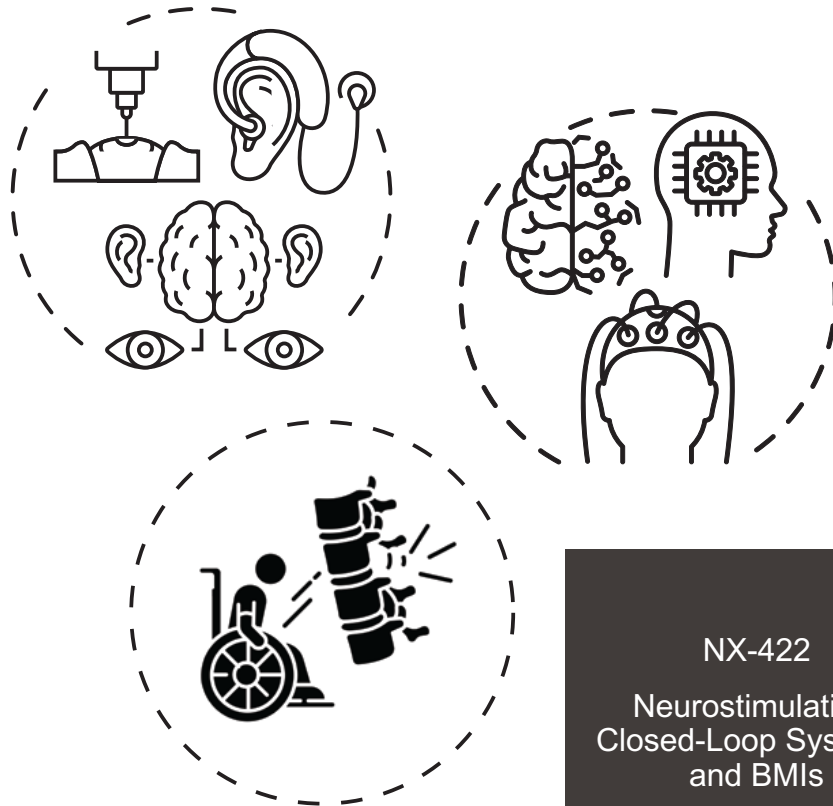




Neural Interfaces

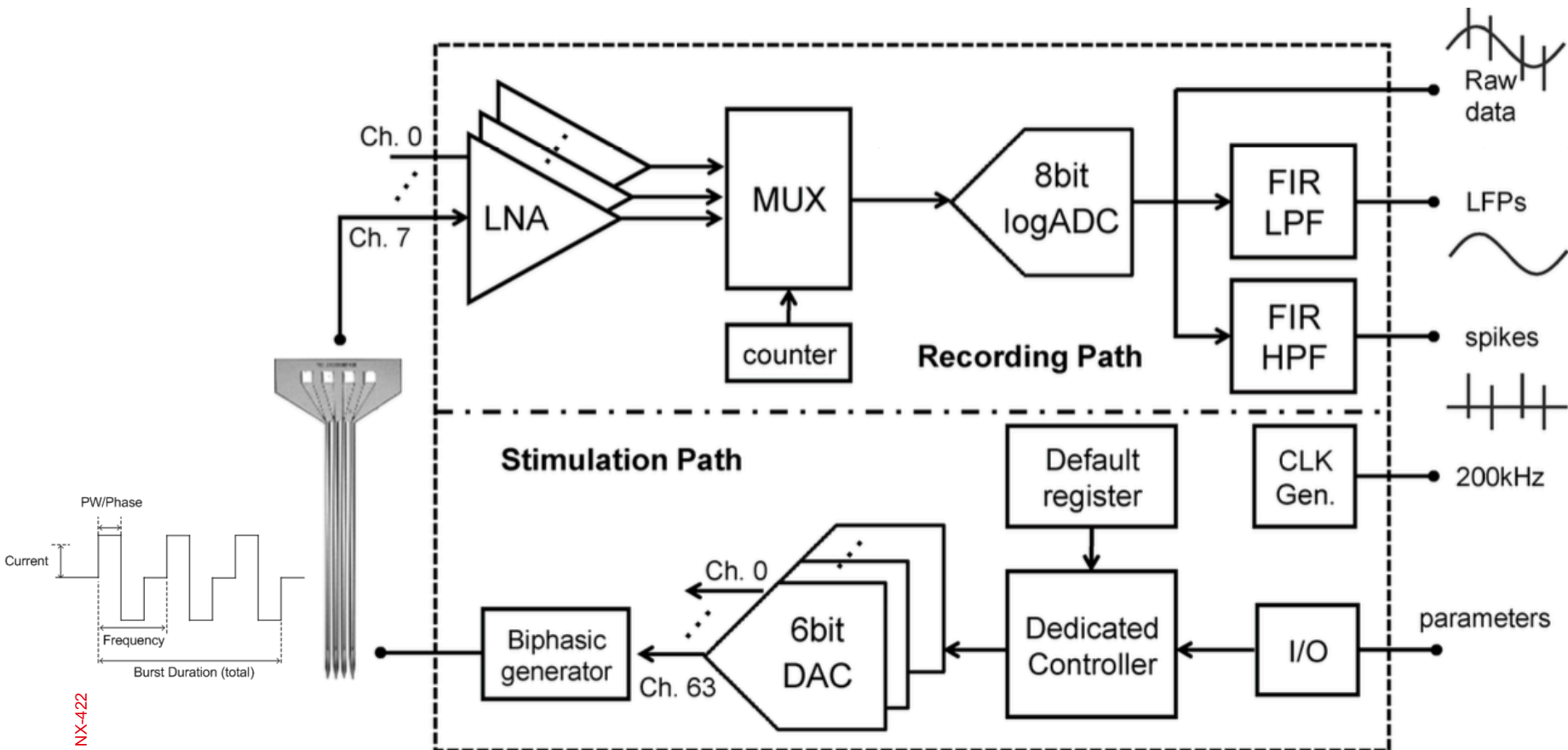
NX-422

Neurostimulation,
Closed-Loop Systems,
and BMIs

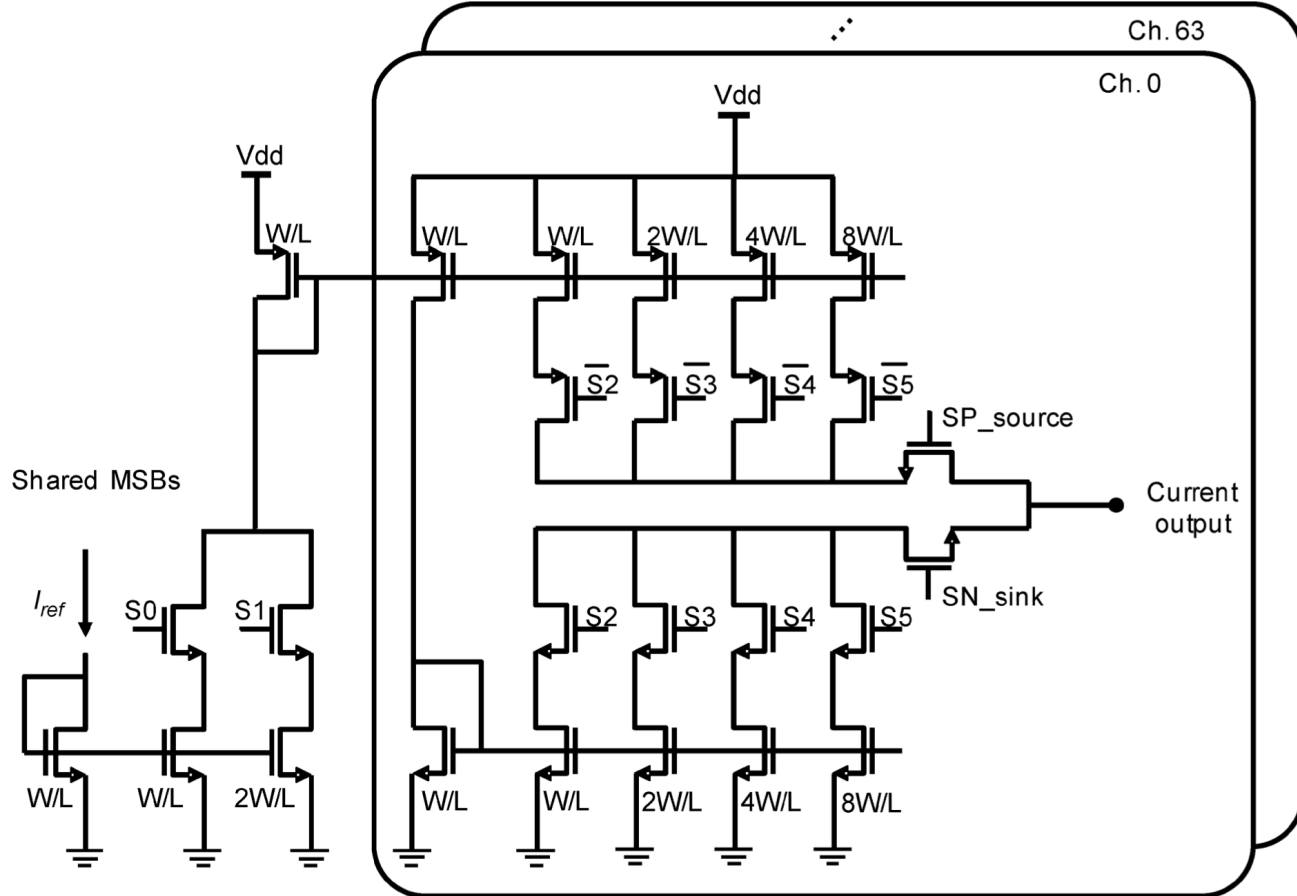
Mahsa Shoaran

IEM and Neuro-X Institutes

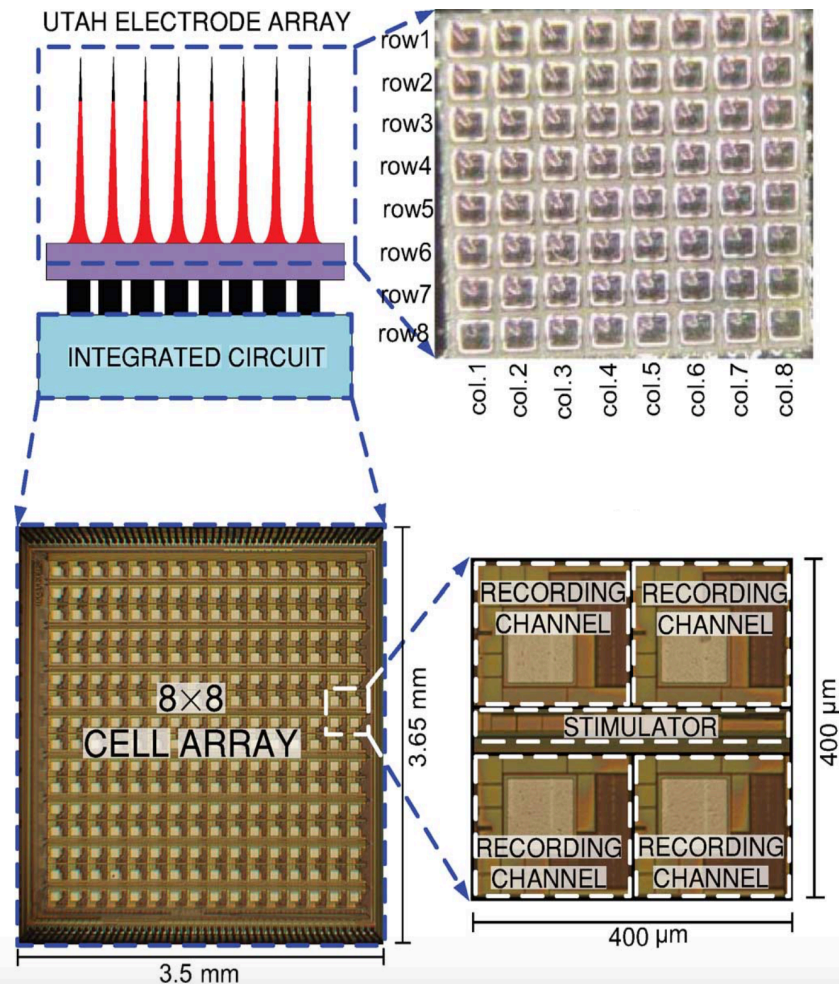
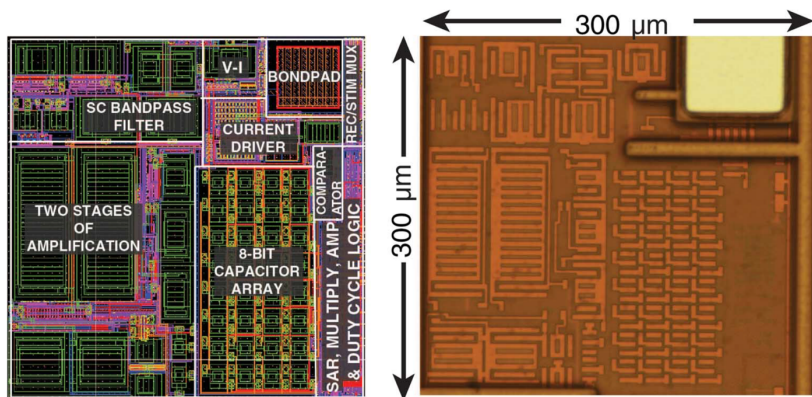
Recap: Neural Recording and Stimulation



Recap: Stimulation Circuit

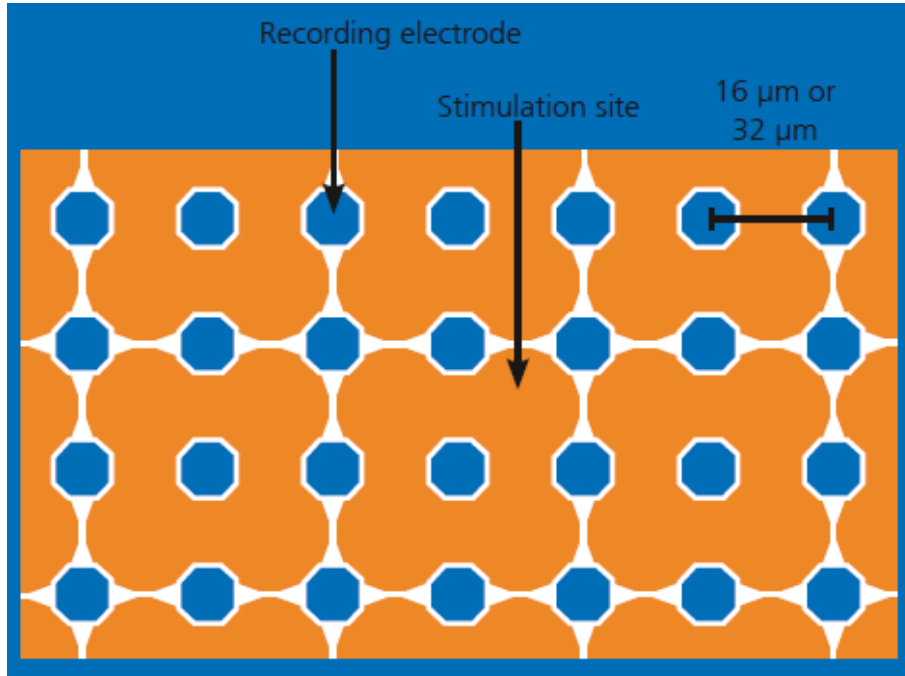


Sensing and Neurostimulation



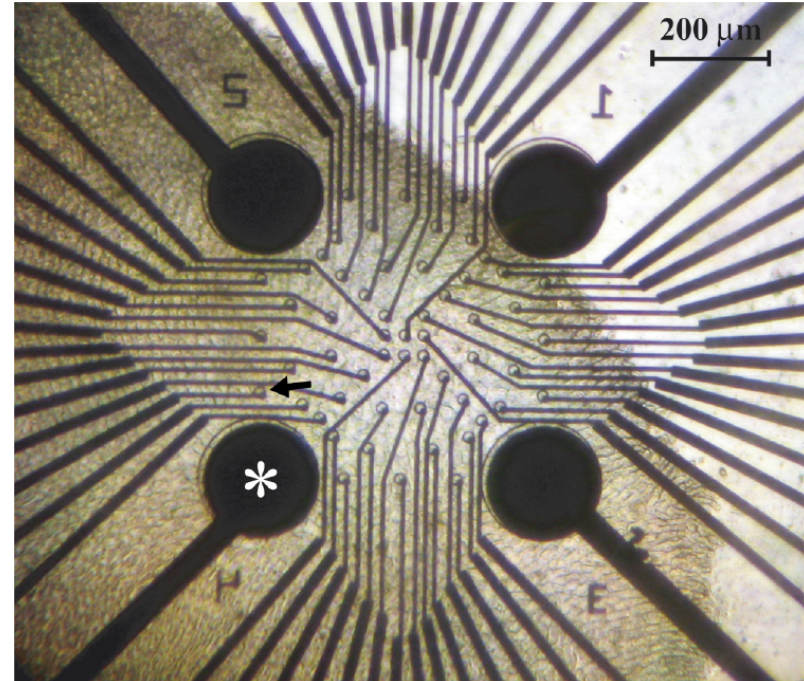
CMOS-MEA5000-System

4225 recording, 1024 stimulating



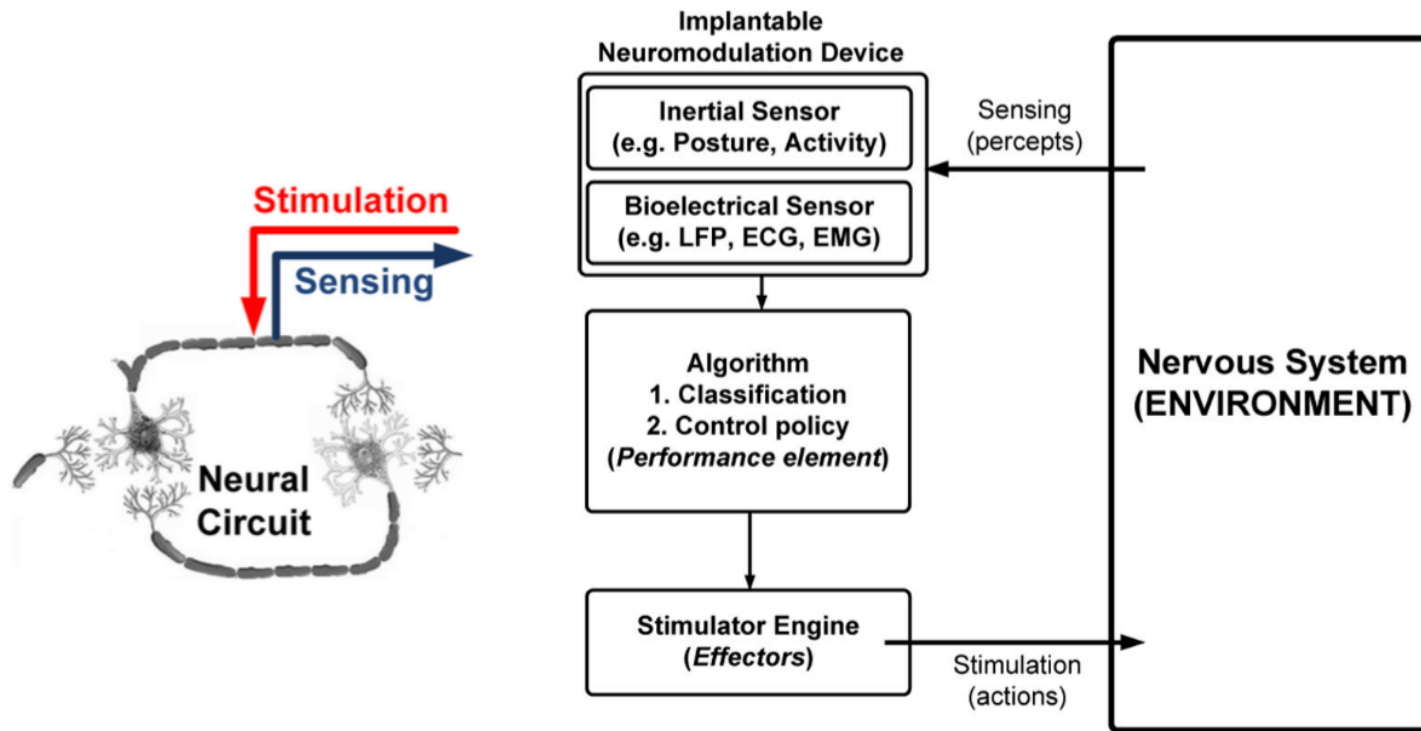
High-density Array

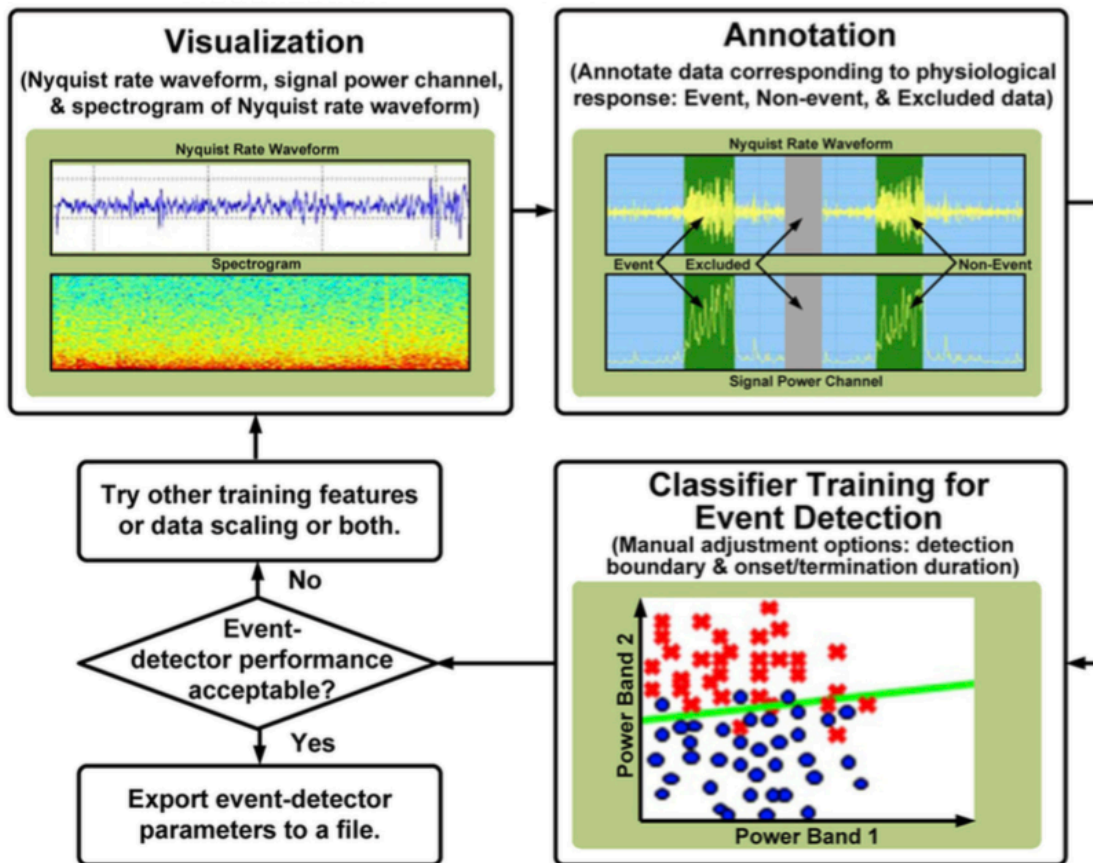
56 recording, 4 stimulating



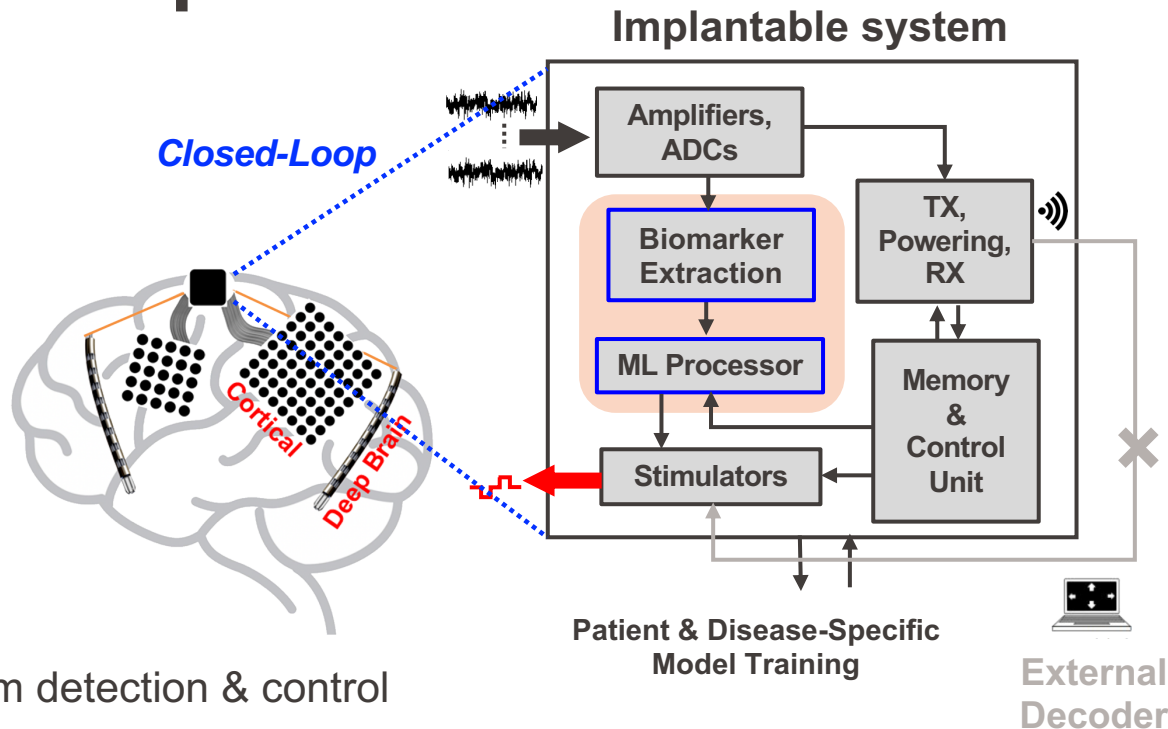
Drawbacks of Open-Loop Stimulation:

- Continuous pulse delivery regardless of the ongoing brain activity
- High energy consumption and potential side effects from stimulation





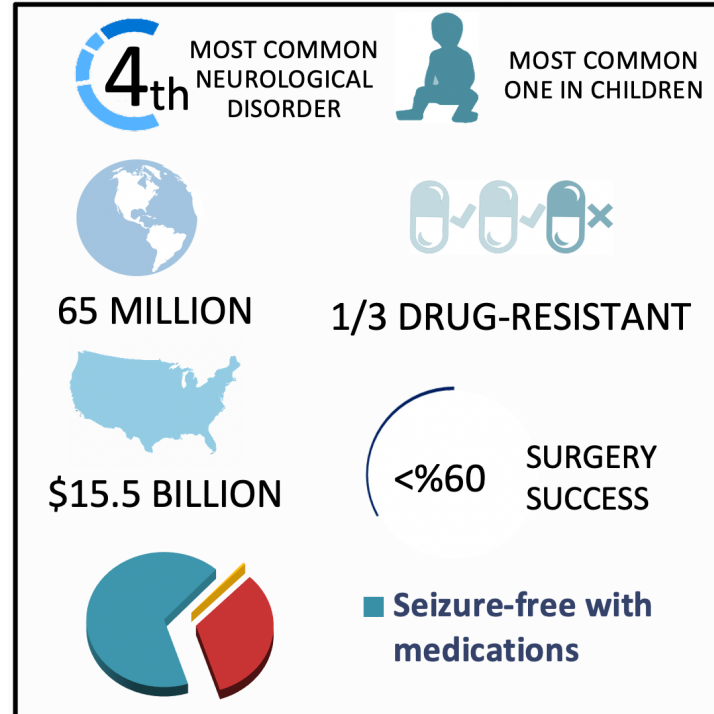
- ✓ Effective, low-latency intervention
- ✓ Reduced telemetry power
- ✓ Better security & privacy



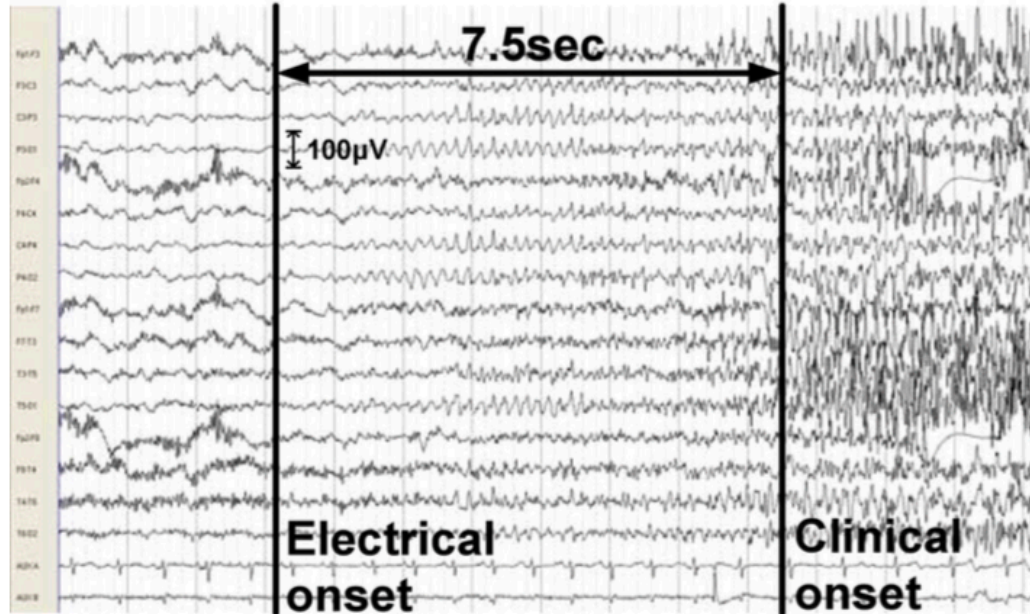
Application: Neurological symptom detection & control

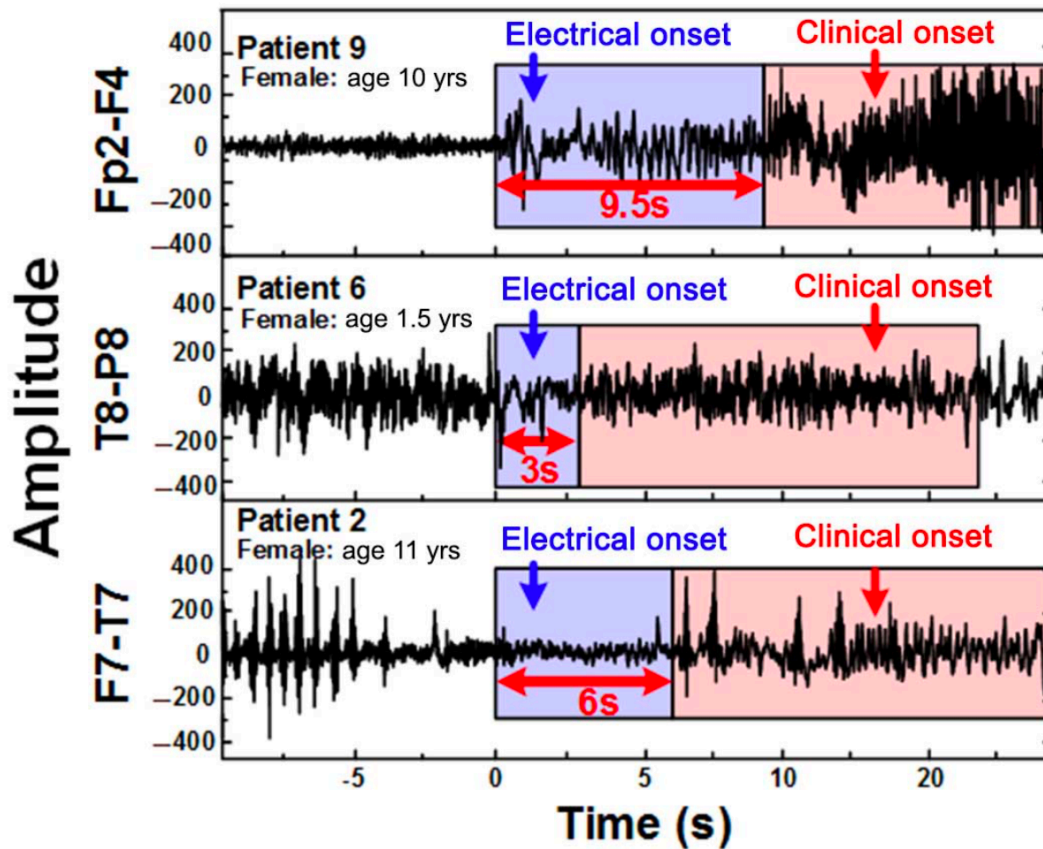
- Epilepsy, movement disorders, depression, ...
- Sensory feedback, restoring movement, ...

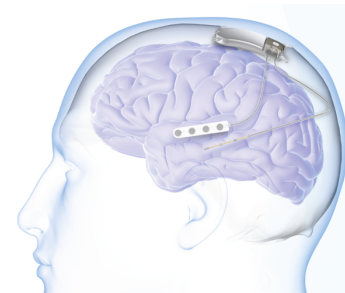
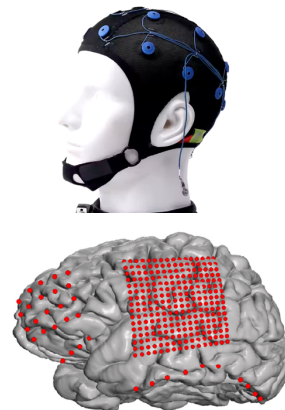
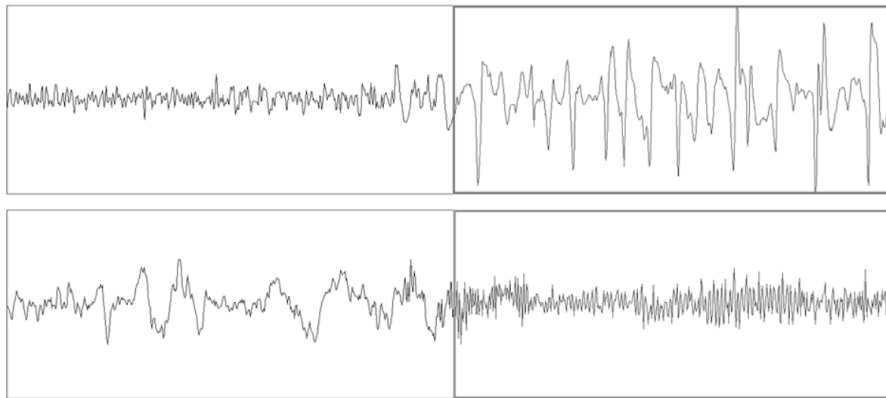
- Can we detect and prevent seizures?



Electrical seizure onset occurs before the clinical onset

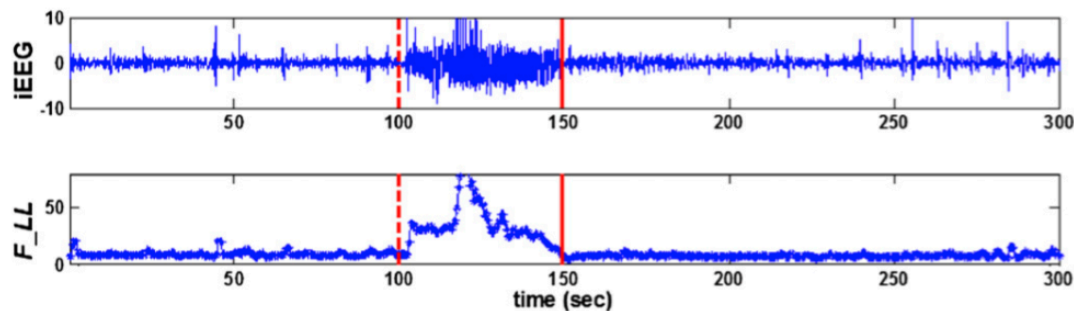






Line-Length

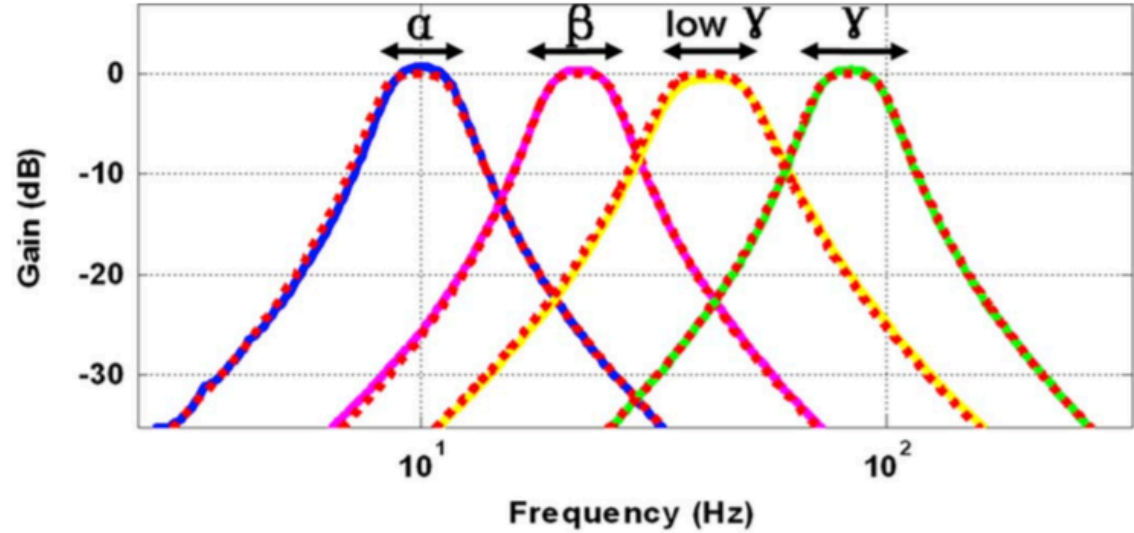
$$LL = \frac{1}{N} \sum_{t=1}^N |x_t - x_{t-1}|$$



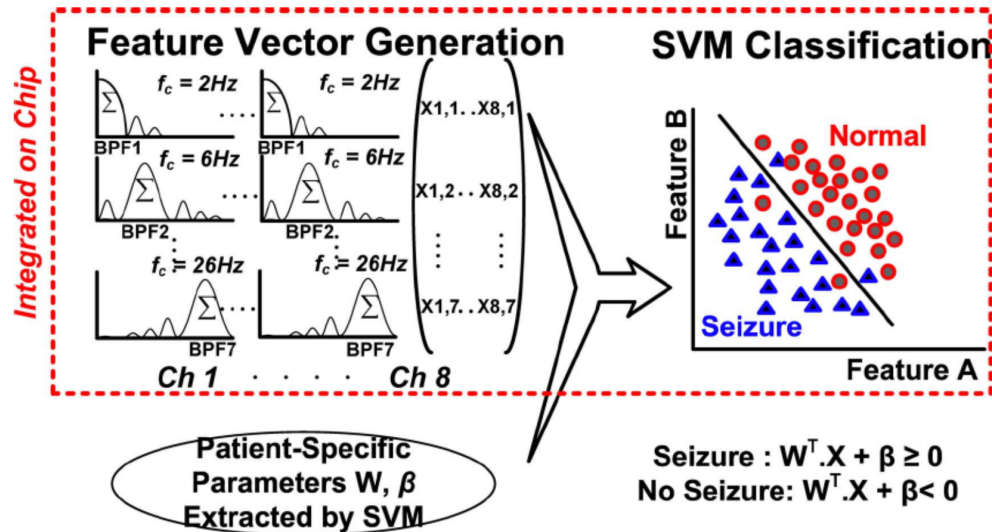
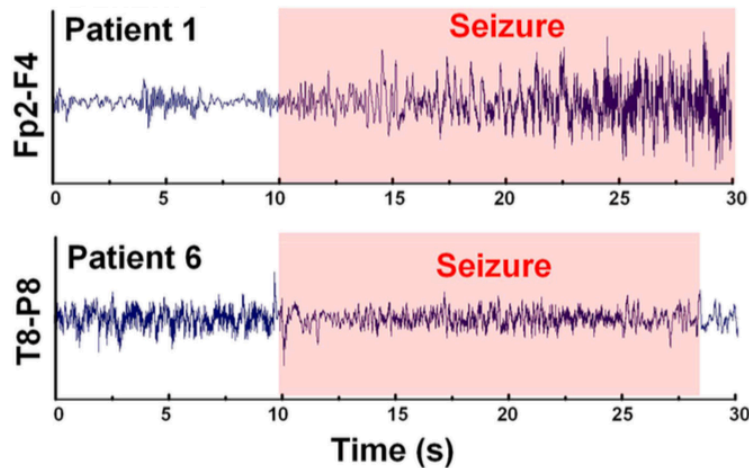
Spectral Energy

$$SE = \frac{1}{N} \sum_{t=1}^N x_{\text{BAND},t}^2$$

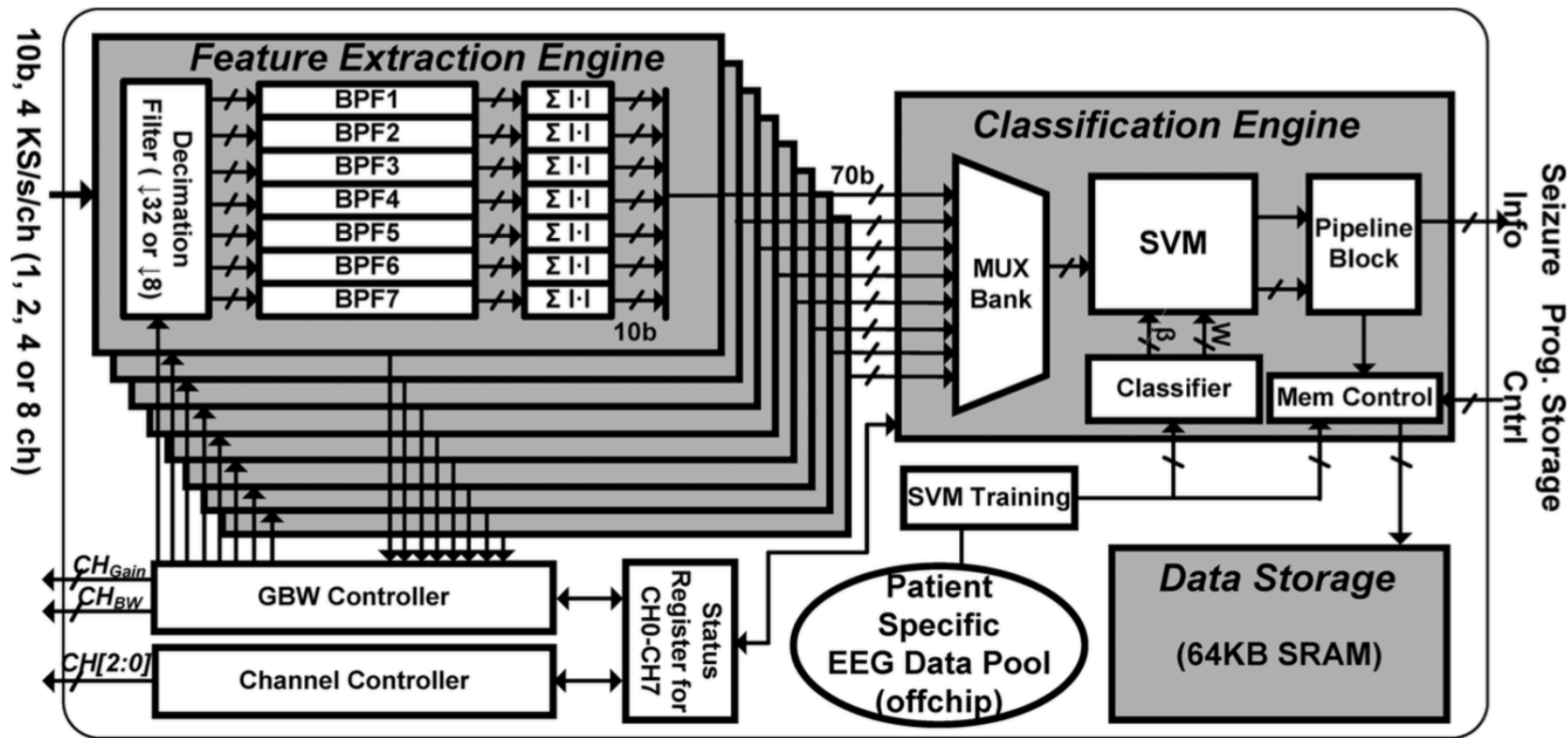
bandpass-filtered signal



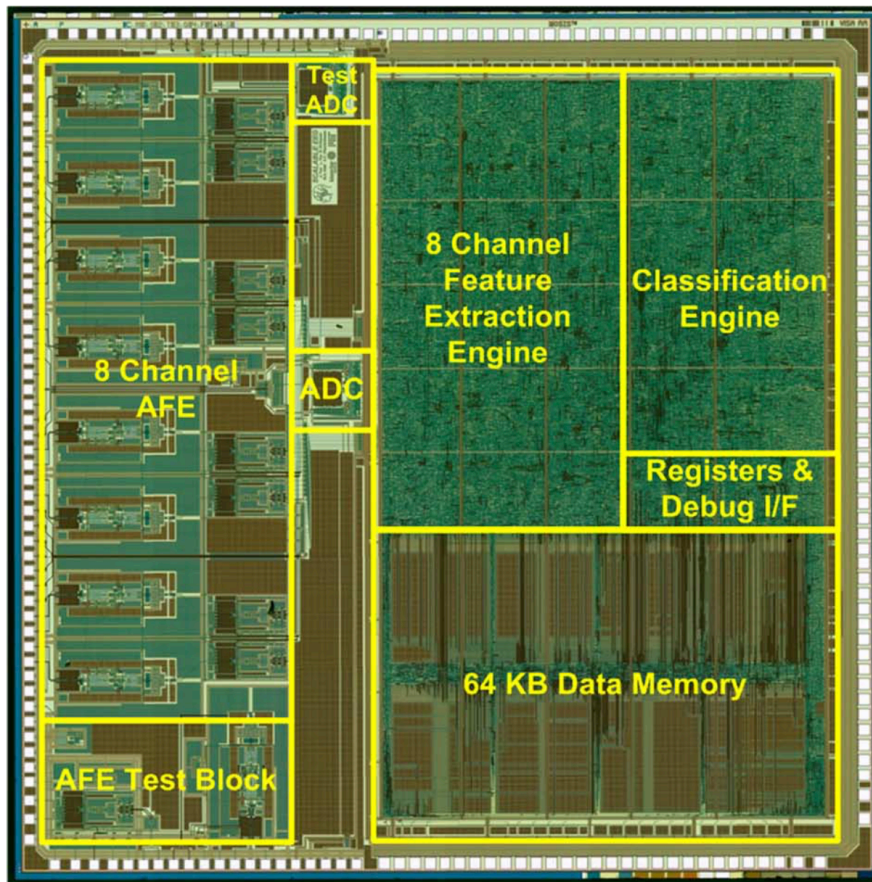
- Seizure patterns vary among patients >> need a classifier



Patient-Specific Classifier for Seizure Detection



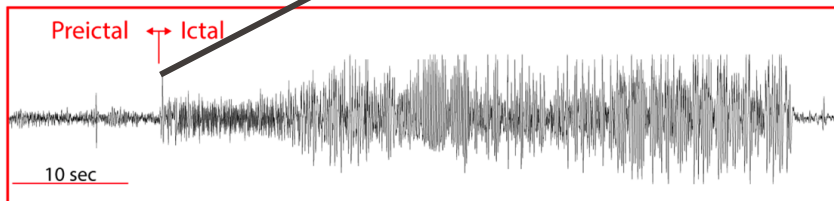
Chip Micrograph and Performance Summary



Process	TSMC 0.18 μm 1P6M CMOS
Area	5.0 x 5.0 mm
Supply Voltage	1.8V (AFE) 1.0V (DBE, ADC)
Channel	1 to 8 Scalable
Input Dyn. Range	30-59 dB (4 step)
AFE Power	66 μW
Bandwidth	30Hz / 100Hz
ADC	Fully Differential SAR ADC
	10b, 4-32KS/s
Classifier Type	Support Vector Machine
Latency	< 2s
Accuracy	84.4%
Efficiency	2.03 μJ /Classification

- Sensitivity: true positive rate
- Specificity: true negative rate
 - False alarms/hour (FAR)
- Latency

Expert-marked onset



Has the disease	Does not have the disease
True Positives (TP) a	False Positives (FP) b
False Negatives (FN) c	True Negatives (TN) d

Sensitivity

TP

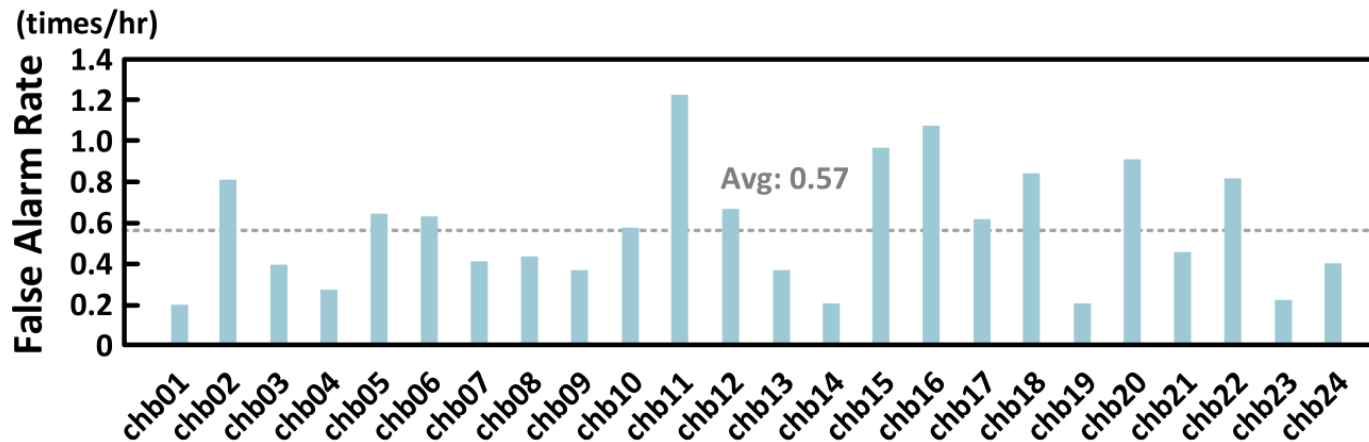
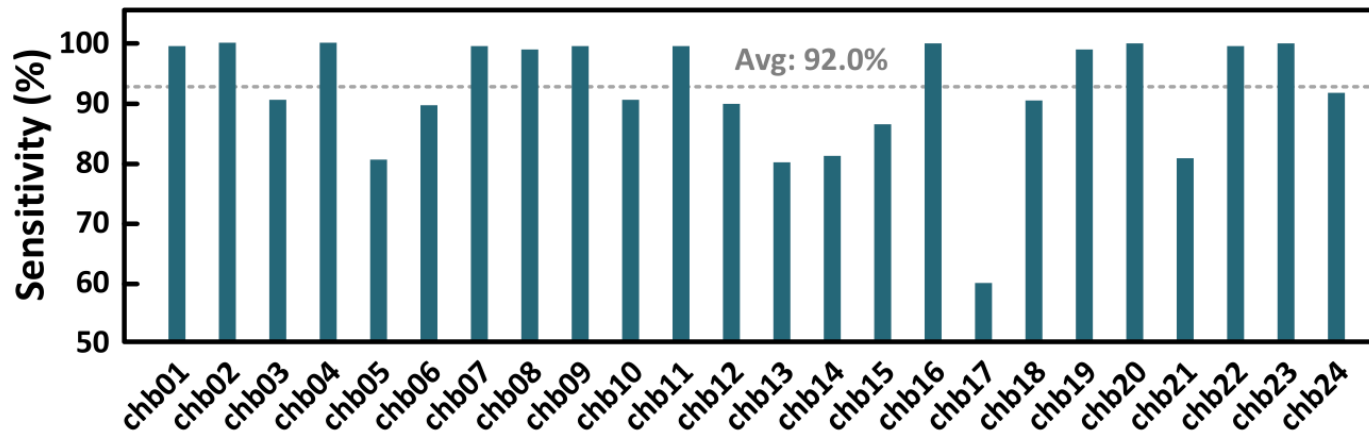
TP + FN

Specificity

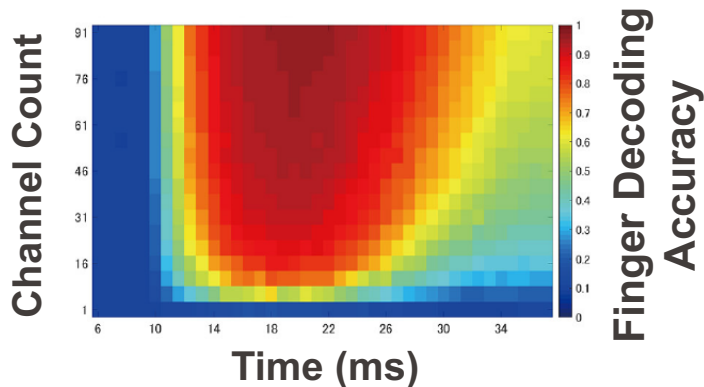
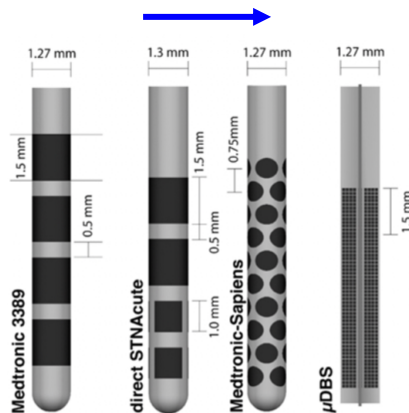
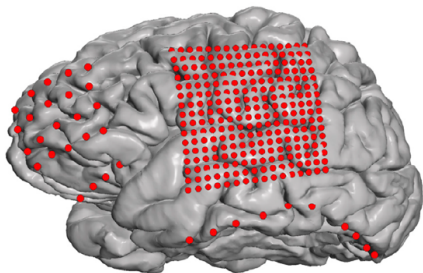
TN

TN + FP

Classification Results on EEG Database



High-Channel-Count Sensing & Stimulation



Epilepsy

- Early detection of seizure onset
- Precise localization of seizure foci

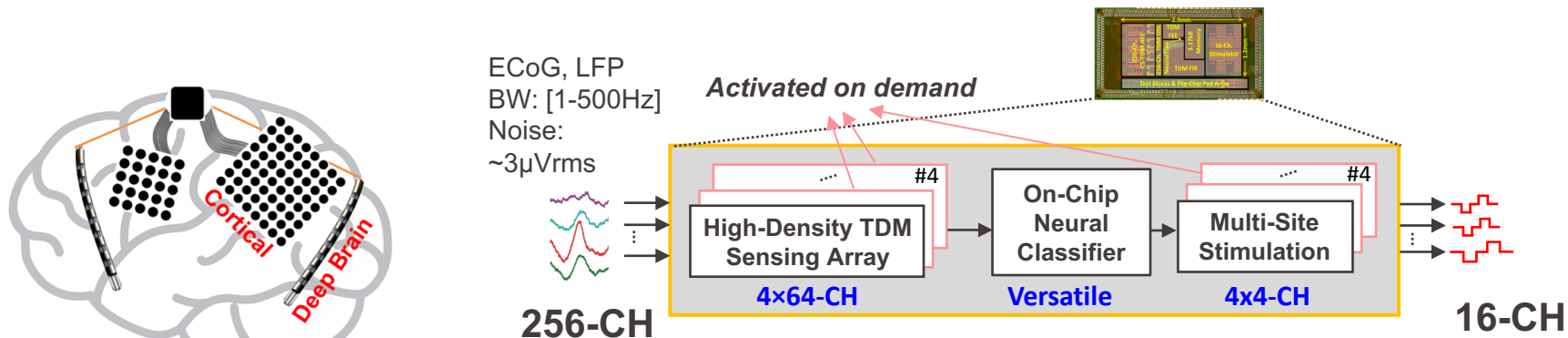
Movement Disorders

- Improved symptom detection/suppression
- Reduced side effects of stimulation

Motor Prosthetics

- Precise motor decoding
- More natural prosthetic control

NeuralTree: A 256-Channel Versatile Closed-Loop SoC

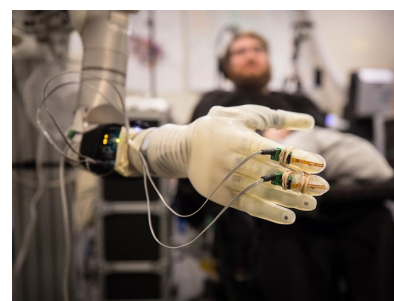
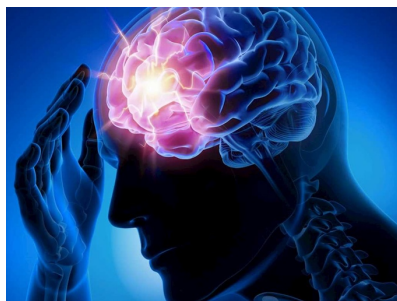


U. Shin et al., ISSCC'22, JSSC'22

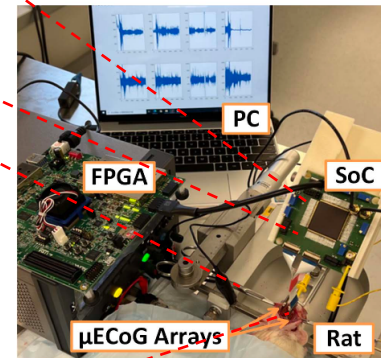
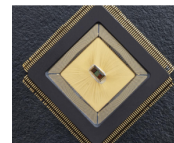
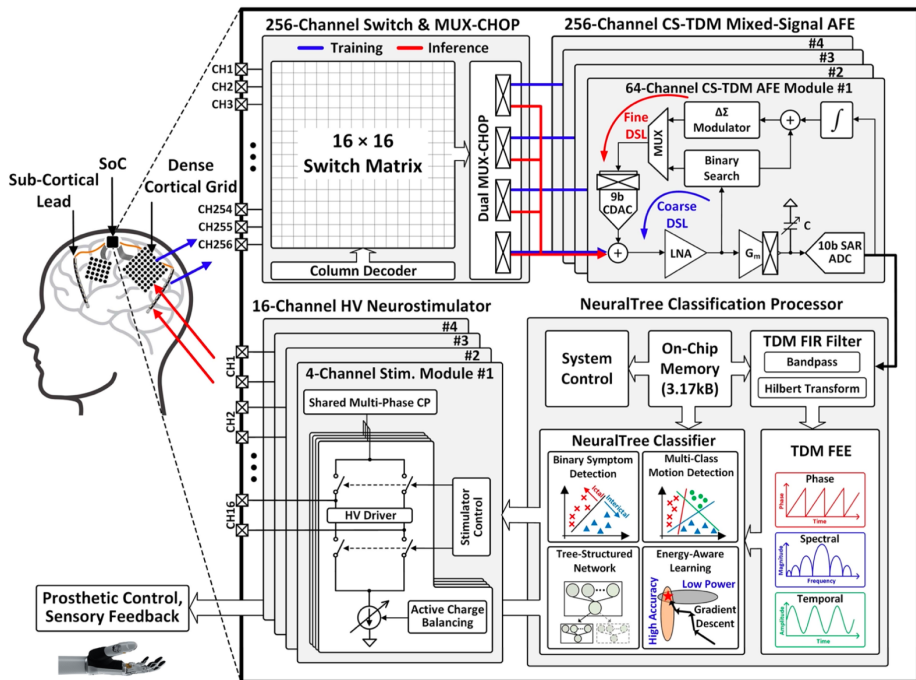
Epilepsy

Parkinson's

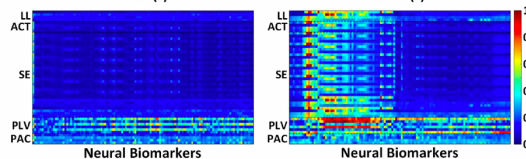
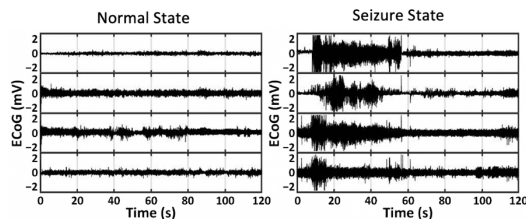
Paralysis



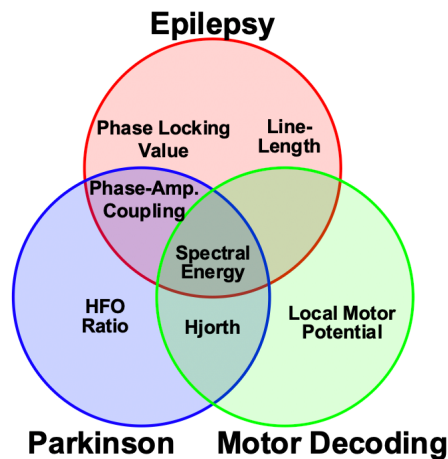
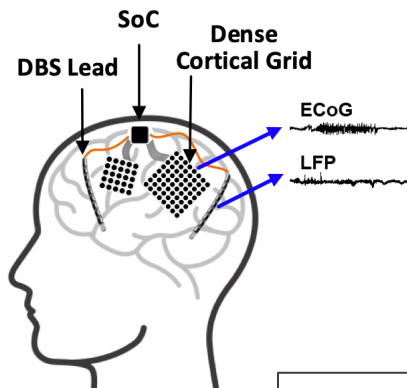
256-Channel Closed-loop Neuromodulation Chip



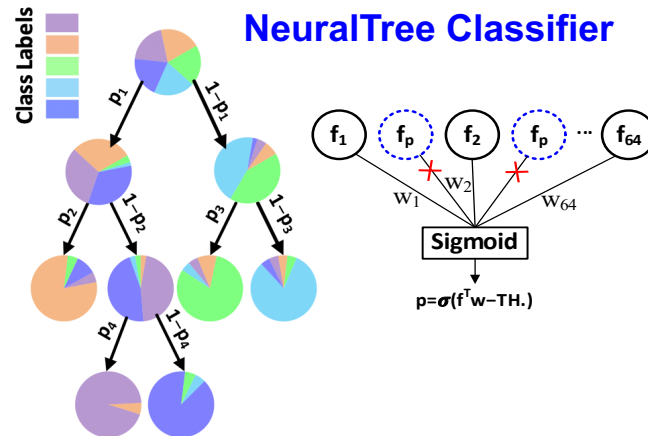
Soft μ ECoG Arrays
(200- μ m diameter)



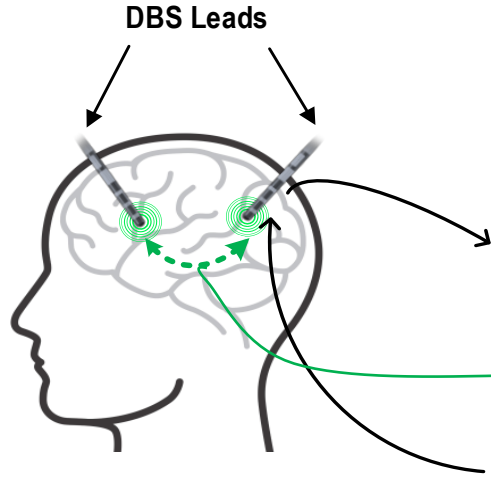
Versatile Brain Activity Classification



PAC: Phase-Amplitude Coupling
PLV: Phase Locking Value
SE: Spectral Energy
LMP: Local Motor Potential
LL: Line-Length
HFO Ratio: High-Frequency Oscillation Ratio
Hjorth: Hjorth Parameters



Cross-Regional Neural Synchrony in Psychiatric Disorders

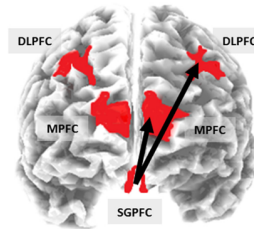


Network-based Biomarkers

$$PLV = \frac{1}{N} \sqrt{\left(\sum_{t=1}^N \sin \Delta \theta_t \right)^2 + \left(\sum_{t=1}^N \cos \Delta \theta_t \right)^2}$$

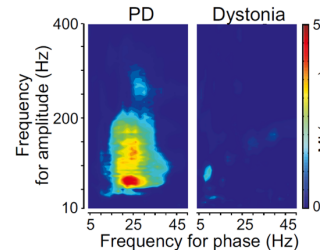
$$PAC = \frac{1}{N} \sqrt{\left(\sum_{t=1}^N A_t \sin \theta_t \right)^2 + \left(\sum_{t=1}^N A_t \cos \theta_t \right)^2}$$

Depression

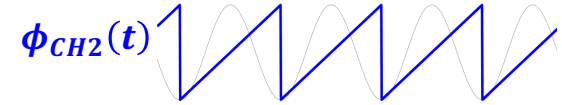
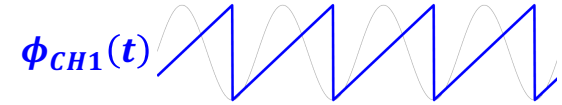


Increased phase synchrony between prefrontal cortex regions

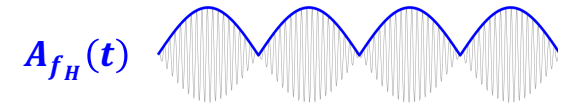
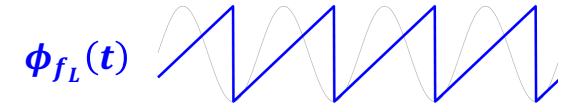
Parkinson



Phase Locking Value (PLV)

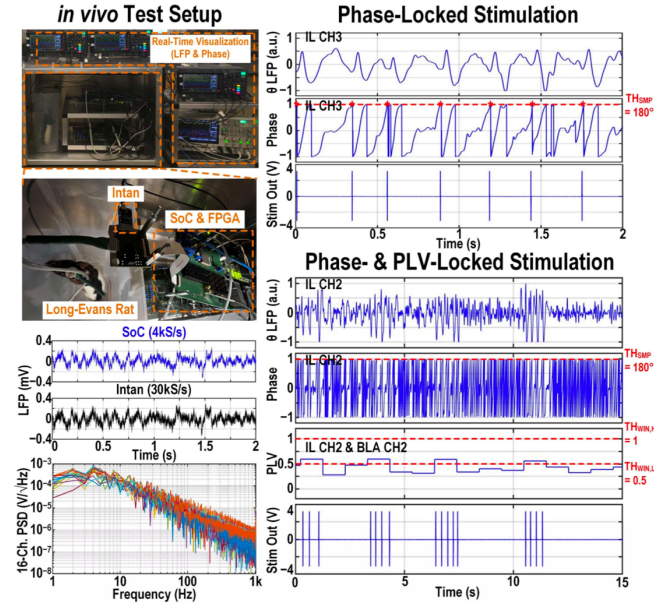
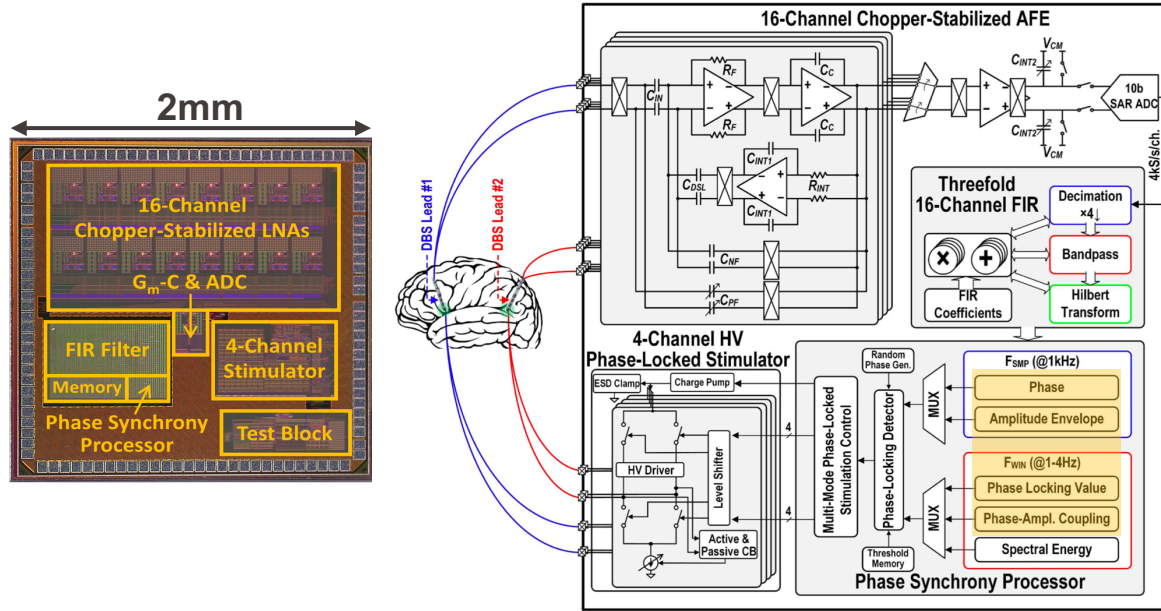


Phase-Amplitude Coupling (PAC)



Excessive coupling between STN phase and M1 amplitude

Neural Synchrony Processor and Closed-Loop DBS



SoC Power: 60μW

**Infralimbic cortex
(Fear extinction)**

**Basolateral amygdala
(Fear learning)**

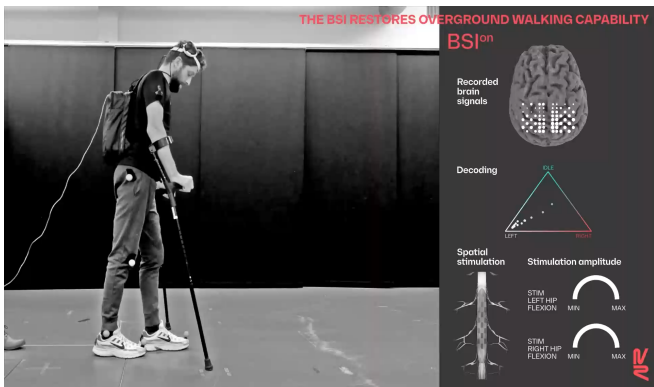
AI-Enabled BMIs



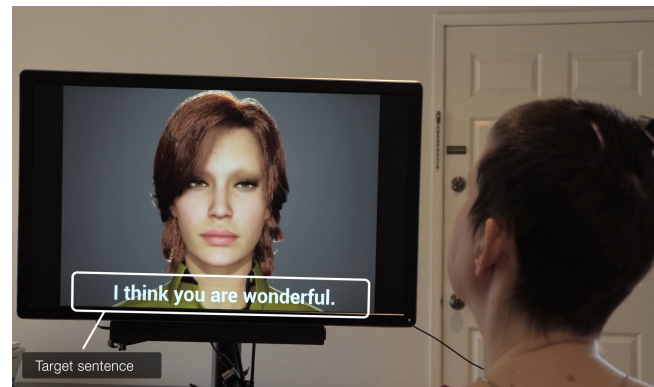
Science'15



Nature'21



Nature'23



Nature'23

Next-Generation BMI Hardware



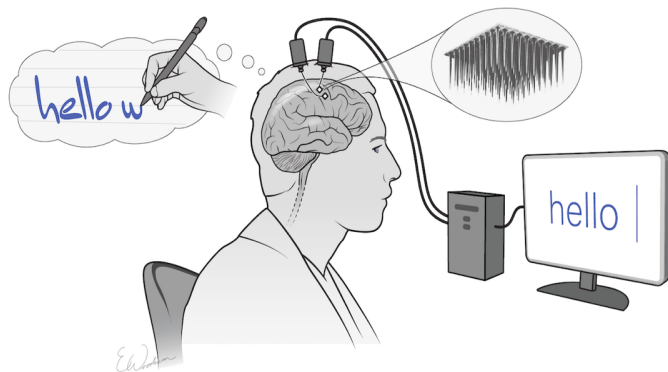
- ✗ Limited mobility
- ✗ Physical size
- ✗ Power consumption



- ✓ Efficiency
- ✓ Convenience

Recent BMIs for Rapid Communication Recovery

Nature'21



Handwriting

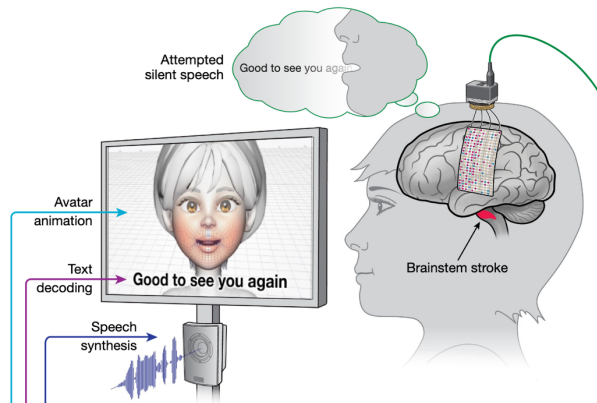
2×96-Ch. Utah

RNN model

90 char./min

94.1% (31 char.)

Nature'23



Speech

253-Ch. ECoG

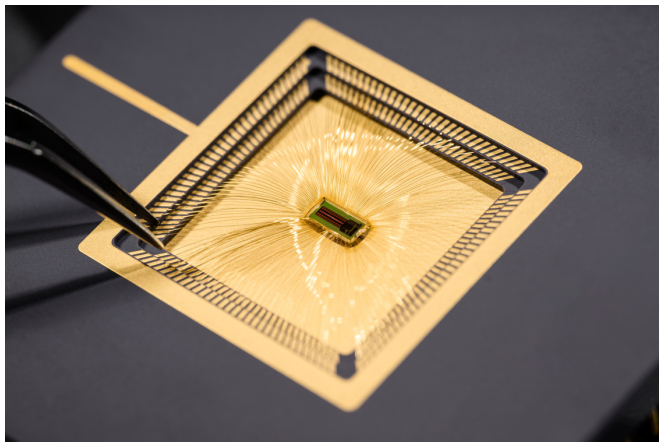
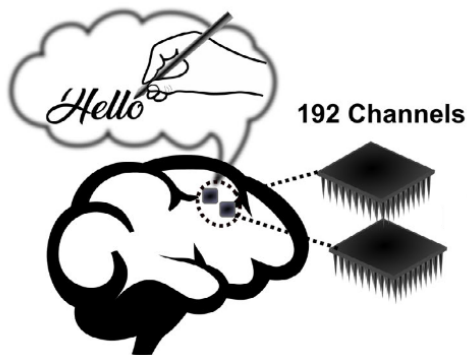
RNN + language model

78 words/min

91.8% (119 words)

74.5% (1024 words)

MiBMI: Miniaturized Brain-to-Text BMI

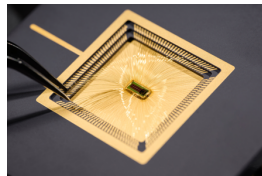
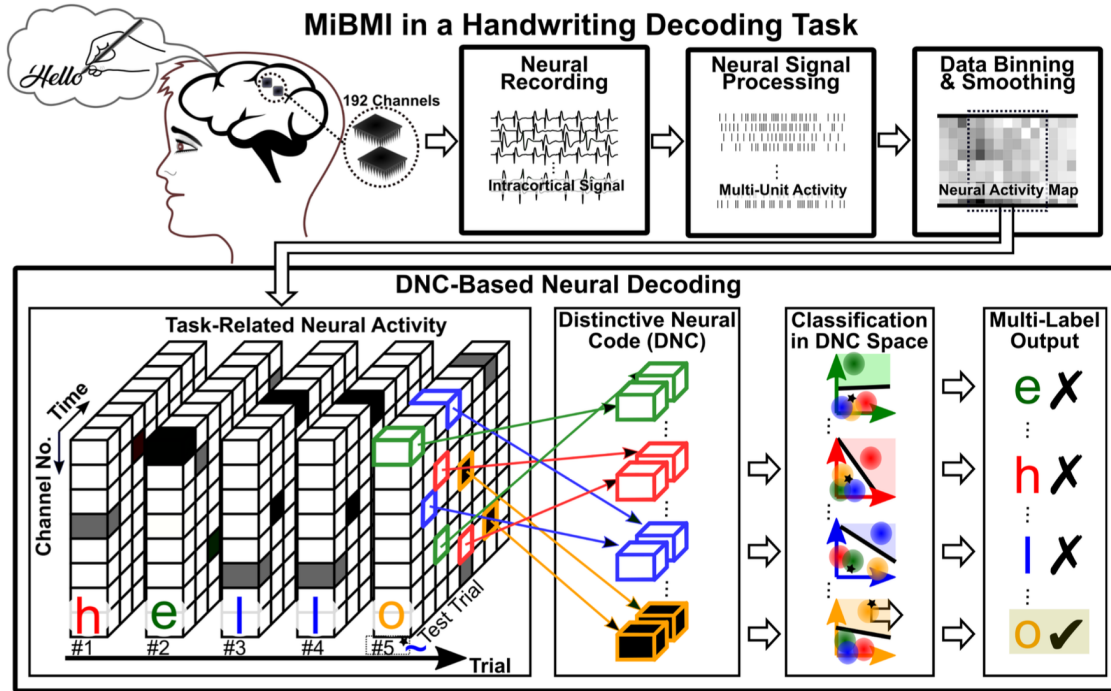


- ✓ Process: 65nm TSMC
- ✓ **192-Ch. Sensing**
- ✓ **512-Ch. Decoder**
- ✓ Total Power: 883 μ W
- ✓ Active Area: 2.46mm²
- ✓ 31-Character
- ✓ **Accuracy: 91.3%**

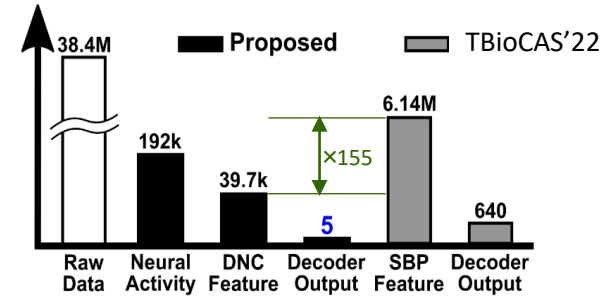
<https://techxplore.com/news/2024-08-miniaturized-brain-machine-interface-neural.html>
<https://newatlas.com/computers/mibmi-text-accuracy/>

M. Shaeri et al., *ISSCC'24, JSSC'24*

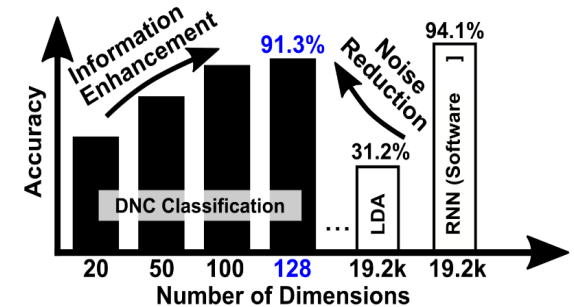
DNC-based Brain-to-Text BMI



Data Rate Reduction

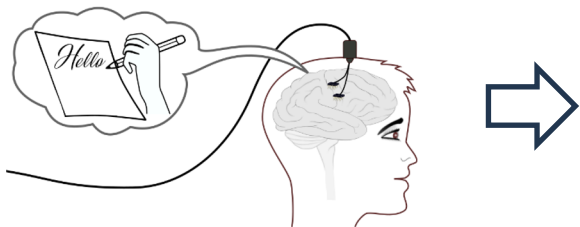


Decoding Accuracy Improvement

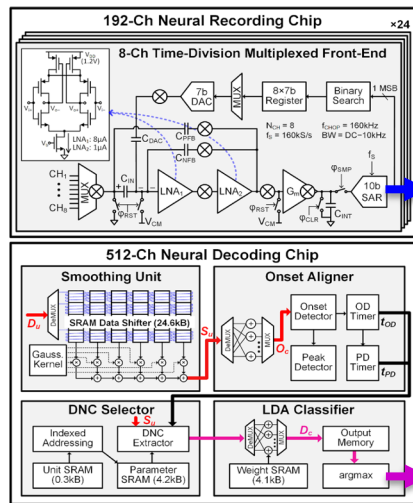


M. Shaeri et al., ISSCC'24, JSSC'24

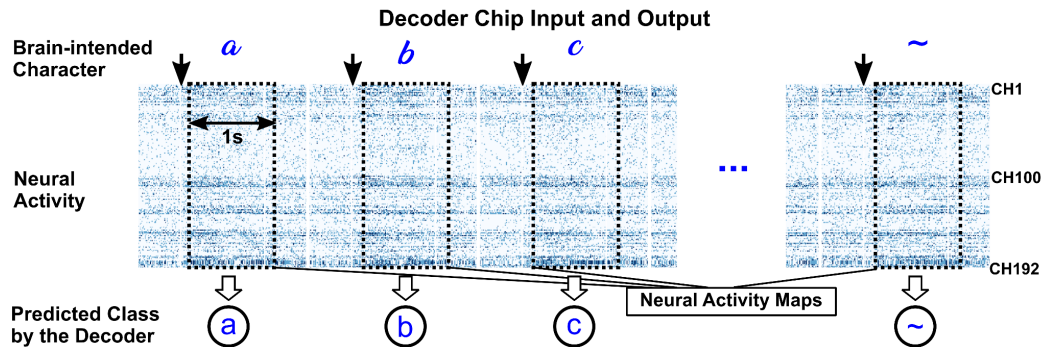
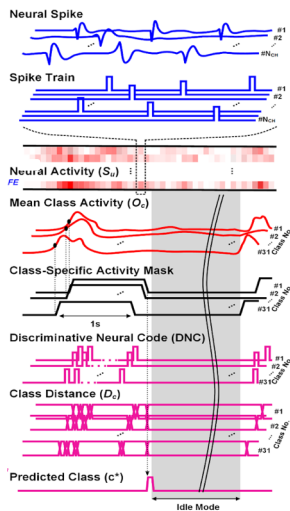
MiBMI Decoding Performance



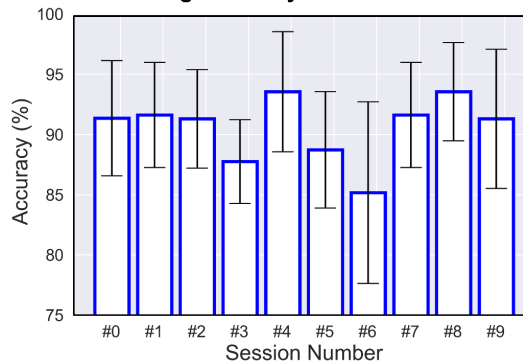
SoC Architecture



Timing Diagram



Decoding Accuracy across Sessions



Decoding Accuracy vs. Feature Dimensionality

