**Master in Electrical and Electronics Engineering**

**EE-518:** Analog Circuits for Biochip

# Lecture #3

# Brain/Machine interfaces: Circuit for Electrical Signals

# Lecture Outline

- Kinds of Neural Signals
- Kinds of Neural Interfaces
- Signal Recording or Stimulation
- BioChip Design for Visual Restoring
- Performance on Wafer scale
- Performance on Bio interface

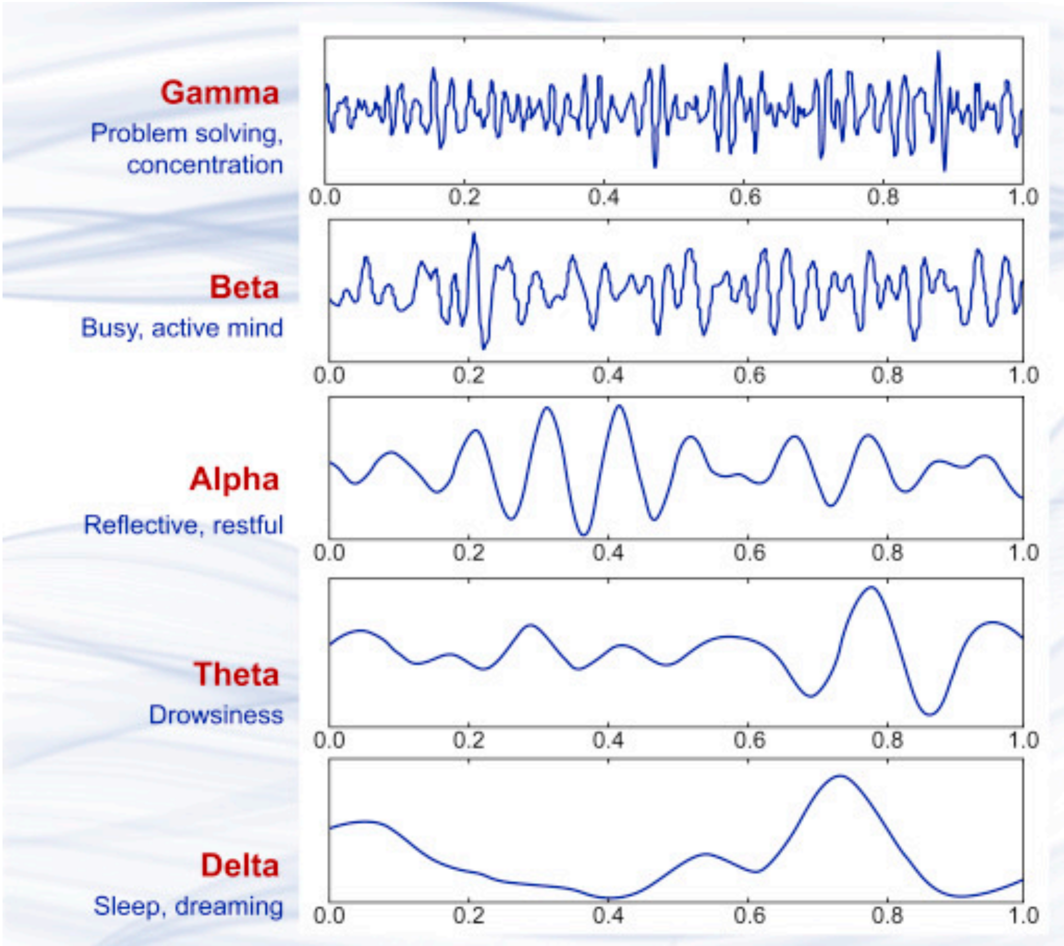
# Two Kinds of Brain Signals

- **Electrical**

  Neurons activity
- **Chemical**

  Neurons regulation

# Electrical Signals of the Brain






Kinds of electrical signals are extremely diversified

# Kind of Neural Electrical Activity

Brain

- **EEG** = electroencephalography
- **iEEG** = intracranial electroencephalography
- **ECoG** = Electrocorticography, EEG with electrodes directly on the brain surface

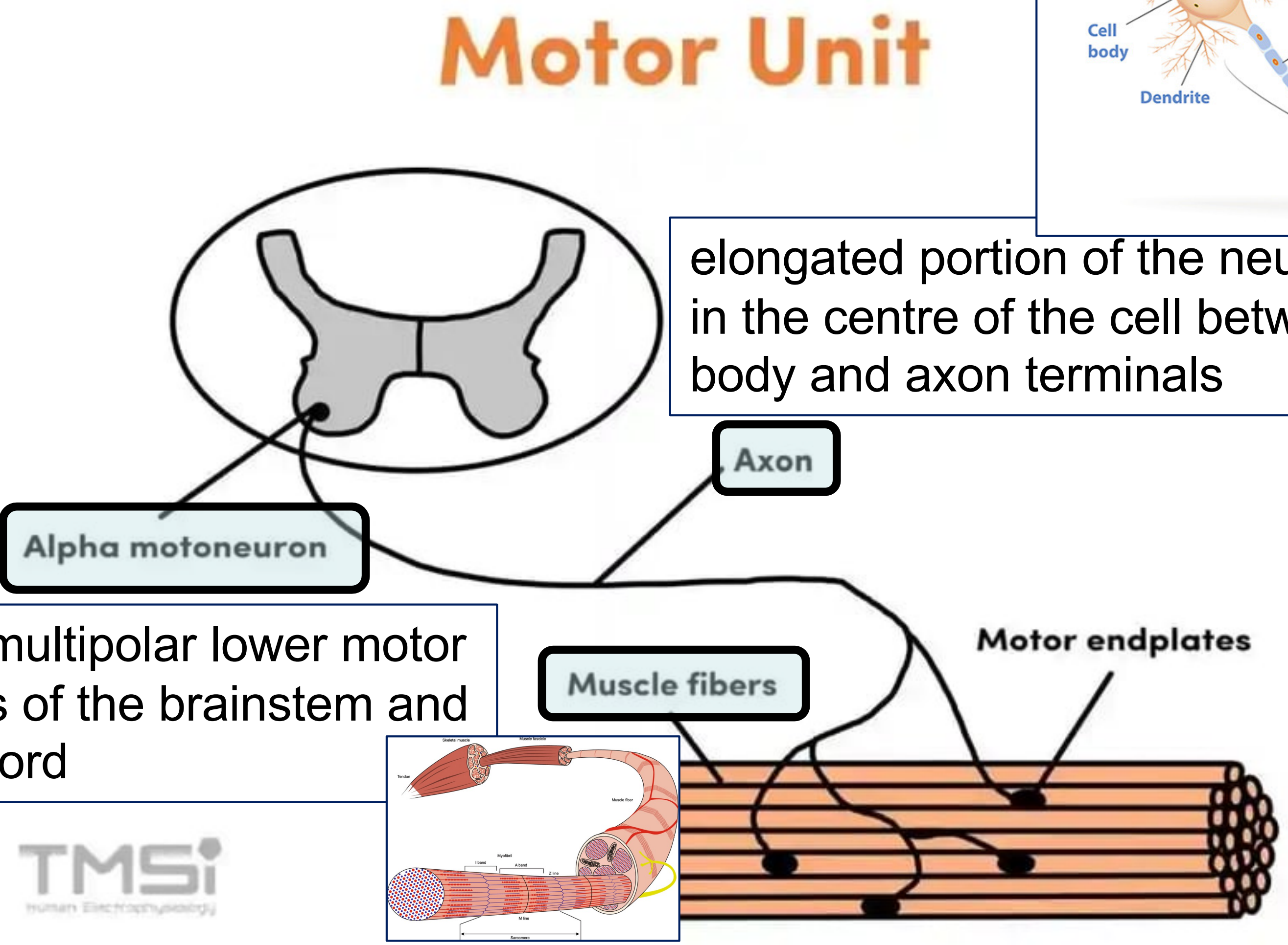
- **EMG** = Electromyography

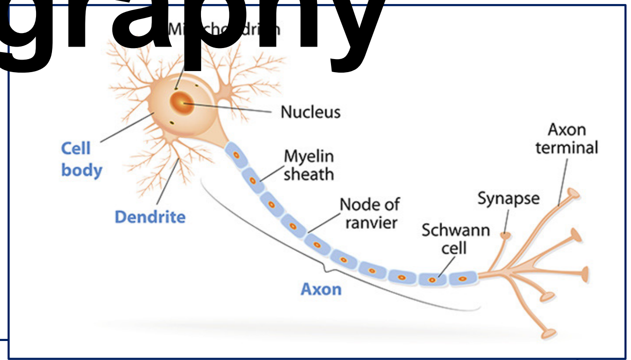
Peripheral Nervous system

# EMG for What?
## (Muscles electrical activity)

- **Electrodiagnostic**
- **Motor restoration**
- **Study motor control**
- **Rehabilitation applications**
- **Humans/robots interaction**
- **…**

# EMG = Electromyography



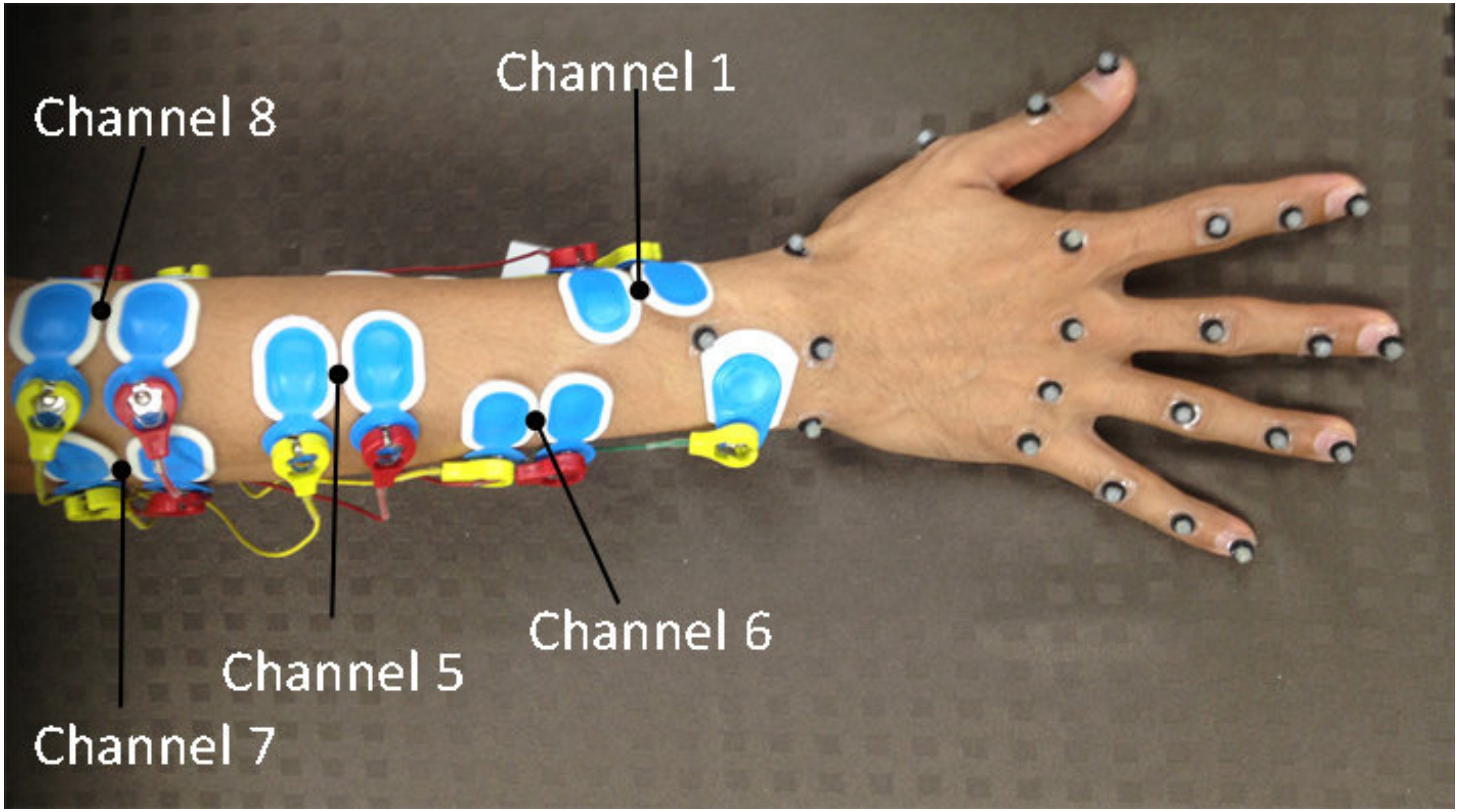




elongated portion of the neuron located in the centre of the cell between the cell body and axon terminals

Large, multipolar lower motor neurons of the brainstem and spinal cord

The Neural Motor System

# Skin Electrodes for EMG

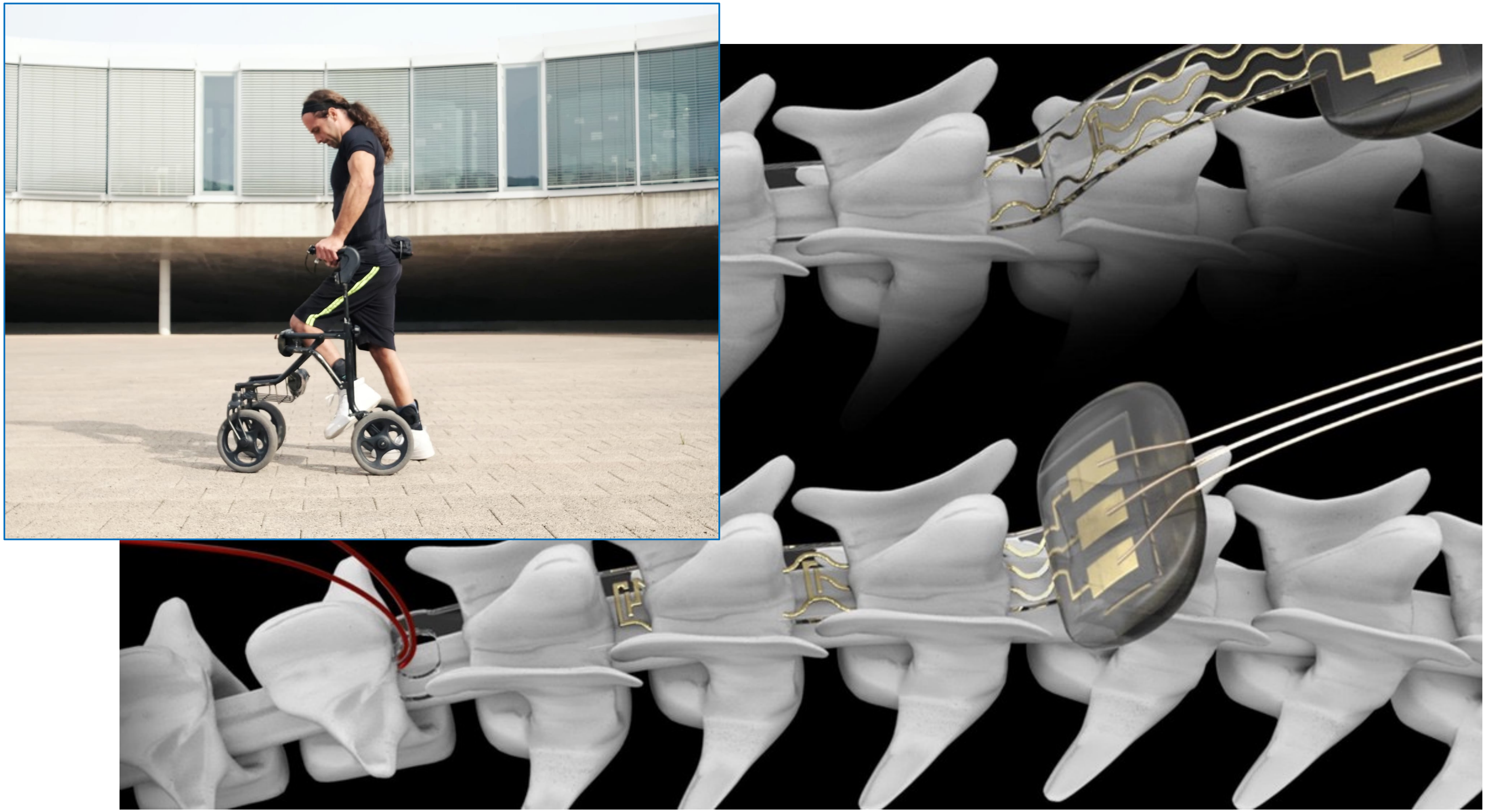



Surface electrodes for EMG signals acquisition

# Subdermal Electrodes for EMG

Movement Restoration from Muscle Signals

# Spinal Cord Electrodes



Muscle Signals to Restore paraplegics' walking

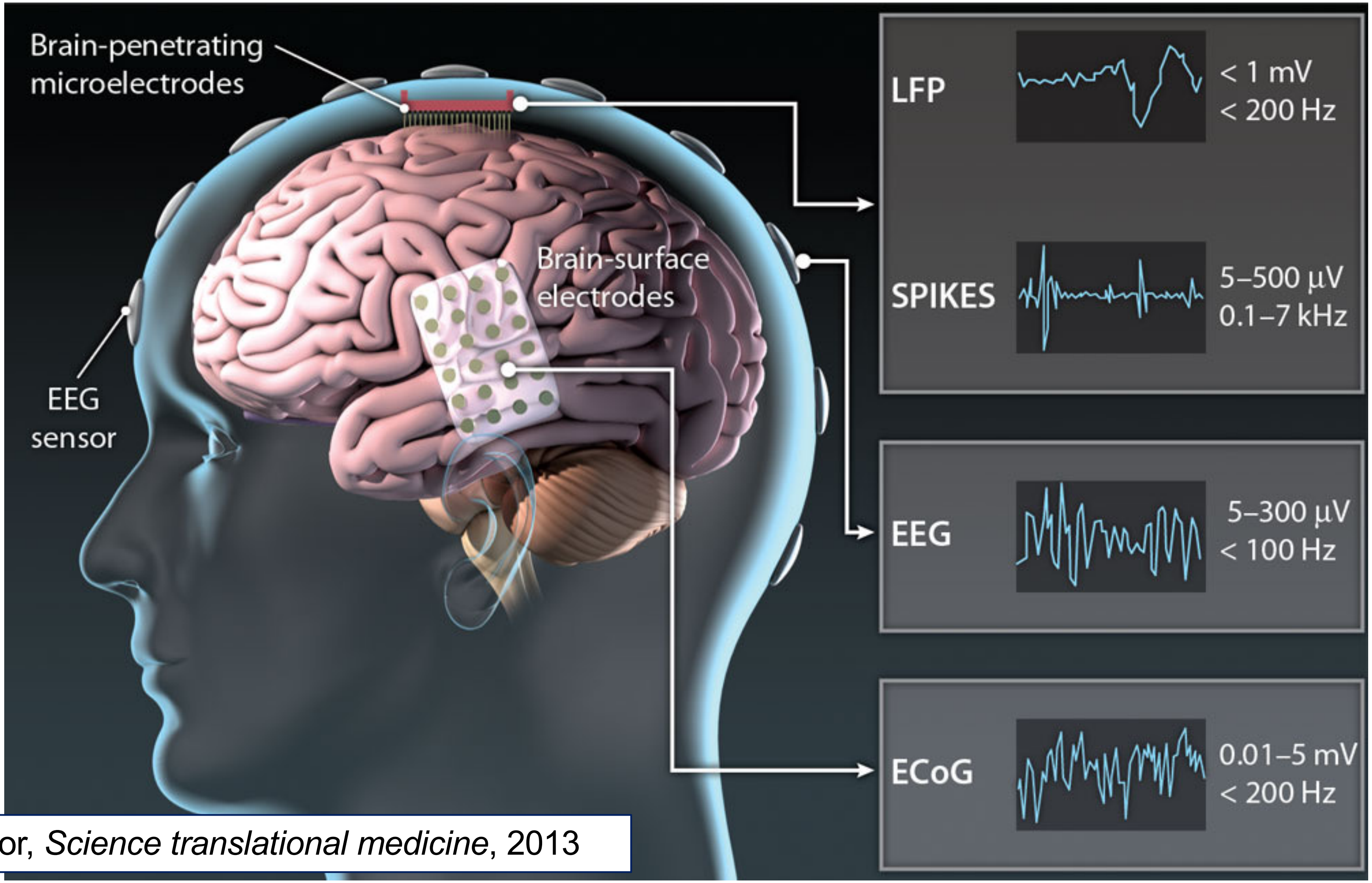
# EEG for What?
# (Brain electrical activity)

- **Epilepsy**
- **Parkinson**
- **Sleep disorders**
- **Brain tumours**
- **Anxiety disorders**
- **Autism**
- **…**

# Surface Brain Electrodes

We can acquire Brain Signals from the surface

# Different Surfaces



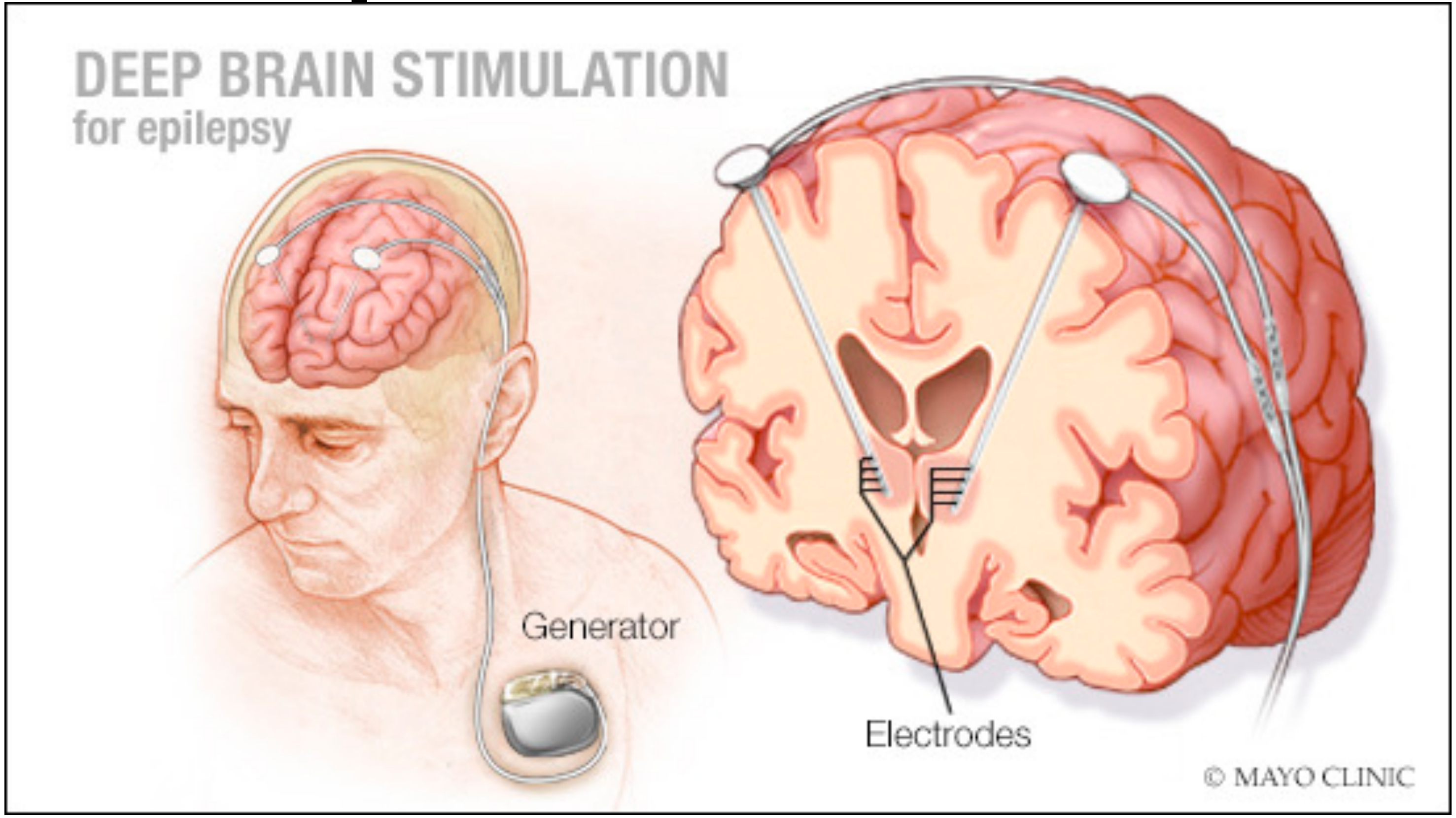

N. V. Thakor, *Science translational medicine*, 2013

Different Locations return Different Kinds of Signals

# Deep Brain Electrodes

We can acquire Brain Signals from the Deep Inside

# Deep Brain Electrodes



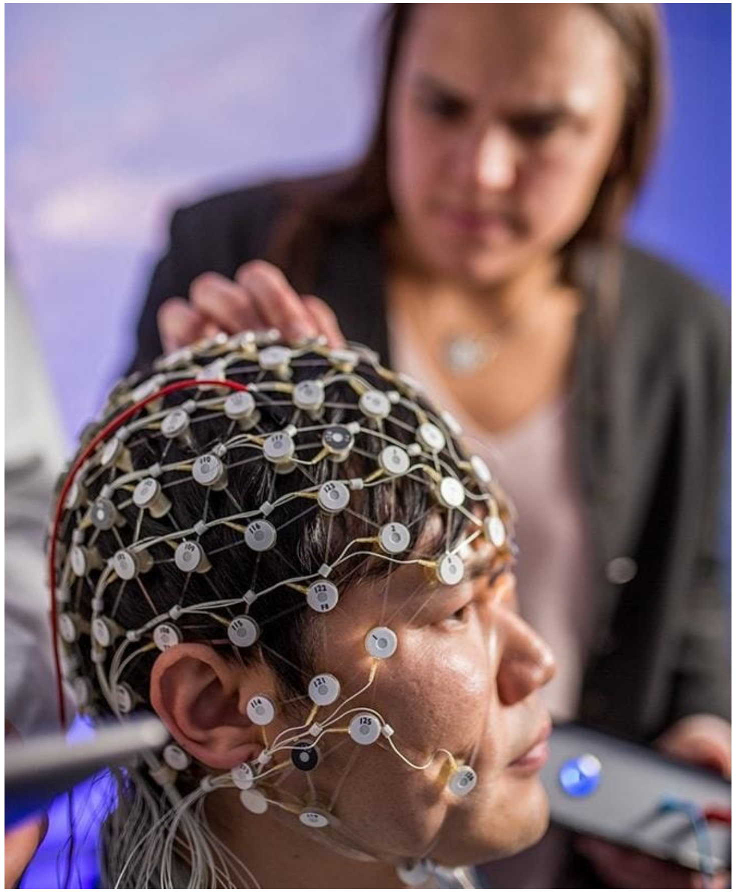

Deep Brain Electrodes involves small holes in the skull to implant Electrodes into Deep Brain Tissue

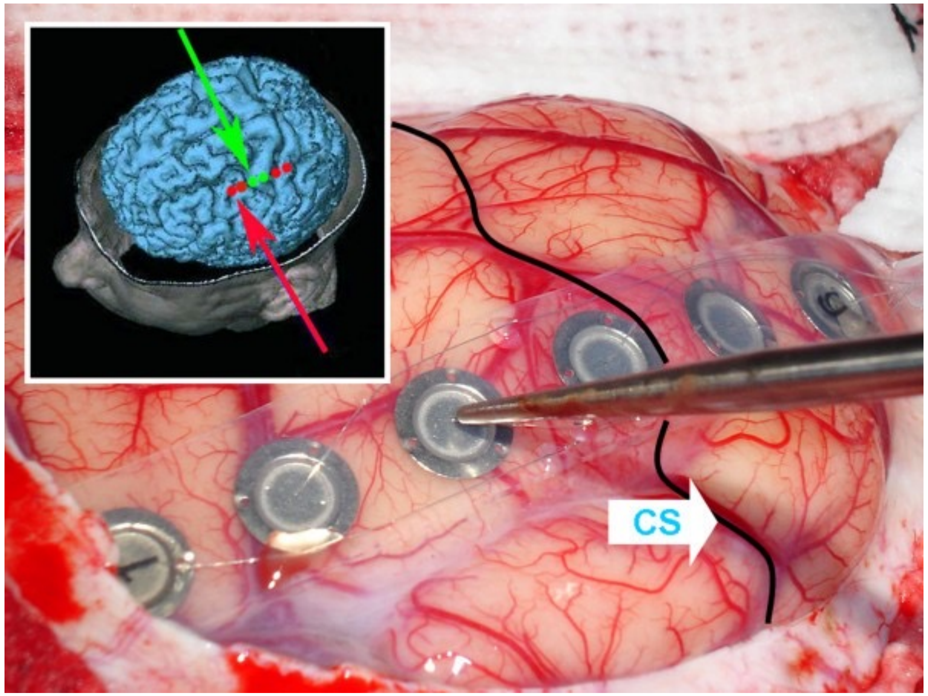
# Surface Brain Electrodes

© Penn Today

Signals from the surface outside the skull

# Brain Electrodes for which Surface?





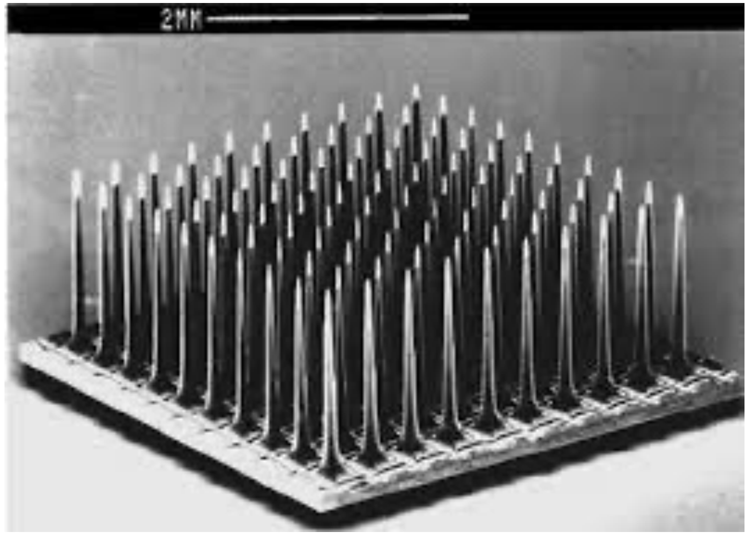

Transcranial

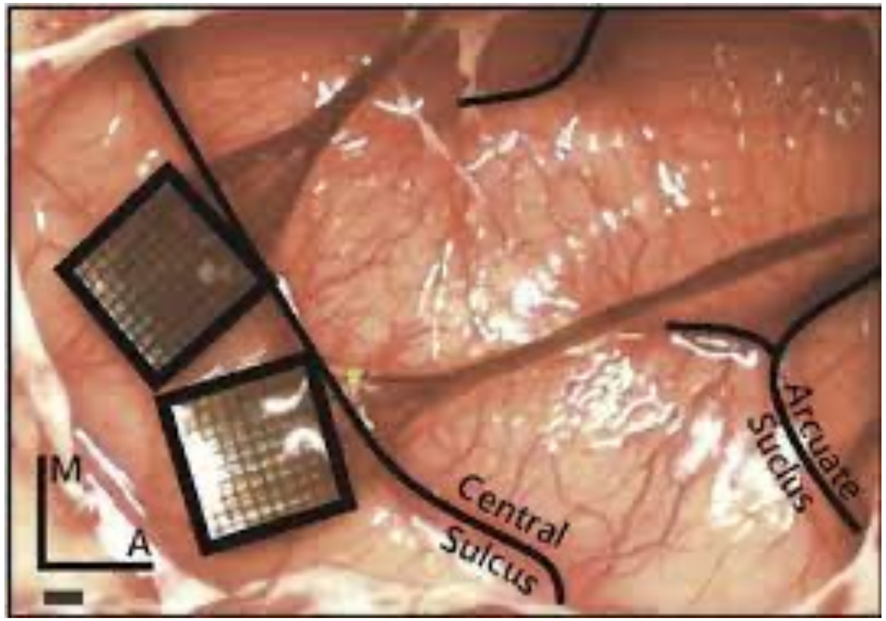
Intracranial (Electrocortical)

# Subdural Brain Electrodes

Signals from the surface of the Brain

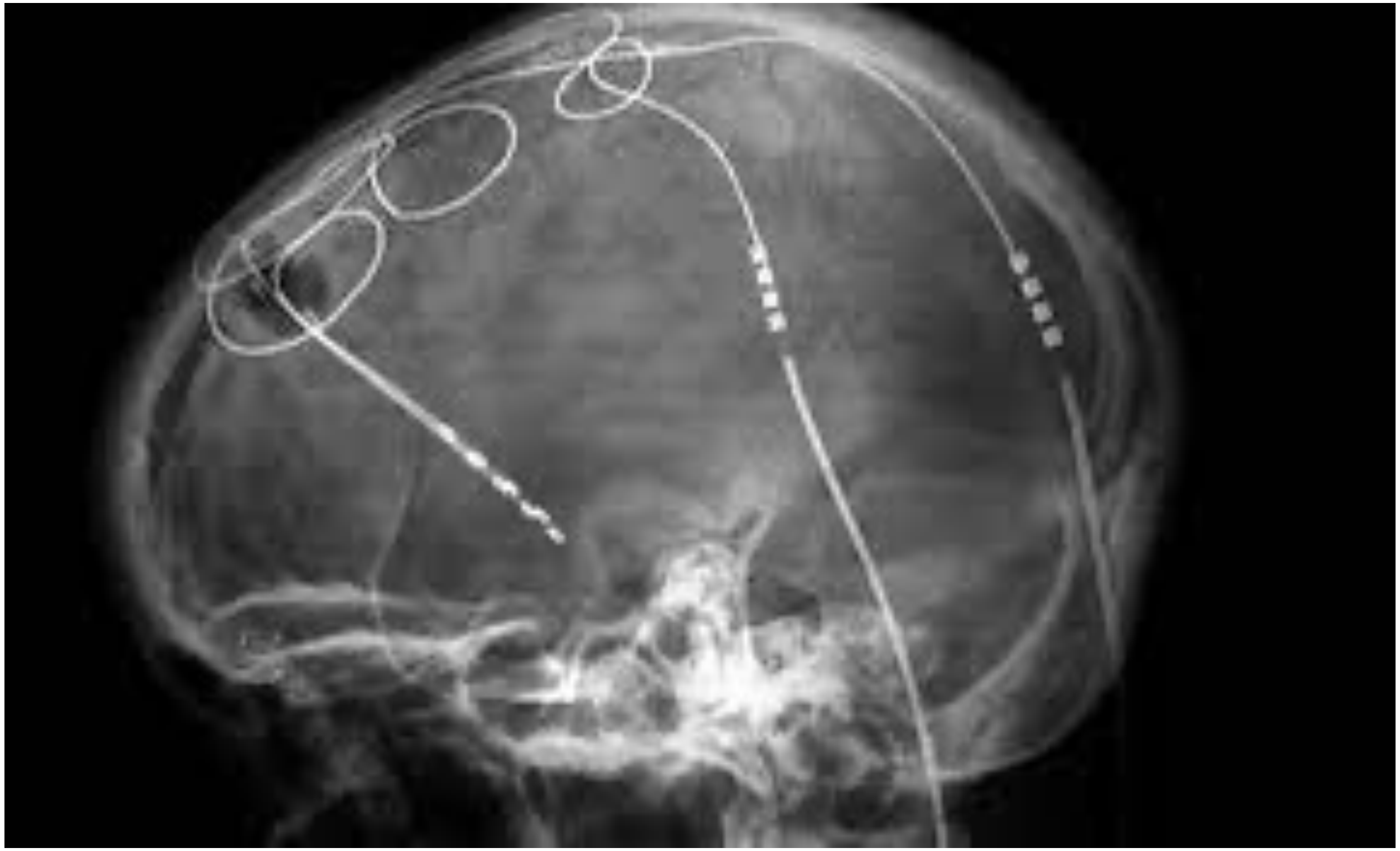
# Intracortical Brain Electrodes




UTAH Array for the Penetration into the Brain Cortex

# Deep Brain Electrodes

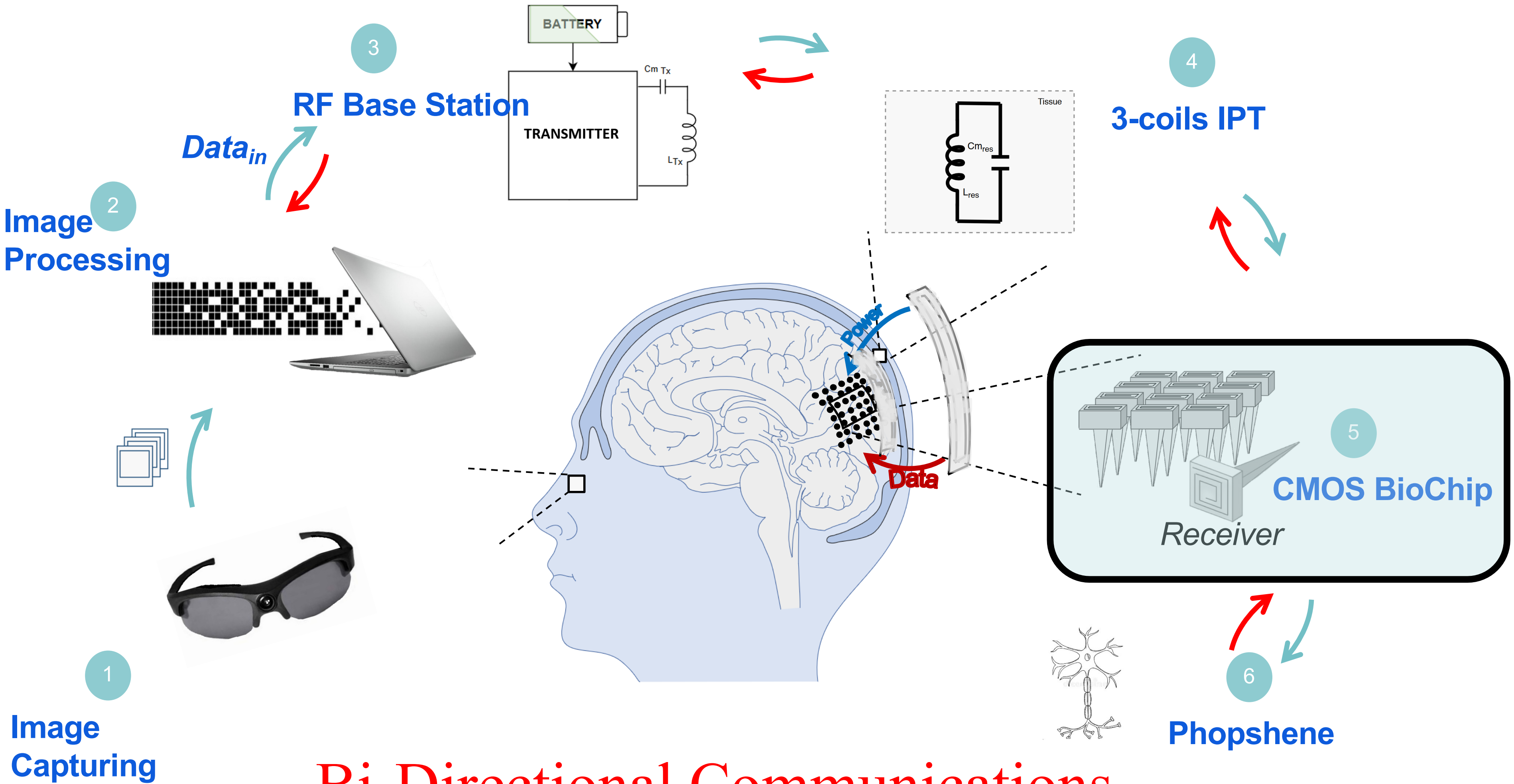


Involves small holes in the skull to implant Electrodes into Deep Brain Tissue

# Two ways to cope with Neural Electrical Signals

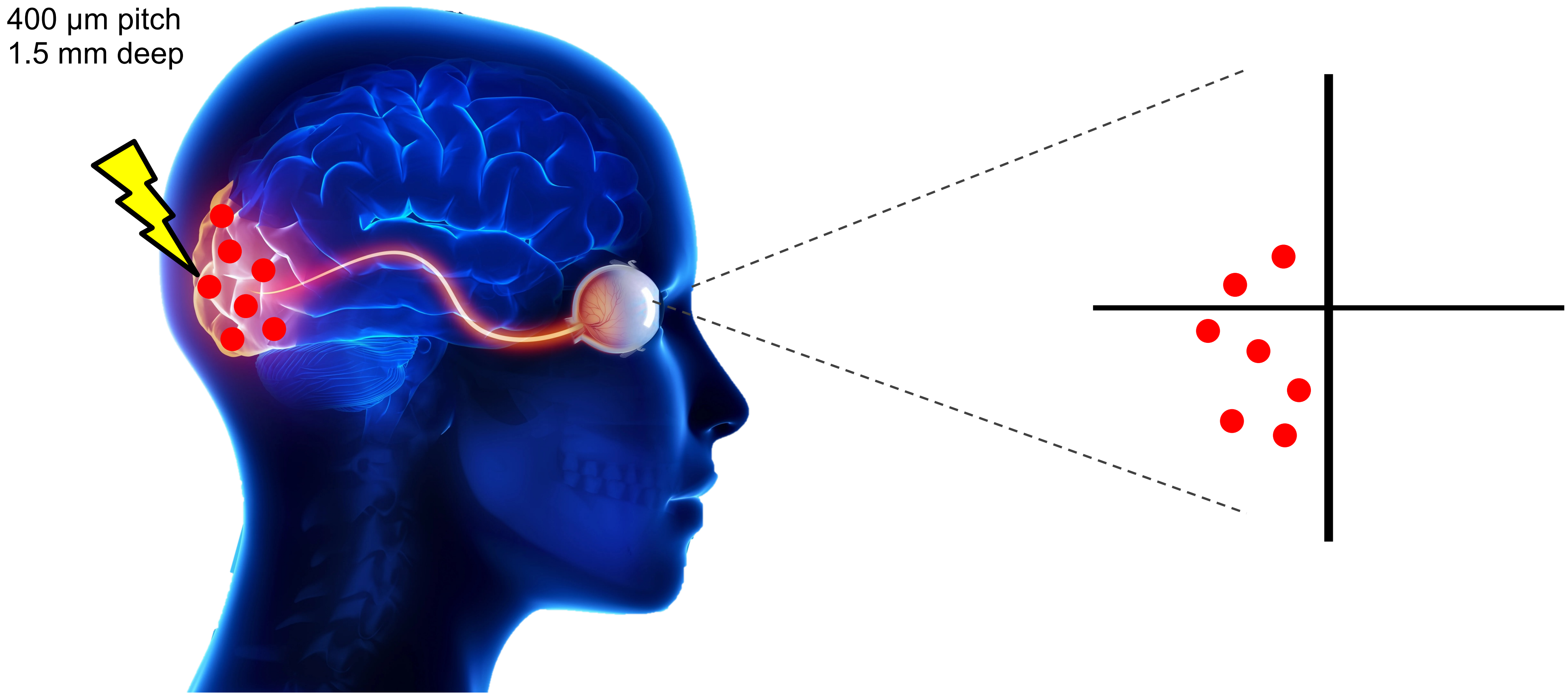
- **Recording**
- **Stimulation**

# (Recall) Brain/Machine interfaces



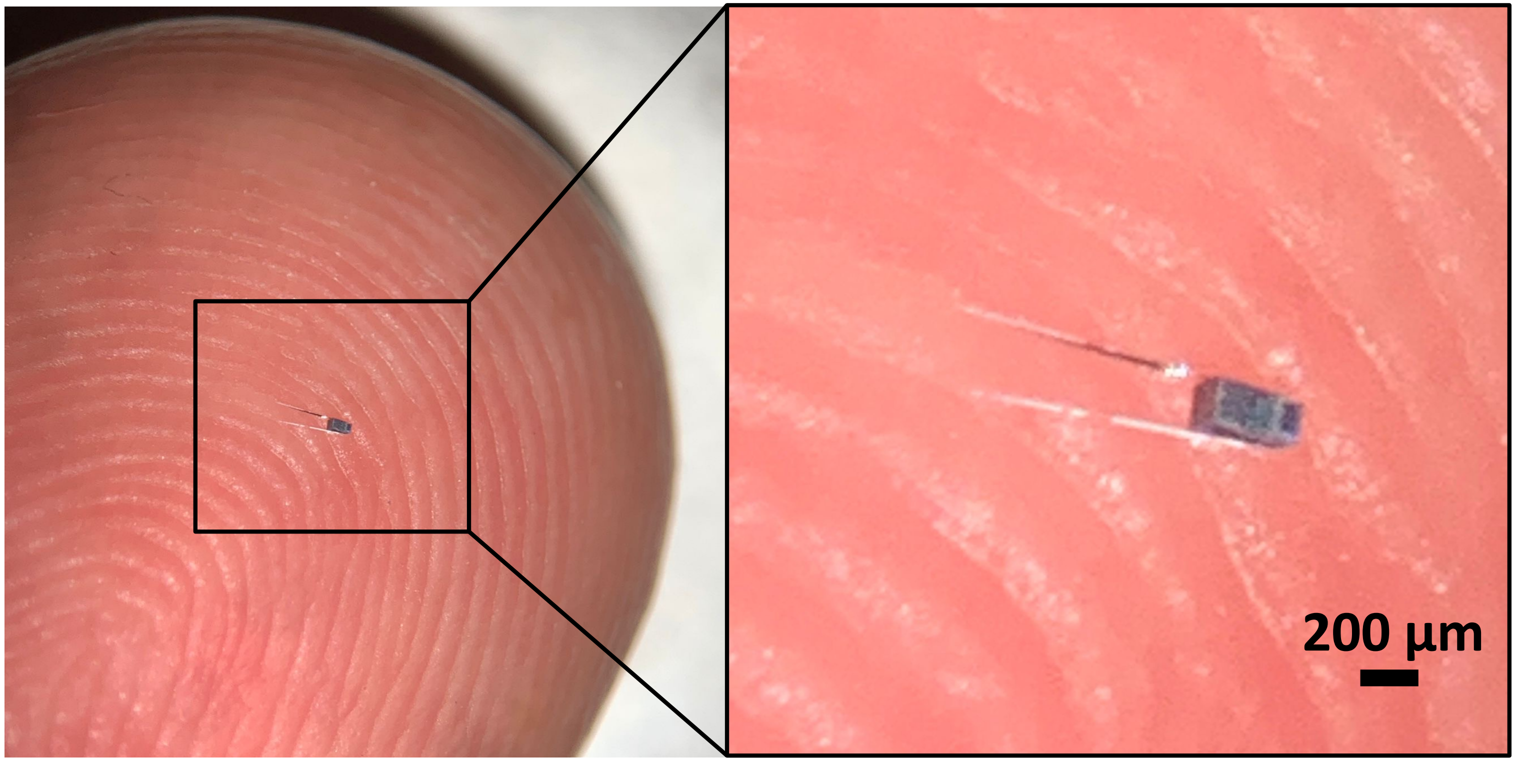

Bi-Directional Communications

# Intracortical Brain Stimulation




For Example, for Visual Prosthesis

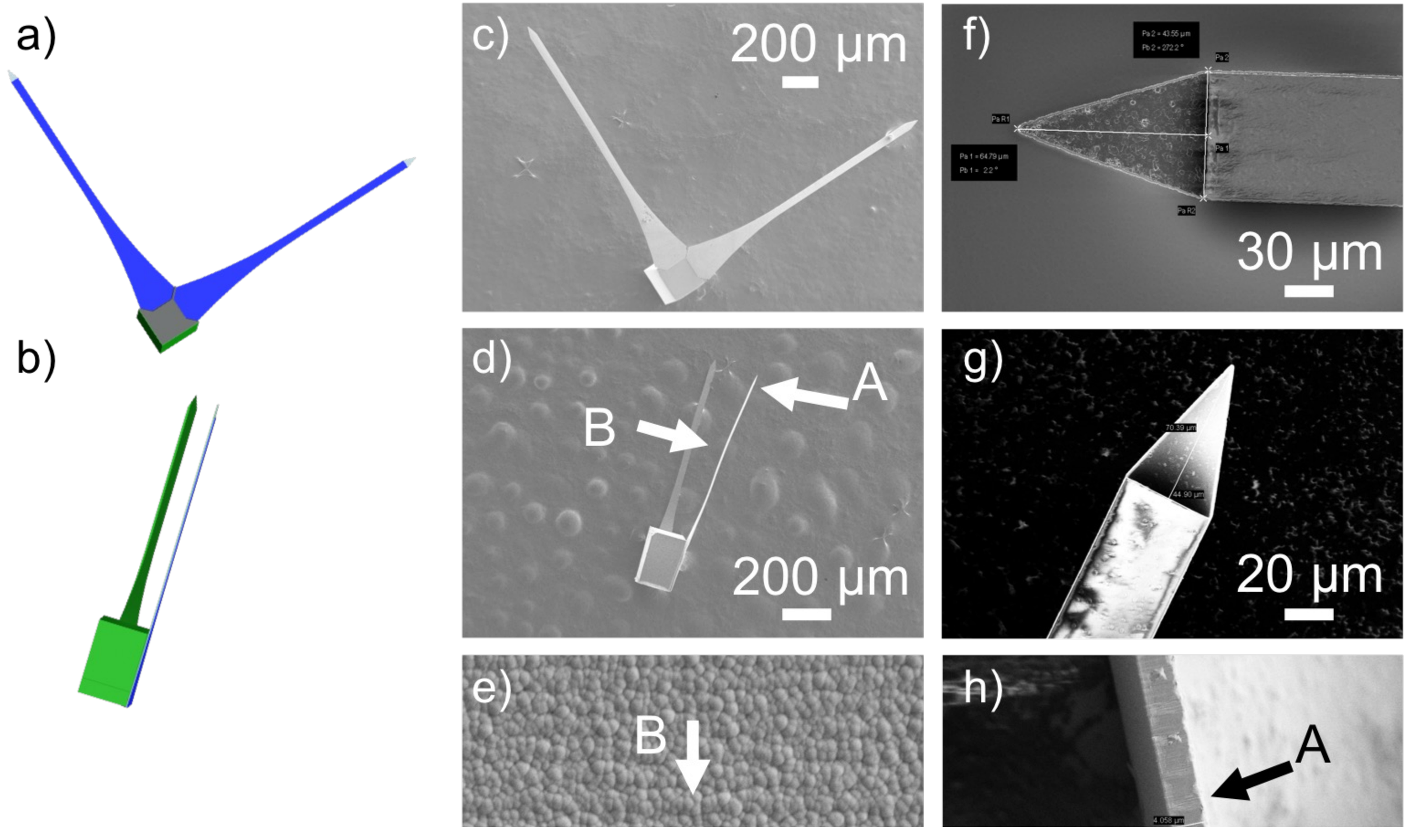
# CMOS BioChip
# for Intracortical Visual Stimulation




Barbruni et al., *PCT/IB2022/059944*, 2022

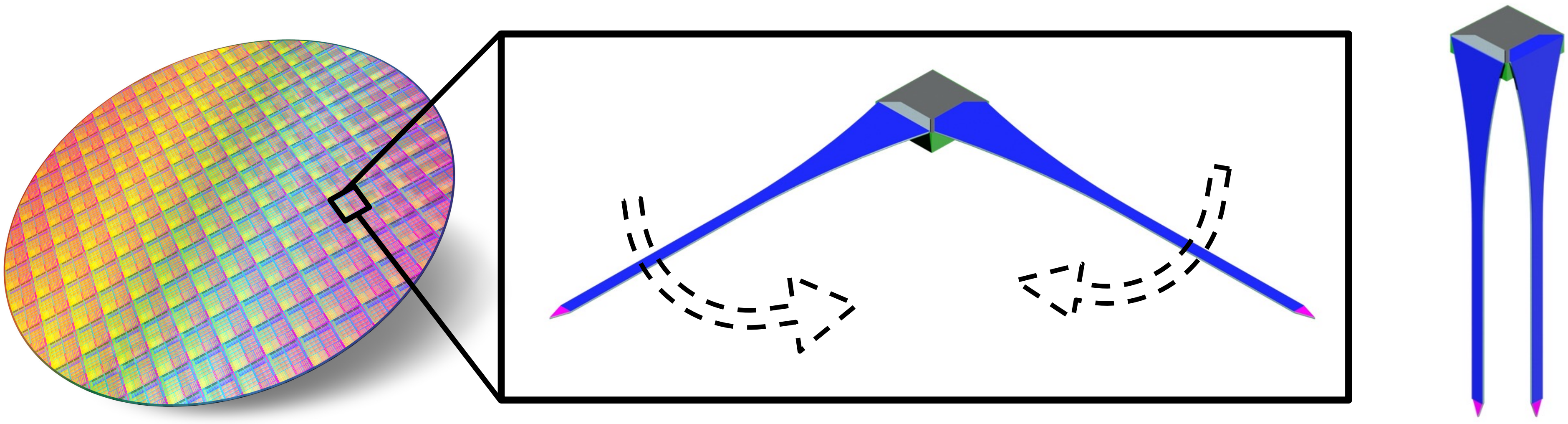
Intracortical BioChip to Vision Restoring in Blind Patients

# Electrodes for Intracortical Stimulation




The Intracortical Electrodes need to be fully integrated into the CMOS BioChip System

# Electrodes for Intracortical Stimulation

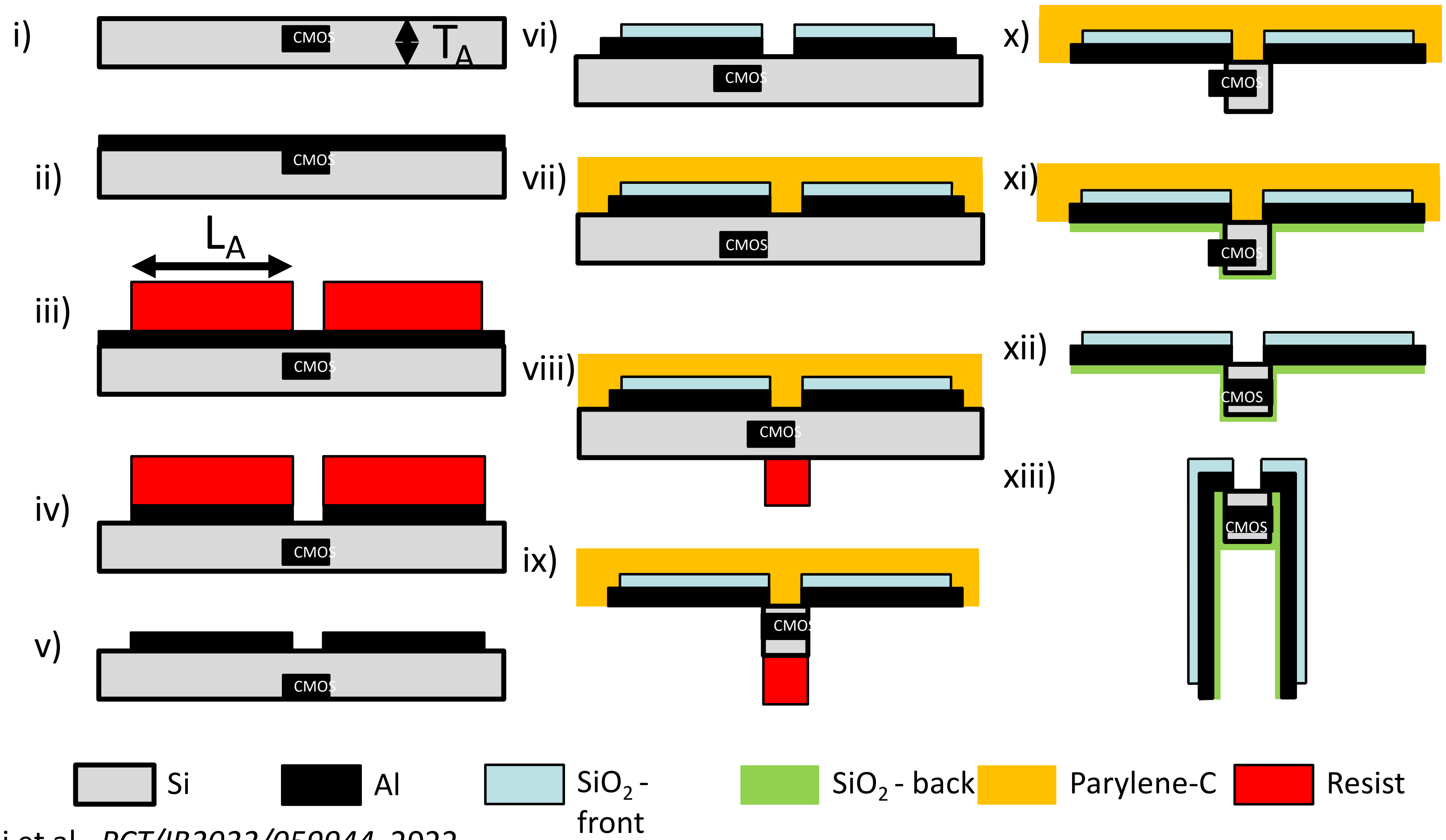


(a) (b) (c)

E

The Cortex Electrodes are integrated into the CMOS BioChip System directly at Wafer Level

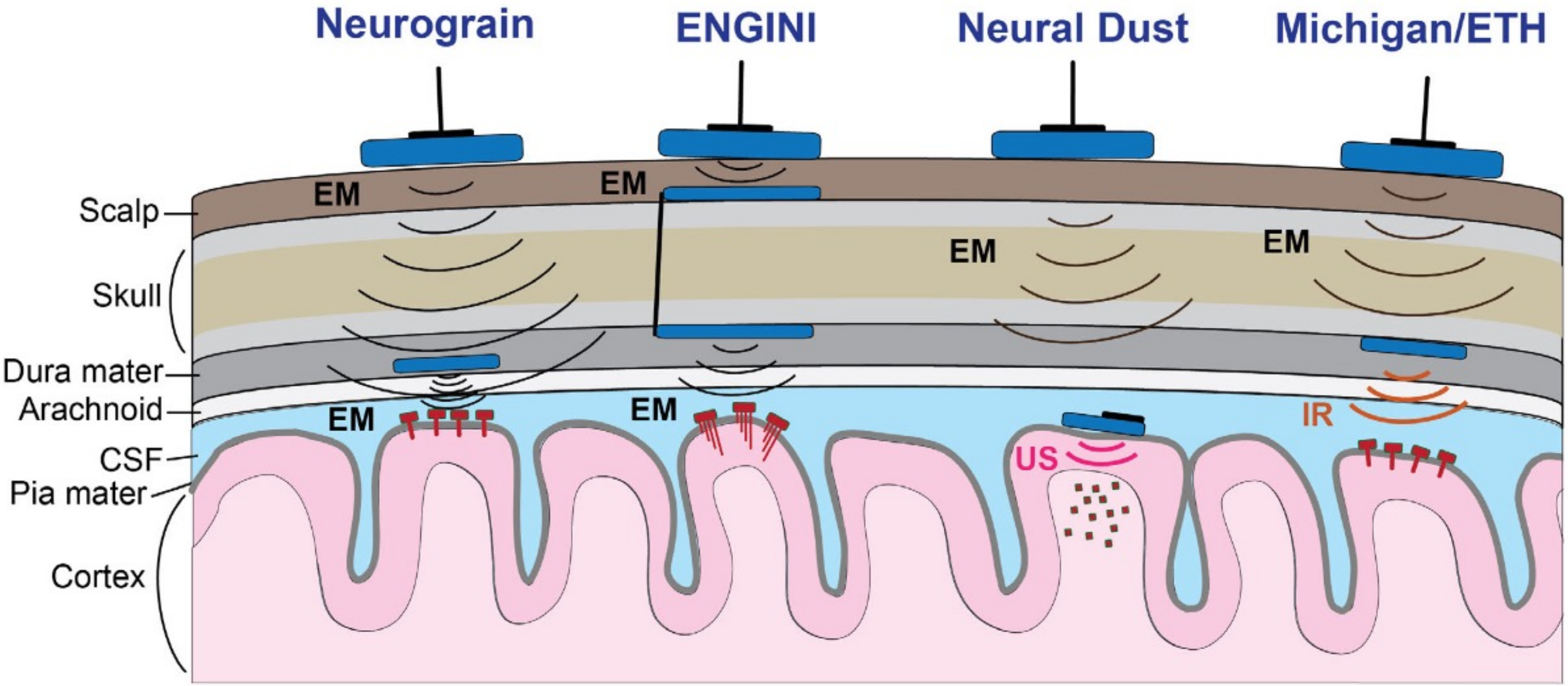
# Electrodes for Intracortical Stimulation




Barbruni et al., *PCT/IB2022/059944*, 2022

The Intracortical Electrodes are integrated by Lithography

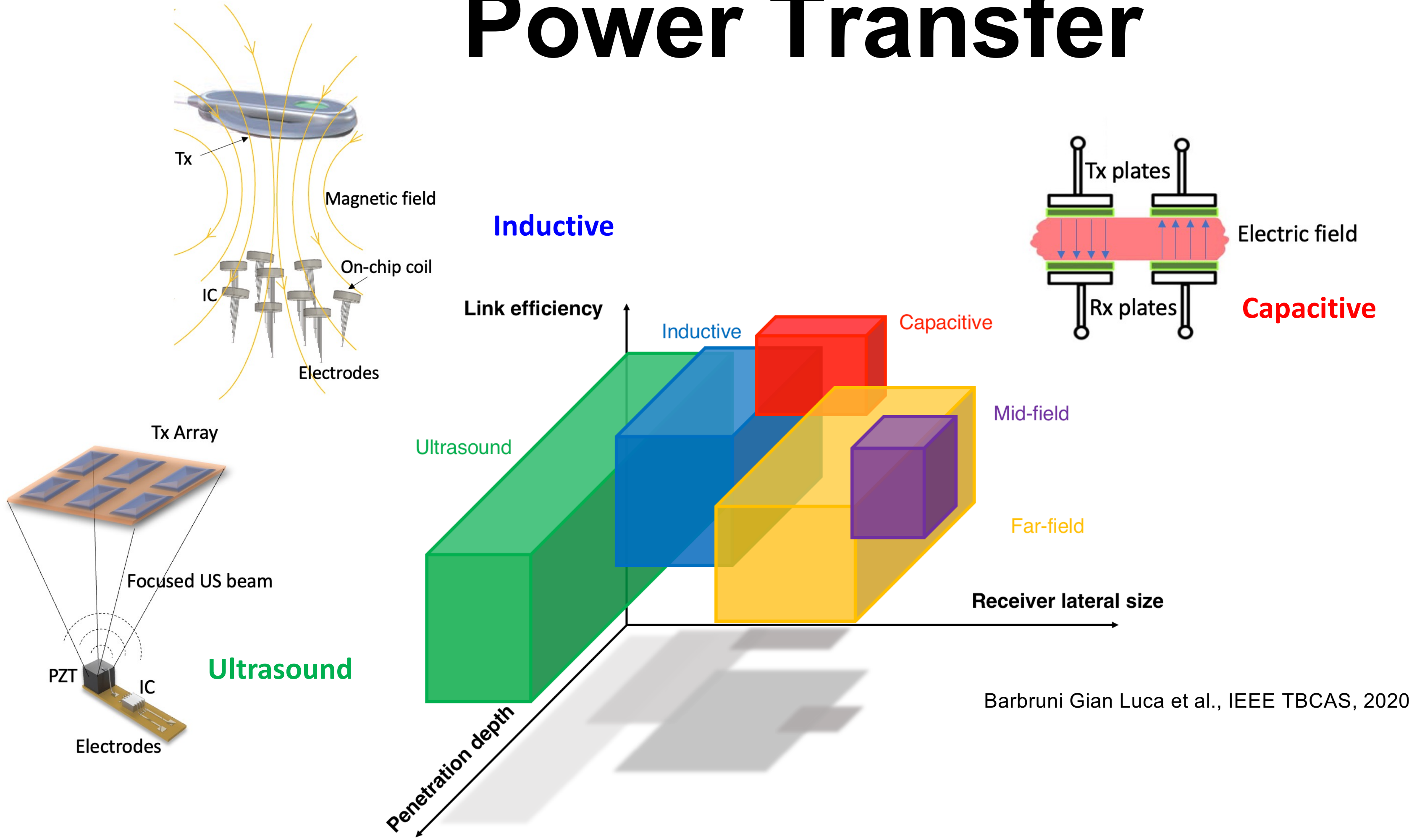
# How to Power so small BioChip?




Yang et al., *IEEE Access*, 2020.

Several Approaches are possible for Power Transfer

# Several Approaches to Power Transfer




Different Approaches return Different Performance

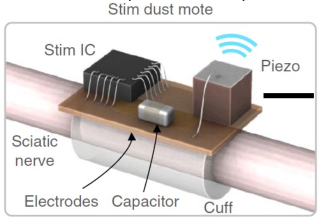
# Several Approaches to Power Transfer

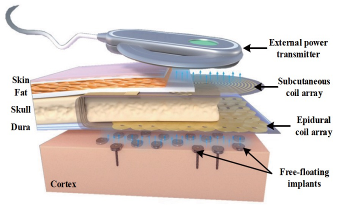
| Feature | ULTRASOUND (APT) | CAPACITIVE (CPT) | INDUCTIVE (IPT) |
|---|---|---|---|
| Fabrication | Difficult (pMUTS) | Simple | Challenging (3-coils) |
| Costs | High | Low | Moderate |
| Integration on-chip | No | Simple | Simple (PSC) |
| Penetration depth | $> 2$ cm | $< 1$ cm | $< 2$ cm |
| Smaller Rx @ 2020 | $0.75^3$ $mm^3$ [16] | $8x8$ $mm^2$ [70] | 0.09 $mm^2$ [39] |
| PTE and PDL @ 2 cm | High | Low | Moderate |
| Effects on misalignment | High | Low | Moderate (3-coils) |
| SAR limit | High | Low | Low |
| Tissue attenuation | Low | High $\propto$ f | High $\propto$ f |
| Multiple IC problems | Focusing (Beamforming) | No | No |
| Electromagnetic interference | No | No | Yes |

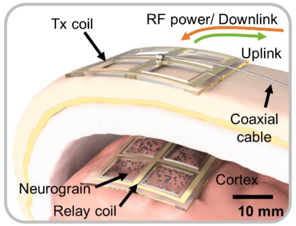
Inductive Power Transfer (IPT) presents best compromise

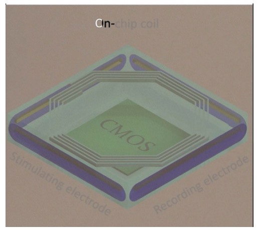
# Several Approaches to Power Transfer

Piech et al., Nature BE, 2020. Ahmadi et al., IEEE NER, 2019. Lee et al., Nature El., 2021. Khalifa et al., IEEE TBCAS, 2019.



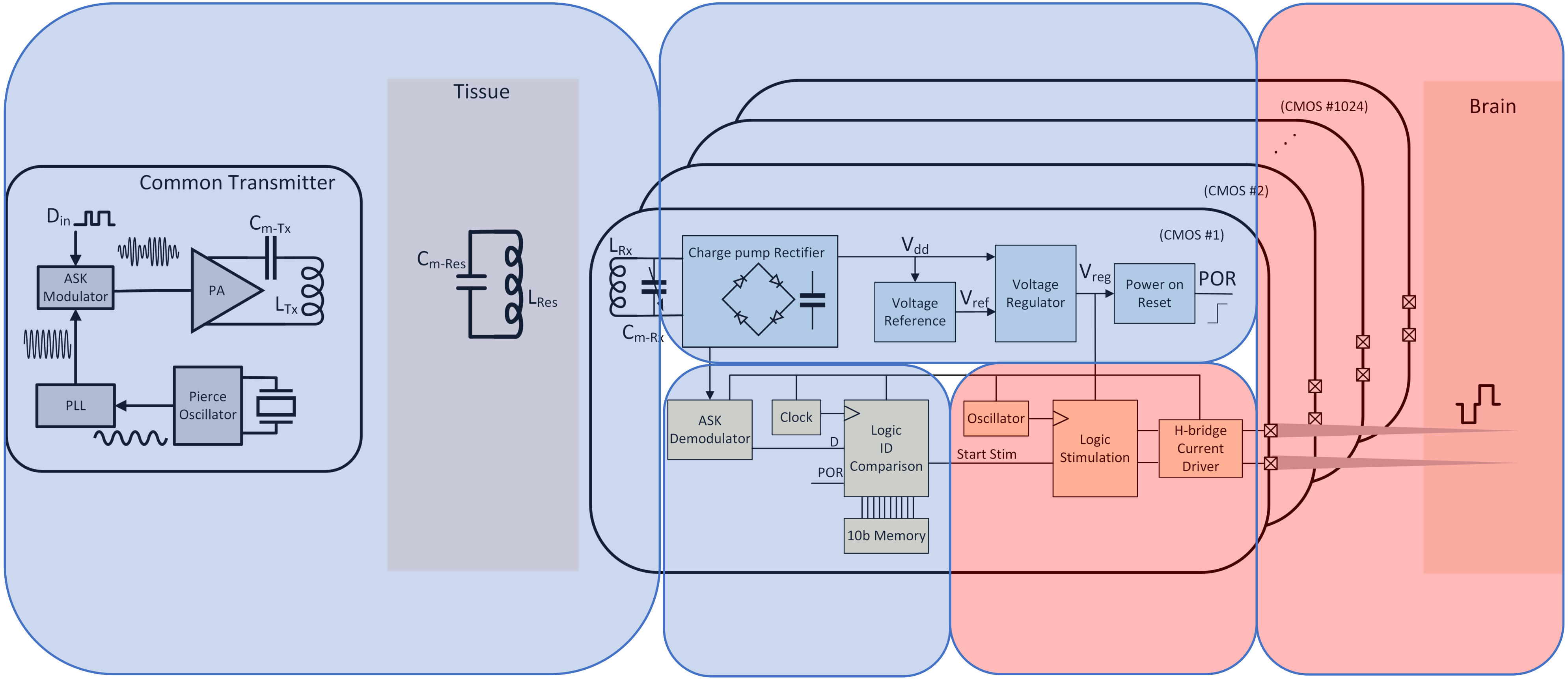




| Feature | STIMDUST | ENGINI | NEUROGRAIN | MICROBEAD | NEURAL DOT |
|---|---|---|---|---|---|
| WPT | APT | IPT 3-coil | IPT 3-coil | IPT 2-coil | FS-IPT |
| Size (μm$^3$) | 3800 x 840 x 850 | 3500 x 3500 x N/A | 650 x 650 x 250 | 340 x 330 x 80 | 200 x 200 x 70 |
| CMOS | TSMC 65 nm | AMS 350 nm | TSMC 65 nm | 130 nm RF | TSMC 180 nm |
| Frequency (MHz) | 1.85 | 433 | 915 | 1180 | 433 |
| Downlink | ASK | ASK | 1 Mbps ASK + PWM | Resonant FSK | 6 Mbps ASK |
| Uplink | Backscattering | 205 kbps LSK | 10 Mbps BPSK | No | No |
| Distance (mm) | 21.5 | 12 | 8 | 6.6 | 14 |
| Goal | Stimulation | Recording | Rec. / Stimulation | Rec. + Stimulation | Stimulation |
| Current (μA) | 400 | N/A | 25 | 46 | > 50 |
| SAR (W/Kg) | N/A | N/A | 19.6 | 30.6 | 1.6 |
| # Chip | 1 | ~ 10 - 100 | ~ 1000 - PUF | ~ 10 | + 1000 |

Different Approaches return Different Performance

# (However) **Power Transfer**




**Alexandre Schmidt** **Sandro Carrara**

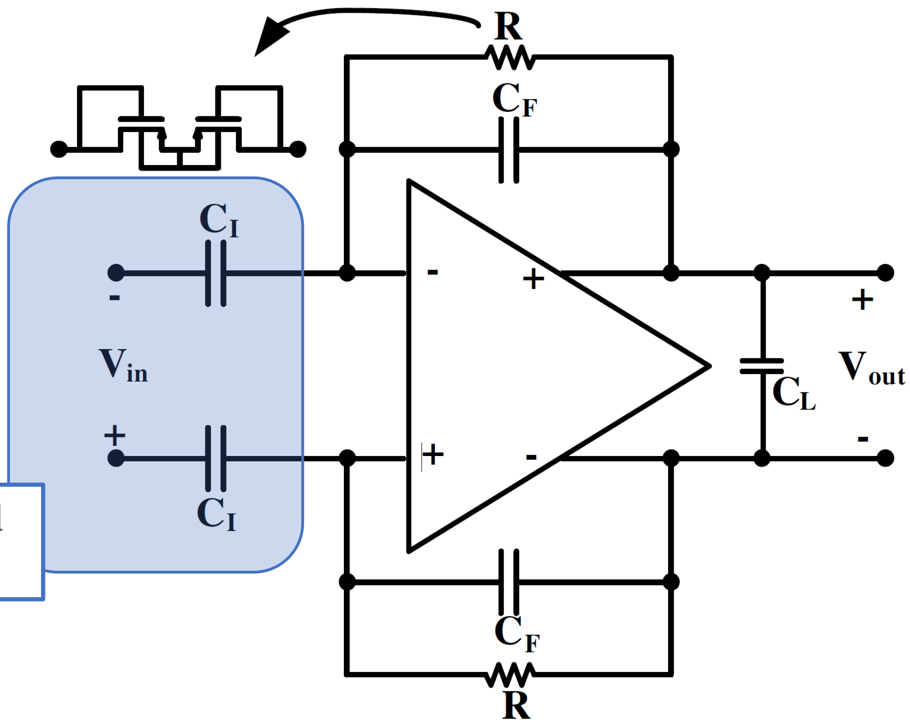
That is the business of the 2nd part of the Course

# BioChip for Intracortical Recording

One simple circuit for signal recording

AC-coupled neural amplifier topology

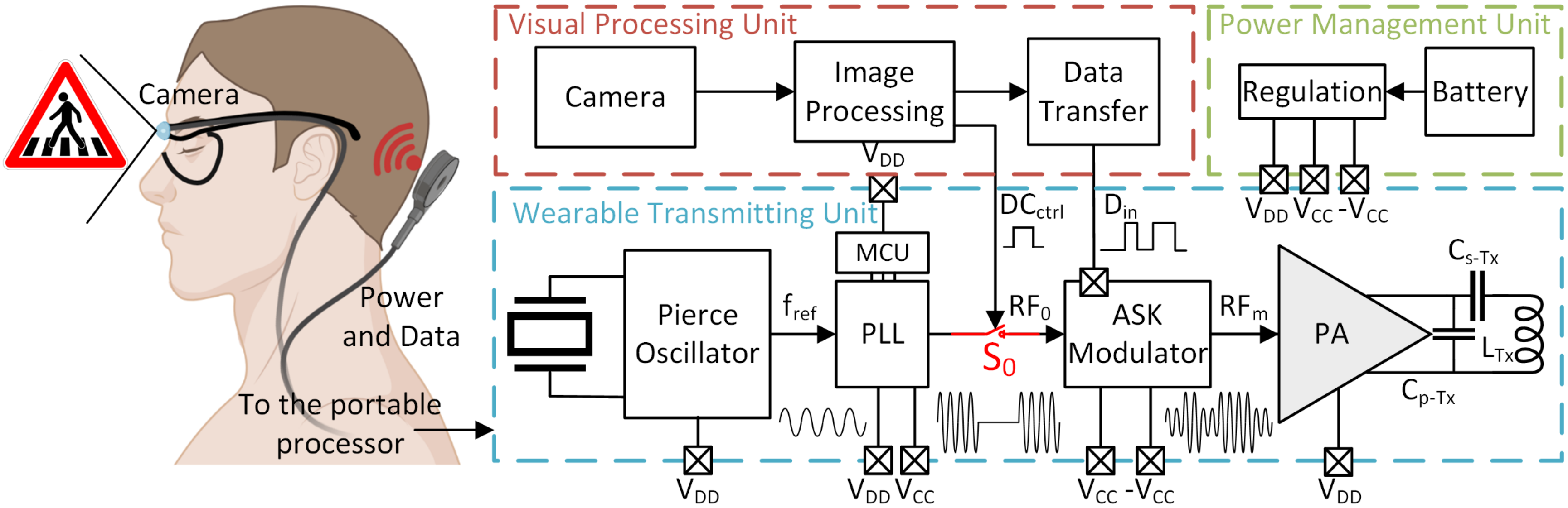
Usage of electrode impedance instead of input capacitor




A simple Double-Inverting Amplifier may be sufficient for Neural Recording

# BioChip for Intracortical Stimulation

Barbruni et al., *IEEE TBCAS*, 2024

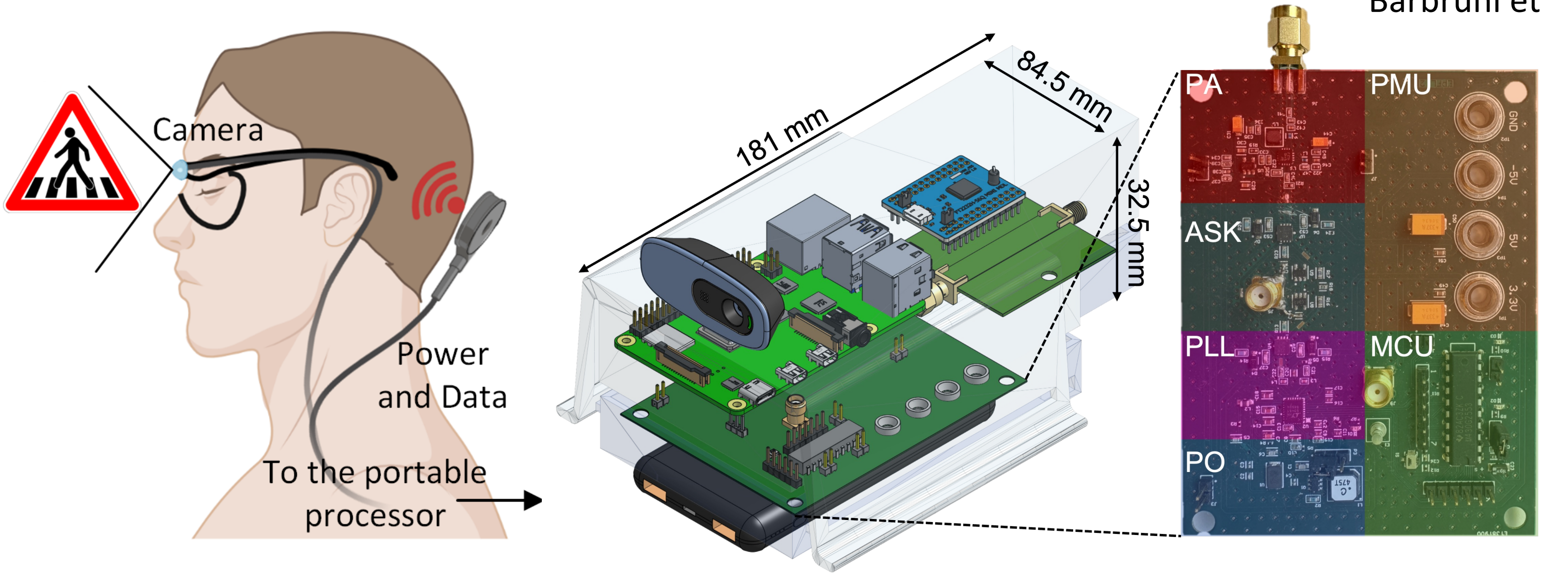


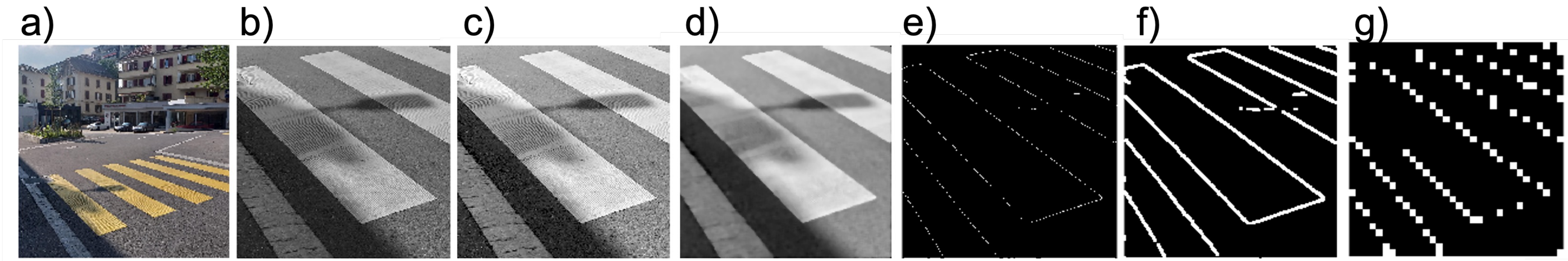

The implanted BioChip needs data from an external camera dealing with the vision field

34

# BioChip for Intracortical Stimulation

Barbruni et al., *IEEE TBCAS*, 2024




The implanted BioChip needs data from an external camera dealing with the vision field

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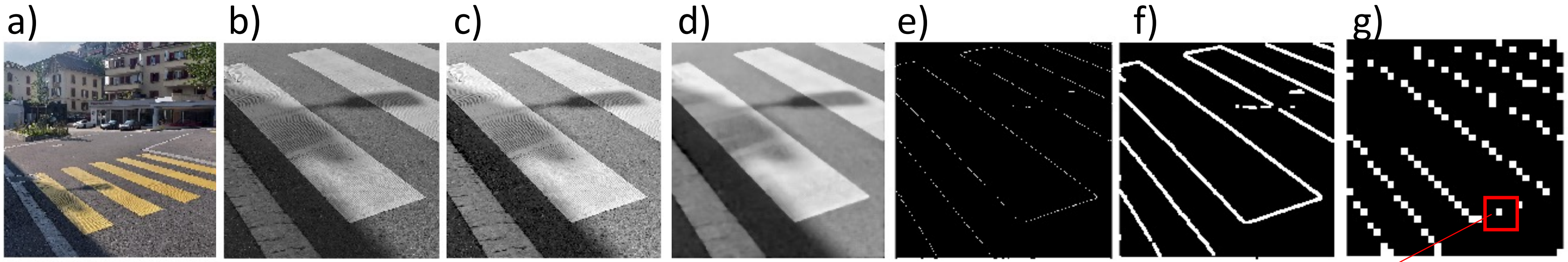
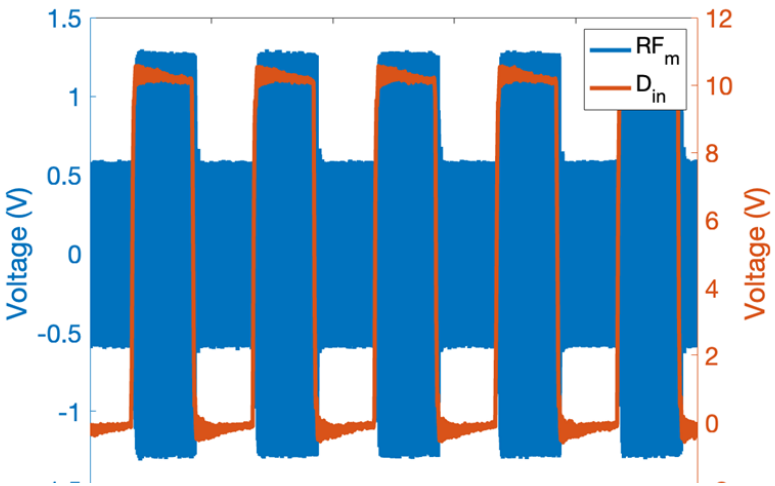
# Data Transmission



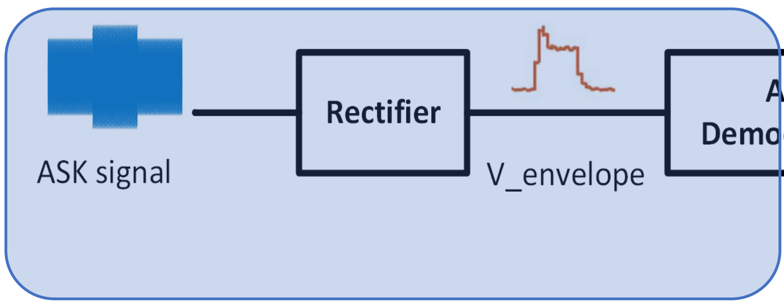

**10 bits for Pixel Address** **3 bits for Stim**

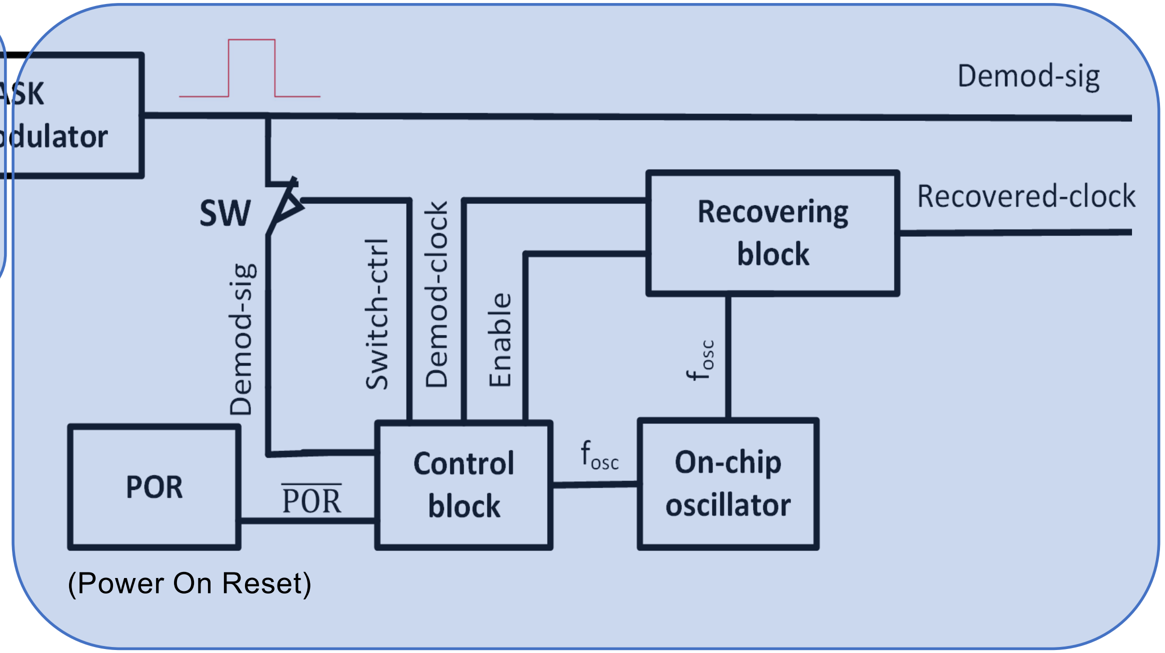
| H | $A_0$ | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $A_5$ | $A_6$ | $A_7$ | $A_8$ | $A_9$ | $N_0$ | $N_1$ | $N_2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 |

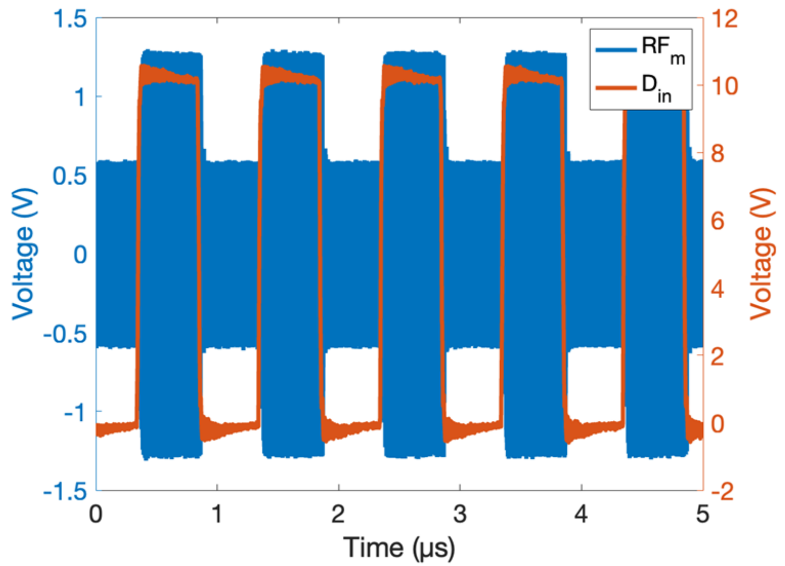
ASK (Amplitude-Shift Keying ) Modulation is chosen for the Data Transmission

# Data Receiver

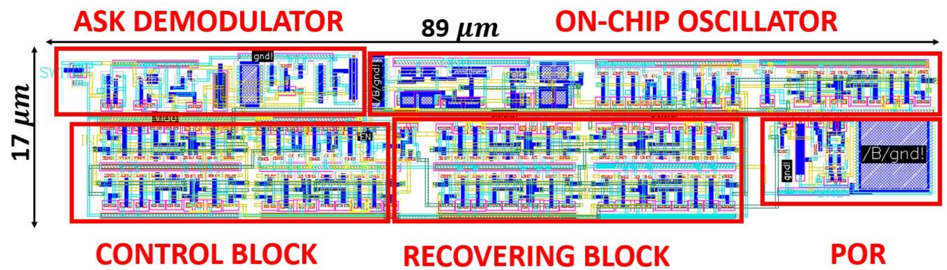
**Alexandre Schmidt**



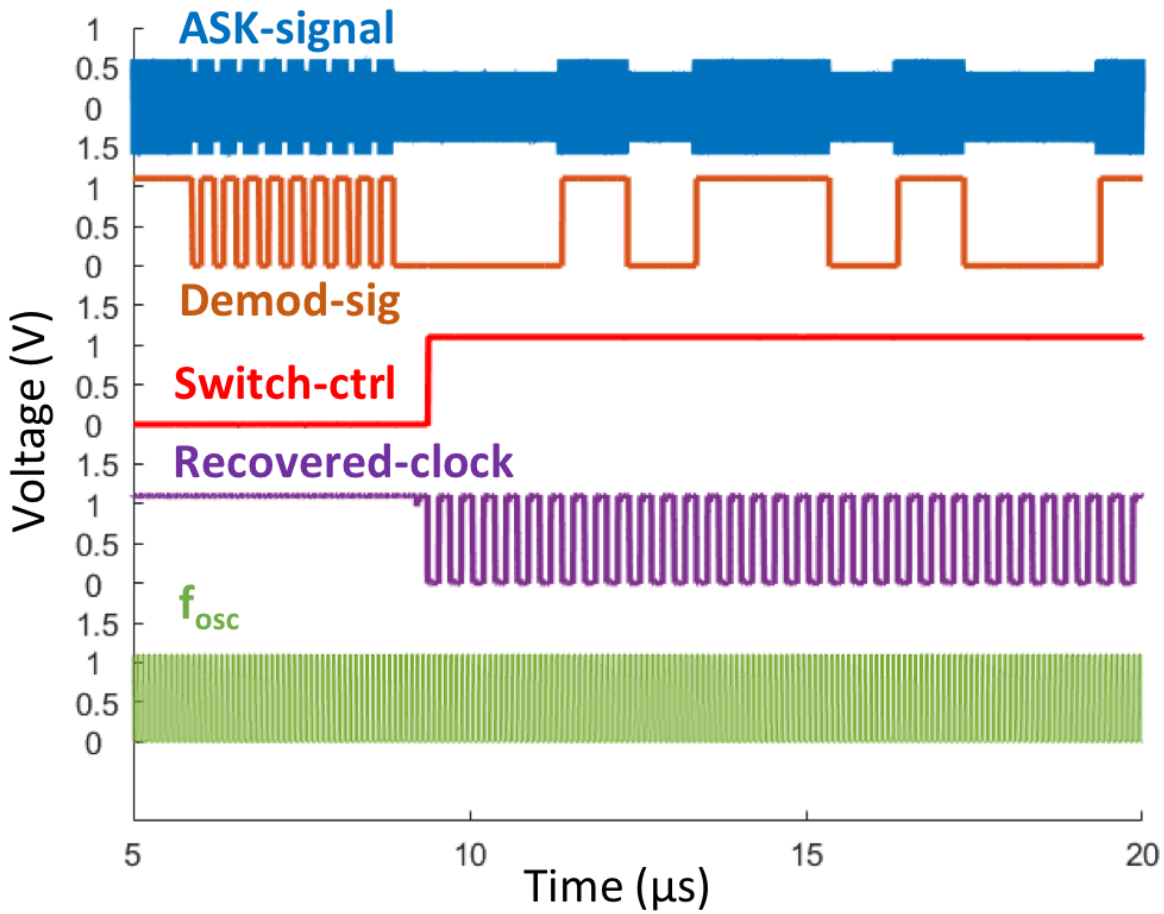




Cerbai, Barbruni et al., *IEEE ISCAS*, 2023




The ASK signal is received for Data Acquisition

# Data at the Receiver




Cerbai, et al., *IEEE ISCAS*, 2023

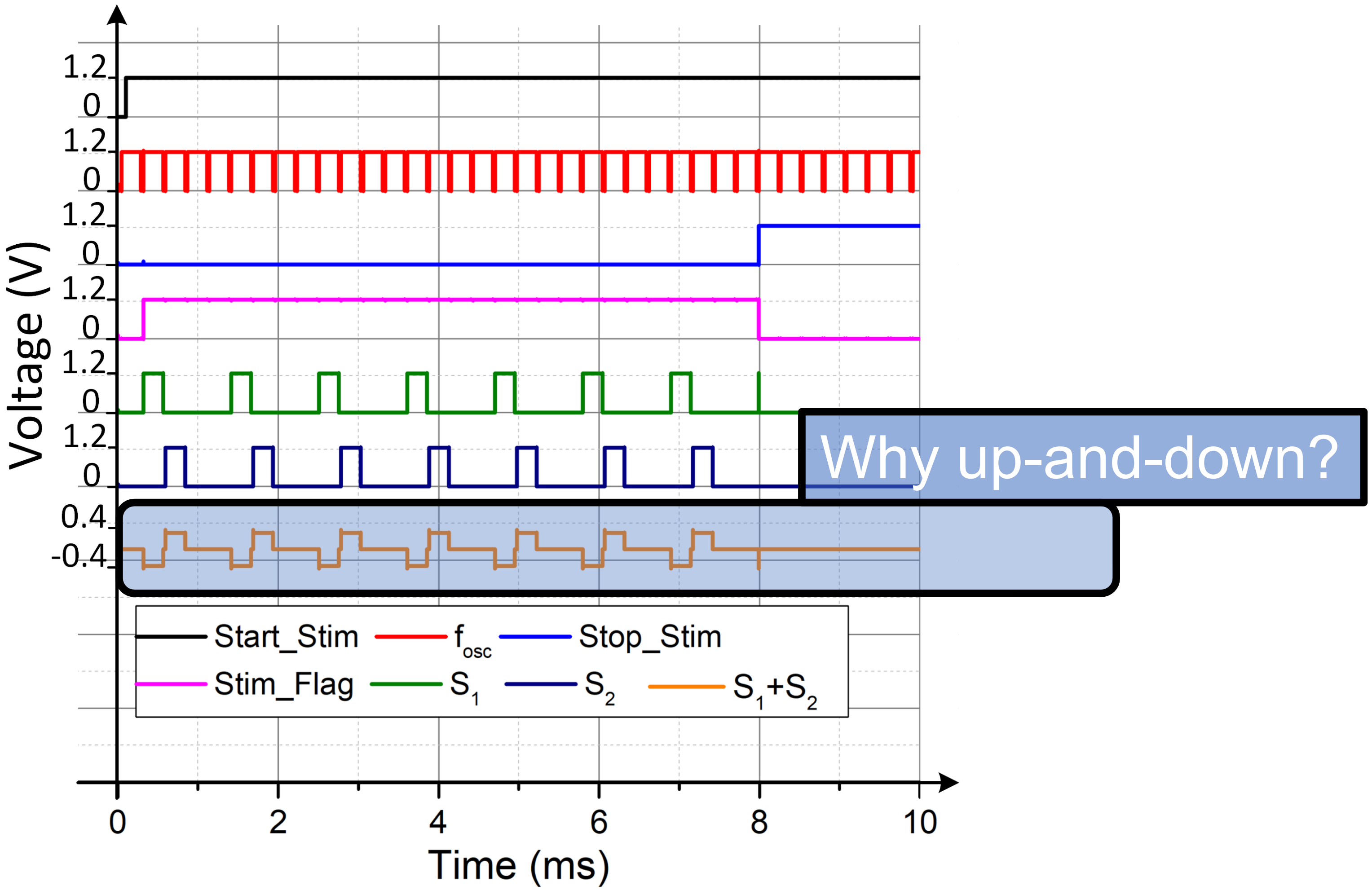
Carrier: 433.92 MHz
Modulation Index: 15%

Clock Rate (CR): 6Mbps
Data Rate (DR): 1 Mbps

$f_{osc}$ > 2 CR (i.e., 16 MHz)

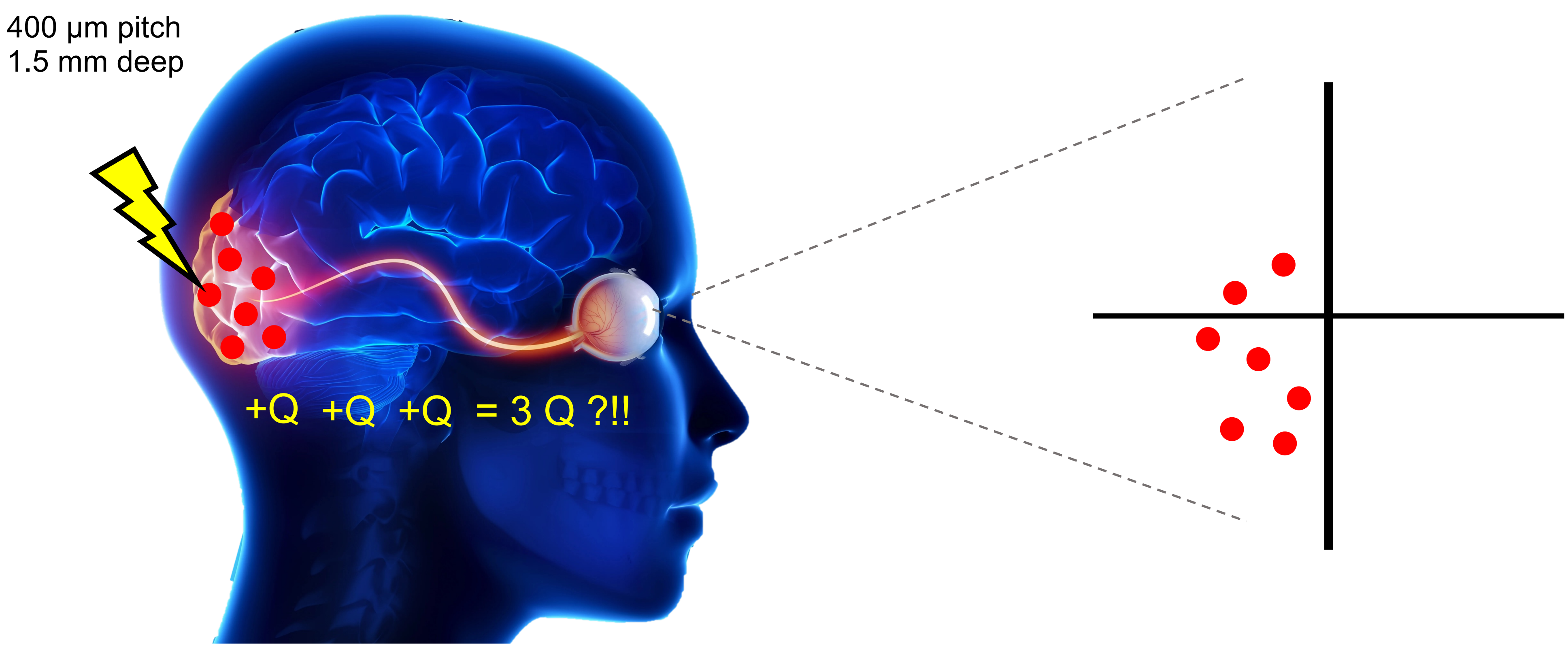
The Receiver need to Reconstruct several Received Data

# BioChip Stimulator



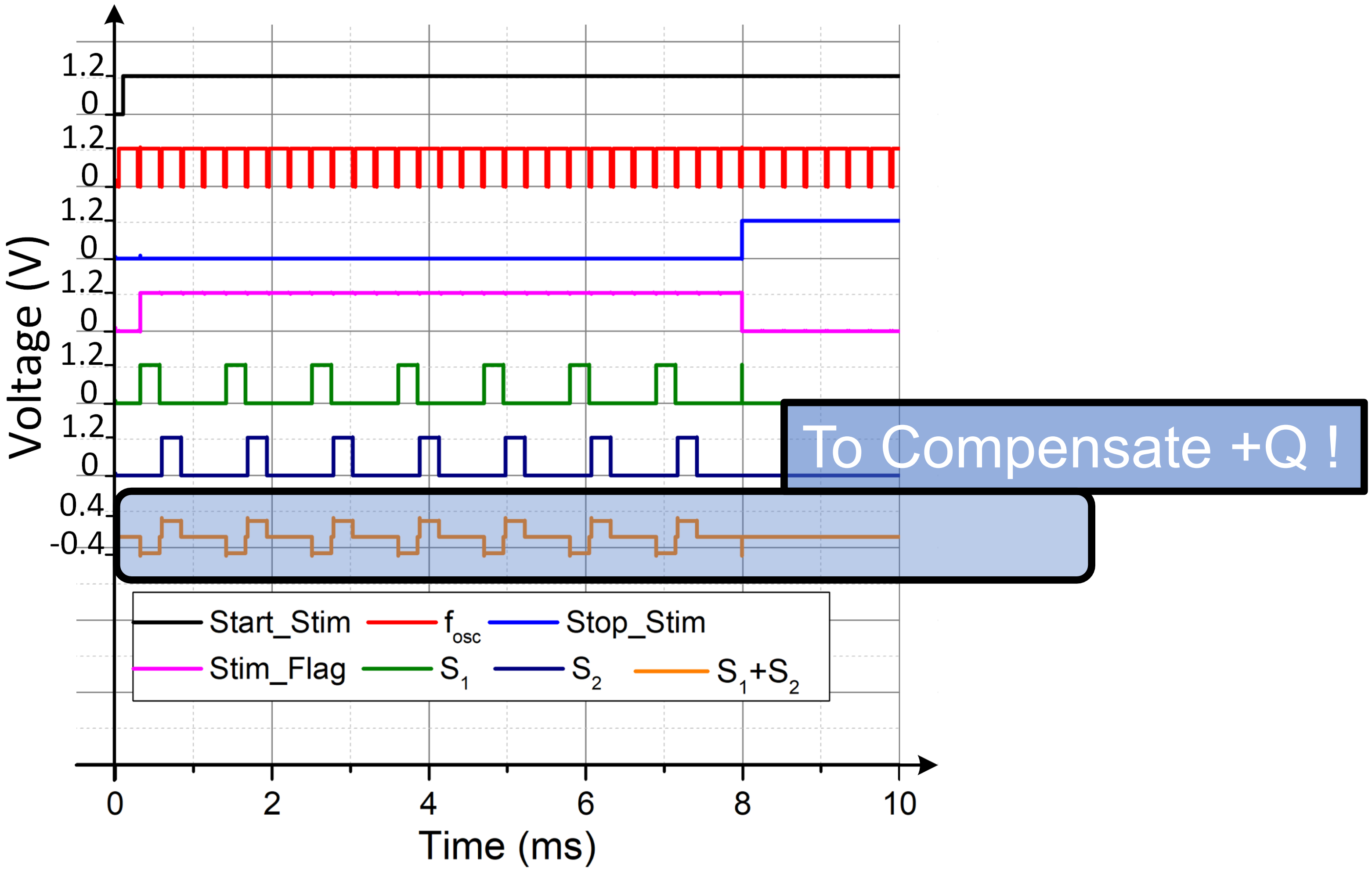

The Identified Logic Signal is now used to Stimulate

# Cortical Stimulation for Vision



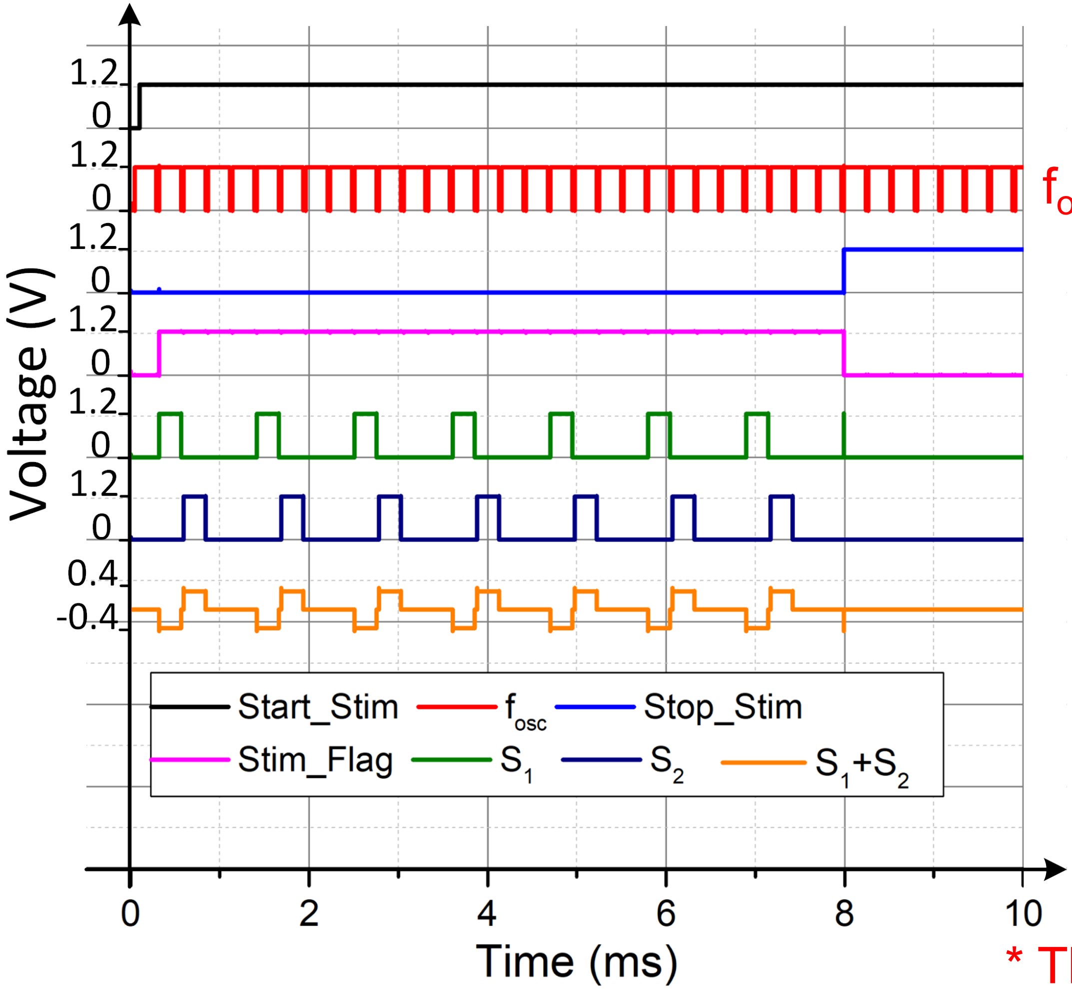

Charges sent to the Cortex need to be Compensated, not Accumulated!

# BioChip Stimulator

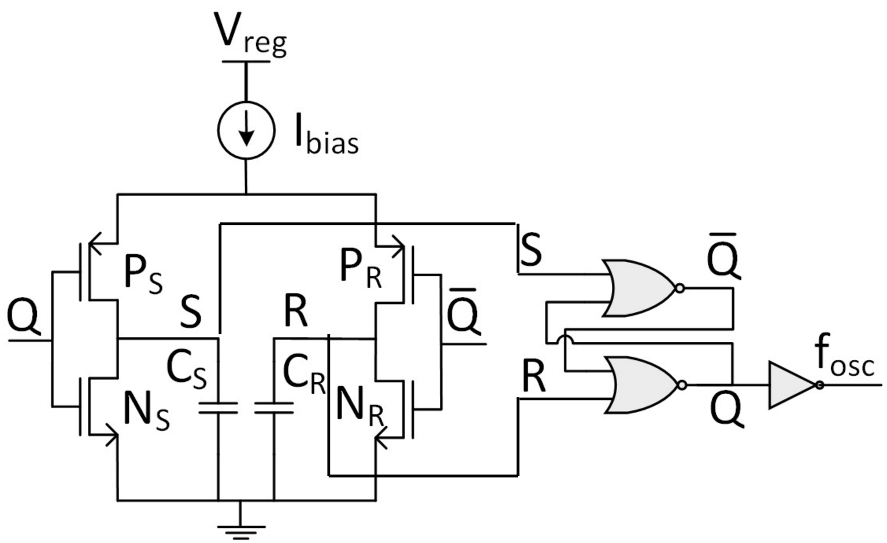



The Identified Logic Signal is now used to Stimulate

# BioChip Stimulator

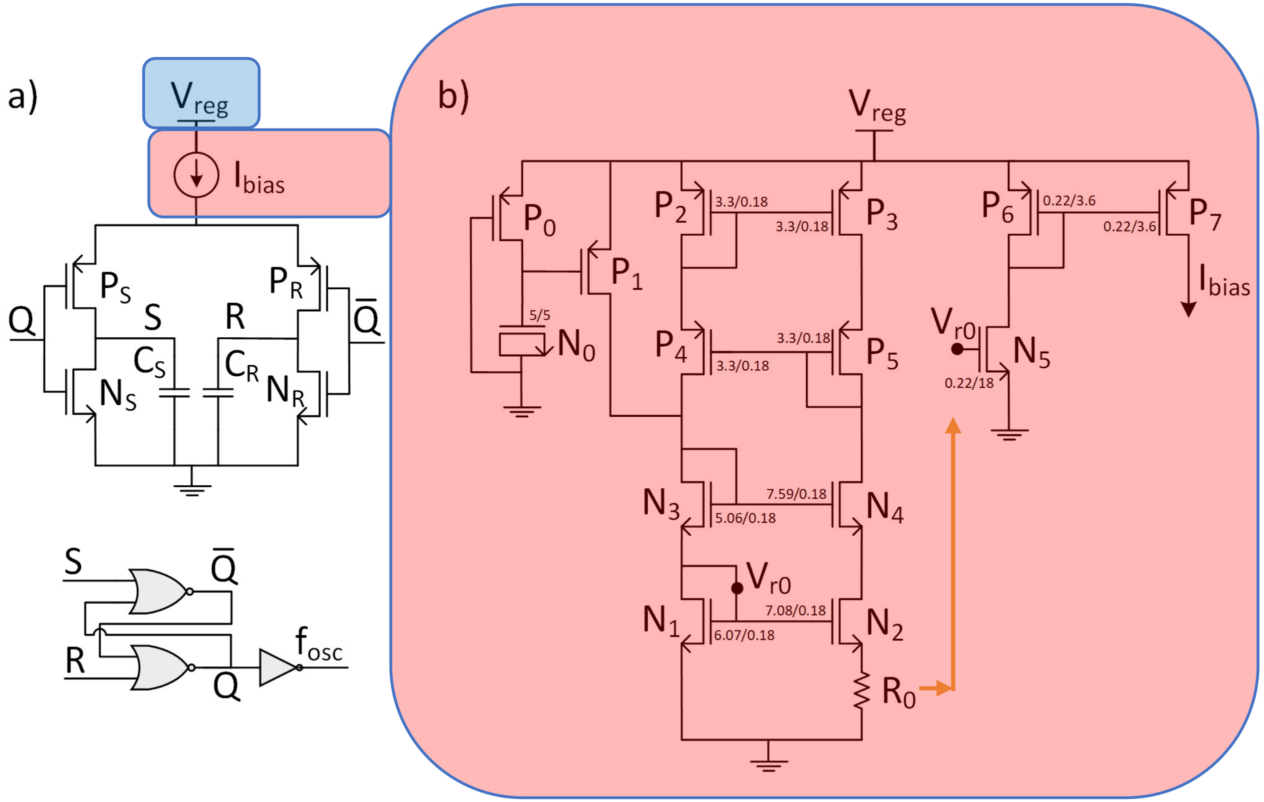



$I_{bias}$ is used to charge $C_S$ and $C_R$ in a relaxation * oscillator, while couple of NOR logic gates return the desired pulses for $f_{osc}$




* The Relaxation Oscillator is a a nonlinear electronic oscillator circuit that produces a non-sinusoidal repetitive output signal

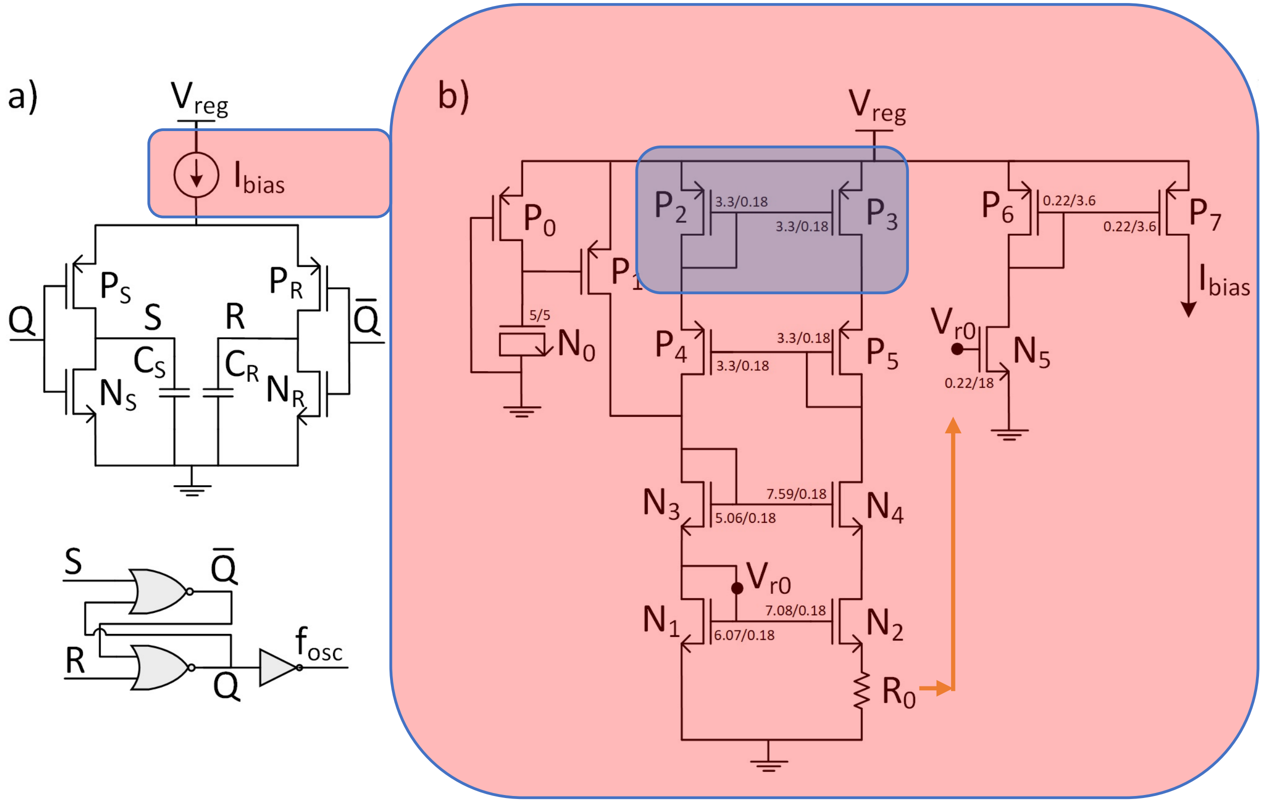
# BioChip Stimulator




$$f_{osc} \propto \frac{I_{bias}}{(C_S + C_R) \cdot V_{reg}}$$

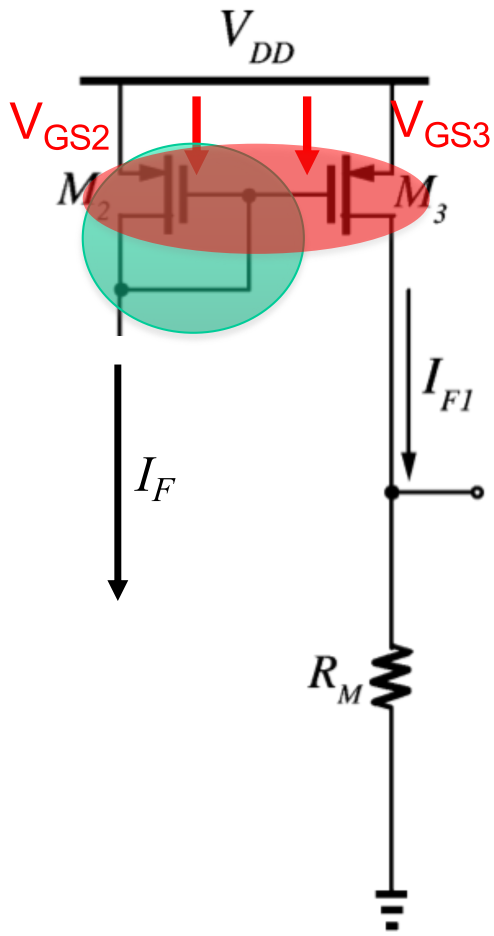
# BioChip Stimulator

**Current Mirror**




$$f_{osc} \propto \frac{I_{bias}}{(C_S + C_R) \cdot V_{reg}}$$

# Current Mirror




$$V_{GS2} = V_{GS3}$$

$$I_{D2} = \Phi(V_{GS2})$$

$$I_{D3} = \Phi(V_{GS3}) = \Phi(V_{GS2})$$

$$I_F = I_{D2} \Rightarrow V_{GS2}$$

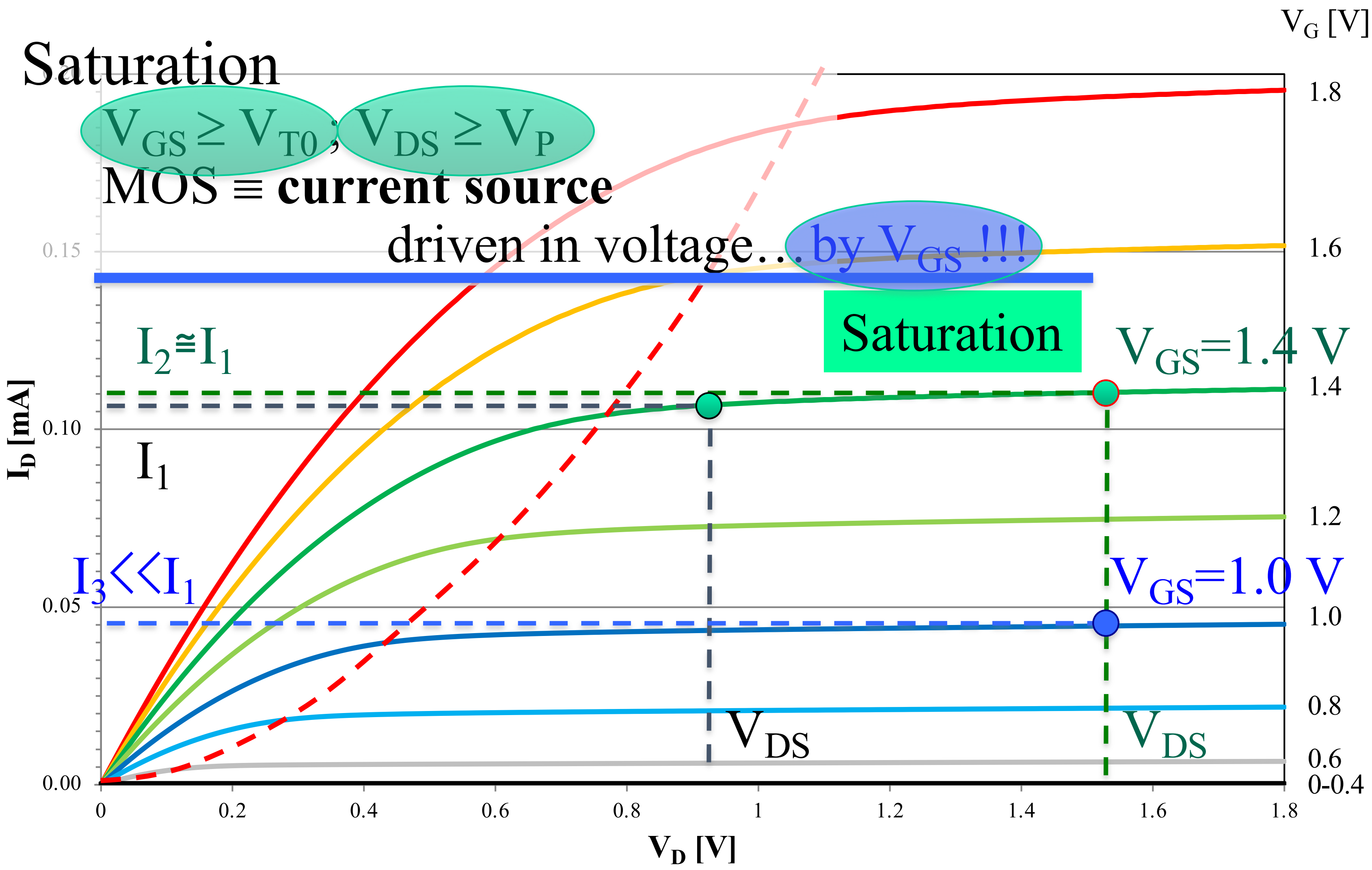
$$V_{GS2} = V_{GS3} \Rightarrow I_{D2} = I_{F1}$$

$$I_F = I_{D2} \Rightarrow V_{GS2} = V_{GS3} \Rightarrow I_{F1} = I_F$$

A current mirror for the current in the path at CE

What's about $V_{DS}$?

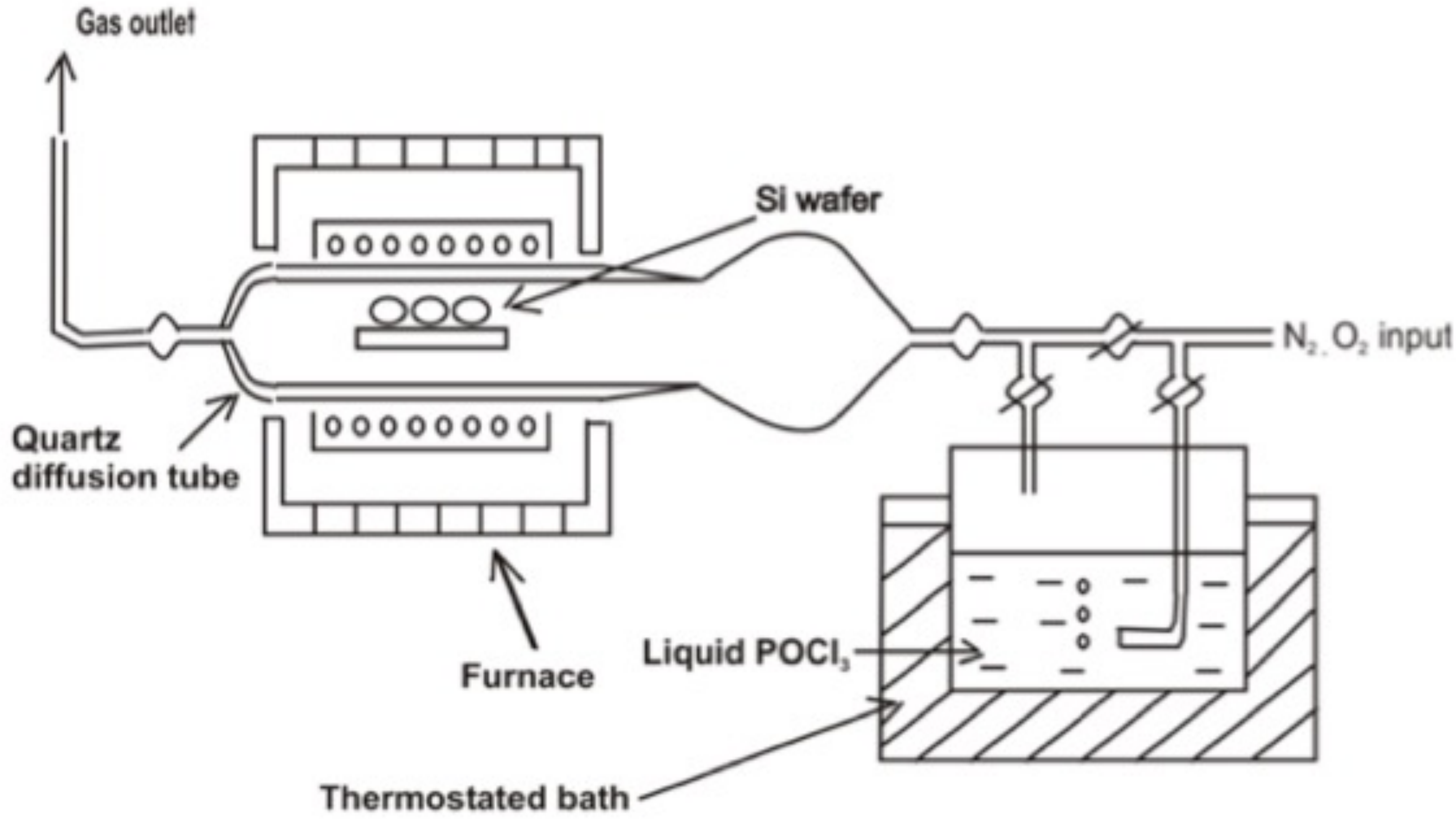
# CMOS FET as Current Generator



# Chip Production by Wafers

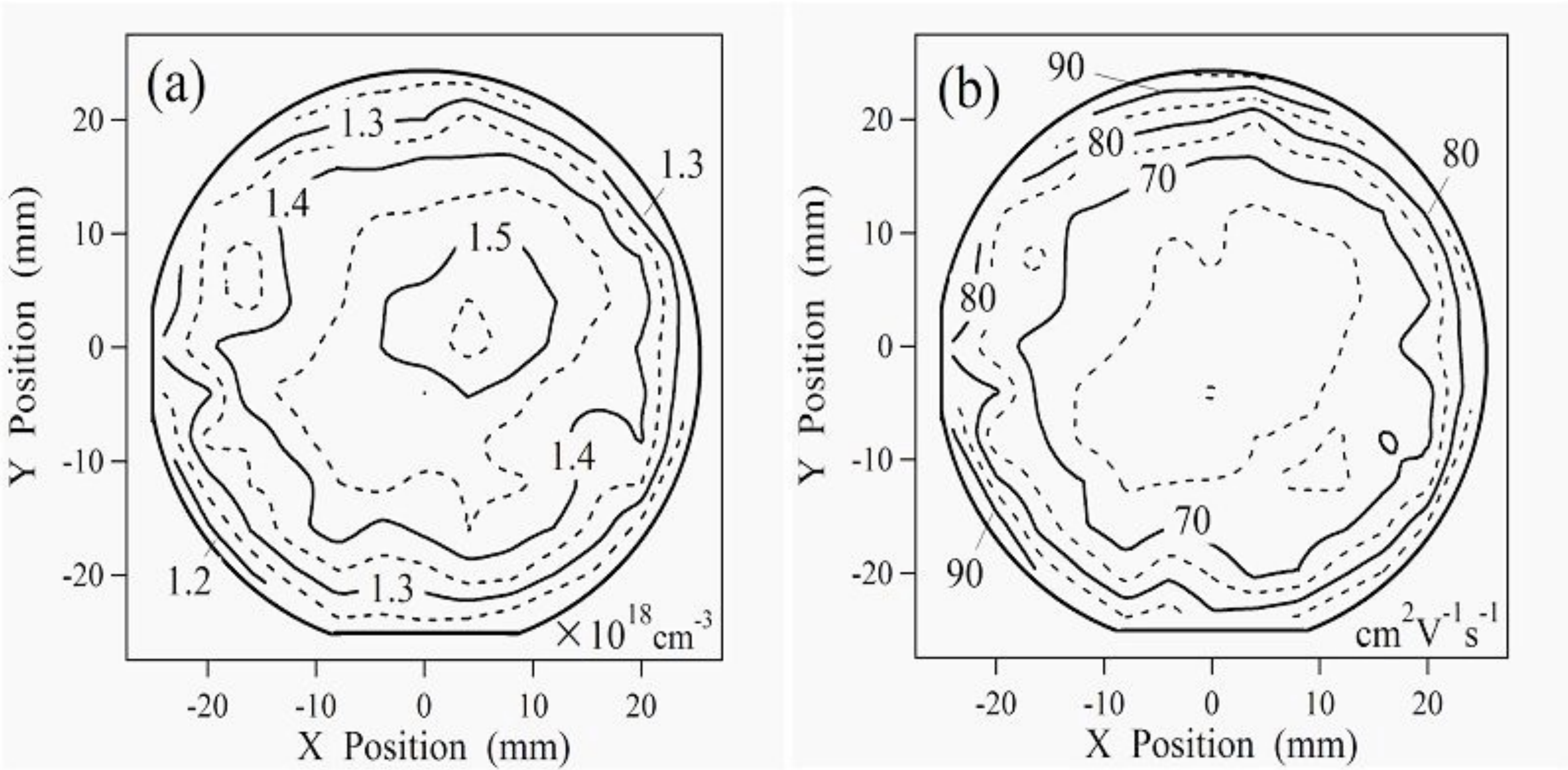

CMOS Matching Problem: Almost identical, while not really!

# Chip Production by Wafers



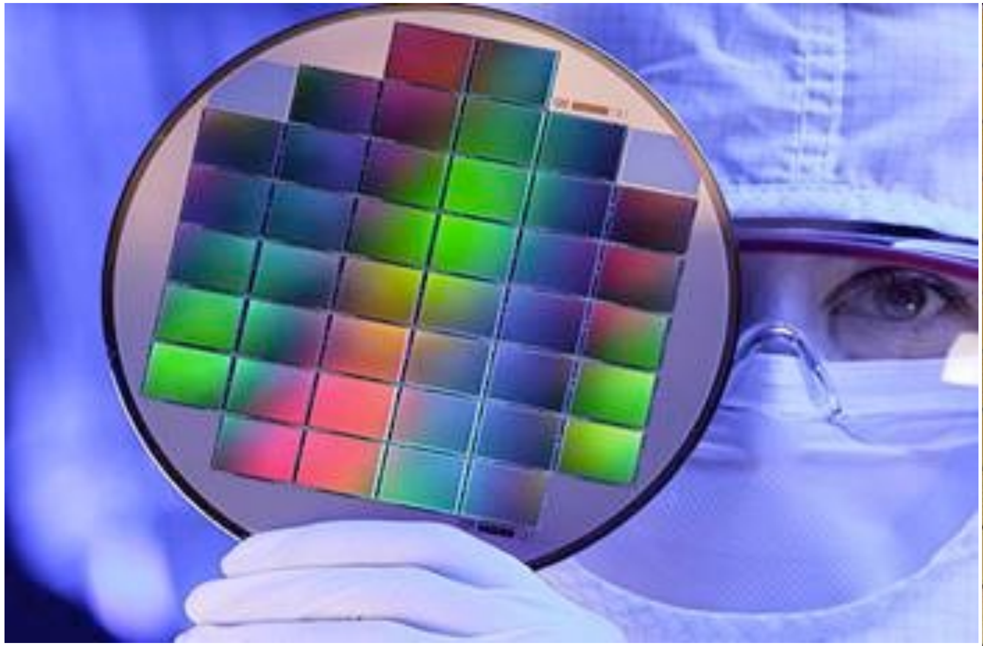

Diffusion Scheme during Chip Production
by CMOS Fabrication Process

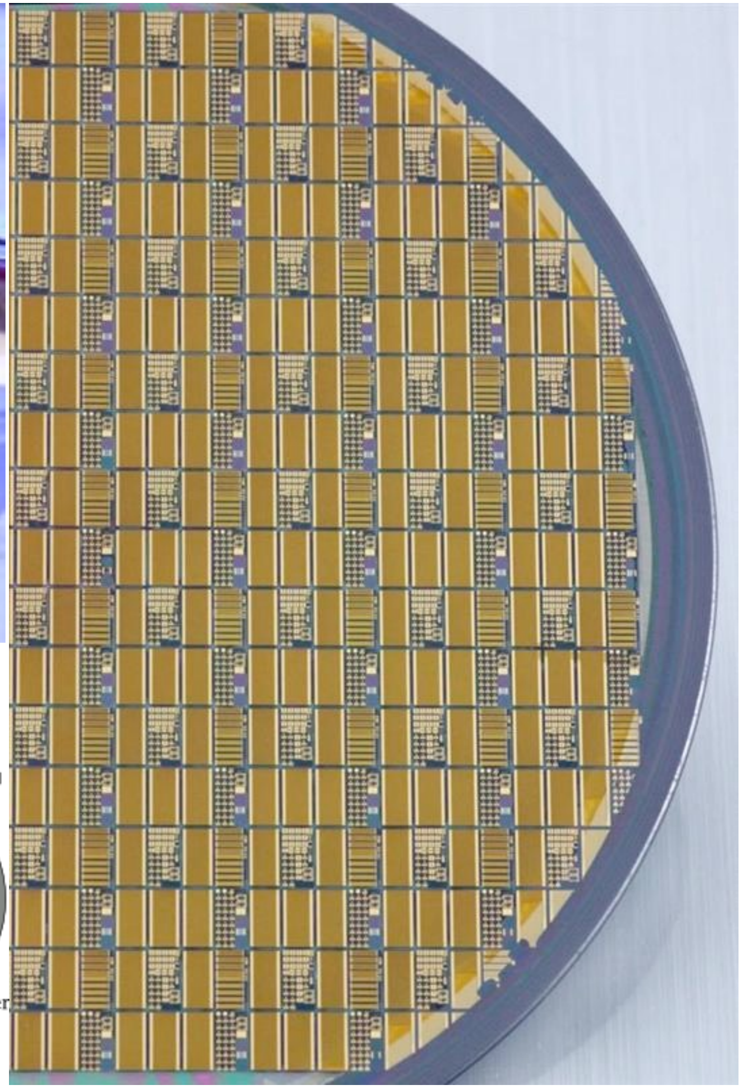
# Chip Production by Wafers

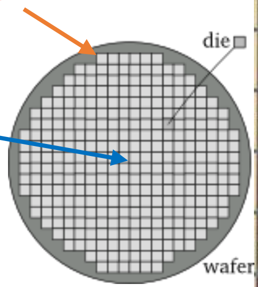



Spatial view of (a) carrier concentration and (b) mobility in a commercial CMOS Wafer

# Chip Production by Wafers

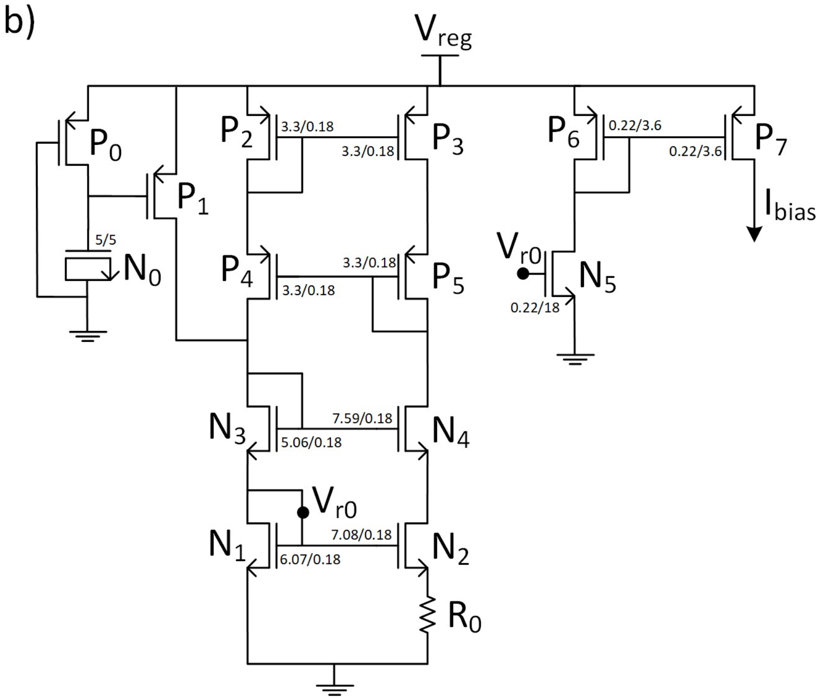


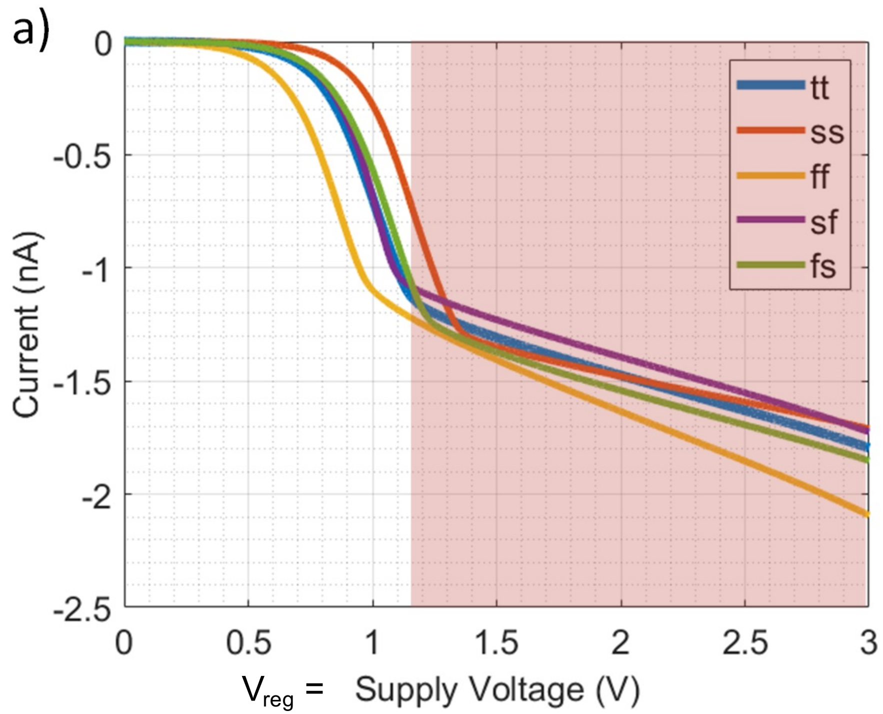





Different chips in
different regions of the wafer

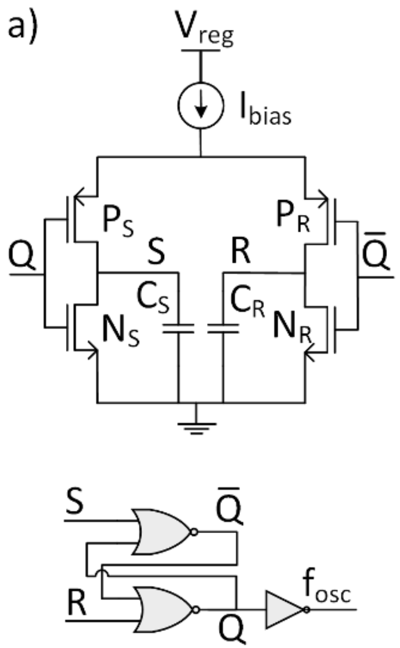
# BioChip Stimulator



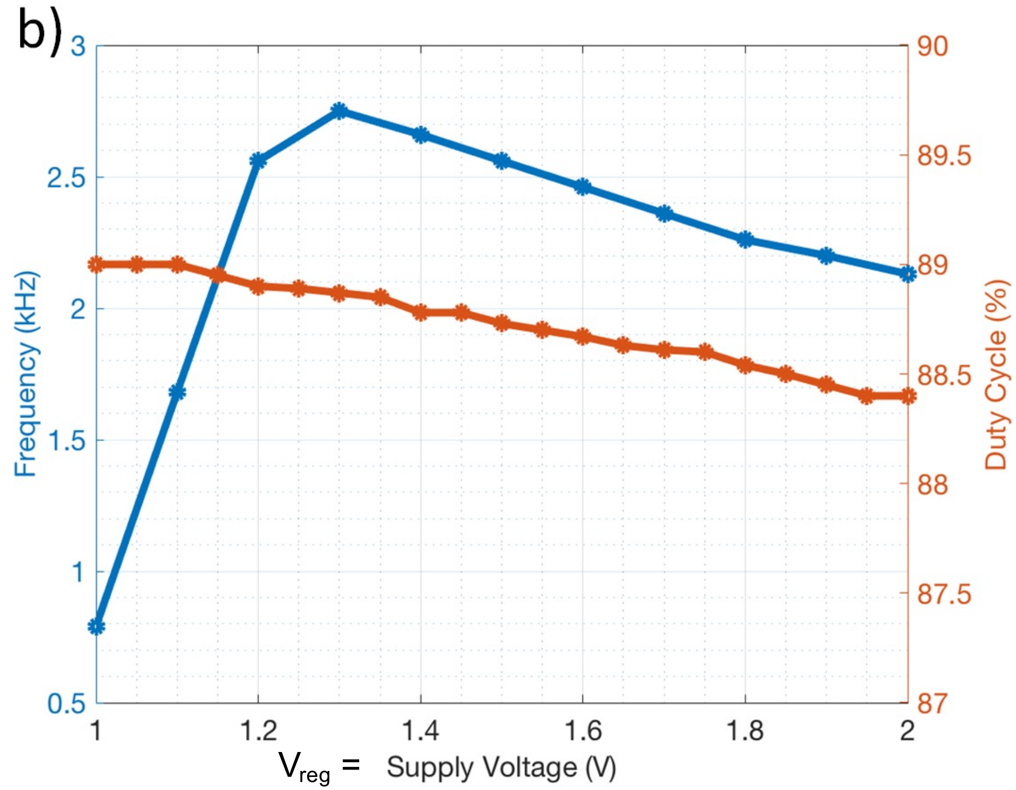




The Bias Current changes with both
Different Supplied Voltages and different Wafer Locations

# BioChip Stimulator




$$f_{osc} \propto \frac{I_{bias}}{(C_S + C_R) \cdot V_{reg}}$$

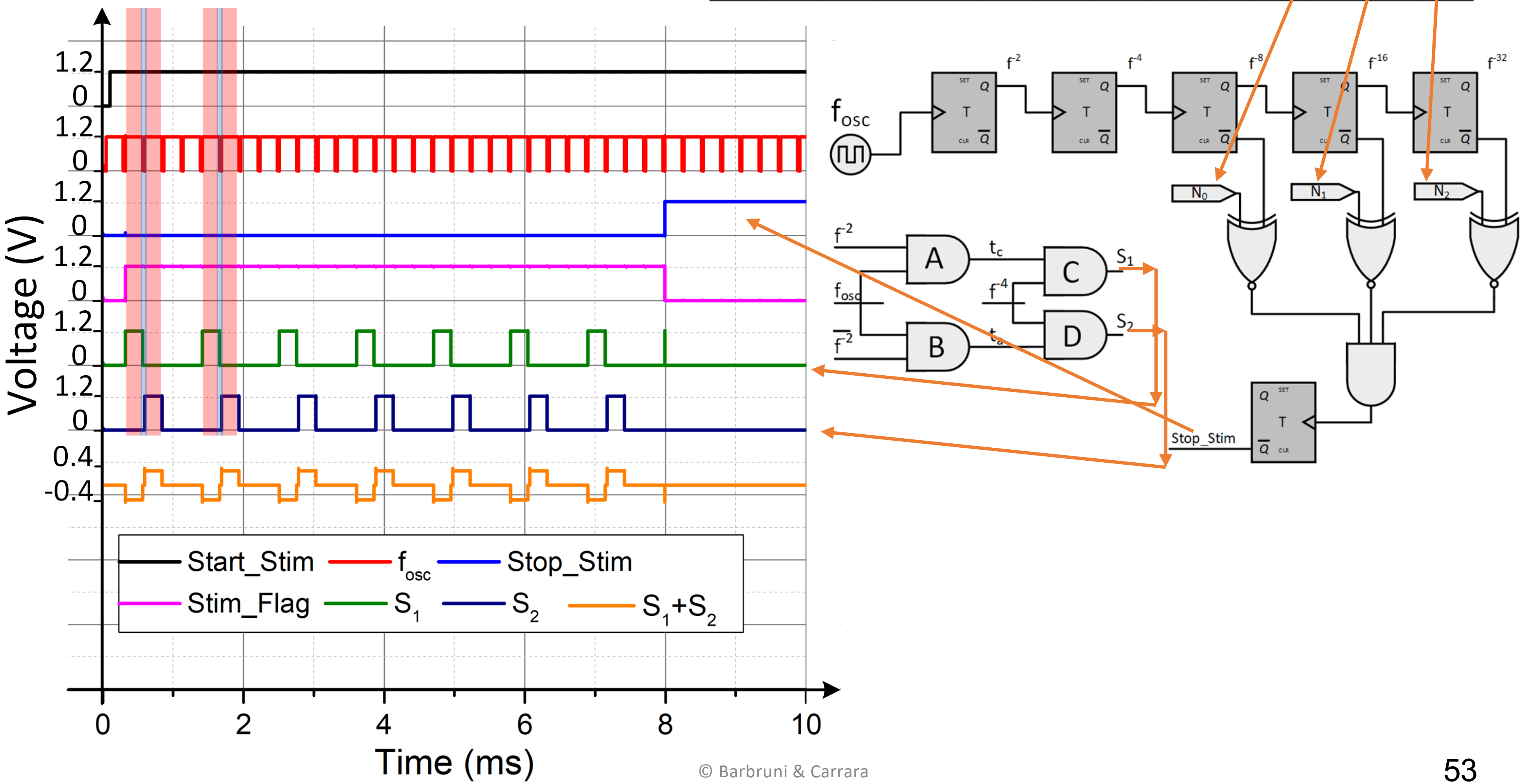



The Frequency of the Stimulation changes with Different Supplied Voltages

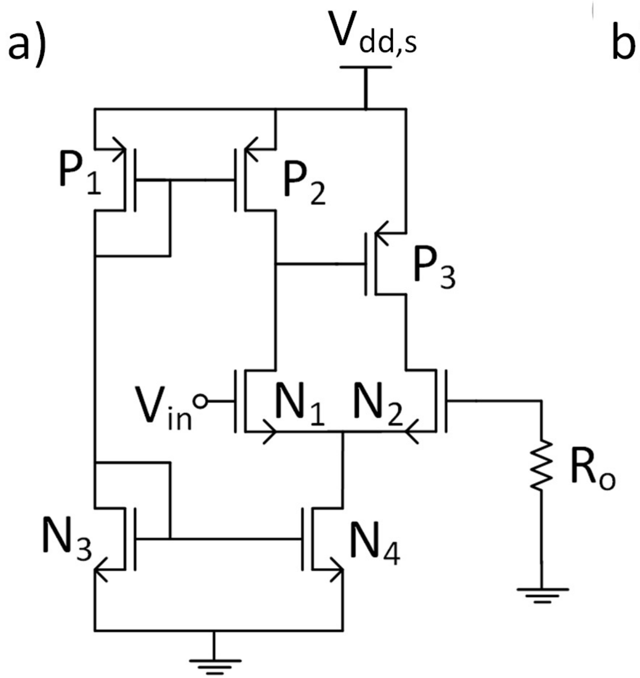
# BioChip Stimulator

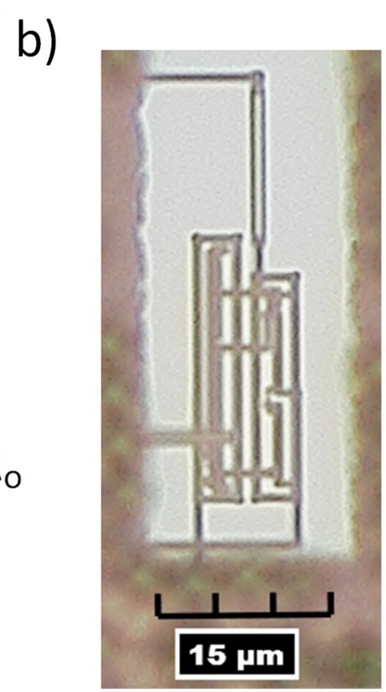
**10 bits for Pixel Address** | **3 bits for Stim**

| H | $A_0$ | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $A_5$ | $A_6$ | $A_7$ | $A_8$ | $A_9$ | $N_0$ | $N_1$ | $N_2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 1 | 0 |



# BioChip Stimulator

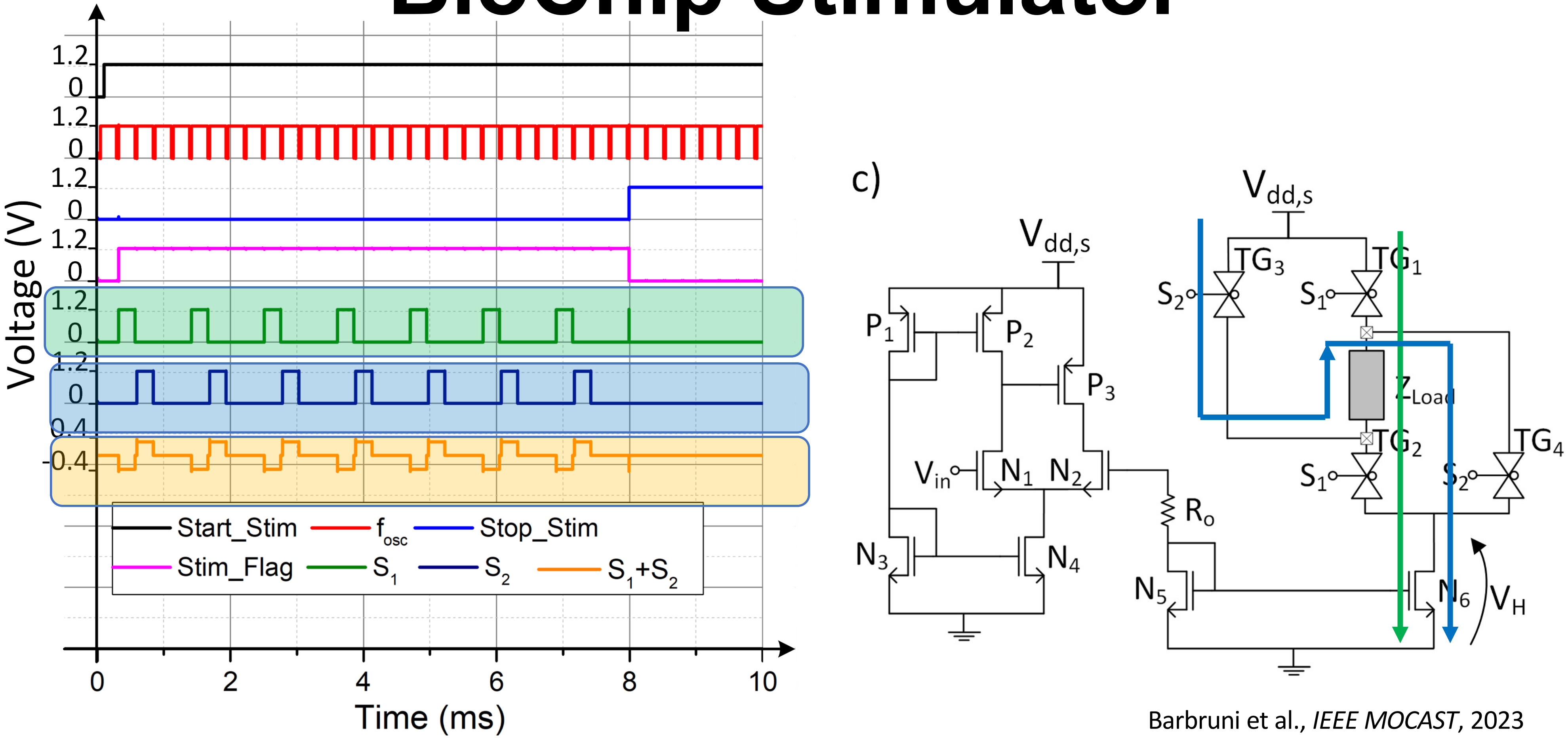



Fotouhi et al., *IEEE JSSC*, 2001

A further block is needed to provide the Right Current required for the Stimulation

# BioChip Stimulator

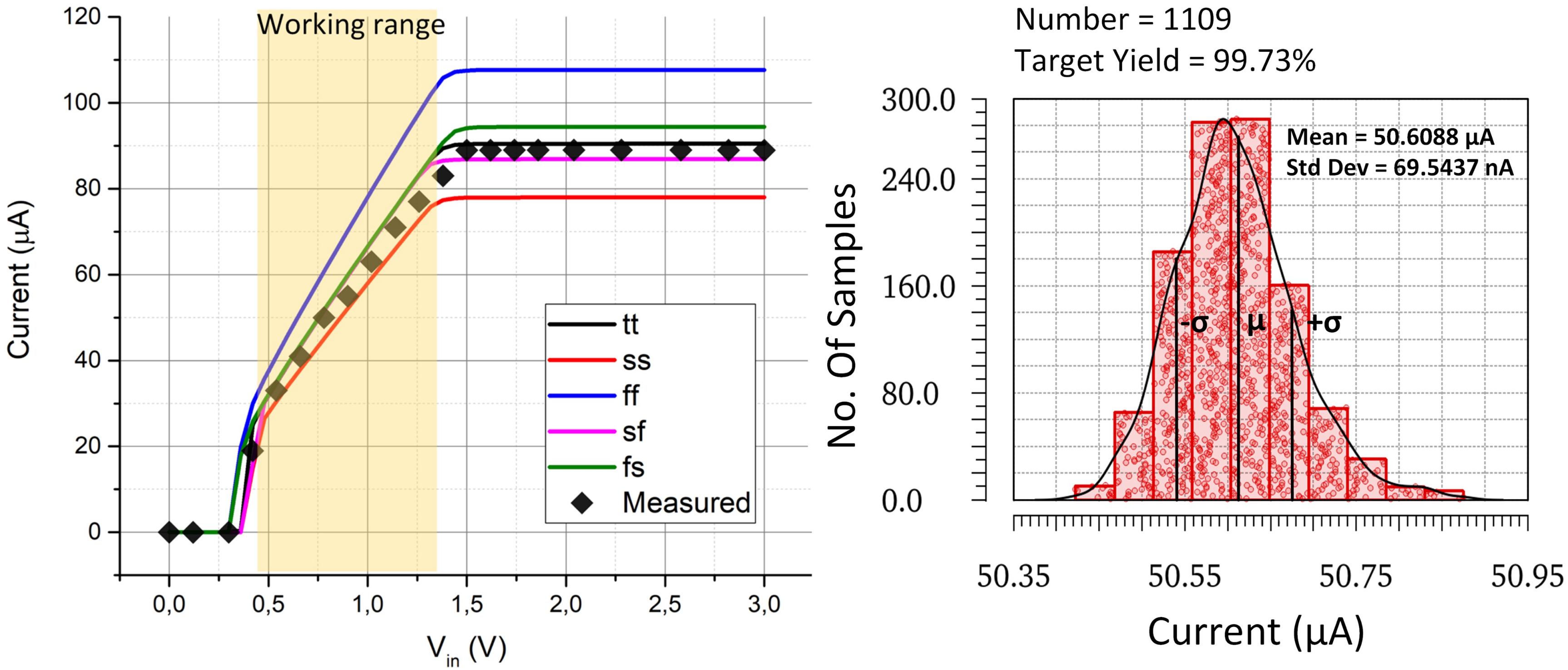



Barbruni et al., *IEEE MOCAST*, 2023

Finally, the H-Bridge provides the Right Current with the mentioned Q-Compensation

# BioChip Stimulator

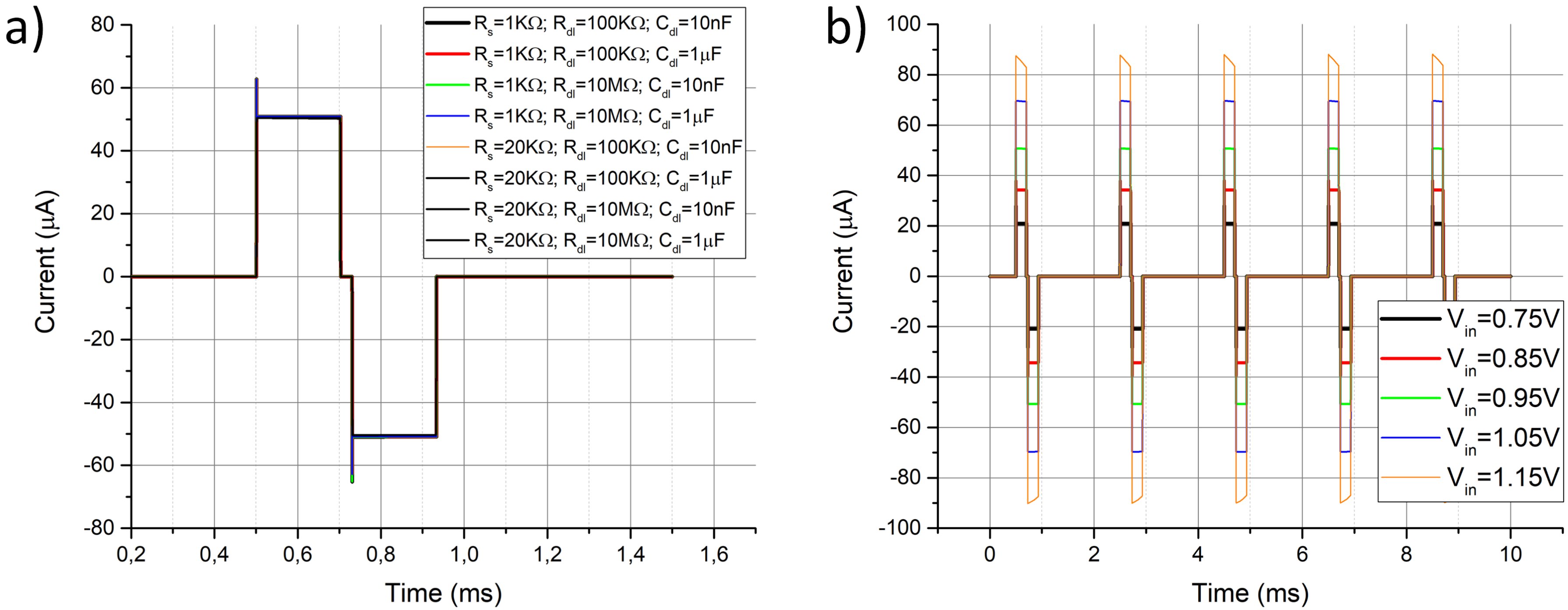
Barbruni et al., *IEEE MOCAST*, 2023




The Stimulator Performance changes in Different Wafer Corners

# BioChip Stimulator

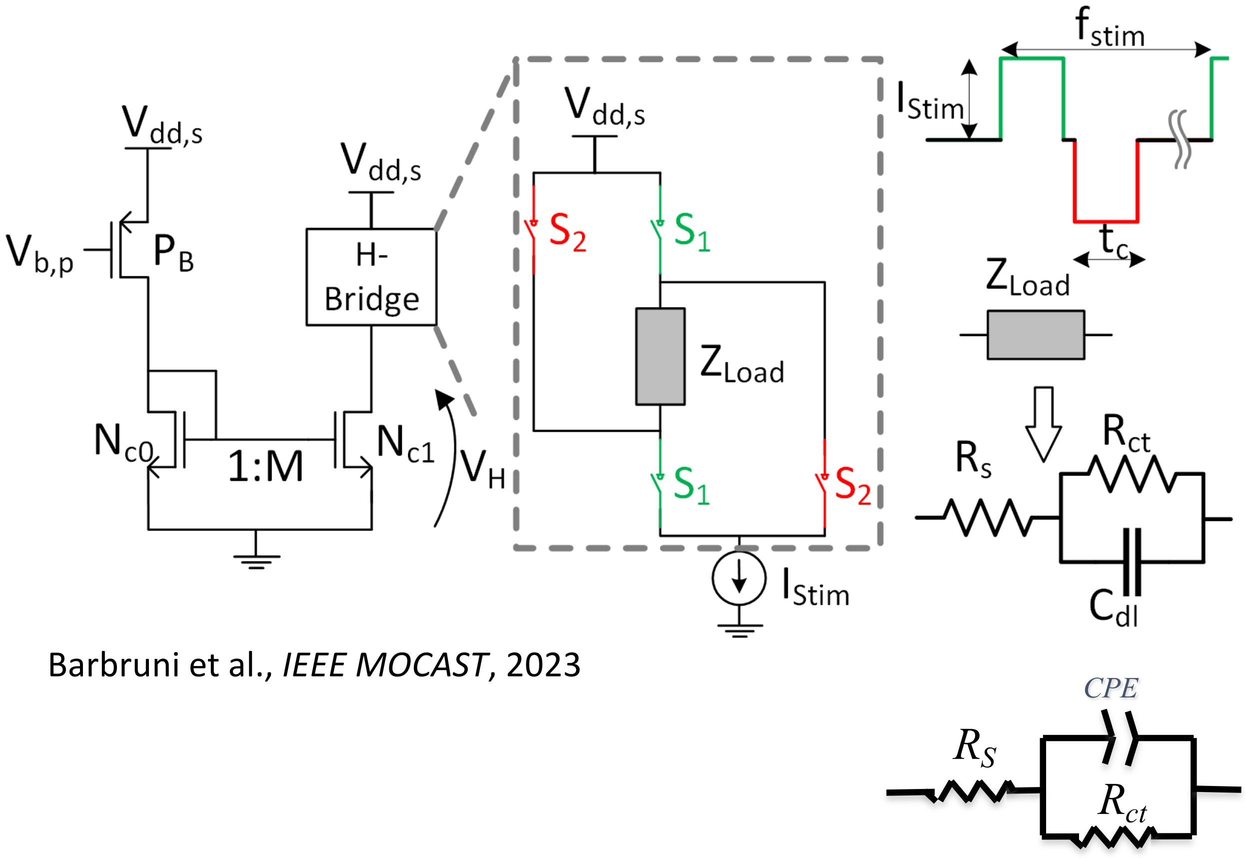
Barbruni et al., *IEEE MOCAST*, 2023



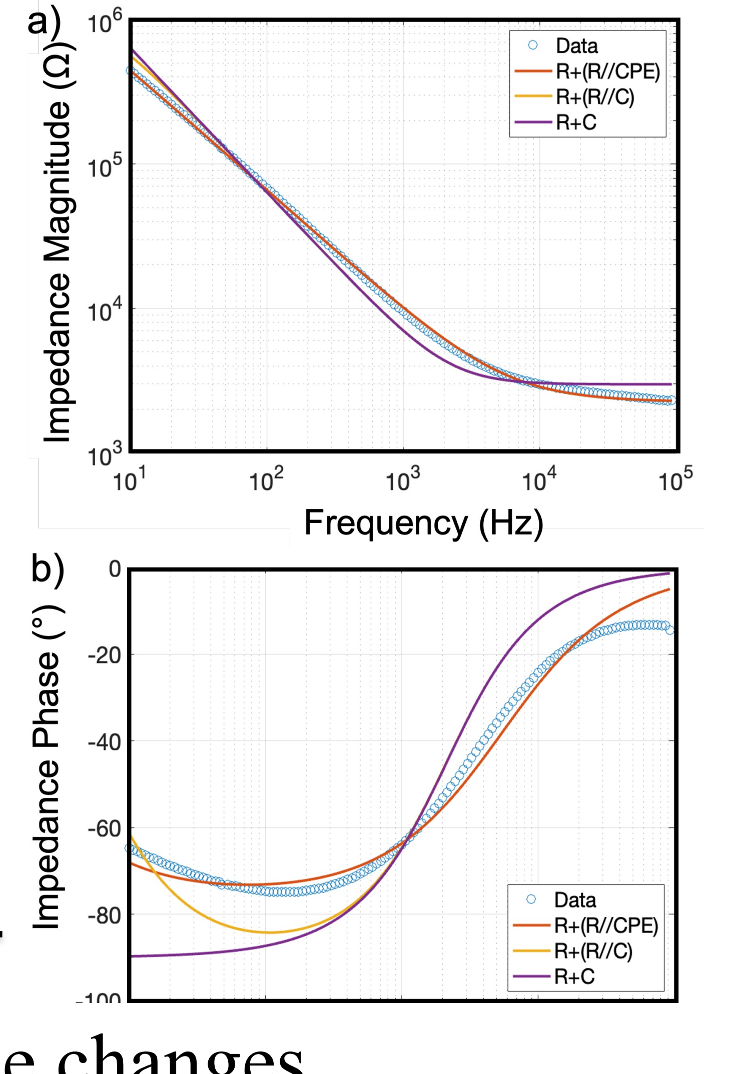

The Stimulator Performance changes

With Different Supplied Voltages

# BioChip Stimulator



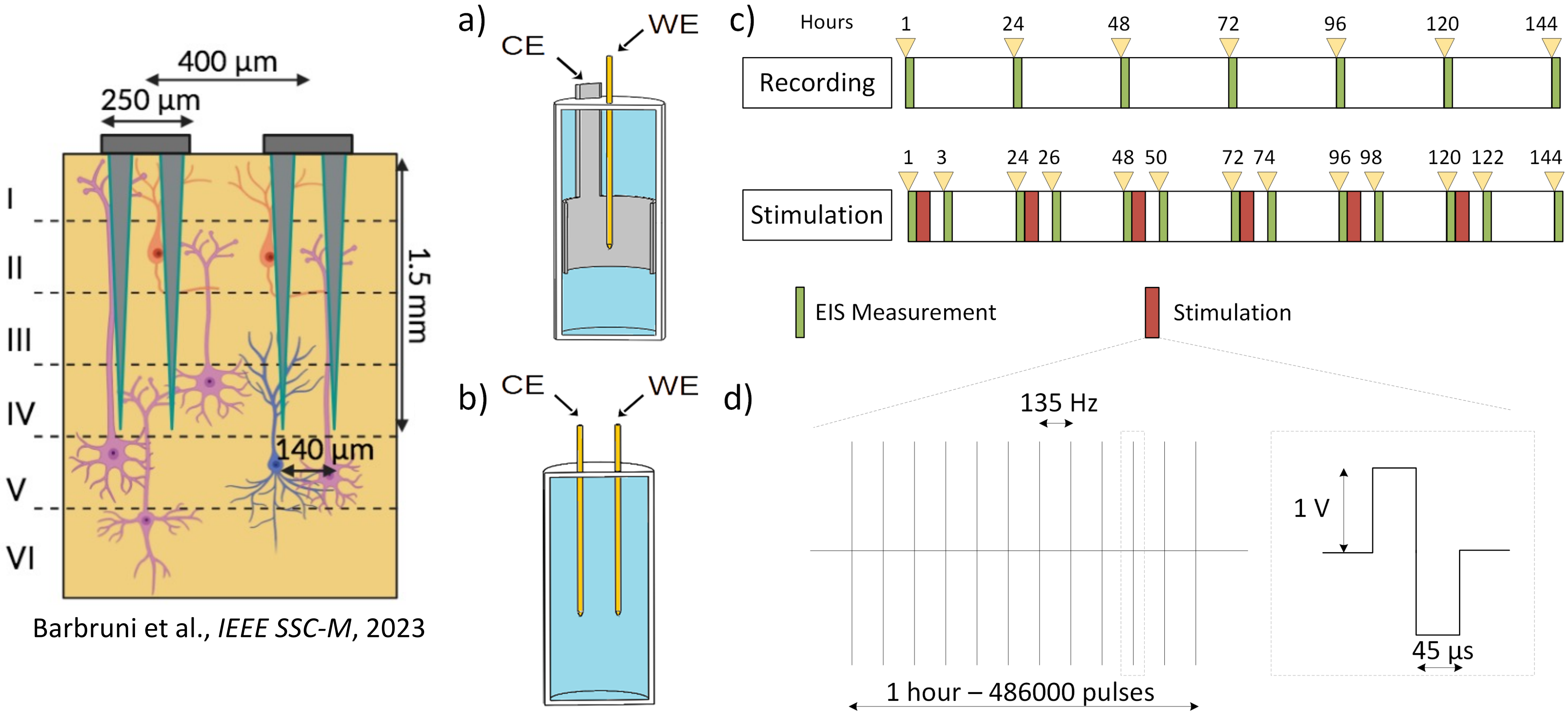

Barbruni et al., *IEEE MOCAST*, 2023




The Simulated Performance changes

with Different Bio/CMOS interface models

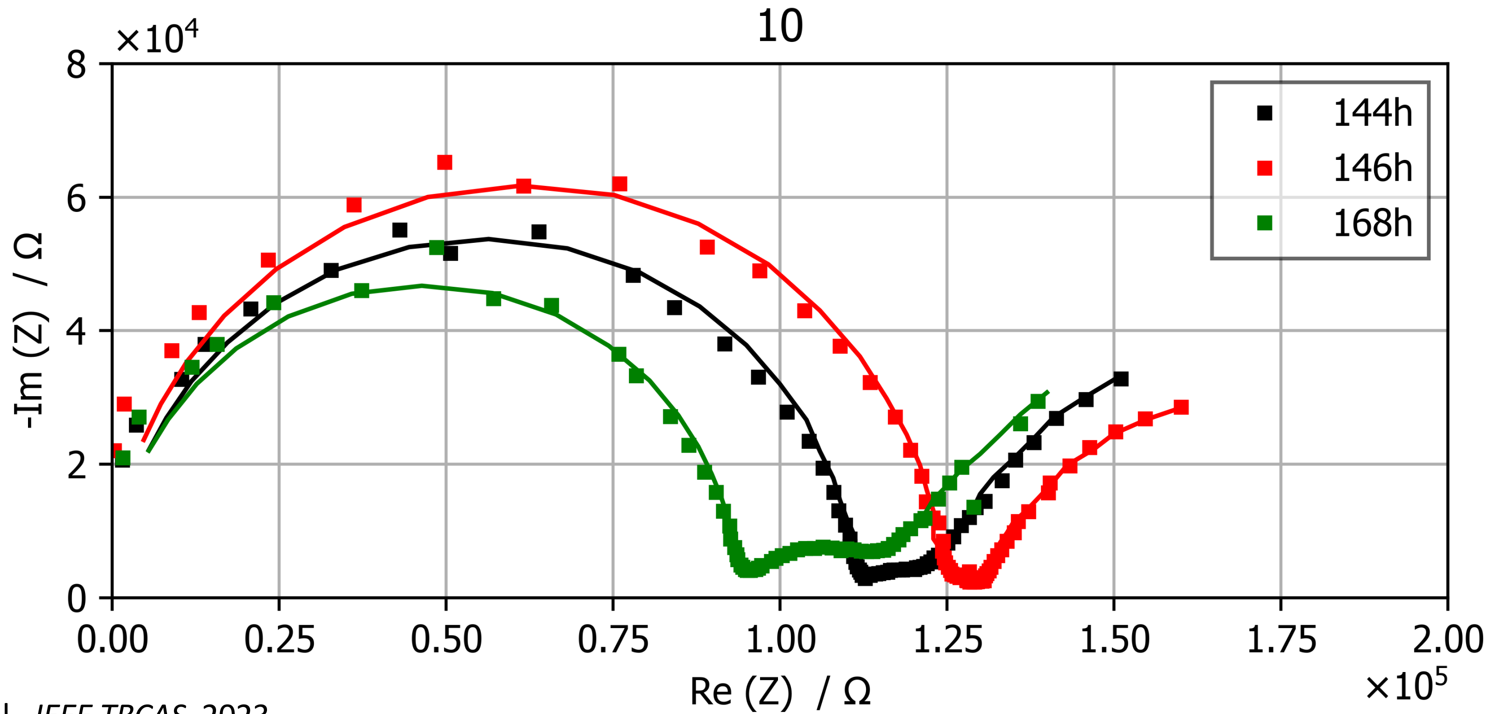
# Bio/CMOS Interface




Barbruni et al., *IEEE SSC-M*, 2023

The Right Bio/CMOS Interface Model need to be identified

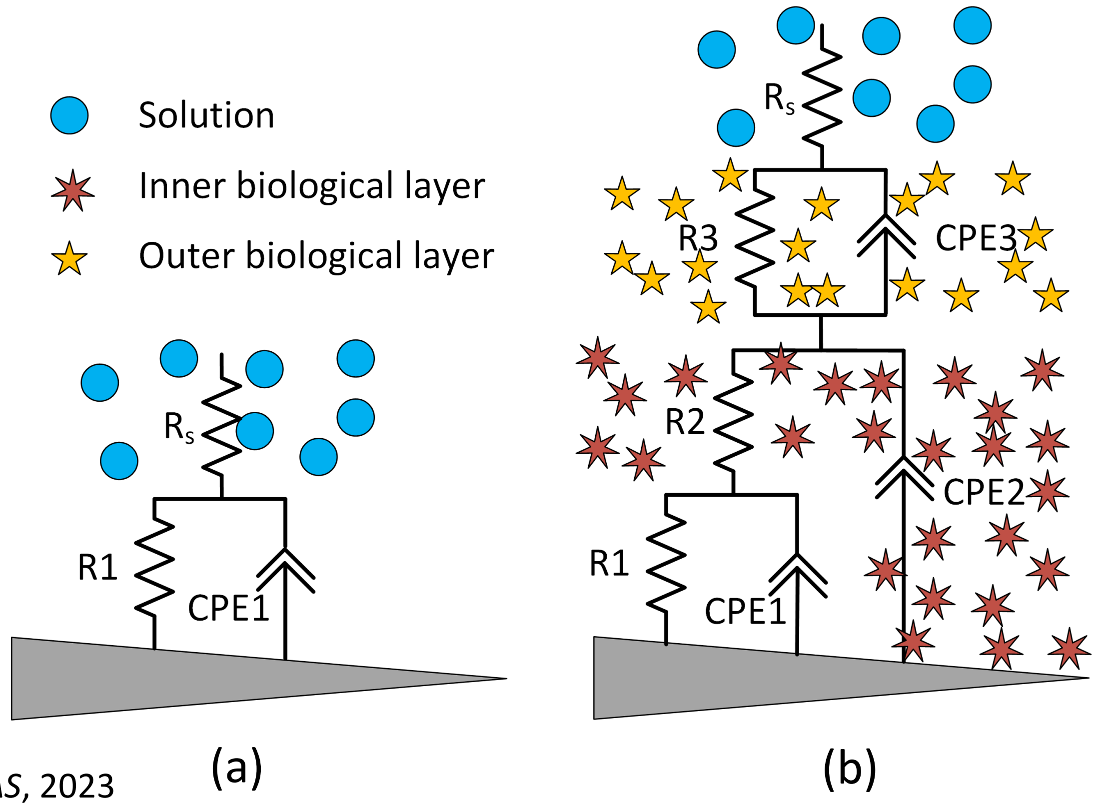
# Bio/CMOS Interface




Barbruni et al., *IEEE TBCAS*, 2023

The Bio/CMOS Interface Model Drift in Time

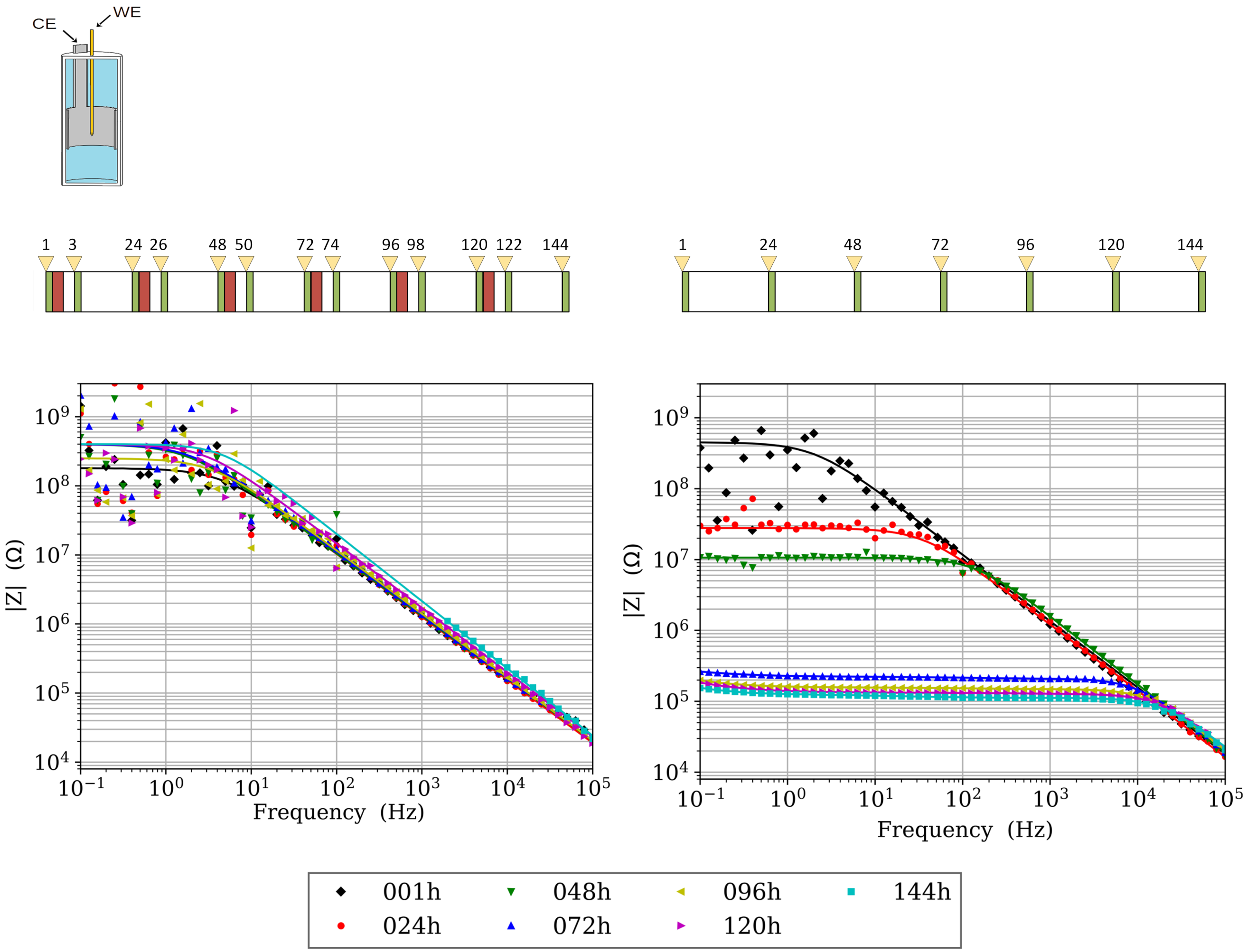
# Bio/CMOS Interface



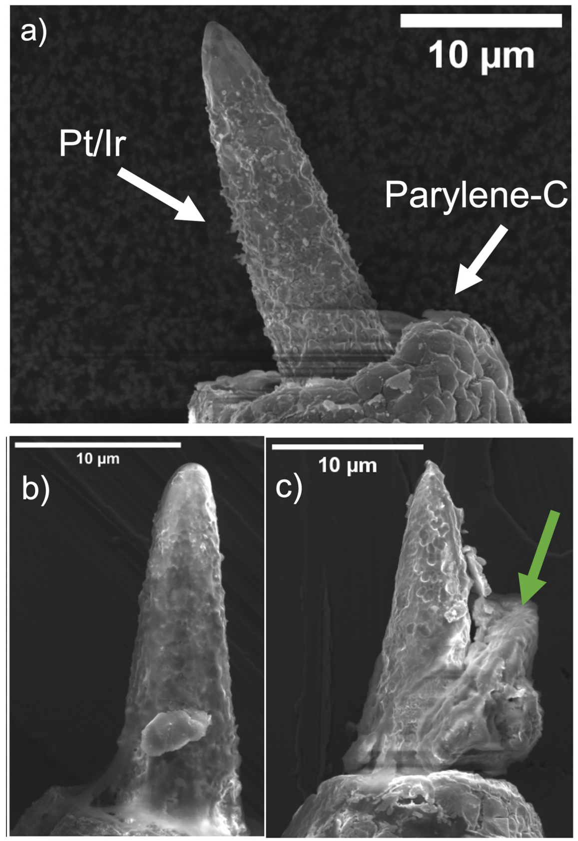

Barbruni et al., *IEEE TBCAS*, 2023

The Model Drift since Biological Tissues are Growing

# Bio/CMOS Interface




Barbruni et al., *IEEE TBCAS*, 2023

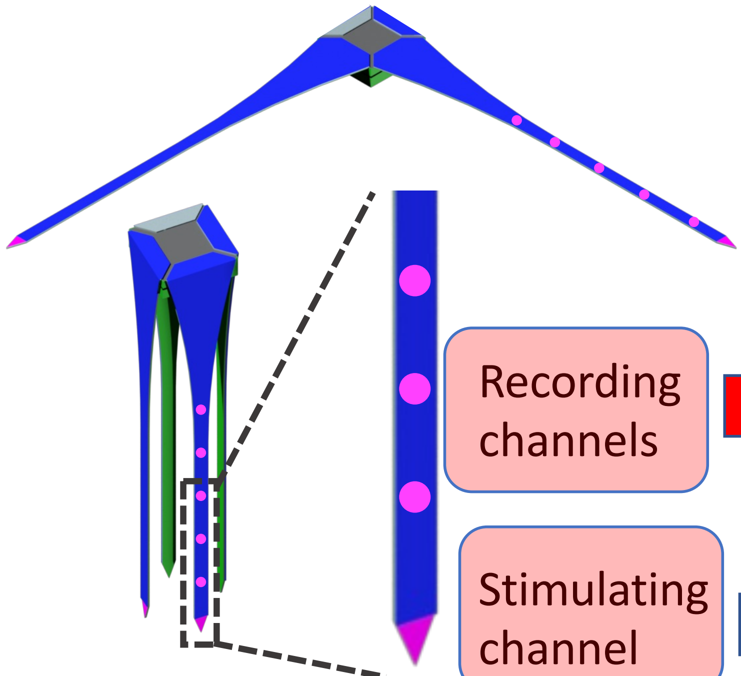



After Recording

After Stimulation

The Model Drift since Biological Tissues are Growing

# BioChip for Cortical Stimulation



Recording channels

Stimulating channel

Barbruni et al., *PCT/IB2022/059944*, 2022

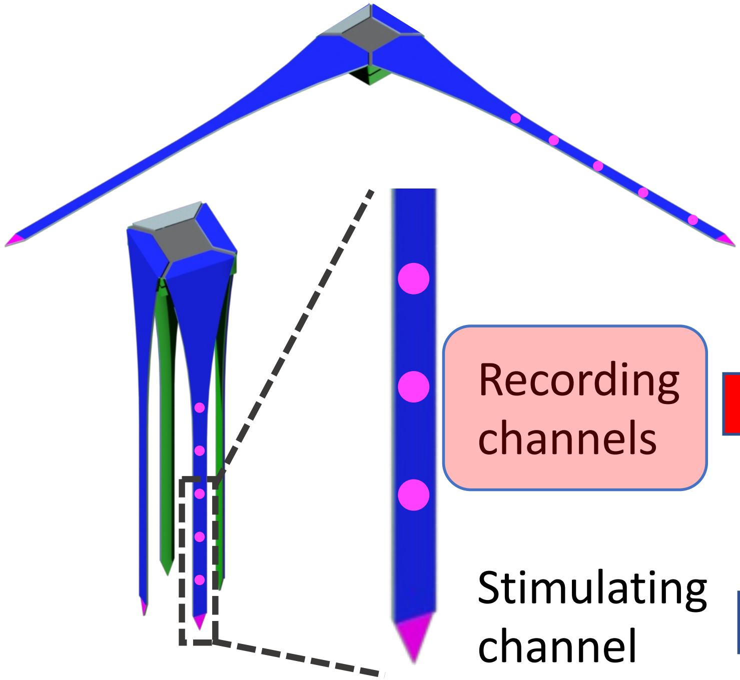
Analog Circuits for:

- Electrical Recording
- Chemical Recording

- Electrical Stimulation

Cortex BioChip to restore the vision in Blind Patients

# BioChip for Intracortical Stimulation




Barbruni et al., *PCT/IB2022/059944*, 2022

Analog Circuits for:

- Electrical Recording
- Chemical Recording

**Next week !**

- Electrical Stimulation

Cortex BioChip to restore the vision in Blind Patients