Ultra Low Power Analog Integrated Circuits for Implantable Medical Devices

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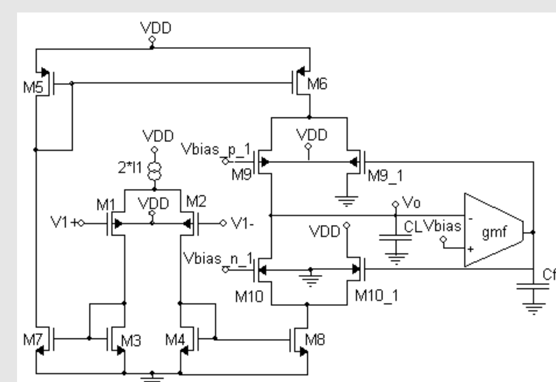
CCC Medical Devices

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

Engineering School
Universidad de la Republica

Wikipedia

Collins/Fing

Wikipedia

- 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.

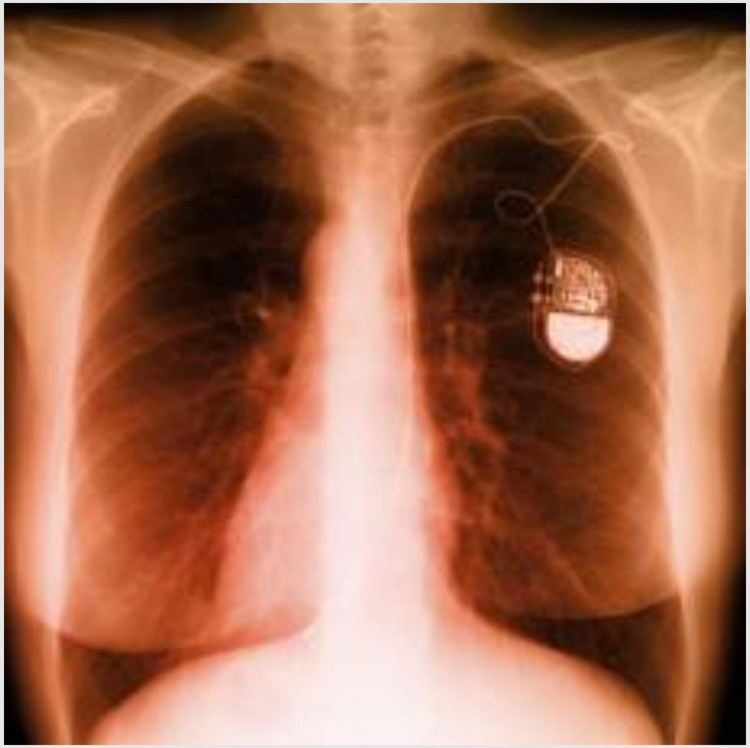
- Transistor Modeling.
- Design Methodology.

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 …

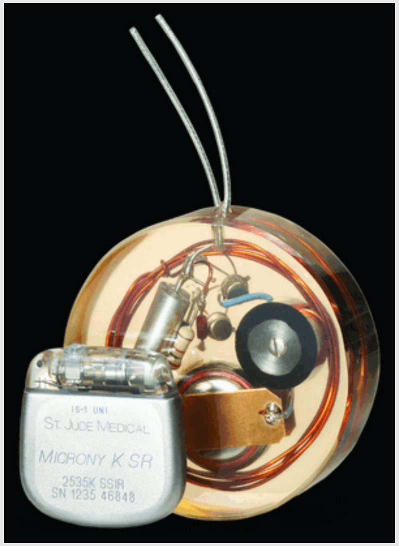
http://mobilewellbeing.wordpress.com/

www.givenimaging.com

AIMDs: Main Historical Milestones (I)

- Cardiac Pacemaker: first implantable device, 1960

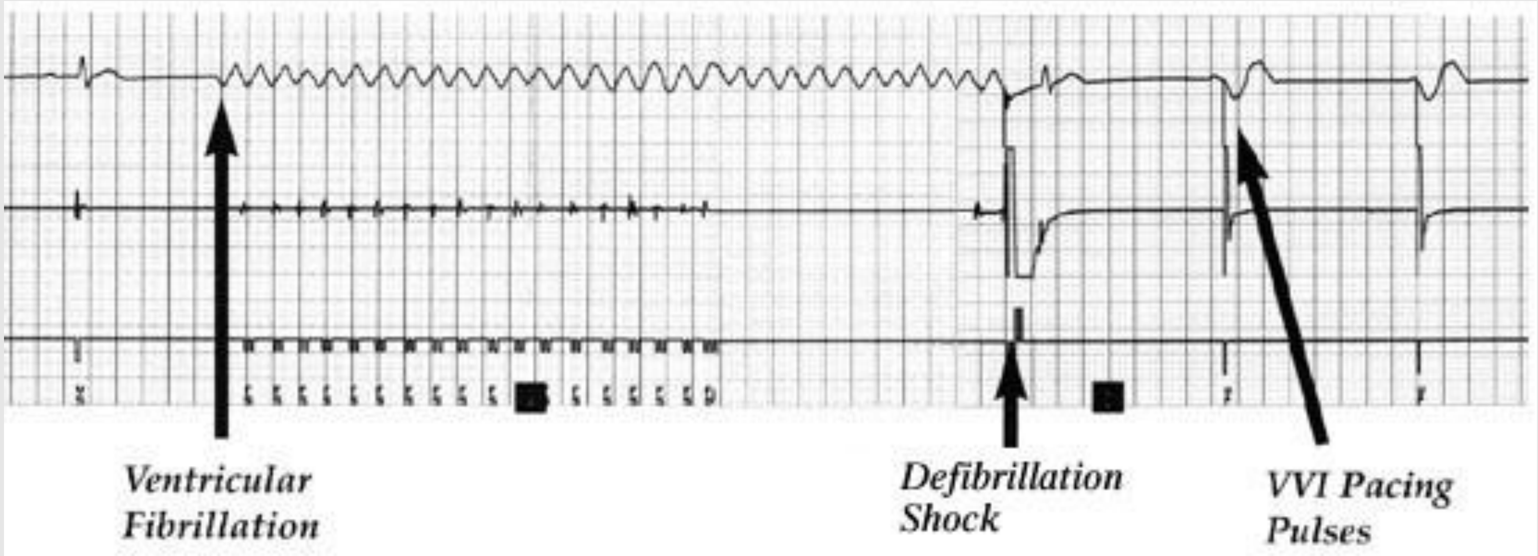




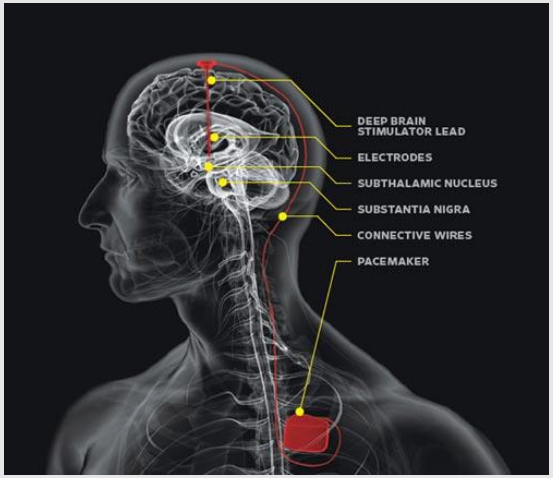
- Cochlear Implants (1960s -)

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

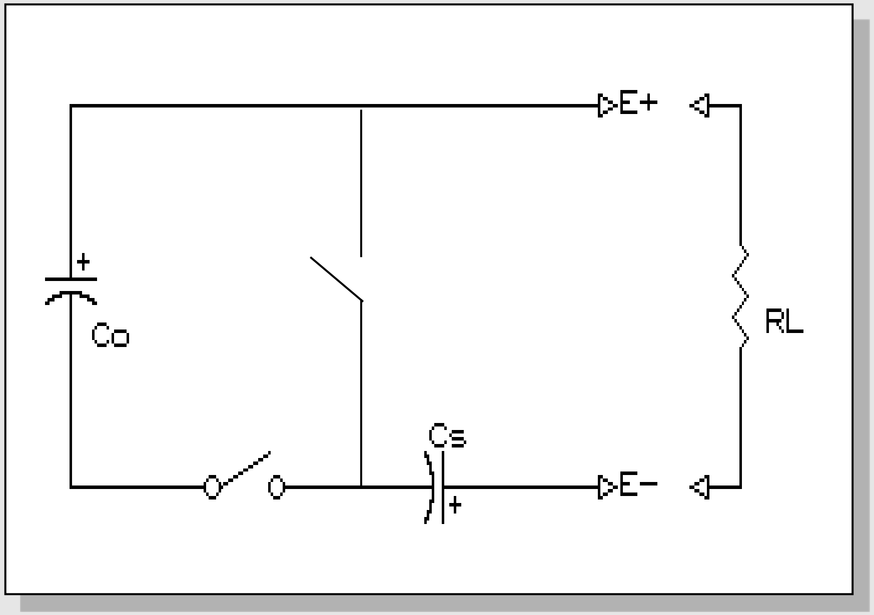
Some system examples

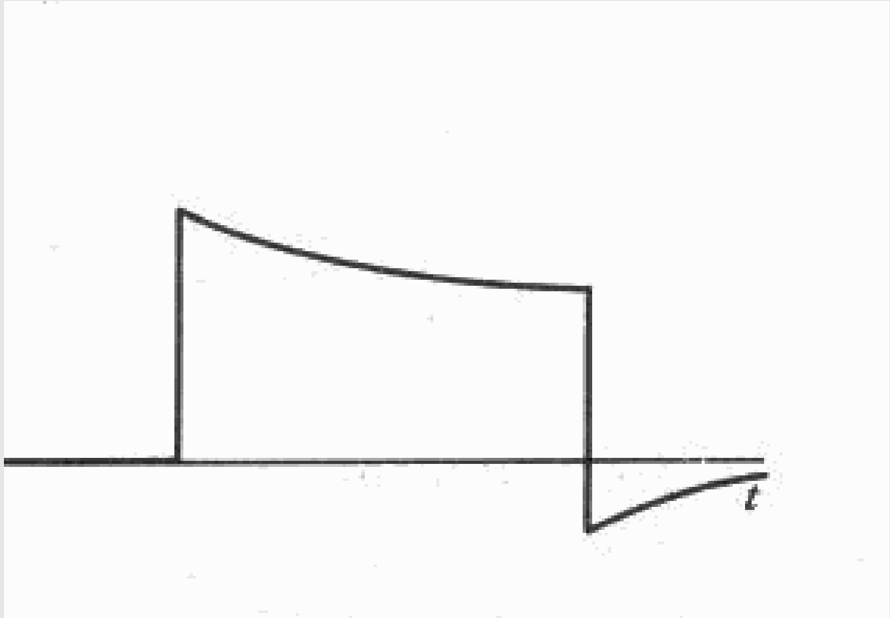
- Pacemaker:
  - **Goal:** Treat Bradycardia (slow heart rythm) and conduction disorders between atria and ventricles
  - **How:** Stimulating to contract the heart when it does not contract spontaneously ("watchdog")
  - **Sensing of:**
    - cardiac muscle signals that indicate ventricles / atria contraction
    - 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

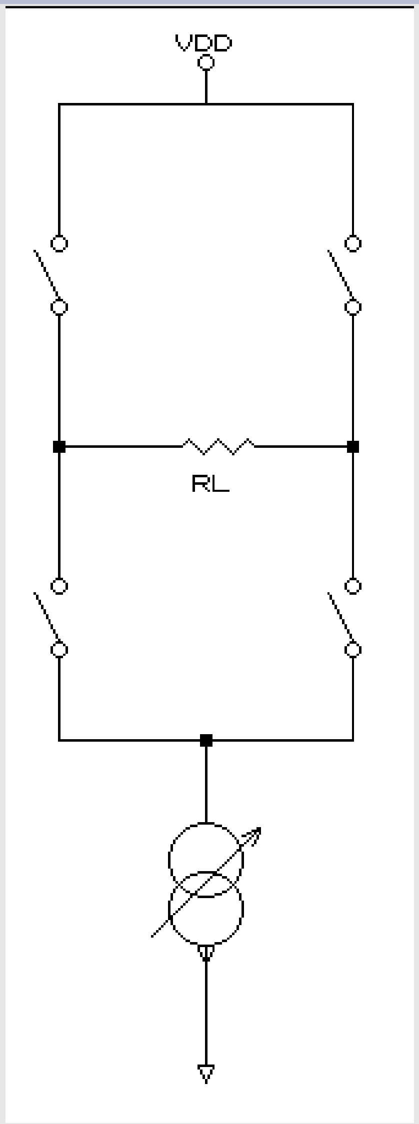
Stimulation: Voltage mode

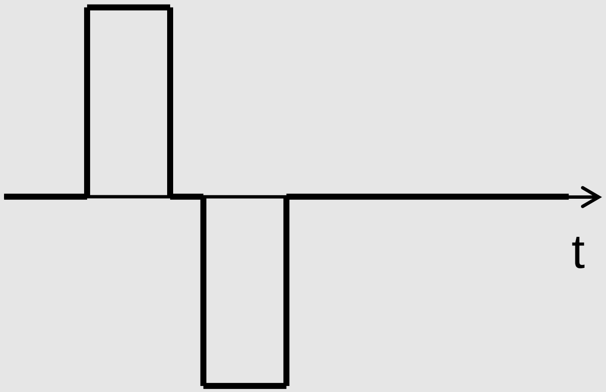




- E.g.: Pacemakers
- 0.1V … 7.5V
- 50µs … 1.5ms
- Requires battery voltage multiplier.
- RL: 500 Ohms typ.

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**: μV 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

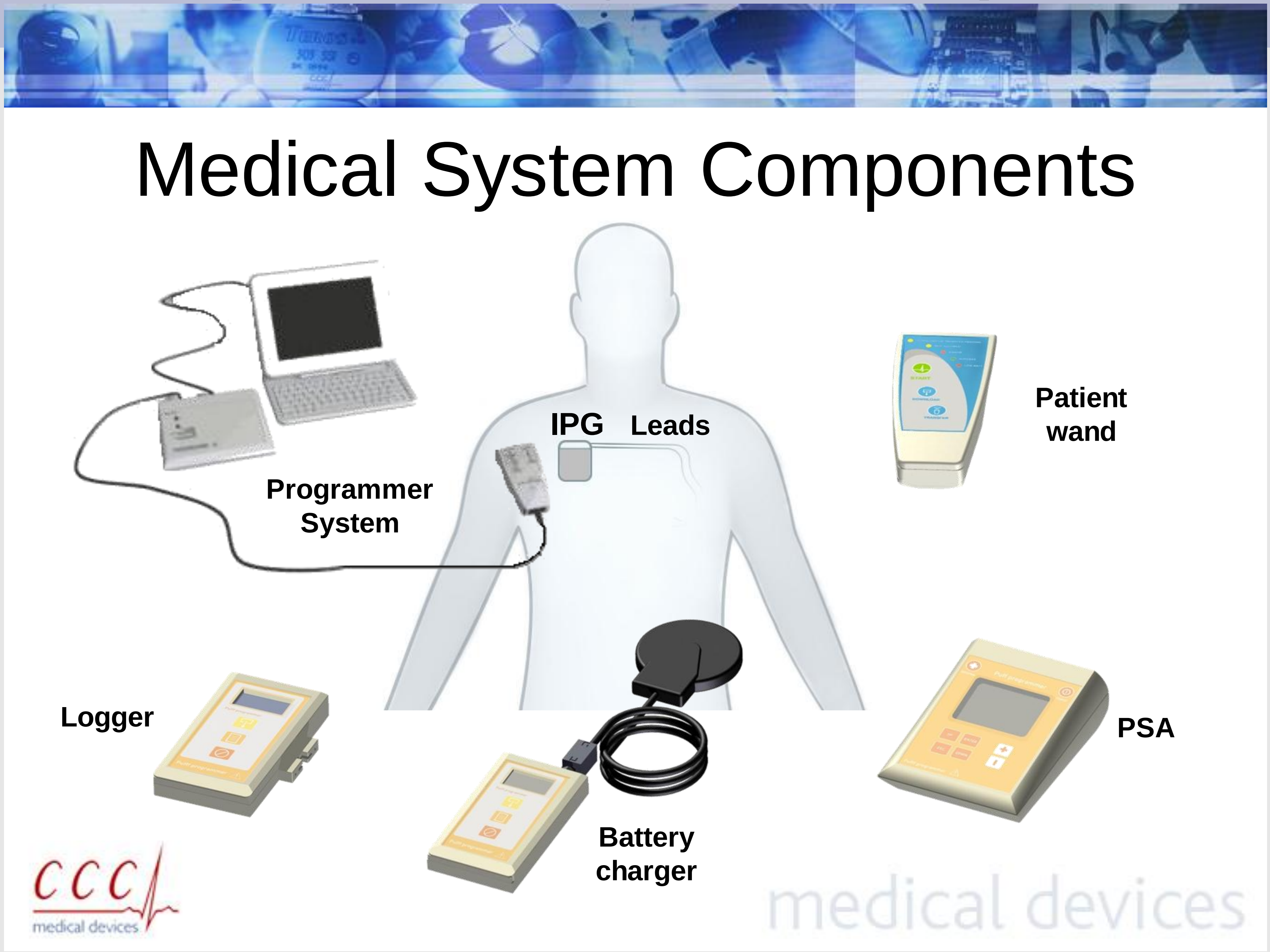
Sensing

- 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

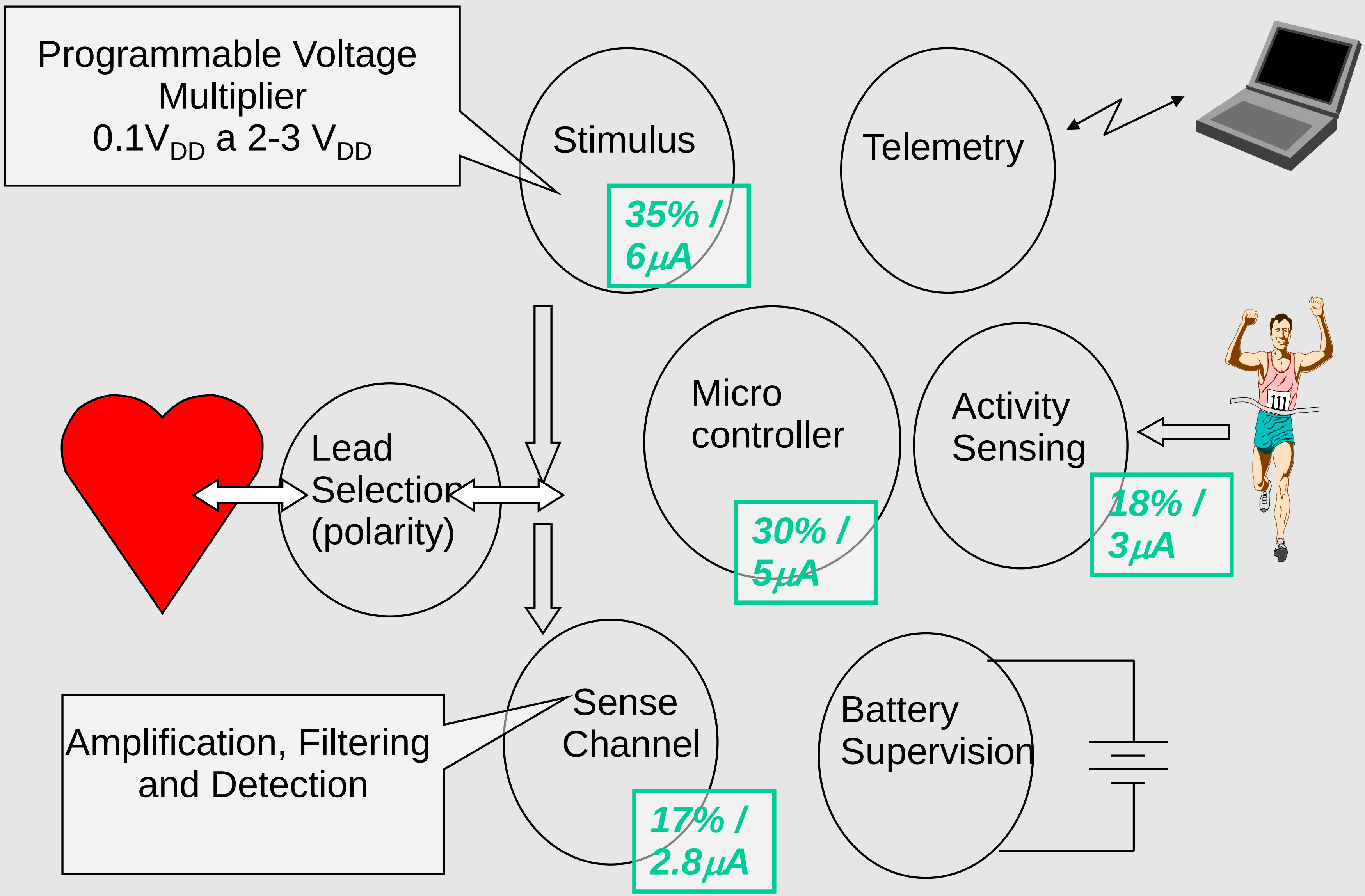
- Telemetry
  - Inductive (up to 10cms)
  - 403 MHz MedRadio Band (a couple of meters)
- Battery Supervision (Voltage / Impedance / Consumed Charge Measurement)
- Lead Impedance Measurement
- Magnet Sensor (Reed Relay / Hall Sensor)
- Battery Recharge (if applicable)
- Control: Microcontroller & Firmware

Non-implantable System Components



Example: Implantable Pacemakers

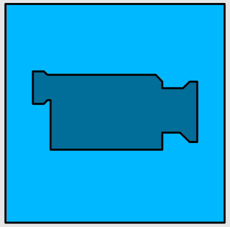
Approx. Consumption Distribution



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)

Biotronik

1968-
1998

(Source: M. Wilkinson, course: MST for Medical Devices)

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

→ **<u>There is room and need for improvement</u>**

General Requirements: Power Supply (II)

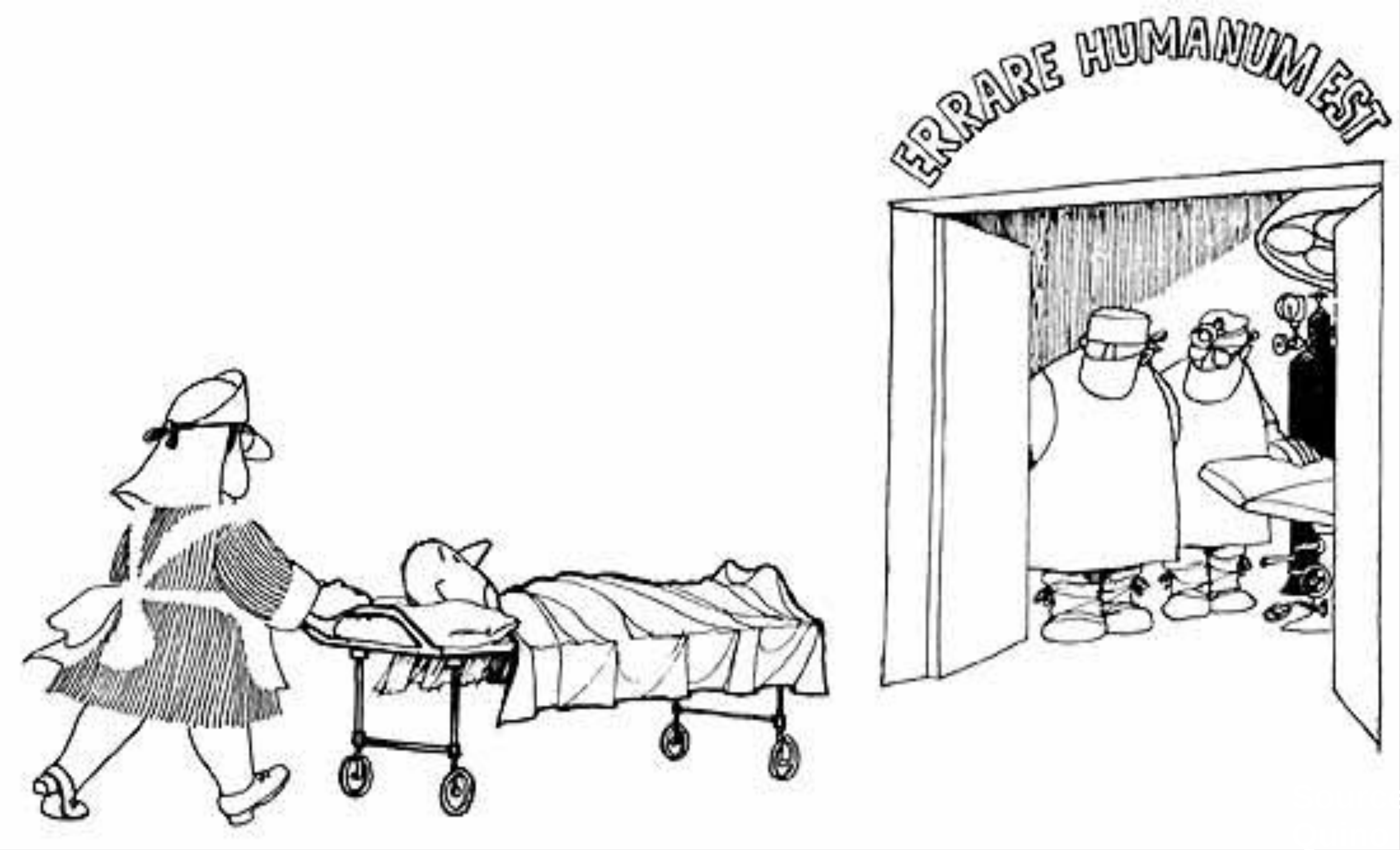
For higher average consumption devices:

- 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 <u>single fault</u> 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 => <u>external capacitors</u>

Importance of paying attention from the very beginning to applicable standards on AIMD safety, risk analysis and applicable regulations.

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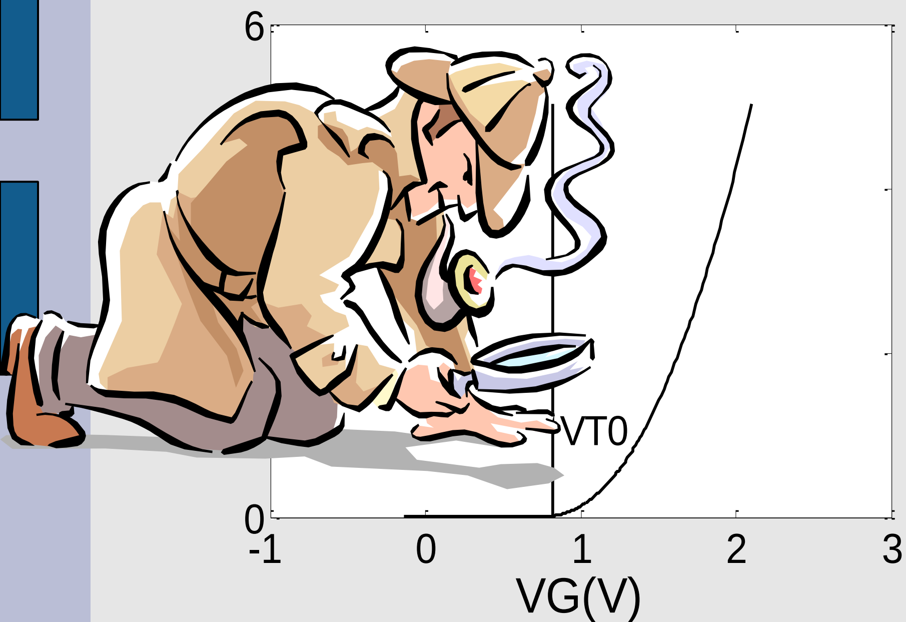
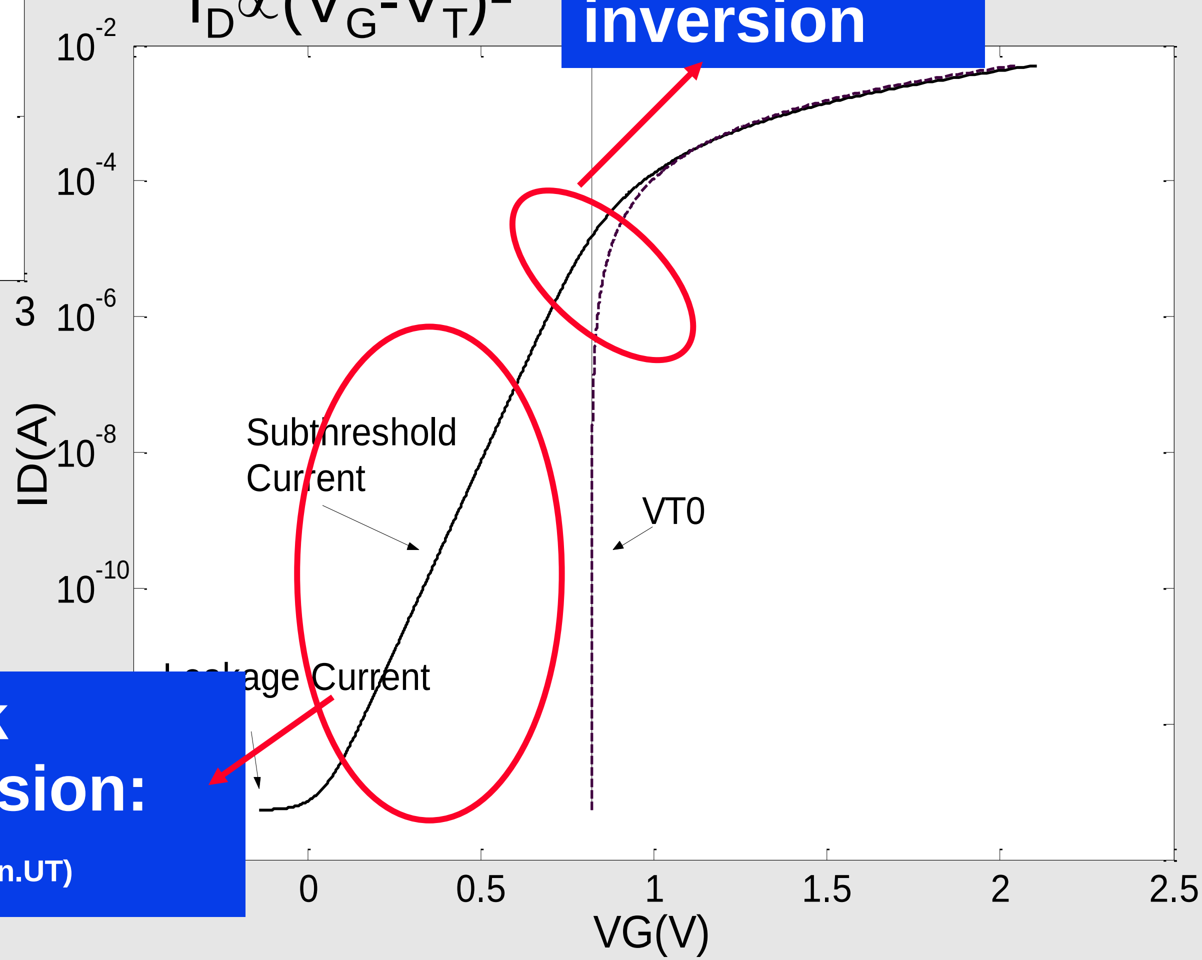
MOST Inversion Regimes (1)



Strong Inversion (S.I.)

$I_D \propto (V_G - V_T)^2$

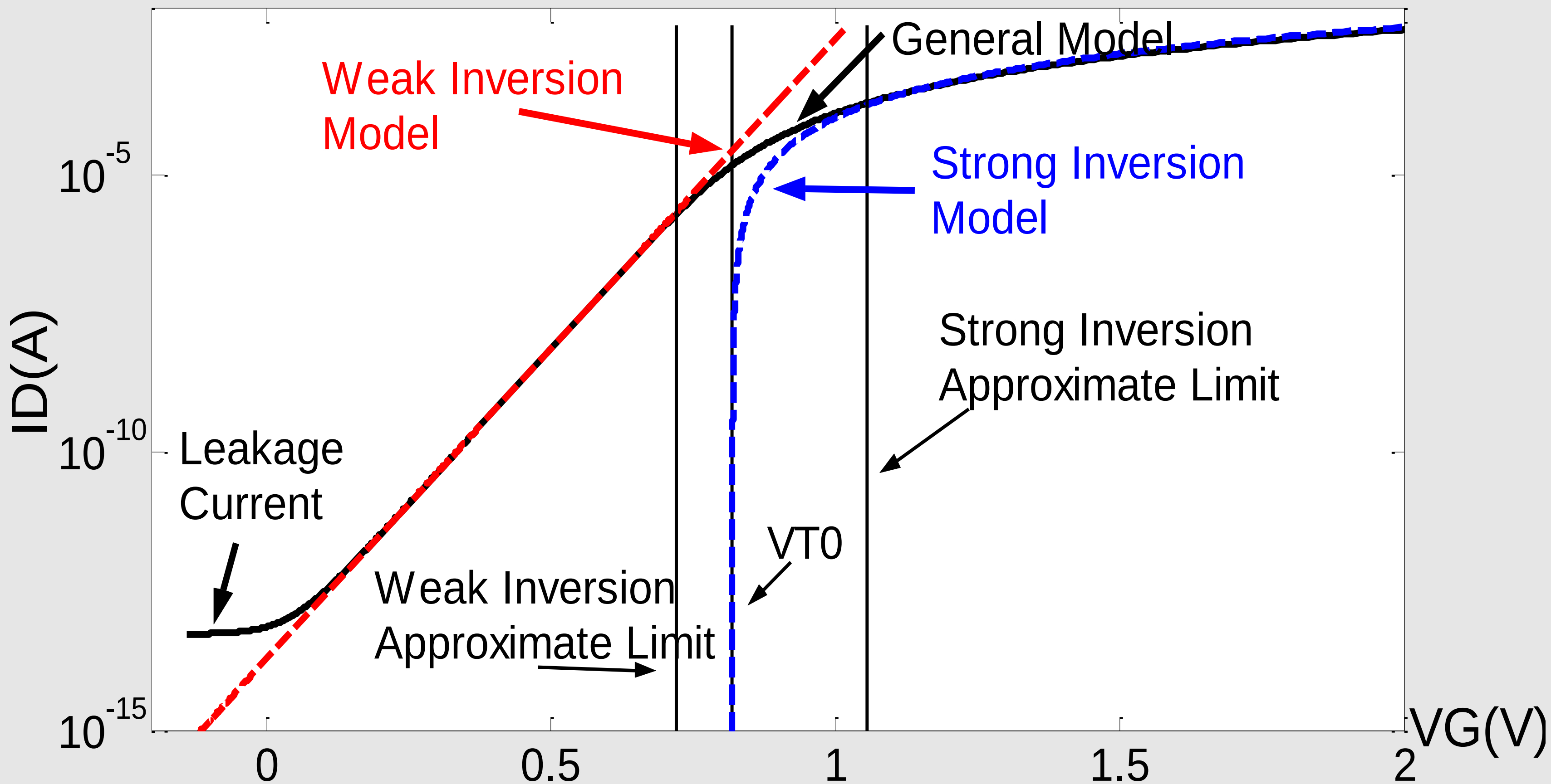
Moderate inversion



Weak inversion:

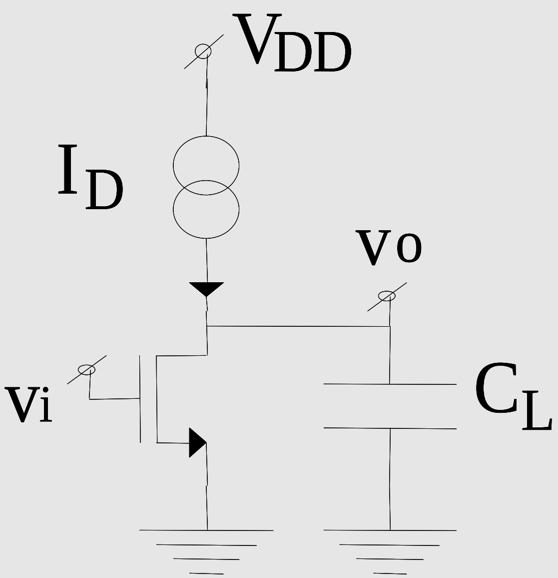
$I_D \propto e^{VG/(n.UT)}$

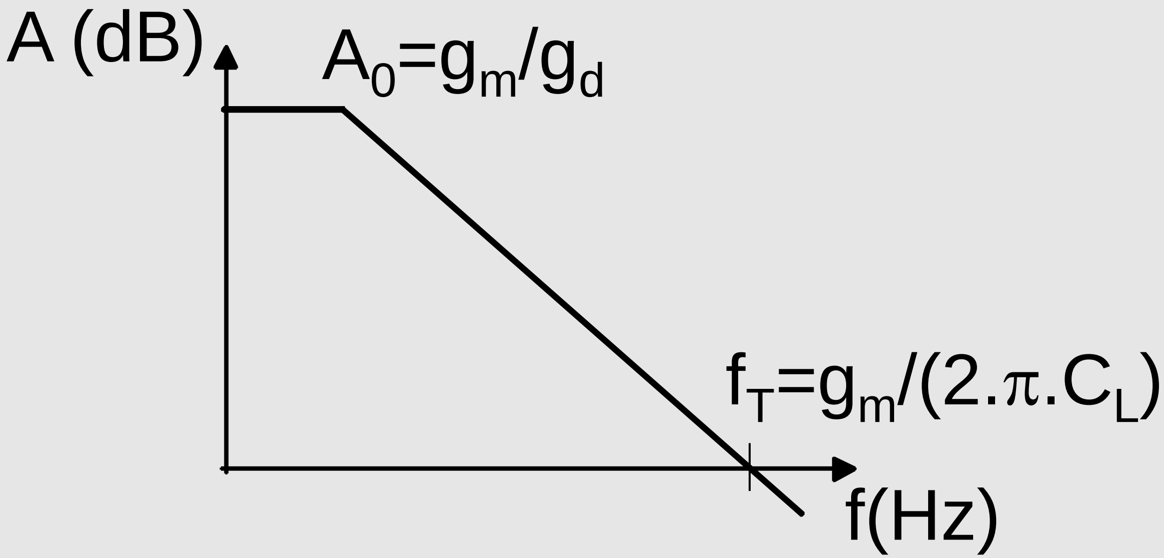
All regions, continuous MOST models



- EKV (Enz, Krummenacher, Vittoz, EPFL, AICSP 1995): originally mathematic interpolation between strong and weak inversion equations, now physical
- ACM (Advanced Compact Model, A. Cunha, C. Galup-Montoro, M. Schneider, UFSC, IEEE JSSC 1998): Physical model.
- … or **experimental** / **simulation curves**

"Intrinsic" MOS Amplifier





OTA: Operational Transconductance Amplifier

$$A_0 = g_m . r_o = \frac{g_m}{g_d} = \frac{g_m}{I_D} . V_A = \frac{g_m}{I_D} \Big/ \frac{g_d}{I_D}$$

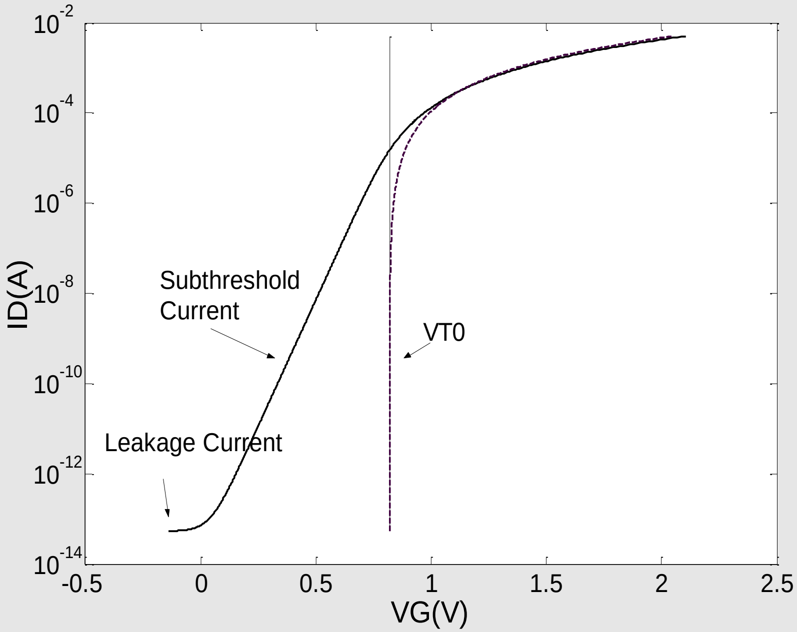
$$f_T = \frac{g_m}{2\pi C_L}, \quad A = \frac{A_0}{1 + \frac{s.A_0}{2\pi f_T}}$$

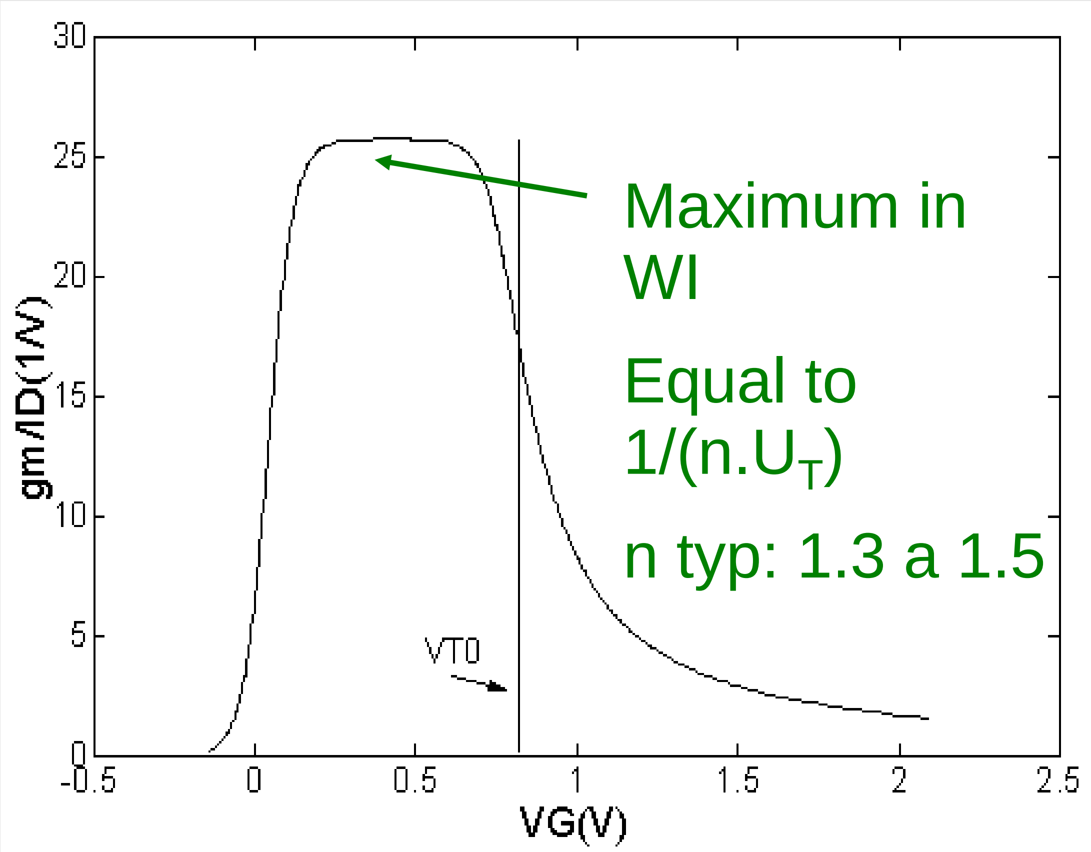
- Consumption: I_D
- Speed g_m/C_L
- C_L: total: external + parasitics
- Speed - Consumption trade-off : g_m/I_D

g_m/I_D vs. V_G

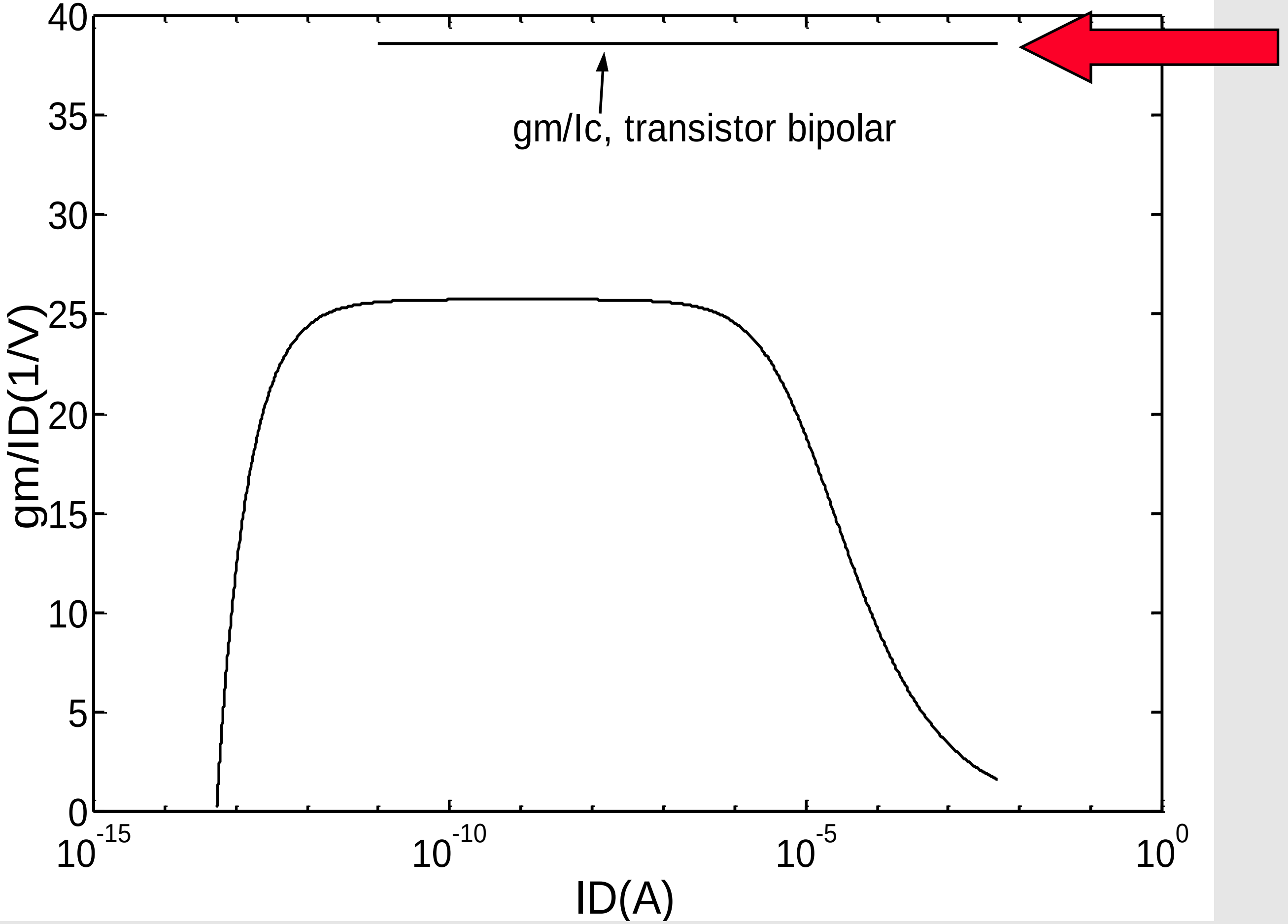
$$\frac{g_m}{I_D} = \frac{1}{I_D} \partial I_D / \partial V_G = \frac{\partial \log(I_D)}{\partial V_G}$$

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





g_m/I_D vs. I_D



Bipolar Transistor:

g_m/I_C independent of current in a wide range

W/L =100 and 0.8μm technology.

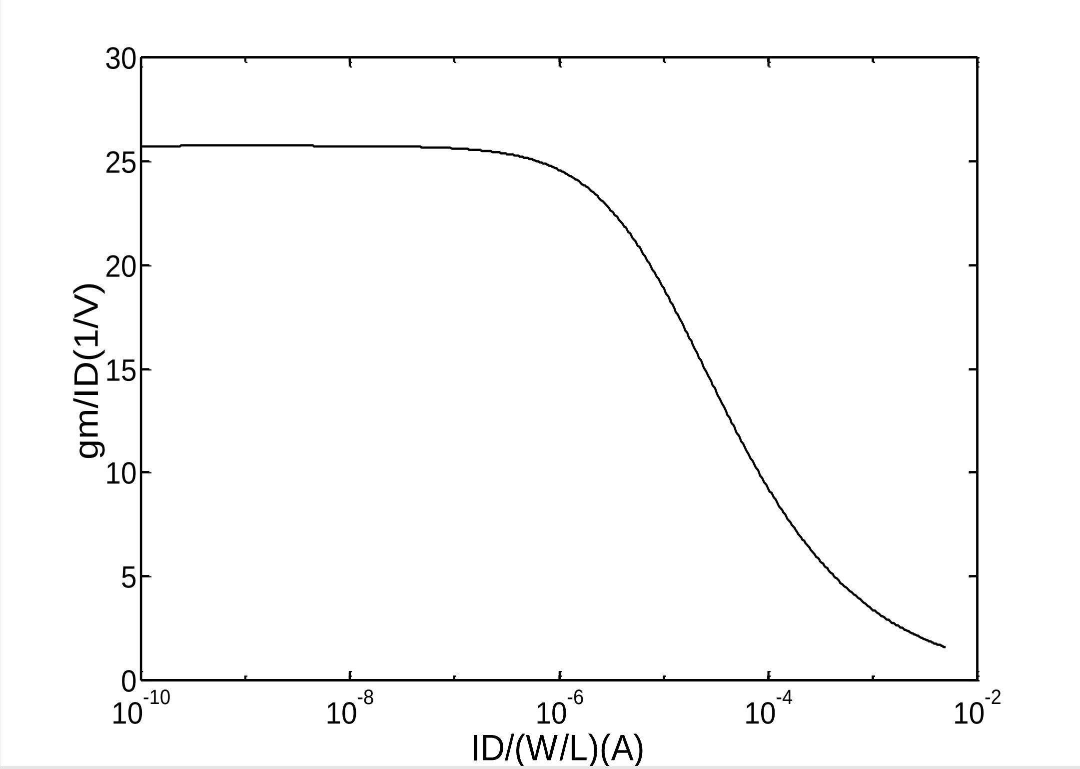
- As the current increases, the “g_m generation efficiency decreases”
- To reach the maximum frequency allowed by the technology:

=> high g_m => high current => strong inversion => low efficiency

g_m/I_D and transistor size

When short channel effects are not significant:

$I_D = \mu C_{ox}(W/L).f(V_G, V_S, V_D)$ ➡ $\left(\frac{g_m}{I_D}\right) = f(I_{norm})$ $\quad I_{norm} = \frac{I_D}{(W/L)}$



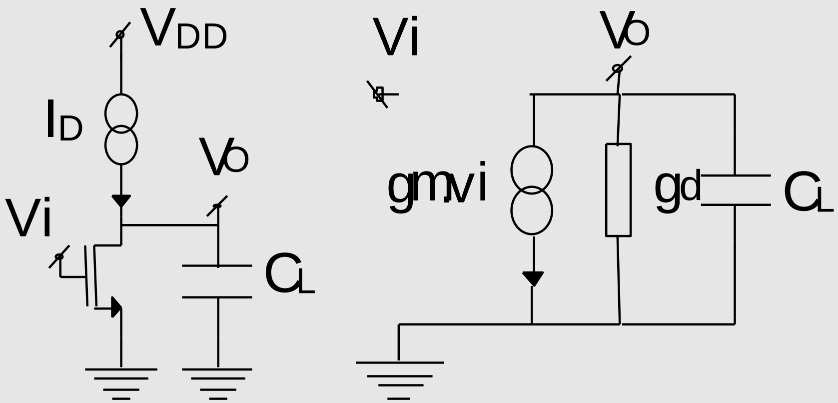
$$I_{norm} = \frac{I_D}{\mu C_{ox}(W/L)}$$

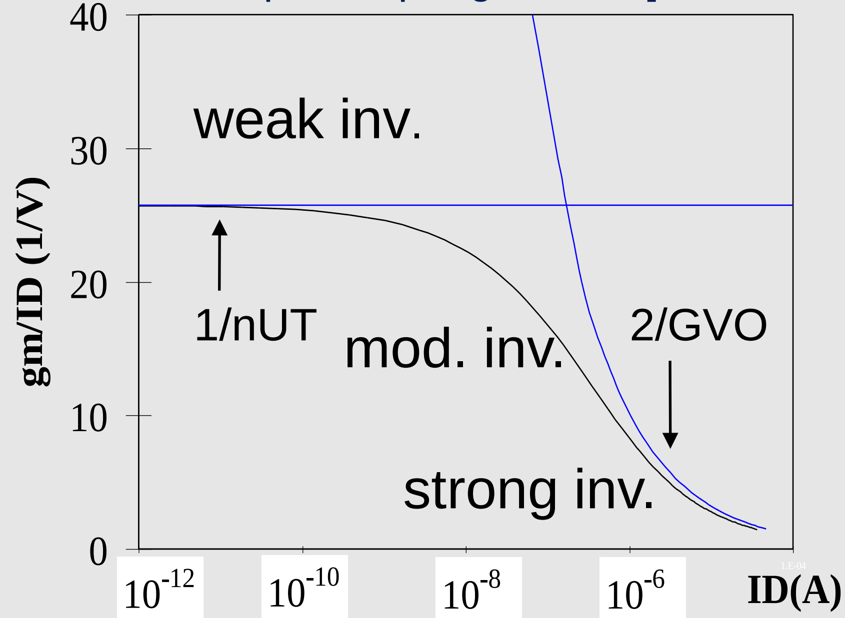
$$I_{norm} = i_f = \frac{I_D}{I_S}$$

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

[Silveira, Flandre, Jespers, IEEE JSSC 1996, P.Jespers, Springer, 2010]





$$A_0 = \frac{g_m}{I_D} V_A \qquad f_T = \frac{1}{2\pi}\frac{g_m}{C_L} = \frac{1}{2\pi C_L}\frac{g_m}{I_D} I_D$$

Circuit Performance ↔ **g_m / I_D** ↔ **Transistor Operating Mode**

Transistor Sizing

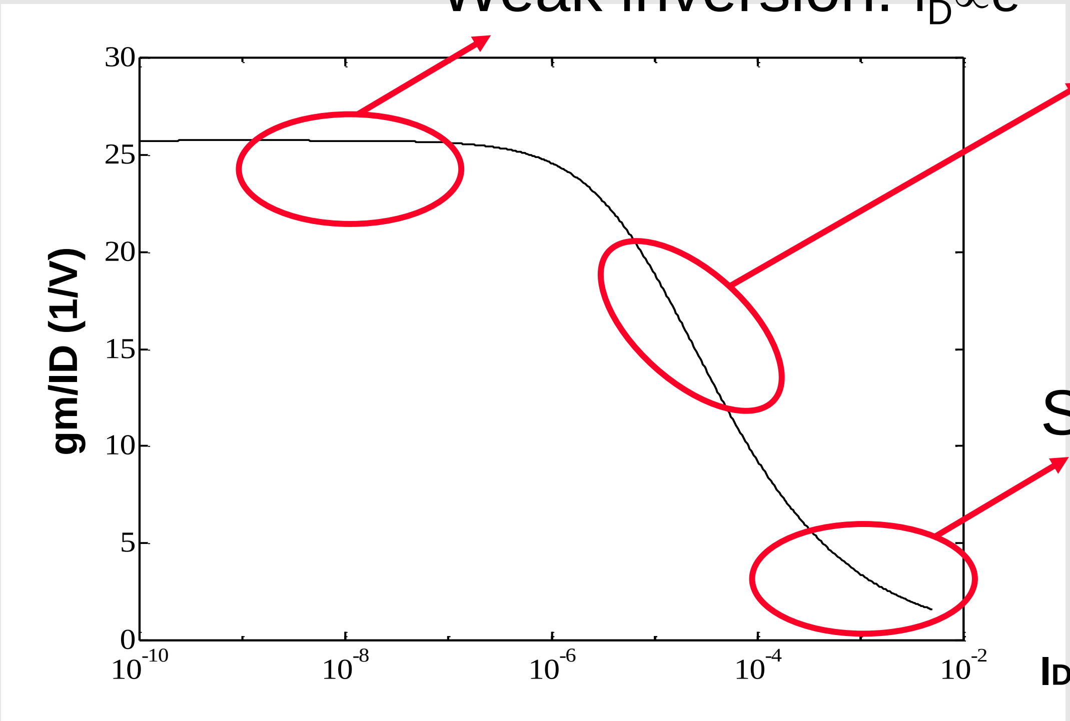
$I_D = \mu C_{ox}(W/L).f(V_G, V_S, V_D)$ ➡

$$\left(\frac{g_m}{I_D}\right) = f\left(I_{norm}\right) \qquad I_{norm} = \frac{I_D}{(W/L)}$$

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

Optimum of Power Consumption

Weak inversion: $I_D \propto e^{VG/(n.UT)}$



Moderate inversion

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

ID/(W/L) (A)

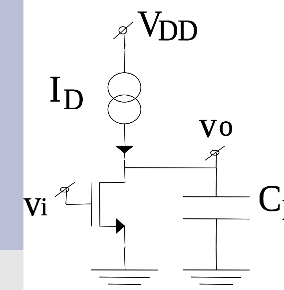
- Working towards WI

$g_m/I_D \nearrow \rightarrow I_D \searrow$

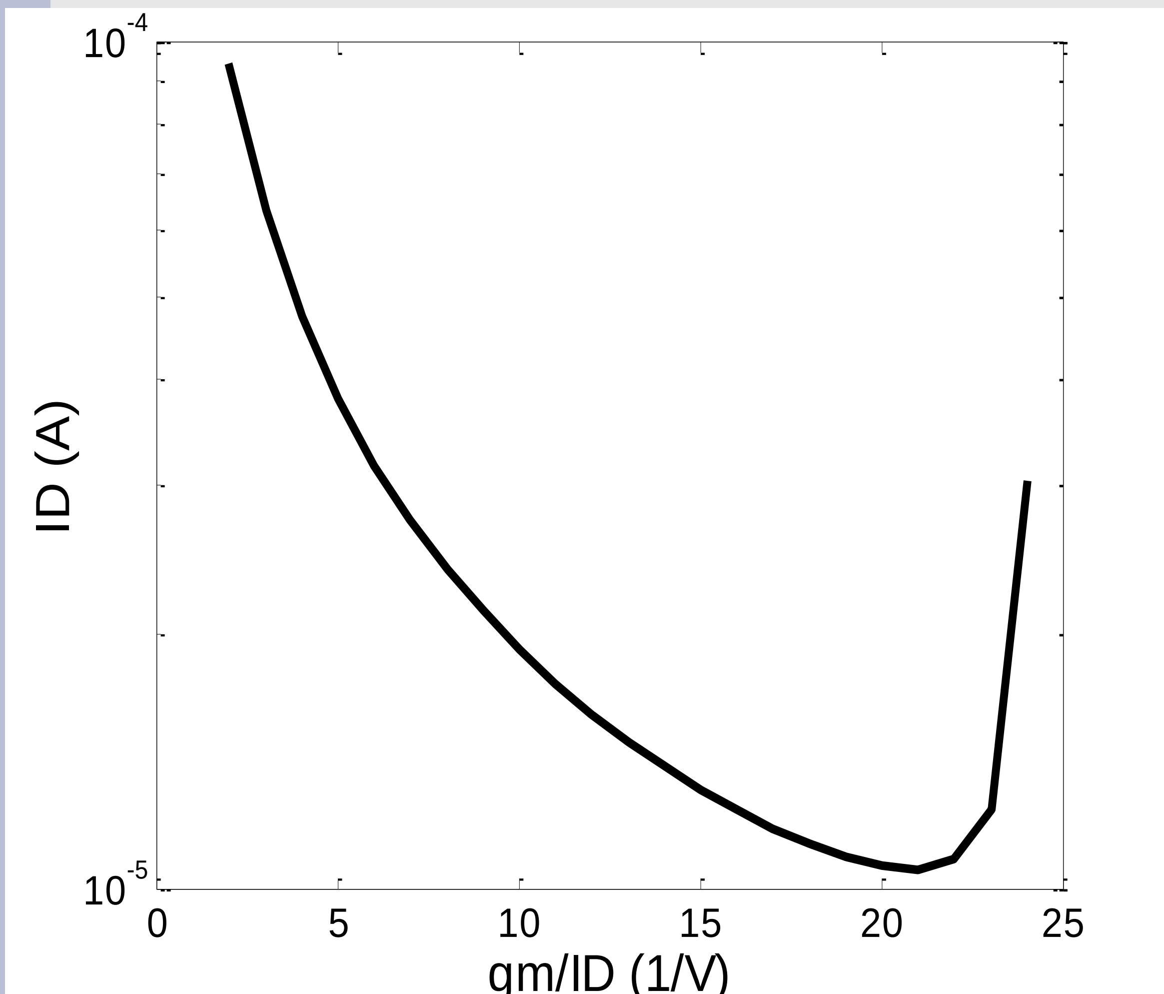
$W/L \nearrow \rightarrow C \nearrow \rightarrow g_m \nearrow$

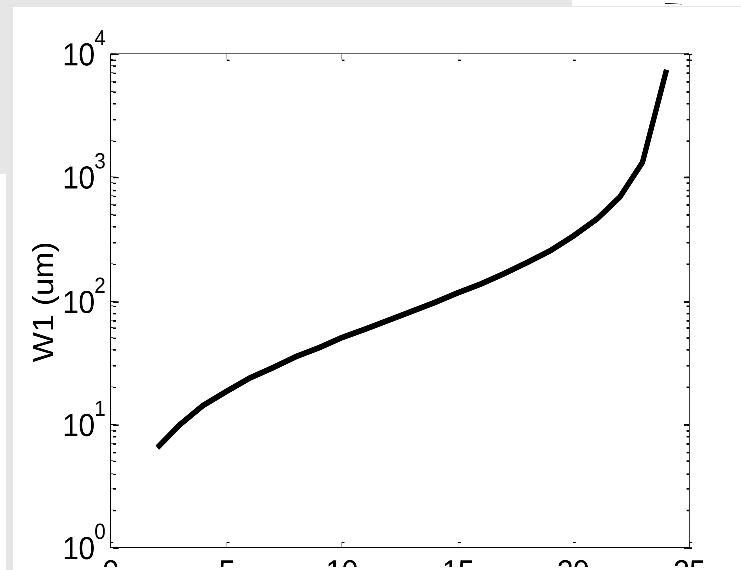
Usually an optimum exists in moderate inversion

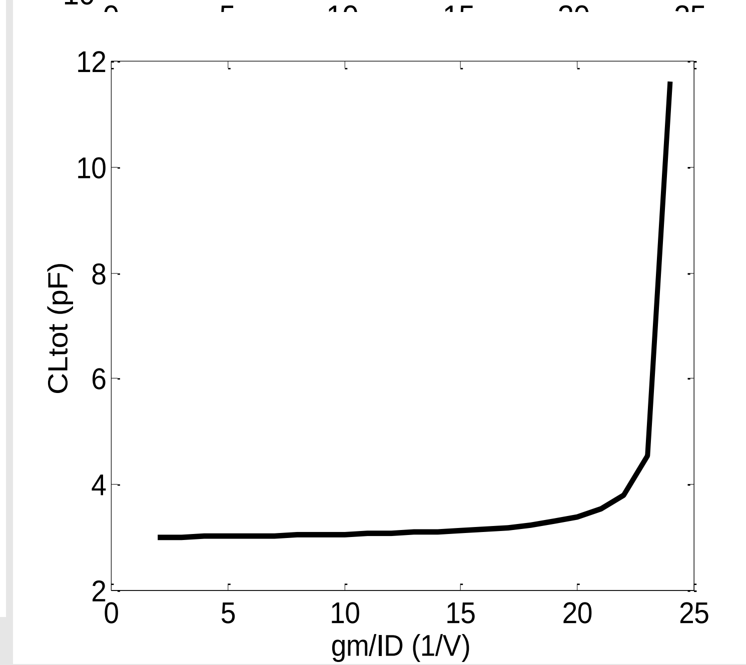
Example
Intrinsic Amplifier: Power Optimum



f_T=10MHz, C_L=3pF, L=2μm, tech: 0.8μm

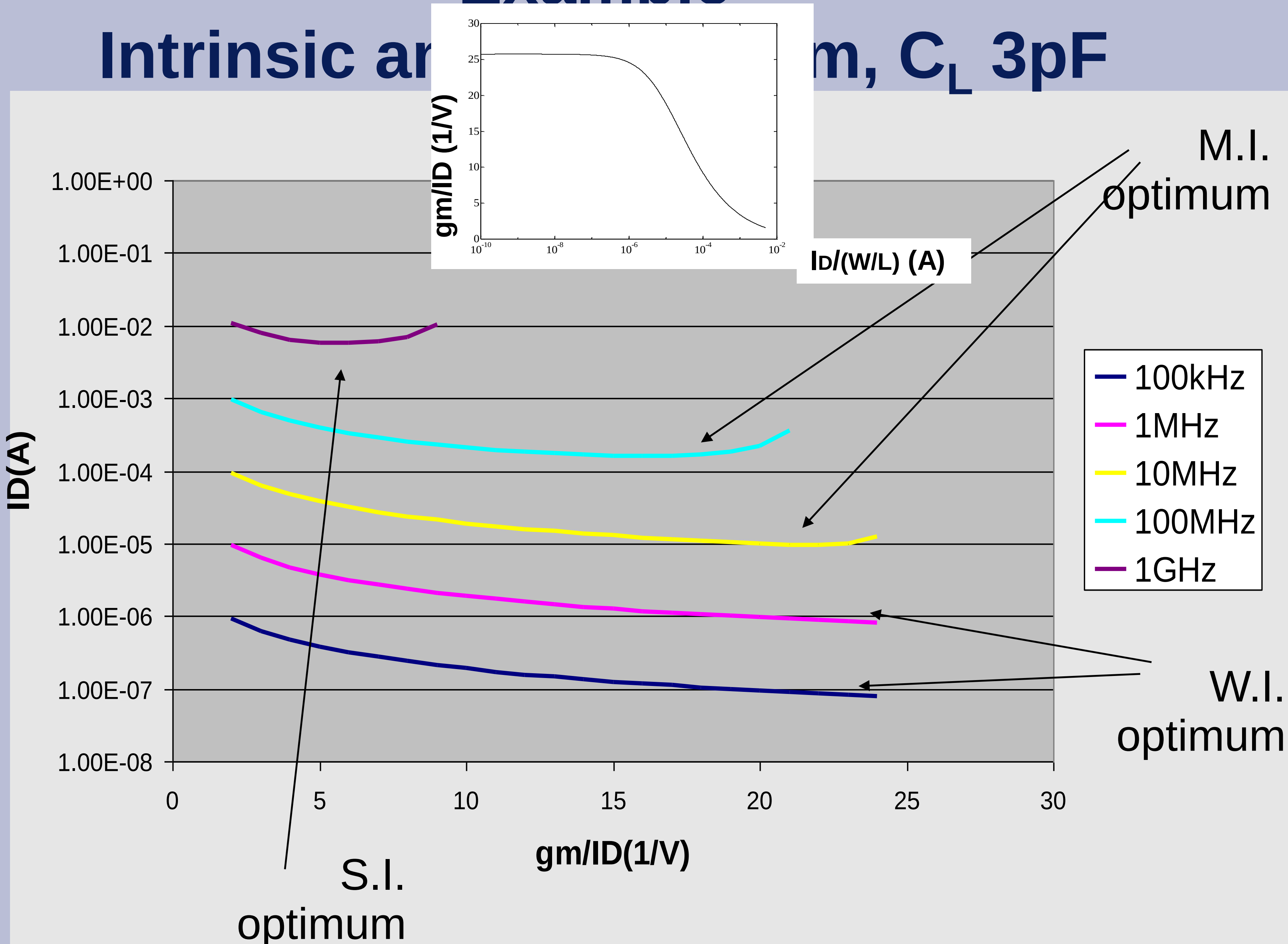




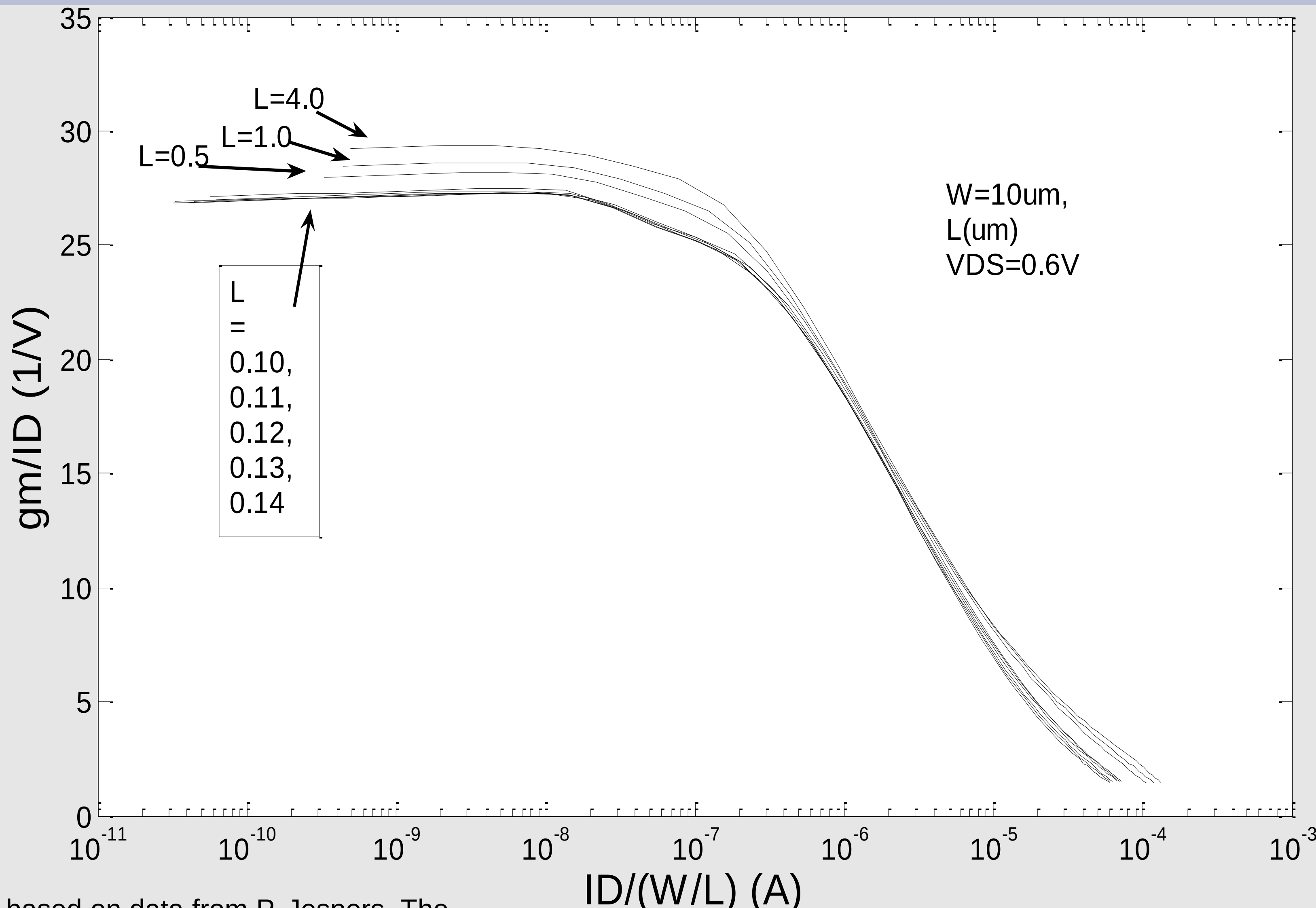


Example

Intrinsic ar… m, C_L 3pF



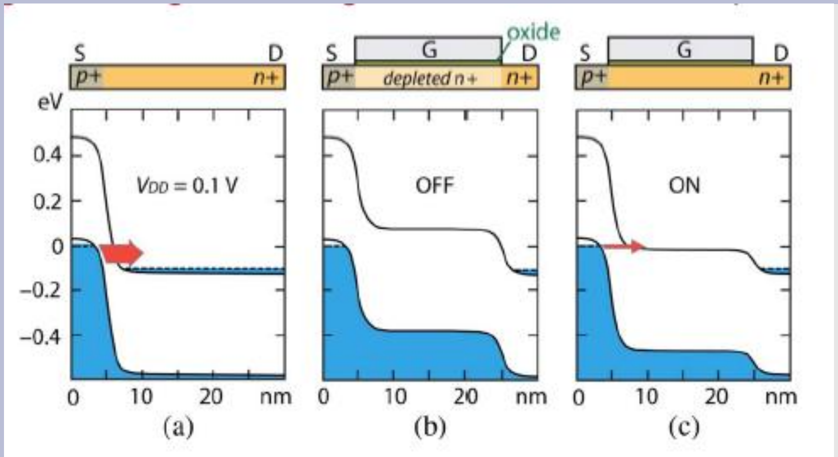
gm/ID in the nanometer era



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

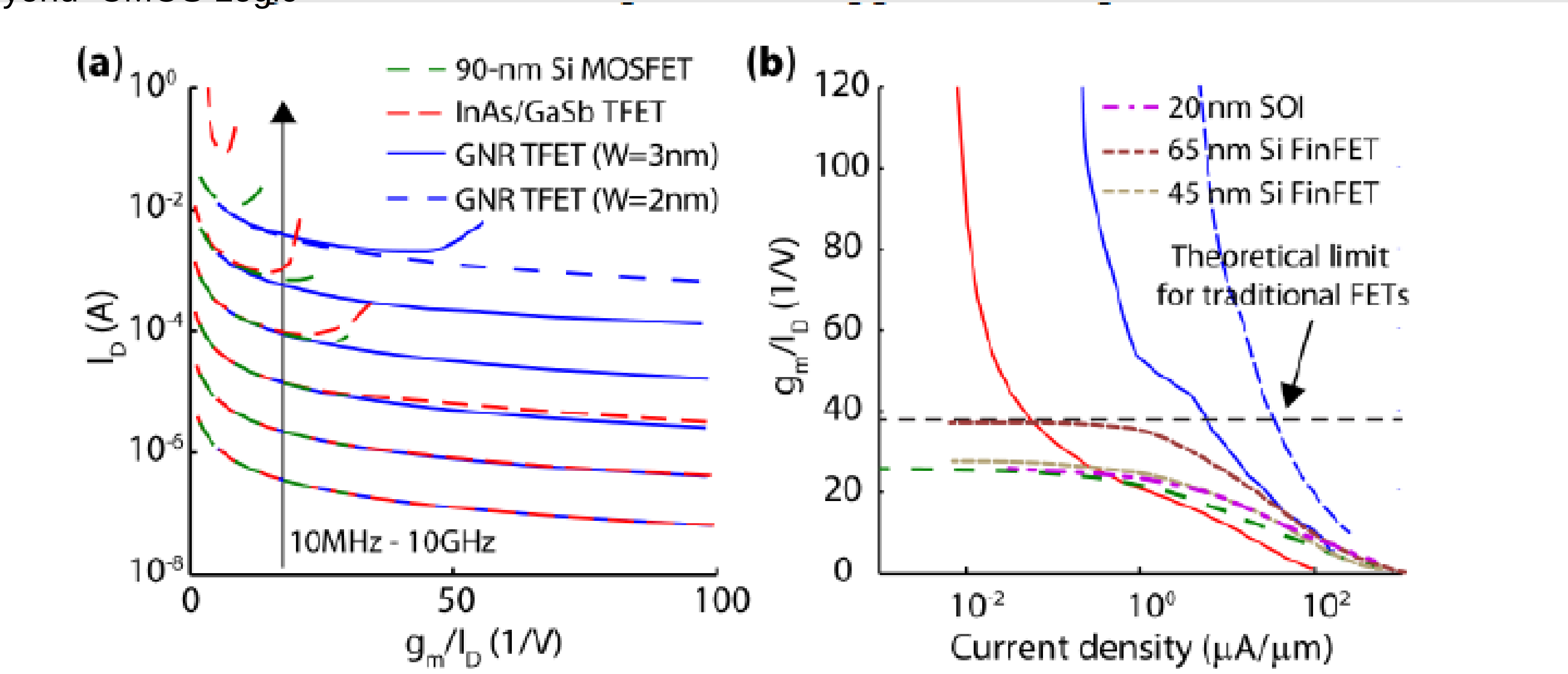
Experimental data, 90nm CMOS process

gm/ID in the post CMOS era



Seabaugh and Zhang: Low Voltage Tunnel Transistors for Beyond CMOS Logic

B. Sensale-Rodriguez et al, IEEE SubVt 2012, joint work with U. Notre Dame, Indiana.



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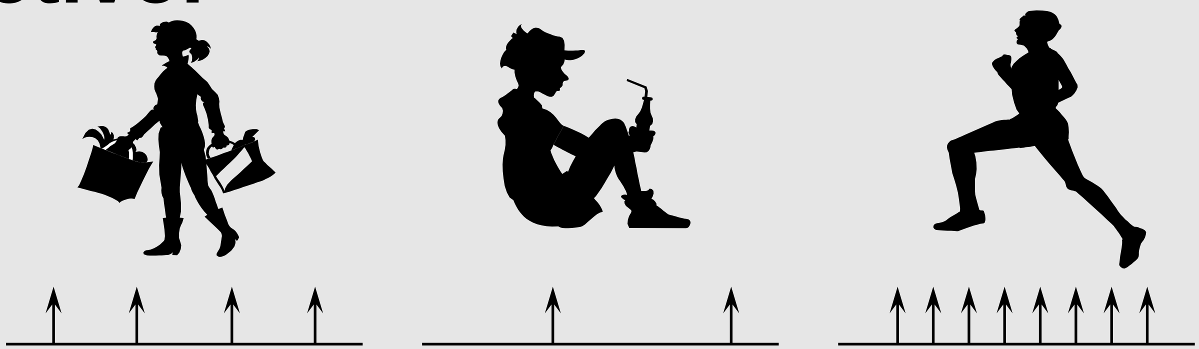
Example of modules: Pacemaker Activity Sense

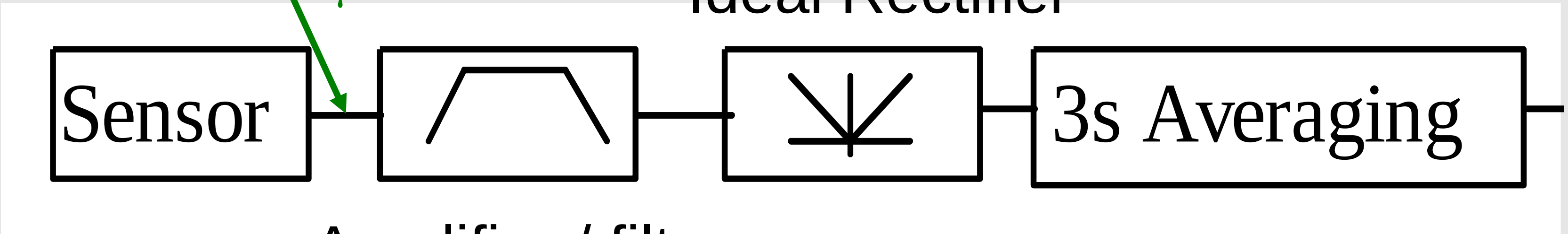
Objective:



◆ 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

Ideal Rectifier



Amplifier / filter

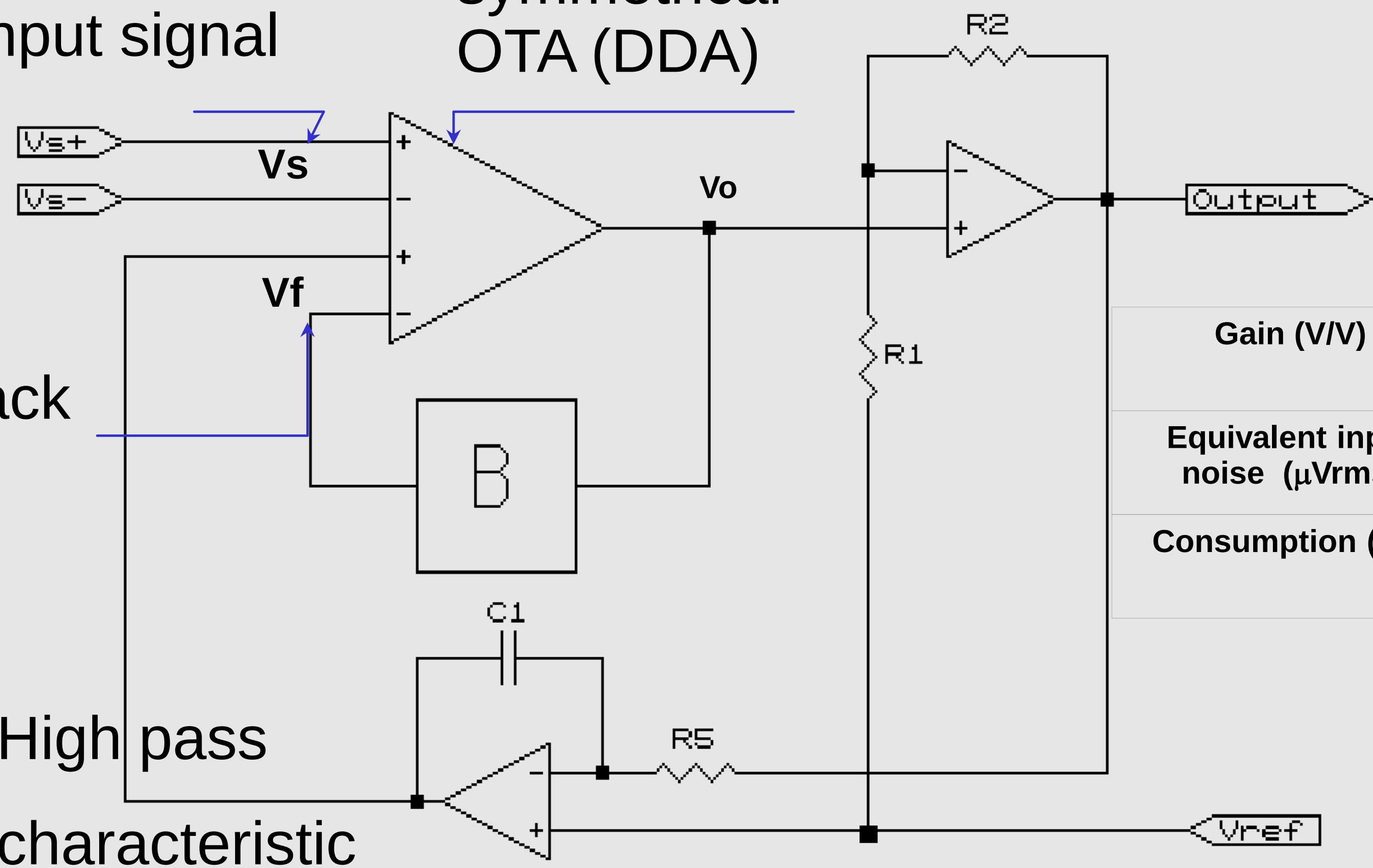
Accelerometer Signal Conditioning (1): Amplifier / Bandpass filter

Input signal

Double input symmetrical OTA (DDA)

$V_o = A_1 V_s + A_2 V_f$

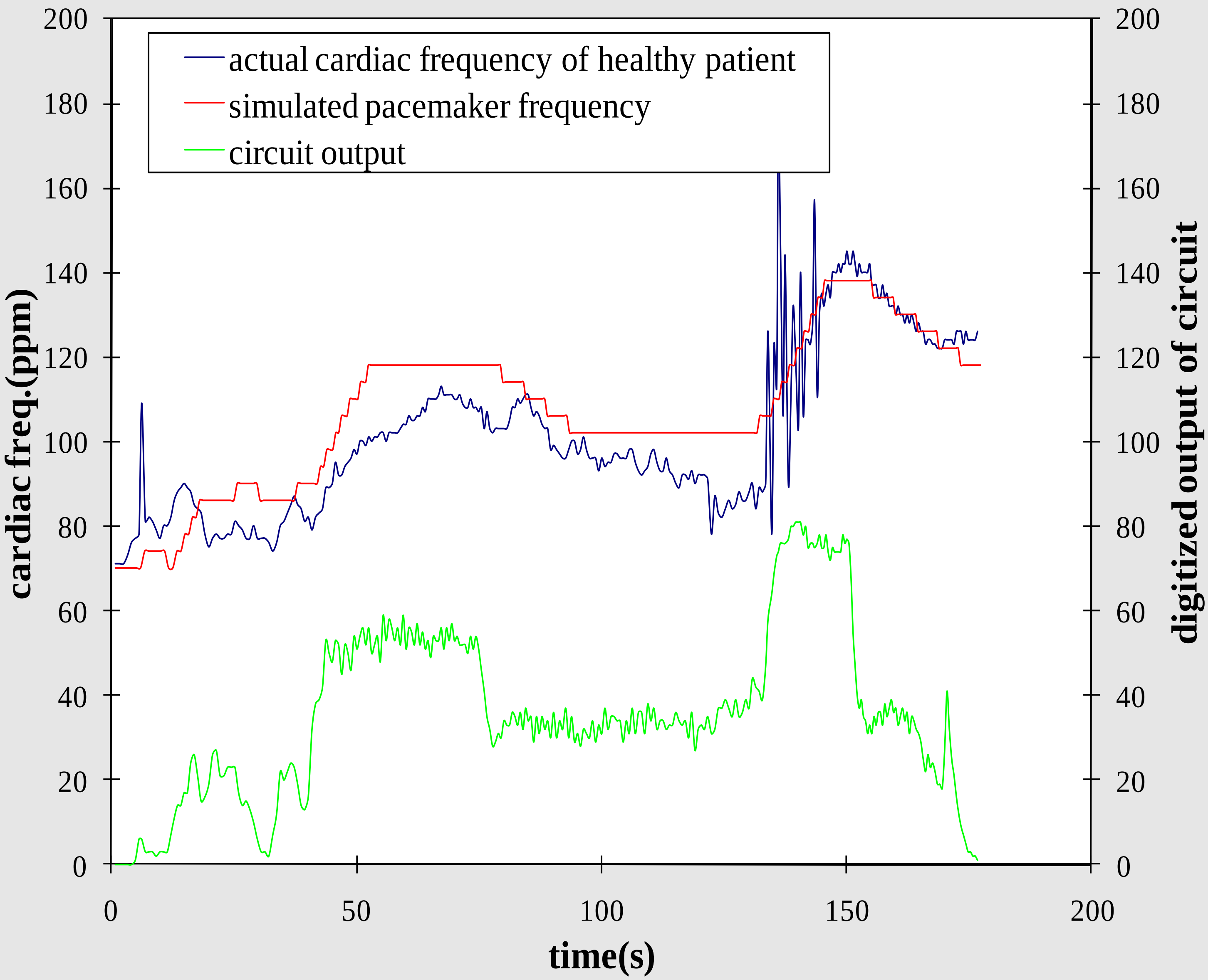
Feedback signal



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

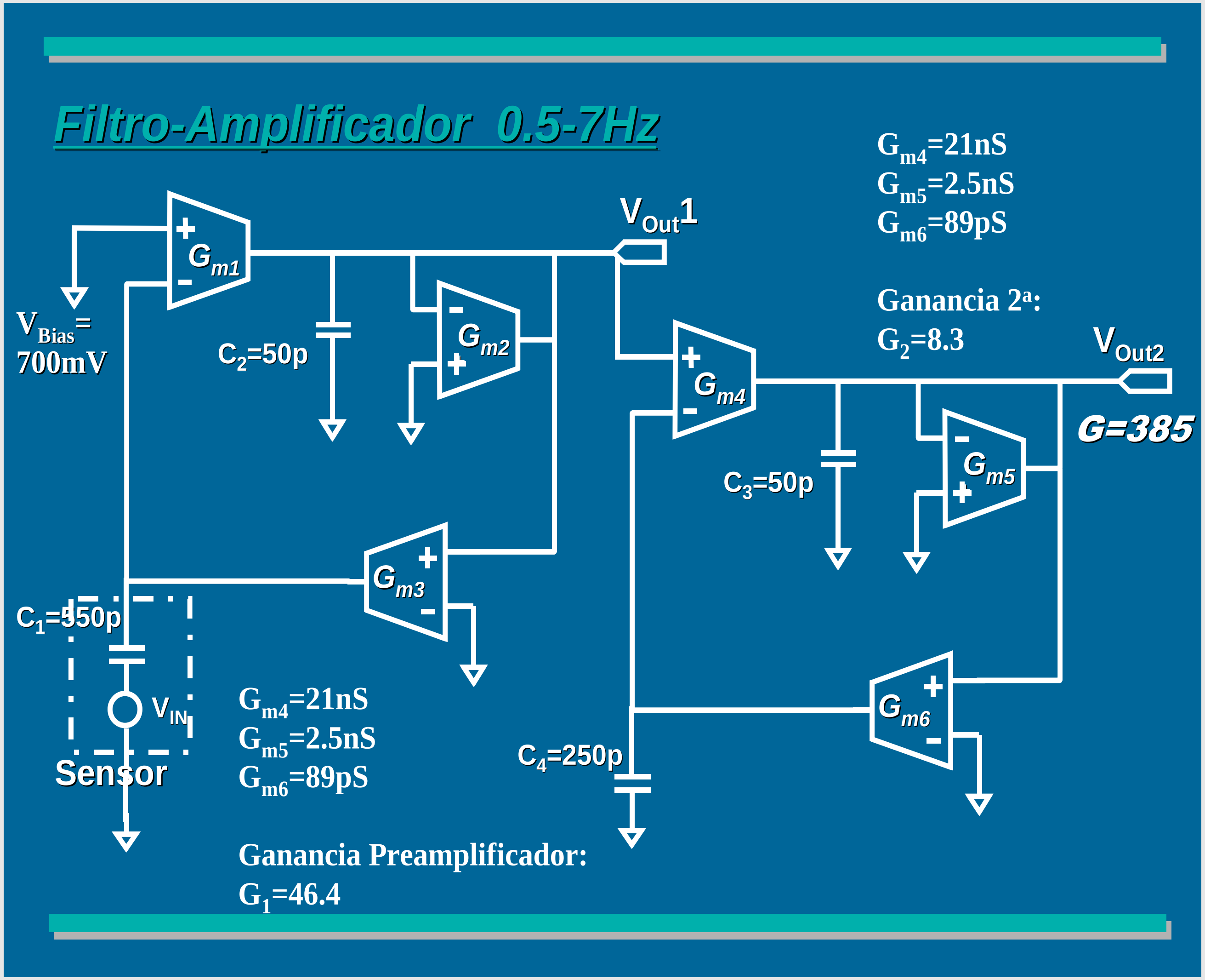
ISCAS 1998

Accelerometer Signal Conditioning (2): Results



Accelerometer Signal Conditioning (3) : Gm-C implementation

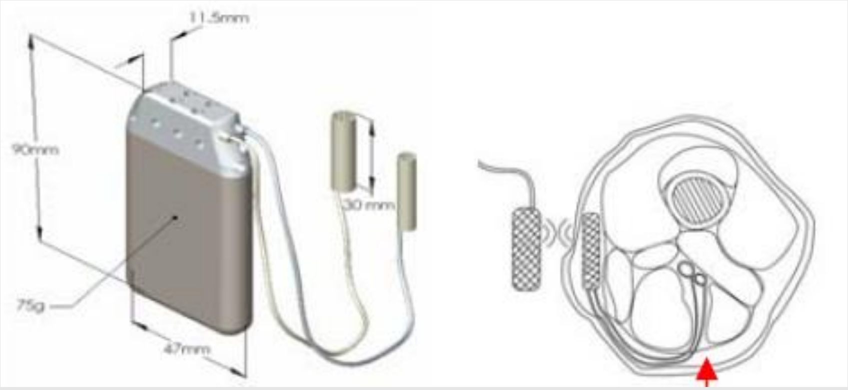
A. Arnaud (UR), C. Galup (UFSC), ISCAS 2004



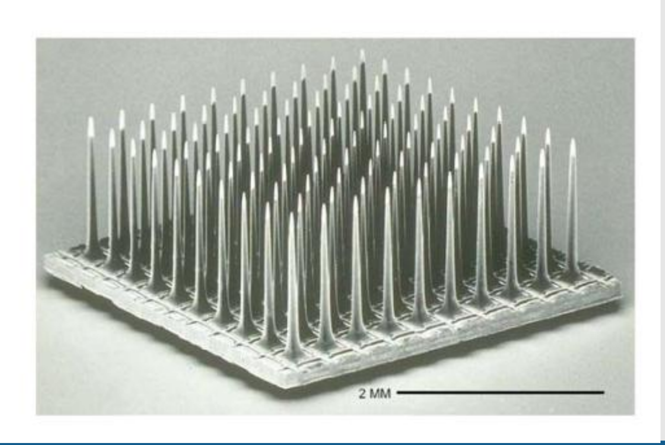
I_{DD}= 290nA
Equivalent Input noise: 2.1µVrms
Gain: 390
Fully integrated

Example of modules: Neural Recording Amplifier

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



- Requirements:
  - 0.5μVrms - 2μVrms 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 ….



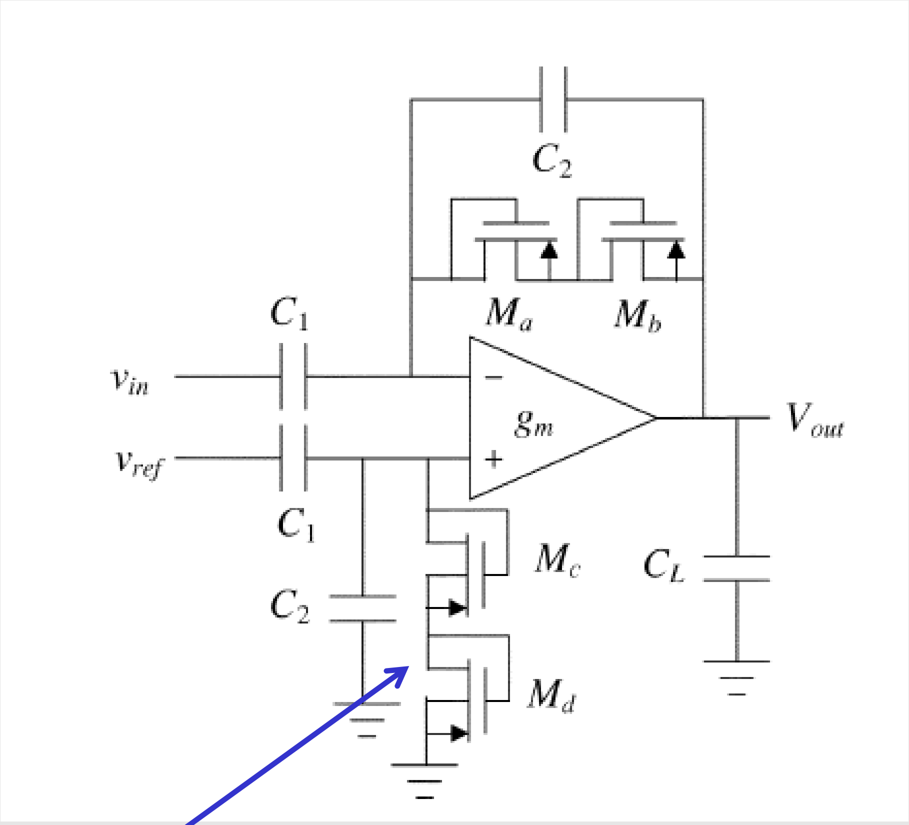
Neural Amplifier Front End (1): Capacitive Feedback

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

$$\mathrm{NEF} = V_{ni,\,\mathrm{rms}}\sqrt{\frac{2I_{\mathrm{tot}}}{\pi \cdot U_{\mathrm{T}} \cdot 4kT \cdot \mathrm{BW}}}$$

Gain	40 dB
BW	0.13 Hz / 7.5 kHz
Itotal	16 µA
NEF	3.8
vnoise rms	2.1 µV
CMRR	> 42 dB

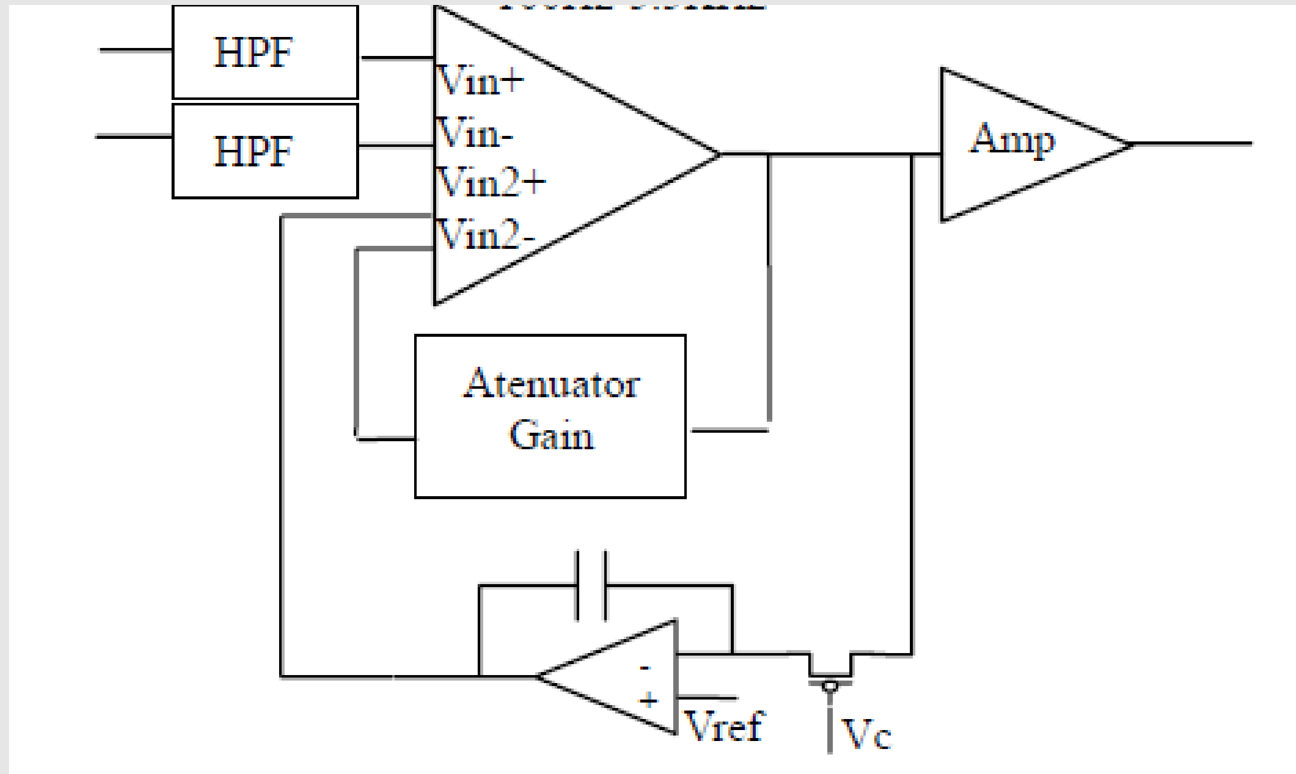
Harrison et al, IEEE JSSC, June 2003



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)



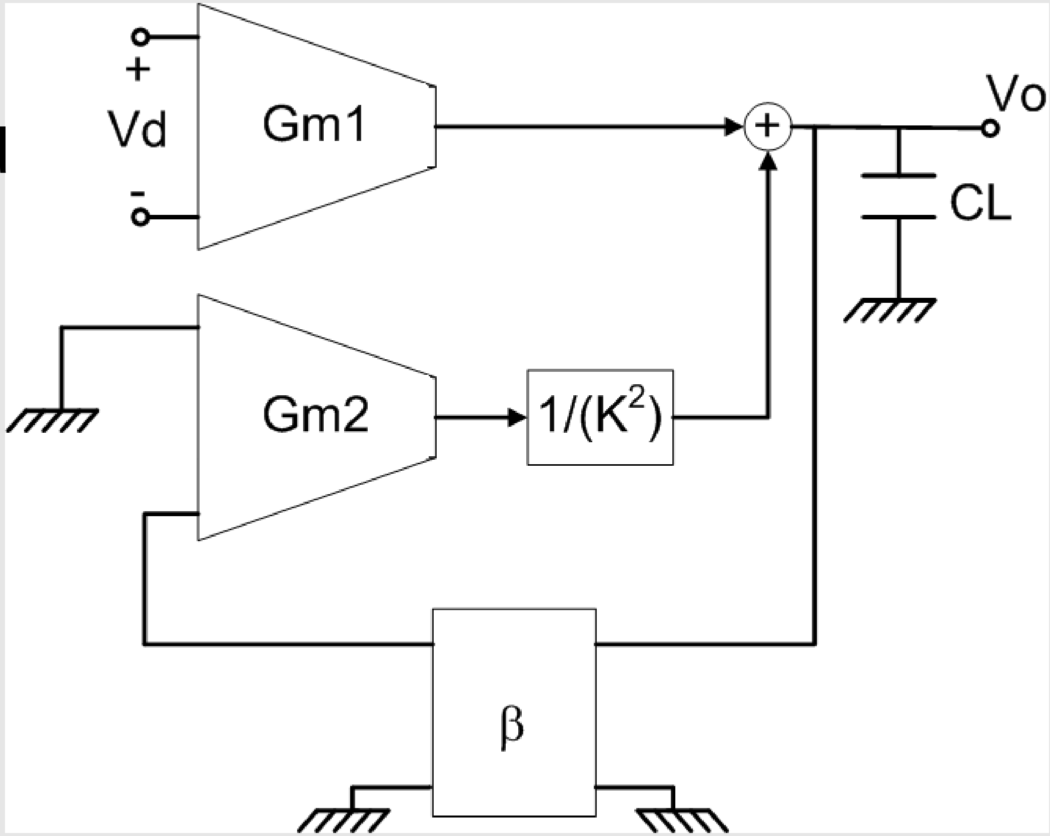
J. Sacristán, T. Oses, IFESS 2002,

Another DDA Based Scheme: M. Baru, U.S. Patent 6.996.435, 2006

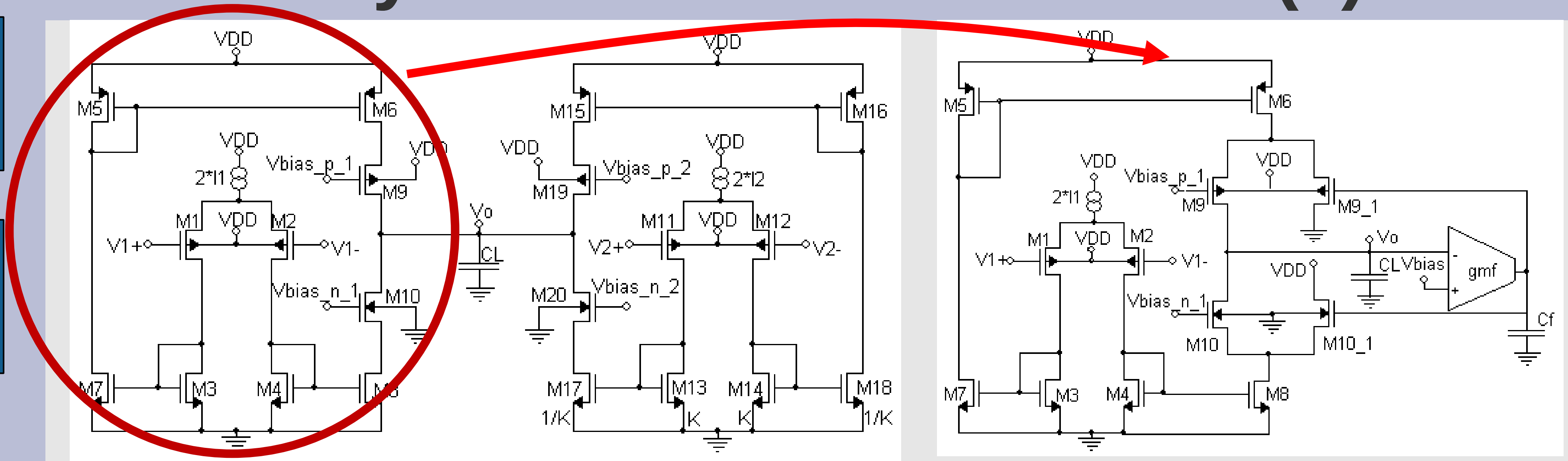
Neural Amplifier Front End (3): "Asymmetrical" DDA Based (I)

- ☺ 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

P. Castro, F. Silveira, ISCAS 2011



Neural Amplifier Front End (4): “Asymmetrical” DDA Based (II)



Spec	Castro, ISCAS 2011	Harrison, JSSC 2003	Wattapanitch, TR. BIOCAS 2007	Sacristan, IFESS 2002
Architecture	Asym. DDA	Capacitive	Capacitive	DDA
A (dB)	48	40	41	80
NEF	4.2	3.8	2.7	53.4
Itotal(μA)	16.5	16.0	2.7	180
vi noise (μVrms)	2.4	2.1	3.1	7.6
CMRR	> 107	> 42	> 66	90

Outline

I. System: Active Implantable Medical Devices Today

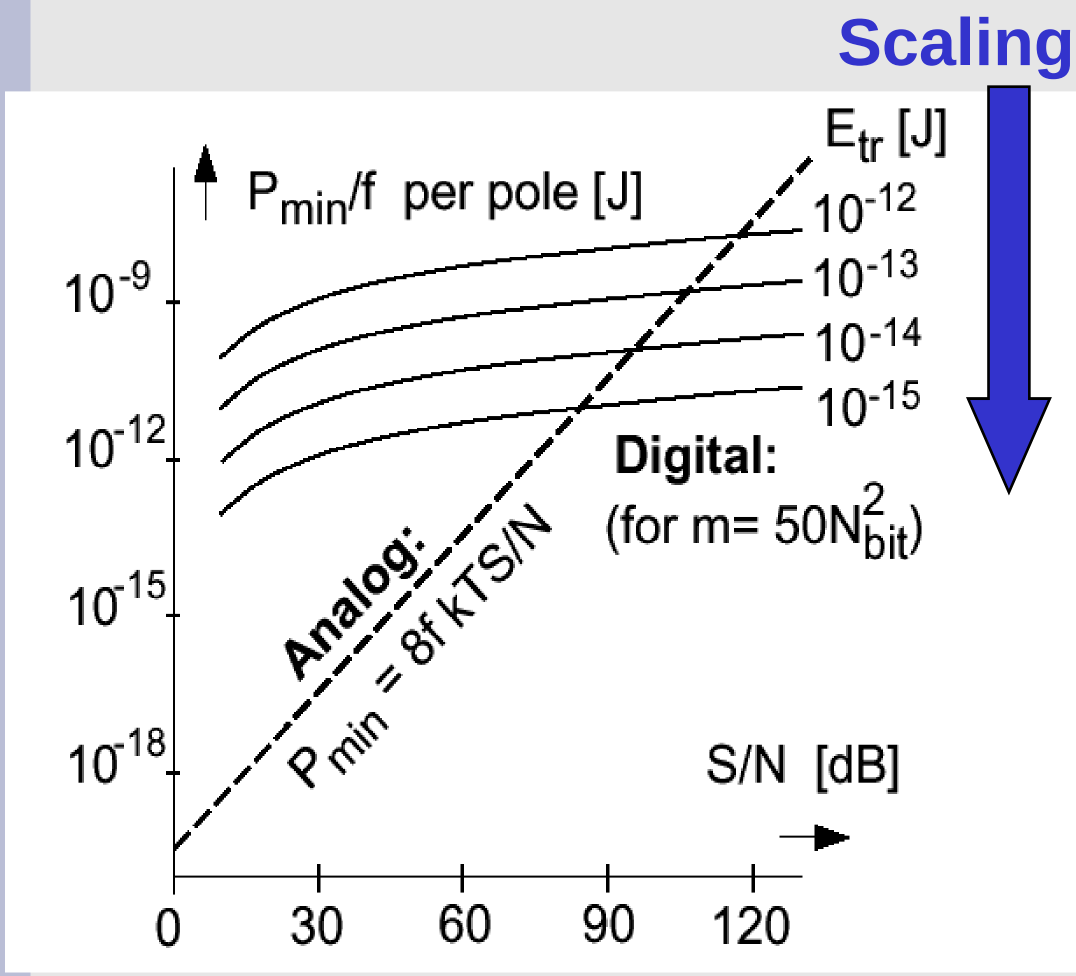
II. Transistors and Circuits: Analog Design for ULP.

- Transistor Modeling.
- Design Methodology.

III. Circuit Techniques: Implementation of AIMDs blocks

IV. Conclusions and Prospects

Prospects: Digital vs. Analog



Source: E. Vittoz

- **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

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

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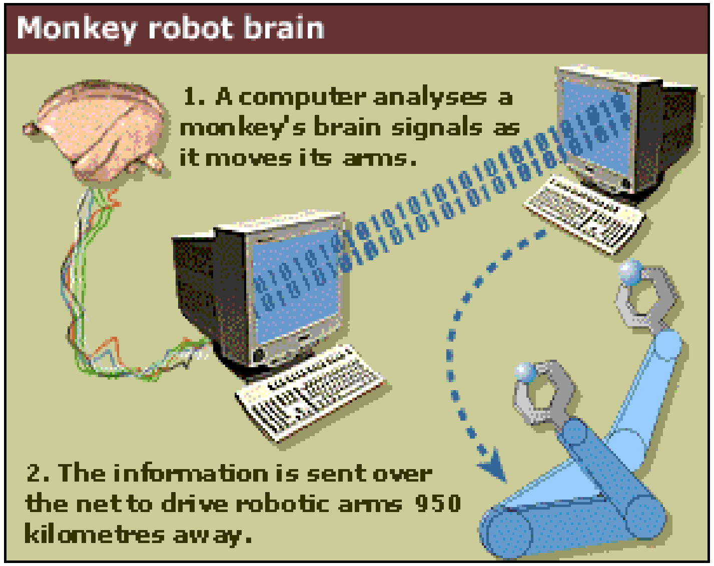
In Depth
AudioVideo

Wednesday, 15 November, 2000, 19:37 GMT

Monkey brain operates machine



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

As the animal stuck out its hand to pick up

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

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.

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More Information

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- CCC Medical Devices, NanoWattICs
- Members (present and past) of Microelectronics Group, UR

Upcoming Regional Events

Deadline: 1st Nov, 2013

10th Nov, 2013

Deadline: 15th Oct, 2013

LASCAS / Iberchip 2015: Uruguay

Thank you !