Implantable Neural Electrodes

Implantable Electronics Session

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Opener - Electrodes Implanted in the Brain

video clip on deep brain stimulation
Today's clinical application involve

- **Peripheral nervous system**
  - Cardiac pacing
  - Cochlear implants
  - Bladder management
  - Pain management
  - Epilepsy treatment
  - Breathing
  - Depression
  - (...)

- **Central nervous system**
  - Parkinson's disease
  - Dyskinesia
  - Obsessive compulsary disorders
  - Retinal implants
  - Epilepsy diagnosis
  - (...)

*Neuromodulator 'Restore Ultra' by Medtronic source: Arle 2011*
Communication Pathways of the Body

- central nervous system
- peripheral nerves
- spinal cord
- spinal roots

source: www.invanet.org (2012-03-14)
Neural Bioelectricity

source: http://upload.wikimedia.org (2012-03-14)
Electrode Designs

- Implanted cardiac pacemakers: since 1950s
- Neural stimulation and recording

- Many lessons learned on materials in living host environment
  - Corrosion resistance of metals
  - Polymer degradation
  - Chemical toxicity

source: Love 2006
Interaction Between Technical Systems and the Body

• For a successful implantation, the following is required:
  - The technical system must withstand the harsh body environment
  - The technical system must not disturb body function

• As consequence,
  - The implant location inside the body restricts potential implant shapes
  - Only a limited set of materials can be used for implants: 'Biomaterials'

• \textit{Pt, Ir, PtIr, IrOx, TiN, cobalt-based alloys, stainless steel, gold}

• \textit{Silicones, PTFE, parylene, polyimide, polyesterimide}
Electrode Designs

- Cochlear electrode array
- Stimulation and recording
- Platinum or PtIr
- 16 electrode sites

source: Zhou 2011
Micromachining (1960s)

250,000
brain cells

250,000
transistors

source: www.livenano.org (2012-03-12)
Micromachining

source: Wise et al., 1969
Micromachining of Silicon Substrates

Silicon-Based Microelectrode Arrays

- silicone substrate
- min. feature sizes ~ 5 µm
- metallisation layers: some 100 nm
- insulation layers: some 1 µm

source: Zhou 2011

source: Grand 2010
Micromachining: 3D Arrays
Micromachining: Integration of Electronics

**Smart Electrodes**
- on-board electronics:
  - radio transmitters
  - amplifiers, etc.
- difficulty: small size hermetic package
- CHECK POSTER!

source: Kim 2009
Reduction of signals quality months (inflammation)
Definition Today

*Biocompatibility* refers to the ability of a material to perform with an appropriate host response in a specific situation.

*source: Grand 2010*
Micromachining: Polymers as Substrate Materials

Polyimide Electrode Array (plain + electronics)

source: Schuettler

source: Stieglitz 2009
Active Arrays (360 channels, integrated silicon switches)

source: Viventi 2011

Biostability?
Simple Equivalent Circuit

- $C_H = \text{Helmholtz Capacitance}$
  defined by electrode surface area

- $V_{EE} = \text{Electrode / electrolyte voltage}$
  dominated by electrode material and electrolyte

- $R_L = \text{Leakage resistance}$
  dominated by electrode surface area, and electrode material, allows current to leak through $C_H$

- $R_A = \text{Access Resistance}$
  dominated by electrode size and electrolyte resistivity $\rho$
Limits for Miniaturization

Stimulation Properties

- Pulse testing
- Max. injectable charge

- Electrode potential vs. SHE
  - 1.32 V: oxygen gassing (pH 0)
  - 0.82 V: start of oxygen evolution (pH 7)
  - 0.57 V: oxidation of platinum

- Water window for platinum electrodes (~ 2 V)
  - H-atom plating
    - 0.41 V: start of hydrogen evolution (pH 7)
    - 0.83 V: hydrogen gassing (pH 14)
Limits for Miniaturization - Electrochemistry

Shrinking Geometrical Electrode Area

- Decreases electrode capacitance
  - reducing safe charge injection limit
- Increases access resistance
  - increases thermal noise
  - increases compliance voltage required

Increasing Active Electrode Area

- Surface roughness increases electrode capacitance
  - Mesh electrodes
  - Platinum black / grey

source: Schuettler, 2007
source: Park, 2007
source: Schuettler, 2005
Electrode Coatings

Metal / Metaloxides
- Pt gray / black
- Iridium oxide

Polymeric Electrode Materials
- Nanotubes, doped PEDOT, doped diamond, ....
- Very high (initial) charge injection capacity
- Option of filling with chemical agents, controlled drug release

Long-Term Biostability?
Laser Micromachining

Laser Fabrication

- Only approved implant materials
- Lean production line
- Limited definition (~25 µm)
- Soft & stretchable
- Fluidic channels (controlled drug release)
- Integration of electronics (see poster)

Source: Suaning 2007

Source: Schuettler 2011

Source: Schuettler 2009
Optogenetics

*nature: method of the year 2010*

- Virus infection of selected nerve cell population
- Cell activity becomes sensitive to light
  - 473 nm (facilitate)
  - 593 nm (inhibit)
- Facilitated or attenuated spiking activity (detected electrically)
- Investigation of local function of specific nerve cell population within complex neural circuits (behaviour).

source: Rubehn 2011
Summary

In a Nutshell

• Neural electrodes have to be designed according to the application
• Each application is associated with a most suitable fabrication technology (hand / laser / photolithography)
• Microfabrication of neural electrode arrays is now transferred (after 40 years!) to clinical applications.
• This (among the technological progress in hermetic packaging) permits the fabrication RELIABLE active implantable medical devices with high channel count, opening the door for many challenging applications like
  - Retinal implant
  - Brain computer interfaces
• Optogenetics: Neuroscience gets a novel, powerful tool
• Problems: Mechanical properties / active electronics / wiring