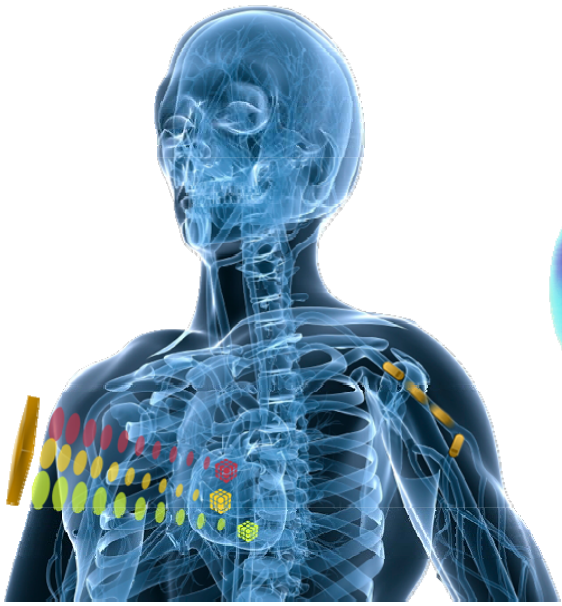
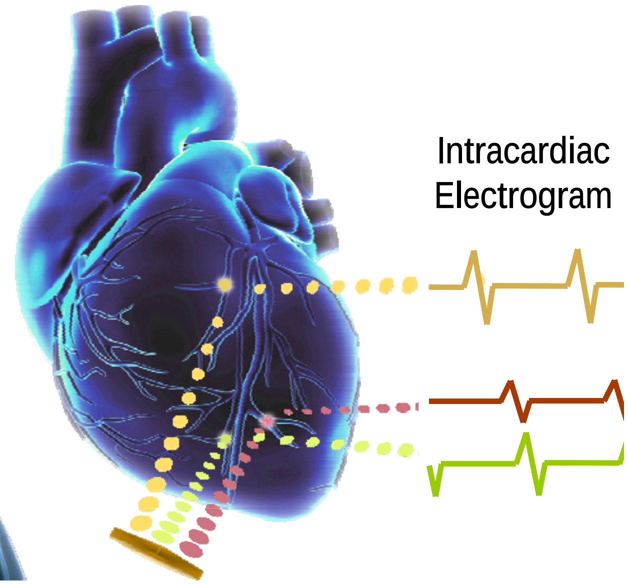
1st Invitational Workshop on
Body Area Network Technology and Applications
Future Directions, Technologies, Standards and Applications
June 19-20, 2011
Worcester Polytechnic Institute

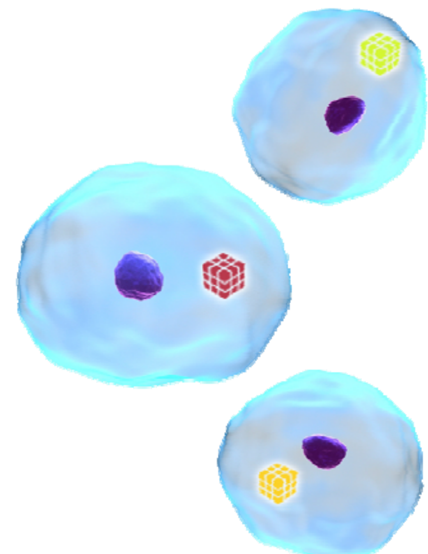
Future Implantable Systems

Ada Poon
Stanford University

Real Time, Distributed *In Vivo* Diagnostics







- **Moving implants**
- **Wireless endocardial pacing and sensing**

- **Multielectrode epicardial mapping for EP study**

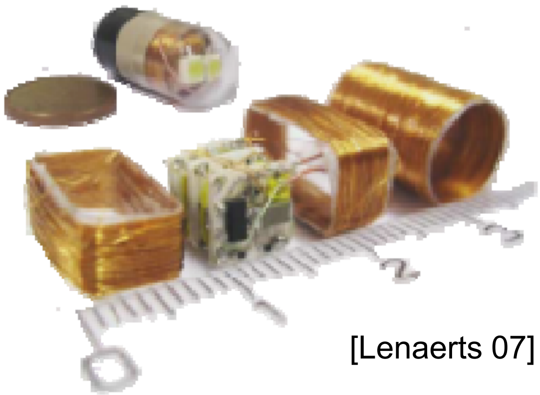
- **Chip in cell for cellular-level monitoring and therapeutic treatments**

1 mm → **100 μm** → **10 μm**

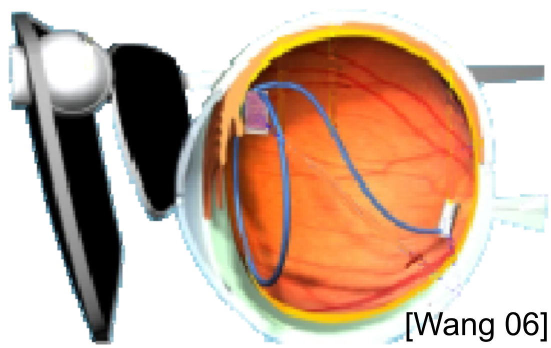
Implant Dimension

Current Autonomous Implants

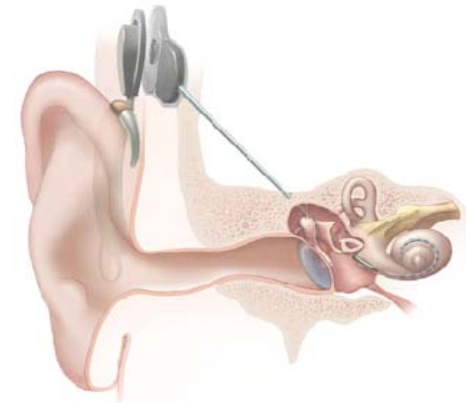
Endoscope



Retinal implant



Cochlear implant



- Use remote power source to remove the battery partially or completely.
- Power transmission is like a transformer – **inductive coupling**.
- Power receiver is large – 1 to a few cm.
- Extremely short distance (almost touching)
- Coil alignment is critical.
- **Still, we haven't solved the problem of miniaturization.**

Can we do better than inductive coupling?

Back to Physics …

$$\nabla \times \mathbf{H} = -i\omega\epsilon_0\epsilon_r\mathbf{E} + \sigma\mathbf{E}$$
$$\nabla \times \mathbf{E} = i\omega\mu_0\mathbf{H}$$

In the past 50 years, analyses on wireless power transmission within biological tissues omit the displacement current – the term Maxwell added to Ampere's Law and resulted in the Maxwell equations.

- Lower frequency is better!
- Most systems operate at 10 MHz or lower.

YES when we take into account the displacement current.

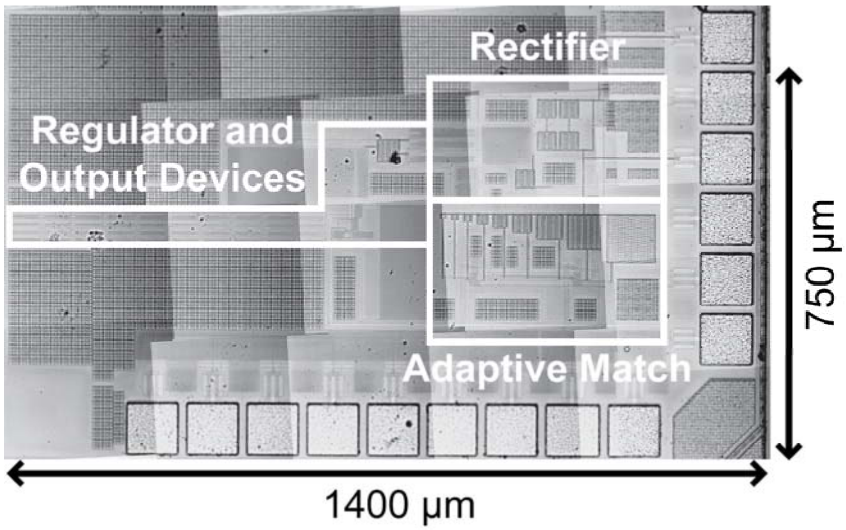
Optimal frequency

$$\omega_{opt} = \sqrt{\frac{c\sqrt{\epsilon_{r0}}}{d\tau(\epsilon_{r0} - \epsilon_{\infty})}} \cdot \sqrt{1 - \frac{4a_{\perp}^2 + \left(\sigma d \sqrt{\frac{\mu_0}{\epsilon_0 \epsilon_{r0}}} - 1\right) a_{\parallel}^2}{\left[\frac{d\epsilon_{r0}^{3/2}}{c\tau(\epsilon_{r0} - \epsilon_{\infty})} + 1\right] a_{\parallel}^2}}$$

Tissue Type	Freq (GHz)
Blood	3.54
Bone (cancellous)	3.80
Bone (cortical)	4.50
Brain (grey)	3.85
Brain (white)	4.23
Fat (infiltrated)	6.00
Fat (not infiltrated)	8.64
Heart	3.75

Tissue Type	Freq (GHz)
Kidney	3.81
Lens cortex	3.93
Liver	3.80
Lung	4.90
Muscle	3.93
Skin	4.44
Spleen	3.79
Tendon	3.71

Prototype Receiver at .13 μm CMOS



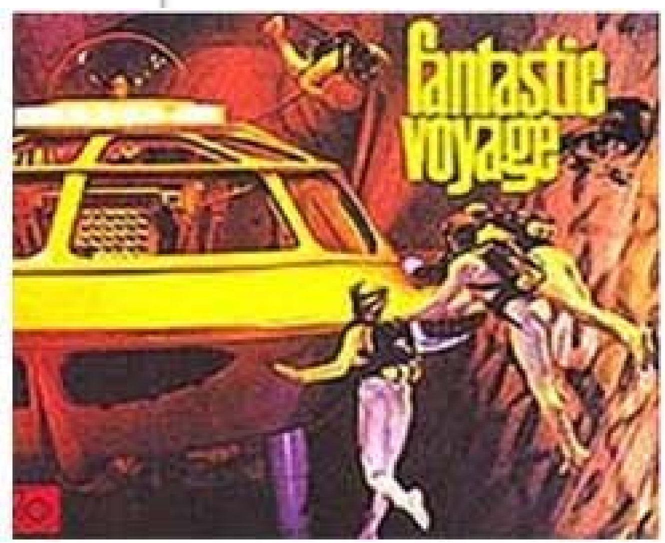
Operating frequency	915 MHz or 1 GHz
TX antenna size	20 mm × 20 mm
RX antenna size	2 mm × 2 mm
Inter-antenna dielectric	15 mm, bovine muscle tissue
Startup time	4 μs
Rectifier efficiency	65%
Regulator efficiency	70%
Gain of link + rectifier + regulator	-33.2 dB (theoretical 31.0 dB)
DC output power	140 μW @ 1.2 V regulated

ISSCC 09

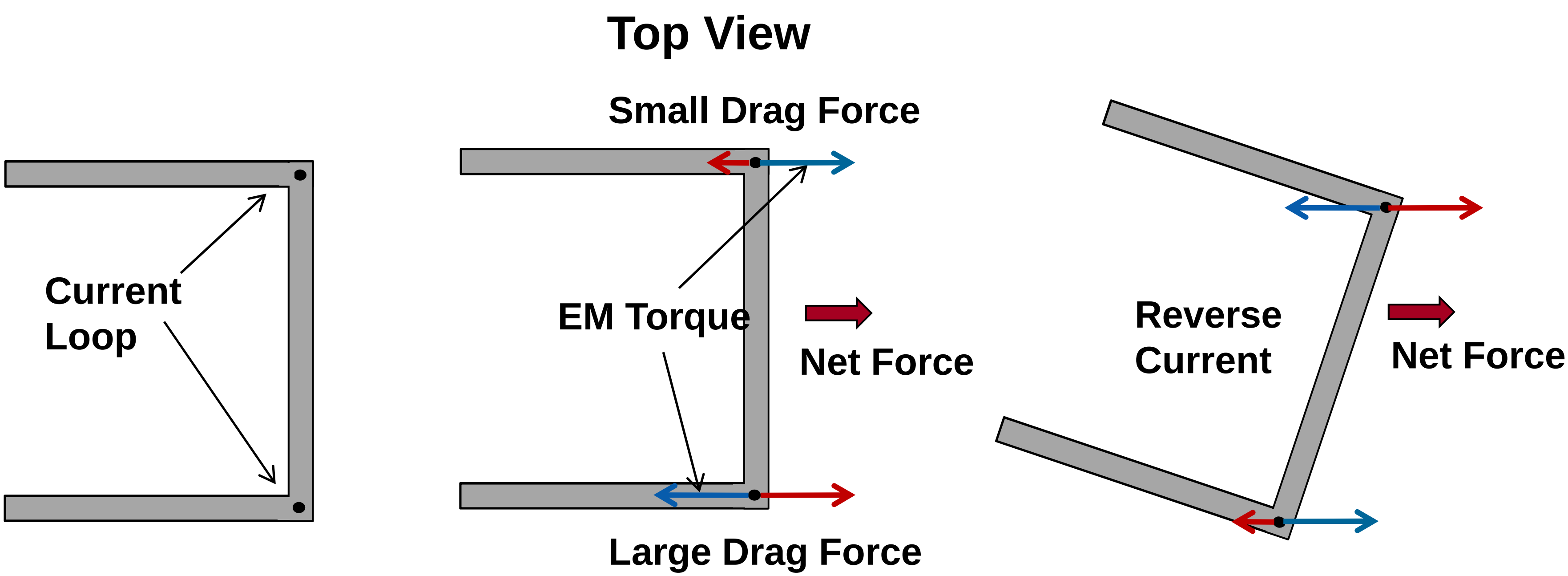
- Unique features
  - Adaptive conjugate matching
  - Highly efficient rectifier
- Coil dimension is 2 mm × 2 mm which is **100 times smaller** than previous designs in the literature at the same power transfer efficiency and range.

1959, Richard Feynman, *Plenty of Room at the Bottom*:

> A friend of mine (Albert R. Hibbs) suggests a very interesting possibility for relatively small machines. He says that, although it is a very wild idea, it would be interesting in surgery if you could swallow the surgeon. You put the mechanical surgeon inside the blood vessel and it goes into the heart and "looks" around. (Of course the information has to be fed out.) It finds out which valve is the faulty one and takes a little knife and slices it out. Other small machines might be permanently incorporated in the body to assist some inadequately-functioning organ.



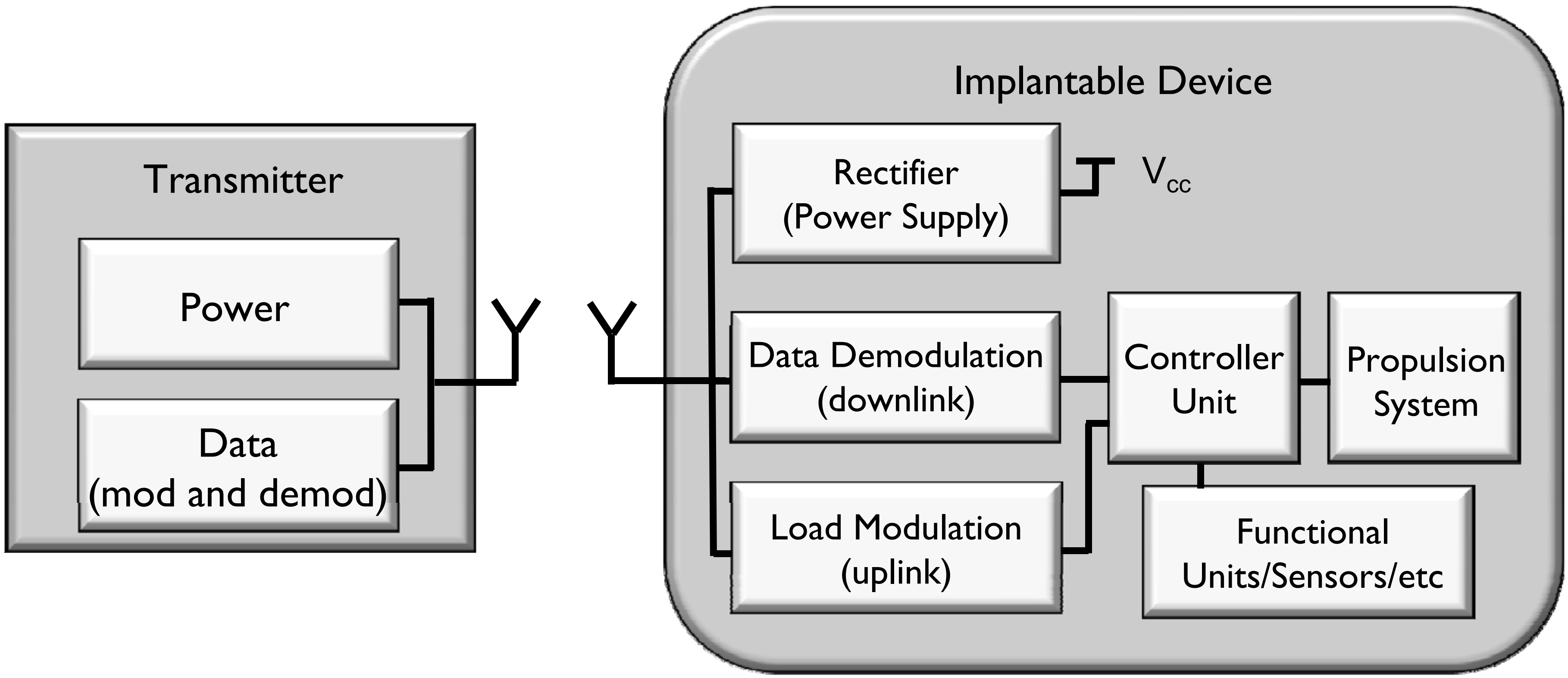
Translating Torques into Motion



- Idea is similar to the paddle in kayaking.
- Asymmetrical shape produces asymmetrical drag forces.
- Alternate direction of EM torque results in net forward force.
- Device can be optimized in terms of shape, frequency of current switching, and magnitudes of currents.

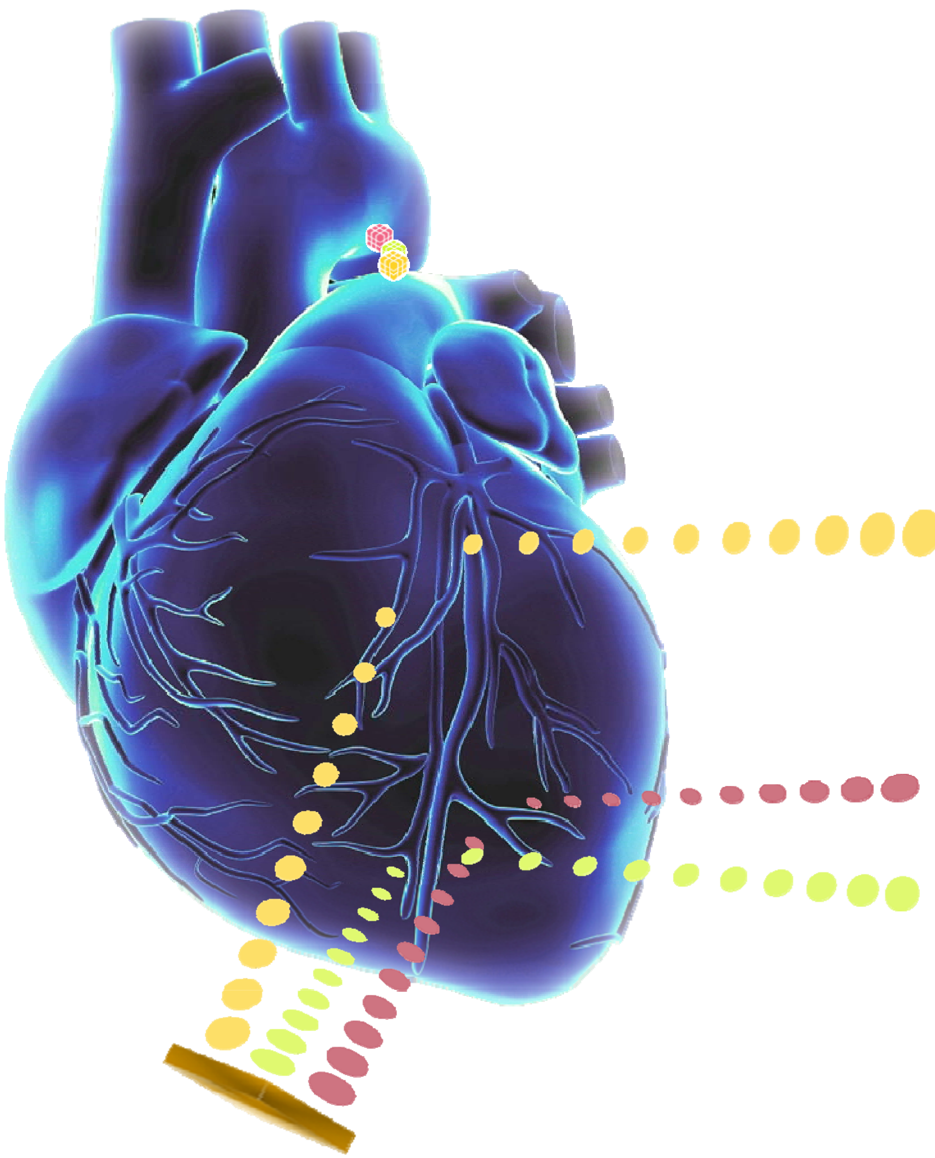
Preliminary Experiments

System-Level Block Diagram



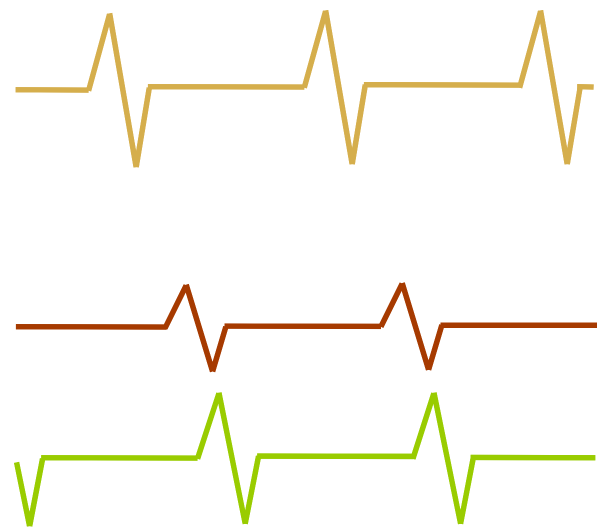
- Power and data are transmitted from same antenna
- Propulsion dominates power consumption, and must be efficient.
- Plan to tape out in mid June

Wireless Probing of the Heart



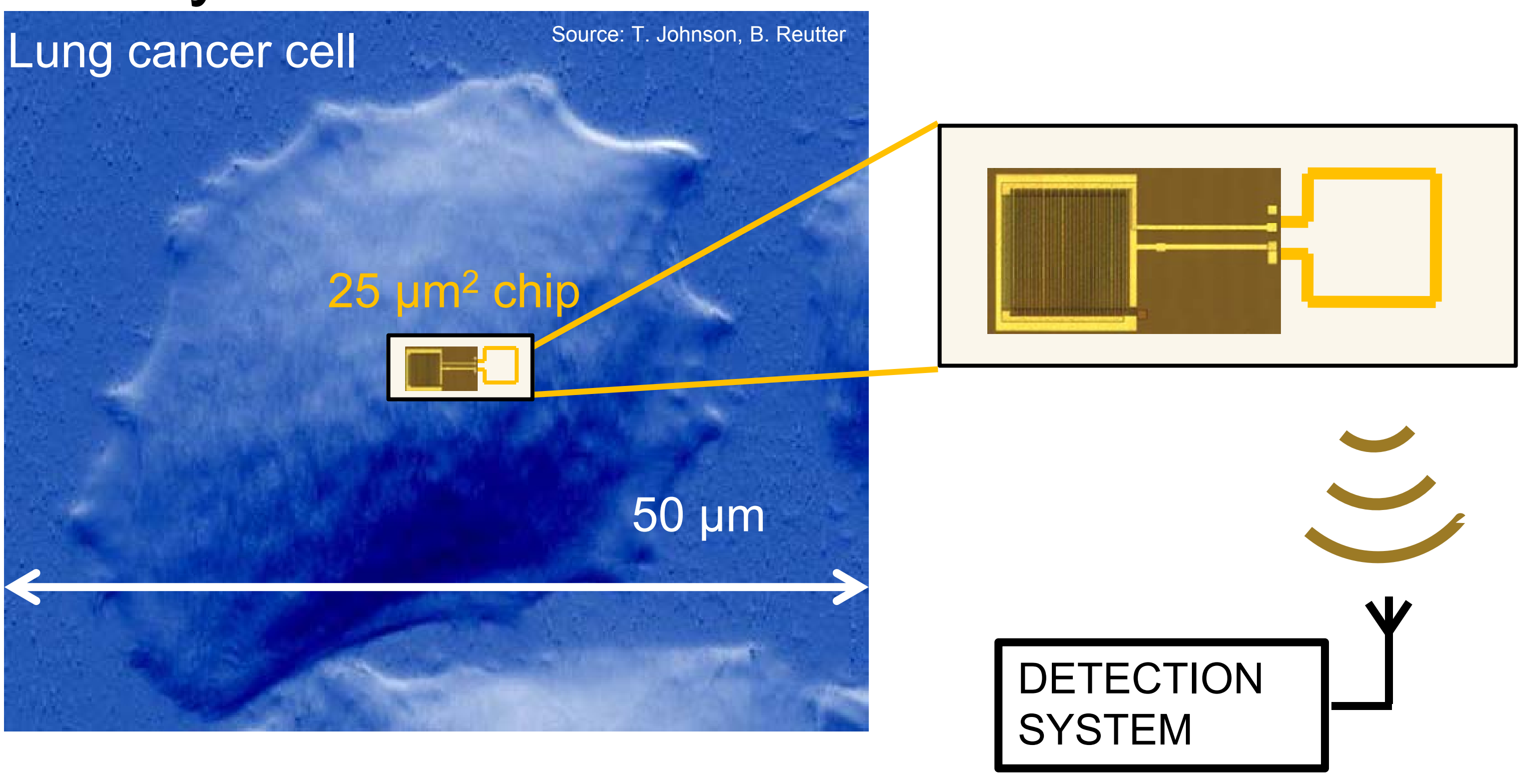
In the United States, about half of the cardiac mortality is due to ventricular arrhythmia, which accounts for approximately 300,000 deaths per year.

Intracardiac Electrogram



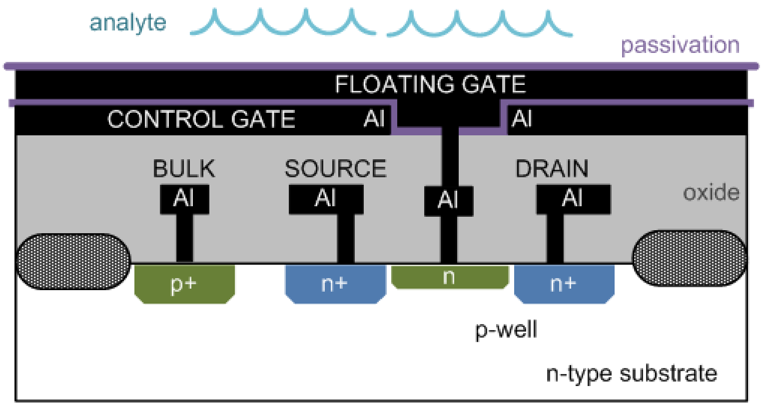
CHIC (CHip In Cell)

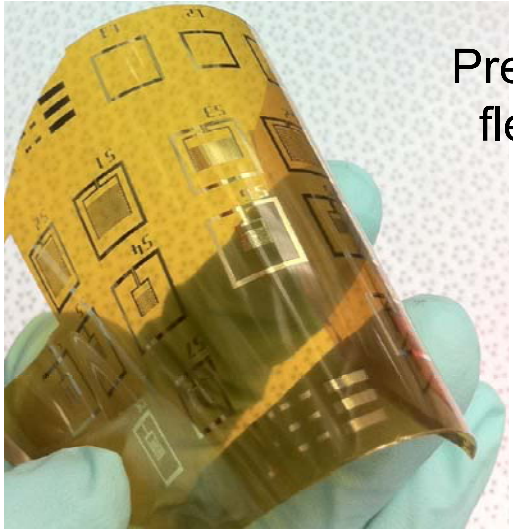
- Autonomous, wireless, implantable sensor
- Active, continuous-time monitor of cellular activity



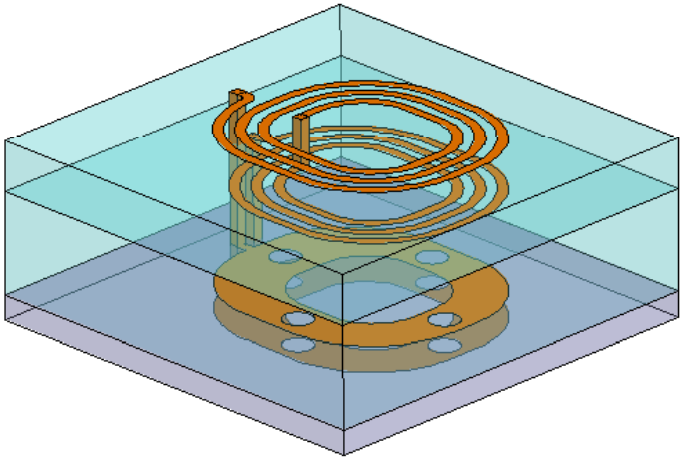
Sensors and Resonantors

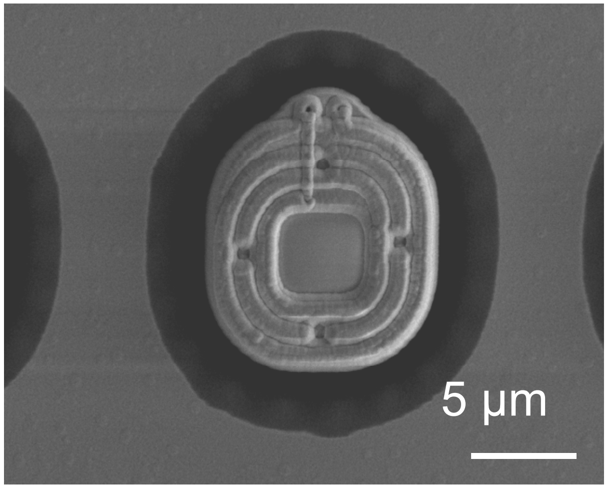
CMFET chemical sensor





Pressure sensor on flexible substrate





Micro resonantor

Choice of Cells

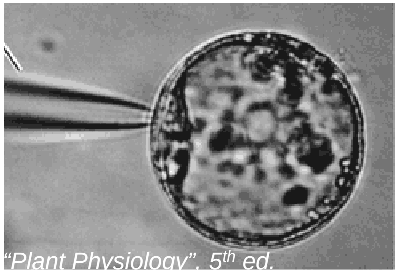
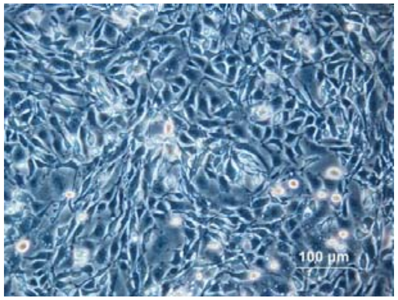
	Cell Type	Cell Size	Device Size
	*Xenopus* Oocytes	1.0 mm (spherical)	50 μm
	Plant Protoplasts	60 μm (spherical)	10-15 μm
	Chinese Hamster Ovary (CHO)	2x 25x 100 μm (spread on surface)	~ 5 μm

Image credits: Xenopus.com; "Plant Physiology", 5th ed.