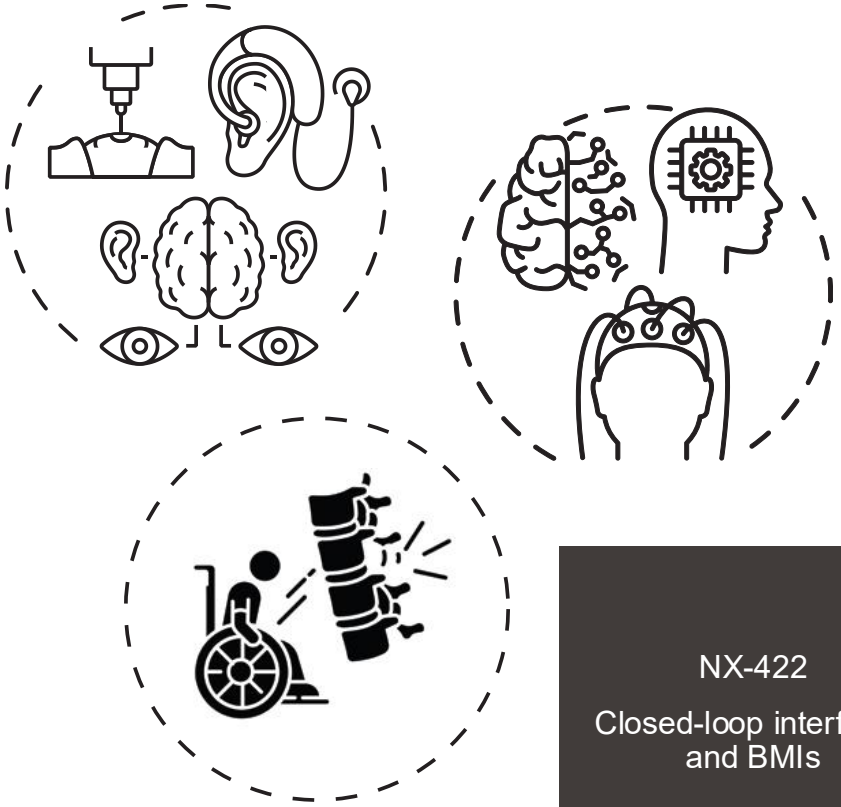


Neural Interfaces

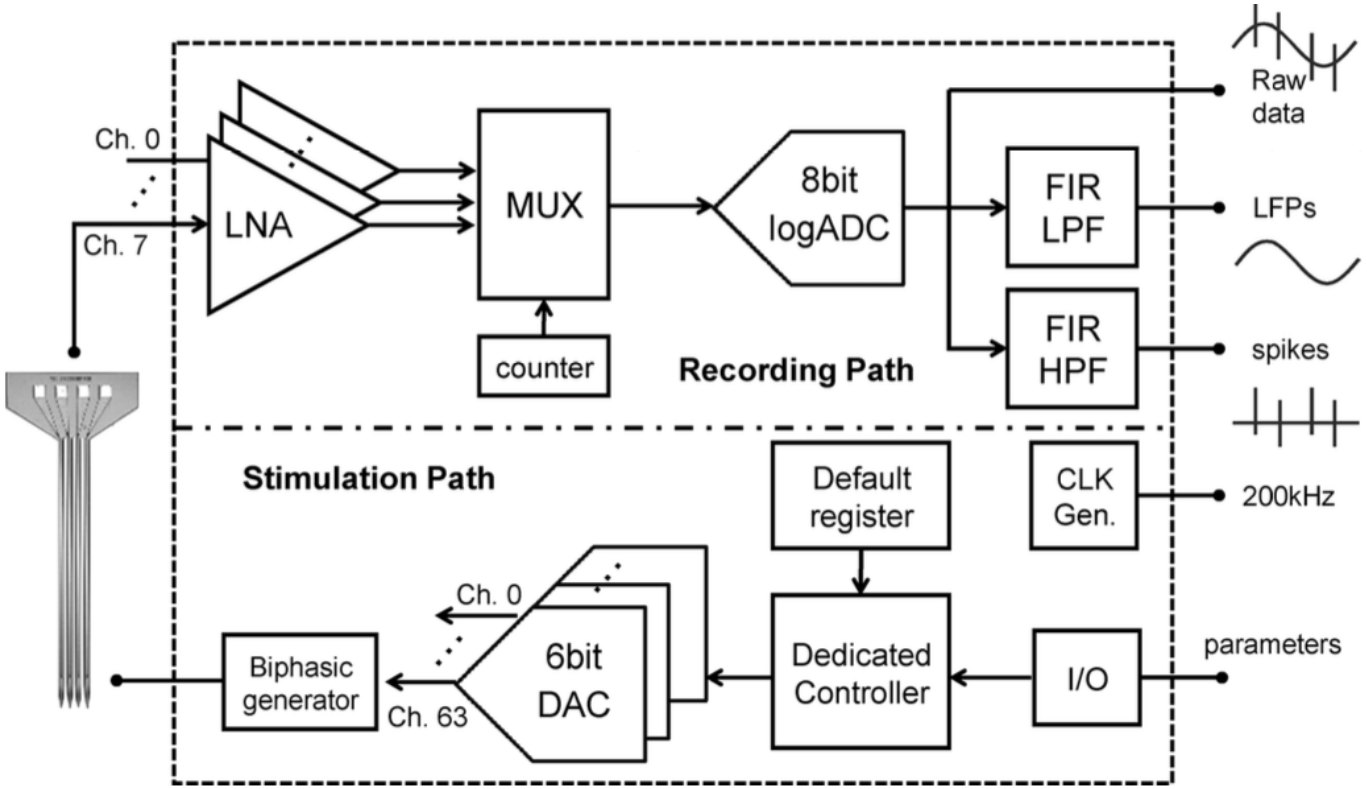
NX-422

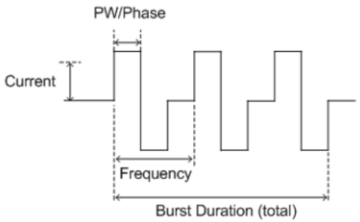
Closed-loop interfaces and BMIs

Mahsa Shoaran

IEM and Neuro-X Institutes

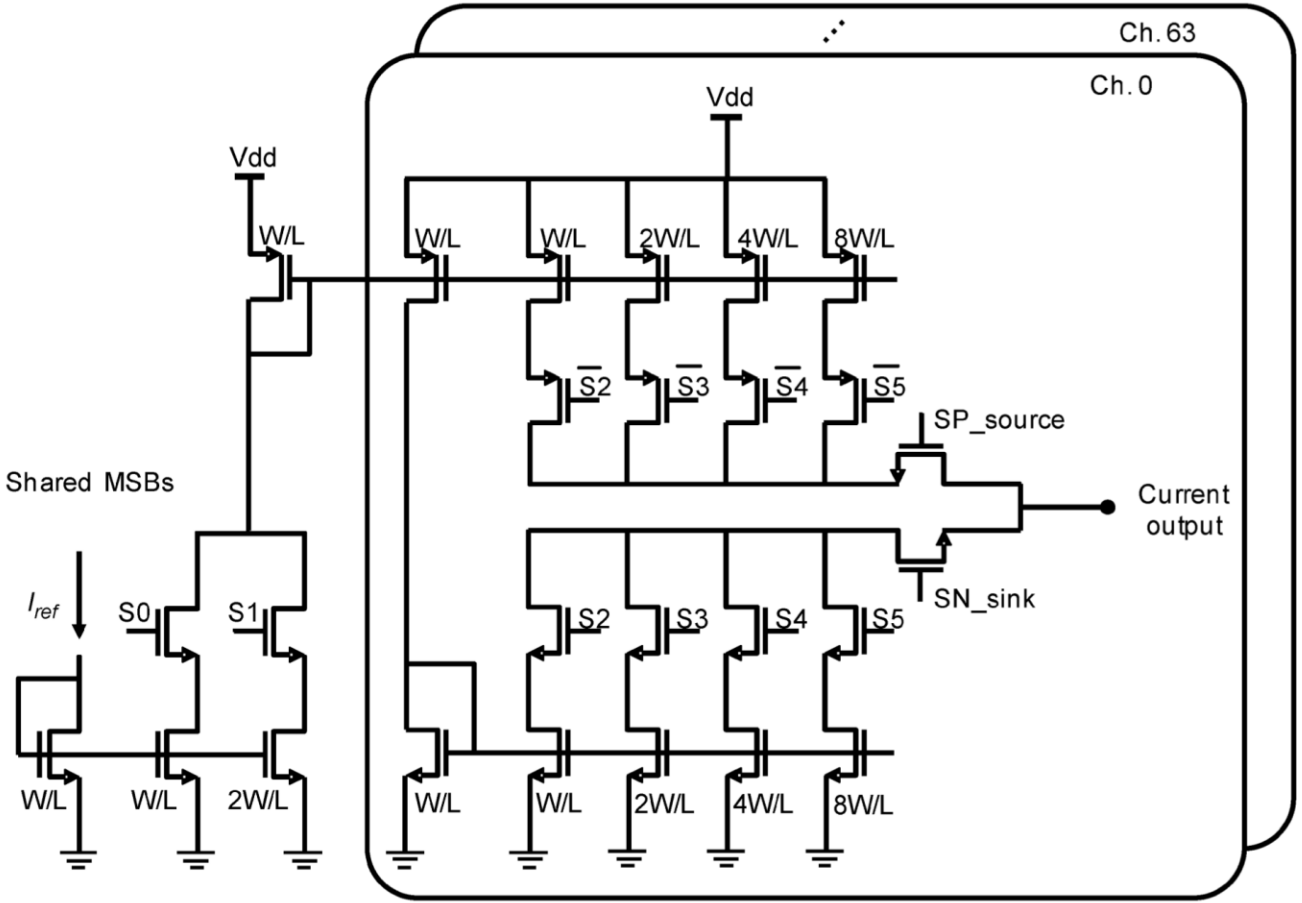
Recap: Neural Recording and Stimulation





J. Lee et al, JSSC'10

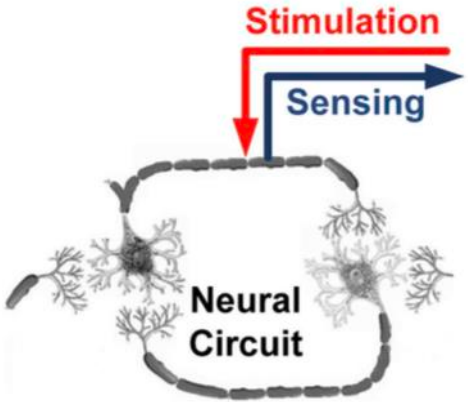
Recap: Stimulation Circuit

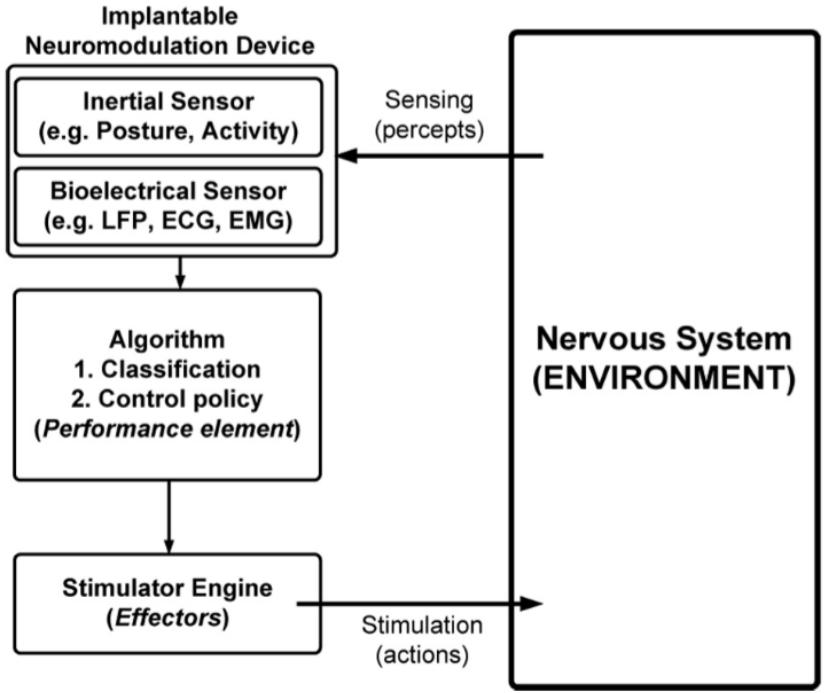


Closed-loop Neurostimulation

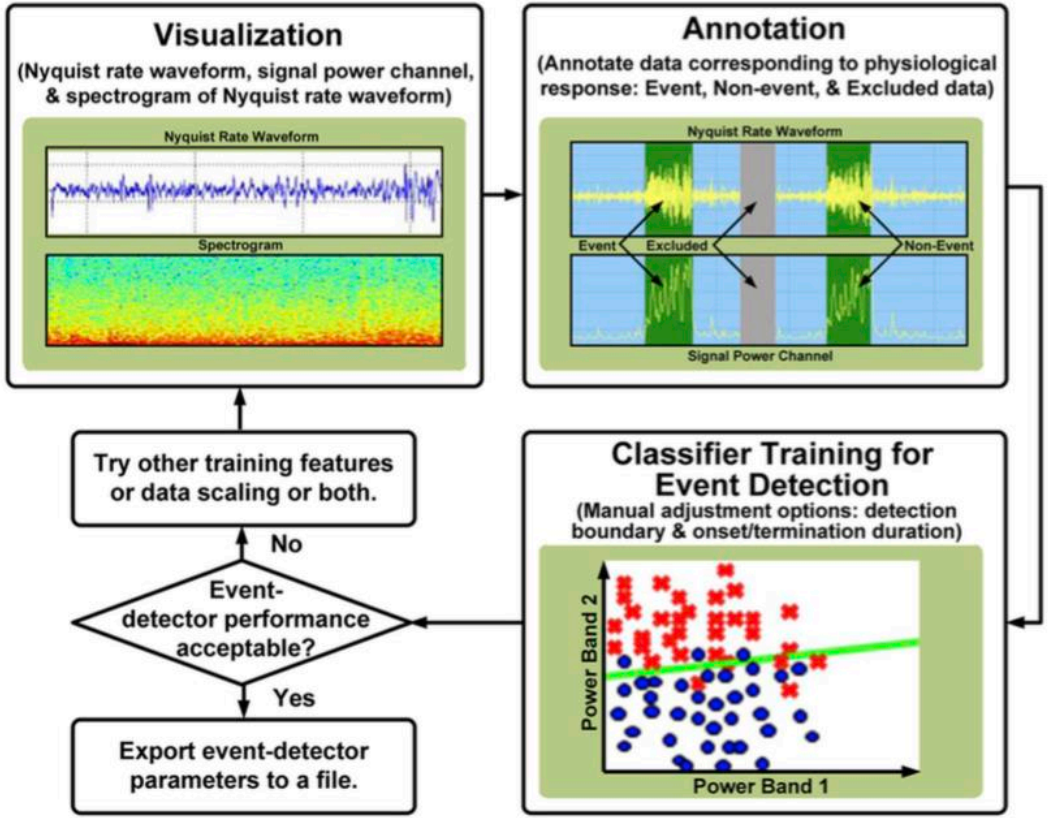
Drawbacks of Open-Loop Stimulation:

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



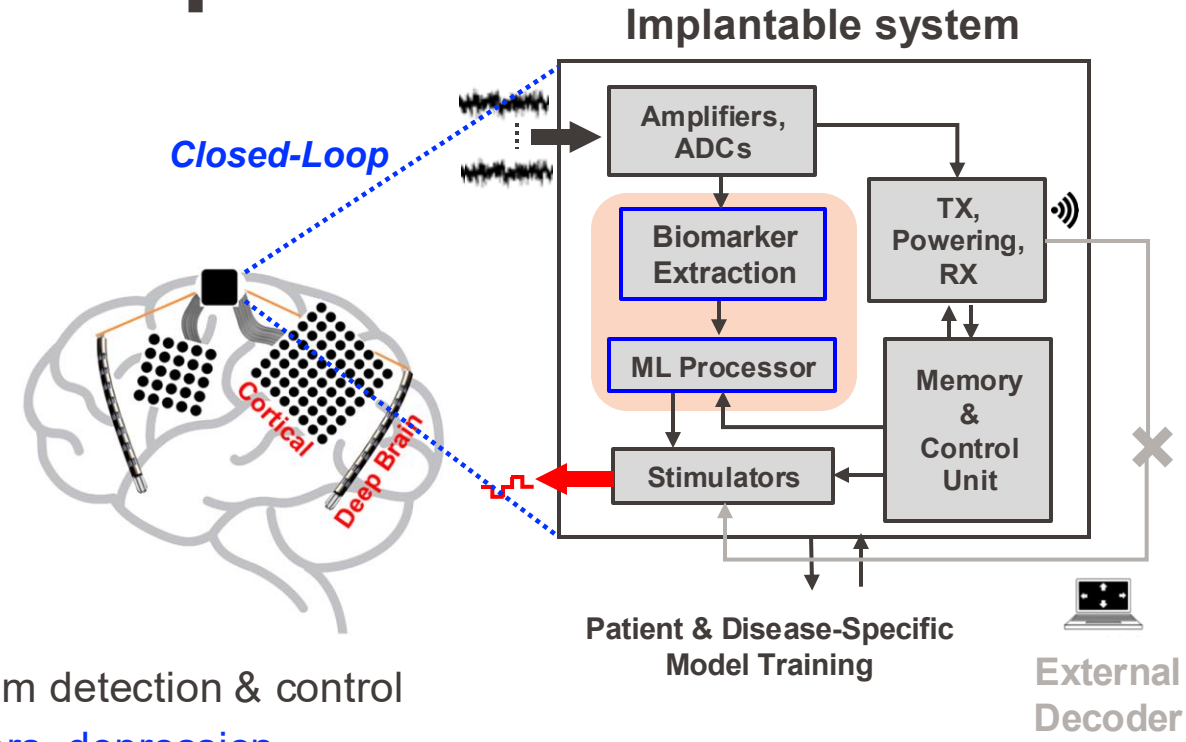


Neural Data Classification



Intelligent Closed-Loop Stimulation

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



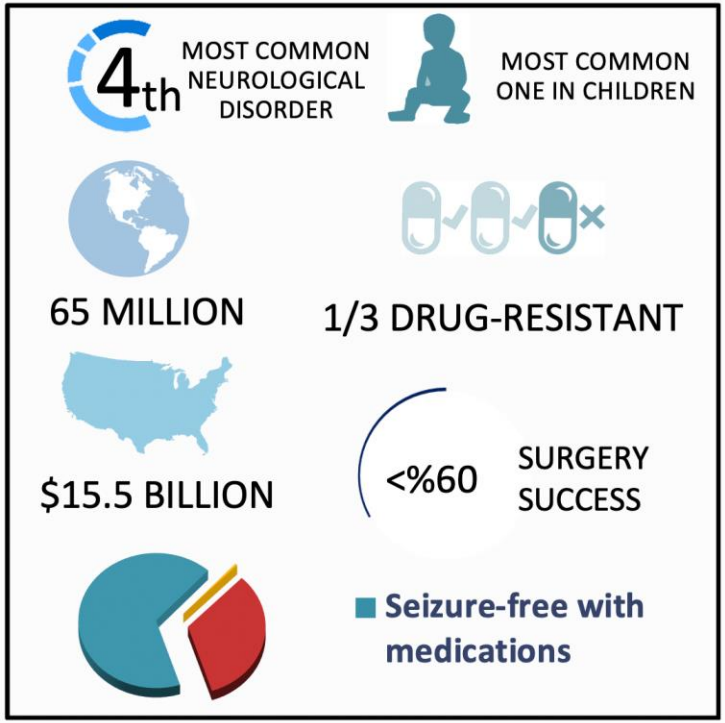
Application: Neurological symptom detection & control

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

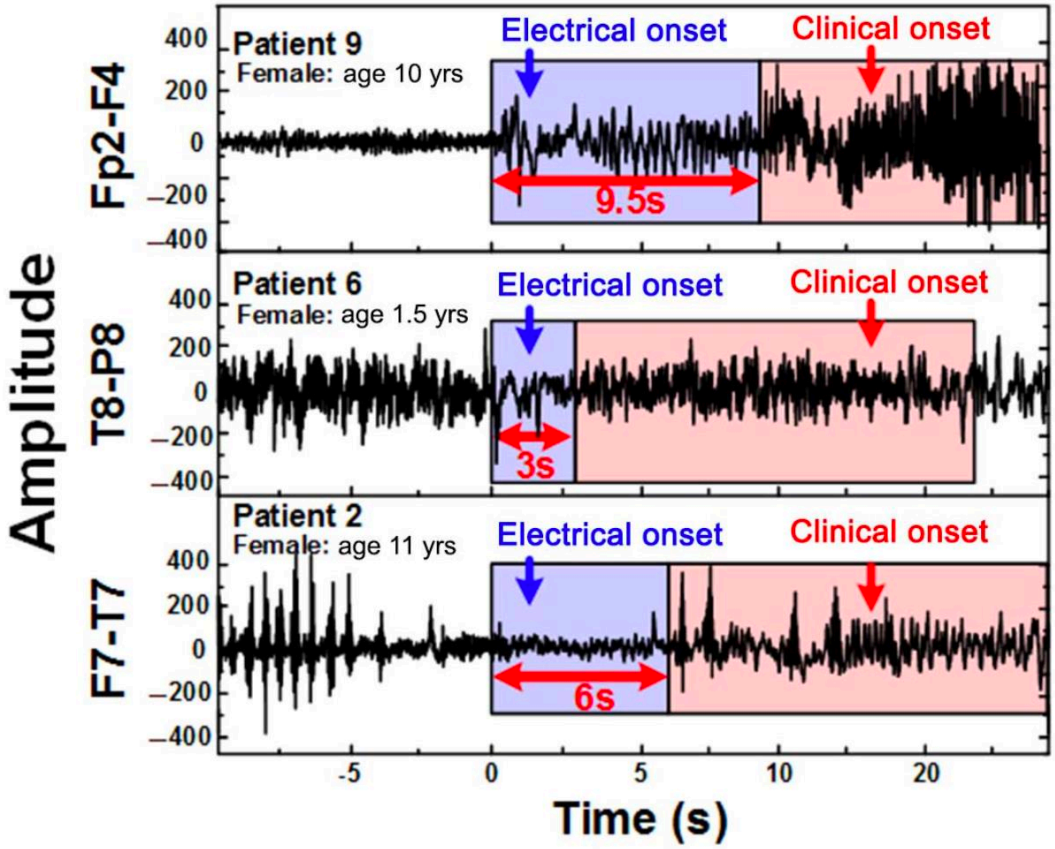
M. Shoaran, *Solid-State Circuits Magazine'23*
J. Yoo and M. Shoaran, *Curr. Opin. Biotechnol.'21*

Closed-Loop Stimulation for Epilepsy

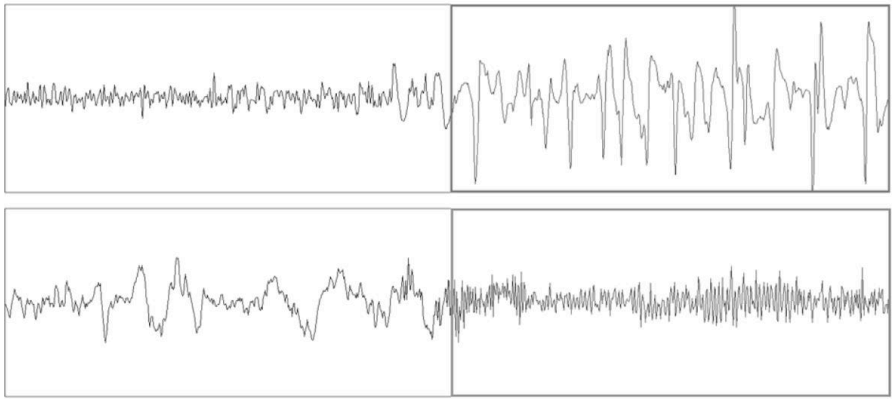
- Can we detect and prevent seizures?

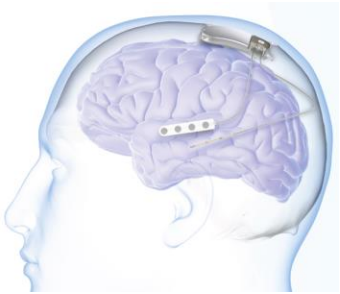


Epilepsy: Seizure Onset



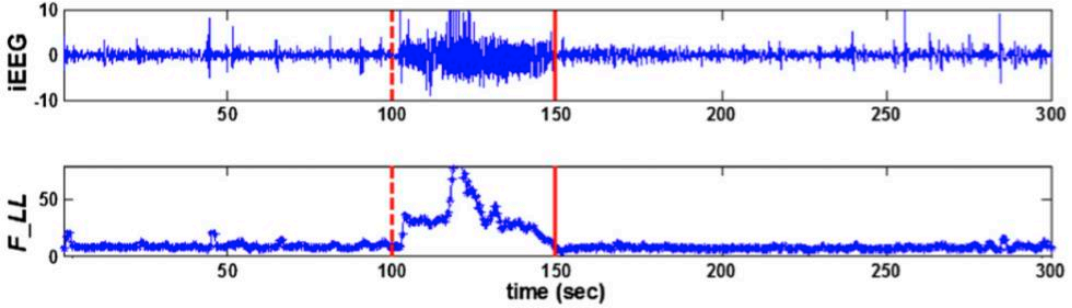
Feature (Biomarker) Extraction





Line-Length

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

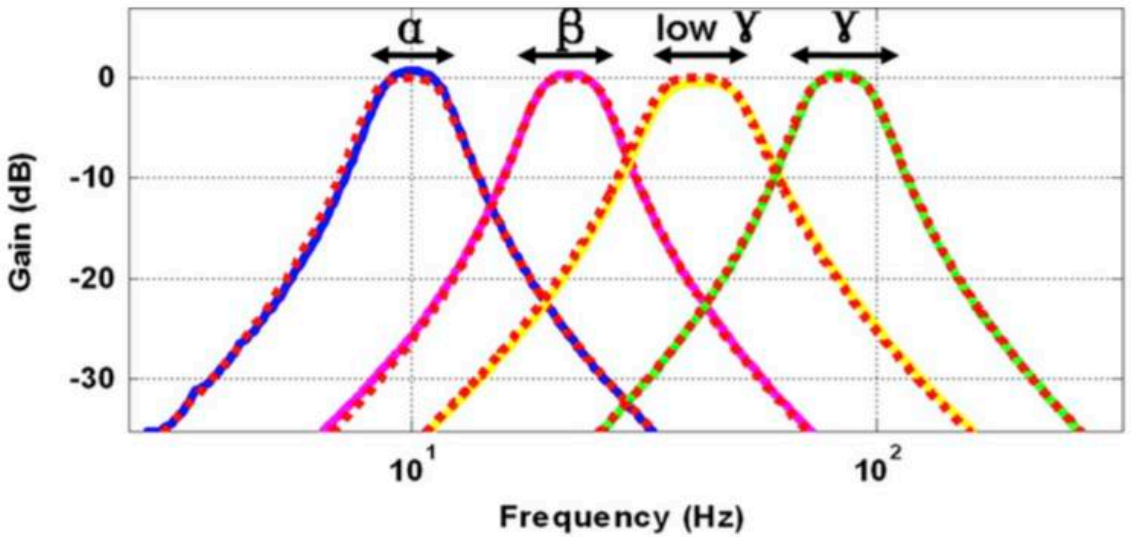


Feature (Biomarker) Extraction

Spectral Energy

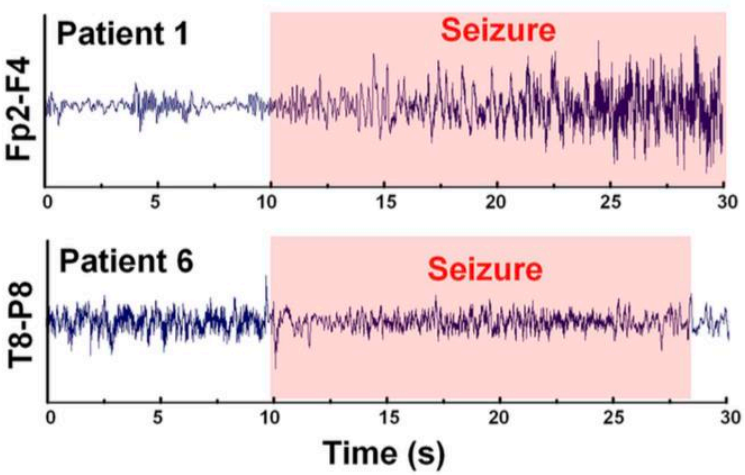
$$SE = \frac{1}{N}\sum_{t=1}^{N} x_{\mathrm{BAND},t}^{\,2}$$

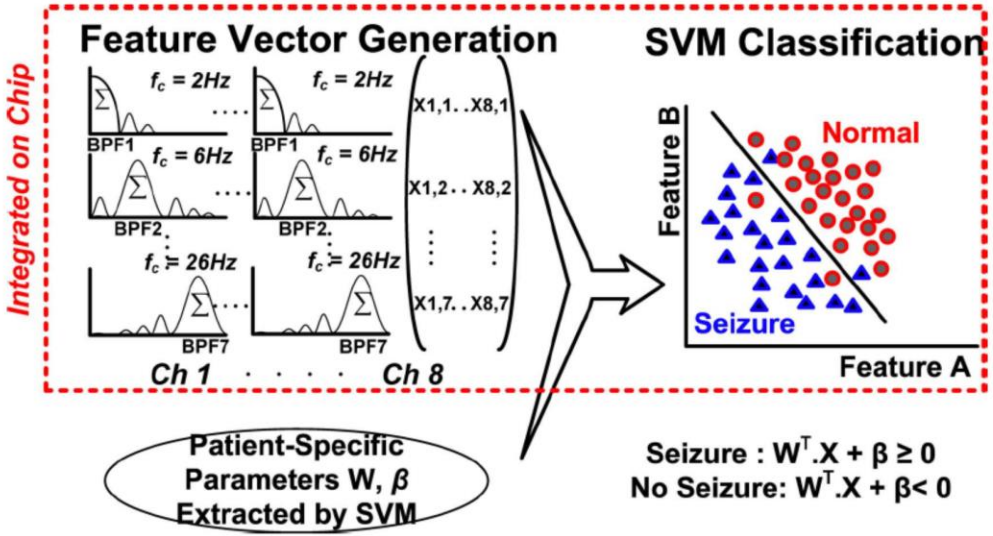
bandpass-filtered signal



Seizure Detection

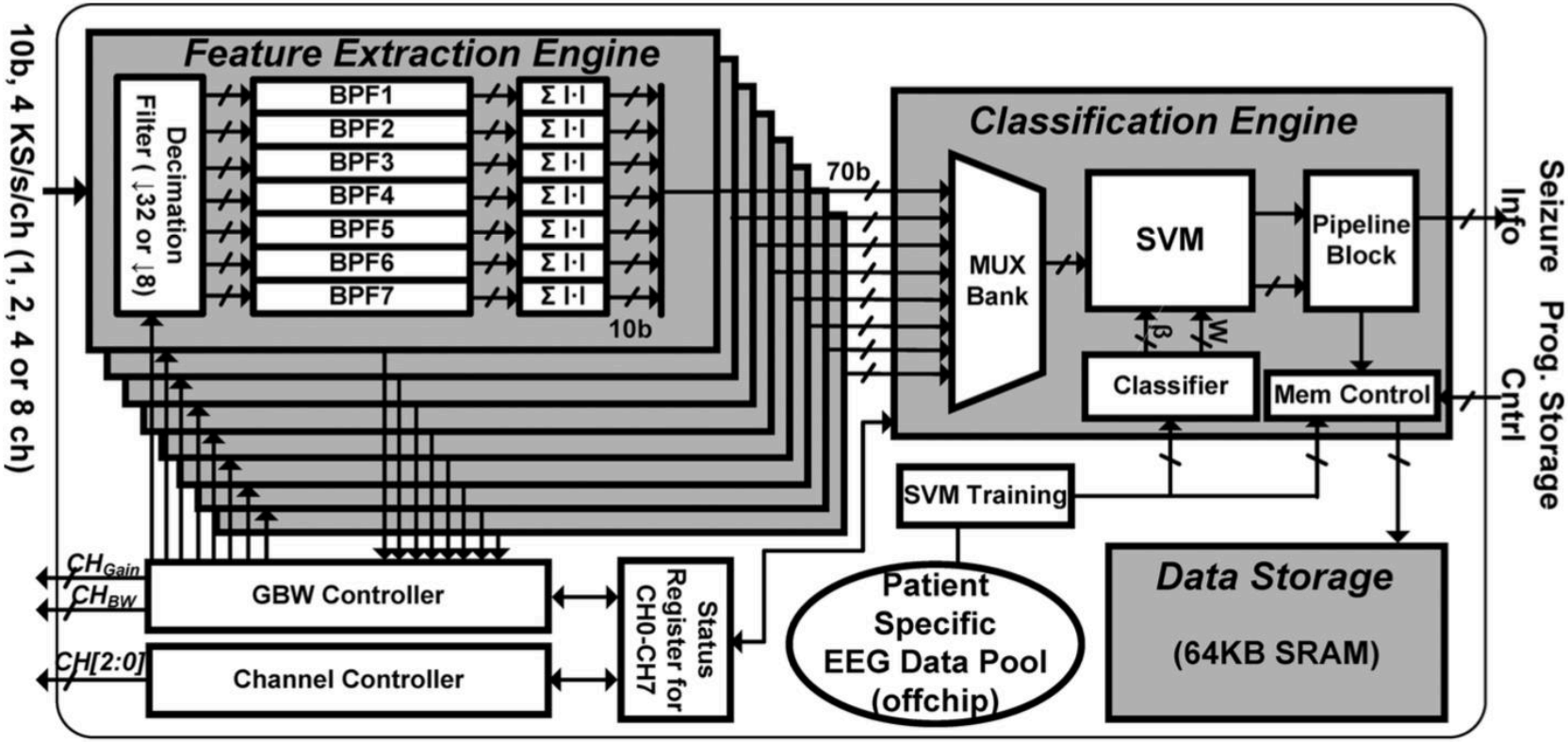
- Seizure patterns vary among patients >> need a classifier



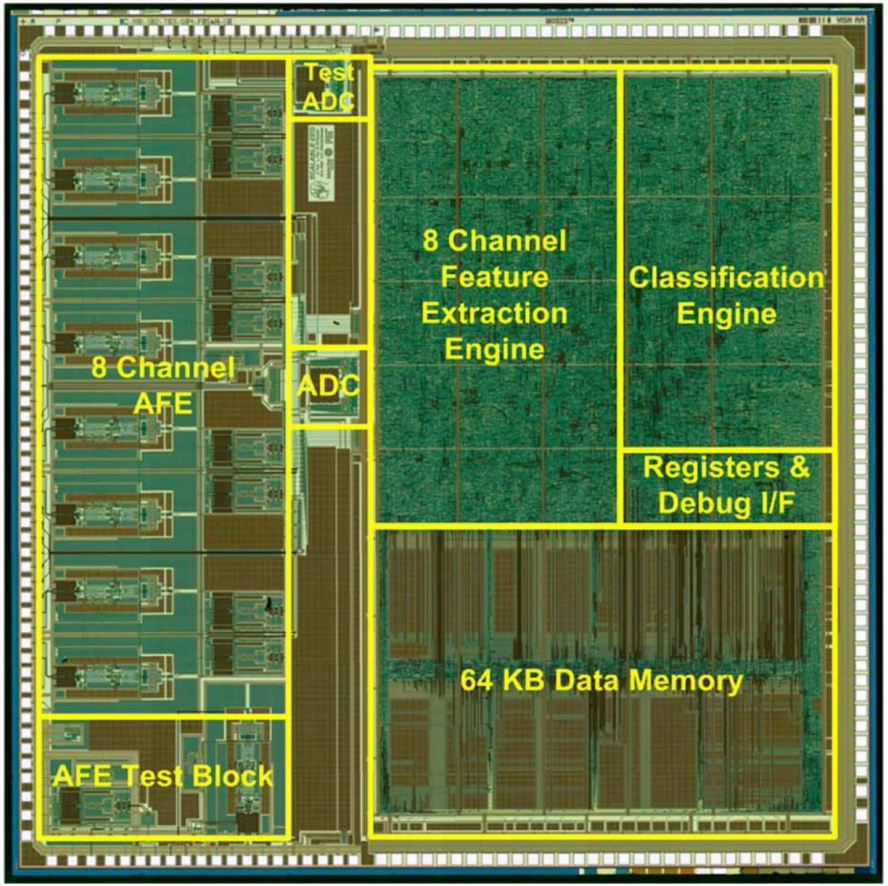


Model: Support Vector Machine (SVM)

Patient-Specific Classifier for Seizure Detection



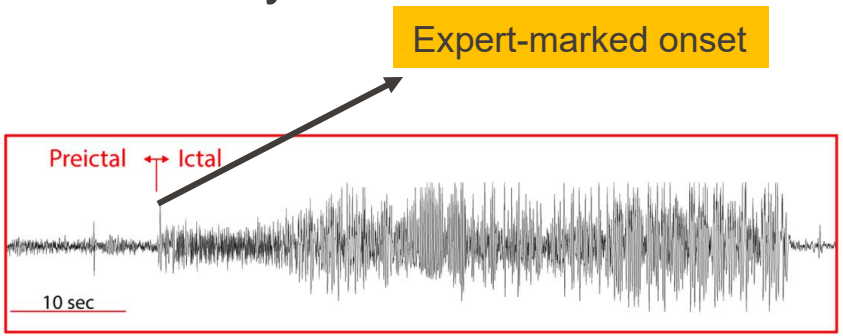
Chip Micrograph and Performance Summary



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	66μW
Bandwidth	30Hz / 100Hz
ADC	Fully Differential SAR ADC
	10b, 4-32KS/s
Classifier Type	Support Vector Machine
Latency	< 2s
Accuracy	84.4%
Efficiency	2.03μJ /Classification

Disease Detection Performance Metrics

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

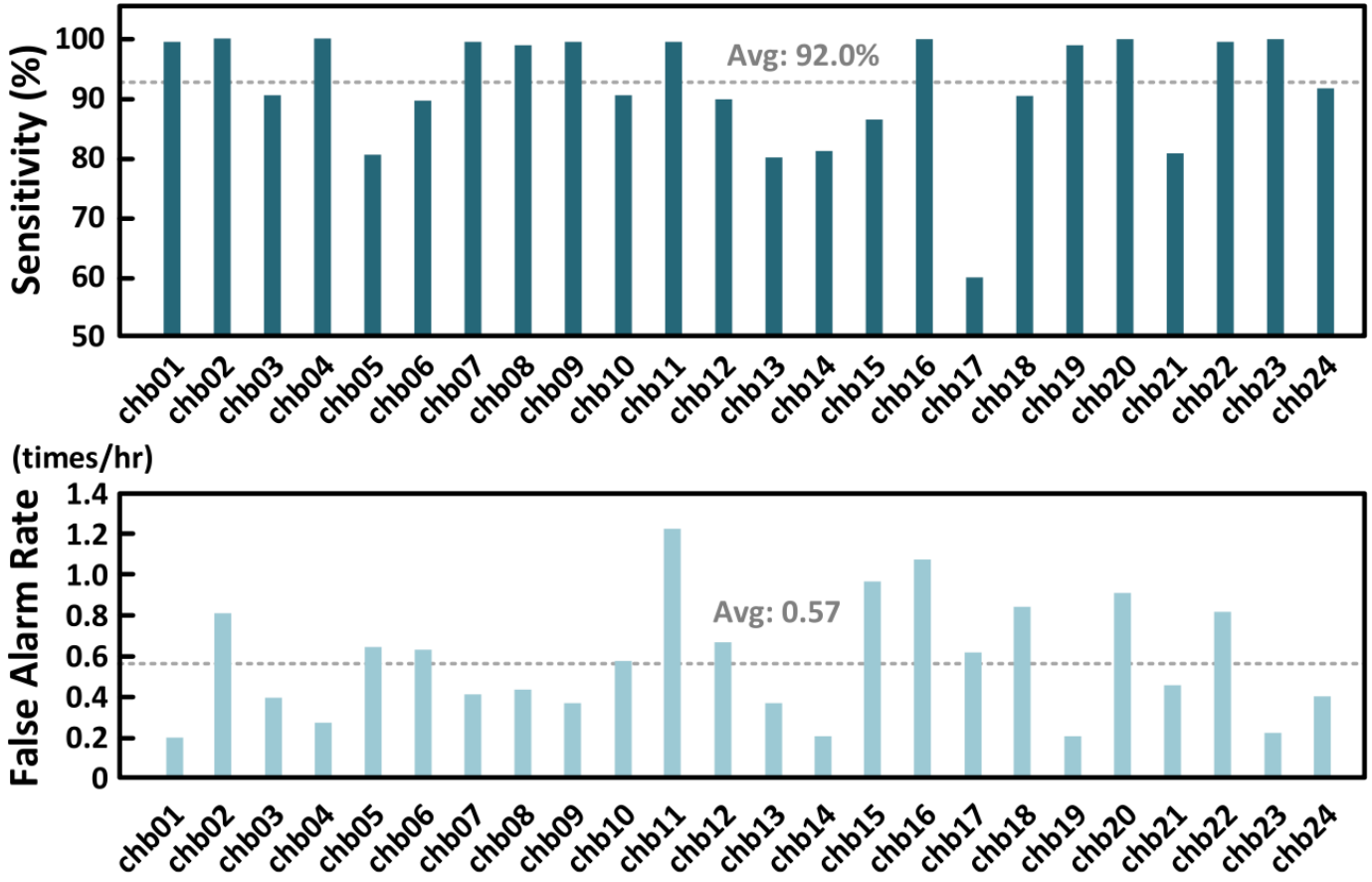


	Has the disease	Does not have the disease
	True Positives (TP) a	False Positives (FP) b
	False Negatives (FN) c	True Negatives (TN) d

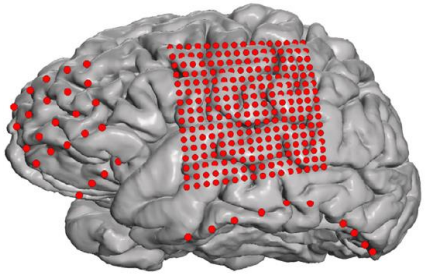
$$\text{Sensitivity} = \frac{TP}{TP + FN}$$

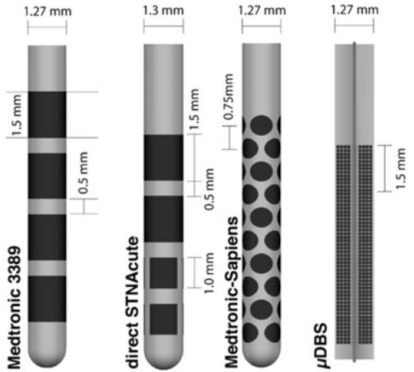
$$\text{Specificity} = \frac{TN}{TN + FP}$$

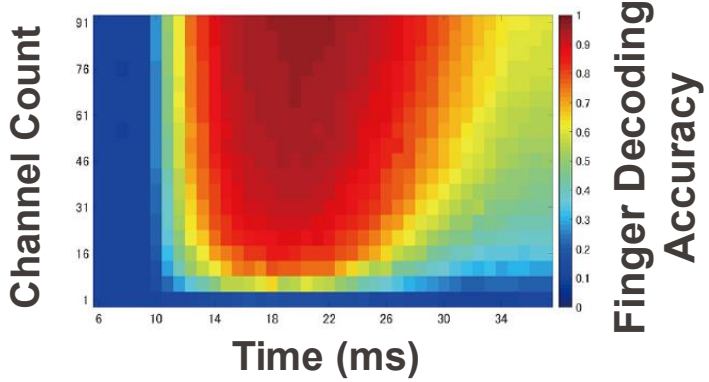
Classification Results on EEG Database



High-Channel-Count Sensing & Stimulation







Epilepsy

→ Early detection of seizure onset

→ Precise localization of seizure foci

Movement Disorders

→ Improved symptom detection/suppression

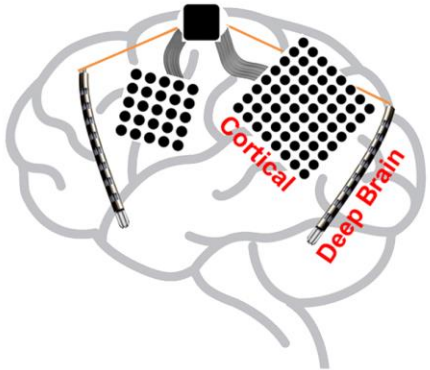
→ Reduced side effects of stimulation

Motor Prosthetics

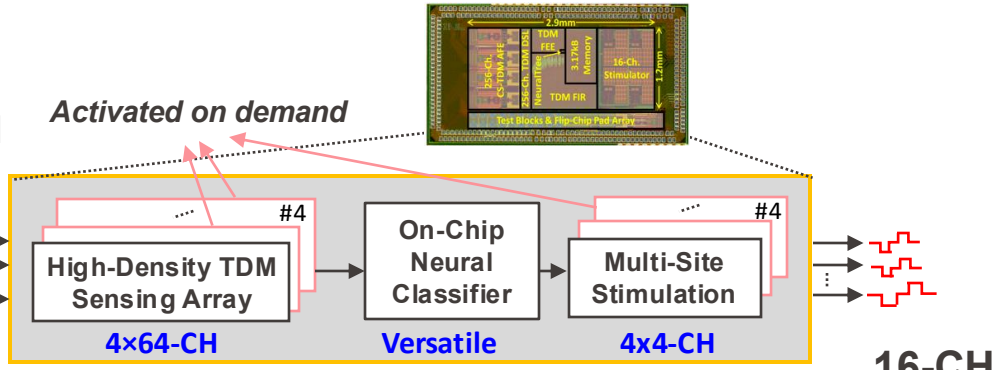
→ Precise motor decoding

→ More natural prosthetic control

NeuralTree: A 256-Channel Versatile Closed-Loop SoC



ECoG, LFP
BW: [1-500Hz]
Noise:
~3μVrms

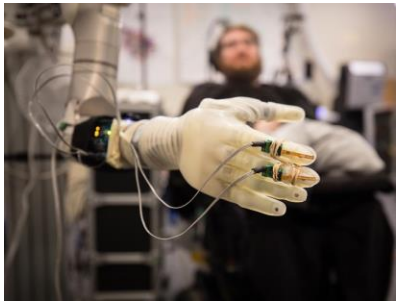


U. Shin et al., *ISSCC'22, JSSC'22*

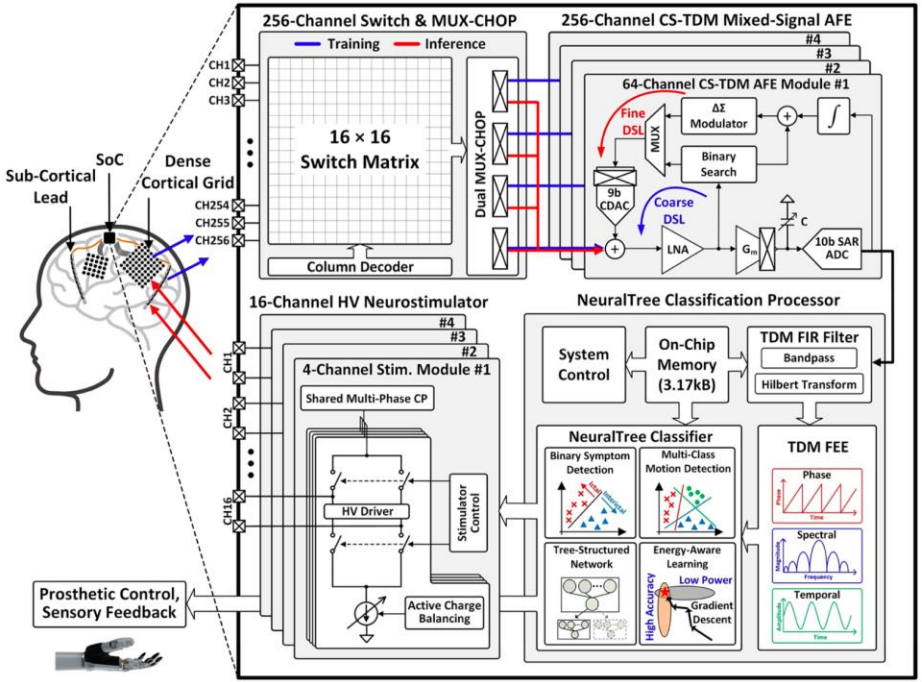
Epilepsy

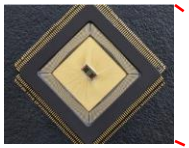
Parkinson's

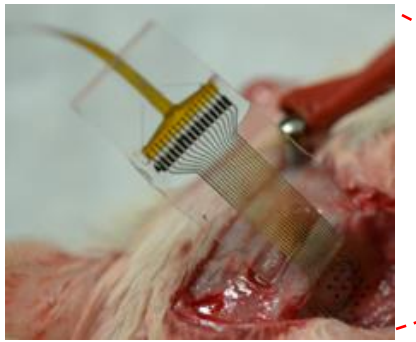
Paralysis

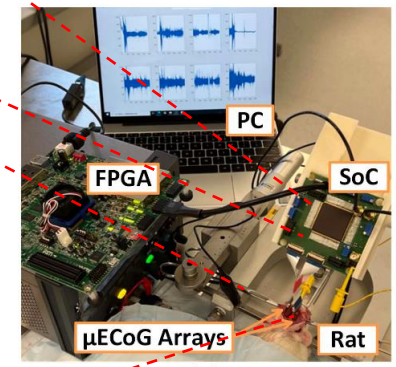


256-Channel Closed-loop Neuromodulation Chip

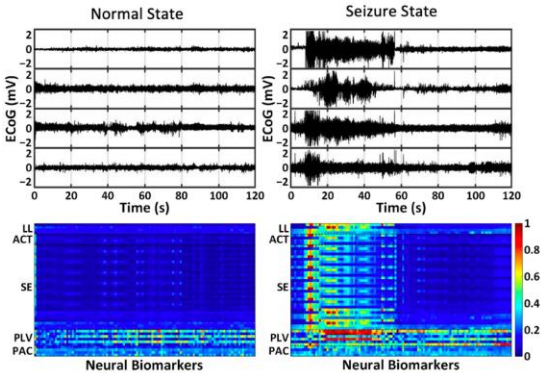






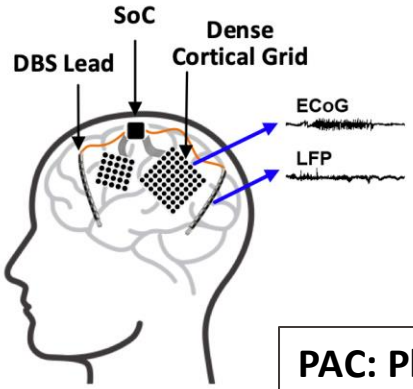


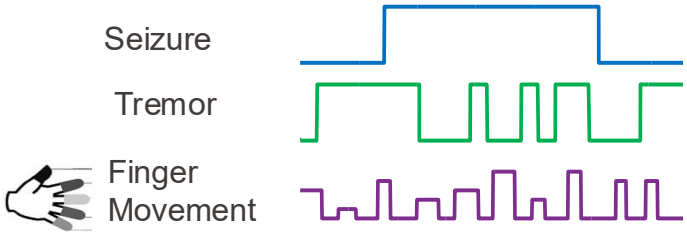
Soft µECoG Arrays (200-µm diameter)

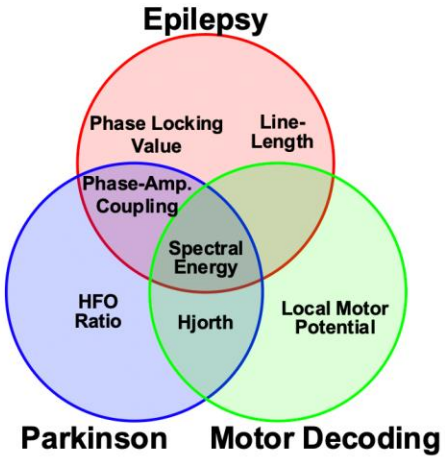


U. Shin et al., ISSCC 2022, JSSC 2022

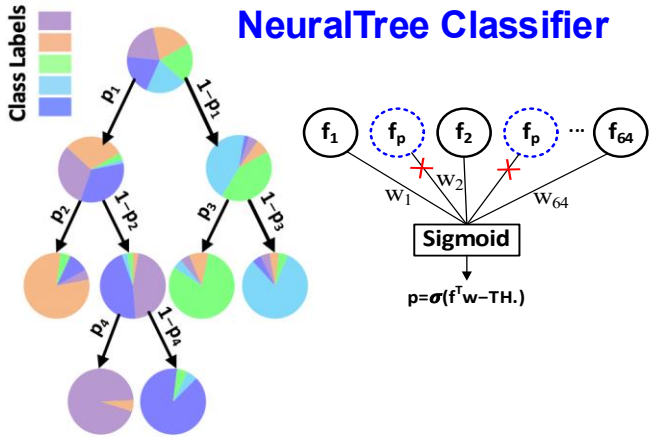
Versatile Brain Activity Classification



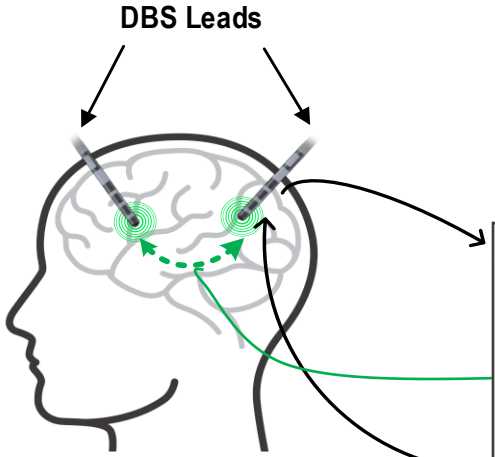




PAC: Phase-Amplitude Coupling
PLV: Phase Locking Value
SE: Spectral Energy
LMP: Local Motor Potential
LL: Line-Length
HFO Ratio: High-Frequency Oscillation Ratio
Hjorth: Hjorth Parameters



Cross-Regional Neural Synchrony in Psychiatric Disorders

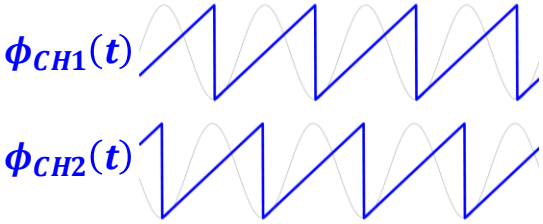


Network-based Biomarkers

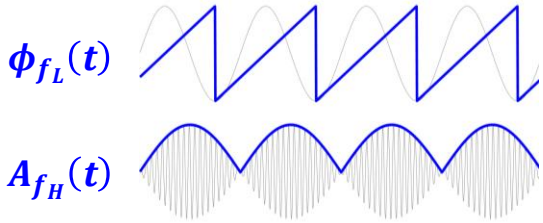
$$\mathrm{PLV} = \frac{1}{N}\sqrt{\left(\sum_{t=1}^{N}\sin\Delta\theta_t\right)^2 + \left(\sum_{t=1}^{N}\cos\Delta\theta_t\right)^2}$$

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

- **Phase Locking Value (PLV)**

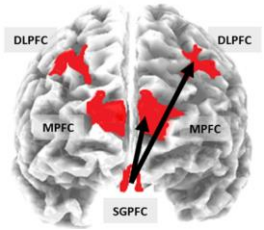


- **Phase-Amplitude Coupling (PAC)**



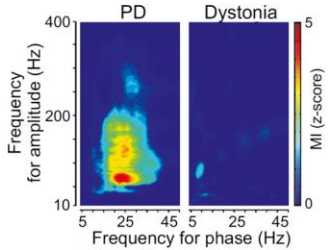
Depression

Increased phase synchrony *between prefrontal cortex regions*



S. Olbrich et al., *Psychiatry Res'14*

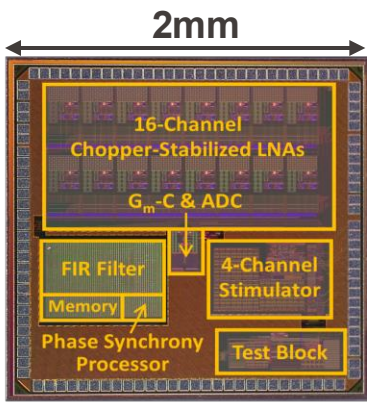
Parkinson



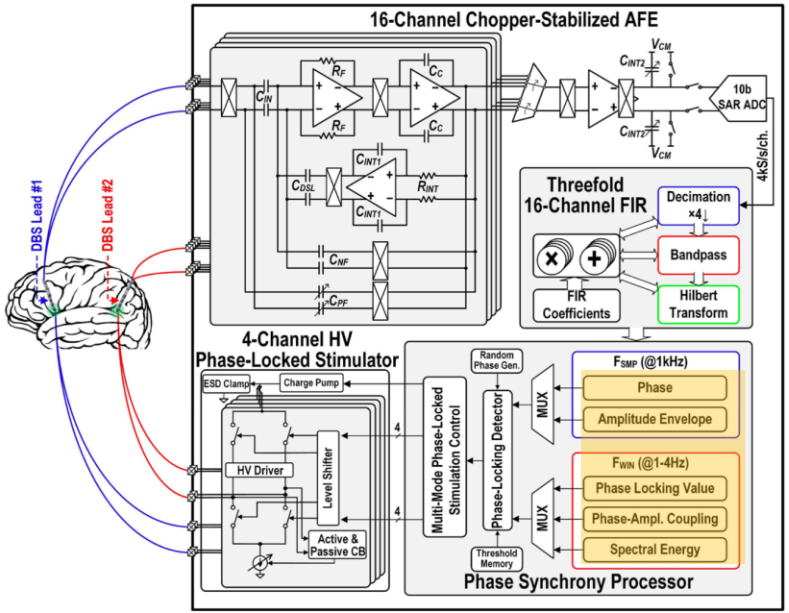
Excessive coupling *between STN phase and M1 amplitude*

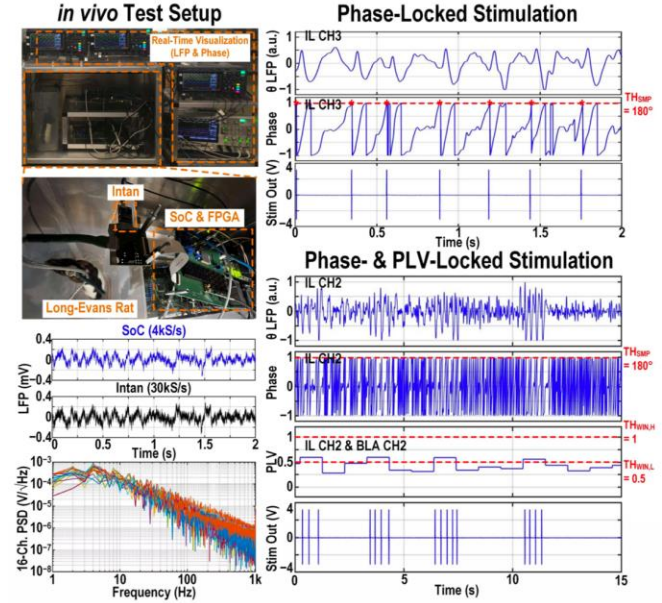
C. De Hemptinne et al, *PNAS'13*

Neural Synchrony Processor and **Closed-Loop DBS**



SoC Power: 60µW





Infralimbic cortex (Fear extinction)

Basolateral amygdala (Fear learning)

NIH National Institute of Mental Health

U. Shin et al, *CICC'22, SSCL'23*

EPFL