ dBm
- Healed Tr. Stress $P_{out} = 7$ dBm

- Lifetime@10% Fresh Tr.: 1.2 year
- Lifetime@10% Healed Tr.: 81.2 years

$\Delta I_{D6}$ (%)

Time (s)

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Measured TX EVM versus $P_{out}$

- Fresh 9dBm
- Stress cond. 12.5dBm with $V_{DD}=1.5V$ (40hr)
- Damaged 5dBm
- Healed 8dBm

IEEE802.11ad MCS12(16QAM) specification 7Gb/s
# 60GHz TRX Performance Comparison

<table>
<thead>
<tr>
<th>Ref.</th>
<th>CMOS Process</th>
<th>Data rate (Modulation)</th>
<th>$P_{\text{out}} / \text{each PA}$ (dBm)</th>
<th>TX efficiency $P_{\text{out}} / P_{\text{DC}}$ (%)</th>
<th>HCI healing</th>
<th>Core area (mm²)</th>
<th>Power Consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tokyo Tech [1]</td>
<td>65nm</td>
<td>10.56Gb/s (64QAM) 28.16Gb/s (16QAM)</td>
<td>8.5* @TX EVM = -21dB</td>
<td>2.8</td>
<td>NO</td>
<td>3.9</td>
<td>TX: 251mW RX: 220mW</td>
</tr>
<tr>
<td>NEC [2]</td>
<td>90nm</td>
<td>2.6Gb/s (QPSK)</td>
<td>6</td>
<td>3.0 w/o PLL</td>
<td>NO</td>
<td>3.4</td>
<td>TX: 133mW RX: 206mW w/o PLL</td>
</tr>
<tr>
<td>Panasonic [3]</td>
<td>90nm</td>
<td>2.5Gb/s (QPSK)</td>
<td>1.9 @TX EVM = -19.6dB</td>
<td>0.4</td>
<td>NO</td>
<td>5.7</td>
<td>TX: 361mW RX: 260mW</td>
</tr>
<tr>
<td>Broadcom [4]</td>
<td>40nm</td>
<td>4.6Gb/s (16QAM)</td>
<td>-4* @TX EVM = -23dB</td>
<td>0.5</td>
<td>NO</td>
<td>26.3†</td>
<td>TX: 1190mW RX: 960mW 16x16 array</td>
</tr>
<tr>
<td>This work</td>
<td>65nm</td>
<td>7Gb/s (16QAM)</td>
<td>9.3 @TX EVM = -21dB</td>
<td>3.9</td>
<td>YES</td>
<td>2.3</td>
<td>TX: 218mW RX: 188mW</td>
</tr>
</tbody>
</table>

*Estimated from literature  †Chip area
Conclusions

– 60-GHz CMOS transceiver with HCI damage healing function by using charge ejection technique.
– 81-year lifetime without sacrificing the output power and efficiency
– The transceiver demonstrates an EVM of -27.9dB and can transmit 7Gb/s in 16QAM within 2.16GHz bandwidth.
Acknowledgement

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References


References


