Ultra Low Power
Analog Integrated Circuits
for Implantable Medical Devices

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CCC Medical Devices
nanoWattICs
Objectives of this talk

- Introduce the needs and characteristics of Active Implantable Medical Devices (AIMDs) from the circuit designer point of view.
- Present the techniques and circuits applied in Analog ULP
  - Device Modeling
  - Design Methodology
  - Circuit techniques
- Show the current research and development topics and prospects of the area
Founded 1888, approx. 1k new students / year, 670 teaching staff
Microelectronics Group

- Since 1991
- Under Graduate & Graduate Teaching (MSc, PhD)
- Research
  - Design of Analog / RF and Mixed-Signal Integrated Circuits, particularly Ultra-Low Power (ULP)
  - Also works on ULP Digital / DC-DC and Embedded
- Industrial Experience
  - Implantable Medical Devices
- **2007: spin-off: NanoWattICs**
Implantable Devices in Uruguay

Feb. 3, 1960: Drs. O. Fiandra and R. Rubio performed the first effective pacemaker implant to a human being in the world.

1969: Dr. O. Fiandra founded CCC to develop and manufacture pacemakers.

1999: CCC develops a pacemaker line based on an ASIC designed by the Microelectronics Group of Universidad de la Republica.

Today: CCC designs and manufactures active implantable devices and complete medical systems for third parties.
Outline

I. System: Active Implantable Medical Devices Today

II. Transistors and Circuits: Analog Design for ULP.
   Transistor Modeling.
   Design Methodology.

III. Circuit Techniques: Implementation of AIMDs blocks

IV. Conclusions and Prospects
Active Implantable Medical Devices (AIMD)

- **Implantable**: Introduced **inside the body** by a medical procedure and **intended to remain there** after the procedure.

- **Active**: Including a Power Source

- Not considered here:
  - Passive implants (e.g. bone prostheses, valves, stents)
Portable, Wearable, Swallowable Medical Devices ...
AIMDs: Main Historical Milestones (I)

- Cardiac Pacemaker: first implantable device, 1960

- Cochlear Implants (1960s -)
AIMDs: Main Historical Milestones (II)

- Cardiac Defibrillators (1980)

- Deep Brain Stimulator for Parkinson (1995)
AIMDs: Some of the new developments

• Heart Failure
• Obesity
• Diabetes

• Neurostimulators:
  • Pain control
  • Blood pressure control
  • Foot drop correction
  • Urinary incontinence
  • Sleep Apnea
  • ...

• Patient monitoring
• Brain – computer interface
Some system examples

• Pacemaker:
  • **Goal**: Treat Bradycardia (slow heart rhythm) and conduction disorders between atria and ventricles
  • **How**: Stimulating to contract the heart when it does not contract spontaneously (“watchdog”)
  • **Sensing of**:
    • cardiac muscle signals that indicate ventricles / atria contraction
    • other indicators of physical activity, additionally in some cases
Basic Functions

- **Stimulation (Open Loop)**
  - Early Pacemakers
  - Cochlear Implants
  - Deep Brain Stimulators for Parkinson
  - Neurostimulators (sometimes “Man/Woman in the loop”)

- **Stimulation and Sensing (Closed Loop)**
  - Cardiac area (Pacemakers, Defibrillators, Heart Failure)
  - Obesity
  - Some Neurostimulators

- **Only Sensing**
  - Implanted “long term Holter” (“insertable loop recorder”)

- **Sensing + external actuation: Brain-computer interface**
Stimulation: Voltage mode

- E.g.: Pacemakers
- 0.1V … 7.5V
- 50μs … 1.5ms
- Requires battery voltage multiplier.
- RL: 500 Ohms typ.
Stimulation: Current mode

- Neurostimulators and others
- 0.1mA … 10mA
- 30μs … 300μs
- Load voltages up to 15V => Requires battery voltage multiplier
Sensing: Medical signals in general

- **Low frequency**: from $< 1$ Hz to a few kHz (neural signals)
- **Low amplitude**: $\mu$V to mV
- **Variability**: 

  "Most measured quantities vary with time, even when all controllable factors are fixed. Many medical measurements vary widely among normal patients, even when conditions are similar." (Source: J. Webster, *Medical Instrumentation. Application and Design*).

Objective of most analog signal processing: **qualitative** detection for closed loop control.

Traditionally advantage to **analog** implementation in terms of consumption, process scaling is changing this...
Sensing

- Biopotentials:
  - mioelectric signals (mVs, 100s Hz - 1kHz)
  - cardiac signals (mVs, 10s Hz – 300Hz)
  - neural signals (μVs, up to 8kHz)
- Impedance (tens of mOhms => μVs, few Hz)
- Movement (Physical activity, position) => accelerometer (μVs (sensor dependent), up to 10Hz)
Auxiliary Functions

- Telemetry
  - Inductive (up to 10cms)
  - 403 MHz MedRadio Band (a couple of meters)
- Battery Supervision (Voltage / Impedance / Consumed Charge Measurement)
- Lead Impedance Measurement
- Magnet Sensor (Reed Relay / Hall Sensor)
- Battery Recharge (if applicable)
- Control: Microcontroller & Firmware
Non-implantable System Components

Medical System Components

- IPG
- Leads
- Programmer System
- Patient wand
- Battery charger
- Logger
- PSA

IPG: Implantable Pulse Generator
Leads: Electrical connections to the heart
Logger: Data logger for monitoring
Battery charger: Device to charge the battery
PSA: Pacemaker System Accessory
Example: Implantable Pacemakers

Programmable Voltage Multiplier
0.1V_{DD} to 2-3 V_{DD}

Stimulus
35% / 6μA

Telemetry

Lead Selection (polarity)

Microcontroller
30% / 5μA

Activity Sensing
18% / 3μA

Sense Channel
17% / 2.8μA

Battery Supervision

Amplification, Filtering and Detection

Approx. Consumption Distribution
Example: Closed Loop Stimulator for Drop Foot Correction (I)

- Neurostep System (Simon Fraser Univ, Canada, Neurostream Technologies)
- Closed loop operation based on neural signal sensing and neural stimulation
- On clinical trials
Example: Closed Loop Stimulator for Drop Foot Correction (II)

http://www.youtube.com/watch?v=xH2vNu2BbnU
General Requirements: Size (and Battery)

Currently approximately 12 cc (5cm x 4cm x 0.6cm)
Approx. 30 to 40% occupied by the battery

Less consumption = Smaller size @ Equal Service Life

Consumption internal to the circuit: 50% to 75% of total consumption

There is room and need for improvement
General Requirements:  
Power Supply (II)

For higher average consumption devices:

- **Rechargeable lithium batteries** (since approx. year 2000, capacity in the order of **0.3Ah**)

- **Direct powering from RF energy transmitted transcutaneously**
General Requirements: Safety and Reliability

This is not acceptable !!!
General Requirements:
Safety and Reliability

Reliability => Frequency and probability of faults

Safety: Involves many aspects, particularly:

=> A single fault must not provoke a catastrophic event

High Reliability => Probability of single fault is low and double fault is virtually impossible

+ Safety

=> Probability of malfunctioning is low
=> Catastrophic Failure: virtually impossible
General Requirements: Safety and Reliability

Involves all the stages:

- System and Circuit Design
- System and Circuit Verification, Qualification and Medical Validation
- Medical Device Application, Configuration and Use

Strongly conditions design: E.g. Limiting DC leakage towards the heart under single fault conditions => external capacitors

Importance of paying attention from the very beginning to applicable standards on AIMD safety, risk analysis and applicable regulations.
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MOST Inversion Regimes (1)

Strong Inversion (S.I.)

\[ I_D \propto (V_G - V_T)^2 \]

Subthreshold Current

Moderate inversion

Weak inversion:

\[ I_D \propto e^{V_G/(n \cdot U_T)} \]

VG(V)

ID(A)

VT0
All regions, continuous MOST models

- **EKV** (Enz, Krummenacher, Vittoz, EPFL, AICSP 1995): originally mathematic interpolation between strong and weak inversion equations, now physical
- … or **experimental / simulation curves**

![Graph of current vs. voltage for different regions of MOST model](image-url)
“Intrinsic” MOS Amplifier

\[ A_0 = \frac{g_m}{g_d} \]

\[ f_T = \frac{g_m}{2\pi C_L} \]

• Consumption: \( I_D \)
• Speed \( \frac{g_m}{C_L} \)
• \( C_L \): total: external + parasitics
• Speed - Consumption trade-off : \( \frac{g_m}{I_D} \)
\[ \frac{g_m}{I_D} = \frac{1}{I_D} \frac{\partial I_D}{\partial V_G} = \frac{\partial \log(I_D)}{\partial V_G} \]

- \( g_m/I_D \) is the slope of \( I_D \) vs. \( V_G \) in log scale

Maximum in WI

Equal to \( 1/(n.U_T) \)

\( n \) typ: 1.3 a 1.5
\( \frac{g_m}{I_D} \) vs. \( I_D \)

- As the current increases, the “\( g_m \) generation efficiency decreases”
- To reach the maximum frequency allowed by the technology:
  \( \Rightarrow \) high \( g_m \) \( \Rightarrow \) high current \( \Rightarrow \) strong inversion \( \Rightarrow \) low efficiency

Bipolar Transistor:

\( \frac{g_m}{I_C} \), transistor bipolar

\( \frac{g_m}{I_C} \) independent of current in a wide range

\[ \frac{W}{L} = 100 \] and 0.8\( \mu \)m technology.
$g_m/I_D$ and transistor size

When short channel effects are not significant:

\[
I_D = \mu C_{ox} (W/L) \cdot f(V_G, V_S, V_D) \rightarrow \left( \frac{g_m}{I_D} \right) = f(I_{norm}) \quad I_{norm} = \frac{I_D}{(W/L)}
\]

\[
I_{norm} = \frac{I_D}{\mu C_{ox} (W/L)}
\]

\[
I_{norm} = i_f = \frac{I_D}{I_S}
\]

When short channel effects are significant:

\[
\left( \frac{g_m}{I_D} \right) = f(I_{norm}, L)
\]
Design Methodology: $g_m/I_D$ key variable

\[ A_0 = \frac{g_m}{I_D} V_A \]
\[ f_T = \frac{1}{2\pi} \frac{g_m}{C_L} = \frac{1}{2\pi C_L} \frac{g_m}{I_D} \]

Circuit Performance

Transistor Operating Mode

Transistor Sizing

\[ I_D = \mu C_{ox} (W/L) \cdot f(V_G, V_S, V_D) \]

\[ \left( \frac{g_m}{I_D} \right) = f(I_{norm}) \quad I_{norm} = \frac{I_D}{(W/L)} \]

\[ I_{norm} = \frac{I_D}{\mu C_{ox} (W/L)} \]

Optimum of Power Consumption

Weak inversion: \( I_D \propto e^{V_G/(nUT)} \)

Moderate inversion

Strong inversion \( (I_D \propto (V_G - V_T)^2) \)

- Working towards WI
  \[ \frac{g_m}{I_D} \rightarrow I_D \rightarrow \frac{W}{L} \rightarrow C \rightarrow g_m \]

Usually an optimum exists in moderate inversion
Example
Intrinsic Amplifier: Power Optimum

$f_T=10\text{MHz}, C_L=3\text{pF}, L=2\text{µm}, \text{tech: } 0.8\text{µm}$
Example

Intrinsic amplifier 0.8um, C_L 3pF

<table>
<thead>
<tr>
<th>gm/ID (1/V)</th>
<th>ID (A)</th>
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<tbody>
<tr>
<td>1.00E-08</td>
<td>0</td>
</tr>
<tr>
<td>1.00E-07</td>
<td>5</td>
</tr>
<tr>
<td>1.00E-06</td>
<td>10</td>
</tr>
<tr>
<td>1.00E-05</td>
<td>15</td>
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<tr>
<td>1.00E-04</td>
<td>20</td>
</tr>
<tr>
<td>1.00E-03</td>
<td>25</td>
</tr>
<tr>
<td>1.00E-02</td>
<td>30</td>
</tr>
</tbody>
</table>

M.I. optimum

W.I. optimum

S.I. optimum
gm/ID in the nanometer era

Derived based on data from P. Jespers, The \( g_{m}/I_D \) Methodology a sizing tool for low-voltage analog CMOS circuits, Springer, 2010, extras.springer.com

Experimental data, 90nm CMOS process
gm/ID in the post CMOS era


Seabaugh and Zhang: Low Voltage Tunnel Transistors for Beyond CMOS Logic
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Example of modules: Pacemaker Activity Sense

Objective:

- E.g. Activity indicator: 3s Average of the absolute value of acceleration in the 0.5 - 7 Hz band.

Amplitude: tens to hundreds of μV
Accelerometer Signal Conditioning (1): Amplifier / Bandpass filter

Vo = A1Vs + A2Vf

Input signal

Feedback signal

High pass characteristic

Gain (V/V) | 2900
Equivalent input noise (µVrms) | 18
Consumption (µA) | 2.4

ISCAS 1998
Accelerometer Signal Conditioning (2): Results

![Graph showing acceleration signal conditioning results](image-url)

- **blue line**: actual cardiac frequency of healthy patient
- **red line**: simulated pacemaker frequency
- **green line**: circuit output

**Axes:**
- **Y-axis**: Cardiac freq. (ppm)
- **X-axis**: Time (s)

**Legend:**
- **Digitized output of circuit**
Accelerometer Signal Conditioning (3): Gm-C implementation

A. Arnaud (UR), C. Galup (UFSC), ISCAS 2004

**Filtro-Amplificador 0.5-7Hz**

- $G_m = 21nS$
- $G_m5 = 2.5nS$
- $G_m6 = 89pS$
- Gainancia 2$^a$: $G_2 = 8.3$
- Ganancia Preamplificador: $G_1 = 46.4$

**Diagram Details**

- $V_{bias} = 700mV$
- $C_1 = 550p$
- $C_2 = 50p$
- $C_3 = 50p$
- $C_4 = 250p$
- $I_{DD} = 290nA$
- Equivalent Input Noise: $2.1\mu V_{rms}$
- Gain: 390
- Fully integrated
Example of modules:
Neural Recording Amplifier

- **Objective:** Signal detection from e.g. cuff electrodes or cortical electrodes arrays

- **Requirements:**
  - 0.5\( \mu \)Vrms - 2\( \mu \)Vrms noise
  - BW: 300Hz – 8kHz
  - High CMRR (particularly in Cuff)
  - Block high DC offsets (100mV or more) due to electrode/tissue contact
  - Negligible DC input current
  - A lot of research in this area ….
Neural Amplifier Front End (1): Capacitive Feedback

- Inversion region for noise / power optimization: e.g. input pair weak inversion, current mirror active load: strong inversion
- CMRR limited by capacitor matching.

\[
\text{NEF} = V_{ni, \text{rms}} \sqrt{\frac{2I_{t\text{ot}}}{\pi \cdot U_T \cdot 4kT \cdot \text{BW}}}
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Gain</td>
<td>40 dB</td>
</tr>
<tr>
<td>BW</td>
<td>0.13 Hz / 7.5 kHz</td>
</tr>
<tr>
<td>$I_{t\text{ot}}$</td>
<td>16 $\mu$A</td>
</tr>
<tr>
<td>NEF</td>
<td>3.8</td>
</tr>
<tr>
<td>$v_{\text{noise rms}}$</td>
<td>2.1 $\mu$V</td>
</tr>
<tr>
<td>CMRR</td>
<td>&gt; 42 dB</td>
</tr>
</tbody>
</table>

Harrison et al, IEEE JSSC, June 2003

MOS–Bipolar Pseudoresistor (100s Mohms equivalent)
Neural Amplifier Front End (2): DDA Based

- ☻ High CMRR (Given by Input Differential Pair)
- 😞 Both Differential Pairs contribute equally to Input Noise (hence to area and consumption)

J. Sacristán, T. Oses, IFESS 2002,
Another DDA Based Scheme: M. Baru, U.S. Patent 6,996,435, 2006
Neural Amplifier Front End (3): “Asymmetrical” DDA Based (I)

- ☀ Effect of noise (and hence consumption and area) of Gm2 greatly reduced while keeping high CMRR (given by input differential pair)

- Gm2 less effective in compensating input offset and DC components => Output DC and high pass characteristic fixed by local feedback at the output
Neural Amplifier Front End (4): “Asymmetrical” DDA Based (II)

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<tr>
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</thead>
<tbody>
<tr>
<td>Architecture</td>
<td>Asym. DDA</td>
<td>Capacitive</td>
<td>Capacitive</td>
<td>DDA</td>
</tr>
<tr>
<td>A (dB)</td>
<td>48</td>
<td>40</td>
<td>41</td>
<td>80</td>
</tr>
<tr>
<td>NEF</td>
<td>4.2</td>
<td>3.8</td>
<td>2.7</td>
<td>53.4</td>
</tr>
<tr>
<td>I_{total}(μA)</td>
<td>16.5</td>
<td>16.0</td>
<td>2.7</td>
<td>180</td>
</tr>
<tr>
<td>vi noise (μVrms)</td>
<td>2.4</td>
<td>2.1</td>
<td>3.1</td>
<td>7.6</td>
</tr>
<tr>
<td>CMRR</td>
<td>&gt; 107</td>
<td>&gt; 42</td>
<td>&gt; 66</td>
<td>90</td>
</tr>
</tbody>
</table>
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Prospects: Digital vs. Analog

- Theoretical limits of power consumption for Analog and Digital Signal Processing
- Analog better for low S/N, but the border is moving ...
- “Digital” pacemaker already present in marketing

Source: E. Vittoz
Prospects: Analog ULP and AIMD

- Intense growth of applications / therapies on development and reaching the market

- Broad Analog / Circuit research area:
  - Sensing
  - Stimulation, Power Management / Battery Recharge, Communication, ...
  - Once very specific area, now wider (wireless sensor networks, body area networks, portable devices, energy scavenging devices, RFID, ...).
Prospects: AIMDs
Brain Computer Interface

Set. 2000, Nicolelis, Duke University

You are in: Sci/Tech
Wednesday, 15 November, 2000, 19:37 GMT

Monkey brain operates machine

Monkey robot brain

1. A computer analyses a monkey's brain signals as it moves its arms.

2. The information is sent over the net to drive robotic arms 950 kilometres away.

Miguel Nicolelis, Duke University
"We are trying to investigate how we could tap into brain signals"

Scientists have used the brain signals from a monkey to drive a robotic arm.

As the animal stuck out its hand to pick up...
Prospects AIMDs:
Brain Computer Interface

July 2004: Pilot FDA trial started by spin/off company of Brown Univ., several tetraplegic patients implanted.
Some Conclusions

• ULP ICs for AIMDs: Each nA counts => **Methodology and Optimization**

• AIMDs: Very broad field in strong expansion
  ✓ Many R & D opportunities
  ✓ Microtechnology is often the enabling factor.

• AIMDs: Price is not the main concern, but application and performance
  ✓ Suitable for developments with lower volume productions than in other areas
  ✖ High investment associated with long development cycles, qualification, clinical testing and regulatory aspects.
More Information

iie.fing.edu.uy/vlsi
silveira@fing.edu.uy

Acknowledgements

• CCC Medical Devices, NanoWattICs
• Members (present and past) of Microelectronics Group, UR
Upcoming Regional Events

**LASCAS 2014**

*5th IEEE Latin American Symposium on Circuits and Systems*
Santiago, Chile
February 25-28, 2014

**Deadline: 1st Nov, 2013**

**10th Nov, 2013**

**LASCAS / Iberchip 2015: Uruguay**
Thank you!