THE ART OF ANALOG INTEGRATED CIRCUITS

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WHAT ARE ANALOG FUNCTIONS?

Source: B. Razavi, “Fundamentals of Microelectronics”
WHAT ARE ANALOG CIRCUITS?
EXAMPLE: SMARTPHONE

Source: Chipworks Teardown Report, BPT-1509-801
... AND THERE ARE LOTS OF ANALOG APPLICATIONS

Cellular RF (PA, filter) | Power management | Sensors (proximity, ambient light, compass, gyro, accelerometer, barometer, fingerprint)

Audio

Cellular RF (transceiver, filter) | Power management | Power management | Audio NFC

Interface (microphones, touch, display, camera)

WiFi+BT (RF transceiver, modem)

Source: TECHINSIGHTS, teardown.com
HOW SMALL ARE NM?

- Mark: 1.66 m
- Fly: 7 mm
- Mite: 300 um
- Blood Cell: 7 um
- Virus: 100 nm
- Silicon Atom: 0.24 nm

Source: M. Bohr, IDF 14
1874: Karl Ferdinand Braun discovers the rectifying effect of galena. This is later used as a radio receiver using a crystal detector ("Cat’s whisker"), the first semiconductor electronic device.
1906: Robert von Lieben and (independently) Lee de Forest invent the first amplifier based on a vacuum tube: The triode (or “Audion”)
1947: John Bardeen, William Shockley and Walter Brattain demonstrate the first semiconductor transistor (Ge) at Bell Labs.

Source: Bell Telephone Labs; Computer History Museum
HISTORY: THE INTEGRATED CIRCUIT (IC)

After the first solid-state circuit by Jack Kilby (1958), Robert Noyce and team build the first monolithic integrated circuit with PN-junction isolation at Fairchild (1960):

A flip-flop in transistor-resistor logic

Source: Computer History Museum; B. Lojek “History of Semiconductor Engineering”, EE Times
1964: Robert J. Widlar, the “Father of Analog Integrated Circuits”, designs the first integrated op-amp: The µA702

Source: T. Lee “Tales of the Continuum: A Subsamples History of Analog Circuits" 2007; Smithsonian
1965: Gordon E. Moore, based on 4 data points, makes a bold prediction which would eventually become “Moore’s Law”.

Source: G. E. Moore “Cramming more components onto integrated circuits”, Electronics, 1965
1974: Robert H. Dennard and his group at IBM create the foundation of the modern semiconductor world based on their scaling rules.

Source: B. Holt, ISSCC’16 keynote; IEEE
HISTORY: PLANAR MOSFET POISED TO SHRINK

<table>
<thead>
<tr>
<th>Device or Circuit Parameter</th>
<th>Scaling Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device dimension $t_{OX}$, $W$, $L$</td>
<td>$1/K$</td>
</tr>
<tr>
<td>Doping concentration $N_a$</td>
<td>$K$</td>
</tr>
<tr>
<td>Voltage $V$ [VDD, $V_T$]</td>
<td>$1/K$</td>
</tr>
<tr>
<td>Current $I$ [$I_D$]</td>
<td>$1/K$</td>
</tr>
<tr>
<td>Capacitance $\varepsilon A/t$</td>
<td>$1/K$</td>
</tr>
<tr>
<td>Delay time/circuit $VC/I$</td>
<td>$1/K$</td>
</tr>
<tr>
<td>Power dissipation/circuit $VI$</td>
<td>$1/K^2$</td>
</tr>
<tr>
<td>Transit frequency</td>
<td>$K$</td>
</tr>
<tr>
<td>Power density $VI/A$</td>
<td>$1$</td>
</tr>
<tr>
<td>Line resistance $R_L = \rho L/Wt$</td>
<td>$K$</td>
</tr>
</tbody>
</table>

**HISTORY: PLANAR MOSFET POISED TO SHRINK**

Source: Dennard et al., "Design of Ion-Implanted MOSFET's with Very Small Physical Dimensions", JSSC, 1974
WHAT IF...?

Source: J. Bradford DeLong, UCB; ITRS; Computer History Museum
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BUT: Classical CMOS scaling running out of steam

😍 Gate oxide too thin
😡 Leakage currents too large (D-S, G-S, D-B)
🙄 Wavelength of lithography
😡 Economics

SHRINKING IS GETTING TOUGHER

How are Circuits designed and Why is that an Art?
THE DEVELOPMENT FLOW OF ANALOG CIRCUITS & SYSTEMS

Brainstorm Ideas
Evaluate Specifications

Design Block-Level System

Design Component-Level Circuit

Test & Debug

Layout & Fabricate

Simulate Design
THE PLANAR MOSFET IS A VERSATILE DEVICE

Depending on bias conditions can act as

- Switch
- Resistor (variable)
- Capacitor (variable)
- Diode
- Voltage-controlled current source

\[
I_{DS} = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})^2 (1 + \lambda V_{DS})
\]

Source: Razavi, Fundamentals of Microelectronics
HUGE VARIETY OF CIRCUIT TOPOLOGIES
EXAMPLE: VARIOUS CIRCUITS USING TWO FETS

- INVERTER (OR AMPLIFIER)
- T-GATE
- CURRENT MIRROR
- (PSEUDO) DIFF PAIR
- PUSH-PULL
- MULTIPLEXER
- CS WITH ACTIVE LOAD
- NEG RESISTOR
- SAMPLE & HOLD (OR RC-FILTER) (OR SWITCH-CAP)
- CS WITH CASCODE (OR CURRENT SOURCE)
- VOLTAGE REFERENCE
- PEAK DETECT
- SOURCE FOLLOWER
- VOLTAGE DIVIDER
A LOT TO CONSIDER FOR NOVEL CIRCUITS

Production tolerance  Device mismatch  Wiring impact (R, L, C, K)  Environmental factors (supply / temperature)

Short channel effects  Topology selection

Model deficiencies  Interactions between blocks

Design trade-offs (area / power / performance)  Architectural trade-offs (analog-digital / HW-SW)

Source: TECHINSIGHTS, teardown.com
FUTURE RESEARCH

- Wireless
- Power Management
- New Technologies

Source: Intel; 3GPP
FUTURE RESEARCH: WIRELESS

Wireless will further proliferate
- Today: 450Mb/s in LTE-Advanced
- In Reach: 1Gb/s

Next step: 5th generation mobile
- Hot topic in academia & industry
- >10Gbit/s
- Billions of devices, 10yrs on battery
- New technology: mm-Wave (28/38GHz)
  - Low-power implementation is key

Source: Anritsu, “Understanding 5G”
FUTURE RESEARCH: POWER MANAGEMENT

„Wireless“ bogged down by need to recharge battery

- Main factor is increased usage
  - Assuming 1800mAh battery
  - Standby: 25 days (@ 3mA idle current)
  - Talk time: 18h (@ 100mA 3G current)

- Target for IoT connectivity
  - 10yrs on 2 AA batteries (~6000mAh)
  - Idle current: 70µA

Alternative: Battery-less

- For tiny sensors battery volume (and waste) is a burden
- Generate energy from fields (RF, LF) or from harvesters (photovoltaic)

- Wireless data & energy critically important for medical use

Source: Energizer E91 datasheet; Ericsson/NSN “LTE Evolution for Cellular IoT”; Shenoy, ISSCC 2016
**FUTURE RESEARCH: NEW TECHNOLOGIES**

- **FinFET** (or TriGate-FET) from 22nm (Intel) resp. 16nm (Samsung, TSMC) in production for digital IC
- Improved performance for analog (future)
  - Very low VDD (<1V)
  - PMOS almost as strong as NMOS
  - Less DIBL, good subthreshold

![Image of FinFET device]

**Different technologies under investigation → novel devices**

Source: Holt, ISSCC 2016 keynote; TSMC, IEDM 2014
TWO THOUGHTS TO TAKE HOME WITH YOU

Without decades-long progress in semiconductors the world would look drastically different today – But it is getting more difficult to keep the exponential alive!

New applications, new technologies and new ideas will drive forward analog integrated circuit design – It will continue to be a highly fascinating field!