Power Harvesting and Integrated Sensing in Implantable Devices

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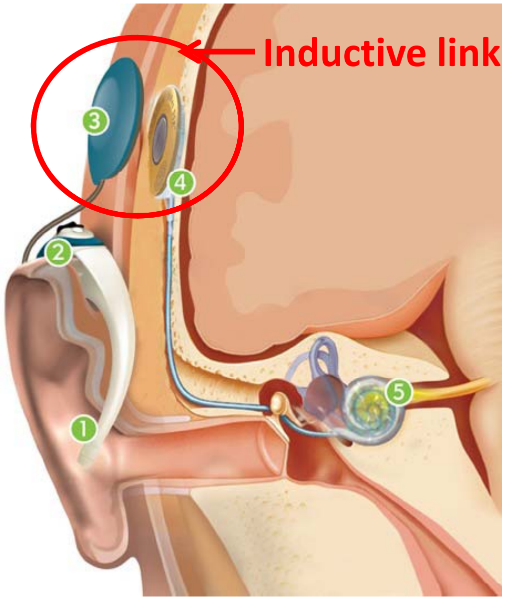
Outline

- **Motivation**
  – Brain-chip interface
- **Inductive Link and techniques for improved power efficiency**
  – Optimal distance between external coil and body
  – Dual external coil
- **Power harvesting and telemetry IC**
- **Integrated Sensing**
  – Neural recording
  – Neurotransmitter Concentration Monitoring
- **3-D Integration Technology for Brain Implants**
  – Case Study: 3-D Integrated Potentiostat
- **Conclusions**

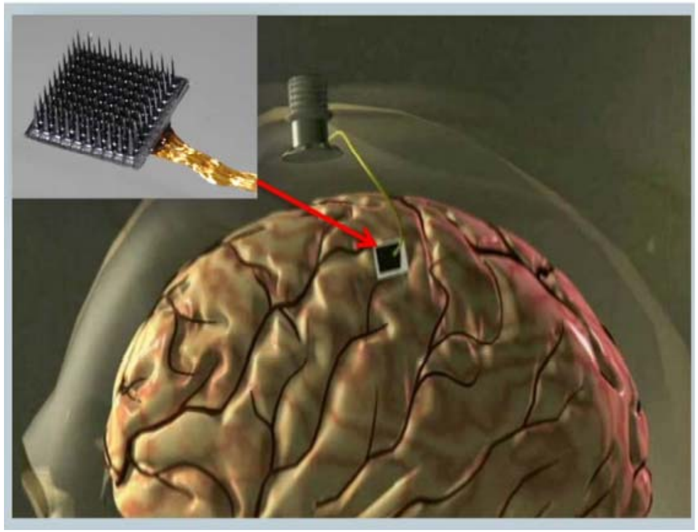
Motivation

- **Wired implantable devices: wires serve to power and communicate with the implanted electrodes**
  - Patients can not move normally, commonly are “tethered” to a single location with this wiring harness
  - Wires through skin are major source of infection
- **Wireless implantable devices**
  - Battery powered
    - Pacemakers
  - Inductively powered:
    - Cochlear implants
    - Visual prosthesis
    - Neural recording implants
    - Neuromuscular stimulators



Cochlear Implant: Advanced Bionics Inc.

Brain-Chip Interfaces



Nurmikko, A.V., et. al., Proceedings of the IEEE , 2010

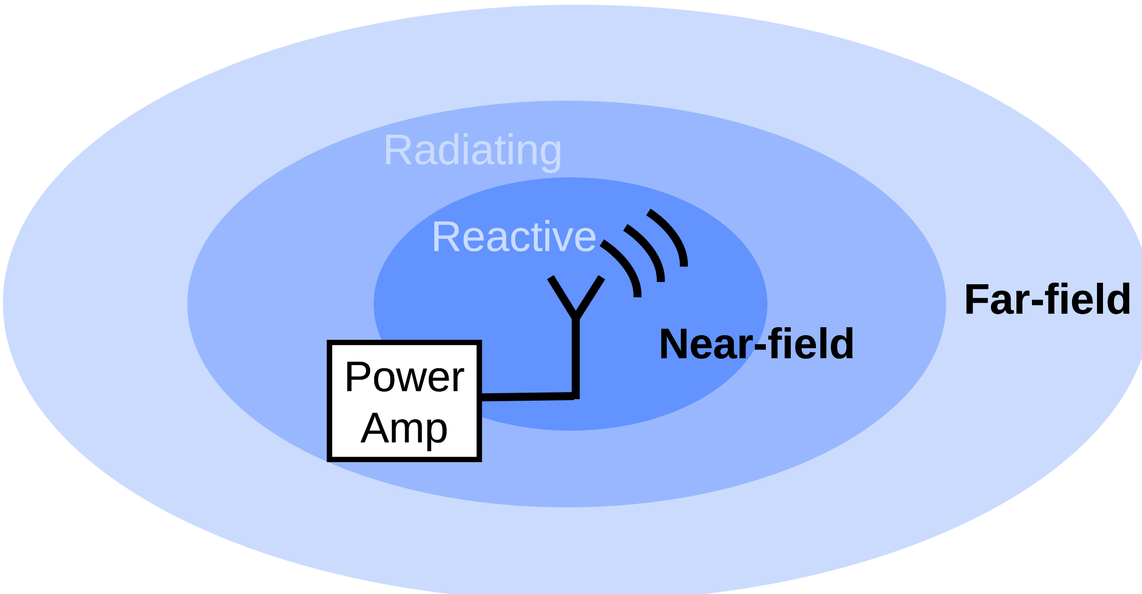
- **Deep brain implants**
  – Located under the skull
  – Monitor and record neural activities in specific locations
  – Also used for stimulation by transmitting electrical impulses
    - Crucial part of neural prosthesis

- **Ultimate goal – Challenging yet inspiring**
  – Observe the brain activity (sensors and circuits)
  – Decode the extracted neural information (statistical and mathematical techniques)
  – Restore a disabled function to the body (brain and spinal cord injury)

Form Factor is a Key Parameter

- **A smaller form factor**
  - Mitigates issues related to implantation
  - Provides more robust and longer operation
  - Achieves more flexibility in recording (“awake primate”)
  - Enables multiple devices to be implanted at different sites of the cortex
    - Important to accurately decode information
  - Very large scale integration (VLSI) technology has been utilized to achieve smaller form factors

EM Field Regions



λ : wavelength of the carrier signal

D: maximum antenna dimension

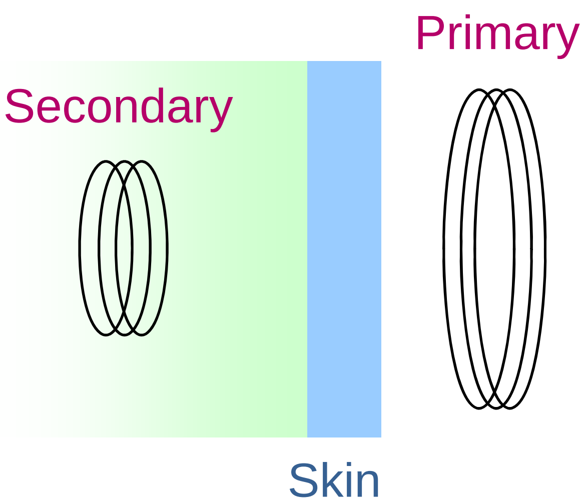
λ (10MHz) = 30m

λ (1GHz) = 30cm

- **For electrically small antennas reactive near field is up to distance of λ/2π**
- **In the reactive near field, energy is stored in the field and can be absorbed by the coupling antenna (inductive link)**

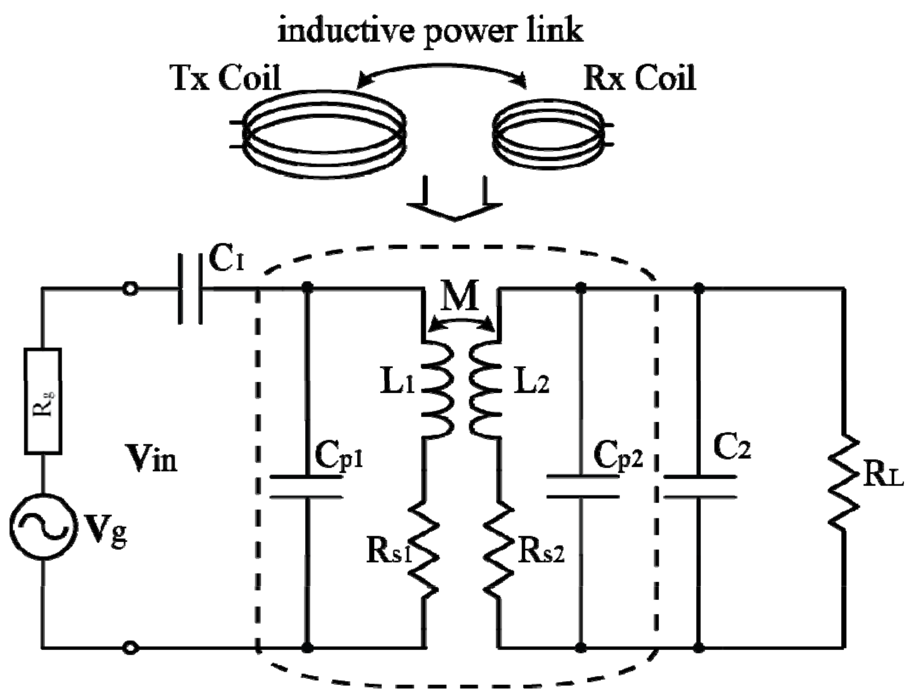
Inductive Link

- **External primary coil is driven by power (class E) amplifier**
- **With resonant coupled coils the voltage induced in the secondary implanted coil is an order of magnitude higher than in the case of non-resonant coils**
- **Received power is a factor of drive power, coupling between the two coils, and environmental factors**
- **The medium between tag and reader is body**
  - Attenuation of EM field in body



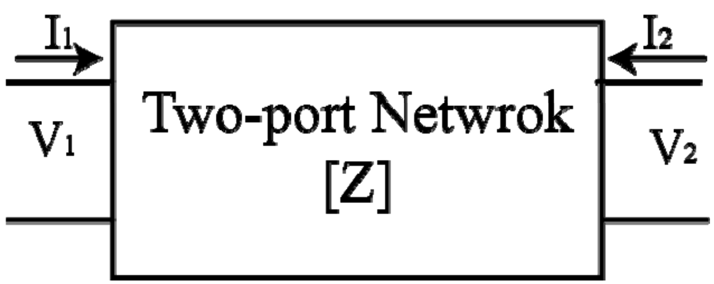
Quasi-static Analysis

- **Suitable for low-frequency, electrically small system with two coils with relatively short distance**
  - *Advantage:* easy, convenient, straight, quick
  - *Disadvantage*: less-precise, can't involve the tissue attenuation effort, which become severe for high frequencies, into model completely, unsuitable for high-frequency analysis



Full-wave Analysis

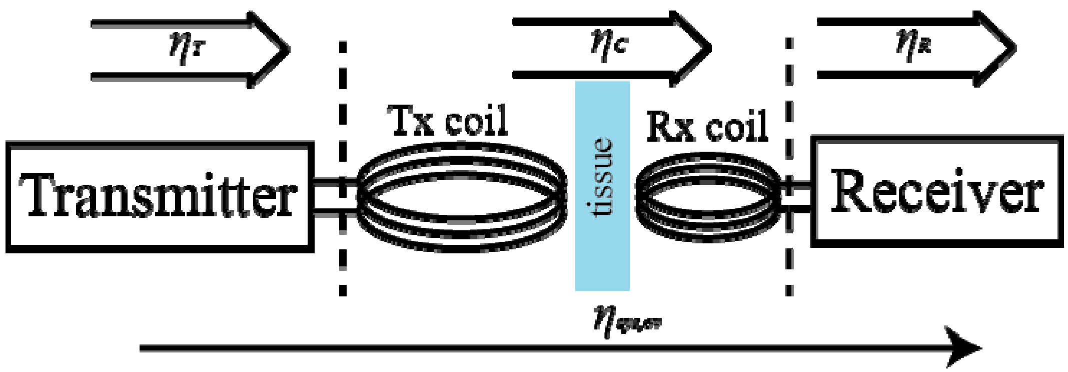
- **General description**
  - Consider coil-pair as general microwave two-port network;
  - Use numerical method solving all the equations, and then extracting network parameters;
  - Capable calculate field strength all over the space
  - FEM-based EM solver: HFSS
- **Network parameters:**
  - Z-parameters:



$$V_1 = Z_{11}I_1 + Z_{12}I_2$$
$$V_2 = Z_{21}I_1 + Z_{22}I_2$$

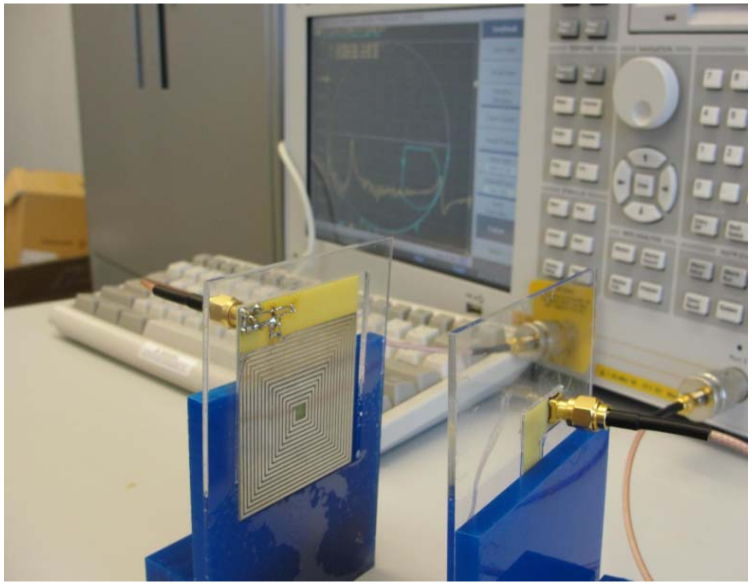
Power Link Characterization

- **Power transfer efficiency:** $\eta = \dfrac{P_L}{P_S}$

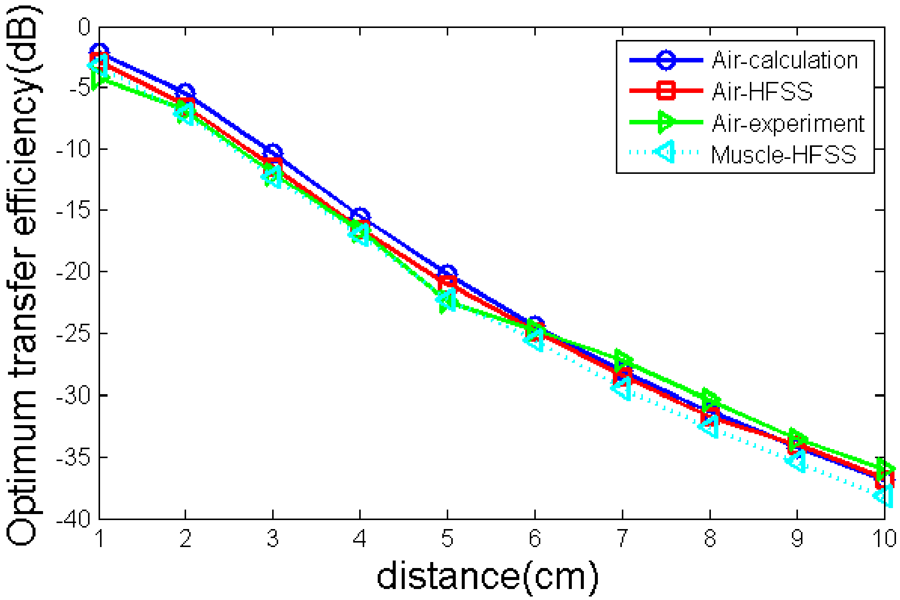


- **The maximum power delivered to the load**
- **The power transfer efficiency and the maximum delivered power depend on the loading impedance**

Inductive Link Measurements



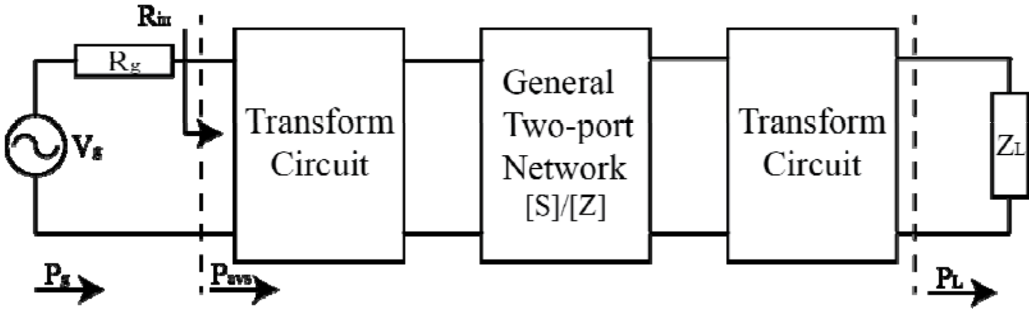
Experimental setup



Calculated and measured power efficiency

Optimal Load Impedance

- **For optimal loading impedance:**
  - matching network
  - intermediate coils



$$\eta_C = \frac{\alpha}{\left(1+\sqrt{1+\alpha}\right)^2} \qquad \alpha = \frac{\left|Z_{12}\right|^2}{\mathrm{Re}\{Z_{11}\}\mathrm{Re}\{Z_{22}\} - \mathrm{Re}\{Z_{11}\}^2}$$

- **Quasi-static model:**

$$\eta_{C,res} = \frac{k^2 Q_T Q_R}{\left(1+\sqrt{1+k^2 Q_T Q_R}\right)^2} \qquad R_{L,opt} = \frac{Q_R^2 R_{s2}}{\sqrt{1+k^2 Q_T Q_R}}$$

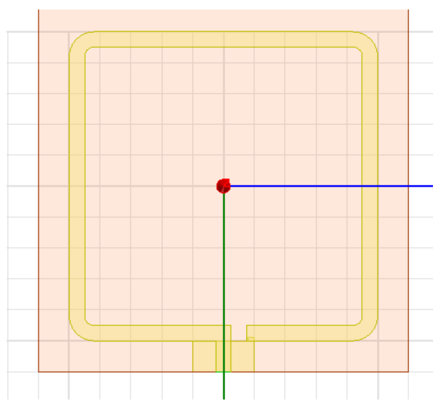
Safety Restrictions

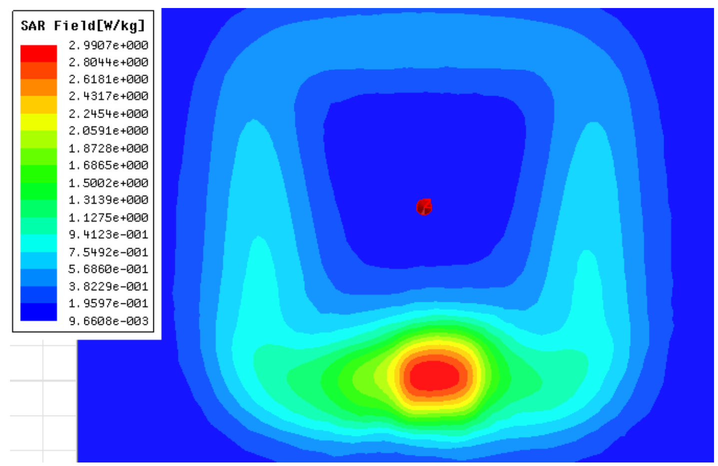
- **Thermal effect on tissue is expressed by specific absorption rate (SAR), which describe the EM power absorption rate by biological tissue**
- **SAR hot spot for Tx coil**
  - Hot spot is near the feed point of coil
  - Real coil = ideal coil + virtue short wire with opposite current at feed point
  - E-fields produced by virtue wire break the balance

$$SAR = \frac{\sigma |E|^2}{\rho}$$

σ: conductivity of the tissue

ρ: mass density of the tissue



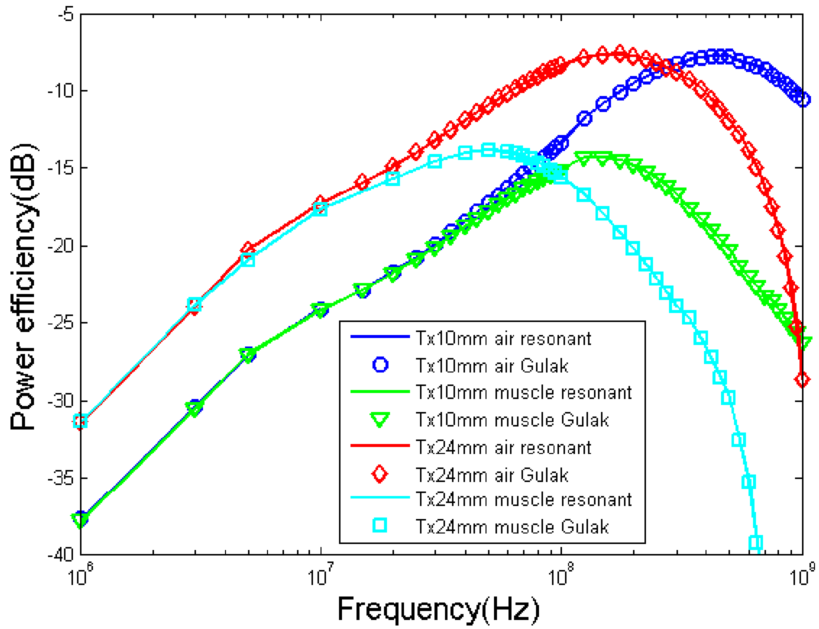


SAR distribution when Tx coil 1mm away from tissue

Design of the WPL

- **For the specific problem, the size of the receiver coil and the separation distance are usually defined**
- **More freedom in the design of the external coil**

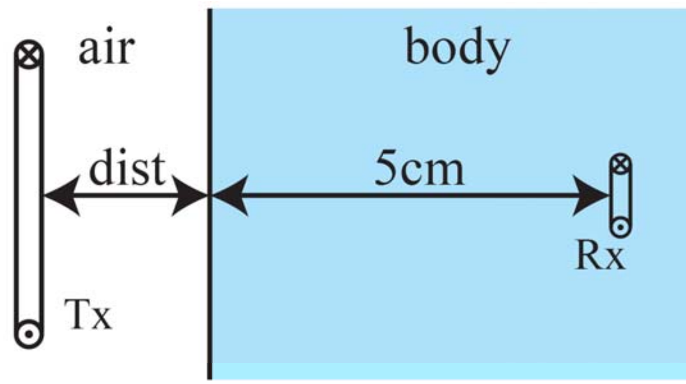
- **Model:**
  - 2-turn Tx coil
  - 3-turn Rx coil 3mmx3mm
  - distance 1cm
  - Both coils have 300um medical silicone layer on top as coating
- **Effect of tissue on the optimal transmission frequency and power efficiency**

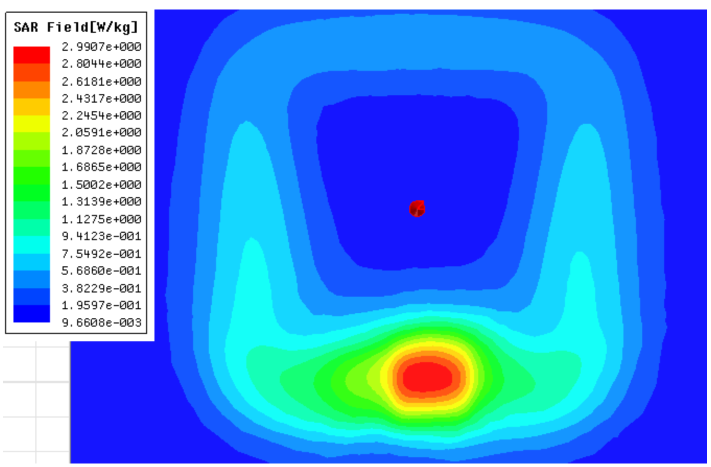


Note: Tx coil has width 1.2mm, space 0.8mm;
Rx coil has width 0.16mm, space 0.16mm.

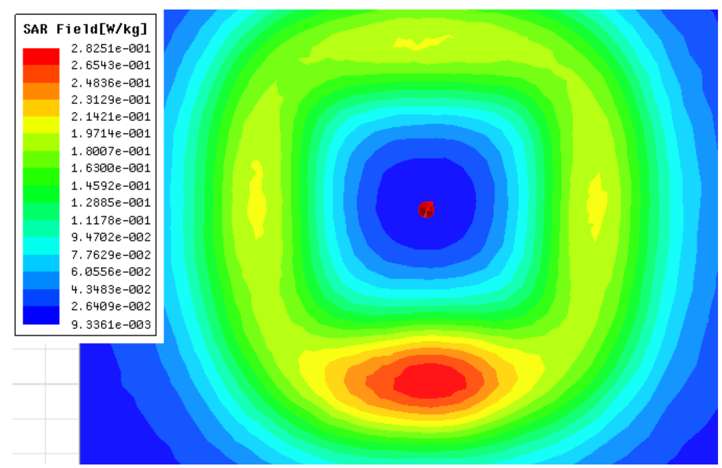
Optimal Position of Tx Coil

- **SAR sport drops quickly as Tx coil moving away from tissue**



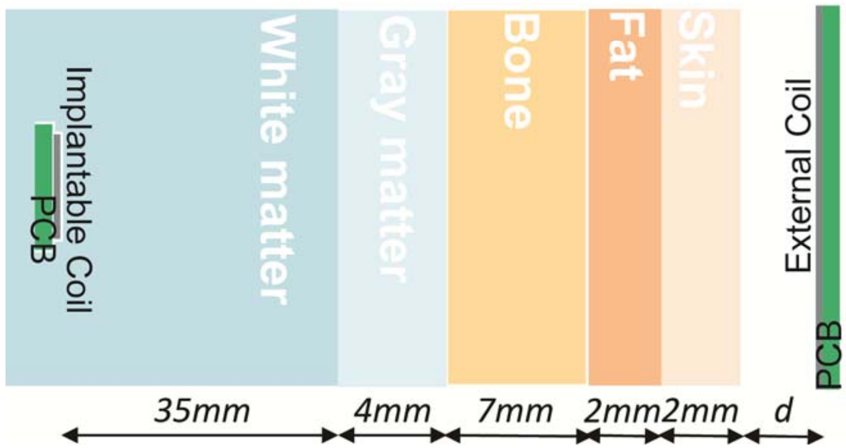


SAR distribution when Tx coil 1mm away from tissue

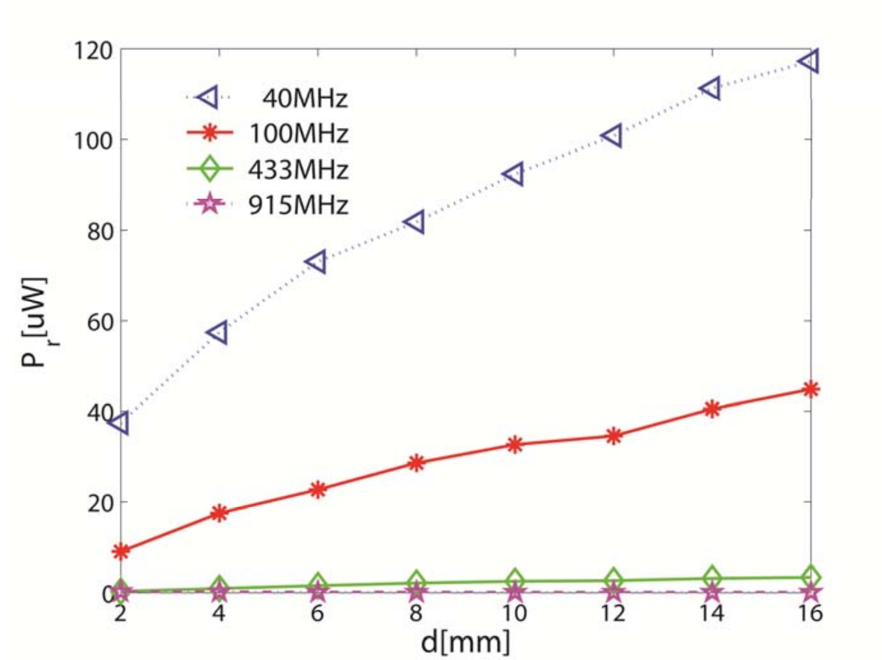


SAR distribution when Tx coil 10mm away from tissue

Deep Brain Implant



Model of the wireless channel for the deep-brain implant.

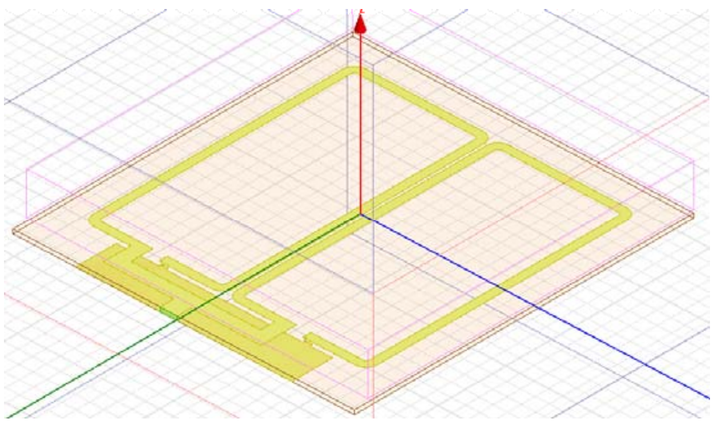


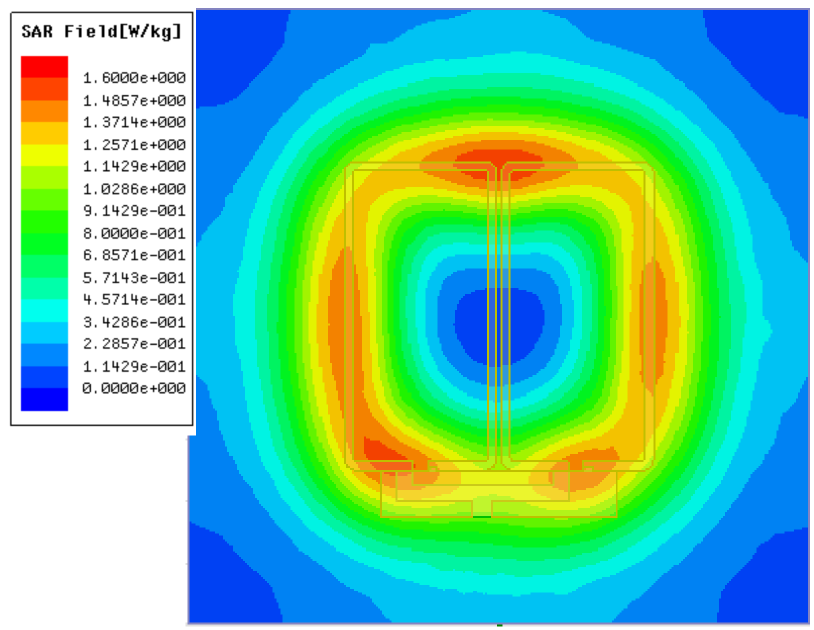
Jian and Stanaćević (2014)

The maximum deliverable power to the implantable device as the function of the distance between the transmitting coil and the skin for the deep brain implantable device.

Dual-coil antenna

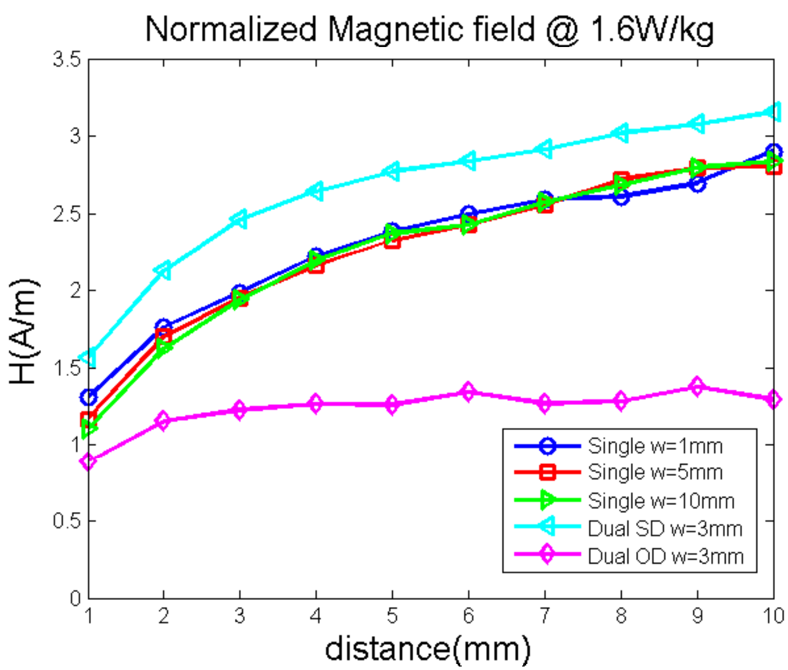
- **Two virtue wire may diminish E-field and SAR.**
- **Dual- coil spreads out SAR and reduces the peak SAR value**

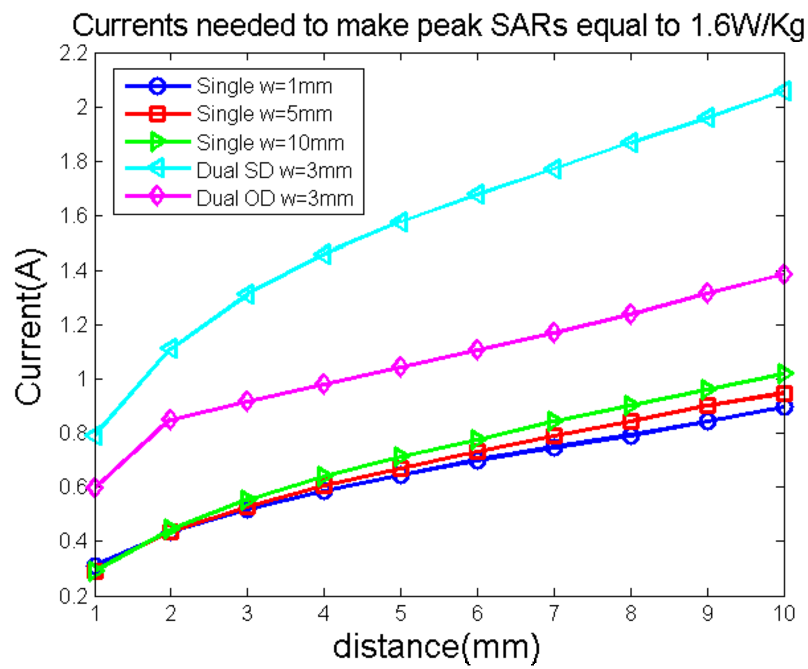




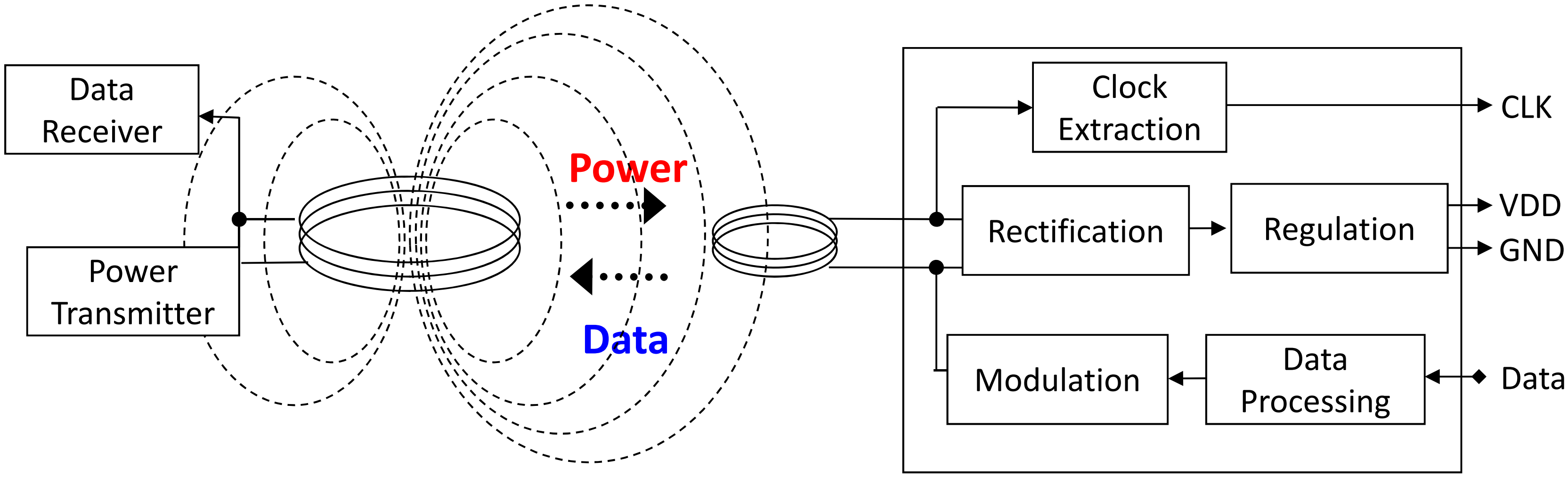
SAR pattern dual-coil with same current directions

Dual-coil antenna



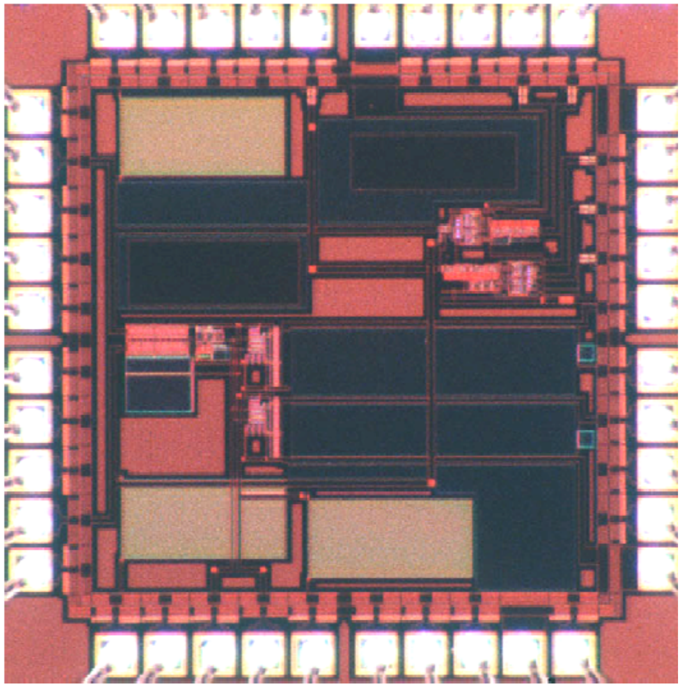


Power harvesting and telemetry IC



- The magnetic field induces a sinusoidal current on the implanted coil
- A full wave rectifier followed by a voltage regulator creates a DC voltage for the associated sensor
- A clock is recovered from power signal
- Data is sent back via load modulation of the secondary coil

Power harvesting and telemetry IC

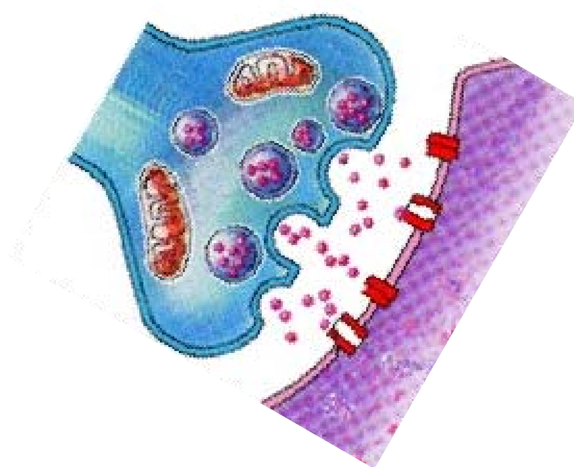


Sauer, Stanaćević, Cauwenberghs, and Thakor (2004)

- **1.5*mm* x 1.5*mm* in 0.5μ*m* CMOS technology**
- **Chip harvests power from a 4 MHz RF signal**
- **Chip is able to supply 2mA of current at 3.3 V to associated sensor**
- **Transmitted data encoded with modified Miller scheme**
- **Power consumption of the chip is 300 μW**

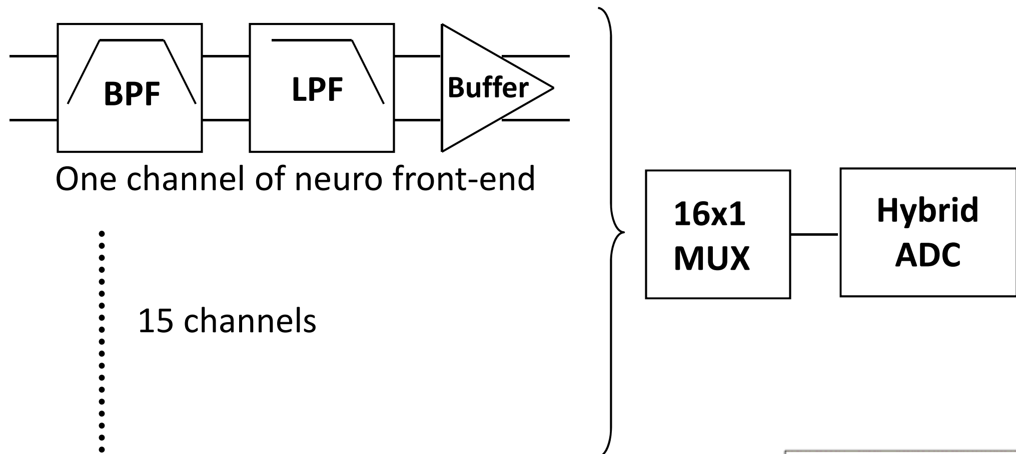
Sensing ICs in Brain Implants

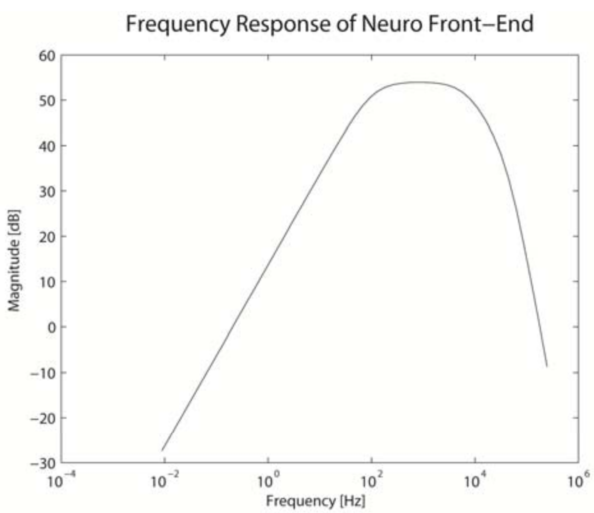
- **Neural recording: observing the simultaneous electrical activity of large numbers of neurons**
  - Local field potentials
  - Spikes
- **Sensing neurotransmitters: concentration of the messenger molecules between neurons**
  - Understanding neural pathways
  - Neural disease etiology
  - Dopamine, Glutamate, GABA etc.

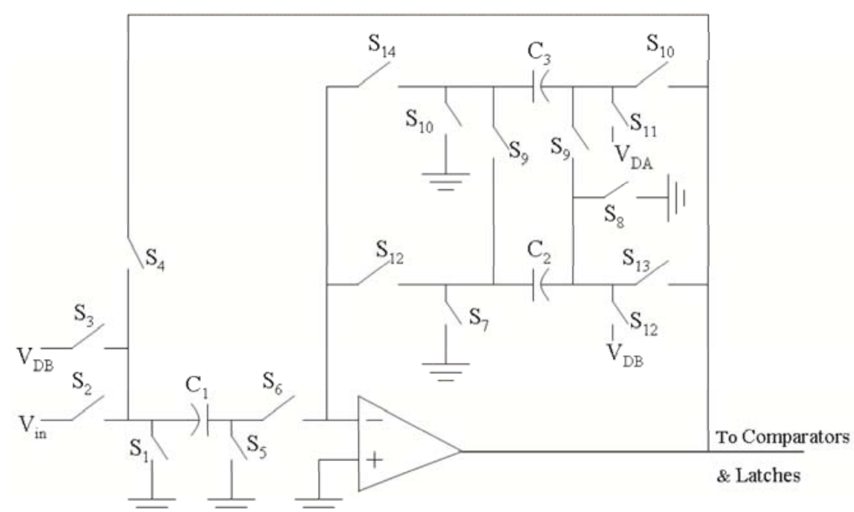


Neural Recording IC

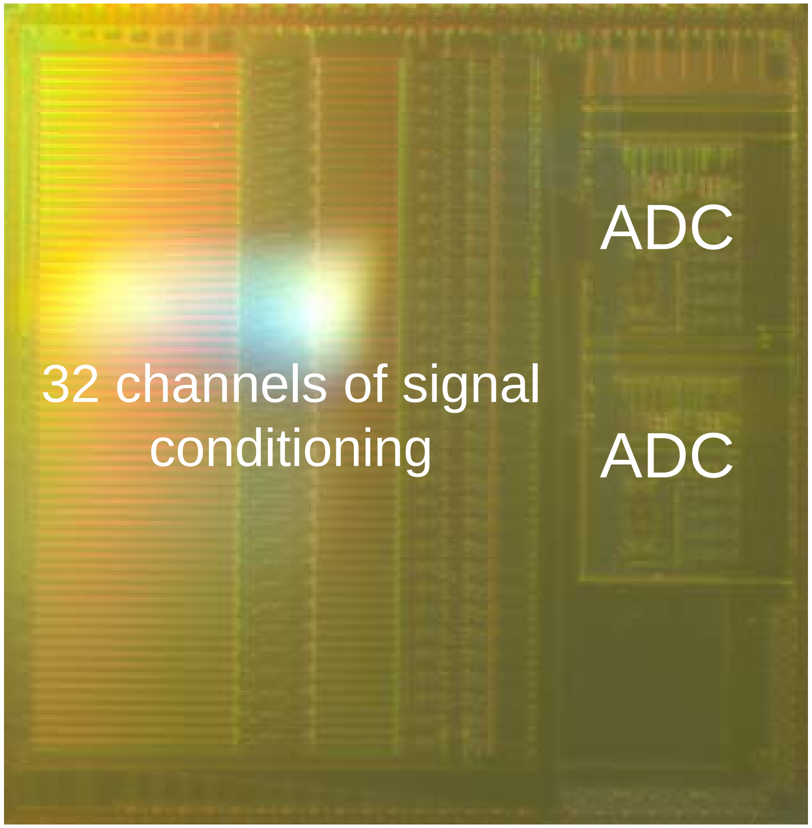
Signal Conditioning **Analog-to-digital conversion**







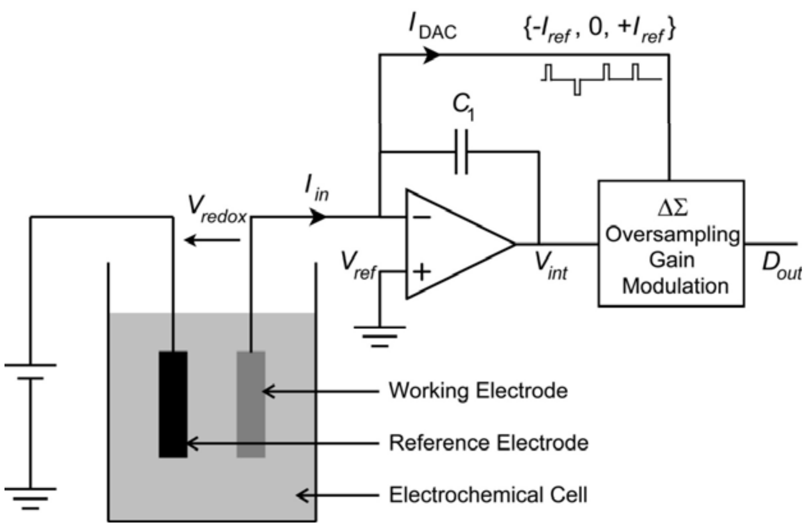
Neural Recording IC

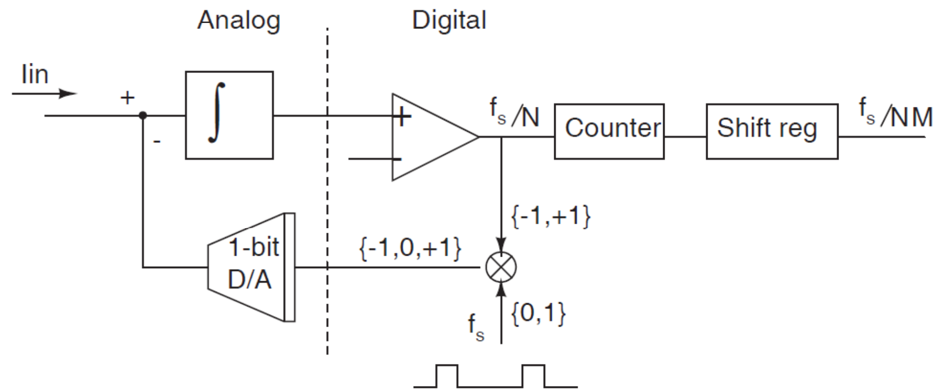


Yun, Kim, Stanaćević and Mainen (2007)

- **3*mm* x 3*mm* in 0.5μ*m* CMOS technology**
- **Signal Conditioning**
  - Gain: 39.5dB
  - Input noise: 3.35μV
  - Power: 13.68 μW
  - Noise efficiency factor: 3.18
- **ADC**
  - Resolution: 13bits
  - Sample frequency: 512kHz
  - Power: 5mW

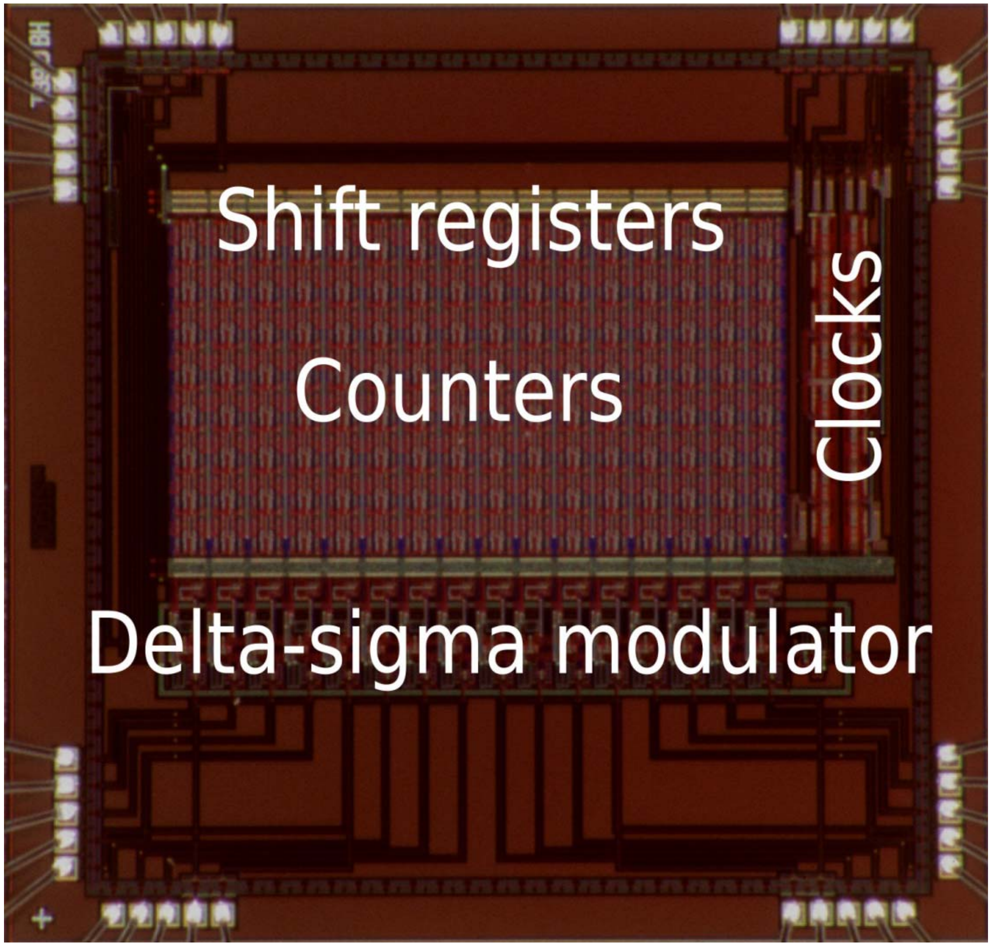
Multi-Channel Potentiostat





- **Detecting neurotransmitters**
  - Electrochemical analysis: measure the output current due to electron transfer while maintaining constant voltage at the sensing electrode
  - Single channel consists of integrator, comparator, D/A converter, counter, and shift register

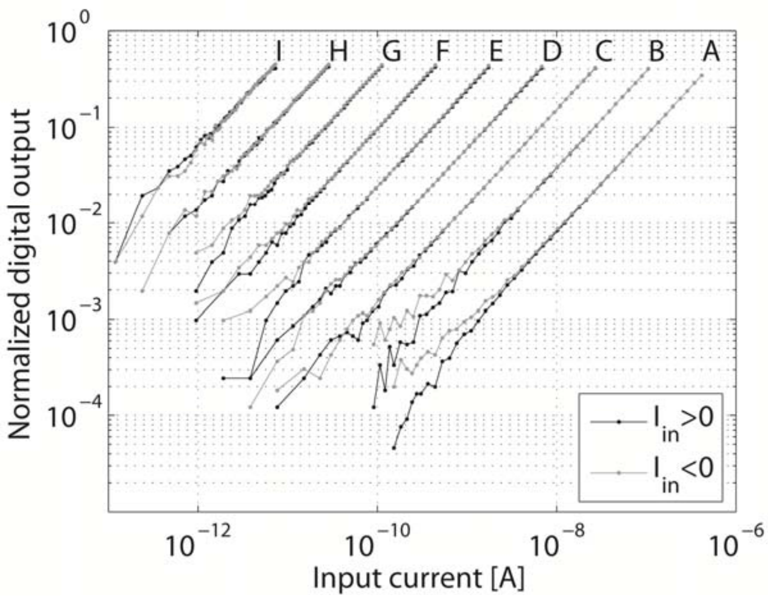
Multi-Channel Potentiostat



Stanaćević, Murari, Cauwenberghs and Thakor (2007)

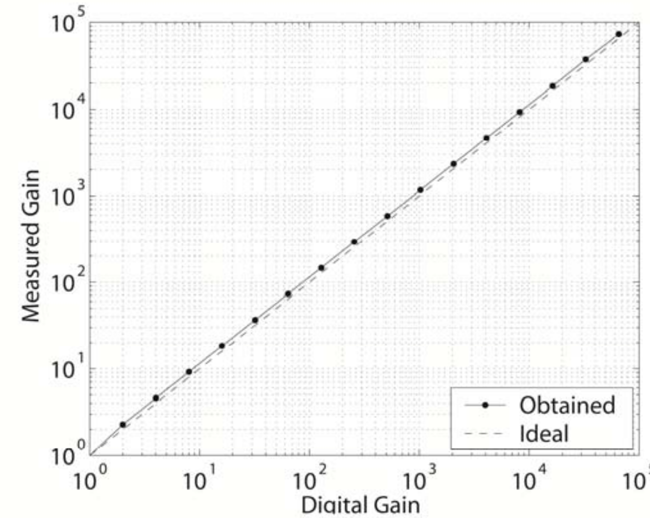
- 3mm x 3mm in 0.5μm CMOS technology
- Compact, fast, accurate and distributed neurotransmitter sensing
- Wide dynamic range of measuring currents spans through 6 orders of magnitude, with 100 fA sensitivity
- Power dissipation is 300 μW at 3.3V supply and 1MHz clock

Current measurement characterization



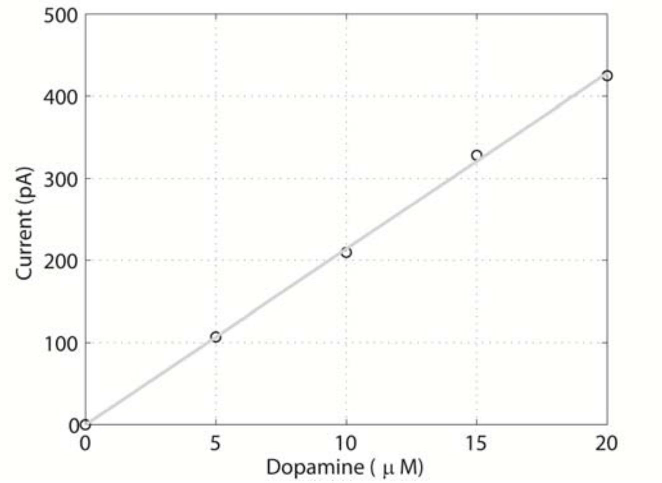
Trace	Gain (G)	OSR	Input current range	Conversion time (ms)	Power mW
A	2^0	2^{16}	±500nA	32	1.27
B	2^2	2^{15}	±125nA	65	0.97
C	2^4	2^{14}	±30nA	131	0.67
D	2^6	2^{13}	±8nA	262	0.57
E	2^8	2^{12}	±2nA	524	0.54
F	2^{10}	2^{11}	±500pA	1048	0.54
G	2^{12}	2^{10}	±125pA	2097	0.54
H	2^{14}	2^9	±30pA	4194	0.54
I	2^{16}	2^8	±8pA	8388	0.54

Normalized digital output as function of the input current for different values of gain and oversampling ratios.

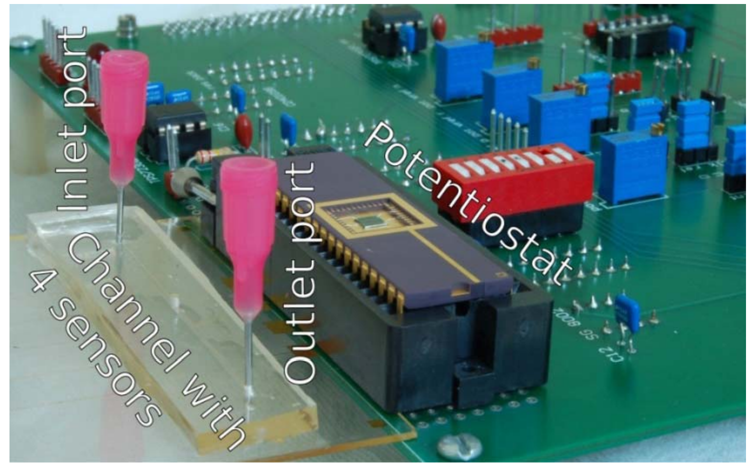


Actual gain as a function of digitally programmed gain G of current measurement.

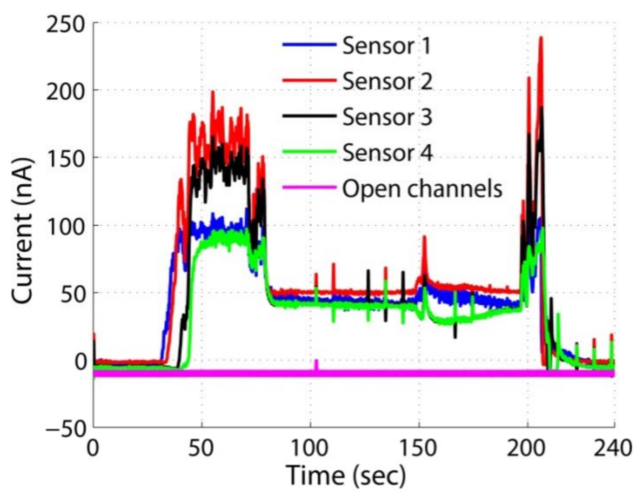
Dopamine measurements



The static current output of the potentiostat chip in response to additions of 5μM dopamine.

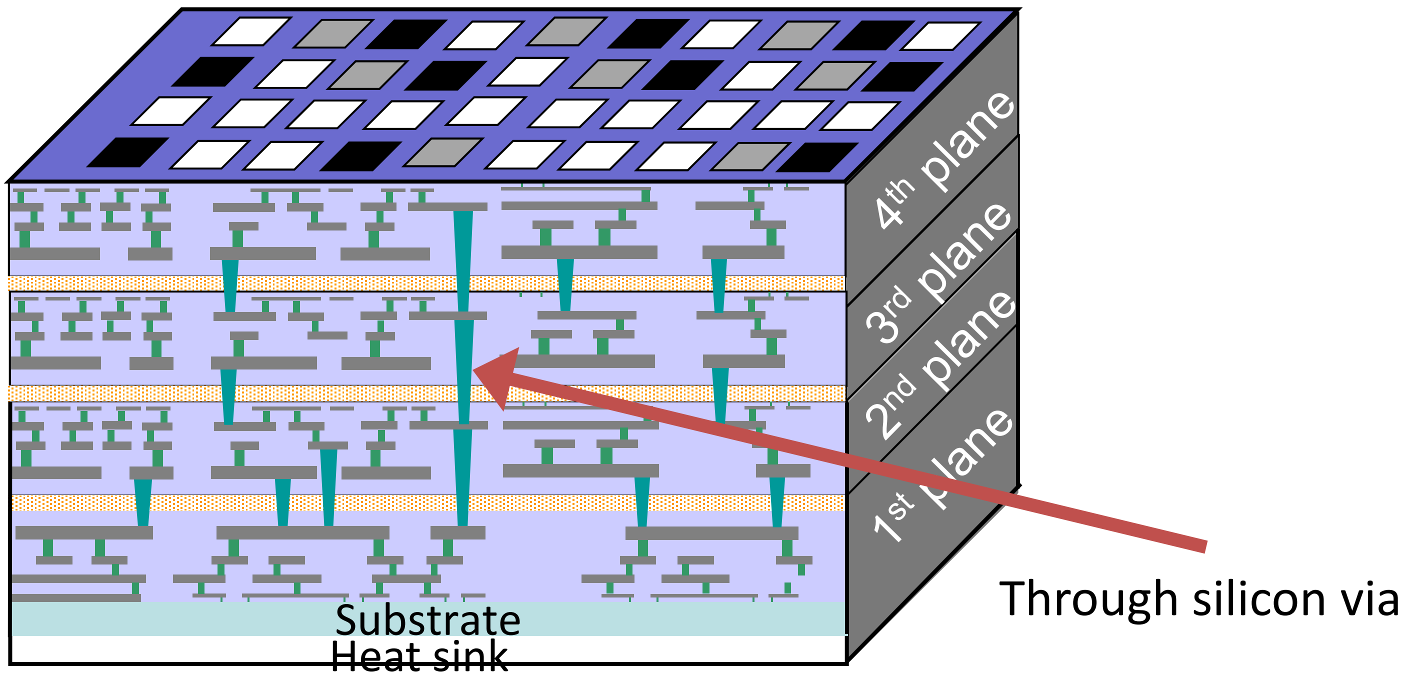


Experimental setup showing the potentiostat chip interfaced to the multichannel flow sensor.



Real-time 4 channel simultaneous monitoring of neurotransmitters flowing in a fluidic channel.

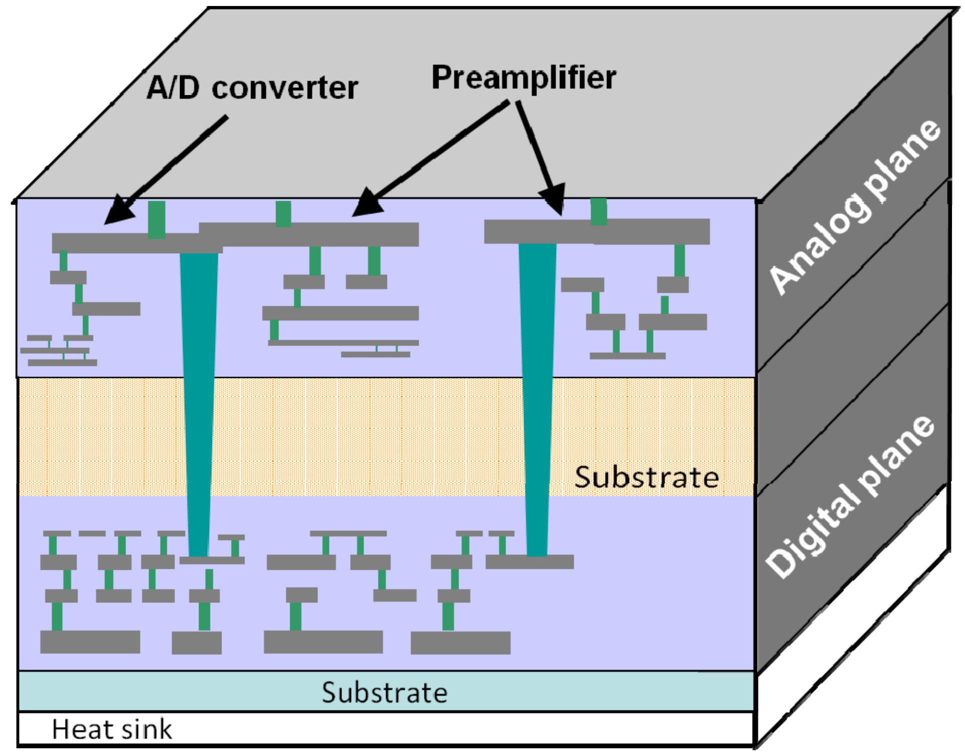
3-D Integration Technology



- **Utilize vertical dimension rather than scaling the devices in two dimensions**
  - Higher integration
  - Shorter and less number of global interconnects
  - Opportunity to alleviate the interconnect bottleneck

Advantages of 3-D Technology in Implantable Devices

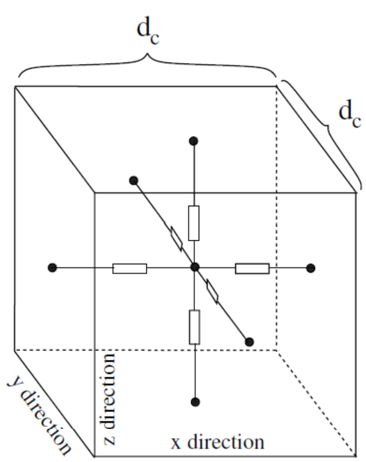
- **Smaller form factor**
  - Neural interface chip* consumes ≈ 30 mm^2
  - Assuming a six plane 3-D stack, area is reduced to ≈ 12 mm^2
- **Heterogeneous integration**
  - Optimize each plane based on required functionality
- **Potentially lower noise due to separate substrates (?)**
  - Low noise is critical
  - Current/voltage levels are in the range of pico to micro amps/volts

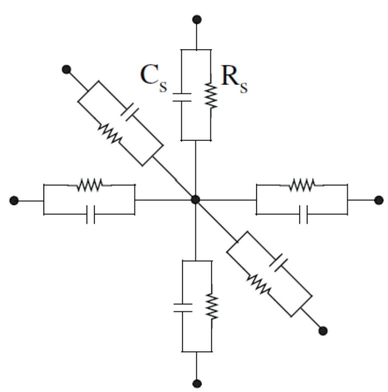


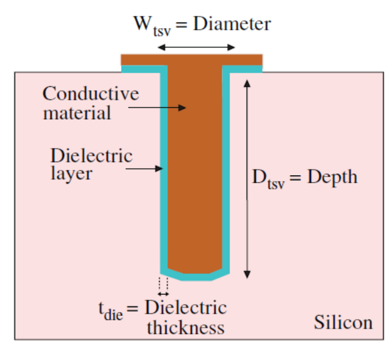
Primary purpose: Evaluate noise characteristics of a 3-D integrated potentiostat

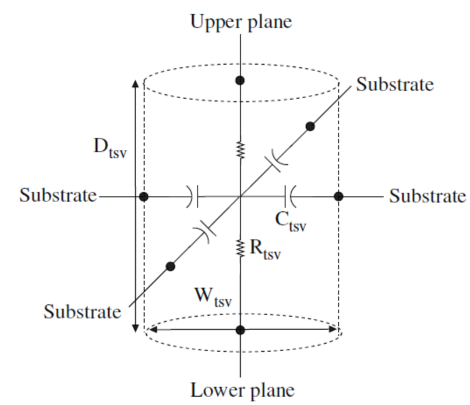
Signal Integrity Analysis Flow

- **Electrical model development for primary noise coupling paths**
  - 2-D circuit: substrate
  - 3-D circuit: substrate and through silicon vias (TSVs)
- **Simulate the entire network**
  - 2-D → potentiostat (transistors) + substrate
  - 3-D → potentiostat (transistors) + substrate + TSVs
- **Determine noise and primary noise coupling paths**

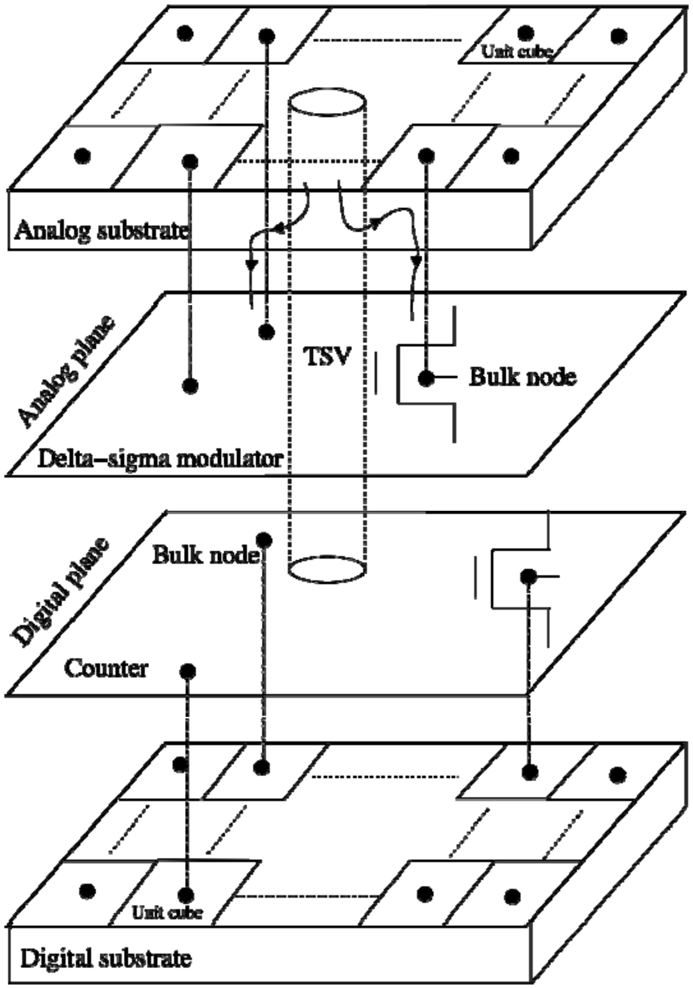




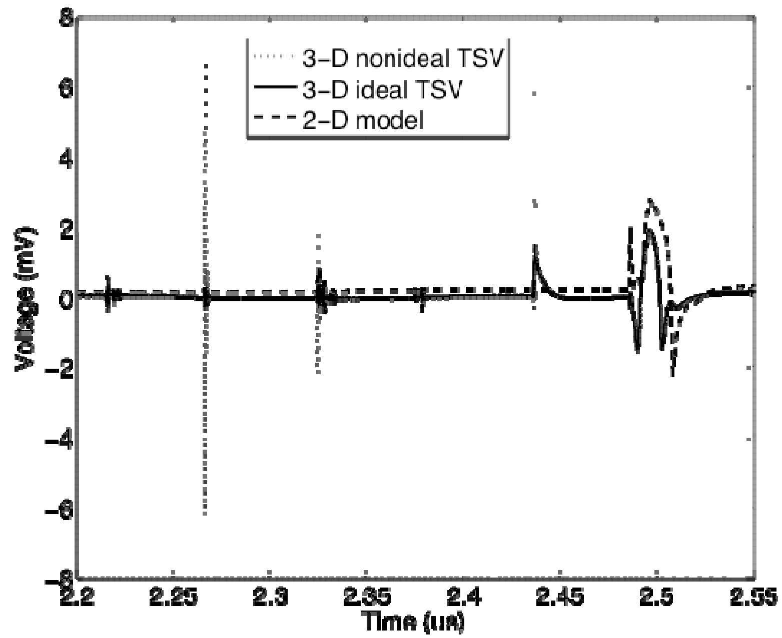




Signal Integrity Analysis Results for 3-D



- Bottom Plane: Counter
- Top Plane: ∑-Δ modulator
- Via-first, face-to-face bonding



Asgari, Salman and Stanaćević (2011)

Comparison

Case	RMS noise at bulk node
2D common power network	232 µV
2D dedicated power network	224 µV
3D non-ideal TSV	242 µV
3D ideal TSV	107 µV

- **TSV related noise coupling is significant in 3-D integrated implantable devices**
  - TSVs to carry the clock signal to the digital plane
- **Noise isolation strategies should be developed for TSVs to fully exploit the advantages of 3-D integration**

Conclusion

- Proposed optimal distance of the external coil from the body increases the maximum power delivered to the load.
- Proposed external dual-coil leads to reduces SAR for the same current as the single coil, which leads to the increase in the maximum power delivered to the load.
- Proposed extended counting ADC for the neural recording system provides best trade-off between resolution, area, power and speed.
- Proposed 16-channel potentiostat has a wide dynamic range of currents that span from picoamperes to microamperes and with sensitivity down to 100 fA.
- TSV related noise coupling is identified as a significant mechanism and if this noise is minimized, 3-D exhibits better noise behavior than 2-D.

Acknowledgement

- SBU graduate students: Xiao Yun (AMD), Donghwi Kim (Intel) and Jinghui Jian
- Potentiostat work in collaboration with K. Murari (University of Calgary), G. Cauwenbergs (UCSD) and N. Thakor (Johns Hopkins Univ)
- 3D Potentiostat work in collaboration with E. Salman (SBU)