

Moving diagnostic, monitoring and therapeutic devices onto and into the body  
Electronics for better treatment and care

Wouter A. Serdijn  
19-9-2013



TU Delft Delft University of Technology Challenge the future

CAS

Biomedical Electronics Group

## IEEE Circuits and Systems Society

*Vision: "The IEEE Circuits and Systems Society (CASS) believes that the Grand Engineering Challenges of the 21st century can only be addressed in an inter-disciplinary and cross-disciplinary manner. The Society's unique and profound expertise in Circuits, Systems, Signals, Modelling, Analysis, and Design can have a decisive impact on important issues such as Sustainable Energy, Bio-Health, Green Information Technology, Nano-Technology, and Scalable Information Technology Systems."*

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CAS

## The Biomedical Electronics Lab (1)

**Vision:** **electroceuticals**, viz. devices that treat patients by means of electricity, will become the mainstay of medical treatment. They will become the medicine of choice for

- treatment of a wide range of diseases,
- repair lost or impaired functions,
- restore healthy set points in a wide array of physiological balances,
- and even introduce new homeostatic control.



## The Biomedical Electronics Lab (2)

**Mission:** to provide the technology for the successful monitoring, diagnosis and treatment of cortical, neural, cardiac and muscular disorders by means of **electroceuticals**.

- Neuroprosthetics
- Biosignal conditioning / detection
- Transcutaneous wireless communication
- Power management
- Energy harvesting
- Bioinspired circuits

**Not on the photo**

Sunit Bagga, Robin van Eijk, Marcel van der Horst, Marion de Vlieger, Chutham Sawigun, Sander Fondse, Joeri Biesbroek



## Outline

- Jump to the year 2057
- About wearable and implantable medical devices
  - Neurostimulation
  - Cochlear implants
  - Neurosensing devices
  - RF energy harvesting
- Where it all may lead to...



1 .

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Jump to the year 2057

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## 2057 The Body



# 2.

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About wearable and implantable  
medical devices

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## Wearable and implantable medical devices (WIMDs)

- Devices

- Worn on the body or
- Implanted inside the body by a surgeon.
- Used to monitor patient conditions and/or deliver therapy to the patient.
- Can facilitate or offer an alternative to drug treatment



## Wearable Medical Devices (WMDs)

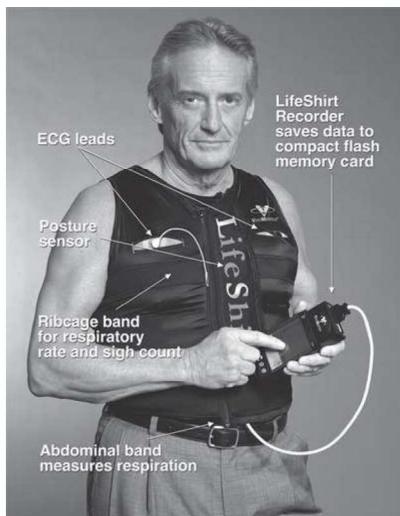
To measure:

- Motion
- Skin temperature
- Galvanic skin response (skin conductance)
- Colorimetry (Spectrophotometry)
- pH
- Blood glucose
- Blood pressure
- Body humidity
- Pulse
- **ECG**
- **EEG**
- Spirometry
- Photoplethysmograph



ECG monitor developed  
by the Holst Centre

## Examples of WMDs



VivoMetrics' LifeShirt



Bodymedia's SenseWear Pro  
Armband measures motion, steps,  
galvanic skin response, skin  
temperature and heat flux

Should be:

- Comfortable
- Washable / waterproof / robust
- Sensors included in the fabric
- Easy to install / operate
- Automatically collect data
- Personal / secure

## Implantable Medical Devices (IMDs) Examples

As a sensor:

- **ECG** (Holter recorder)
- **ENG**
- **ECoG**
- Implantable glucose sensor
- Intracranial pressure sensor
- Glaucoma sensor
- Motion sensor
- Nitric oxide (emitted by cancer cells) sensor

As an actuator:

- Insulin pump
- **Neurostimulator**

In a closed-loop fashion:

- **Cardiac pacemakers**
- **Implantable cardio defibrillator (ICD)**
- **Muscle stimulator**  
(Neurostep)



ANS' Eon

# 3.

## Energy-efficient neurostimulation



## The brain: our mainframe

An electro-chemical machine

**Chemical component**  
"Cure using medicine"

Global effect (side effects)  
19th century approach



**Electrical component**  
"Cure using Electricity"

Local effect  
Instantaneous and reversible  
21st century approach



# Neurostimulation

## Current approach

### Electrodes implanted in the brain

- Suppress unwanted activity
- Generate therapeutic activity
- (Future) modulate activity

### Pulse Generator in the chest

- Generate electrical pulses
- Low power consumption  
(battery size!)
- Safety requirements

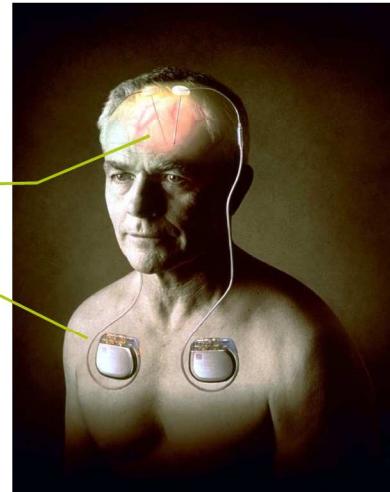


Image courtesy of Medtronic, Inc.



# Neurostimulation: example

### Deep Brain Stimulation of the Subthalamic Nucleus

#### Typical stimulation parameters:

- Amplitude: <10 V (voltage mode), <20 mA (current mode)
- Pulse width: ~100  $\mu$ s
- Repetition rate: ~100Hz



# Neurostimulators

## The future

Use new circuit techniques and alternative forms of stimulation to:

### Make implants fully implantable in the head

- Drastically decrease power consumption

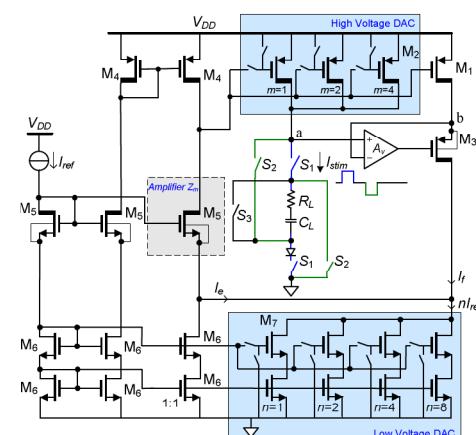
### Make implants smart

- Close the loop by including feedback



# Energy-efficient neurostimulation

- **No coupling capacitors**
- Single-supply bi-phasic stimulator
- Programmable least voltage drop current source
- **The least amount of HV transistors**
- Stimulation current: 10 $\mu$ A-1mA
- $R_L=1\text{k}\Omega\sim 10\text{k}\Omega$ ,  $C_L=1\text{nF}\sim 10\text{nF}$
- Charge error below safety limits



A Dual-Loop Feedback Current Source



## Circuit design: HV and LV DAC

NFETI20H(Iso. HV)  
 $V_{DS, max} = 20V$   
 $V_{GS, max} = 3.6V$

PFET50HS(HV)  
 $V_{DS, max} = 50V$   
 $V_{GS, max} = 20V$

PFET20H (HV)  
 $V_{DS, max} = 20V$   
 $V_{GS, max} = 20V$

NFET (LV)  
 $V_{DS, max} = 1.98V$   
 $V_{GS, max} = 1.98V$

$$I_{stim} = \left( \sum_{u=1}^3 2^u \right) \left( \sum_{l=1}^4 2^l \right) I_{ref}$$

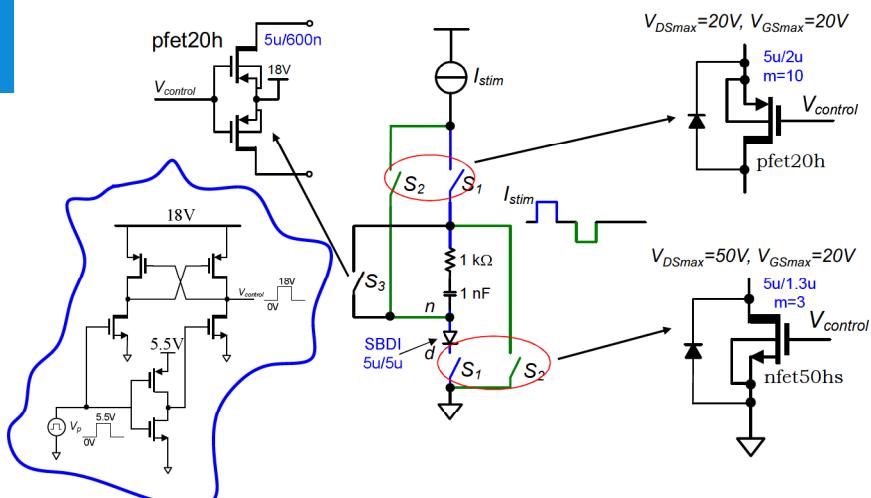


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## Circuit design: switch array

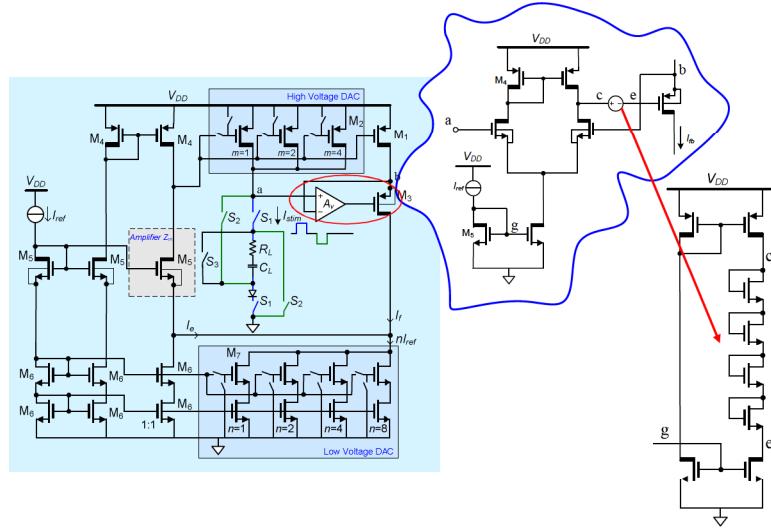


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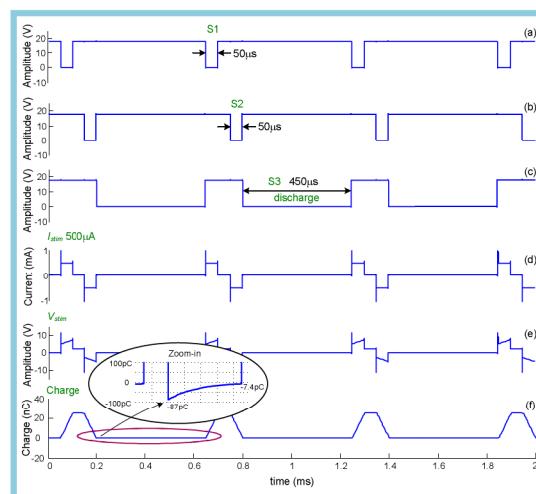


## Circuit design: differential amplifier and offset

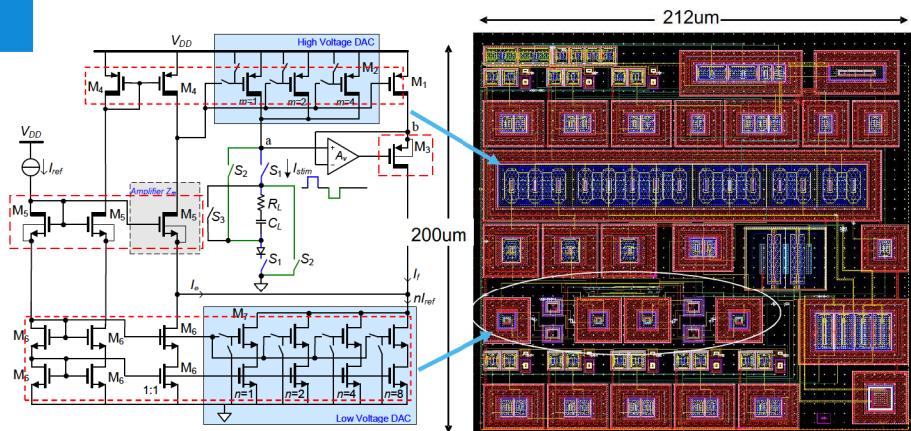


## Simulation results

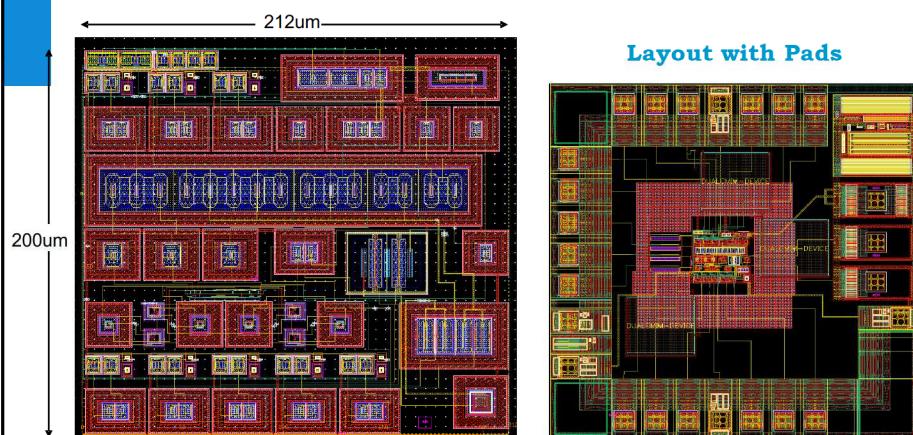
- 0.18um AMS HV CMOS
- $V_{DD} = 18V$
- Stimulation current = 500 $\mu A$
- Load = 10k $\Omega$  + 10nF
- Charge error = 0.03%
- = safe (!)



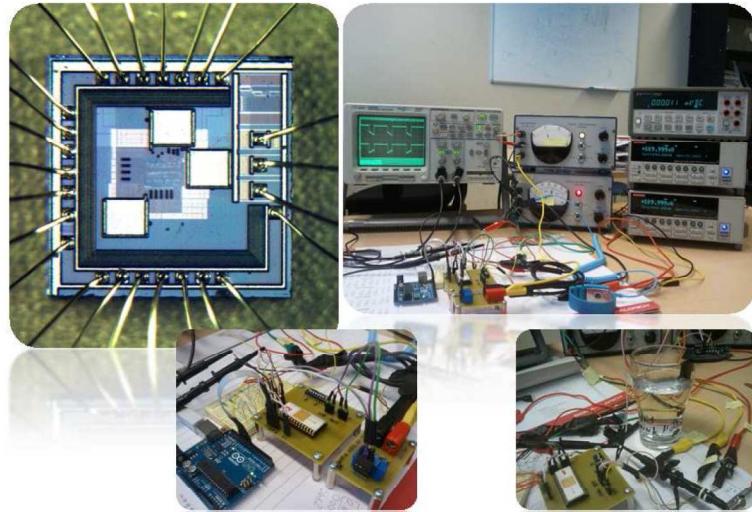
## Layout of the stimulator circuit



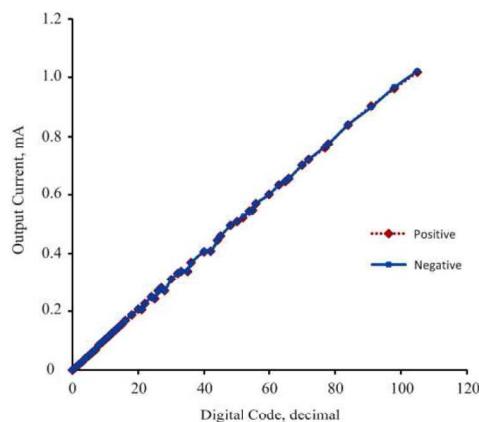
## Layout of the stimulator circuit



## Die photo and measurement setup

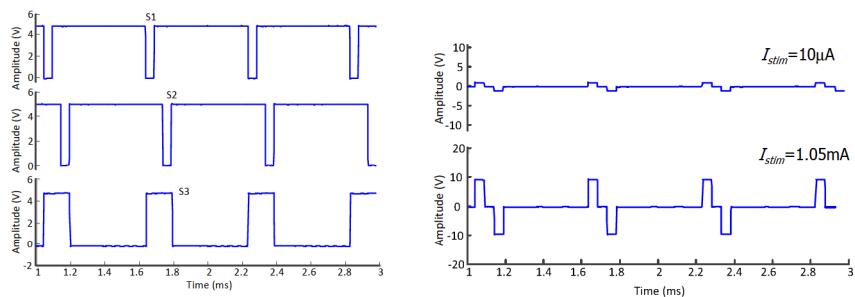


## Measured stimulation current ( $I_{stim}$ ) in positive and negative direction

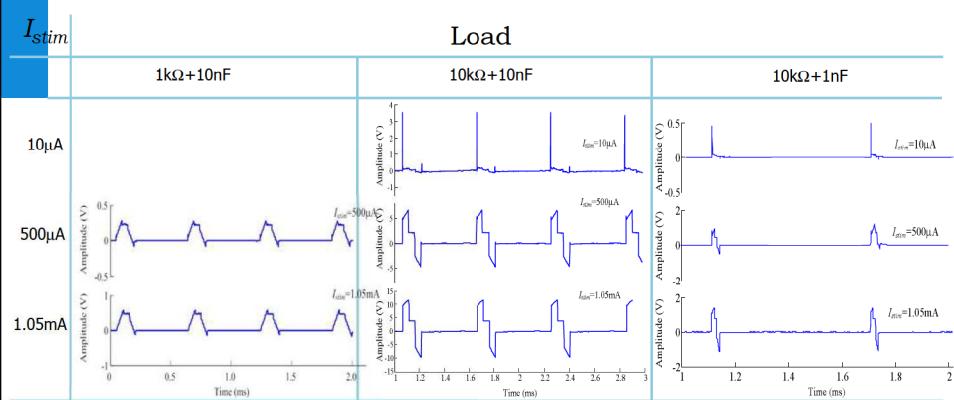


Negative current equals positive current;  
no charge accumulation = safe

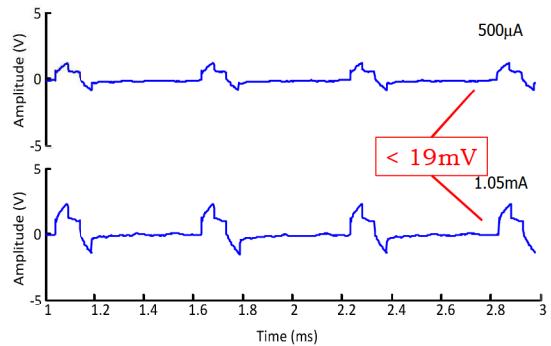
## Control signals and output voltage across load=10kΩ



## Load voltage

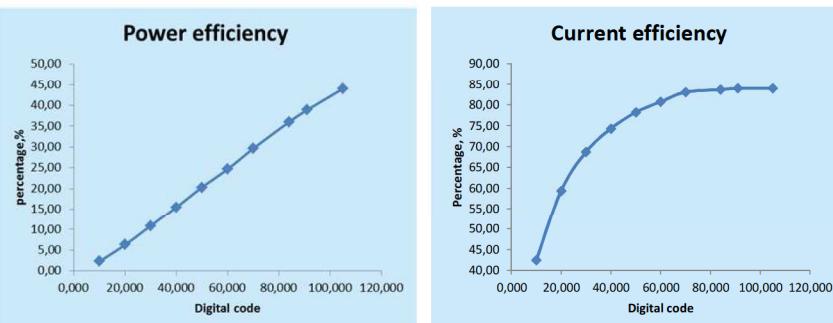


## Load voltage

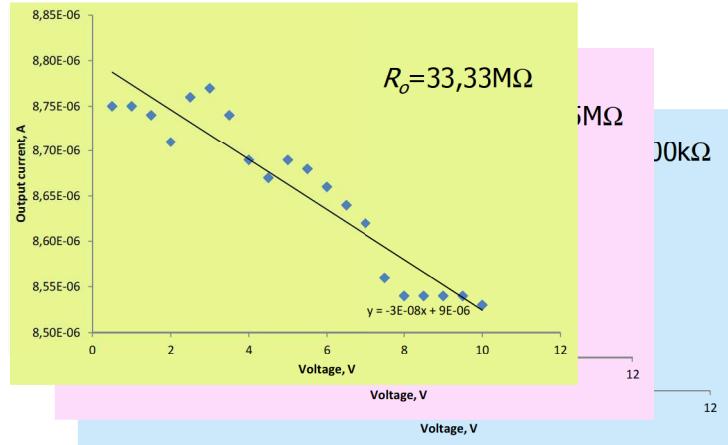


## Power and current efficiency

- At 10kΩ-load



## Output resistance

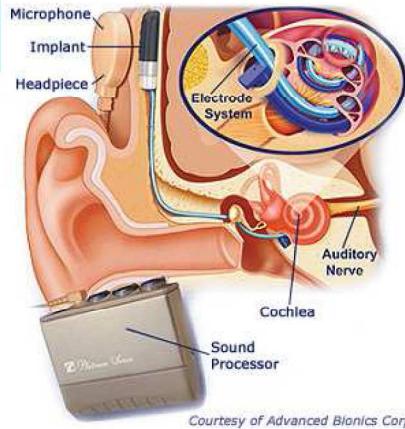


4.

Cochlear implants



## Cochlear implants (CIs)



- Currently (2013), cochlear implants have been implanted in more than 250,000 people worldwide
- Industrial players:



Advanced Bionics®



Cochlear™ Hear now. And always



## Making contact



## Current cochlear implants



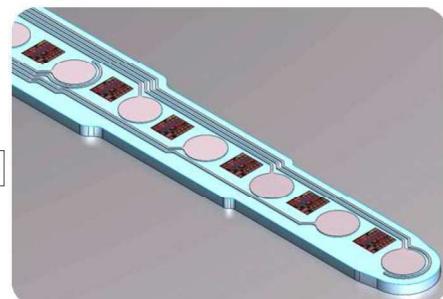
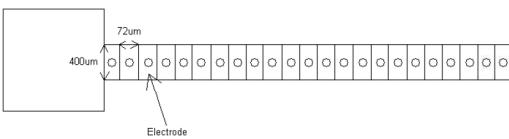
Source: A 32-Site 4-Channel High-Density Electrode Array for a Cochlear Prosthesis, Pamela T. Bhatti, Kensall D. Wise  
Univ. Michigan

- Challenges:
  - Small
  - Smaller



## The wiring problem

- More electrodes are needed for accurate stimulation of nerve fibres
- 230 channels
- Available chip area is **extremely** small

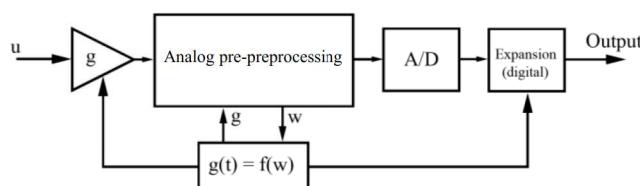


## Improved readout of the neural response

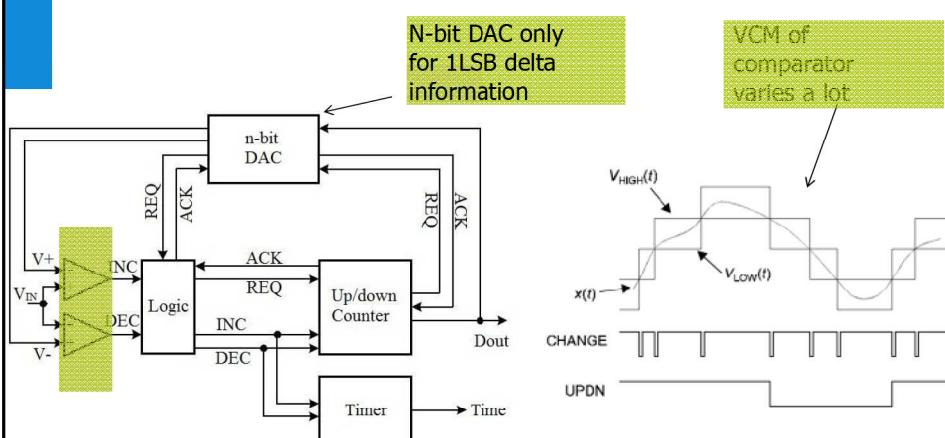
- Evoked compound action potentials (ECAPs)
- Important during placement of the electrodes in the cochlea
- Stimulus is approx. 40000 times greater than neural response ( $>V_{dd}$ )
- First step towards closed-loop operation and “implant and forget”

Approach:

- Instantaneous companding
- Level crossing ADC



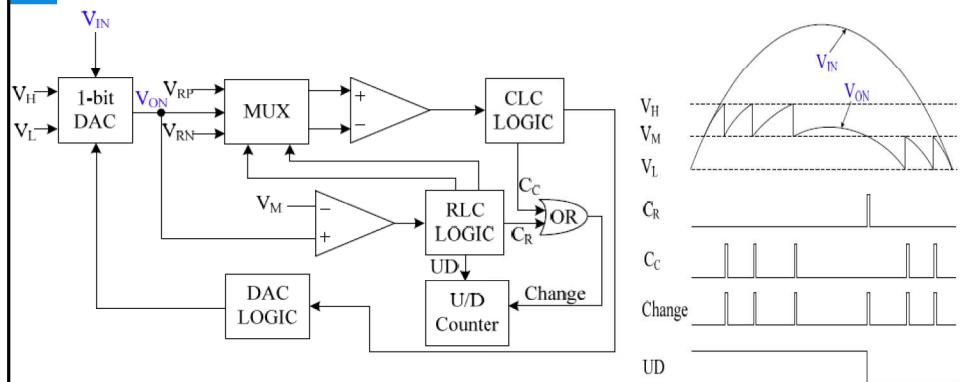
## Conventional level-crossing ADC



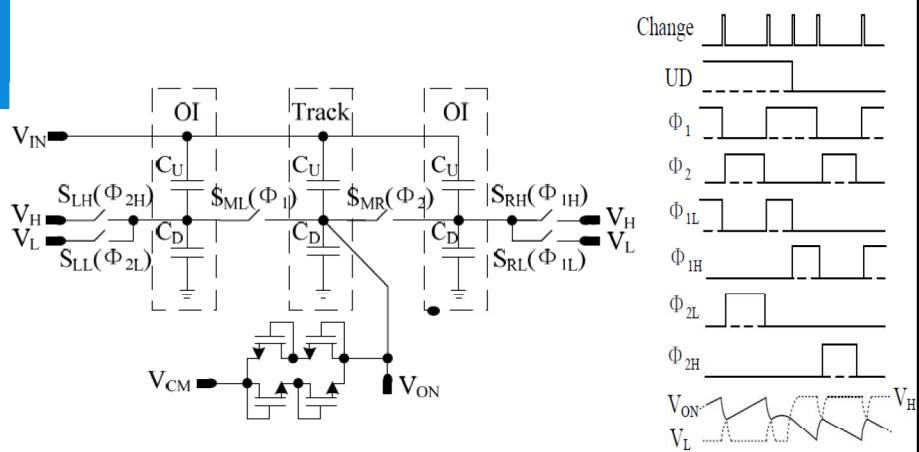
Processes the signal in time domain rather than magnitude domain



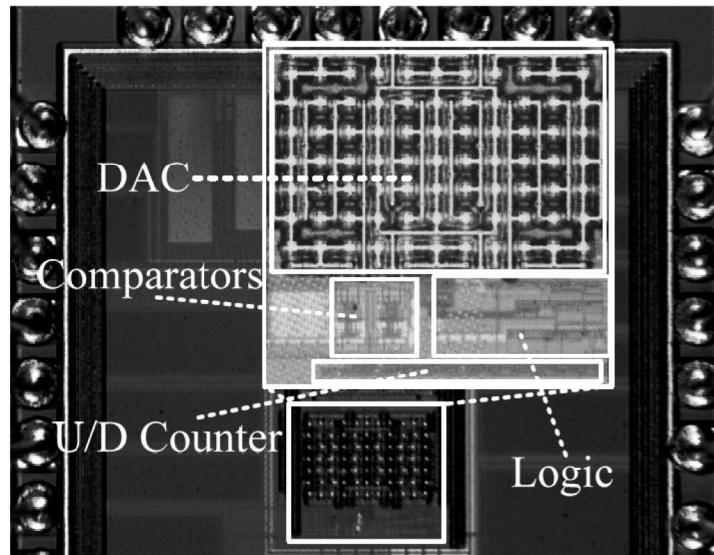
## Proposed level-crossing ADC



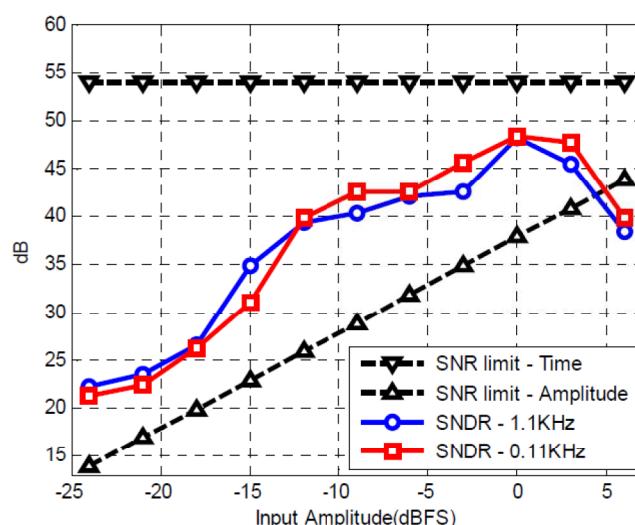
## 1-bit DAC



## Chip micrograph



## Performance (SNDR)



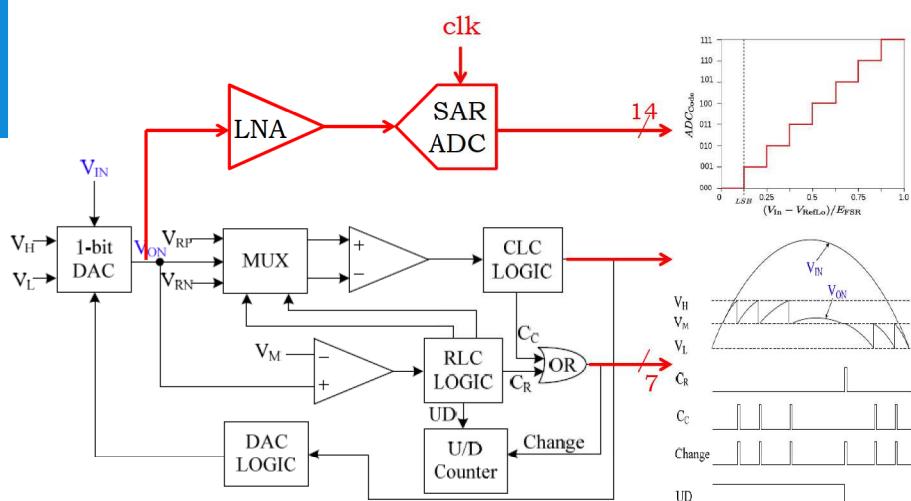
## Performance comparison

Parameter	[4]	[8]	[10]	[15]	This Work
Technology	90 nm CMOS	0.18 $\mu$ m CMOS	130 nm CMOS	0.5 $\mu$ m CMOS	0.18 $\mu$ m CMOS
Supply Voltage	1 V	0.7 V	0.8 V	3.3 V	0.8 V
Amplitude Resolution	8 bits	4 - 8 bits	4 - 8 bits	7 bits	7 bits
Timer Resolution	w/o timer	1 $\mu$ s	w/o timer	-	0.2 to 100 $\mu$ s
Adaptive Resolution	No	Yes	Yes	No	No
SNDR	47 - 62 dB	Peak 43.2 dB	47 - 54 dB	Peak 34 dB	40 - 49 dB
Input Bandwidth	200 Hz - 4 kHz	1 Hz - 1.1 kHz	20 Hz - 20 kHz	-	5 Hz - 5.1 kHz
Full-Scale Input	0.5 V <sub>PP</sub>	1.4 V <sub>PP</sub>	0.72 V <sub>PP</sub>	2.68 V <sub>PP</sub>	1.6 V <sub>PP</sub>
Power Consumption	40 $\mu$ W <sup>a</sup>	25 $\mu$ W <sup>b</sup>	2.6 - 7.4 $\mu$ W	10.73 $\mu$ W <sup>c</sup>	313 to 582 nW
Active Area	0.06 mm <sup>2</sup>	0.96 mm <sup>2</sup>	0.36 mm <sup>2</sup>	-	0.045 mm <sup>2</sup>

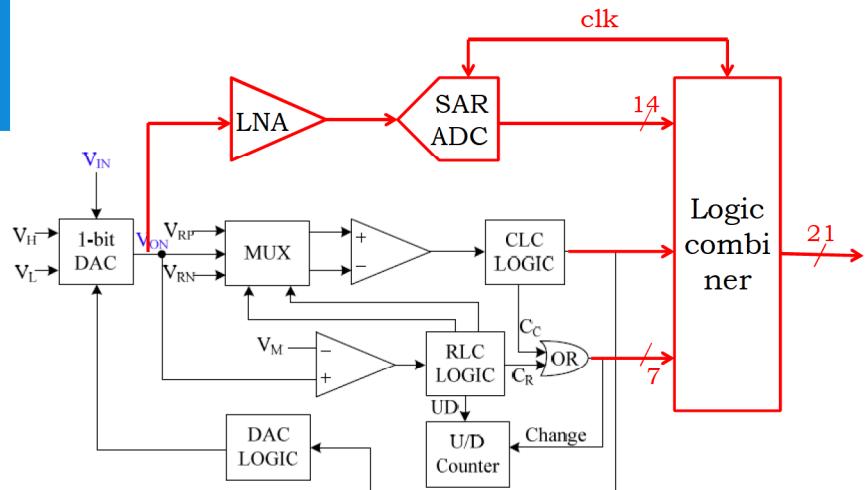
- a. Static power consumption from the two comparators  
b. Without off-chip logic  
c. Calculate from the 4-channel static power consumption



## Towards 21 bits



## Towards 21 bits



5.

Neurosensing devices

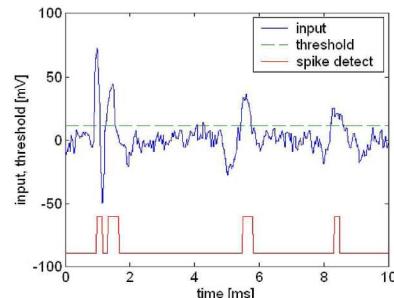
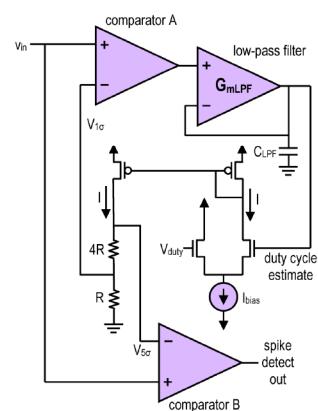


## Monitoring neural activity

- Neuroscientists
  - Understanding the central nervous system/brain
  - Understanding the peripheral nervous system
  - Diagnose
  - Select proper treatment
- Brain machine interface
  - Control of prosthetic devices
  - Seizure alarm
- Closed loop neurostimulators
  - Monitoring and stimulating of neural tissue



## Action potential detection

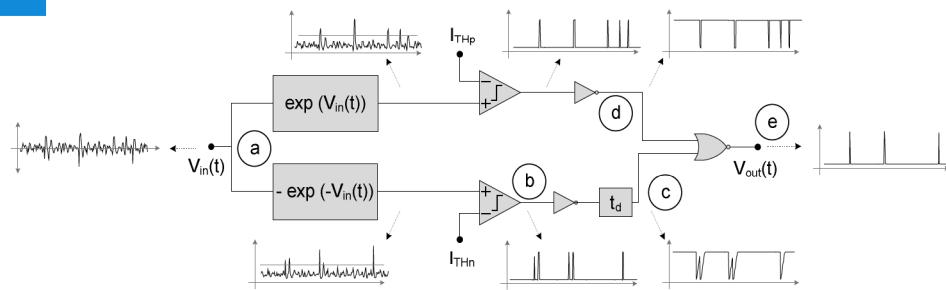


[R. Harrison: The Design of Integrated Circuits to Observe Brain Activity,  
Proc. IEEE, Vol. 96, No. 7, July 2008, pp. 1203-1216]



# Dual-threshold detector (I)

## block diagram

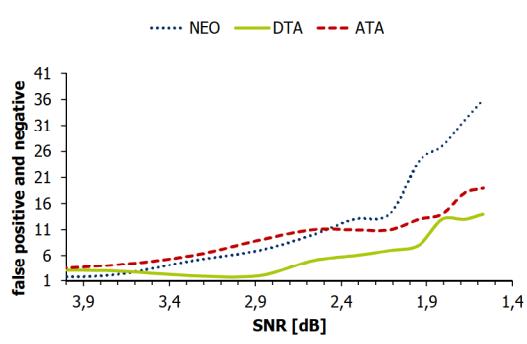


This "dual threshold" AP detection algorithm was originally proposed by Borghi [1], including additional filtering.

[1] T. Borghi, R. Gusmeroli, A. S. Spinelli, and G. Baranauskas, "A simple method for efficient spike detection in multiunit recordings," *Journal of Neuroscience Methods*, vol. 163, no. 1, pp. 176 – 180, 2007.



# Performance comparison



- NEO = Nonlinear Energy Operator is used as a preprocessor [2]
- ATA = Adaptive Threshold Algorithm [3]
- DTA = Dual Threshold Algorithm, this work

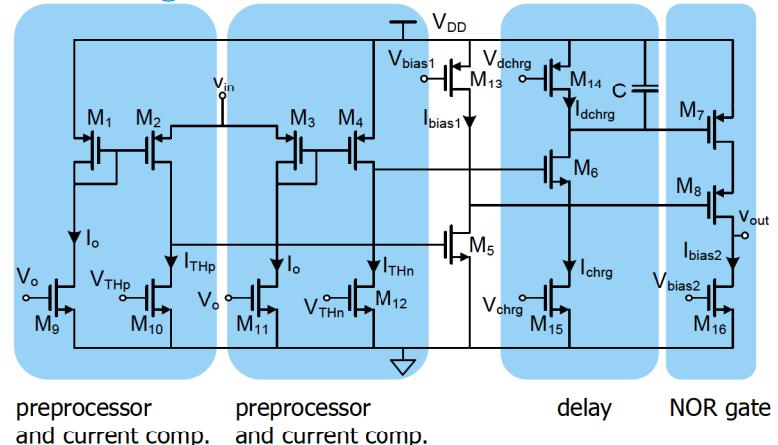
[2] J. F. Kaiser, "On a simple algorithm to calculate the 'energy' of a signal," *Acoustics, Speech, and Signal Processing, 1990. ICASSP-90, 1990 International Conference on*, pp. 381–384 vol.1, Apr 1990.

[3] R. R. Harrison, "A low-power integrated circuit for adaptive detection of action potentials in noisy signals," *Engineering in Medicine and Biology Society, 2003. Proceedings of the 25<sup>th</sup> Annual International Conference of the IEEE*, vol. 4, pp. 3325–3328 Vol.4, Sept. 2003.



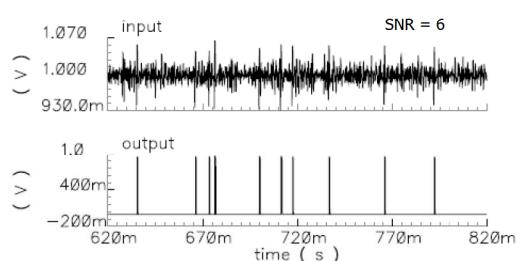
## Dual-threshold detector (II)

circuit diagram



## Circuit simulations results

using AMIS 0.35  $\mu$ m, Cadence, RF Spectre



- Supply Voltage = 1V
- Static power consumption is 1.5 nW @ 37 deg.
- Annotations confirmed by neuro-scientist



## Tinnitus (intro)



## Tinnitus

- = the perception of sound without a corresponding external sound
- Due to a restructuring of the auditory cortex
- Approximately a billion people suffer from tinnitus worldwide.
- In 2% - 3% of the population, tinnitus can lead to insomnia, anxiety and depression.
- No proven treatments for tinnitus
- Some patients benefit from **electrical brain stimulation.**



The Scream,  
by Edvard Munch  
1893



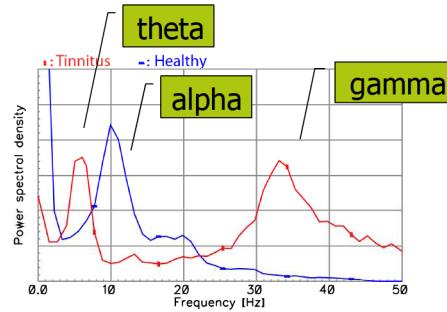
# Tinnitus detection and treatment

## Current stimulation

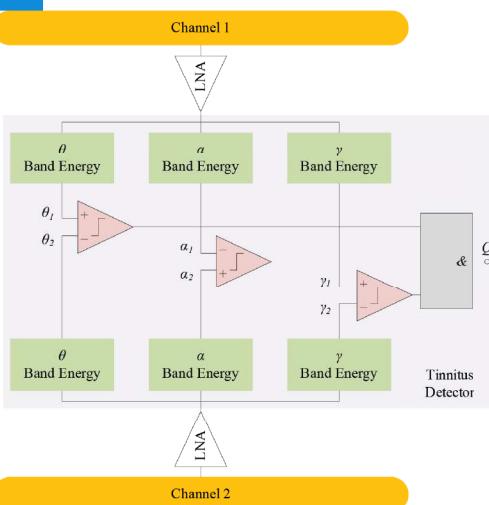
- requires a patient's subjective opinion to select an individualized stimulation therapy.

## Future stimulation

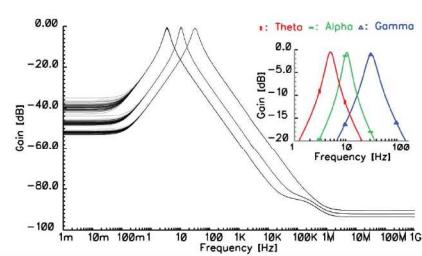
- Based on an automatic tinnitus detector
- to automatically adapt and choose stimulation therapy, in a closed-loop (CL) manner.



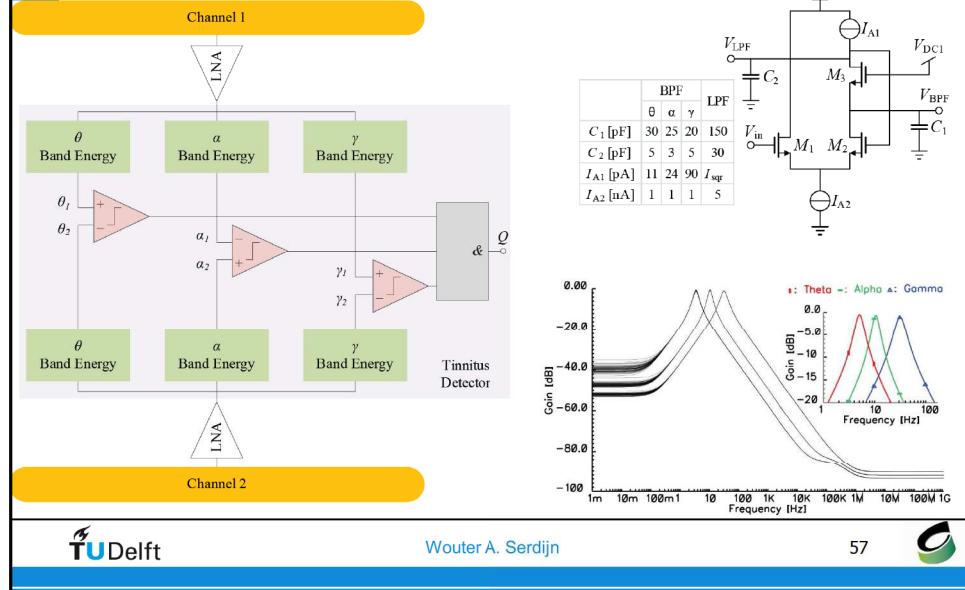
# Proposed Tinnitus Detector



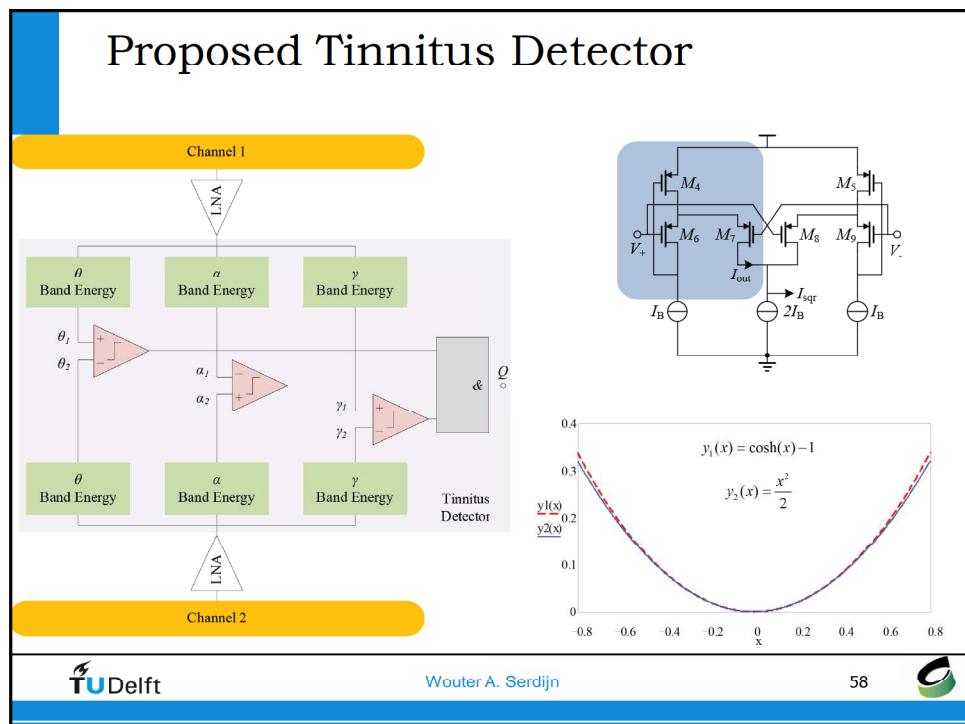
1. Select frequency band (filter)
2. Obtain power (square)
3. Integrate (filter) power into energy
4. Compare and decide



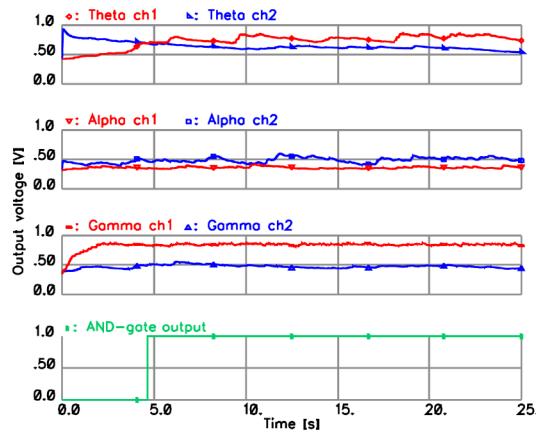
## Proposed Tinnitus Detector



## Proposed Tinnitus Detector



## Results



- Real ECoG input signal from a tinnitus patient.
- 60 nW

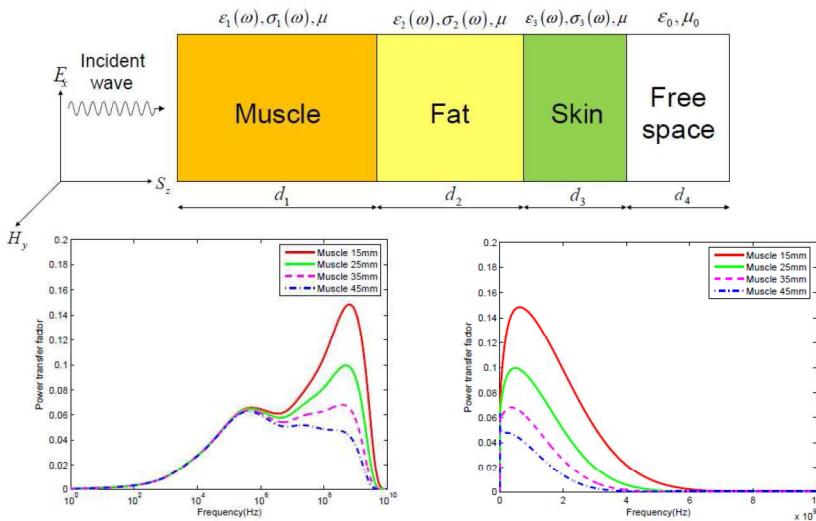


# 6.

## WIMD communication



## Characterizing the transcutaneous wireless channel

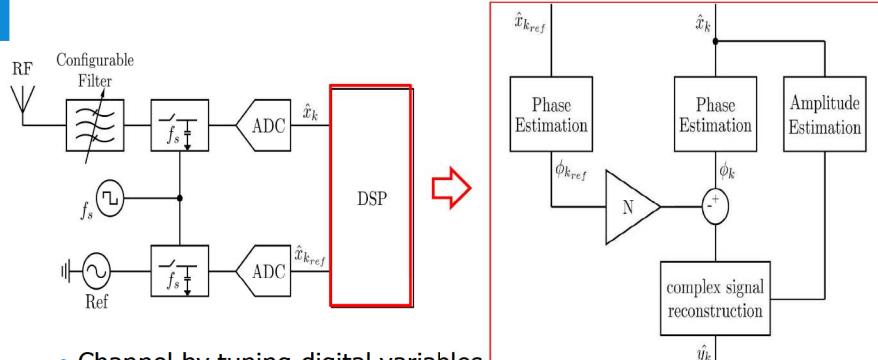


## Wireless In-Body Area Networks

- Existing and emerging standards (i.e. IEEE802.15.6) for WIBAN require wireless front-ends that are:
  - Low power
  - Reconfigurable
  - Able to deal with congested radio frequency bands
- Solution: Subsampling based Software Defined Radio (Su-SDR)
  - Advantage: Low power, reconfigurable, easy structure
  - Disadvantage: Poor noise performance and frequency stability
- Jitter is the main issue which degrades the performance of subsampling SDR.



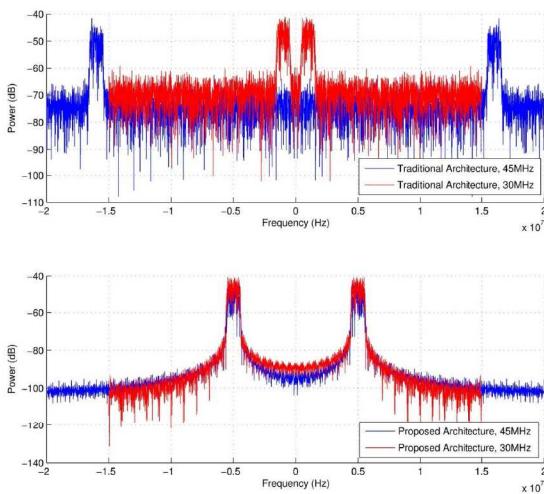
## Subsampling based Software Defined Radio (Su-SDR) with jitter compensation



- Channel by tuning digital variables.
- Reduction of sampling jitter due to clean reference signal
- Low power operation due to subsampling nature



## Output signal spectra



- Sampling frequencies of 40 MHz and 42 MHz
- 20ps RMS sampling clock jitter
- 1MHz clock reference without jitter.
- pi/8-D8PSK modulated RF input at 2404 MHz
- 600 kS/s data rate

(a) Traditional architecture:

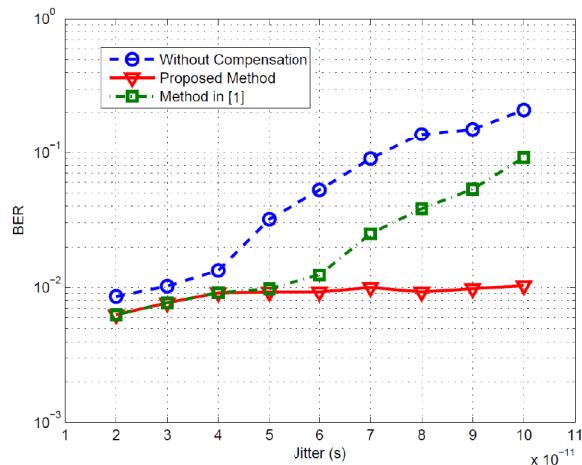
- N=0 (no sub-sampling)

(b) Su-SDR architecture:

- N=2404



## Bit error rate (BER) performance

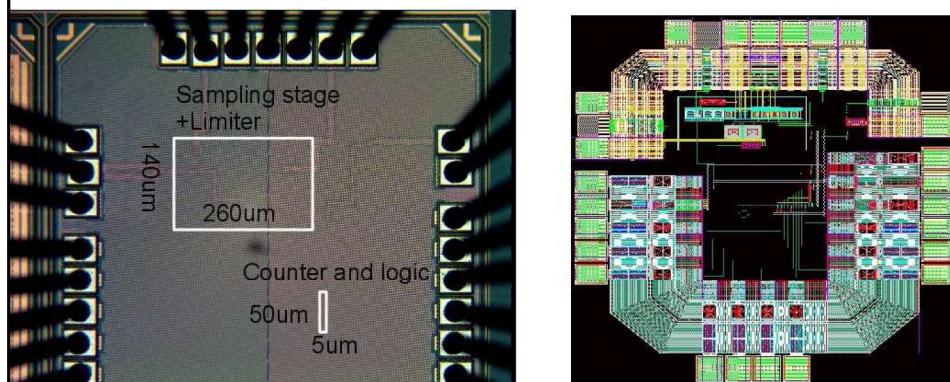


[1] Towfic, Z.J.; Shang-Kee Ting; Sayed, A.H.; , "Sampling clock jitter estimation and compensation in ADC circuits," *Circuits and Systems (ISCAS), Proceedings of 2010 IEEE International Symposium on* , vol., no., pp.829-832, May 30 2010-June 2 2010

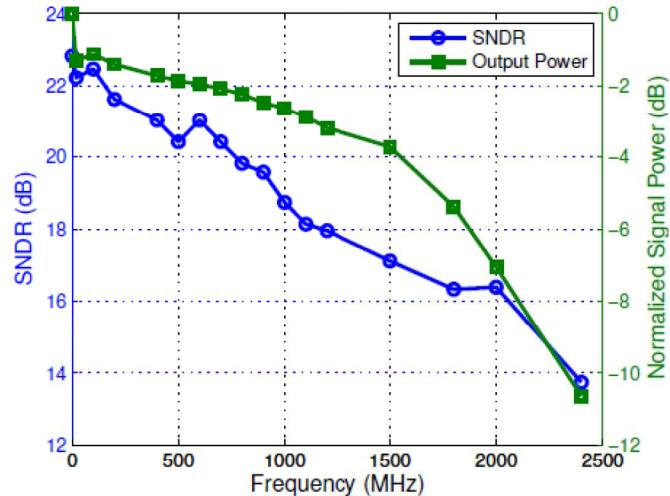


## Microphotograph and layout

- Phase readout ADC designed for PSK demodulation
- Voltage to pulse duty-cycle conversion



## Measurement results on the phase readout ADC



## Phase readout ADC performance comparison

	this work	ISSCC09[4]	ASSCC11[5]
Process	40nm	90nm	90nm
Supply	1V	1V(0.4V digital)	1.3V
Sampling frequency	20MHz	1MHz	4.4GHz
Resolution	5	9	4
Power	210 $\mu$ W	14 $\mu$ W	24.5mW
ENOB	3.71	7.9	3.51
FoM	803fJ/Step	89fJ/Step	490fJ/Step
Sampling Bandwidth	1.2GHz	300KHz	1GHz
Sensitivity@12dB	-80dBm@20KHz	NA	NA

[4] S. Naraghi, M. Courcy, and M. Flynn, "A 9b 14  $\mu$ w 0.06mm<sup>2</sup> ppm adc in 90nm digital cmos," in *Solid State Circuits Conference - Digest of Technical Papers, 2009. ISSCC 2009. IEEE International*, feb. 2009, pp. 168 –169,169a.

[5] M. Takayama, S. Dosho, N. Takeda, M. Miyahara, and A. Matsuzawa, "A time-domain architecture and design method of high speed a-to-d converters with standard cells," in *Solid State Circuits Conference (ASSCC), 2011 IEEE Asian*, nov. 2011, pp. 353 –356.



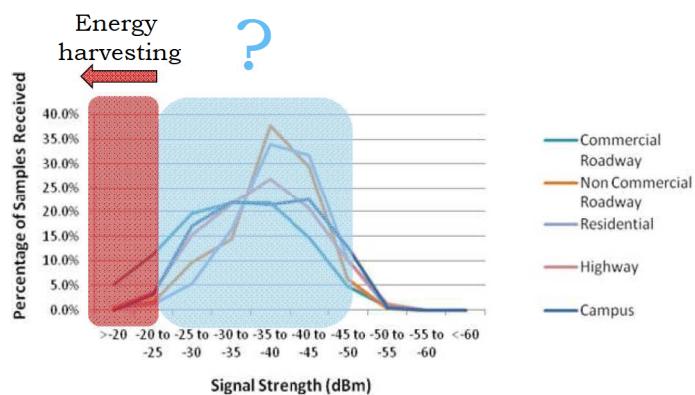
# 6.

## RF energy harvesting



## Introduction

Distribution of peak RF signal strength in suburban landscape



Source: "Low power Smartdust Receiver with novel applications and improvements of an RF Power Harvesting Circuit". T. S. Salter JR., PhD Thesis 2009



## Challenges in RF energy harvesting

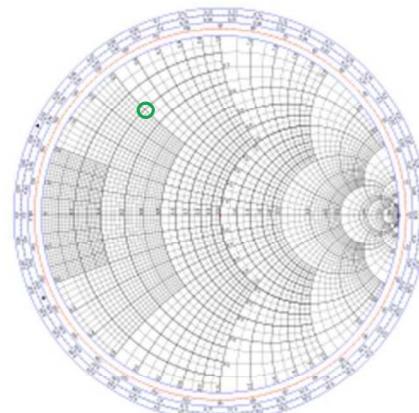
1. Robustness against environment, power level and process variations
  - Antenna impedance is influenced by the surrounding environment
  - Rectifier input “impedance” is nonlinear
  - Difficult to obtain a good conjugate impedance match
2. Limited wireless range
  - Rectifier cannot be activated when input voltage is lower than the turn-on voltage



### 1<sup>st</sup> approach: desperately try to get a conjugate impedance match

- Maximum power theorem (Jacobi's Law)

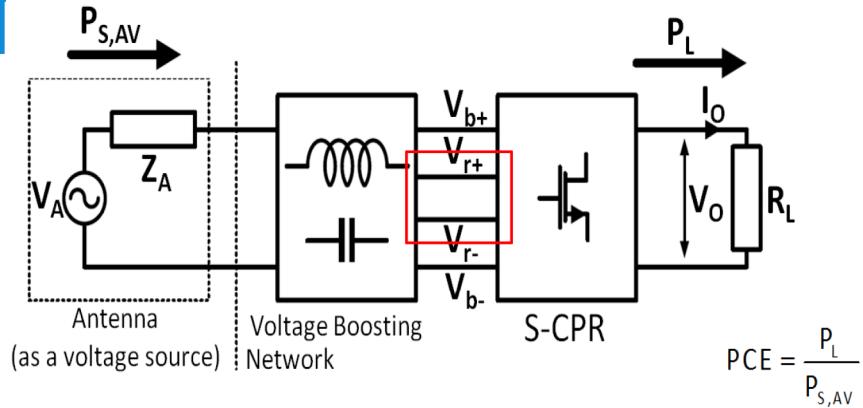
$$Z_{rect,in} = Z_{ant}^*$$



- The theorem results in maximum power transfer, not maximum efficiency.

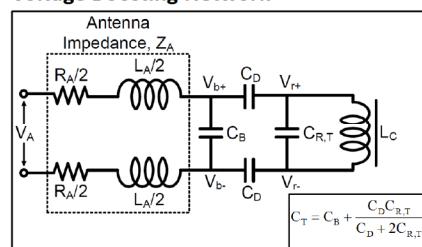


## 1st approach: split power path and switching control (I)



## 1st approach: split power path and switching control (II)

**Voltage Boosting Network**



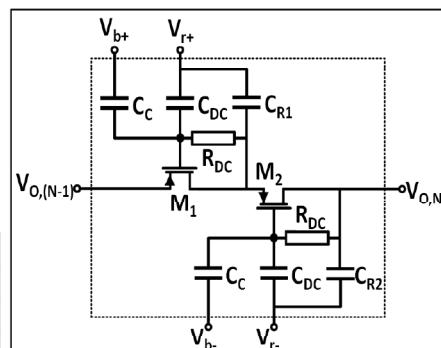
**PCE Optimized for N-stages**

$F_C$ (MHz)	PCE(%) <sup>(1)</sup>	$N^{(1)}$	PCE (%) <sup>(2)</sup>	$N^{(2)}$
13.56	6.7	4	9.4	8
433.92	5.7	6	12.7	6
915	5	5	11.9	5

<sup>(1)</sup> for  $P_{S,AV} = -18.2$  dBm and  $R_L = 0.1\text{M}\Omega$

<sup>(2)</sup> for  $P_{S,AV} = -18.2$  dBm and  $R_L = 1\text{M}\Omega$

**Rectifier Circuit**



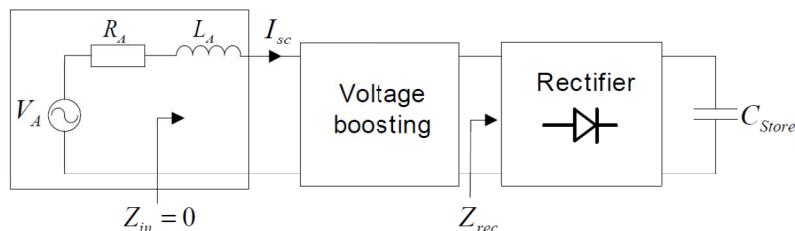
## 1st approach: split power path and switching control (III)

Specification	This Work	[1]	[2]	[3]	[4]
Frequency (MHz)	915	915	906	869	450
Conditions	Standard CMOS	Deep N-Well	Pre-charge Phase	Schottky Diodes	Low- $V_{TH}$
Number of stages	5	17	36	n.a.	16
$V_o$ (V) <sup>(1)</sup> ( $RL=1M\Omega$ )	1.35	0.9	1.3	n.a.	1.3
PCE (%) <sup>(1)</sup> ( $RL=1M\Omega$ )	11.9	5/12 <sup>(3)</sup>	8.5 <sup>(4)</sup>	14.5 (at -20.1dBm)	11.2
PCE (%) <sup>(1)</sup> ( $RL=0.5M\Omega$ )	9.7	2.8	n.a.	n.a.	n.a.
PCE (%) <sup>(1)</sup> ( $RL=0.3M\Omega$ )	8.3	n.a.	1.3	n.a.	n.a.
PCE (%) <sup>(1)</sup> ( $RL=0.1M\Omega$ )	5	n.a.	n.a.	n.a.	n.a.
PCE (%) <sup>(2)</sup> ( $RL=1M\Omega$ )	9.2	2.25	9.1	n.a.	n.a.
	Simulated	Measured	Measured	Measured	Measured
Technology (nm)	CMOS (90)	CMOS(90)	CMOS(250)	CMOS (500)	CMOS(250)



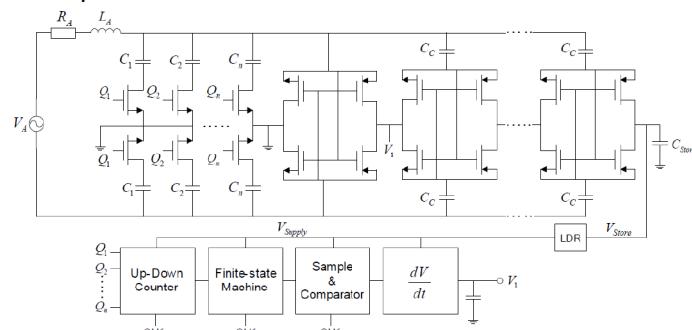
## 2<sup>nd</sup> approach: optimal mismatch (I)

- An optimally *mismatched* antenna-electronics interface
- Charging current is maximized when  $Z_{in}=0 \Omega$
- Antenna & rectifier form a high-Q resonating network
- Large passive voltage boost increases rectifier sensitivity
- Choose rectifier topology with minimum “resistance”



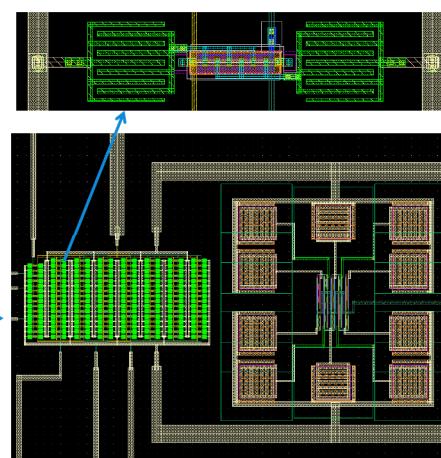
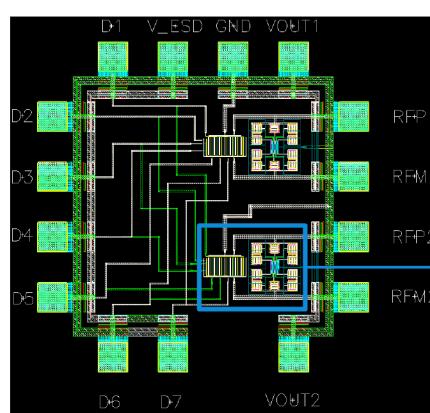
## 2<sup>nd</sup> approach: optimal mismatch (II)

- A feedback controlled voltage boosting & tuning network
- Maximize the slope of the rectified voltage
- Digitally controlled capacitor bank
- Loop requires  $\sim$ kHz bandwidth  $\rightarrow$  negligible power consumption



## IC layout

TSMC 90 nm, two 250x160 um rectifiers, ESD protection  
7 bit digital (external) control loop

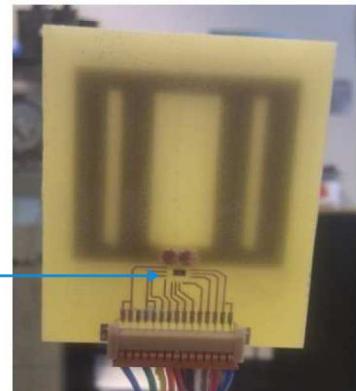
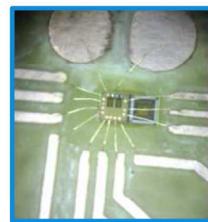


## Antenna-IC co-design

Antenna impedance of  $10+j400 \Omega$  at 900 MHz

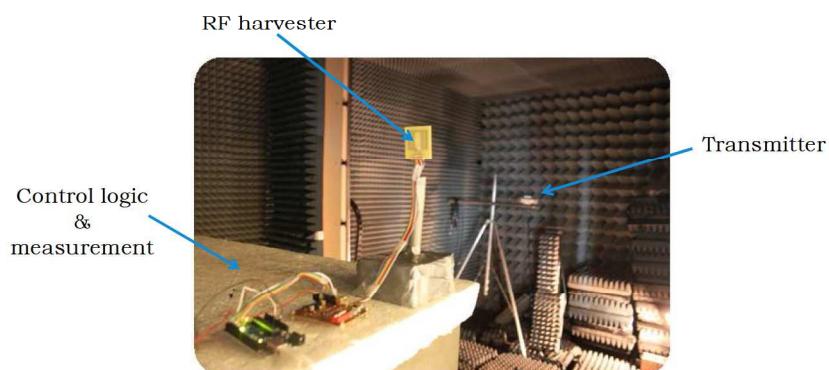
Design challenges:

- Highly reactive (high Q)
- Difficult to measure
- Antenna-IC co-design

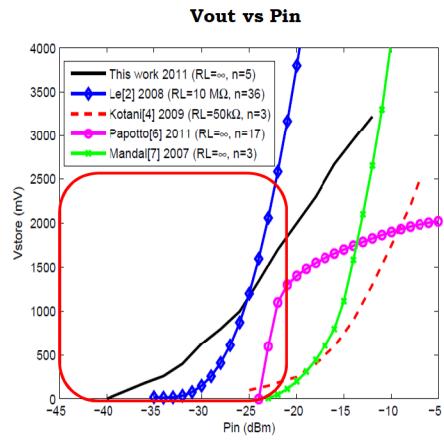


## Measurement setup

Delft University Chamber for Antenna Test (DUCAT) to emulate free space and far field condition



## Measurement results



- Loop compensates for  $\pm 33\%$  variation in antenna inductance
- Shows excellent performance over a large power level range
- -30 dBm sensitivity equals 68 meter range for 4W
- Low cost solution:
  - only 5 stages,
  - standard 90 nm CMOS technology,
  - no calibration



7.

Where it all may lead to...



## The plan

- To design a flexible cortical implant for the effective treatment of tinnitus
- To serve as a platform for various types of implantables
- Use a polymer as a substrate
- Use silicon as base material for
  - Electrodes
  - Electronic circuits
    - To measure the ECoG
    - To electrically stimulate cortical tissue
    - To power and control the implant
  - Battery foil
  - Antenna
    - For RF energy harvesting
    - And wireless communication



Picture courtesy of  
University of Pennsylvania



## Medical impact (I)

- Better treatment of urge incontinence
- Restore hearing (cochlear implant)
- Restore sense of balance (vestibular implant)
- Restore sight (ocular implant)
- Better understanding of the peripheral nervous system
- Better treatment of pain (spinal cord implant)
- Better understanding of the central nervous system
- Better understanding of the brain
- Better brain-machine interfaces



## Medical impact (II)

- Better treatment of brain disorders
  - Better treat tinnitus and auditory hallucinations,
  - Better treat addictions (a.o. alcoholism),
  - Better treat essential tremor, Parkinson, dystonia
  - Better treat urge incontinence,
  - Better treat migraine, cluster headaches and other forms of headache
  - Better treat psychoneuroimmunological disorders
  - Better treat chronic, phantom and neuropathic pain,
  - Better treat depression, mania
  - Better treat OCD spectrum disorders
  - Better treat PTSD and anxiety
  - Better treat schizophrenia
  - Better treat epilepsy
  - Treat autism,
  - Treat dementia, including Alzheimer's disease
  - Treat Tourette's syndrome, minimally conscious state (MCS) after traumatic brain injury, obesity, anorexia



[Reference: C.O. Oluigbo, A.R. Recai, Addressing Neurological Disorders With Neuromodulation, IEEE Transactions on Biomedical Engineering, Vol. 58, No. 7, July 2011]

## Conclusions

- A glimpse into the future
- Neurostimulation:
  - Small!
  - Energy efficient
- Cochlear implants
  - Measuring ECAPs: instantaneous companding
- Neurosensing devices:
  - Objective detection of tinnitus
- RF energy harvesting:
  - Splitting the power and switching paths
  - optimal mismatch

## Electronics for better treatment and care

- Thank you for your attention
- Thanks to Guillaume Barrault and Marcio Schneider for inviting me
- Thanks 2 the Biomedical Electronics Lab members @ Delft
- More info: <http://elca.et.tudelft.nl/~wout>



### **Not on the photo**

Sumit Bagga, Robin van Eijk, Marcel van der Horst, Marion de Vlieger, Chutham Sawigun, Sander Fondse, Joeri Biesbroek



## Advertisement

### BiCAS 2013

IEEE Biomedical Circuits and Systems Conference

Oct. 31 - Nov. 2, 2013, Rotterdam, the Netherlands

