Next-Generation, Implantable Technologies: Materials, Power/Telemetry, and Sensors

An alternative and accessible version of this presentation is available at 1:15 pm in the Videocast of Day Two

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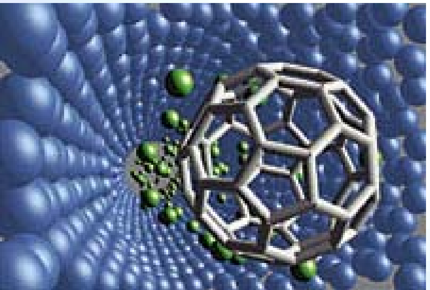
Curing Epilepsy 2007

March 28-30, 2007



Grand Challenge: Neurological Disorders

What is required to:

- Measure, analyze, and understand the spatial and temporal characteristics of normal and abnormal neuronal events
- Respond to the abnormal, excessive and/or hypersynchronous, neuronal activity within the brain leading up to and during seizures

Why Implantable Devices?

- Seizures are uncontrolled by AEDs in a large fraction of patients, and in such instances epilepsy surgery or implantable devices may be appropriate

- Intracranial EEG monitoring (with depth, strip or grid electrodes) is employed to determine areas of seizure onset and plan the surgical procedure

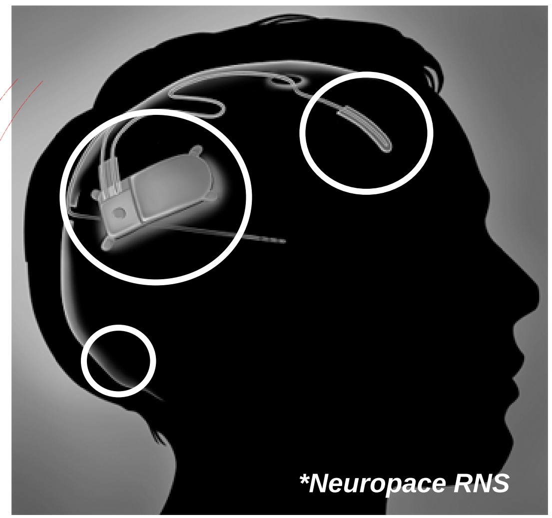
- Limitations of intracranial EEG monitoring
  - Infection
  - Patient mobility
  - Mass of wires
  - Signal to noise ratio
  - Modalities, sensor size, spatial sampling

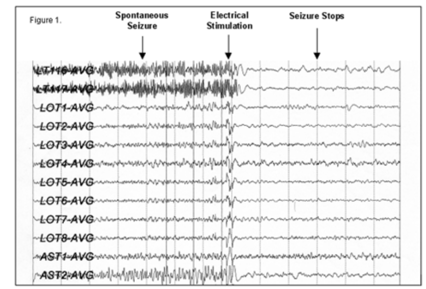
Implantable Devices - Components

Implantable Device
•Microprocessor controlled

Data/Signal Processing

Telemetry/Comm Link
•Broad band/low power





Power

•High Energy Density Generation/storage

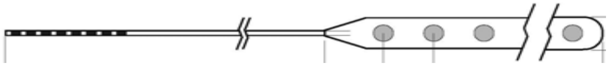
Sensors/Electrodes
•Electrical/optic

Materials
•Bio/MR compatible

- Implantable Device OEMs
  - Neuropace, Medtronic, Cyberonics

Sensors – Electrodes

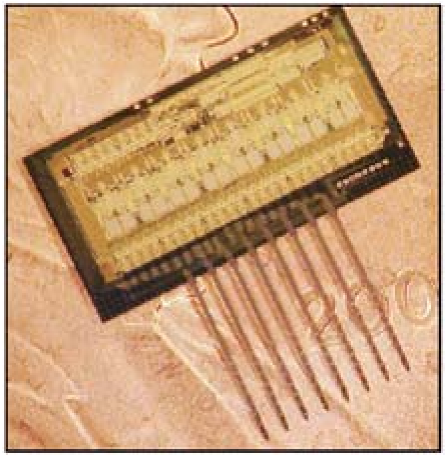
- Building an electronic (chemical) interface to the cellular world
  - Monitoring Electrodes: record local voltage associated with ionic current flow around a neuron when it fires in response to inputs received from other cells



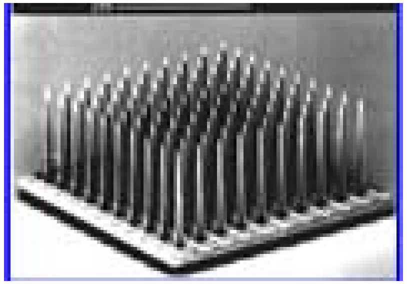
Subdural strip

  - On-chip circuitry (Brain Computer Interface)
    - 8-channel stimulating probe on U.S. penny
      - 127 μA every 4.5 μsec
      - 3 μm features
    - 100-electrode recording system

8-channel Integrated System (U. of Michigan)

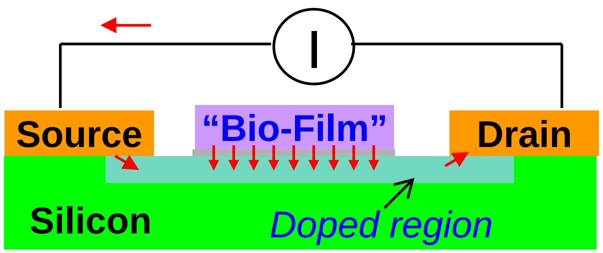


Utah 3-D Array Flip-Chip Bonding



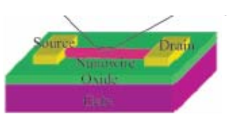
Biosensor – Field Effect Transistor

- Conversion of Biological to Electrical signal with transistor
  - Small size (SOA less than 100 nm) with increased sensitivity
  - Simple function, adaptable to remote operation
- BioFET: principle of operation
  - Injection of holes/electrons from biologically active film into doped-semiconductor (bio-film → “floating gate”)
  - Measure resistance change across source/drain electrodes (apply current)

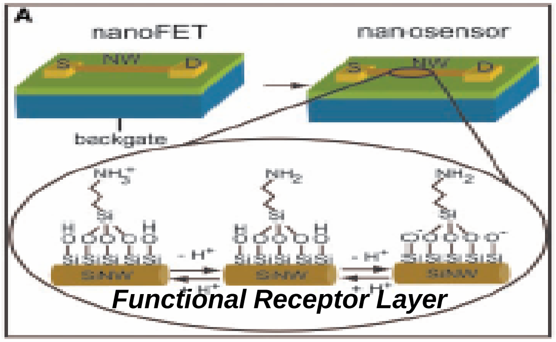


Field Effect Transistor

- Use of silicon nanowires to increase sensitivity/reduce size



Si-Nanowire FET

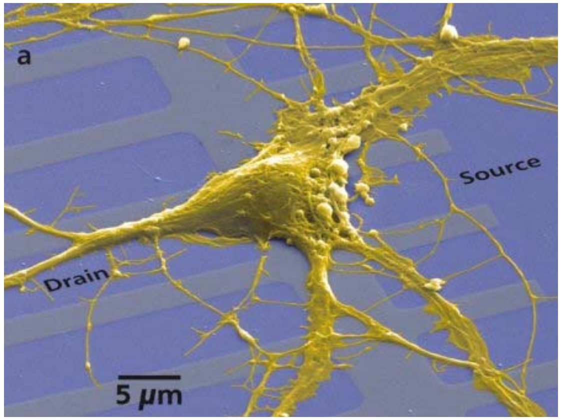


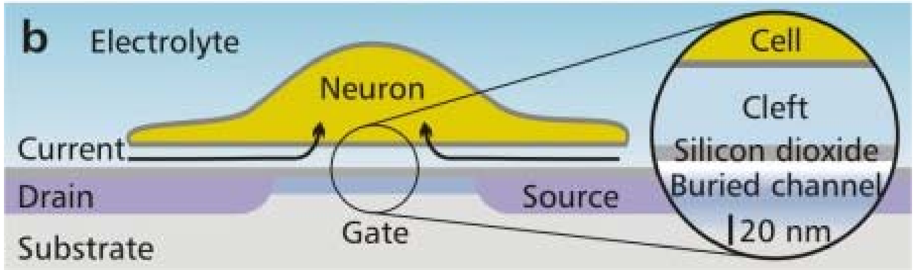
Si-NanowireSensor

(i.e., Lieber)

FET Biosensor

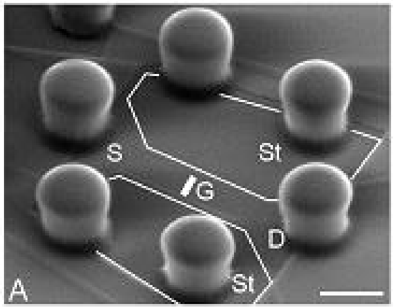
- Neuron-Semiconductor (FET) Interface*
  - Rat Neuron on electrolyte-oxide-silicon transistor



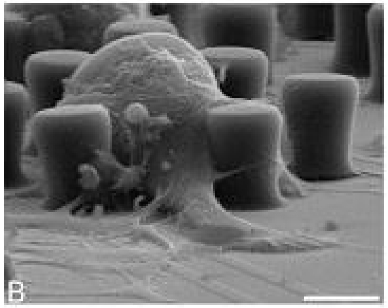


Schematic cross-section of a neuron on a transistor*

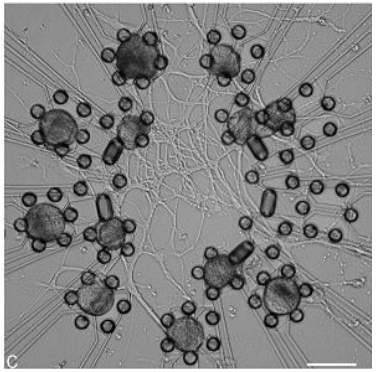
  - Pond snail neuron in polyimide 'picket fence' transistor



Two-way contact with polyimide picket fence*



Fixed neuron from pedal ganglia of Greek pond snail*

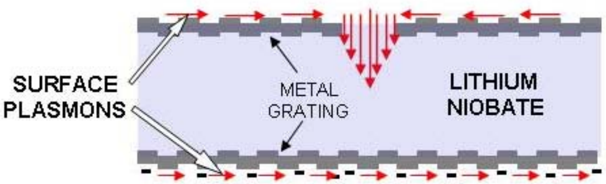


Cultured cell bodies in picket fence*

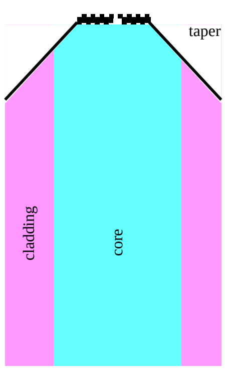
*Max Plank Institute for Biochemistry

Optical Biosensor

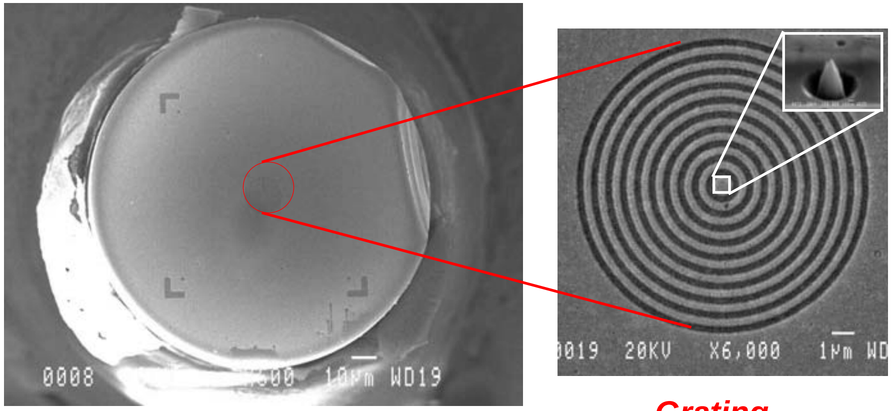
- Use of optical fibers as data/signal conduit
  - Data (high bandwidth) and signal in one pathway
  - Inherently Bio and MR compatible
- Electro-optic material for sensing
  - Conversion of electrical to optical



Electro-Optic Material



Cross Section



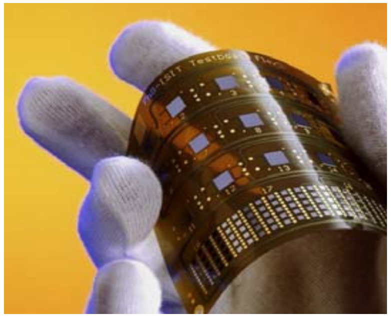
Top View

Grating

***Optical Fiber** (w/grating)*

Materials

- Biocompatibility
  - Chemical (non-toxic, inert)
    - Au, Pt, IrO_2, Silicon
    - SiO_2, Si_3N_4, Silicone, Polyimide
  - Engineered functionality (wettability, electronic)
- MRI compatibility (Non-magnetic)
- Form Factor (Flexible, thin-film)



Flex Electronics

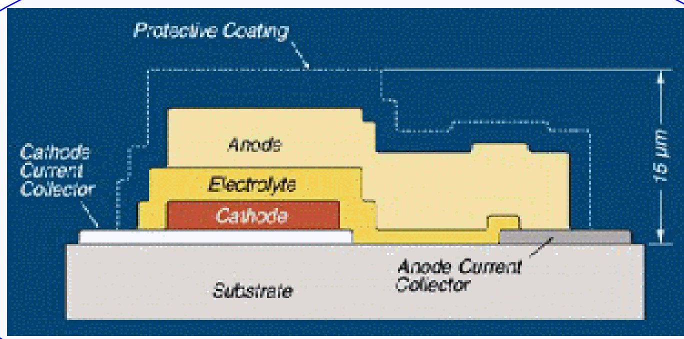
Energy Storage

Power Sources - Implanted

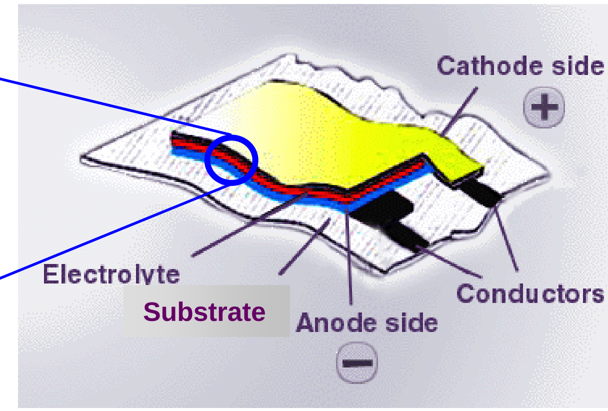
- Limitations of Existing Power Sources (i.e., rechargeable batteries)
  - Energy Density (< 200 Wh/kg)
  - Packaging
    - Balance of System mass (inactive materials)
    - System integration

  - Lifetime (stability)
    - <400 cycles at full Depth of Discharge (DoD)
    - Self discharge (~5%/month)
    - Storage Temperature (-20 to 60^{o} C)
- Alternative Power Sources (Thermoelectric, Bio Fuel Cell, Piezo)

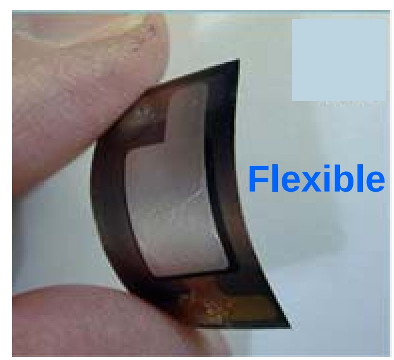
Solid State Battery



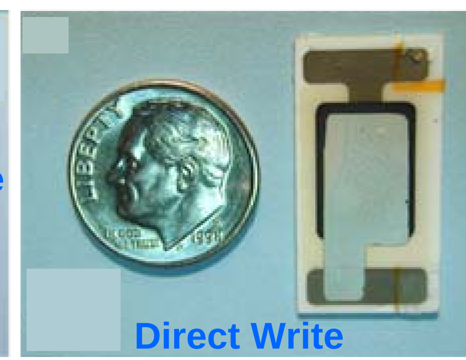
Thin Film



- Stable, safe, reversible chemistry
- *ALL* solid state construction
    - Flexible
    - Versatile
- Highest-energy density (*Li metal anode*) (>300Whr/Kg)
- High Cycle Life (>10,000)
- Long shelf life (Minimal Self Discharge)



Flexible



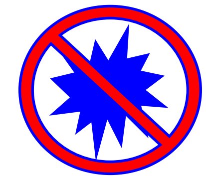
Direct Write

Battery Features

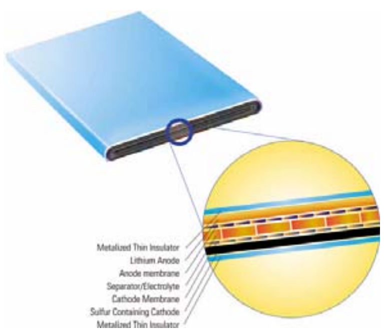
- Truly Reversible Lithium Cell Chemistry

$$Li^{+} \quad + \quad e^{-} \longleftrightarrow \quad Li_{\text{(metal)}}$$

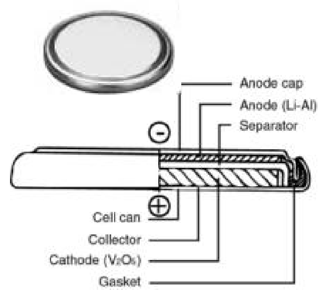
- Long Life, Safe (Both operationally and environmentally)



- All Solid State Construction

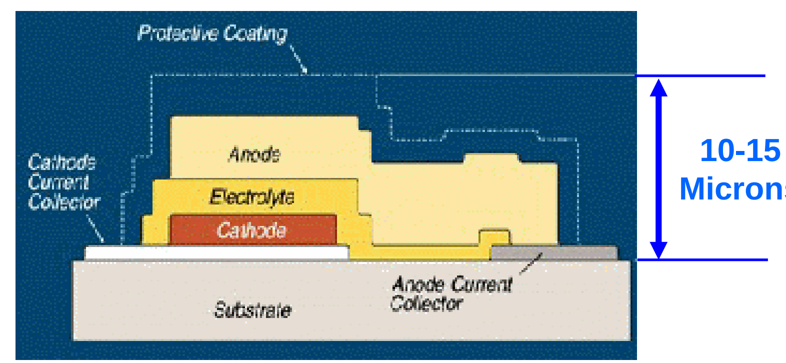


Prismatic

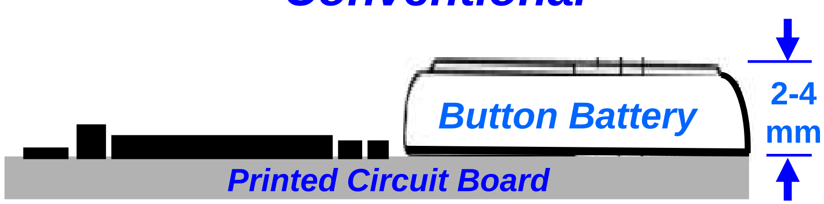


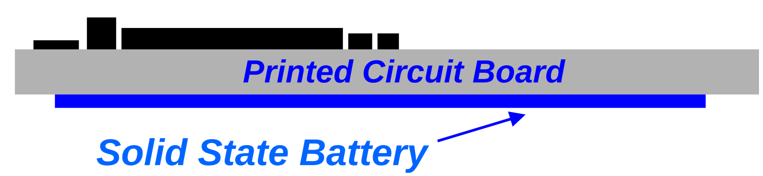
Button Cell

Conventional



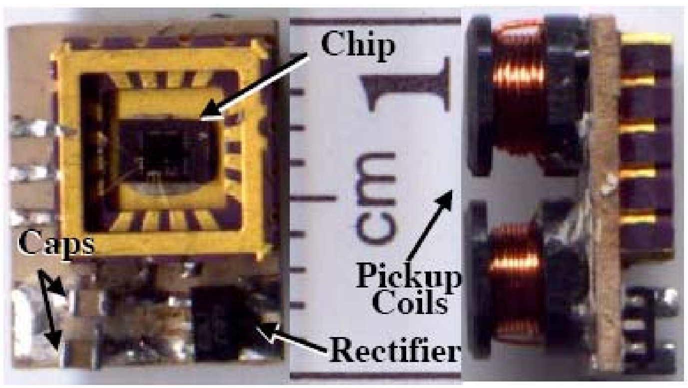
Solid State





Transcutaneous Power Sources

- Electromagnetic Energy Source/battery storage
  - Near Field (Inductance): Inductive antennas (coils of wire around a dielectric or ferrite core)



Wireless Implantable Transceiver
(Single channel: From Pastor UCLA)

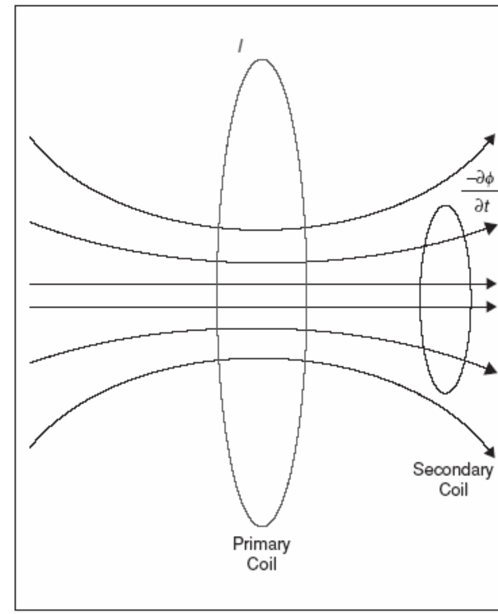
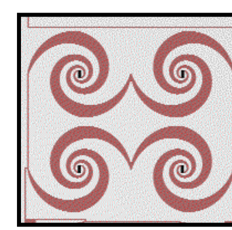


Illustration of inductive powering process

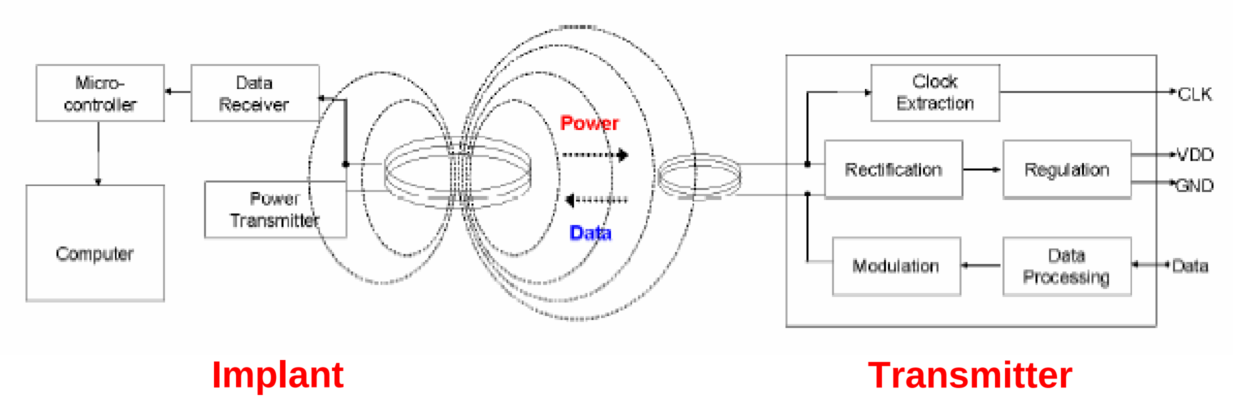
  - Far Field: Beaming or harvesting of background or parasitic RF/microwave power (rectenna array)



Broad band, low power

Telemetry/Communication Link

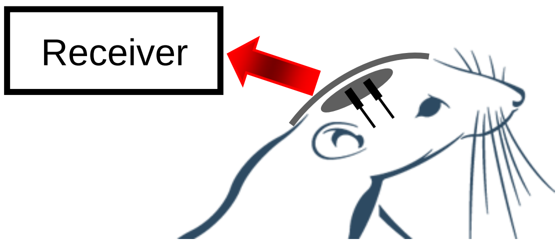
- Similar challenge as power harvesting
  - Near Field (Inductive)
    - Low data rates (bandwidth), issues with size/weight and range
  - Far Field (RF, IR, Acoustic)
  - Embedded antennas in a lossy environment (highly conductive)
  - Antenna size scales with frequency, power with range
- Basic elements of telemetry system (i.e., CMOS from Sauer, JHU)
  - Transmit coil
  - Rectifier (DC)
  - Regulator (voltage)
  - Modulator
    - Power (low λ)
    - Data link (high λ)

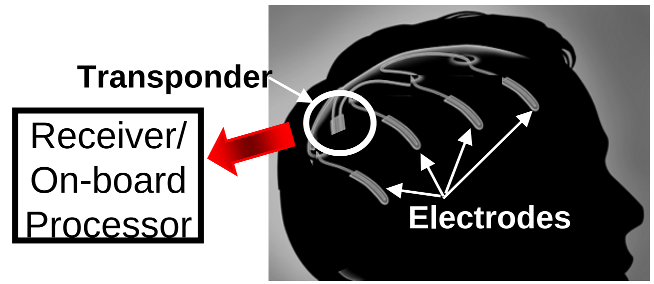


Implantable Wireless EEG system

- Implantable wireless system for simultaneous acquisition/stimulation of EEG signals
  - Powered by 13.56 MHz carrier
  - Transmit/receive via 16 Mbit/s IR link with high immunity to interference (IrDA standard)
  - MR safe and compatible
  - Rates in excess of 500 Hz/channel

Implantable Wireless EEG system



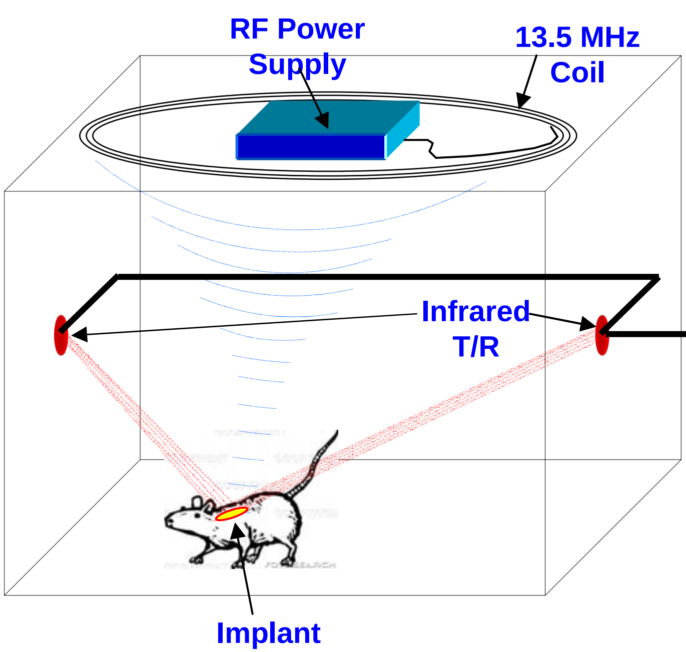


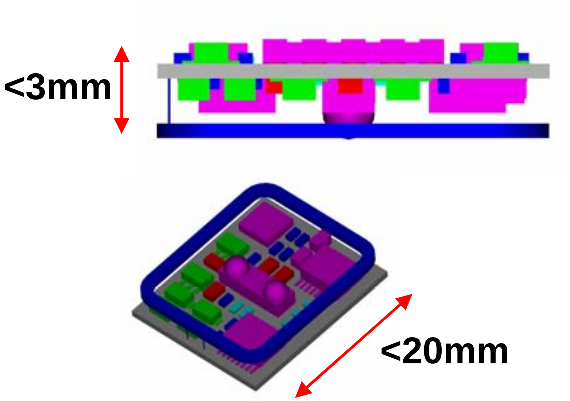
5-Channel System

Rodent Implant

Multi-channel system with 'macro'/thin-film electrodes

Human Implant ***(64 to 256 channels)***





Implantable Device

Summary

- First generation implantable devices with close to 10 years of clinical testing and use
- Innovations and improvements in *sensors*, *materials*, *power sources*, and *telemetry* open the stage for a new class of implantable devices with:
  - Lower volume/mass
  - Increased sensitivity, flexibility, and multi-modality
  - Improved bio/MR compatibility
  - Remote operation (elimination of wires/noise)
- Next generation technologies for human implants will enable:
  - Expanded range (256 channels) of continuous recording of electrical and chemical activity
  - Active control of stimulation based on seizure prediction analysis and algorithm development