IEEE Brain Initiative

Society Members Research Activities (North America)

Presenter: Roman Genov, University of Toronto
(Contributors are credited throughout the slides)

Circuits and Systems Society
and
Solid-State Circuits Society

IEEE BRAIN Workshop
Dec 14th 2015 New York
Integrated Circuits Interfacing with the Brain

• Neural recording and neural stimulation
  - Both invasive and non-invasive
  - Recording: electrical, chemical, and optical
  - Stimulation: optical stimulation/optogenetics, current/charge-mode

• Closed-loop neural interfaces
  - Responsive neurostimulators (epilepsy), neurotransmitters control

• Neuronal modeling
  - Silicon neurons, spiking neural networks

• Other related topics (not discussed)
  - Wireless communications (transcutaneous)
  - Wireless powering (inductive, ultrasound)
  - Signal/information processing
  - In vivo applications (animal studies, clinical, wellness)
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Ken Shepard | Columbia University

Ultra-high-density multielectrode array

65k amplifiers, data rate almost 3 GB/s.

18,000 lines of Verilog; 38,000 lines of C++
Neural probe chip: electronics for in vivo shank electrodes

- 1024 channels
- 125-µm electrode pitch
- Multi-function: voltage recording, stimulate, current recording, current/voltage course
- Low-power
- 8 µV rms noise

Collaboration with Michael Roukes, Thanos Siapas, Caltech, Andreas Tolias, Baylor
Fully implanted wireless probes

- Eliminate wires through the skull
- Flexible CMOS makes shanks themselves less invasive
Small Size and Light Weight: 
\(~0.5\text{mm} \times 0.2\text{mm}, \sim 0.02\text{g}\)
- Freely-moving
- Multi-point implantation
- Deep brain implantation

Resolution: \(~10\mu\text{m}\)

<table>
<thead>
<tr>
<th>Type</th>
<th>Needle shape for deep brain</th>
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</thead>
<tbody>
<tr>
<td>Die size</td>
<td>450 (\mu\text{m} \times 1500 \mu\text{m})</td>
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<tr>
<td>Pixel number</td>
<td>40 \times 120</td>
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<tr>
<td>Array size</td>
<td>300 (\mu\text{m} \times 900 \mu\text{m})</td>
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<tr>
<td>Pixel size</td>
<td>7.5 (\mu\text{m} \times 7.5 \mu\text{m})</td>
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<tr>
<td>Fill factor</td>
<td>35%</td>
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<tr>
<td>Pixel structure</td>
<td>3T-APS</td>
</tr>
<tr>
<td>Technology</td>
<td>AMS 0.35 (\mu\text{m}) CMOS</td>
</tr>
<tr>
<td>Fluorescence filter</td>
<td>On-chip high-pass</td>
</tr>
<tr>
<td>Exc. light source</td>
<td>Chip LED</td>
</tr>
<tr>
<td>Coating</td>
<td>Parylene-C</td>
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</table>
Deep brain implantation

Observation of Dopamine activity in VTA region by administrating alcohol in TH-GFP Transgenic mice
Contact CMOS imaging device *in vivo* - Brain surface -

<table>
<thead>
<tr>
<th>Type</th>
<th>Planar shape for brain surface</th>
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<tbody>
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<td>Die size</td>
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<td>Array size</td>
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<td>Pixel size</td>
<td>7.5 µm x 7.5 µm</td>
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<td>Fill factor</td>
<td>35%</td>
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<tr>
<td>Pixel structure</td>
<td>3T-APS</td>
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<tr>
<td>Technology</td>
<td>0.35 µm CMOS 2P3M</td>
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<tr>
<td>Light sources</td>
<td>535 nm LED for blood flow</td>
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<tr>
<td></td>
<td>605 nm LED for Hb change</td>
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</table>
Polystim Neurotechnologies

Mohamad Sawan, Professor, Canada Research Chair
Polytechnique Montréal

Montreal, 5 Dec, 2015.
Interfaces cerveau-capteurs et actuateurs sans fil pour la récupération de fonctions nerveuses
Intracortical Neurostimulation: Recover Vision

- Stimulation & monitoring chips
- Wireless transceiver
- Control module
- Antenna

Interfaces cerveau-capteurs et actuateurs sans fil pour la récupération de fonctions nerveuses
Inductive Power & Data Links: Higher Performance

Power link = 1 MHz;
Down/Up links = 13.65 / 6.5 MHz
Unobtrusive Brain-Machine-Body Interfaces

Gert Cauwenberghs
Integrated Systems Neuroengineering Laboratory
http://isn.ucsd.edu
Wireless Non-Contact Biopotential Sensors

Mike Yu Chi and Gert Cauwenberghs, 2010

EEG alpha and eye blink activity recorded on the occipital lobe over haired skull
Non-Contact EEG Recording over Haired Scalp


- 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)

![EEG recordings](image-url)
Real-Time Estimation and 3D Visualization of Source Dynamics and Connectivity Using Wearable EEG

Mobile Dry EEG Brain-Body Activity Imaging

Cognionics 64-channel wireless dry EEG system
http://www.cognionics3.com

Mobile dry EEG ASR and SIFT video demonstration

UCSD SCCN SIFT and ASR http://sccn.ucsd.edu/wiki/SIFT
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Closed-Loop Neuromodulation w/ Electrical Stimulation Controlled by Neurochemistry
Neurochemostat System-on-Chip (SoC)

- Dopamine sensing with fast-scan cyclic voltammetry (FSCV), real-time interferent removal, and feedback-controlled electrical stimulation for closed-loop operation
**Neurochemostat SoC**

**Integrated Functionality**
- FSCV sensing
- FSCV waveform generation
- FSCV signal processing
- Chemometrics
- Feedback-controlled stimulation
- Embedded timing management
- RF-FSK TX @ ~433 MHz

**Power Supply**
- Recording = 2.5 V
- Processing = 2.5 V
- Stimulation = 5 V

- AMS 0.35 µm 2P/4M CMOS
- Die size = 3.3 mm × 3.2 mm

*VLSI’ 15 – Pedram Mohseni, EECS – CWRU*
Dopamine Regulation in Rat Brain

- Closed-loop dopamine regulation *in vivo* after real-time differentiation from pH change and electrode current drift as common interferents

![Graph](image_url)
Georgia Tech: Maysam Ghovanloo
Energy-efficient Neuro-Stimulators for Optogenetics

GT-Bionics Lab
School of Electrical and Computer Engineering
Optical stimulation to visual cortex in the brain of anesthetized viral-transfected rats + local field potential (LFP) recording.

Lee and Ghovanloo, JSSC’15
- Instantaneous LFP Phase

- Optical stimulation (100ms) with $V_{LED} = 2.7V_{Peak}$
- Optical stimulation (100ms) with $V_{LED} = 3.2V_{Peak}$

- Instantaneous phase of light-induced LFP at 1~25Hz

- No phase consistency w/ $V_{LED} = 2.7V_{Peak}$, while clear phase synchronization during optical stimulation w/ $V_{LED} = 3.2V_{Peak}$.
Closed Loop Seizure Detection and Suppression
Herming Chiueh
National Chiao Tung University, Taiwan
Animal Test of Seizure Detection

Long-Evans rats with spontaneous absence seizure

Pre-amplifier with 3,000x gain

Spike-wave discharge shown on LabVIEW-based GUI (200S/sec)
Seizure Detection Without Stimulation

AFE output

Amplitude (V)

-1 to 1

Wireless transmitter signal

Time (s)

4 to 12

Stimulator enable signal

Seizure Detection With Stimulation

AFE output

Amplitude (V)

-1 to 1

Wireless transmitter signal

Time (s)

4 to 12

Stimulator enable signal

Micro-system assembly for animal tests

Functional verification platform
Wireless Closed-Loop Neurostimulators for the Treatment of Intractable Epilepsy

Roman Genov, Tariq Salam, Hossein Kassiri, Nima Soltani, Jose Luis Perez Velazquez

Department of Electrical and Computer Engineering,
Hospital for Sick Children
University of Toronto
roman@eecg.utoronto.ca
Closed-loop neurostimulator
  - For drug-resistant epilepsy
  - Seizures predicted and aborted

Wireless data

Inductive powering
Toronto Integrated Neural Interfaces (TINI)

**2007**
- Toronto Integrated Neural Interfaces (TINI)
- ISSCC 07
- JSSC 09
- 256 recording channels
- On-chip gold electrodes

**2009**
- 128 recording channels
- Column parallel 8-bit SAR ADC
- 128 voltage stimulation channels

**2010**
- 256 recording & stimulation channels
- In-channel 8-bit single slope ADC
- 64 current stimulation channels
- In-channel 8-bit SAR ADC
- 64 FIR filters
- FSK Wireless TX

**2011**
- ISSC 11
- JSSC 13
- 64 recording channels
- UWB Wireless TX
- Seizure detection & control
- Phase synchrony features

**2012**
- TBIOCAS 13
- 64 recording & 64 stimulation channels
- DC-coupled front end
- Triple-band TX
- Seizure detection & control
- Phase synchrony features

**2013**
- CICC 11
- JSSC 13
- 64 recording & 64 stimulation channels
- UWB Wireless TX
- Seizure detection & control
- Phase synchrony features

**2014**
- ESSCIRC 14
- 0.13µm
- 64 recording & 64 stimulation channels
- DC-coupled front end
- Triple-band TX
- Seizure detection & control
- Phase synchrony features
Closed-Loop Neurostimulation

- Monitoring
  - Assisted living
    - e.g., in ALS
- Diagnostics
  - Wireless monitoring
    - e.g., preoperative epileptic seizure localization
- Treatment
  - Automated (closed-loop) control
    - e.g., intractable epilepsy → seizure abortion
Cellular Inductive Powering

BioCAS 13, TBioCAS 16

MAGNETIC FIELD COVERAGE

RAT CAGE FOOTPRINT

CELLULAR INDUCTIVE FLOOR

COIL ORGANIZATION

COMMAND AND POWER RECEIVER (ON-CHIP)

ACTIVE RECTIFIER

VOLTAGE REGULATORS

ASK RX

DAC8

VREF8

VREF1

CLOCK

POWER

REFLECTED FIELD

PA1

PA4

...
Seizure Control Example
with Tariq Salam and J L Perez Velazquez, Epilepsia 2015

- ~5 seizures per day
- 500 seizures
- Detection sensitivity = 89%
- False alarm = 0.24 per day

-5 of 6 animals became seizure free
- No adverse effect
- ~93% seizure reduction
3,500-hour Seizure Control Statistics

with T. Salam, J L Perez Velazquez, Epilepsia 2015
with S. Gabran and R. Mansour, TNSRE 2013-14

• 24/7 chronic video monitoring and treatment
Penn Engineering and School of Medicine

Xilin Liu, Milin Zhang, Timothy Lucas, Drew Richardson and Jan Van der Spiegel
Jan Van der Spiegel University of Pennsylvania Closed-loop Bi-directional BMI System

System Overview

Sensors

Sensing data

Computer
(User Interface)

Config./Mod.*

Data/Feature

BMI Device

Stimulation

Recording

Subject
(Unrestrained Animals)

Sensing Signal

*Modulation

*Xilin Liu, et al., ISCAS 2014 and

TBioCAS 2015

University of Pennsylvania

Closed-loop Bi-directional BMI System
Wireless electrogoniometer

Bidirectional Neural Interface

Neural signal

Action potential spike counts

24h LFP recording from freely moved animal
BOOTSTRAPPING CLINICAL NEUROSCIENCE CONSIDERATIONS FOR THE DESIGN AND DEPLOYMENT OF RESEARCH PAYLOADS

TIMOTHY DENISON, PH.D.
TECHNICAL FELLOW
SR. DIRECTOR OF CORE TECHNOLOGY
MEDTRONIC NEUROMODULATION
CONCEPT OF EMBEDDING “SCIENTIFIC PAYLOADS” IN A MEDICAL DEVICE
PROBE “TRANSFER FUNCTIONS” OF NEURAL NETWORKS AND APPLY TO ALGORITHMS

Stanslaski et al., IEEE Neural Engineering, 2011
NEURAL CIRCUIT TRANSFER FUNCTION AND ALGORITHM EXAMPLE
PARKINSON’S PATIENT’S RESPONSE TO ELEC. STIMULATION (CHRONIC W/ ACTIVA PC+S)

INSTRUMENTATION PAYLOAD CONSIDERATIONS

- Sensing ~1uVrms signals during stimulation (~120dB)
- Ensuring signals are not saturating (robust algorithms)
- Synchronization of instruments (implanted/lab clocks)
- Clinician correlation with symptoms
  - Define the key biomarkers
  - Define transfer function
  - Map to a closed loop algorithm

Quinn et al. Beta Oscillations in Freely Moving Parkinson’s Subjects Are Attenuated During Deep Brain Stimulation, Movement Disorders, 2015
NEED FOR TOOLS FOR ITERATIVE ALGORITHM DEVELOPMENT

COMPUTERS-IN-THE-LOOP/CLINIC → EMBEDDED ARCHITECTURES

A translational platform for prototyping closed-loop neuromodulation systems

Pedram Afshar*, Ankit Khambhati, Scott Stanislawski, David Carlson, Randy Jensen, Dave Linde, Siddharth Dani, Maciej Lazarewicz, Peng Cong, Jon Giftakis, Paul Stypulkowski and Tim Denison*
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Silicon Models of Neurons

Ralph Etienne-Cummings
Dept. of Electrical and Computer Engineering and Computer Science
Johns Hopkins University
Neuron Models in Silicon


After wikipedia.com
Ralph Etienne-Cummings  Johns Hopkins University
Silicon Models of Neurons

Tier C - Neuron

Tier B - Synapse

Tier A - Communication

3D CMOS Design

Request → Receiver → Vsyn → W0-W3

Acknowledge → Transmitter → Spike

Vsyn

\[ \phi_2 \]
\[ C \]
\[ 2C \]
\[ 4C \]
\[ 8C \]

W0 W1 M16

M17 W2 M18

W3 M19

\[ \phi_1 \]

Vm

Comp

Spike

EL

\[ \phi_1 \]

\[ \phi_2 \]

\[ \phi_1 \]

\[ \phi_2 \]

M1

Vm

\[ \phi_1 \]

\[ \phi_2 \]

M2 Cm

Spike

EL

SW1

\[ \phi_1 \]

\[ \phi_2 \]

M3

M4

Spike

As

\[ \phi_1 \]

\[ \phi_2 \]

\[ \phi_1 \]

\[ \phi_2 \]

M5

C9

SW2

\[ \phi_1 \]

\[ \phi_2 \]

SW3

\[ \phi_1 \]

\[ \phi_2 \]

SW4

\[ \phi_1 \]

\[ \phi_2 \]

\[ \phi_1 \]

\[ \phi_2 \]

\[ \phi_1 \]

\[ \phi_2 \]

thetaReset

thetaReset

\[ \theta_\text{Inf} \]

\[ \theta_\text{Reset} \]
Neuron Design Stages

- Tonic Spiking
- Spike Frequency Adaptation

F. Folowosele et al., *IEEE TNN*, 2011
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