BENG 207 Special Topics in Bioengineering

Neuromorphic Integrated Bioelectronics

Week 6: Low-Noise Bioelectronics

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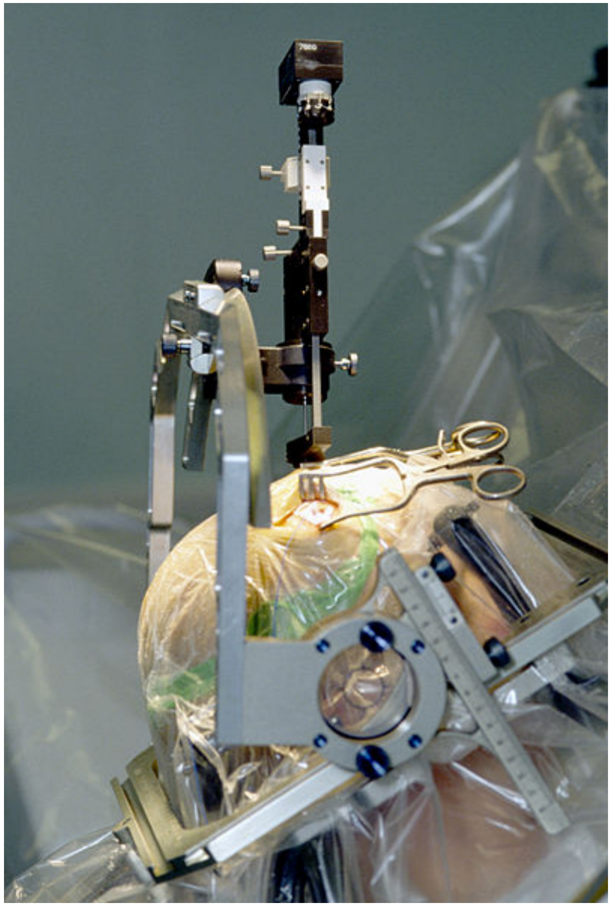
http://isn.ucsd.edu/courses/beng207

BENG 207 Neuromorphic Integrated Bioelectronics

Date	Topic
9/27, 9/29	Biophysical foundations of natural intelligence in neural systems. Subthreshold MOS silicon models of membrane excitability. Silicon neurons. Hodgkin-Huxley and integrate-and-fire models of spiking neuronal dynamics. Action potentials as address events.
10/4, 10/6	Silicon retina. Low-noise, high-dynamic range photoreceptors. Focal-plane array signal processing. Spatial and temporal contrast sensitivity and adaptation. Dynamic vision sensors.
10/11, 10/13	Silicon cochlea. Low-noise acoustic sensing and automatic gain control. Continuous wavelet filter banks. Interaural time difference and level difference auditory localization. Blind source separation and independent component analysis.
10/18, 10/20	Silicon cortex. Neural and synaptic compute-in-memory arrays. Address-event decoders and arbiters, and integrate-and-fire array transceivers. Hierarchical address-event routing for locally dense, globally sparse long-range connectivity across vast spatial scales.
10/28, 11/1	Review. Modular and scalable design for neuromorphic and bioelectronic integrated circuits and systems. Design for full testability and controllability.
11/1, 11/3	Midterm due 11/2. Low-noise, low-power design. Fundamental limits of noise-energy efficiency, and metrics of performance. Biopotential and electrochemical recording and stimulation, lab-on-a-chip electrophysiology, and neural interface systems-on-chip.
11/8, 11/10	Learning and adaptation to compensate for external and internal variability over extended time scales. Background blind calibration of device mismatch. Correlated double sampling and chopping for offset drift and low-frequency noise cancellation.
11/15, 11/17	Energy conservation. Resonant inductive power delivery and data telemetry. Ultra-high efficiency neuromorphic computing. Resonant adiabatic energy-recovery charge-conserving synapse arrays.
11/22, 11/24	Guest lectures
11/29, 12/1	Project final presentations. All are welcome!

Deep Brain Stimulation (DBS)
for Parkinson's Disease Remediation

- Intrusive intervention
  - *"Brain's pacemaker"*
  - *Electrode is implanted in the deep brain's thalamus*
  - *Periodic (130-185Hz) activation of electrical impulses delivered by the electrode to suppress Parkinson-induced tremor*
- Highly invasive procedure
  - *Surgical insertion of electrode and stimulation electronics*
  - *Battery needs to be replaced*
- Open-loop
  - *Adaptation (e.g. Medtronic Activa PC+S) limited to user-mediated control of stimulation amplitude*



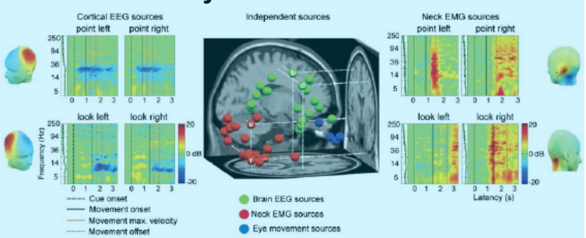
Surgery to insert electrode deep in the brain. Parkinson's patient remains awake during surgery.
http://en.wikipedia.org/wiki/Deep_brain_stimulation

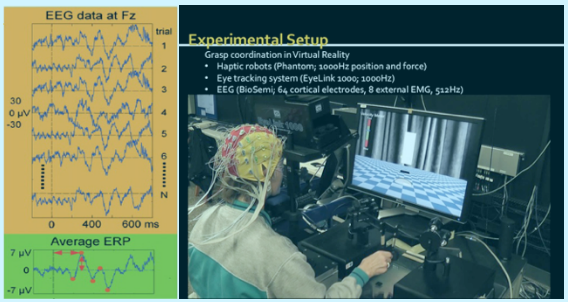
Distributed Brain Dynamics of Human Motor Control

G. Cauwenberghs, K. Kreutz-Delgado, T.P. Jung, S. Makeig, H. Poizner, T. Sejnowski,
M. Arnold, F. Broccard, Y.M. Chi, J. Iversen, C. Maier, E. Neftci, D. Peterson,
A. Akinin, S. Das, N. Govil, S. Hsu, T. Mullen, A. Ojeda, C. Stevenson

NSF EFRI-1137279: Mind, Machines and Motor Control (M3C)

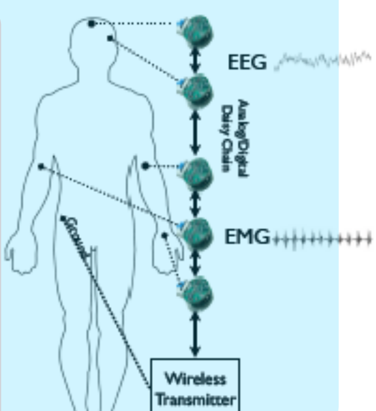
EEG brain dynamics and Parkinson's

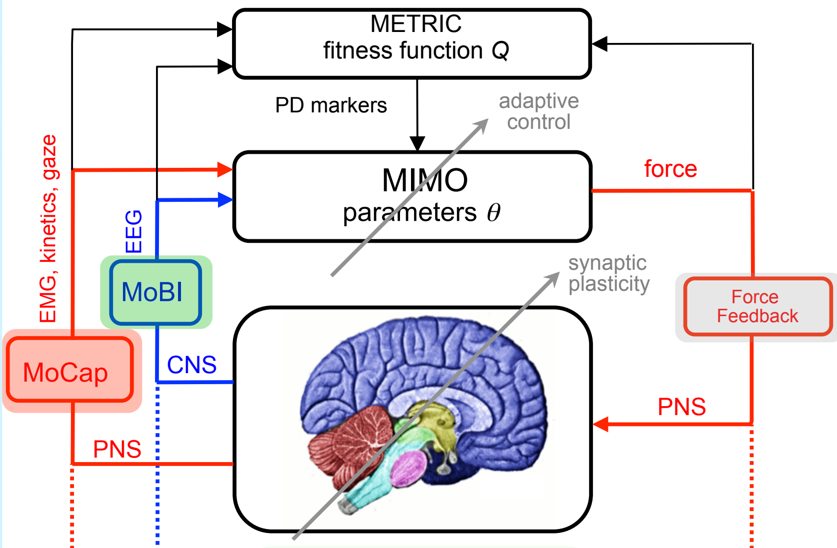




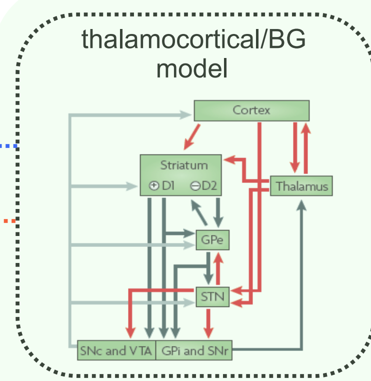
MoCap

MoBI



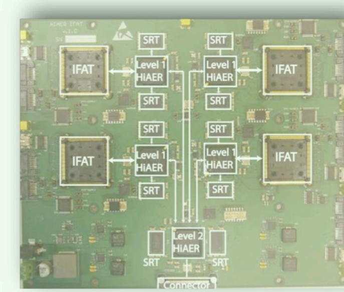


Force feedback

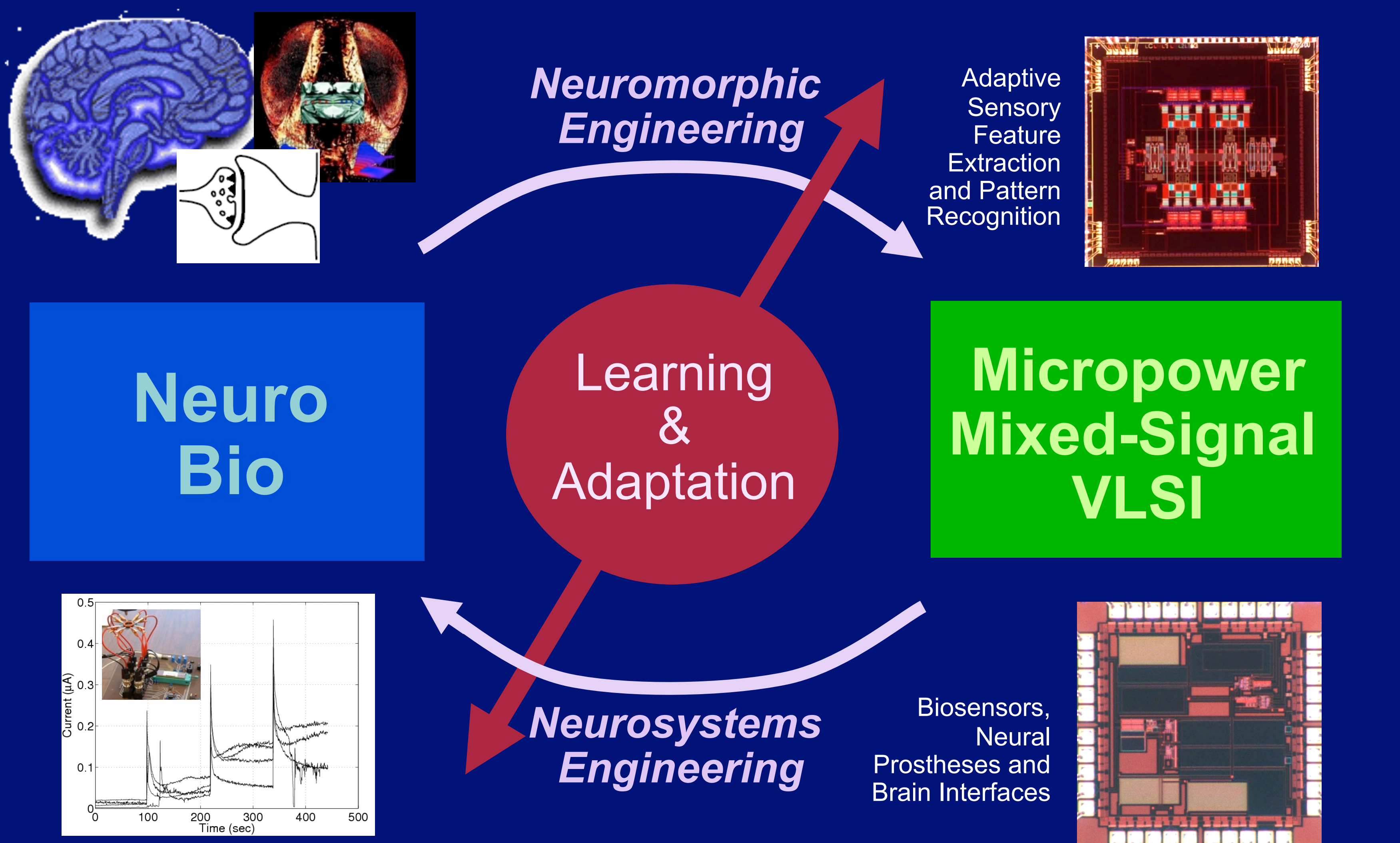


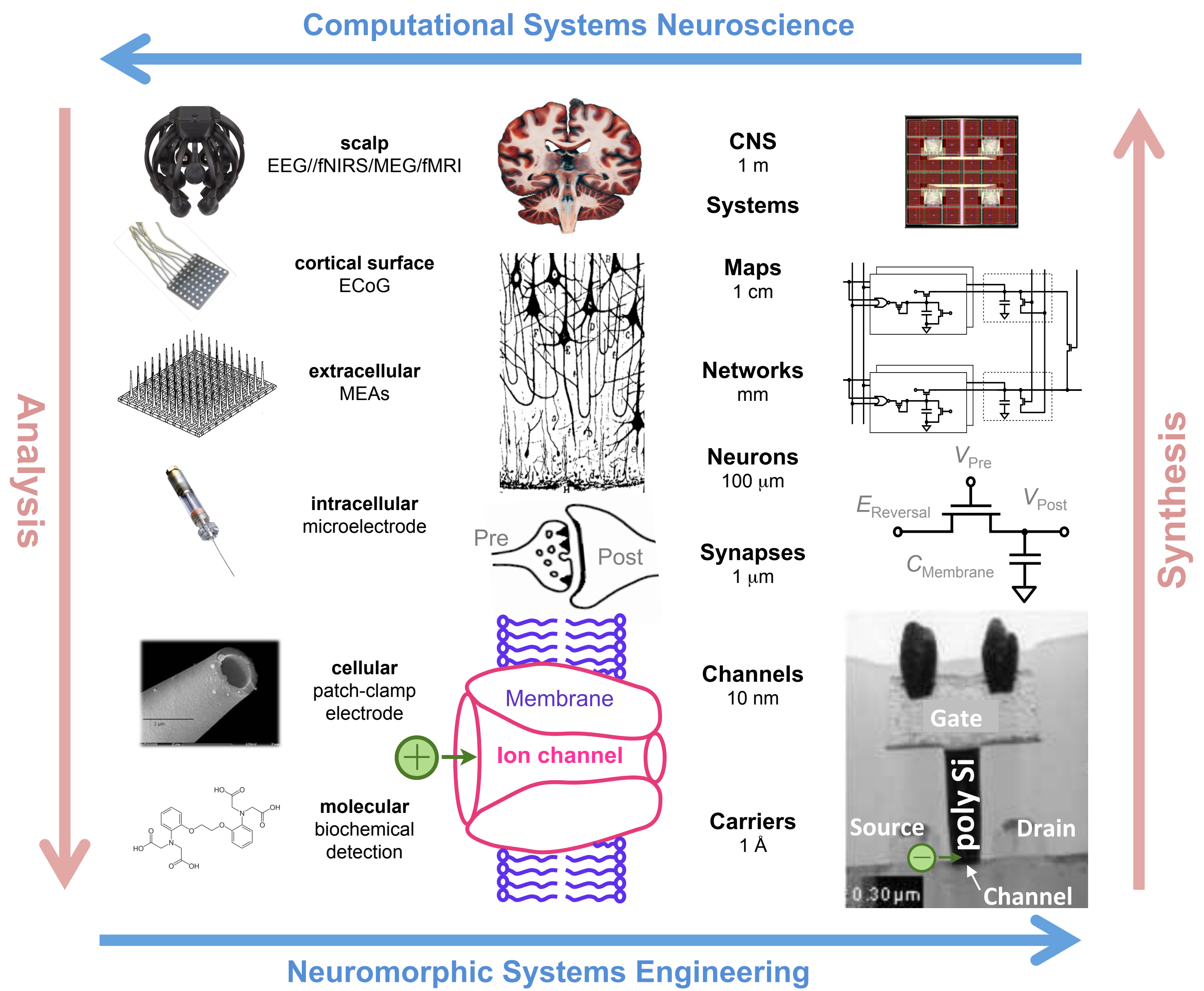
Computational modeling

Neuromorphic emulation of brain dynamics in motor control



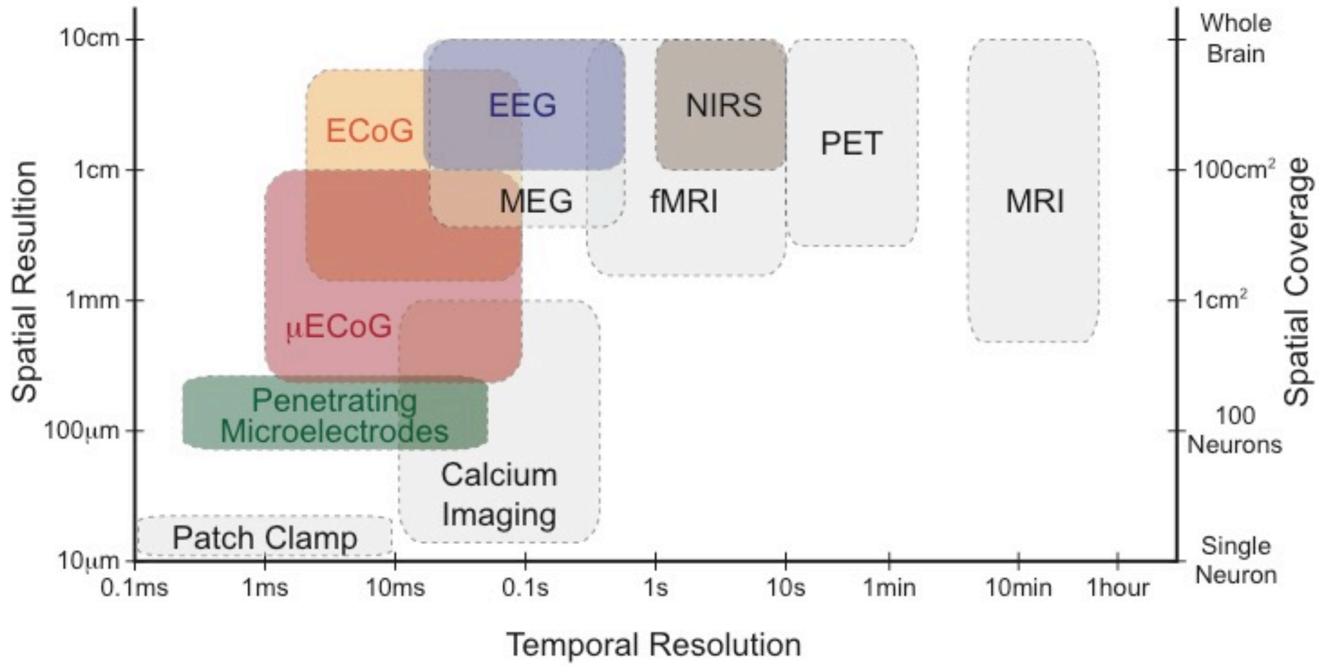
Closing the Loop: Interactive Neural/Artificial Intelligence

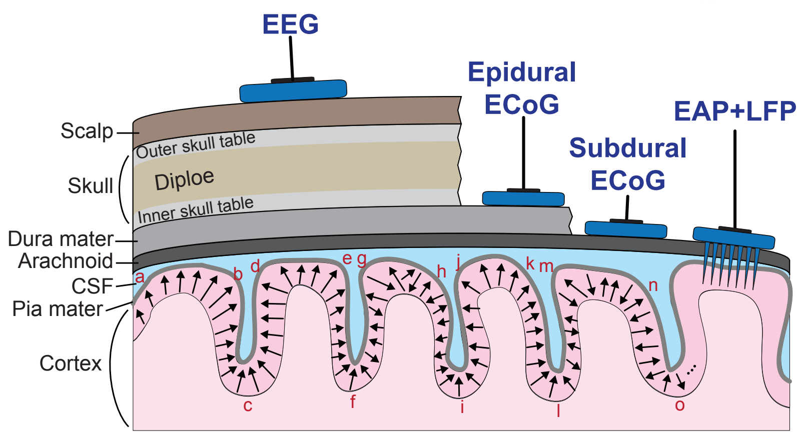


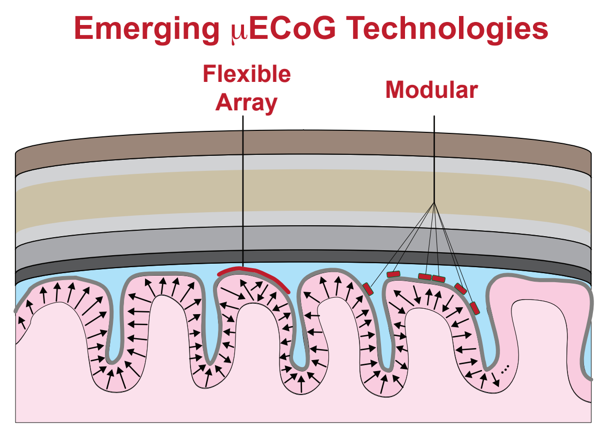


F. Broccard, S. Joshi, J. Wang and G Cauwenberghs, "Neuromorphic neural interfaces: from neurophysiological inspiration to biohybrid coupling with nervous systems," *JNE*, 2017

Minimally Invasive Neurotechnologies

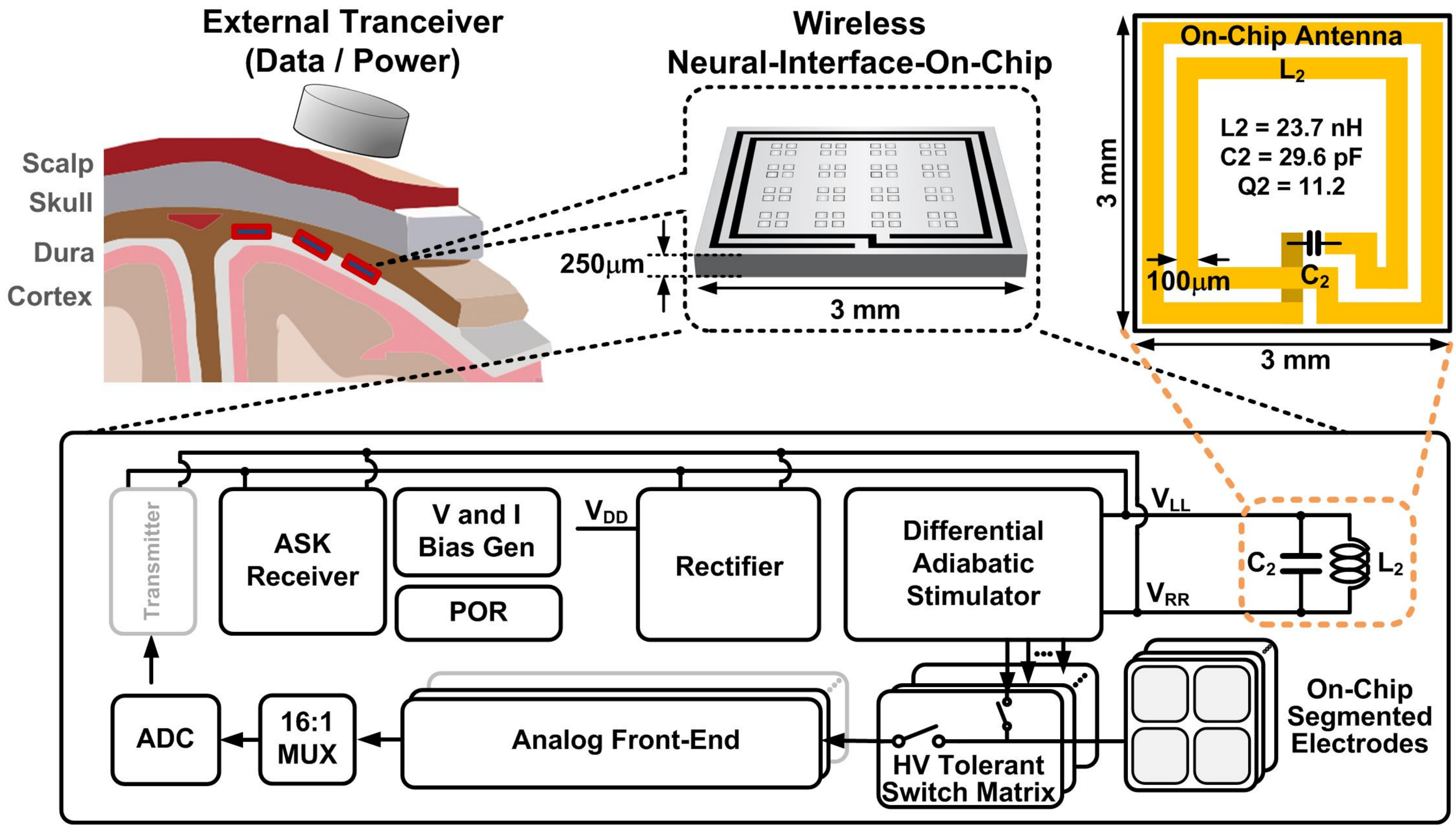






S. Ha, C. Kim, A. Akinin, J. Park, H. Wang, C. Maier, P. Mercier and G. Cauwenberghs, "Silicon Integrated High-Density Electrocortical Interfaces," *Proceedings of the IEEE*, vol.105 (1), pp. 11-33, 2017.

ENIAC:
Encapsulated Neural Interfacing and Acquisition Chip



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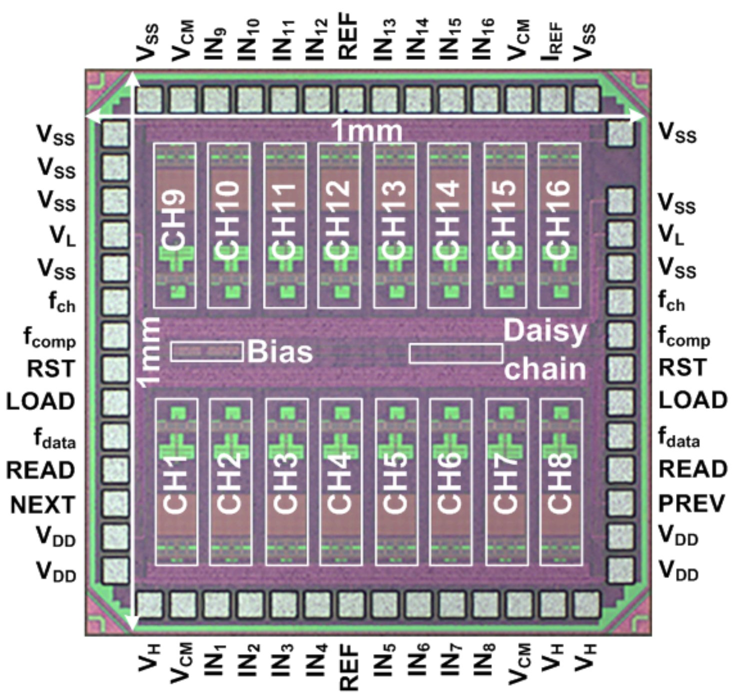
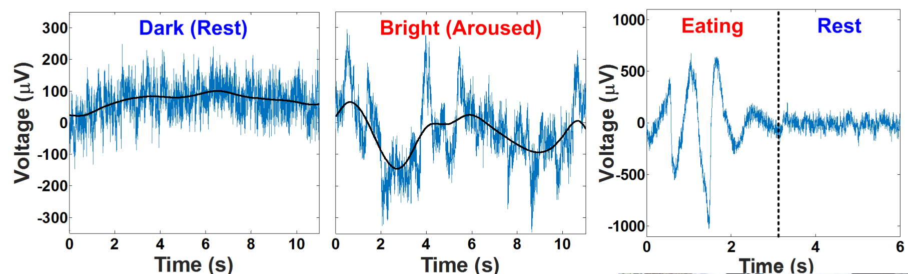
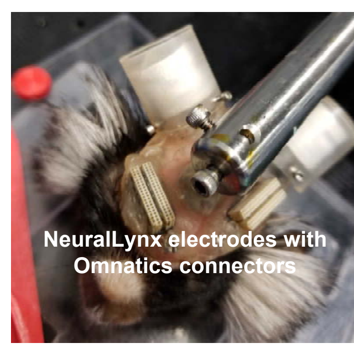
Highly Sensitive, Low-Noise Low-Power Integrated Biopotential Sensing and Acquisition

Kim, Joshi, Courellis, Wang, Miller, and Cauwenberghs, 2018

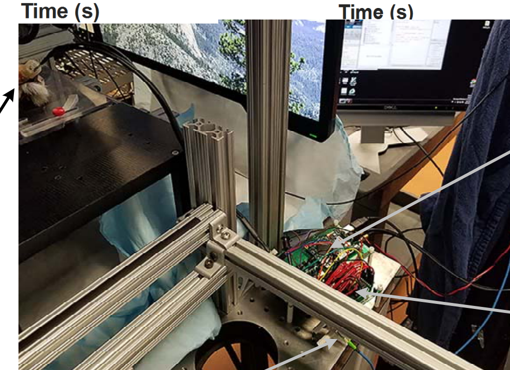
- First biopotential integrated ADC to deliver greater than **90dB dynamic range**, lower than **1μVrms input-referred noise**, and faster than **1ms settling to 200mVpp input transients**, at less than **1μW power** per channel, with 16 recording channels integrated within **1 sq. mm in 65nm CMOS**:







Marmoset
(Callithrix jacchus)



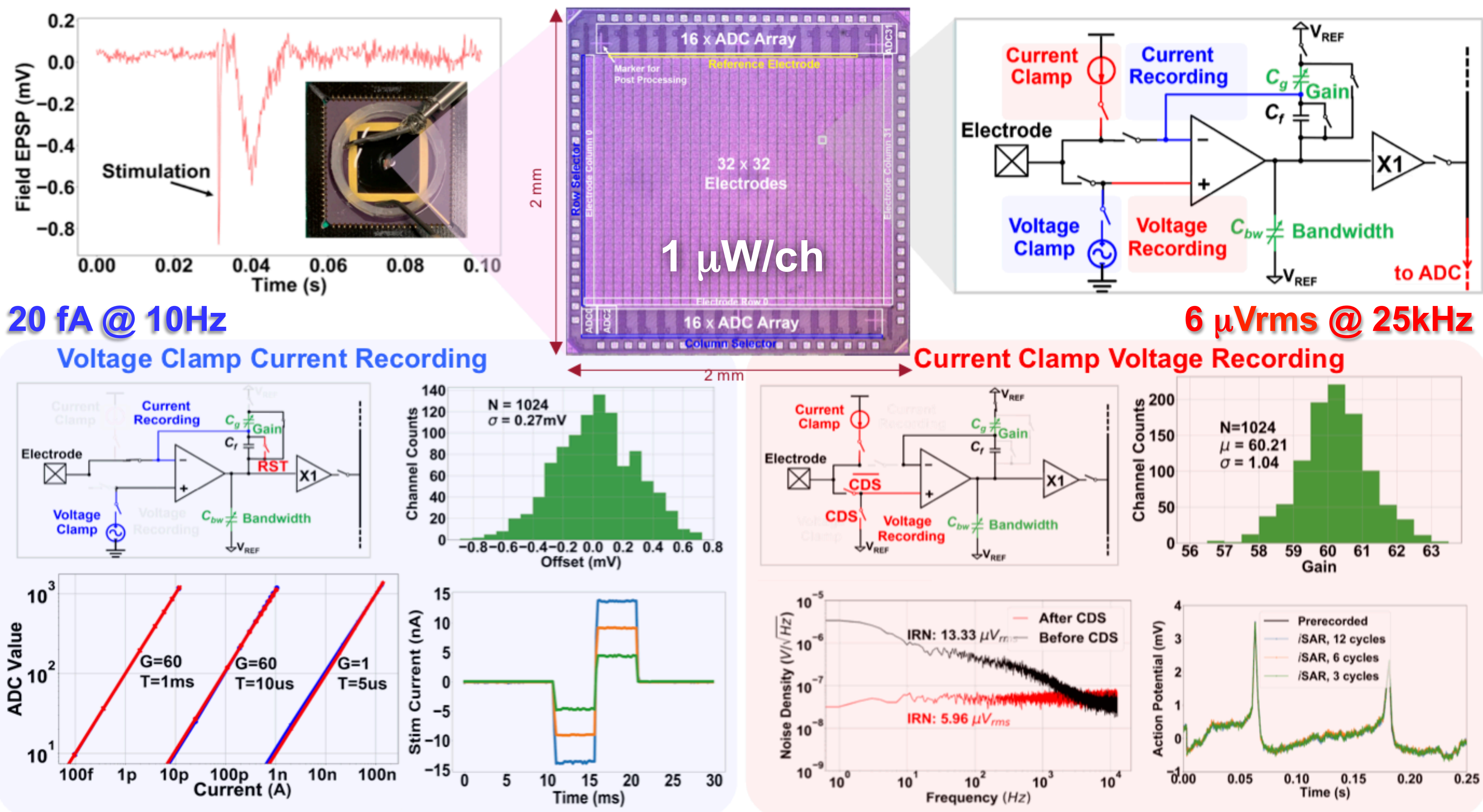
Opal Kelly (XEM6010)

DUT (this work)

Commercial Benchmark
(Intan RHD 2000 systems)

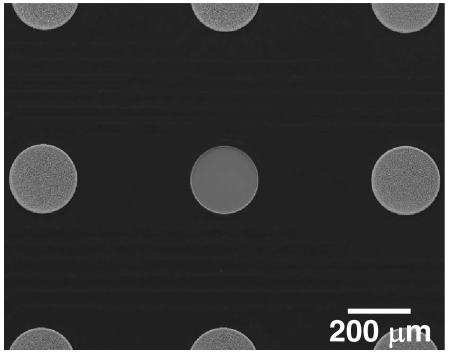
Kim, Joshi, Courellis, Wang, Miller, and Cauwenberghs, "A 92dB Dynamic Range sub-μV rms-noise 0.8 μW/ch Neural-Recording ADC Array with Predictive Digital Autoranging," IEEE ISSCC 2018.

Electrophysiology Lab-on-a-Chip

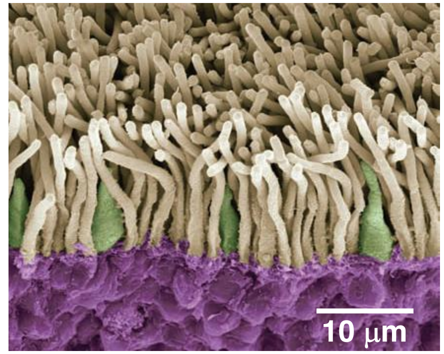


J. Wang, A. Paul, D. Zhang, J. Wu, Y. Xu, Y. Zou, C. Kim, and G. Cauwenberghs, "1024-Electrode Hybrid Voltage/Current-Clamp Neural Interface System-on-Chip with Dynamic Incremental-SAR Acquisition," *2020 IEEE Symposium on VLSI Circuits (VLSI-Circuits)*, Honolulu HI, June 14-19, 2020.

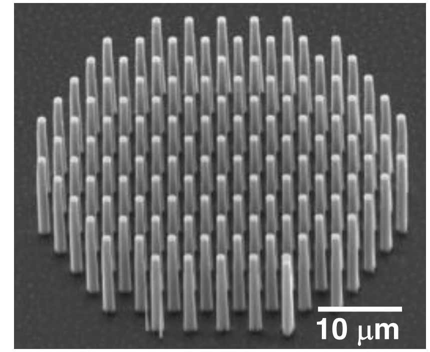
Nanoengineered Retinal Prosthesis



Argus II Electrodes
(Conventional retinal prosthesis)

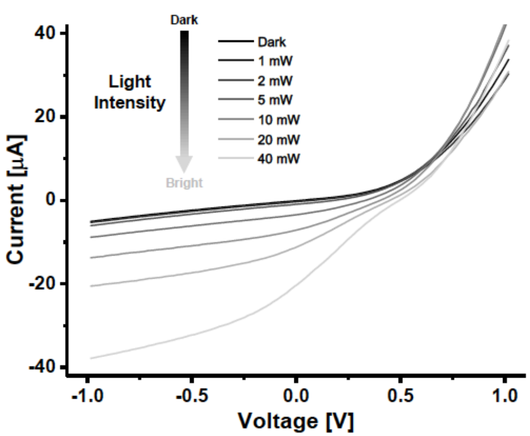


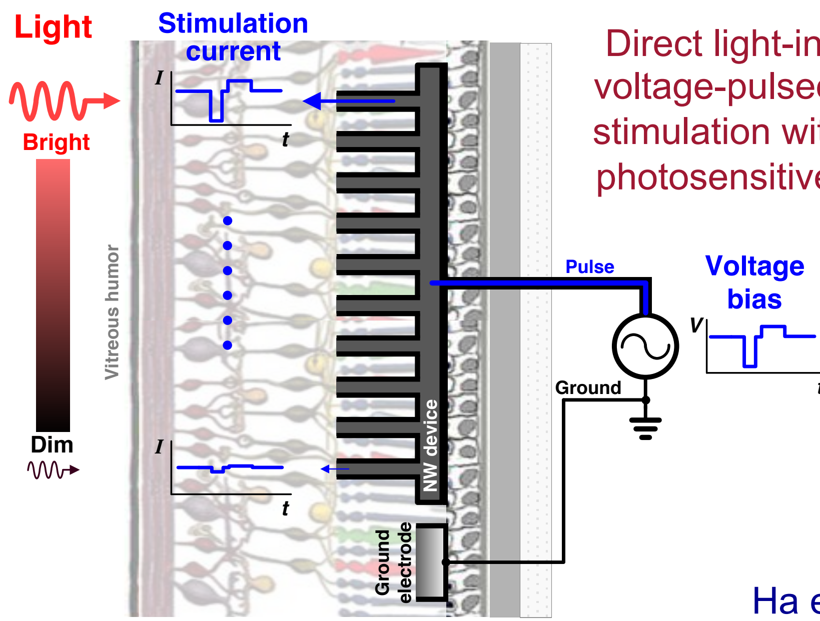
Human Retina
(rods and cones)



UCSD/Nanovision
Nanowire Array

Visual Acuity 20/20: 5 μm resolution

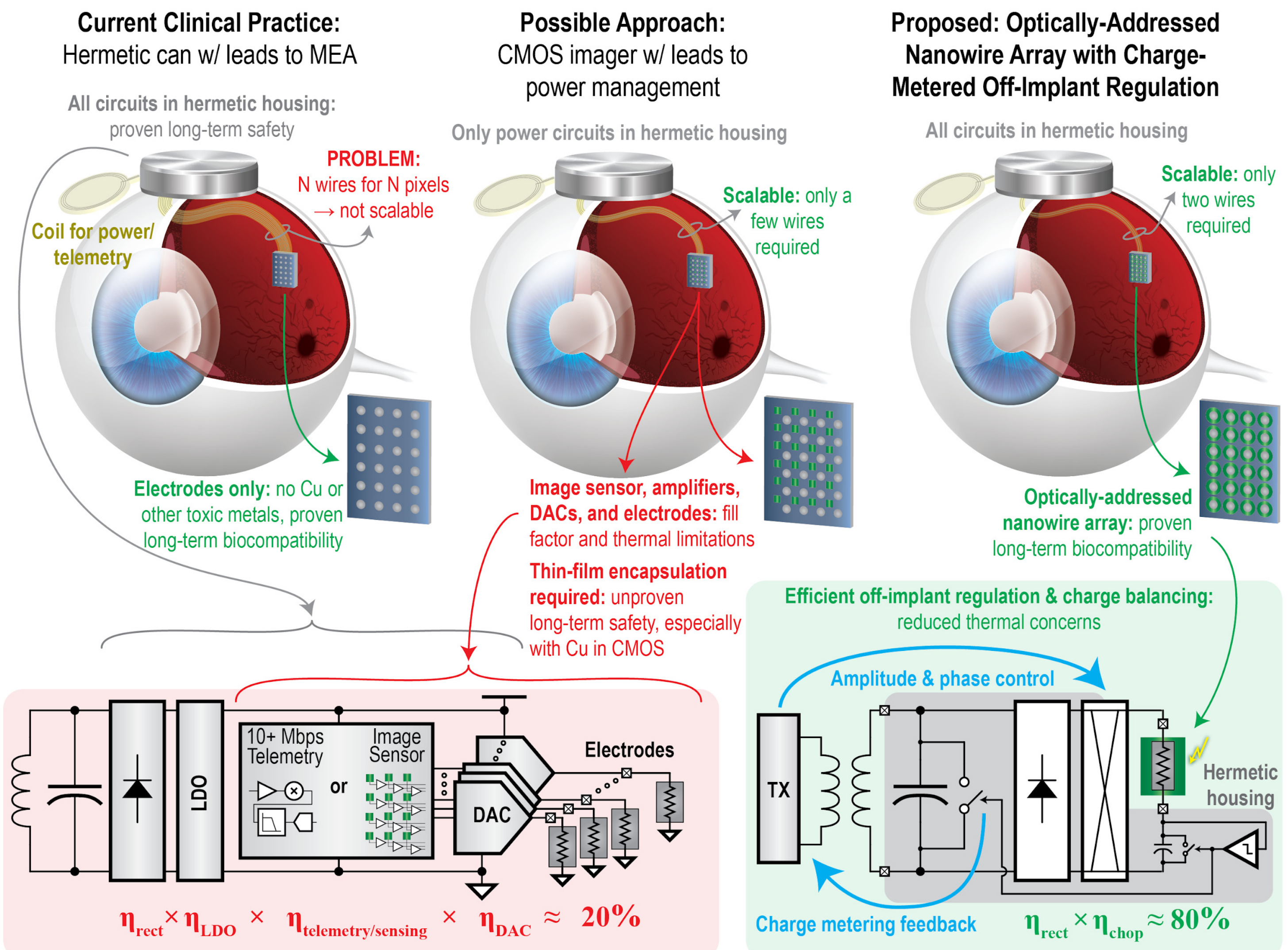




Direct light-induced and voltage-pulsed subretinal stimulation with nanowire photosensitive electrodes

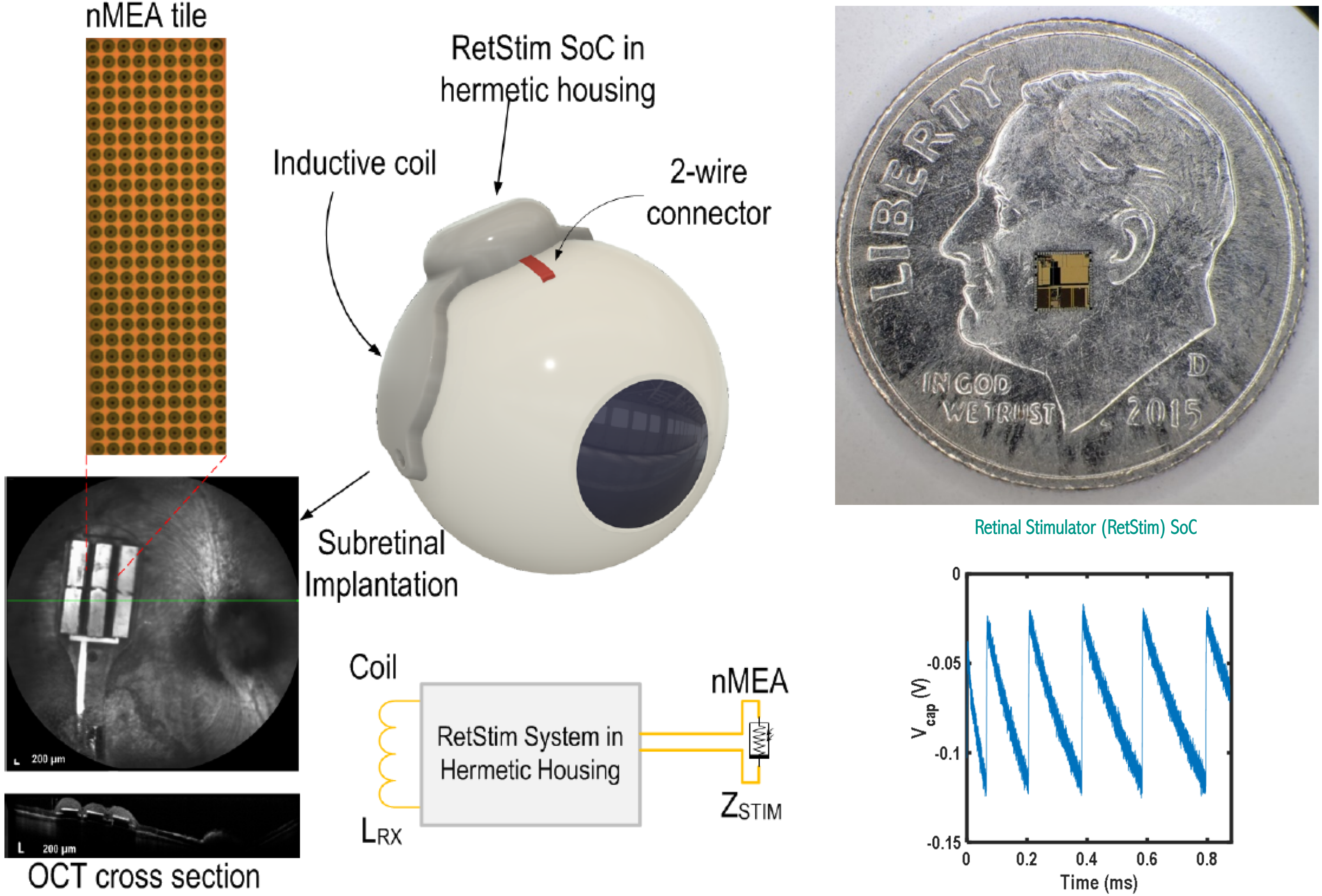
Ha et. al., *JNE*, **13**(5), 2016

Optically-Addressed Nanowire-Based Retinal Prosthesis



Akinin et al, "An Optically-Addressed Nanowire-Based Retinal Prosthesis with 73% RF-to-Stimulation Power Efficiency and 20nC-to-3μC Wireless Charge Telemetering," IEEE Int. Solid-State Circuits Conf. (ISSCC), 2021.

Energy-Efficient RF Powered Charge-Balanced Stimulation



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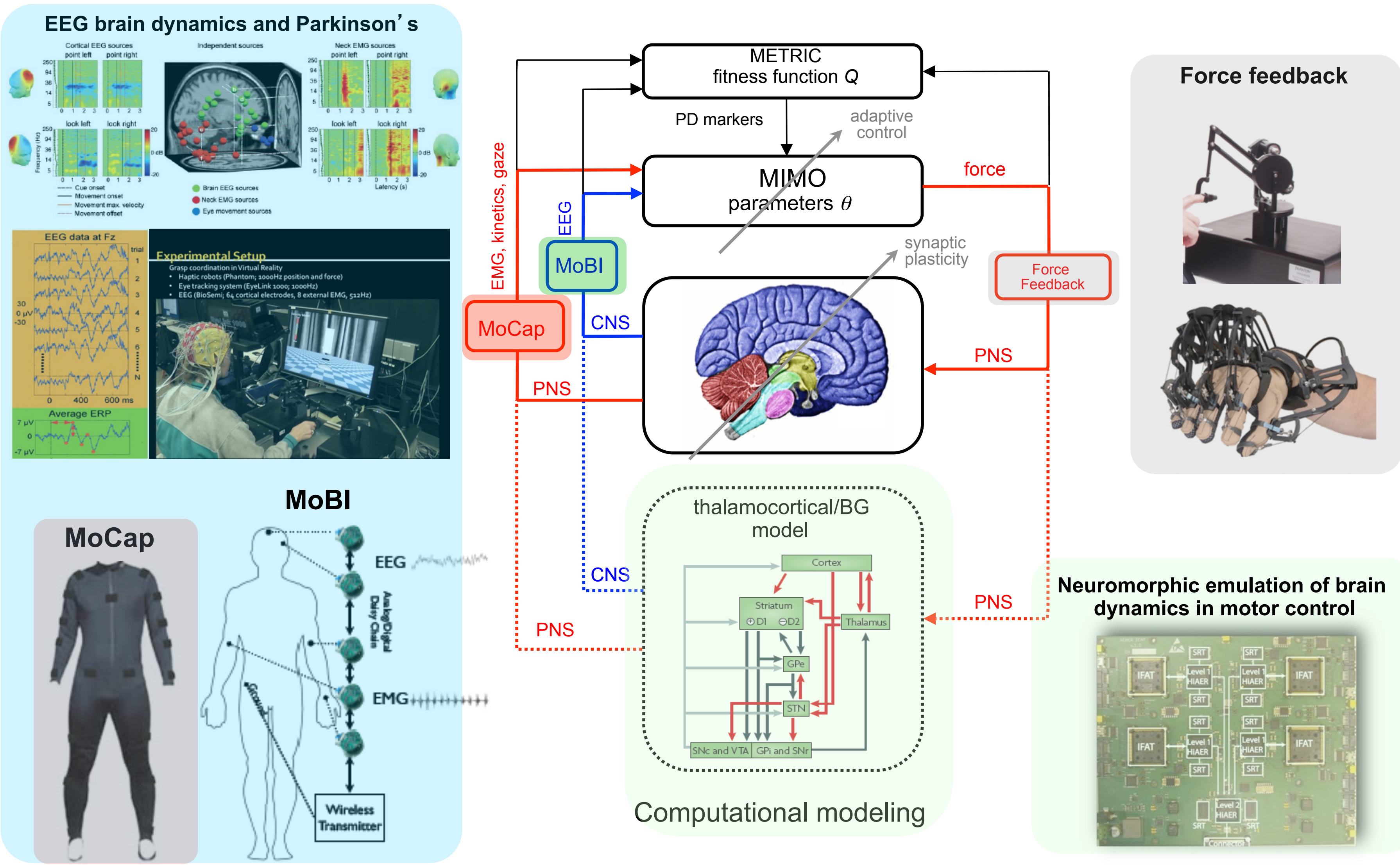
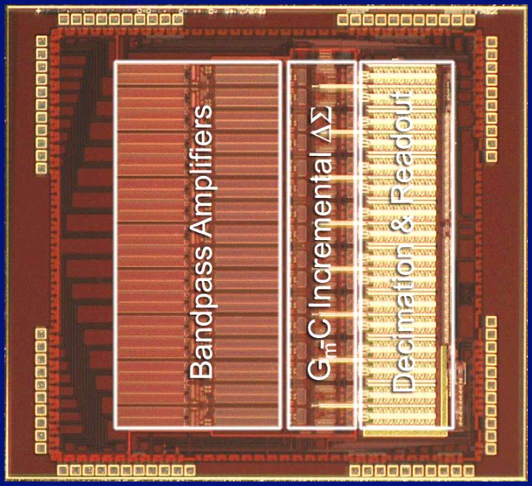
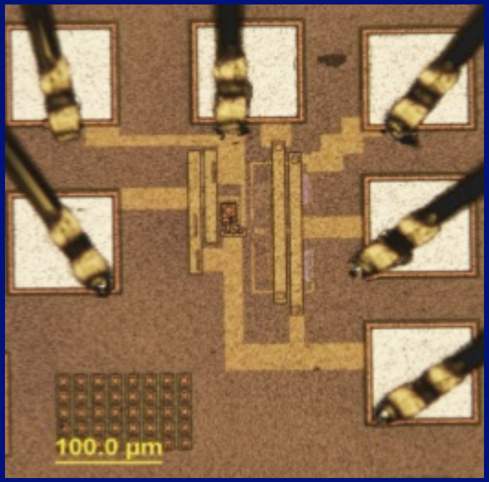


Noise-Energy Efficiency





Digitization

Wireless Telemetry

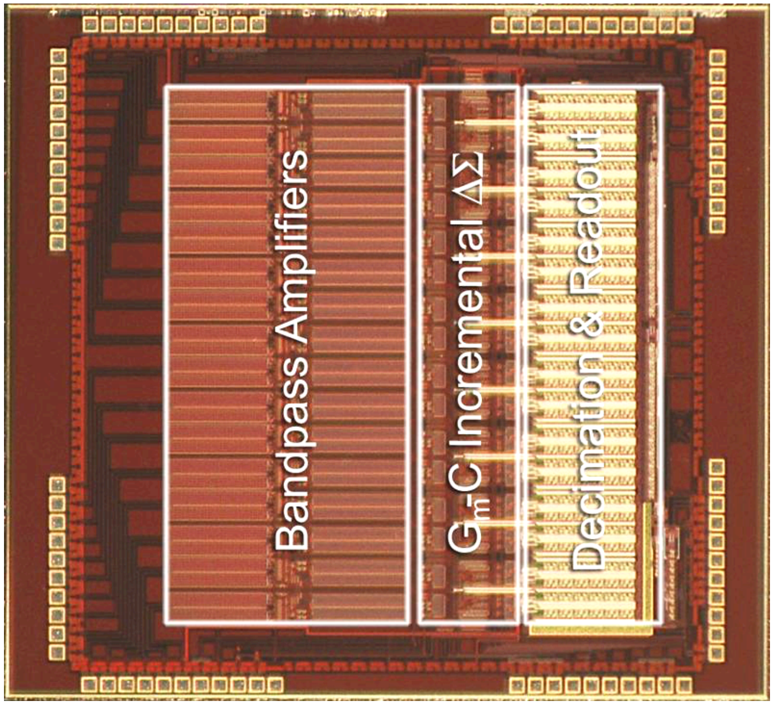
Energy and noise efficiency metrics

Energy and Noise Efficiency Metrics

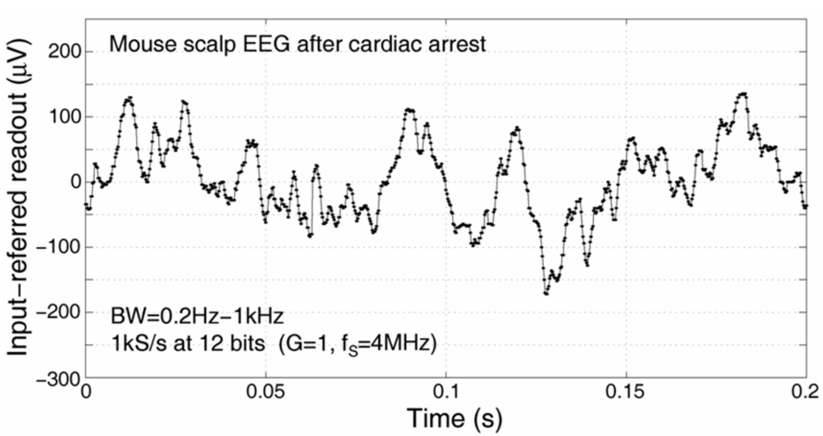
- **Noise Efficiency Factor (NEF):**
  - Relative measure of energy cost of a biopotential amplifier, relative to that of an ideal amplifier with same input referred noise power
  - Thermal noise fundamental limit: NEF = 1
  - Practical limit for CMRR > 80 dB: NEF > 2 (2.3 demonstrated)
- **Energy per Conversion Level Figure of Merit (FoM):**
  - Energy cost of an analog-to-digital converter, per conversion, and divided by the number of quantization levels
  - State of the art: FoM = ~ 10 fJ at 10b and 100ksps
- **Range Efficiency:**
  - Energy per bit, per squared meter of wireless transmission
  - Depends on target BER and power at the receiver
  - State of the art: ~ 10 fJ/m^2

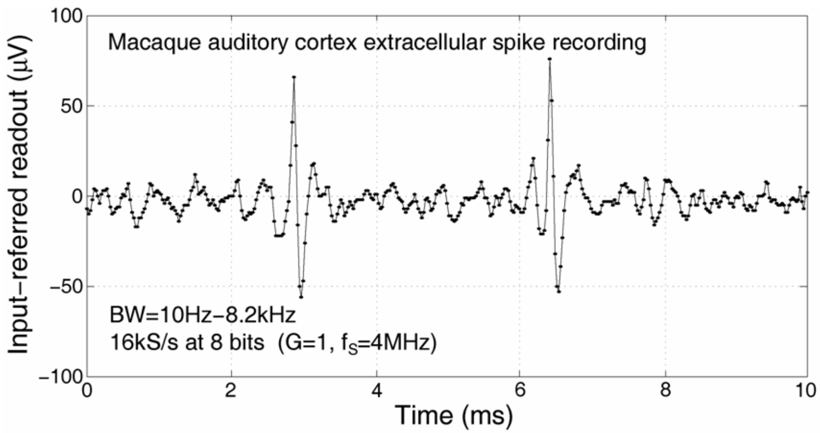
EEG/ECoG/EMG Amplification, Filtering and Quantization

Mollazadeh, Murari, Cauwenberghs and Thakor (2009)



- Low noise
  - *21nV/√Hz input-referred noise*
  - *2.0μVrms over 0.2Hz-8.2kHz*
- Low power
  - *100μW per channel at 3.3V*
- Reconfigurable
  - *0.2-94Hz highpass, analog adjustable*
  - *140Hz-8.2kHz lowpass, analog adjustable*
  - *34dB-94dB gain, digitally selectable*
- High density
  - *16 channels*
  - *3.3mm X 3.3mm in 0.5μm 2P3M CMOS*
  - *0.33 sq. mm per channel*





Implantable Wireless Telemetry and Energy Harvesting

- **Transcutaneous wires limit the application of implantable sensing/actuation technology to neural prostheses**
  - Risk of infection
    - *Opening through the skin reduces the body's natural defense against invading microorganisms*
  - Limited mobility
    - *Tethered to power source and data logging instrumentation*

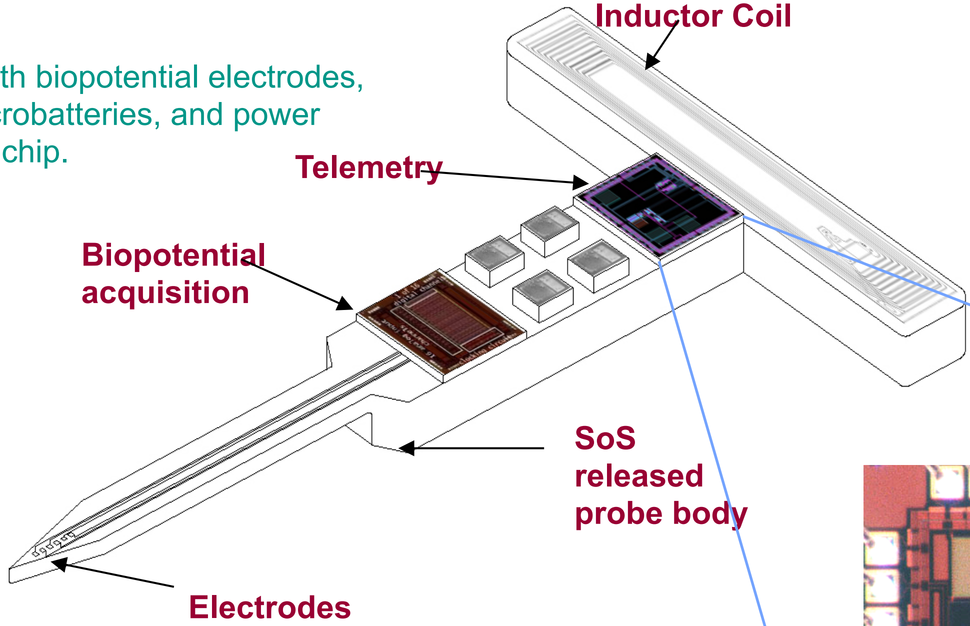
- **Wireless technology is widely available, however:**
  - Frequency range of radio transmission is limited by the body's absorption spectra and safety considerations
    - *Magnetic (inductive) coupling at low frequency, ~1-4 MHz*
    - *Very low transmitted power requires efficient low-power design*

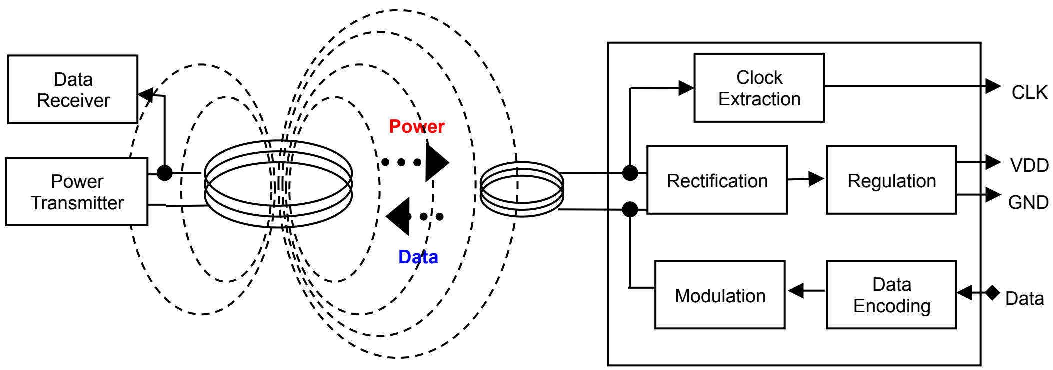
Sauer, Stanacevic, Cauwenberghs, and Thakor, 2005

Sensor Interface Conditioning Telemetry

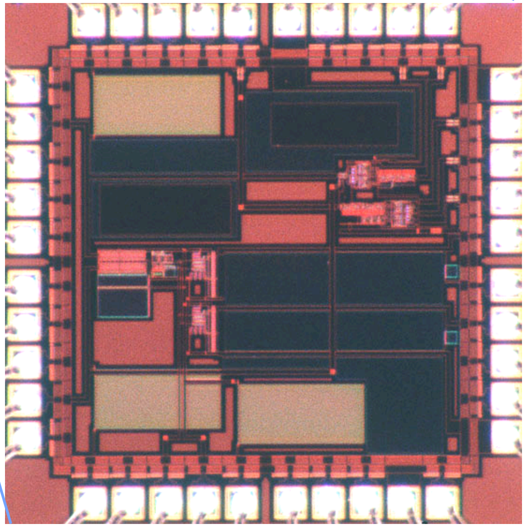
Sauer, Stanacevic, Cauwenberghs, and Thakor (2005)

Implantable probe with biopotential electrodes, VLSI acquisition, microbatteries, and power harvesting telemetry chip.



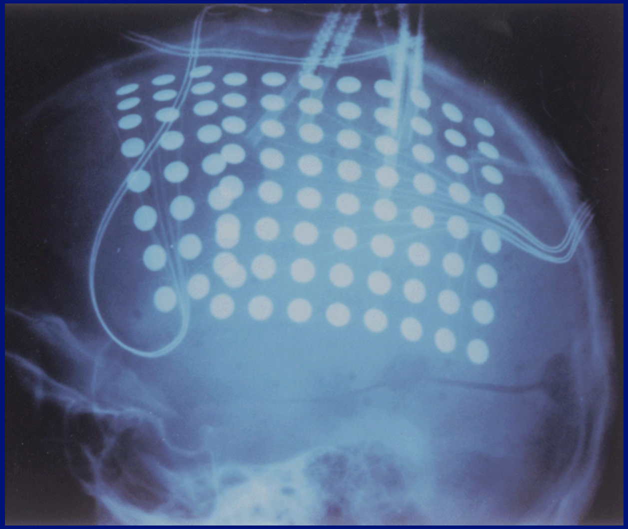


Power delivery and data transmission over the same inductive link



Telemetry chip (1.5mm X 1.5mm)

Non-Invasive and Minimally Invasive Biopotential Recording



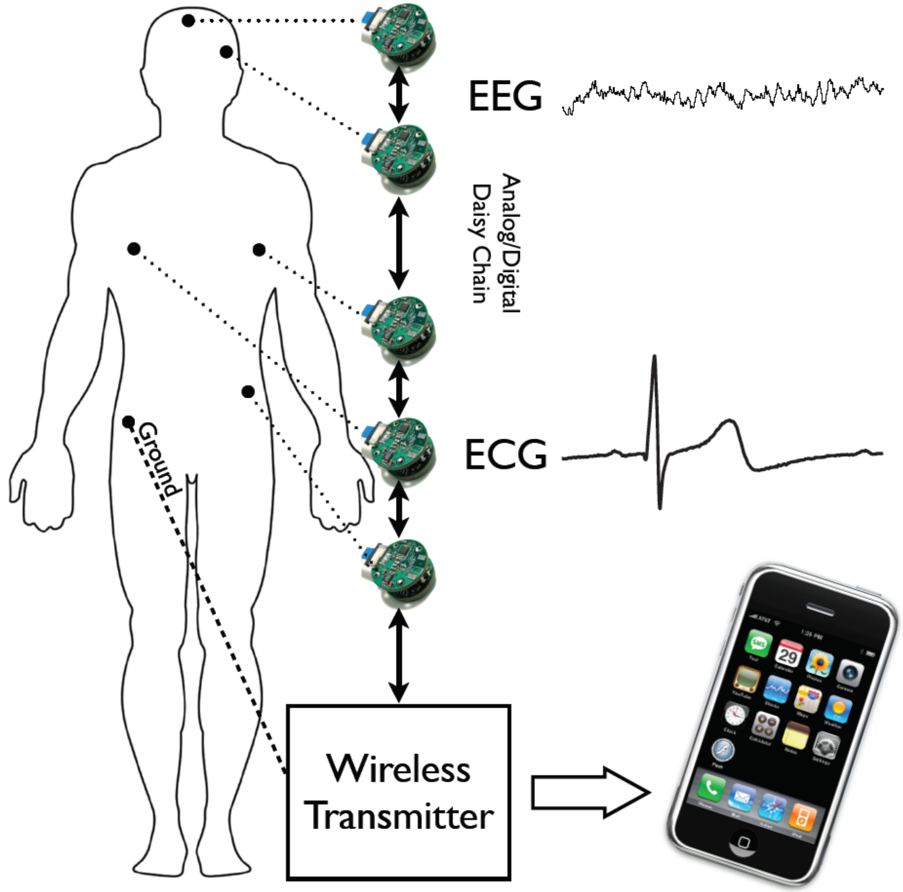
Electrodes

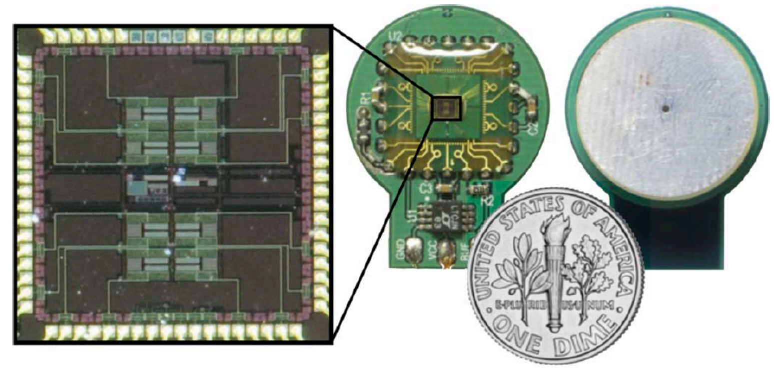
Amplifiers

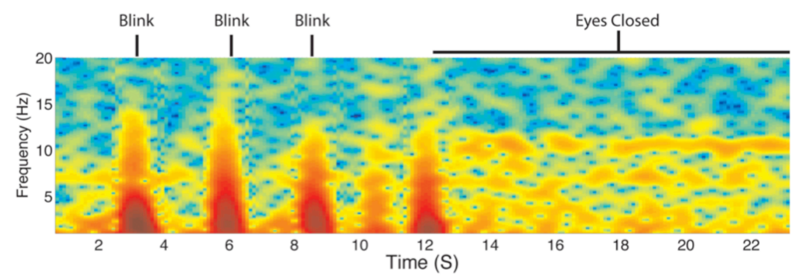
Signal Conditioning

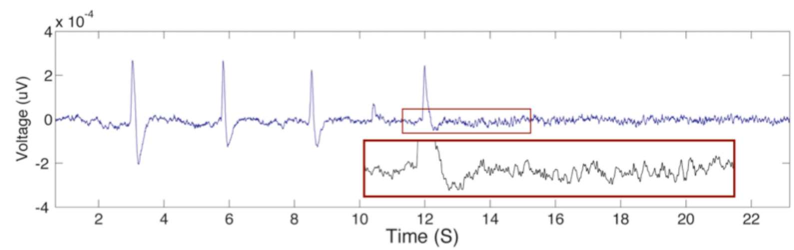
Wireless Non-Contact Biopotential Sensors

Chi et al, 2010-









EEG alpha and eye blink activity recorded on the occipital lobe over haired skull

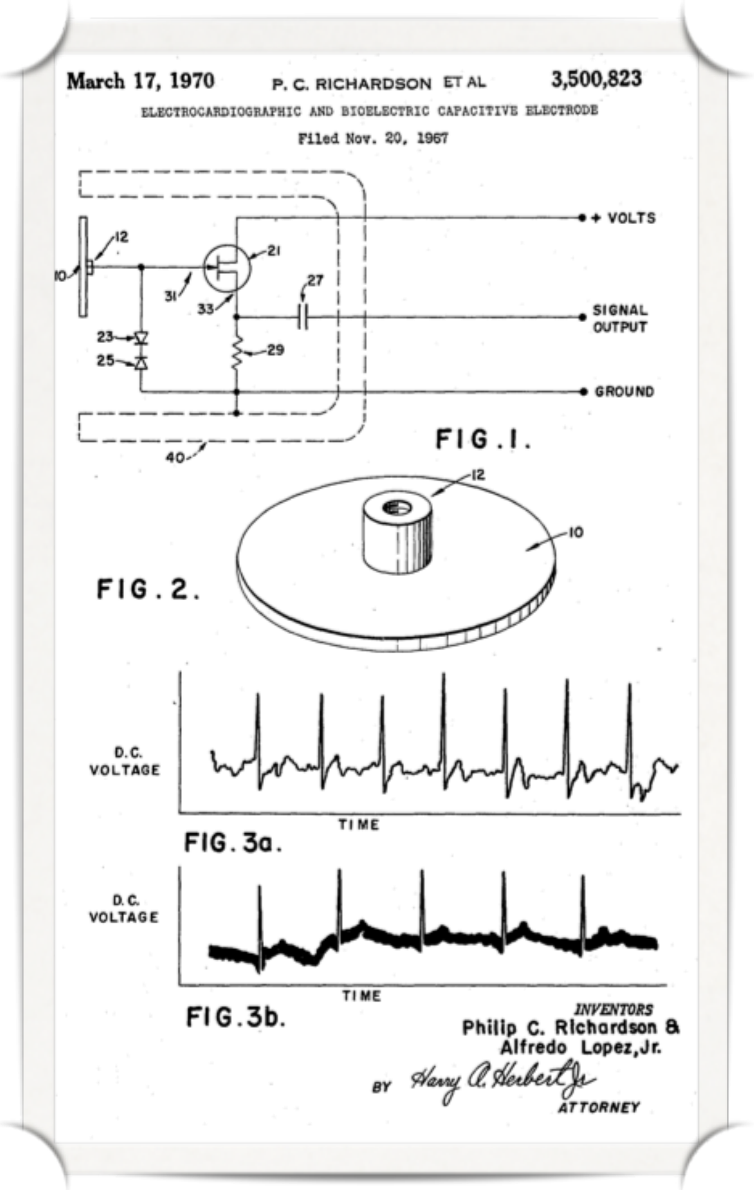
Chi, Maier, Cauwenberghs, "Ultra-high input impedance, low noise integrated amplifier for noncontact biopotential sensing," IEEE JETCAS 1(4), 526-535, 2011.

Joshi, Kim and Cauwenberghs, "A 6.5-μW/MHz Charge Buffer With 7-fF Input Capacitance in 65-nm CMOS for Noncontact Electropotential Sensing," IEEE TCAS-II, 63(12), 1161-1165, 2016.

Chi, Wang, Wang, Maier, Jung, and Cauwenberghs, "Dry and Noncontact EEG Sensors for Mobile Brain-Computer Interfaces," IEEE TNSRE 20(2), 228-235, 2012.

Capacitive Non-Contact Electrodes

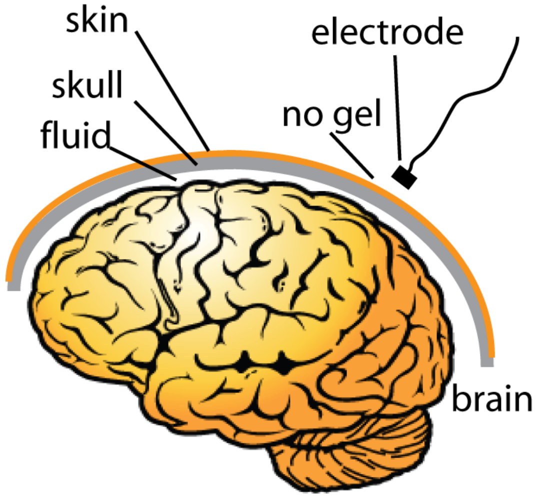
- **Senses biopotential signals without contact**
  - Capacitive signal coupling
  - No electro-gel
  - Through clothing and hair
- **Basic idea is well-known**
  - First patent in 1968 (Richardson)
  - Several groups (Prance) and one company (Quasar) have pursued this
- **Technology still problematic**
  - Noise, interference pickup, artifacts
  - Circuit complexity, materials, construction, cost
  - Nothing beyond 'lab prototype'

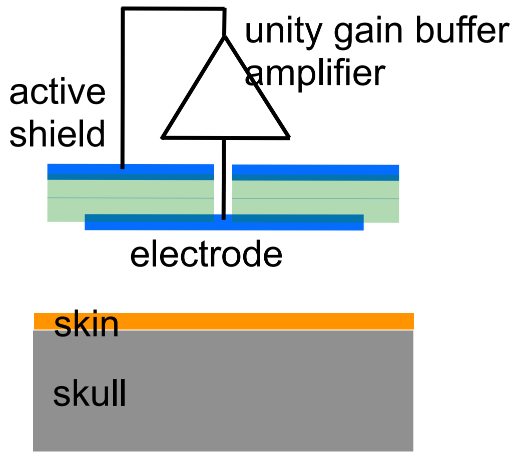


[1] C.J. Harland, T.D. Clark, and R.J. Prance. Electric potential probes - new directions in the remote sensing of the human body. Measurement Science and Technology, 2:163–169, February 2002.
[2] A. Lopez and P. C. Richardson. Capacitive electrocardiographic and bioelectric electrodes. IEEE Transactions on Biomedical Engineering, 16:299–300, 1969.
[3] P. Park, P.H. Chou, Y. Bai, R. Matthews, and A. Hibbs. An ultra- wearable, wireless, low power ECG monitoring system. Proc. IEEE International Conference on Complex Medical Engineering, pages 241–244, Nov 2006.

Challenges in Non-Contact Sensors

Capacitive coupling, rather than ohmic contact, between scalp/skin and electrode

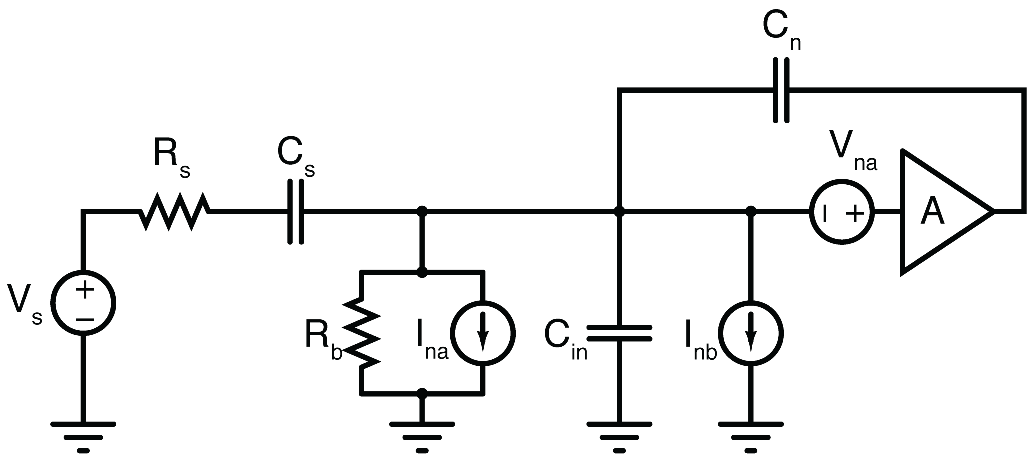


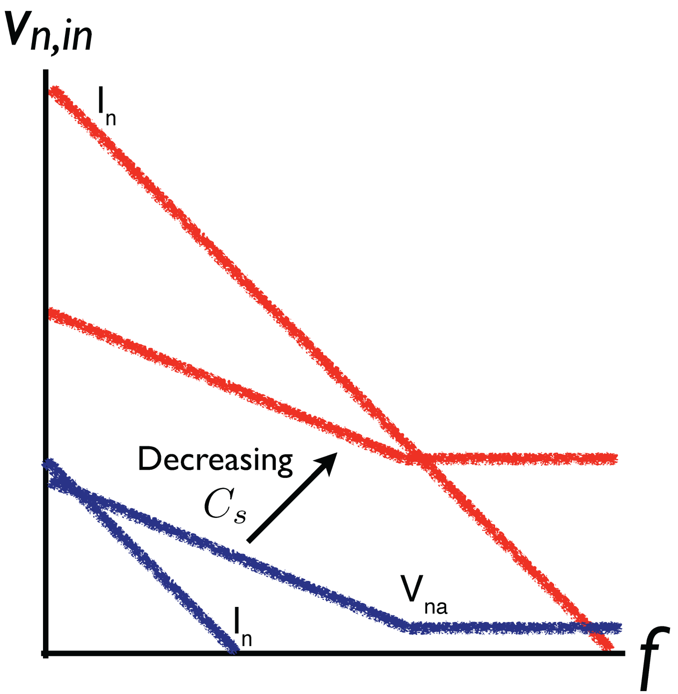


- **Amplifier parasitic input capacitance**
  - Reduces gain as electrode-skin distance changes
  - Severely degrades CMRR
  - Increases the effect of amplifier voltage noise
- **Integrates current noise at biopotential signal frequencies**
  - Amplifier input biasing
  - Large resistance required for adequate low frequency response adds further current noise

Non-Contact Sensor Noise

Generic Capacitive Sensor Noise Model:



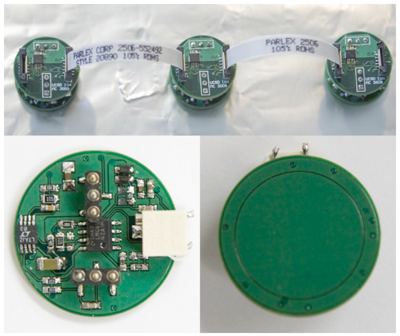


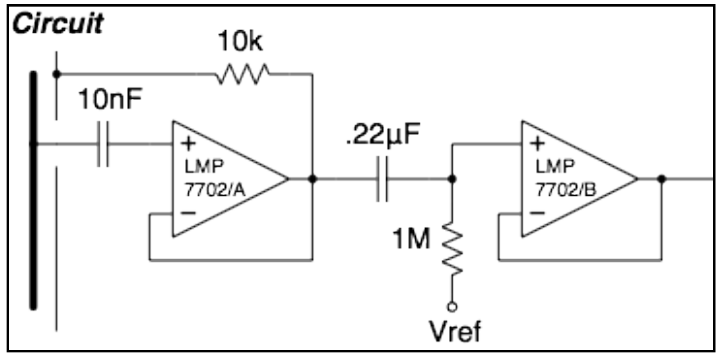
Input Referred Noise:

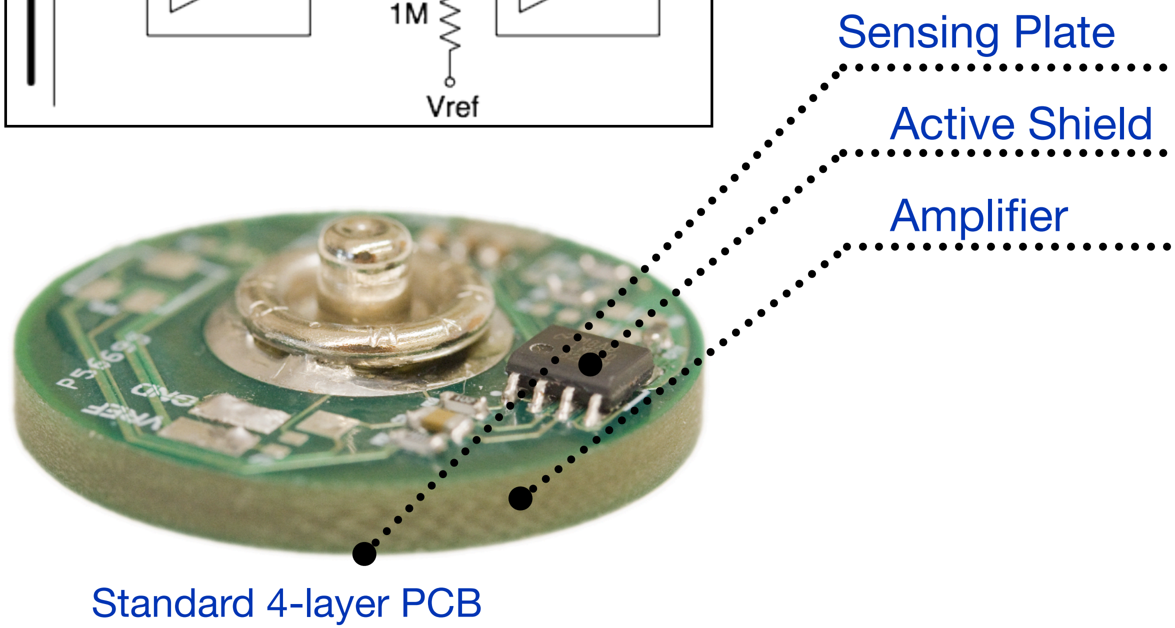
$$v_{n,in}^2 = v_{na}^2 (1 + \frac{C_{in} + C_n}{C_s})^2 + \frac{i_{na}^2 + i_{nb}^2}{\omega^2 C_s^2}$$

Non-Contact Sensor Design

- **Non-contact sensor fabricated on a printed circuit board substrate**







- **Advantages:**
  - Robust circuit
  - Inexpensive production
  - Safe, no sharp edges or fingers, can be made flexible
  - Very low power (<100μW/sensor)
  - Strong immunity to external noise

Chi and Cauwenberghs, 2010

Wearable Wireless EEG/ECG System

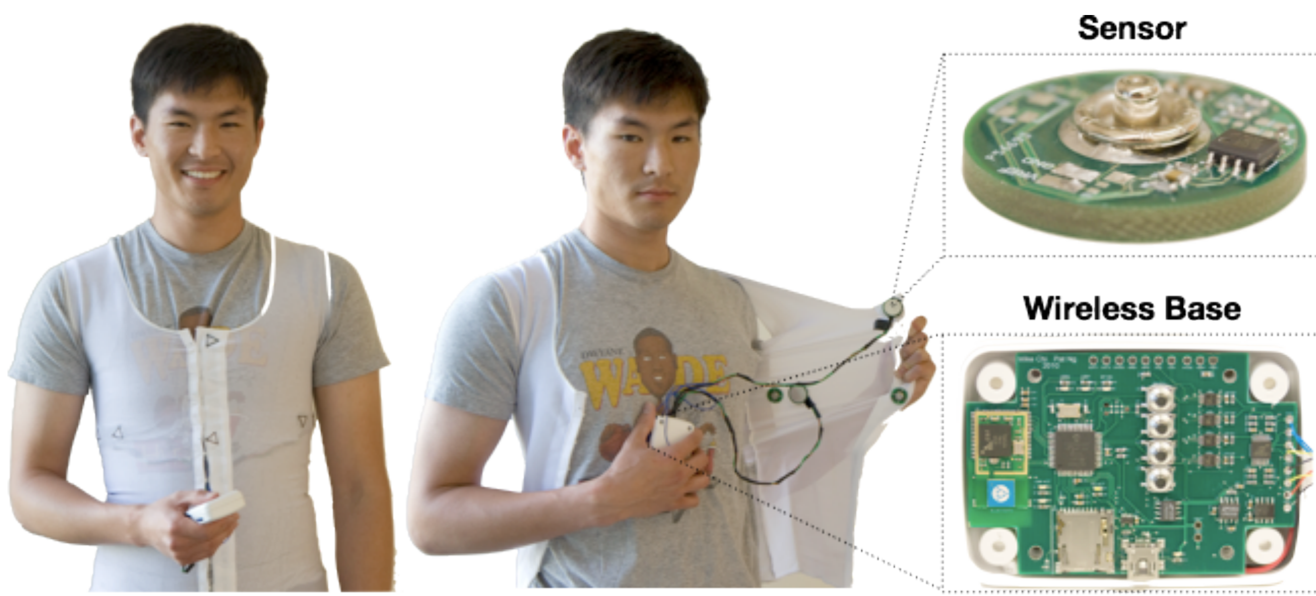
Y. M. Chi, E. Kang, J. Kang, J. Fang and G. Cauwenberghs, 2010

- **Prototype non-contact sensor system with 4-channels**
  - Bluetooth wireless telemetry and microSD data storage
  - Rechargeable battery
- **Mounted in both head and chest harnesses**

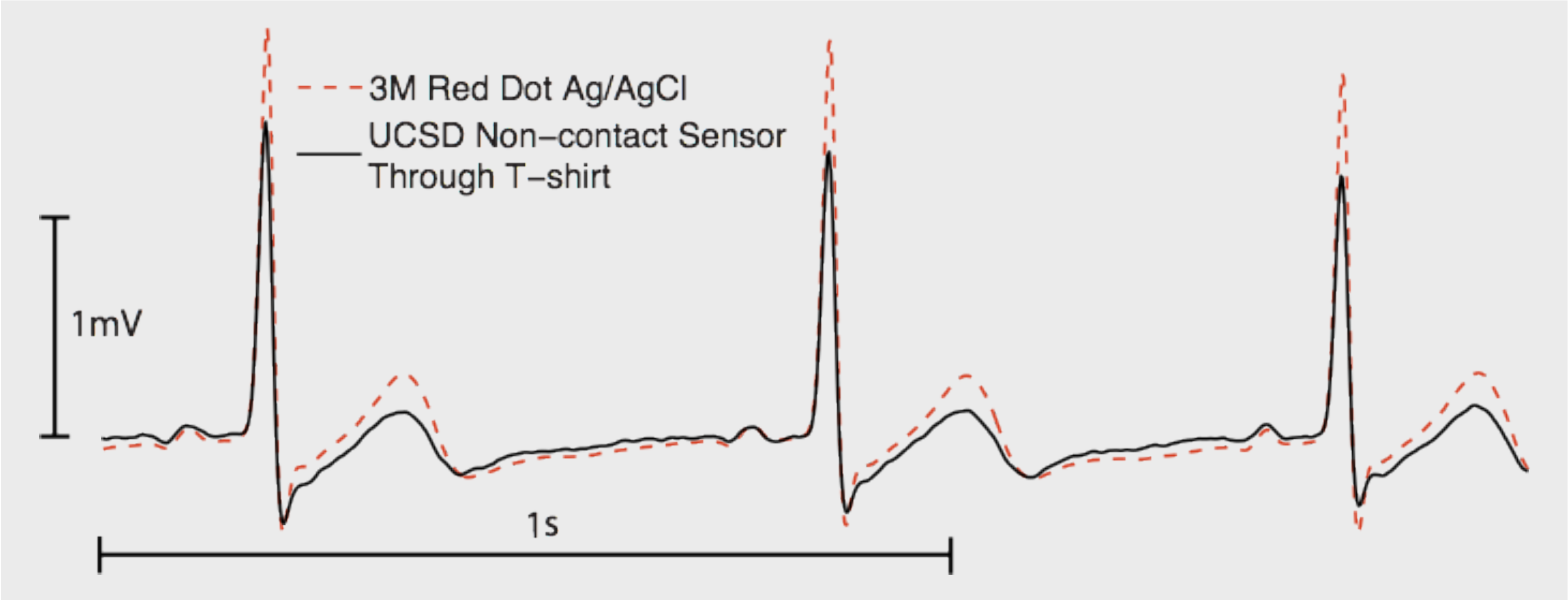
EEG Hand-band

ECG Chest Harness

Electronics



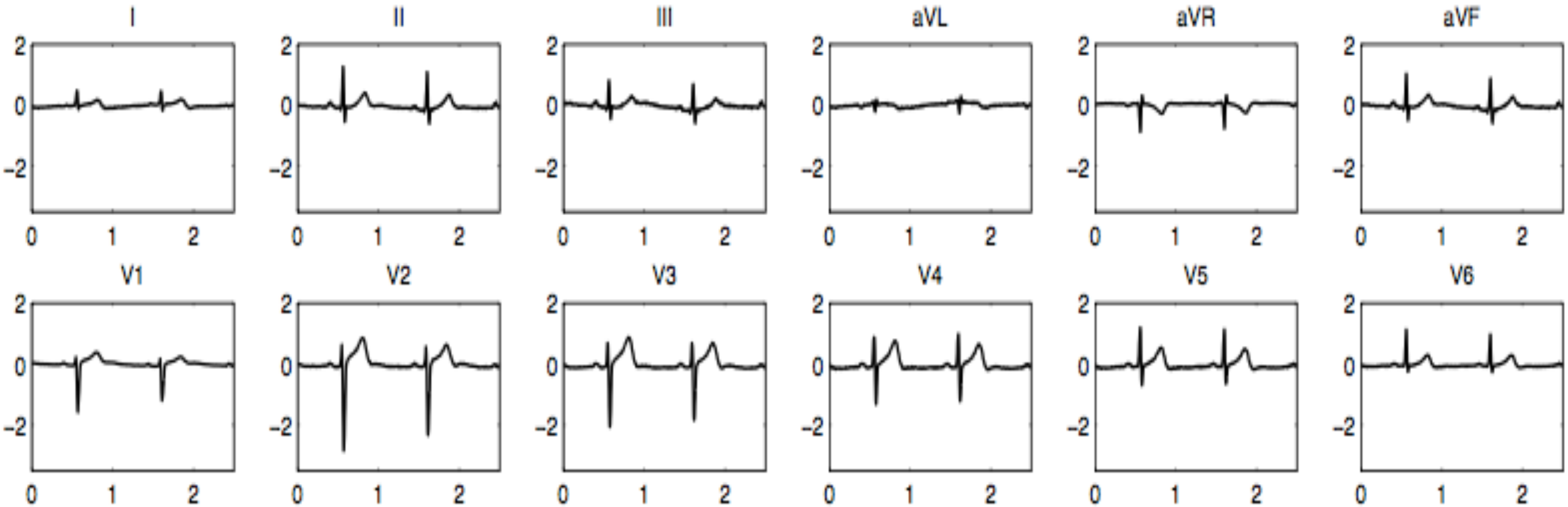
ECG Comparison



Simultaneously acquired ECG in laboratory setting
No 60Hz Filter

Y. M. Chi, E. Kang, J. Kang, J. Fang and G. Cauwenberghs, 2010

Sample ECG Data



Derived 12-lead ECG from 4 electrodes mounted in chest harness

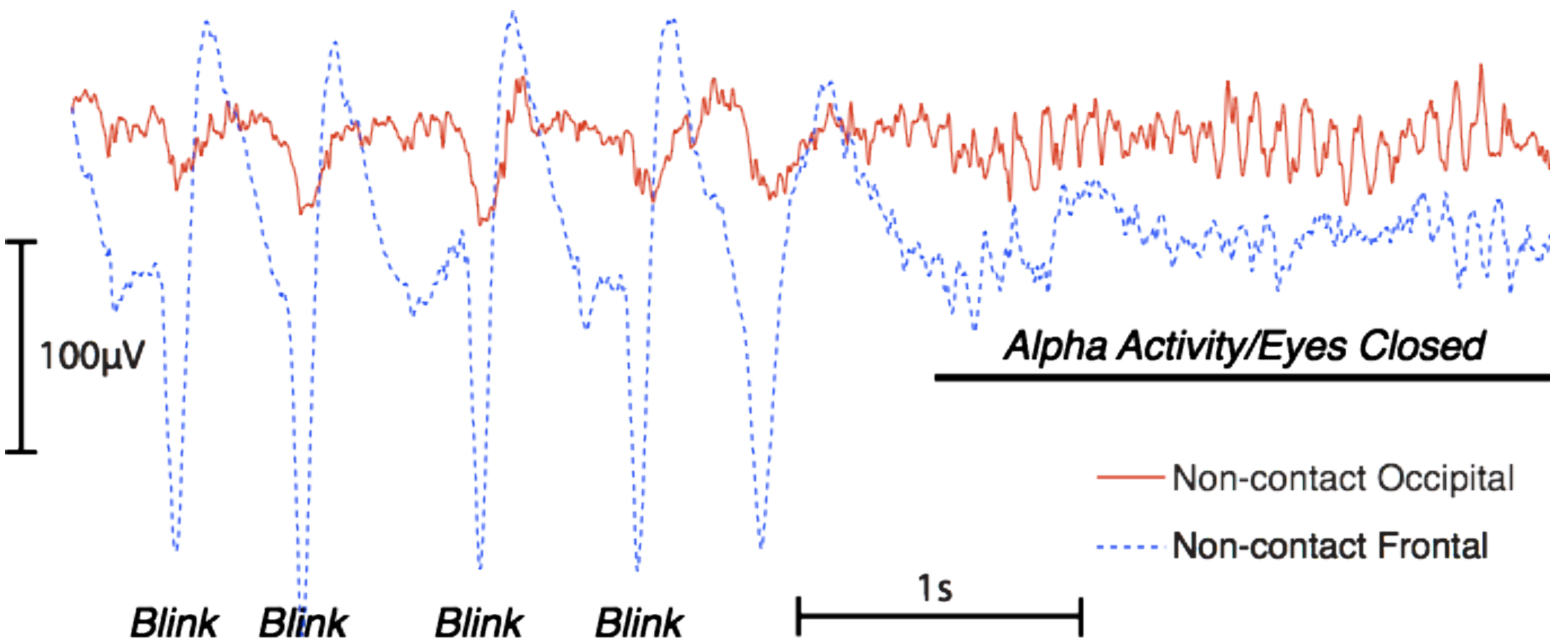
Y. M. Chi, E. Kang, J. Kang, J. Fang and G. Cauwenberghs, 2010

ECG Under Motion

Y. M. Chi, E. Kang, J. Kang, J. Fang and G. Cauwenberghs, 2010

Non-Contact EEG Recording over Haired Scalp

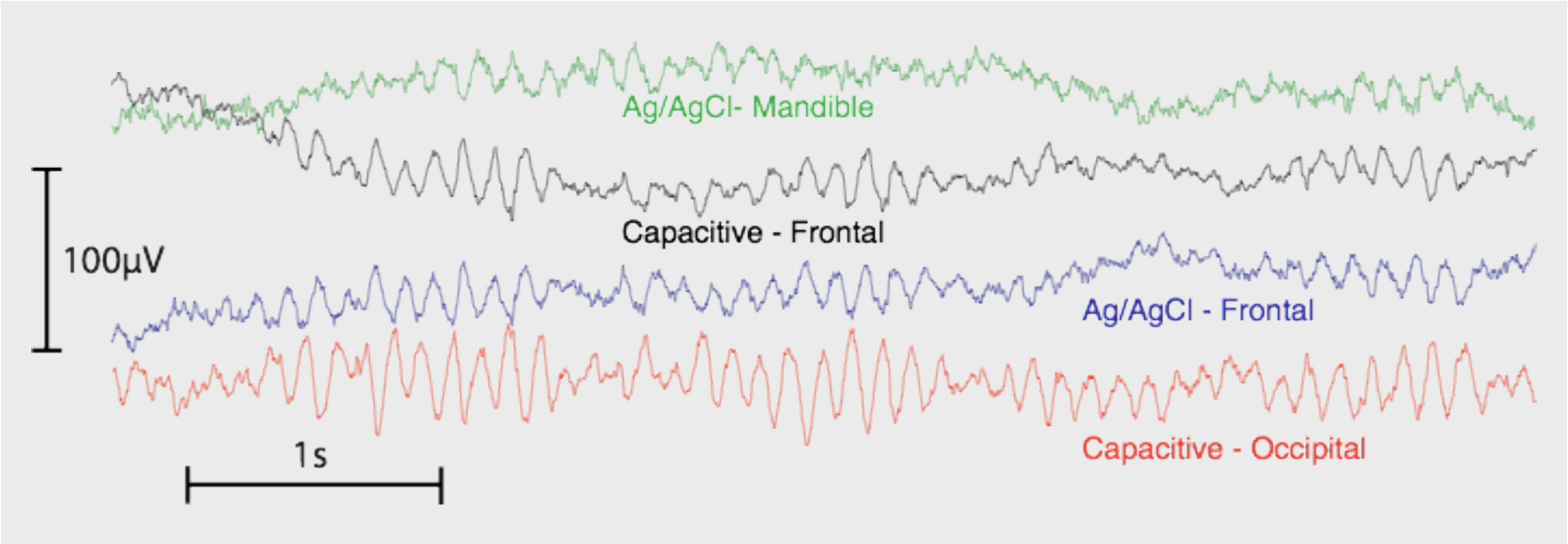
Y. M. Chi, E. Kang, J. Kang, J. Fang and G. Cauwenberghs, 2010



- **Easy access to hair-covered areas of the head without gels or slap-contact**
- **EEG data available only from the posterior**
  - P300 (Brain-computer control, memory recognition)
  - SSVP (Brain-computer control)

Non-Contact *vs.* Ag/AgCl Comparison

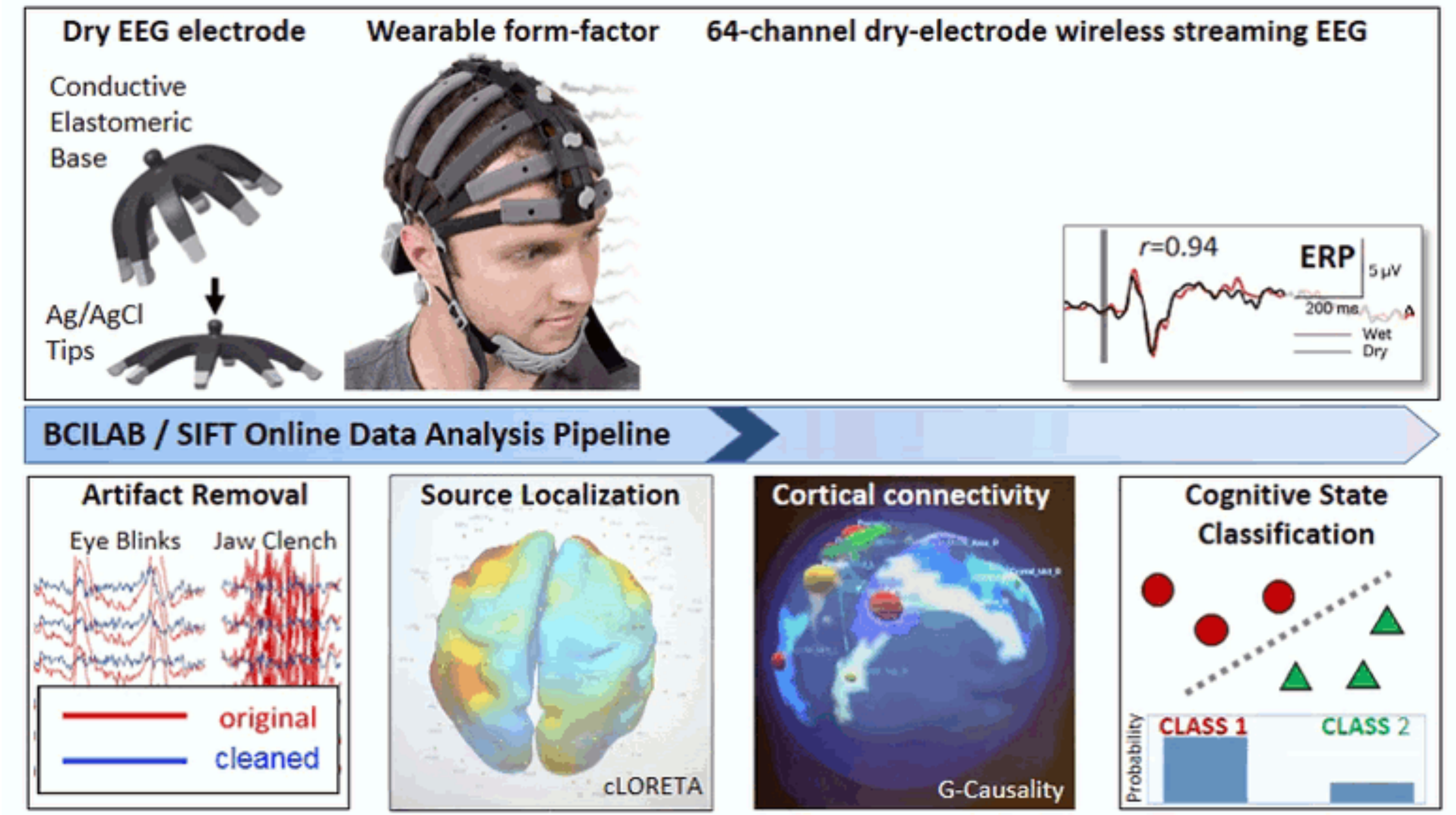
Y. M. Chi, E. Kang, J. Kang, J. Fang and G. Cauwenberghs, 2010



Subject's eyes closed showing alpha wave activity
Full bandwidth, unfiltered, signal show (.5-100Hz)

Unobtrusive Dry-EEG Functional Brain Imaging

Mullen, Kothe, Chi, Ojeda, Kerth, Makeig, Jung, and Cauwenberghs, 2015



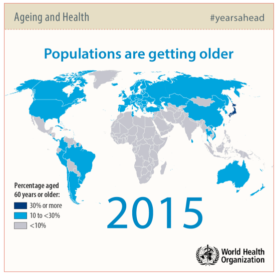
Mullen et al, Real-time Neuroimaging and Cognitive Monitoring Using Wearable Dry EEG. *IEEE TMBE,* 2015.

Opportunities for In-Ear Health Sensing

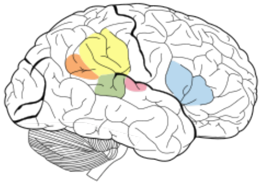
- **Prevalence of wireless personal audio devices:**



- **Rapidly aging global population:**
  - Over the next few decades, people 65 years and older will account for **20% of the global population**, an unprecedented shift. New healthcare challenges and opportunities will arise for which **reliable and continuous high-bandwidth health data will be critical**.



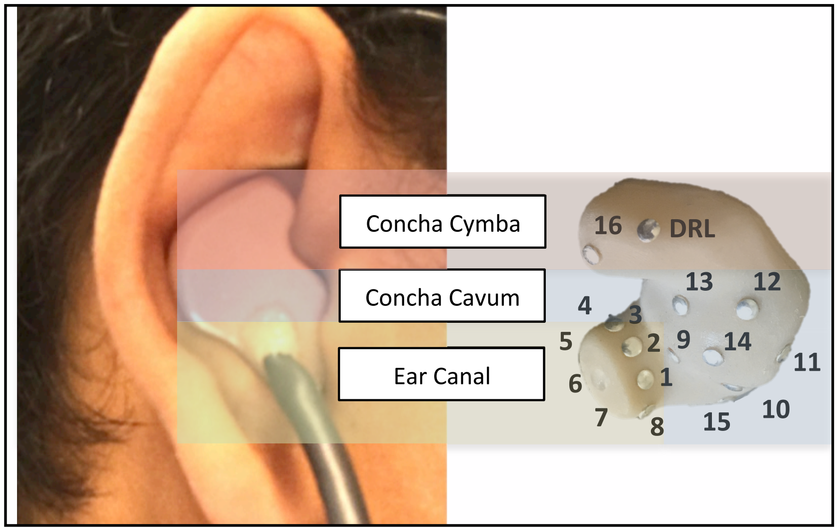
- **In-Ear Health Sensing Platform**
  - An in-ear healthcare platform has the convenience, comfort, and discretion of a consumer audio device, while offering valuable electrophysiological and bio-chemical data.



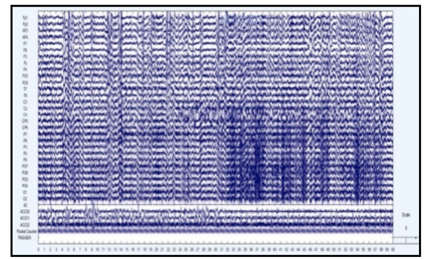
In-Ear Electrophysiology

Paul et al, IEEE NER 2019; IEEE EMBC 2019

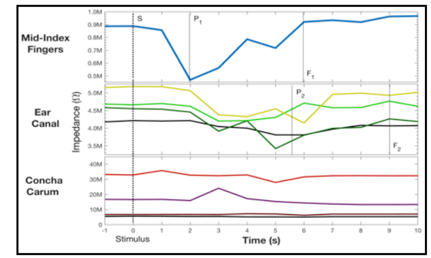
High-density dry-contact electrodes capture a wealth of physiological information from an integrated in-ear device

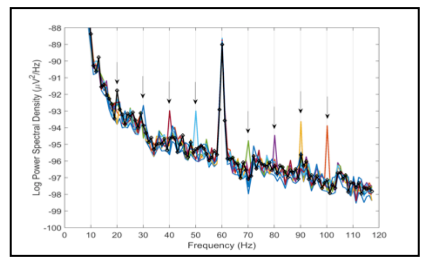


Auditory ERP

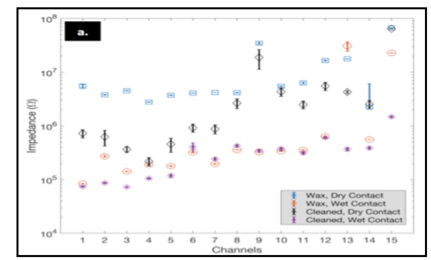


Electrodermal Activity





ASSR PSD



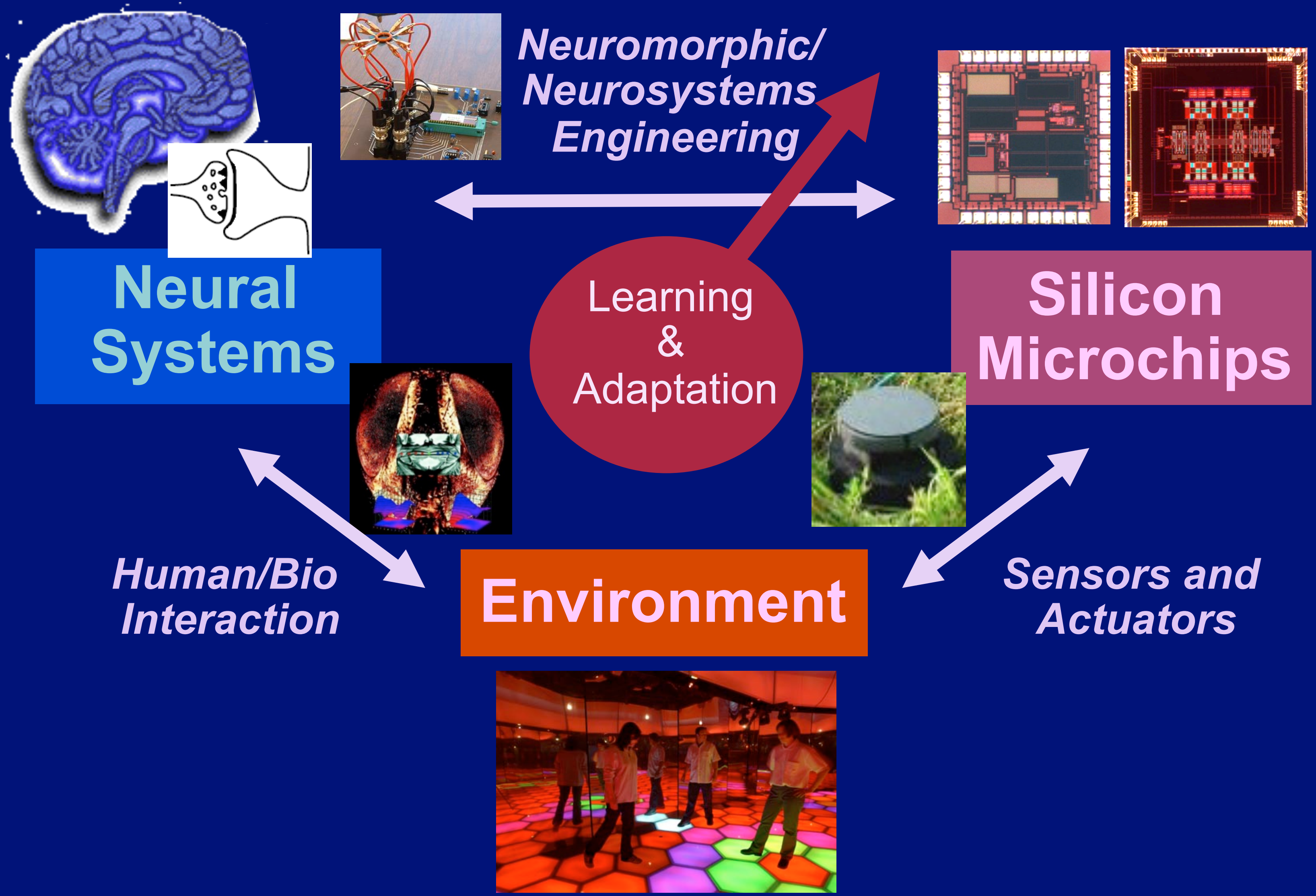
Impedance Imaging

- In-ear, high-density dry-contact electrode recording platform records electroencephalography (EEG) signals from the brainstem, temporal, and visual cortexes with quality comparable to commercial scalp EEG.
- Electrical impedance measurement provides electrodermal activity (EDA).
- Opportunities for closed-loop auditory neurofeedback (tinnitus, insomnia, apnea, etc).

Paul, A., Deiss, S., Tourtelotte, D., Kleffner, M., Zhang, T., and Cauwenberghs, G. Electrode-Skin Impedance Characterization of In-Ear Electrophysiology Accounting for Cerumen and Electrodermal Response. IEEE EMBS Int. Conf. Neural Engineering (NER'19), 2019.

Paul, A., Akinin, A., Cauwenberghs, G. Integrated In-Ear Device for Auditory Health Assessment. 2019 41st Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC'19), 2019.

Integrated Systems Neuroengineering



BENG 207 Neuromorphic Integrated Bioelectronics

Date	Topic
9/27, 9/29	Biophysical foundations of natural intelligence in neural systems. Subthreshold MOS silicon models of membrane excitability. Silicon neurons. Hodgkin-Huxley and integrate-and-fire models of spiking neuronal dynamics. Action potentials as address events.
10/4, 10/6	Silicon retina. Low-noise, high-dynamic range photoreceptors. Focal-plane array signal processing. Spatial and temporal contrast sensitivity and adaptation. Dynamic vision sensors.
10/11, 10/13	Silicon cochlea. Low-noise acoustic sensing and automatic gain control. Continuous wavelet filter banks. Interaural time difference and level difference auditory localization. Blind source separation and independent component analysis.
10/18, 10/20	Silicon cortex. Neural and synaptic compute-in-memory arrays. Address-event decoders and arbiters, and integrate-and-fire array transceivers. Hierarchical address-event routing for locally dense, globally sparse long-range connectivity across vast spatial scales.
10/28, 11/1	Review. Modular and scalable design for neuromorphic and bioelectronic integrated circuits and systems. Design for full testability and controllability.
11/1, 11/3	Midterm due 11/2. Low-noise, low-power design. Fundamental limits of noise-energy efficiency, and metrics of performance. Biopotential and electrochemical recording and stimulation, lab-on-a-chip electrophysiology, and neural interface systems-on-chip.
11/8, 11/10	Learning and adaptation to compensate for external and internal variability over extended time scales. Background blind calibration of device mismatch. Correlated double sampling and chopping for offset drift and low-frequency noise cancellation.
11/15, 11/17	Energy conservation. Resonant inductive power delivery and data telemetry. Ultra-high efficiency neuromorphic computing. Resonant adiabatic energy-recovery charge-conserving synapse arrays.
11/22, 11/24	Guest lectures
11/29, 12/1	Project final presentations. All are welcome!