EEC 216 Lecture #11: Energy Scavenging

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Outline

- **Announcements**
- Review: Batteries
- Wrap-Up: Fuel Cells and Power MEMS
- Energy Harvesting
- Example 1: PicoRadio (Rabaey, UCB)
- Example 2: Piezoelectric Benders (Wright, UCB)
- Example 3: Self-Powered Systems (Amirtharajah et al., MIT)
- Example 4: Integrated Solar Cells (Guilar et al., UCD)

Announcements

- **Project progress meetings next week**
  – Signup sheet on my office door for next Monday
  – Preliminary simulations done
- **Final project presentations in final exam period March 18, 1-3 PM**
  – Email PowerPoint before 12 PM, March 18
- **Final project paper due March 18, 5 P.M. by email to ramirtha@ece.ucdavis.edu (soft copy only!)**
  – Two page, two column ISSCC format (1 page text, 1 page figures)

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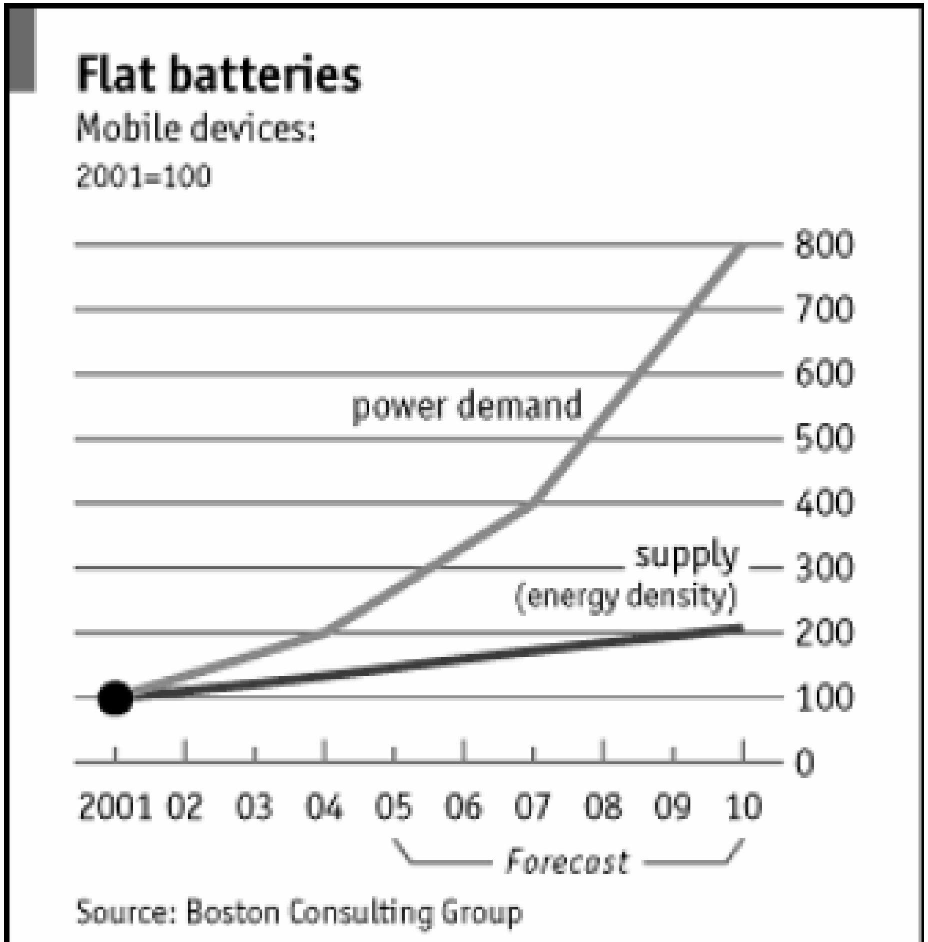
Recent Battery Scaling and Future Trends



- **Battery energy density increasing 8% per year, demand increasing 24% per year (the Economist, January 6, 2005)**

Battery Basics

- **Battery consists of several electrochemical cells**
  - Can be arranged in series (increase output voltage) or parallel (increase output current) or combination
  - Each cell consists of two terminals (anode and cathode) separated by electrolyte
  - These constitute cell's active materials
- **When cell connected to load, oxidation-reduction reaction occurs**
  - Electrons transferred from anode to cathode
  - Transfer converts chemical energy stored in active material to electrical energy
  - Flows as current through external load

Rate Dependent Capacity

- **Battery capacity decreases as discharge rate increases**
  - When fully charged, electrode surface has maximum concentration of active species
  - Under loading, active species consumed by reaction at electrode and replenished by diffusion from electrolyte bulk
  - Diffusion cannot keep pace with electrochemical reaction, so concentration gradient builds up in electrolyte
  - As load increases, active species concentration at electrode drops below threshold (corresponding to cutoff voltage) and reaction cannot be sustained, eliminating current flow
  - Eventually cell recovers (*charge recovery*) as diffusion flattens concentration gradient
- **For sufficiently low discharge rates, operation remains close to ideal**

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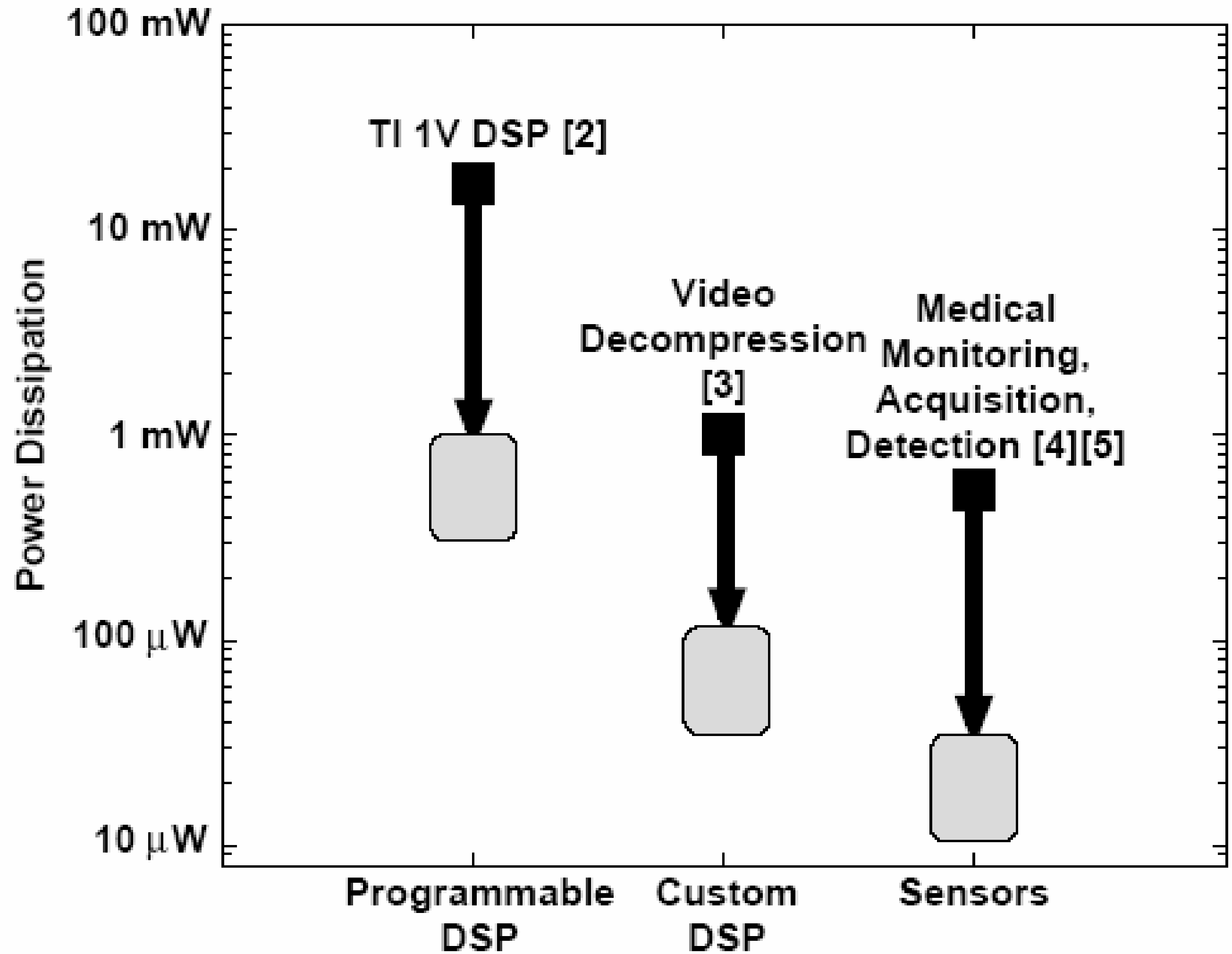
Power Trends for DSP



- **Can we use ambient energy sources to power electronics?**

Sources of Ambient Energy

- **Solar Power**
  - Photovoltaics convert light to electricity
  - Very well established (calculators, watches, etc.)
- **Electromagnetic Fields**
  - Usually inductively coupled, sometimes uses antenna
  - Used in smart cards, pacemaker charging, RFID tags
- **Thermal Gradients**
  - Woven into clothing, power off skin-air temperature gradient (ISSCC 03)
- **Fluid Flow**
- **Mechanical Vibration**

Vibration Based Energy Harvesting

- **Embedded sensor applications**
  - Monitoring of vibrating machinery: turbines, internal combustion engines, machine tools
  - Monitoring of vehicles: ships, submarines, aircraft
  - Monitoring of structures: load-bearing walls, staircases, buildings, bridges
  - Applications demand long lifetime in environments without continuous exposure to incident light
- **Wearable devices**
  - Wrist worn biomedical monitor
  - Computers embedded in clothing, smart textiles

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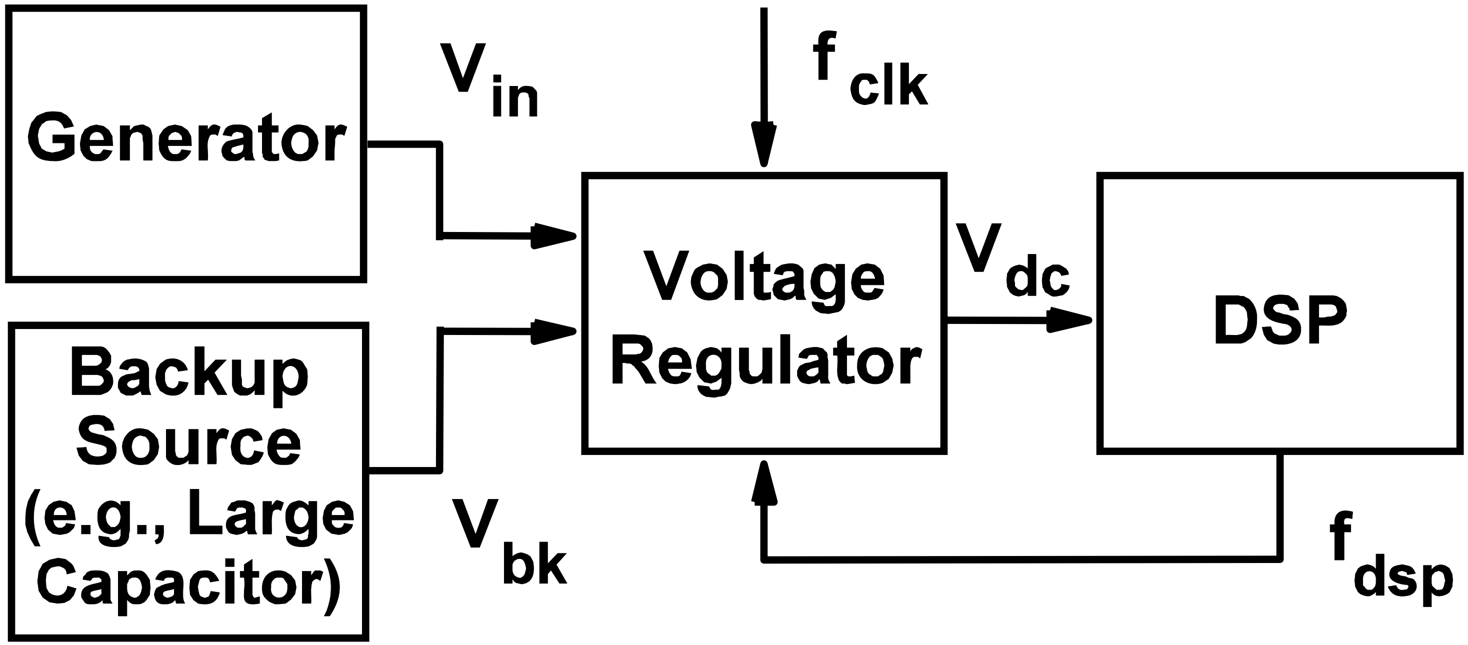
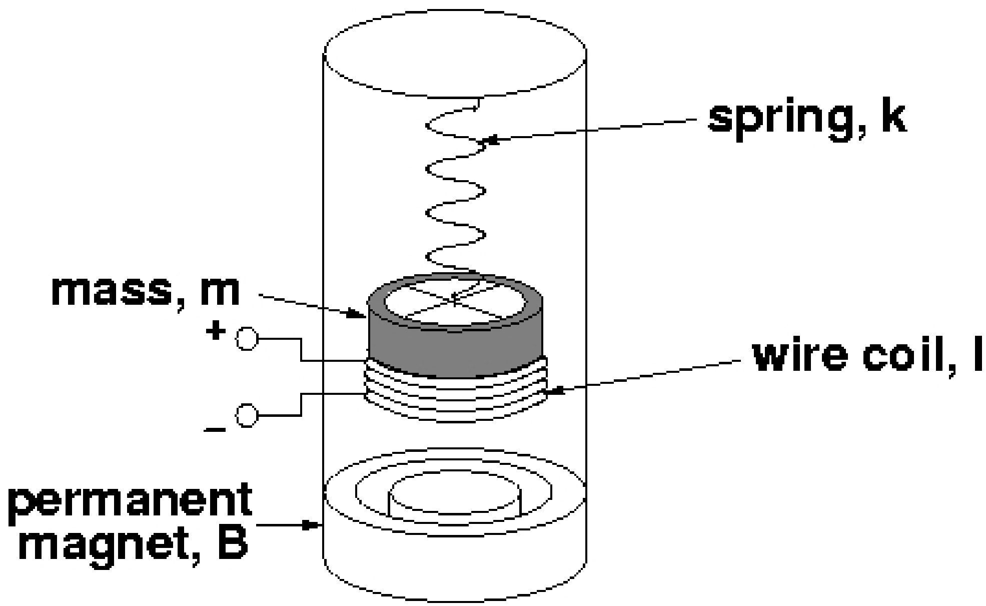
Self-Powered System Overview



- **Generator output (V_{in}) can vary rapidly**
- **Delay feedback vs. voltage feedback**
  - Compensates for temperature, process, and computational workload variations
  - Allows simple *all* digital control (Dancy, TVLSI 00)
- **Full system implemented and tested (Amirtharajah, JSSC 98)**

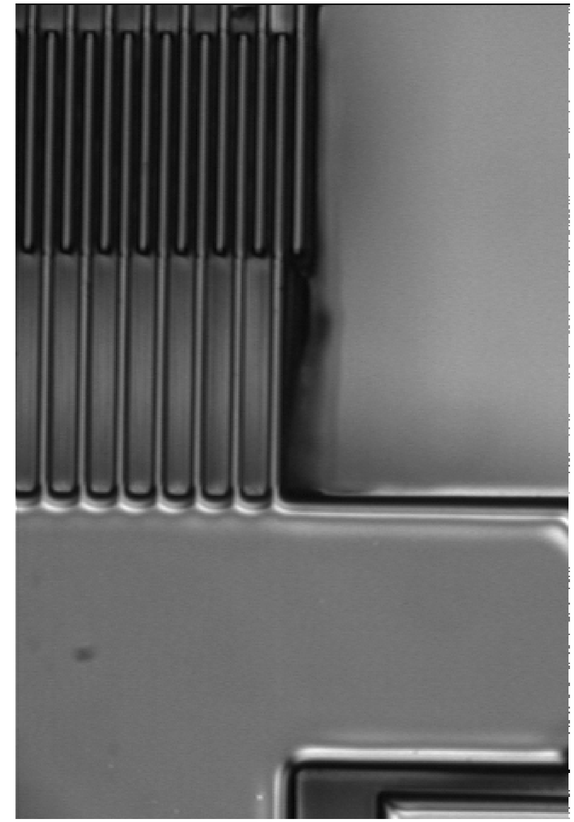
Vibration to Electric Energy Converters

Macroscopic Moving Coil



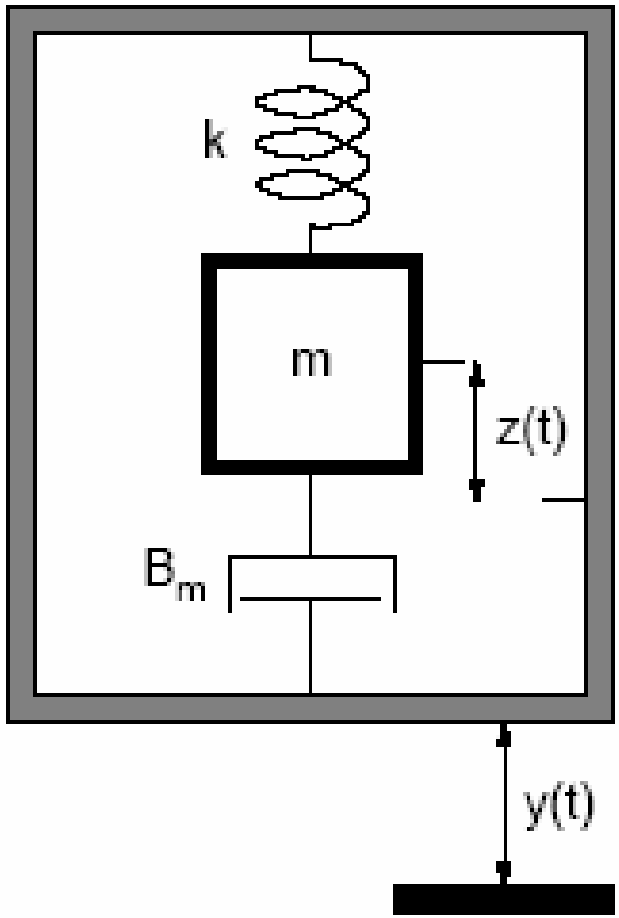
- **Estimated output power: 400 μW**

MEMS Variable Capacitor



- **Estimated output power: 8.7 μW**

Generator Mechanical Model



- **Second order mechanical system: spring + mass + dashpot**
- **Driven by amplitude forcing function**

Output Power Equation

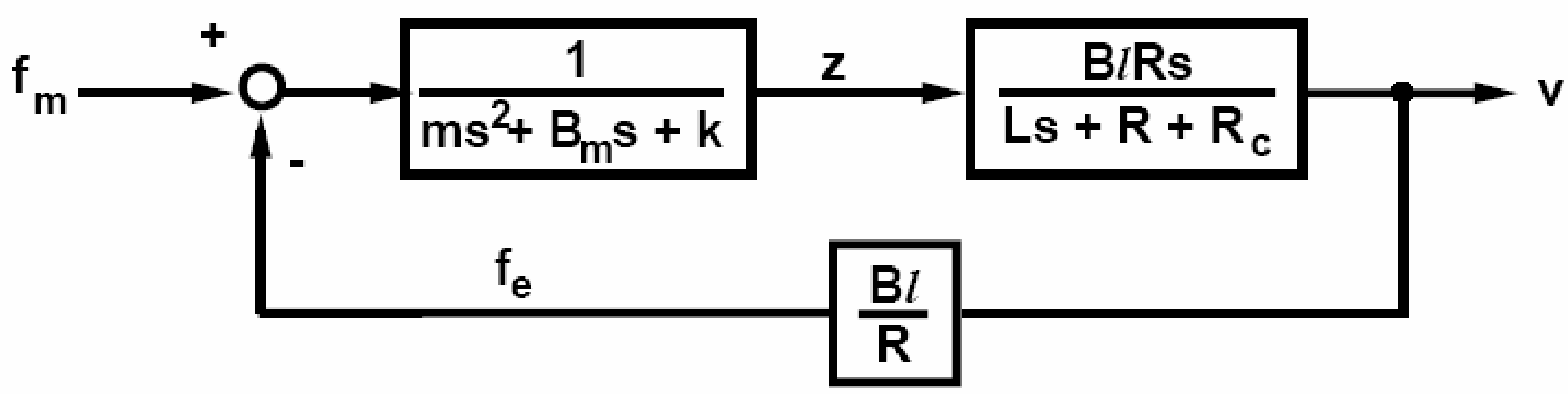
- **Forcing amplitude to mass displacement transfer function:**

$$H(s) = \frac{Z(s)}{Y(s)} = \frac{-s^2}{s^2 + \frac{B_m}{m}s + \frac{k}{m}} = \frac{-s^2}{s^2 + 2\zeta\omega_0 s + \omega_0^2}$$

- **Loss power (dissipated in damper):** $P_o(t) = B_m \dot{z}^2$
- **Output power:**

$$P_{out} = \frac{F_0^2 \zeta \omega^2}{m\omega_0^3 \left[\left(1 - \left(\frac{\omega}{\omega_0}\right)^2\right)^2 + \left(2\zeta \frac{\omega}{\omega_0}\right)^2 \right]}$$

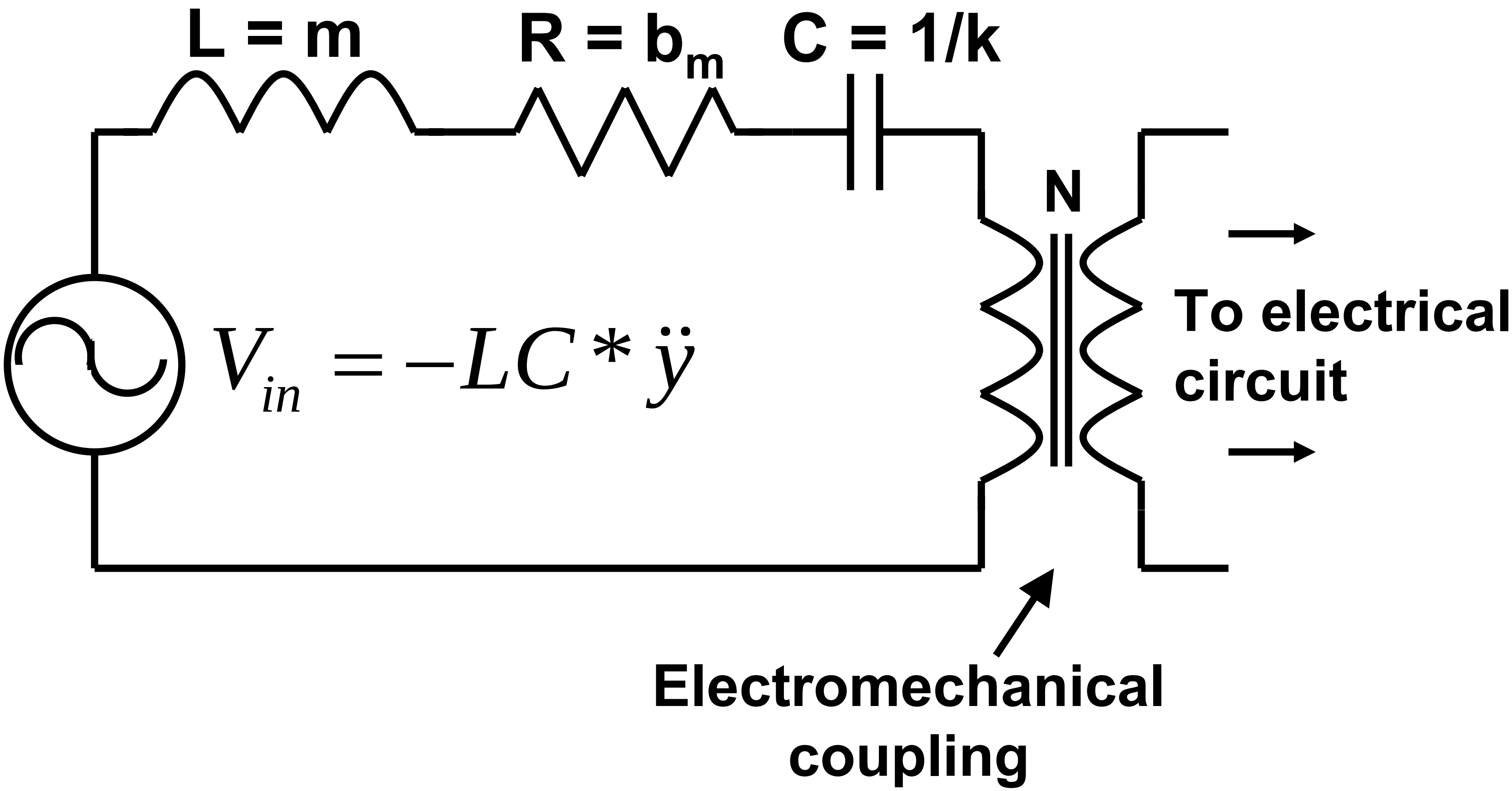
Transducer Output Voltage



- **Third order electromechanical system:**

$$
\begin{aligned}
G(s) &= \frac{V(s)}{F_m(s)} \\
&= \frac{BlRs}{(ms^2+B_m s+k)(Ls+R+R_c)+(Bl)^2 s} \\
&= \frac{BlRs}{Lms^3+B_m Ls^2+(kL+B_m(R+R_c)+(Bl)^2)s+k(R+R_c)}
\end{aligned}
$$

Generator Equivalent Circuit Model



- **Currently incorporating parameterizable model into Hspice to aid load circuit design**

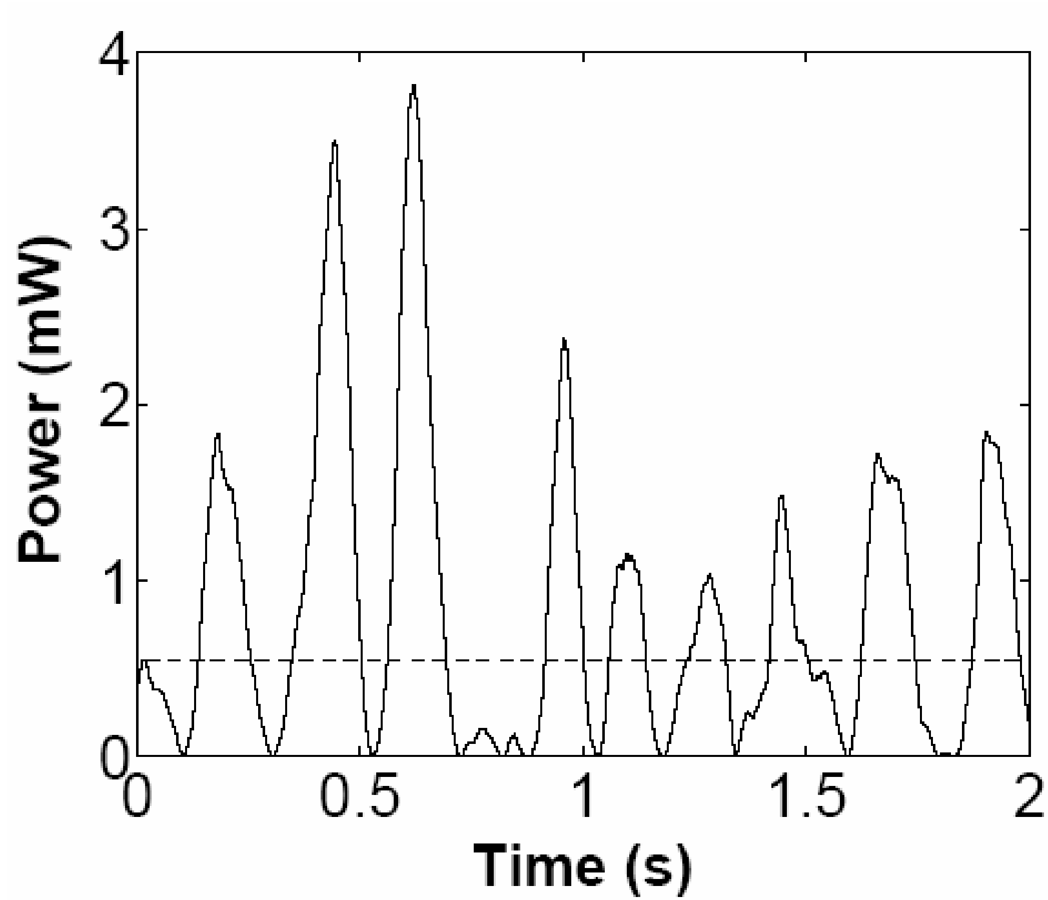
Model Order Reduction

- Assuming inductive time constant fast, reduces to second order electromechanical system:

$$G(s) = \frac{BlRs}{(R+R_c)\left(ms^2 + \left[B_m + \frac{(Bl)^2}{R+R_c}\right]s + k\right)}$$

- Some parameters known at manufacturing time
- Others estimated by fitting model parameters to measured system response

Estimated Output Power for Wearable

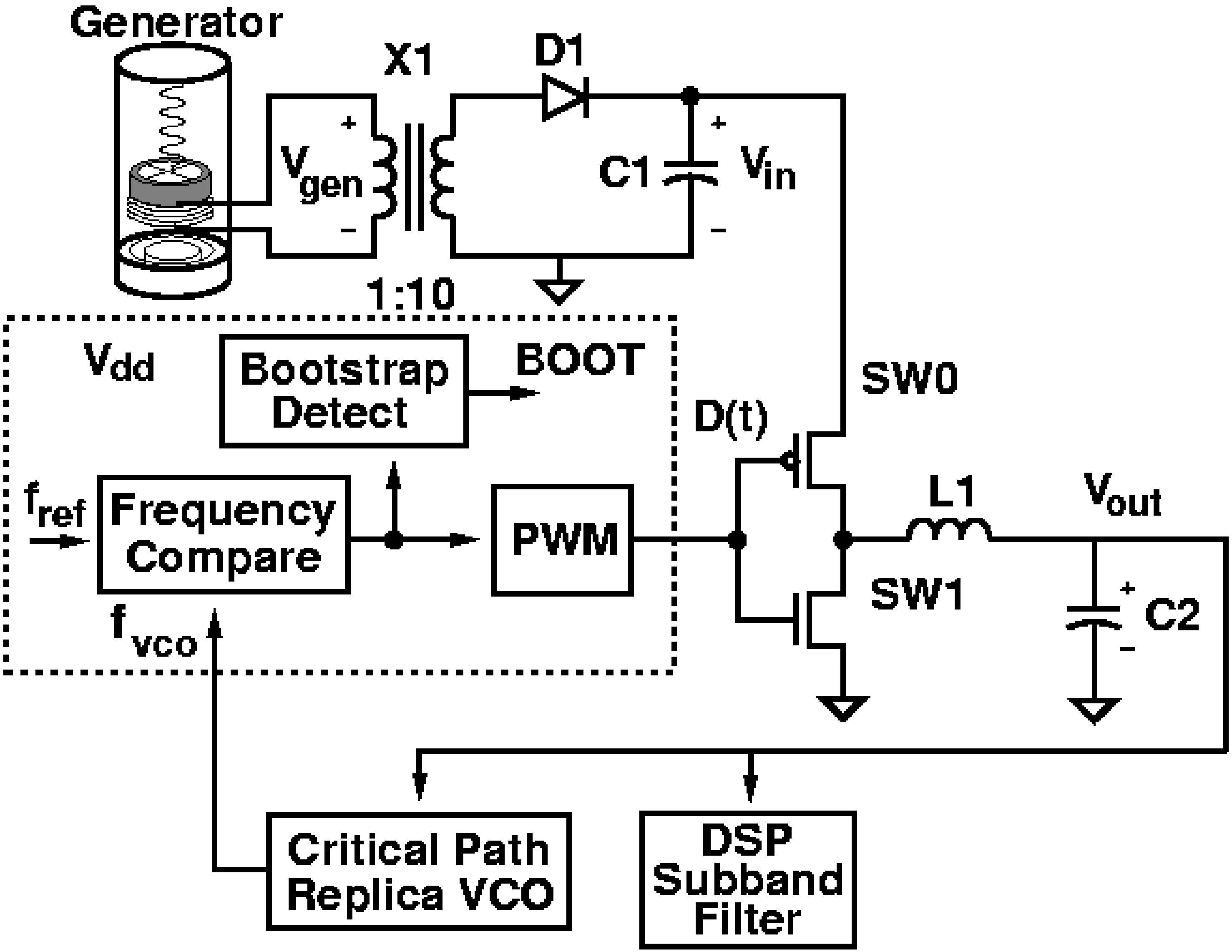


- **Power estimate for forcing function due to walking**
- **Displacement = 1 inch, frequency = 2 Hz**
- **Average output power = 400 μW**

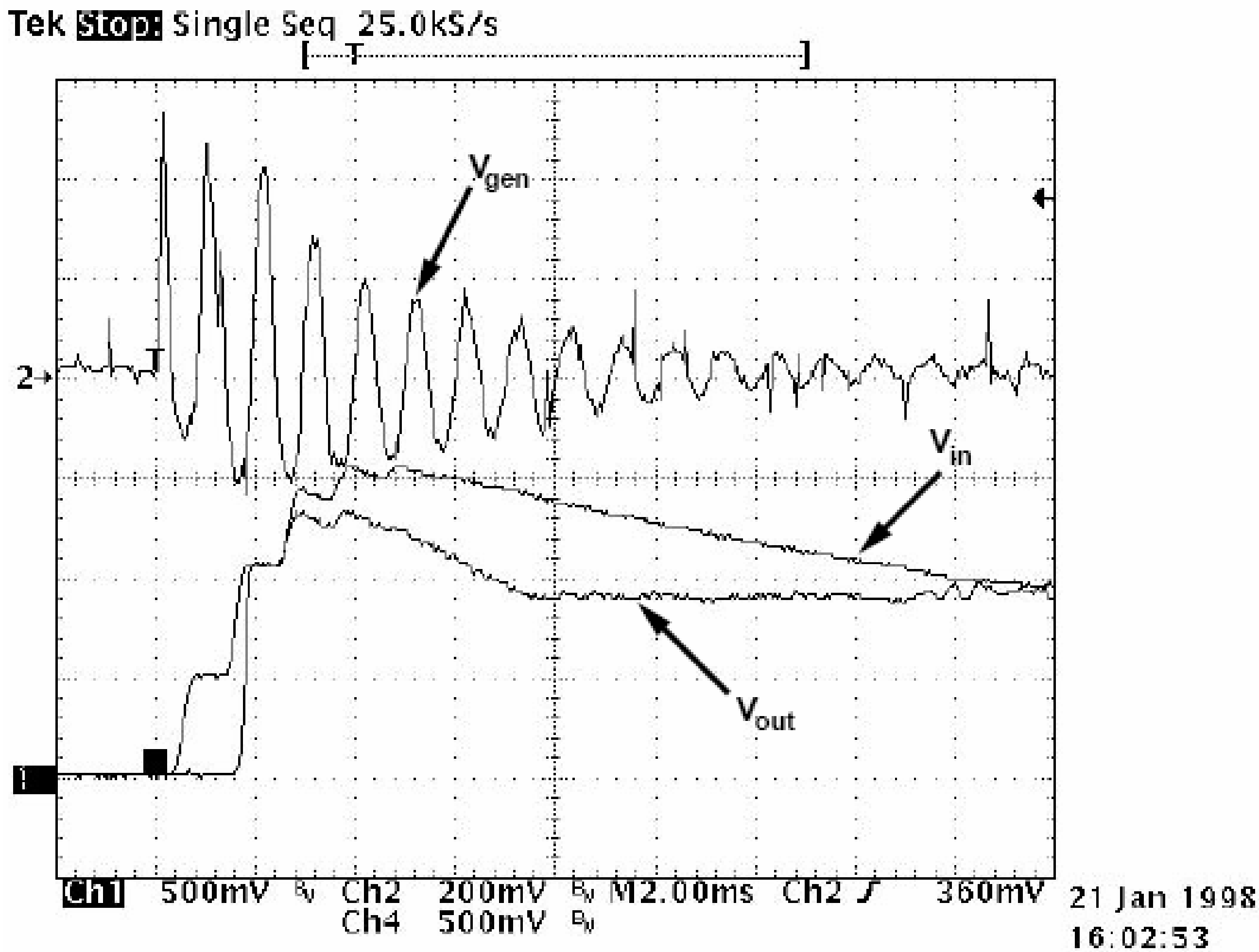
Vibration Based Power Generation

Energy Harvesting Method	Implementation (Previously Reported)	Output Power
Electromagnetic Moving Coil	Amirtharajah 98	18 μW
	Lee 03	830 μW
MEMS Variable Capacitor	Meninger 01	8.7 μW
	Mur Miranda 03	61 μW
	Roundy 02	116 μW
Piezoelectrics (Vibration)	Roundy 03	375 μW
	Ottman 03	12.9 μW
	Glynne-Johns 01	3 μW
	MicroStrain, Inc. 03	60 μW
Piezoelectrics (Shoe Inserts)	Schenck 01	8.4 μW

Moving Coil Self-Powered System Overview

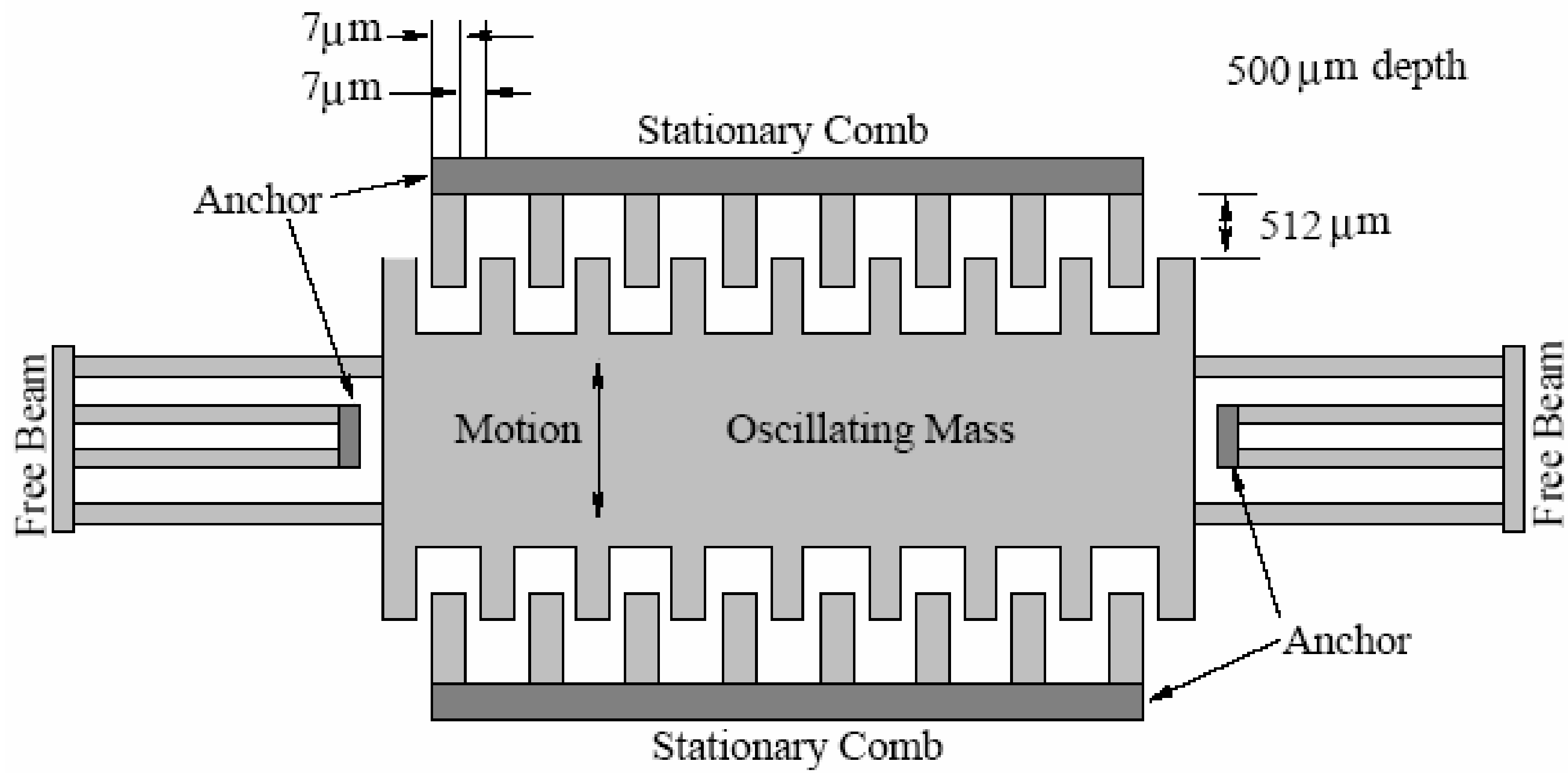


Generator and Output Voltage Waveforms



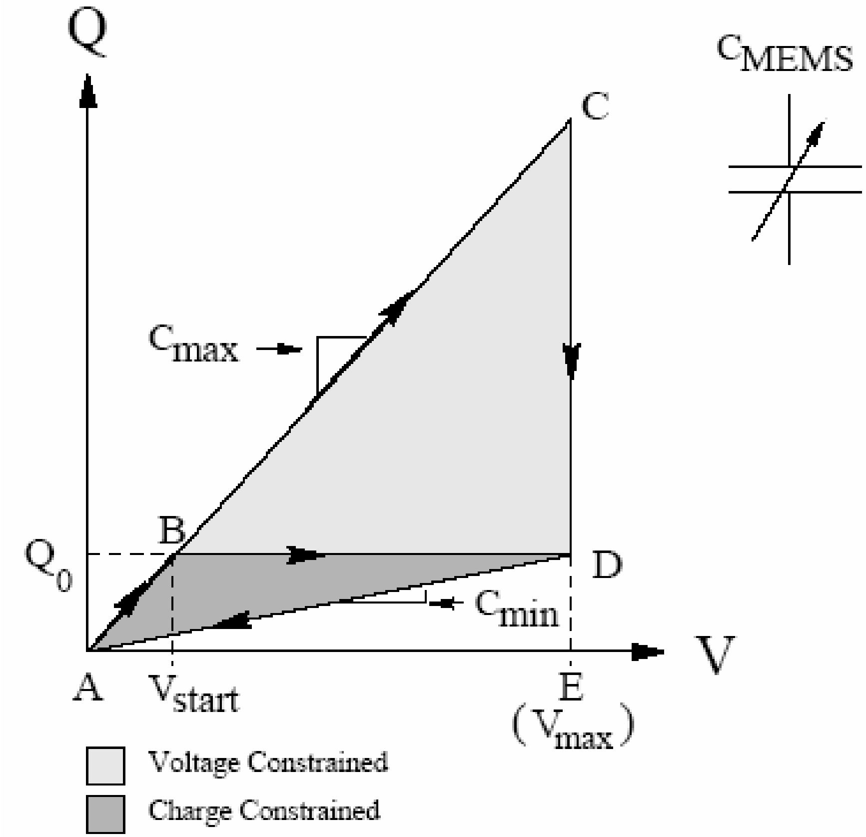
- **Measured for single generator impulse response**

MEMS Variable Capacitor Generator



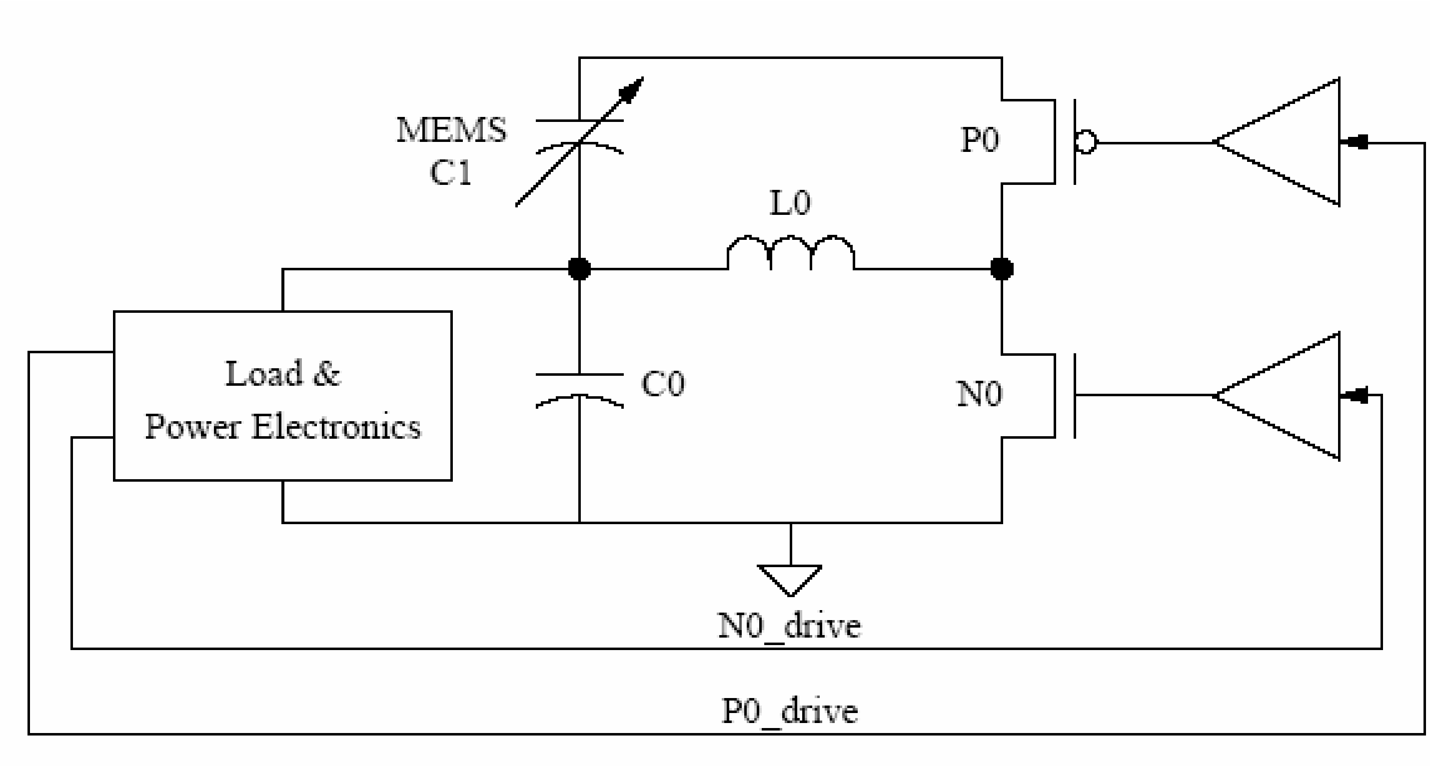
- **Etched fingers form two capacitor plates, movable plate slides past fixed plate**
- **Dual-bar linkages constrain motion in one direction**

MEMS Capacitor Energy Conversion Cycles



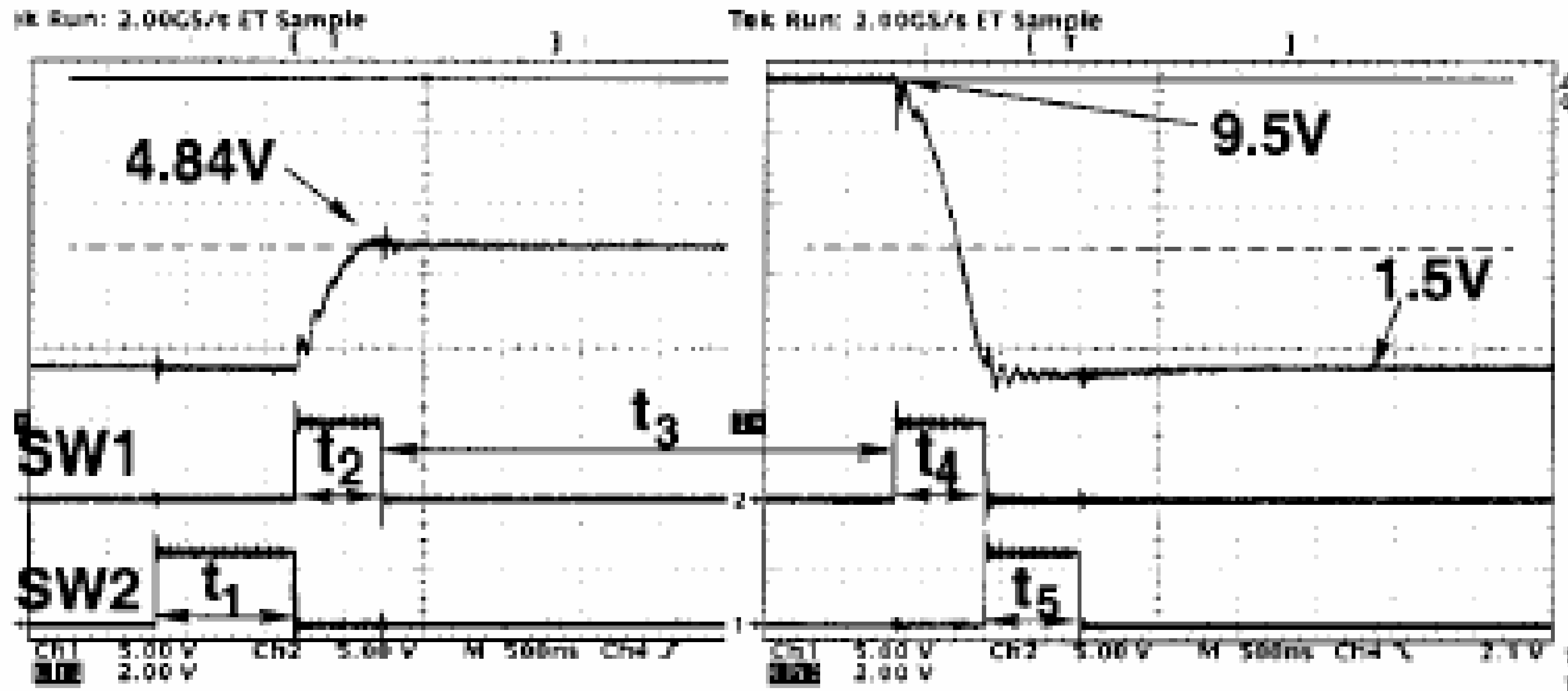
- **Charge constrained: fix charge at max C, move plates decreasing C, remove charge at min C**
- **Voltage constrained: max voltage set by breakdown**

Charge Constrained Cycle Electronics



- **PMOS off, NMOS on: build up inductor current from charge reservoir / battery C0**
- **PMOS on, NMOS off: inductor current charges C1**

Conversion Electronics Operation



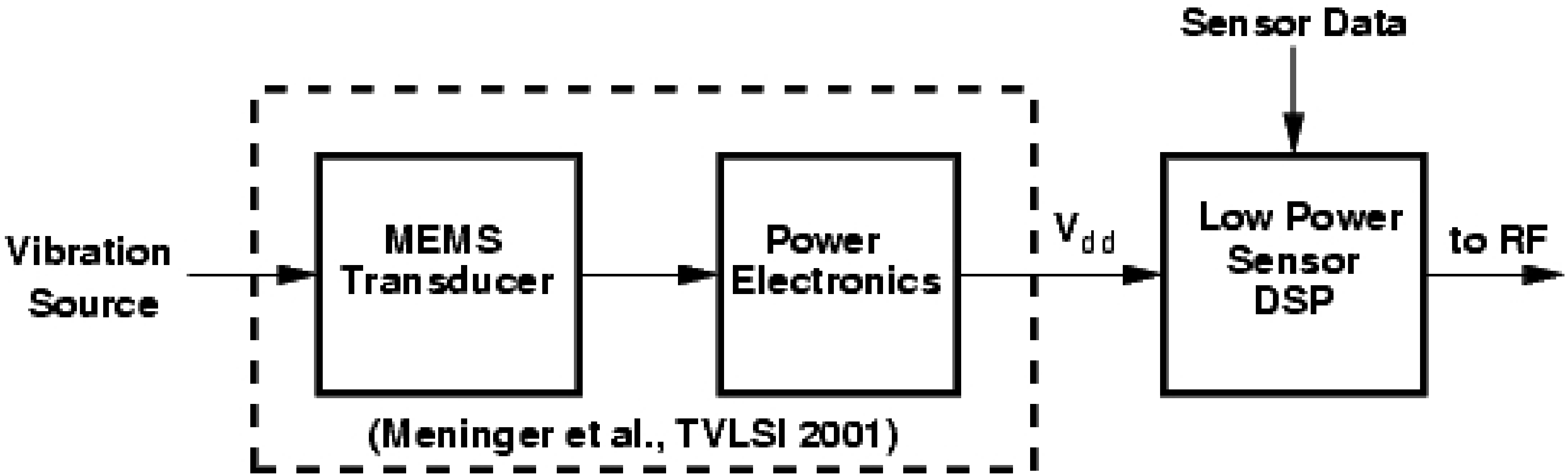
- T1, SW2 (NMOS) on: inductor charges
- T2, SW1 (PMOS) on: variable capacitor charges
- T3: plates move apart, voltage increases
- T4, SW1 (PMOS) on: variable capacitor discharges
- T5, SW2 (NMOS) on: inductor returns charge to C0

Net Output Power Estimate

Area	2163μm x 2554μm
Transistor Count	2661
Process	0.6μm CMOS
Predicted Converted Energy	8.66μW
Core Power	500nW (f_{vib} = 2.5kHz, V_{dd} = 1.5V)
Switch Loss Power	3.87μW (ΔV_{MEMS} = 8.0V)
Predicted Power Out	4.29μW (ΔV_{MEMS} = 8.0V)

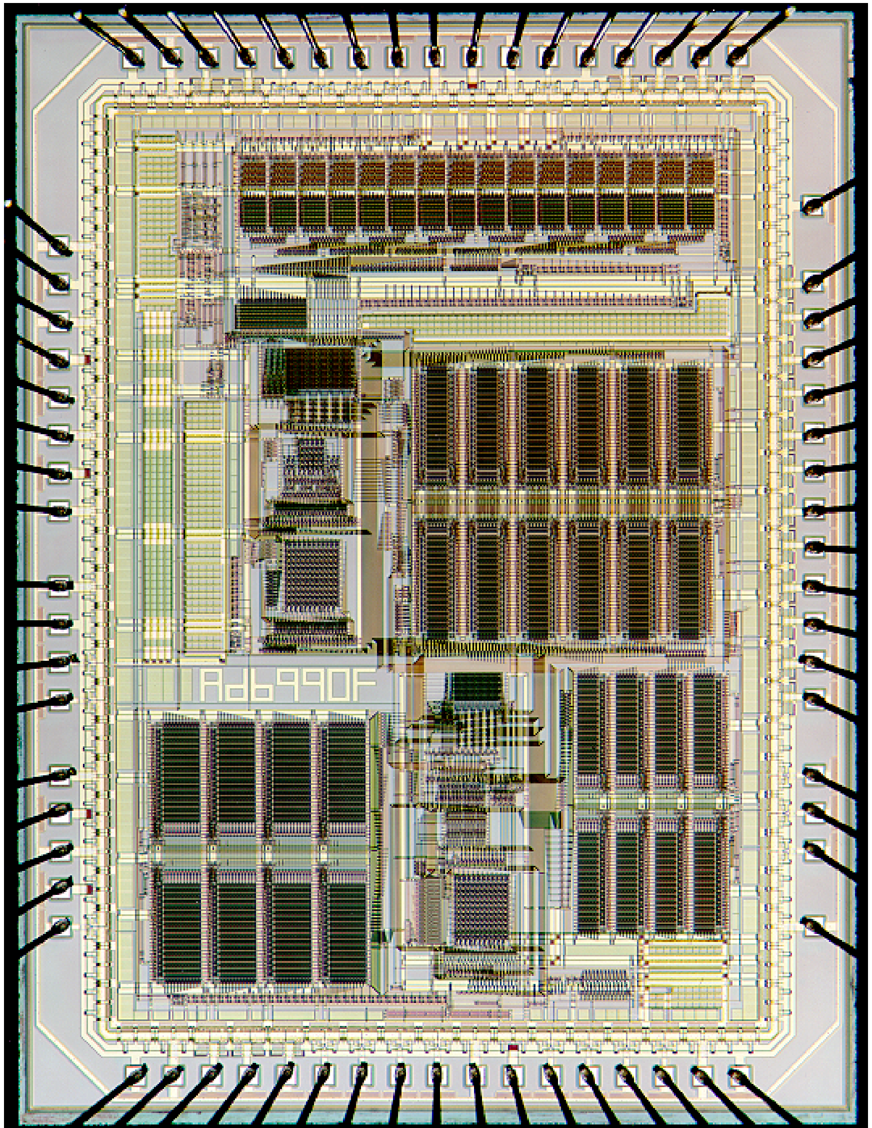
- **Half circuit estimate would be doubled for both movable capacitor plates in operation (each capacitor plate one half cycle out of phase)**
- **Core logic for power electronics very low**
- **Losses dominated by switches in this example**

MEMS Self-Powered System Block Diagram



- MEMS implementation compatible with future systems-on-a-chip
- Ultra low power DSP enables operation using scavenged energy for low throughput applications
- DSP energy scalability enables tradeoff between quality and available energy

Sensor DSP Die Photo



- 0.6 um CMOS
- Area: 4.4 mm x 5.8 mm
- Clock: 1.2 kHz / 250 kHz
- Power Supply: 1.5 V
- 190K transistors
- Predicted MEMS Output: 4.29 μW
- SensorDSP Chip Power: 560 nW
- **SensorDSP Chip Energy: 26.6 pJ / sample**
- **StrongARM SA-1100 Energy: 11 μJ / sample**

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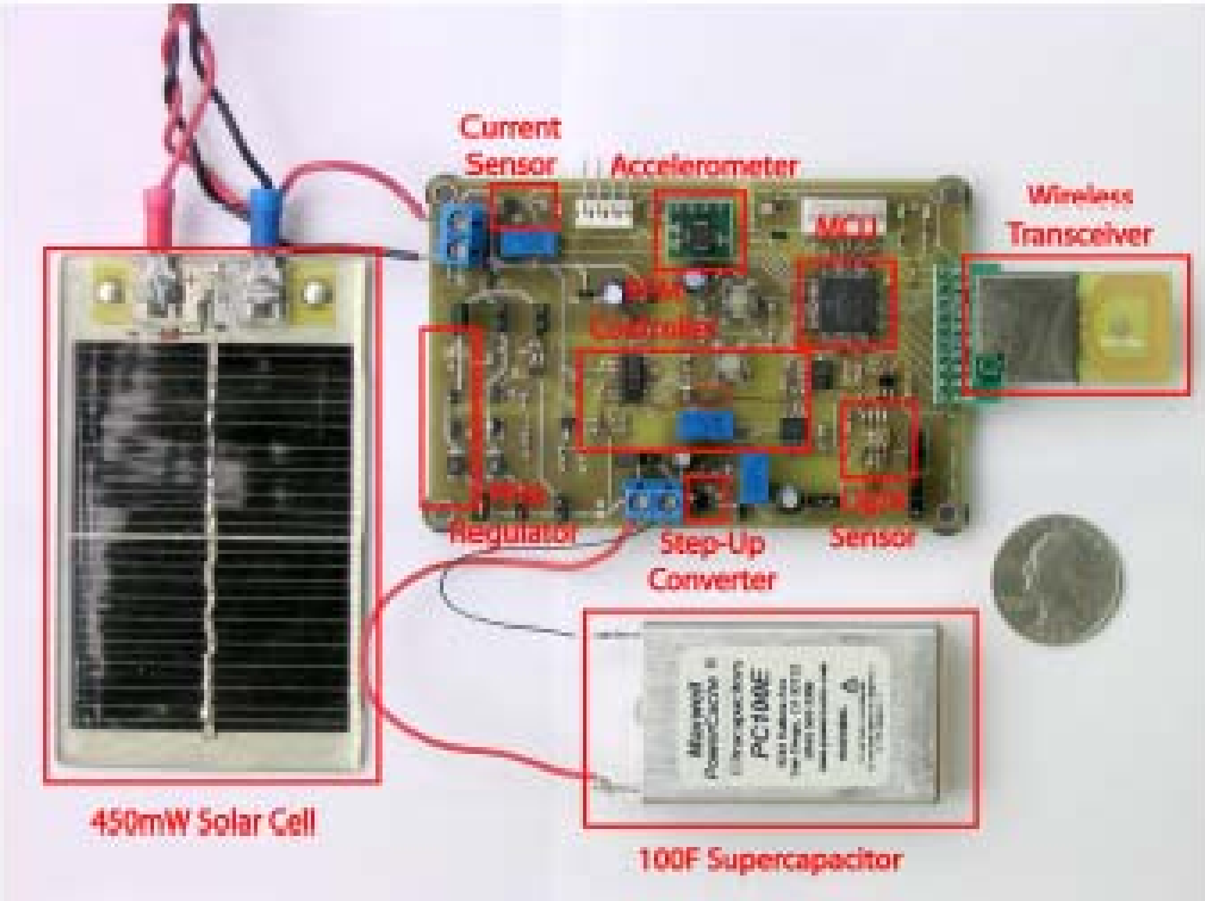
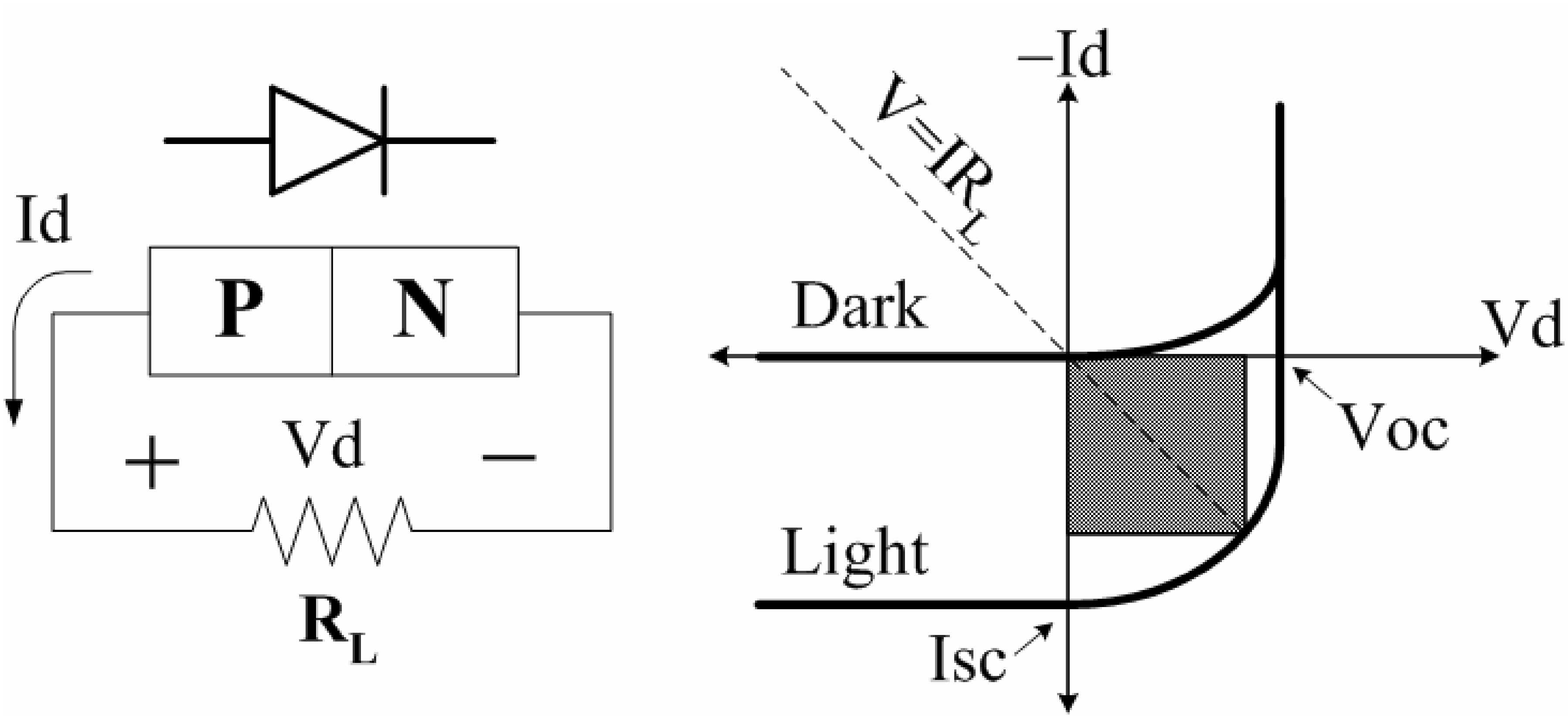
Solar Energy Harvesting



Everlast Mote (Simjee and Chou ISLPED 06)

- Typical solar cells based on crystalline silicon
- Thin-films offer lower costs (amorphous Si, CdTe, etc.)
- Would like to integrate solar cell and capacitor cheaply into standard CMOS logic process

Solar Cell Characteristics

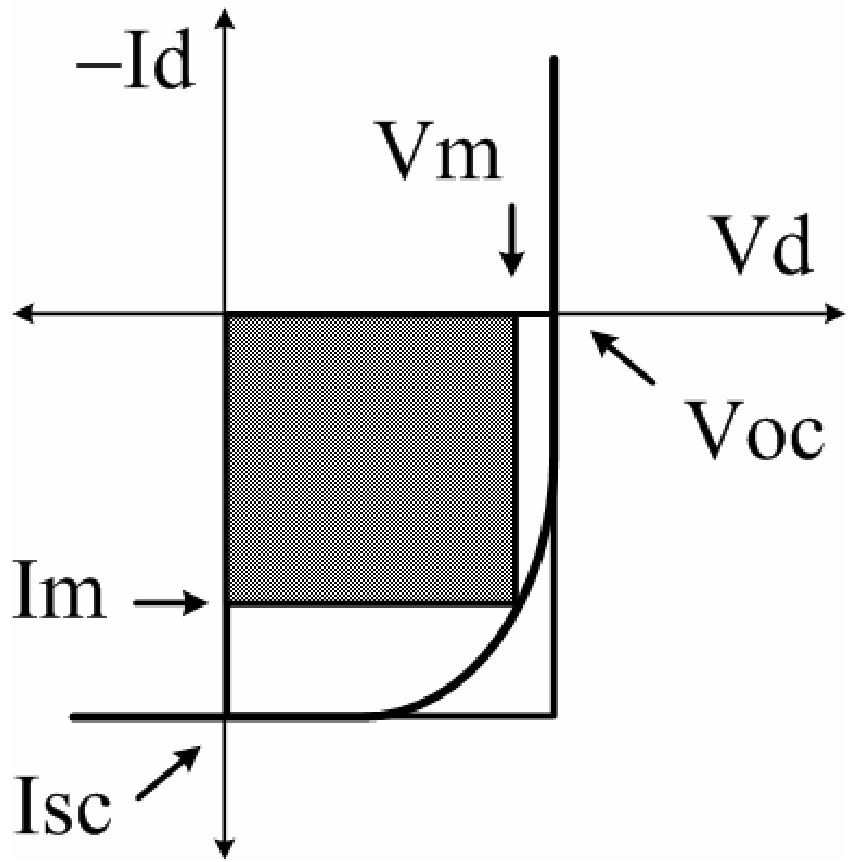


- Current-voltage characteristics under optical illumination
- Load resistor determines bias point

Solar Cell Figure of Merit

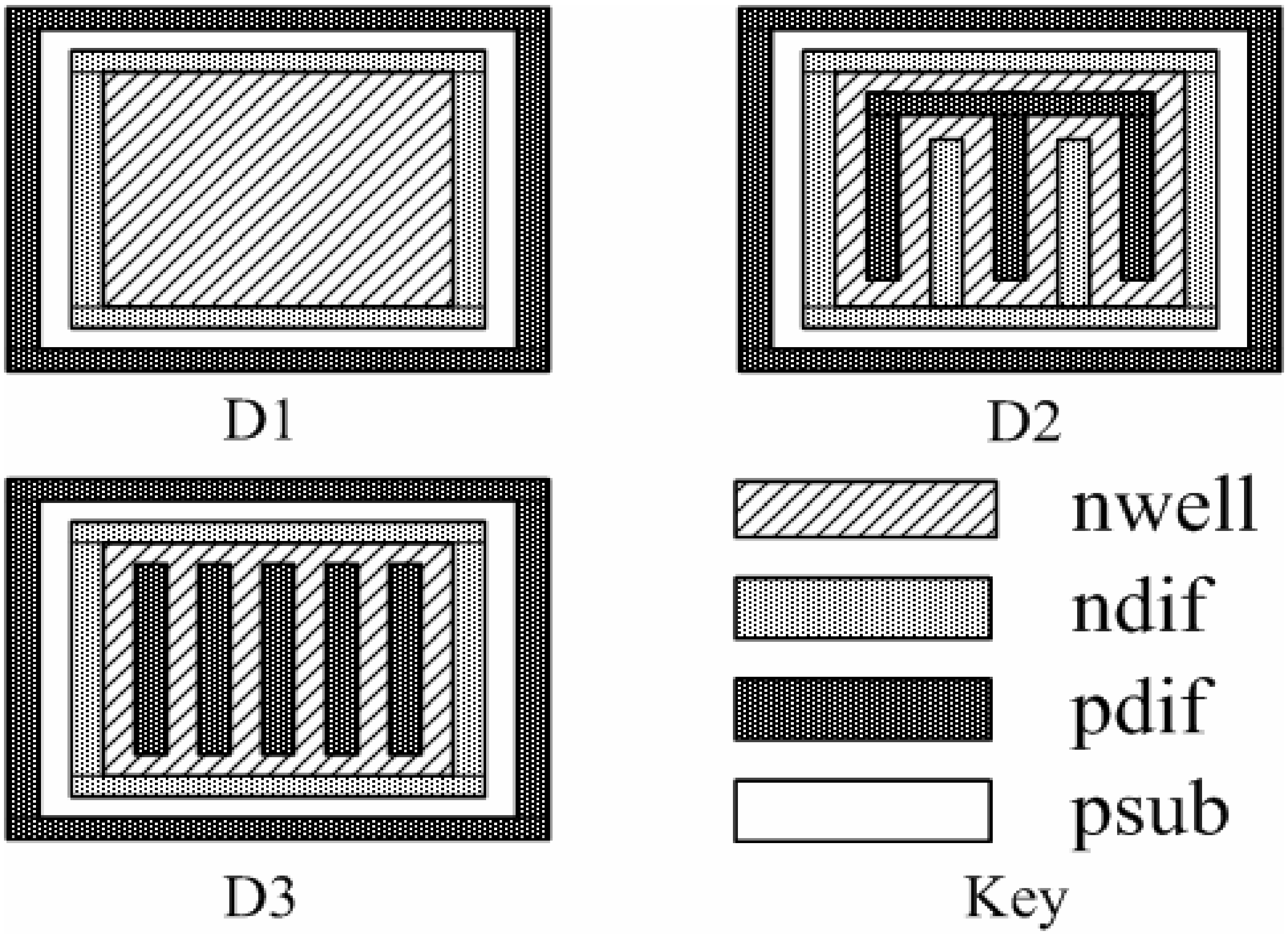
$$\text{FOM} = \frac{\text{Pmax}}{\text{Isc} \cdot \text{Voc}}$$

$$\text{Pmax} = \text{Im} \cdot \text{Vm}$$



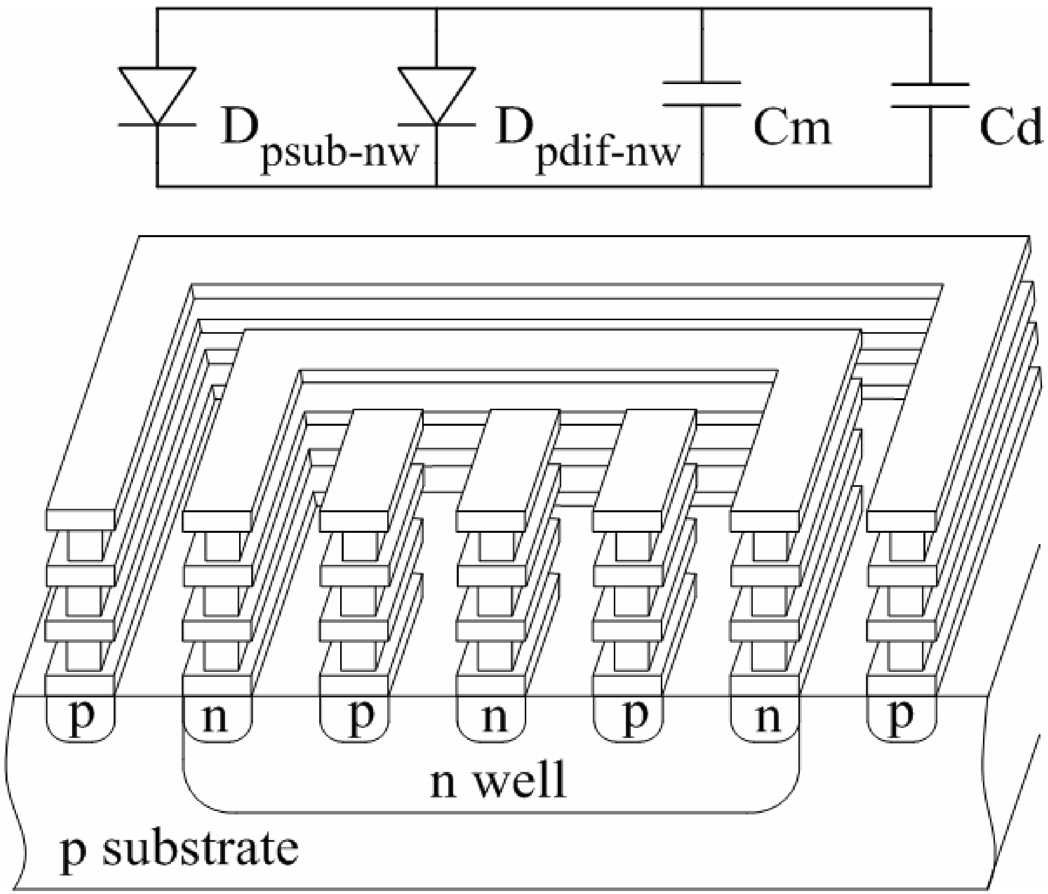
- FOM (Fill Factor) = ratio of two areas, less than 1
- A function of light intensity

Integrated Photodiodes: Top View



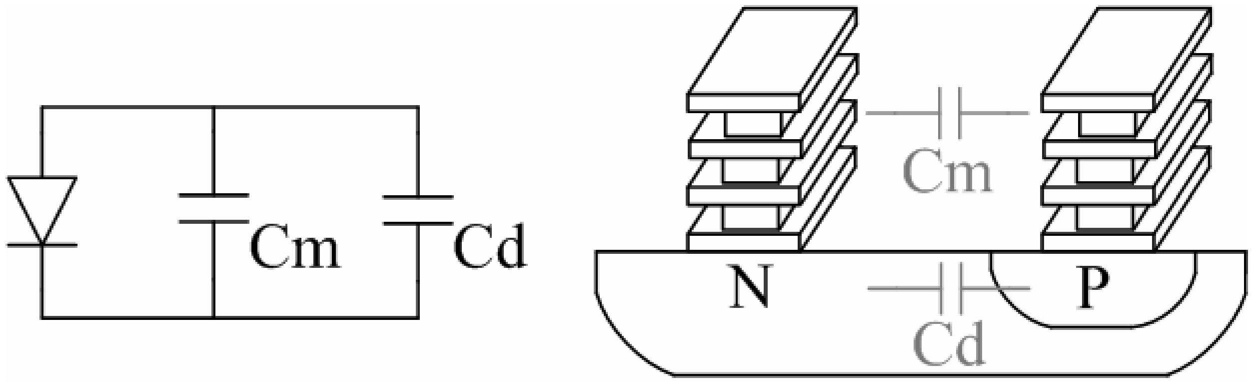
- Based on passive pixel architecture
- Total of 11 different diodes fabricated

Integrated Photodiodes: Side View



- Side view cutaway of diode D2. Metal connected to p- and n- diffusions correspond to top and bottom capacitor plates, respectively

Capacitance Characterization

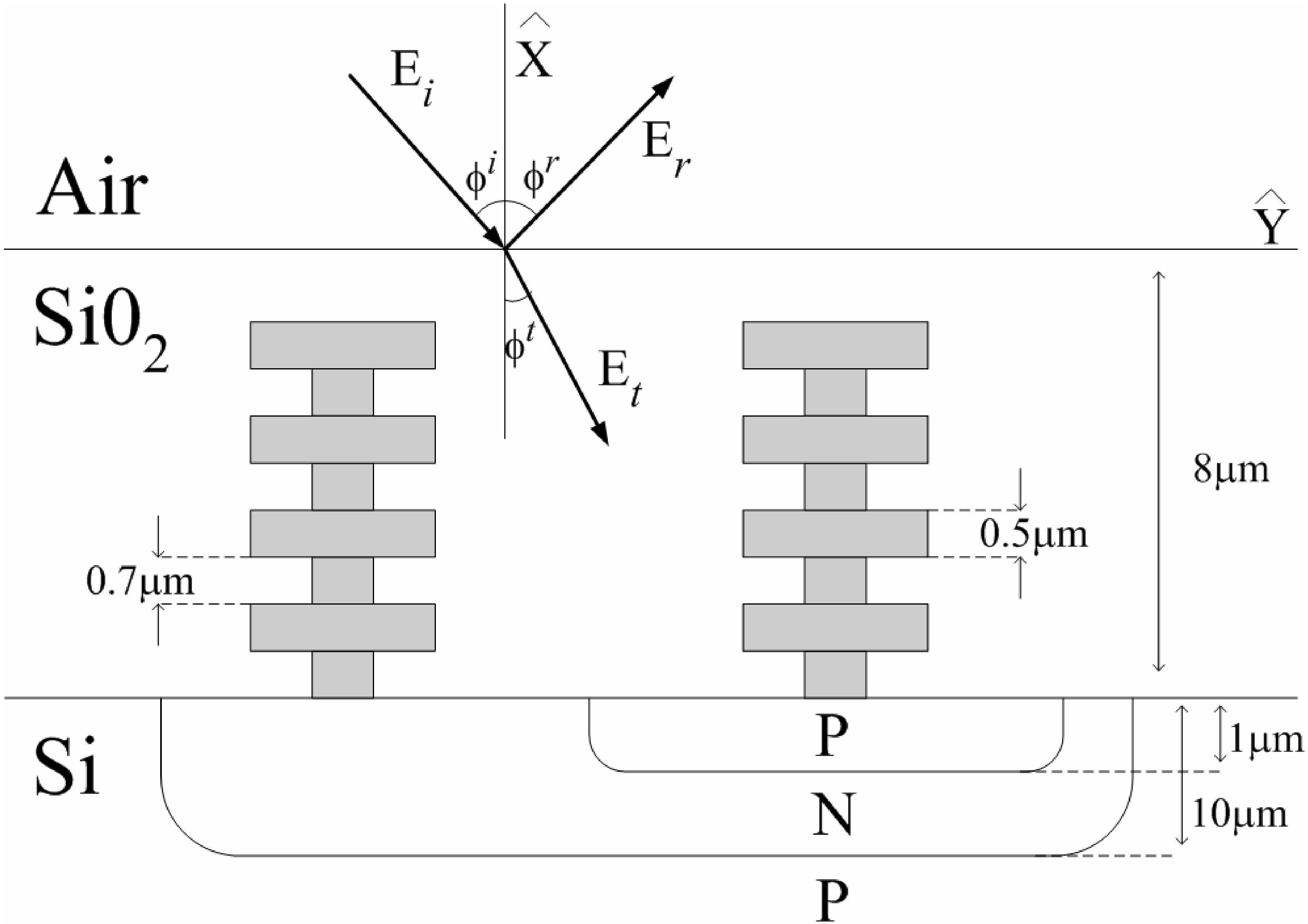


	D1	D2	D3	TL1 †	SEUB †
Cm **(pF)**	**0.254**	**0.254**	**0.216**	**1.004**	**0.616**
Cdo **(pF)**	**0.070**	**0.178**	**0.285**	**–**	**–**
Cd **(pF)***	**0.113**	**0.286**	**0.460**	**–**	**–**

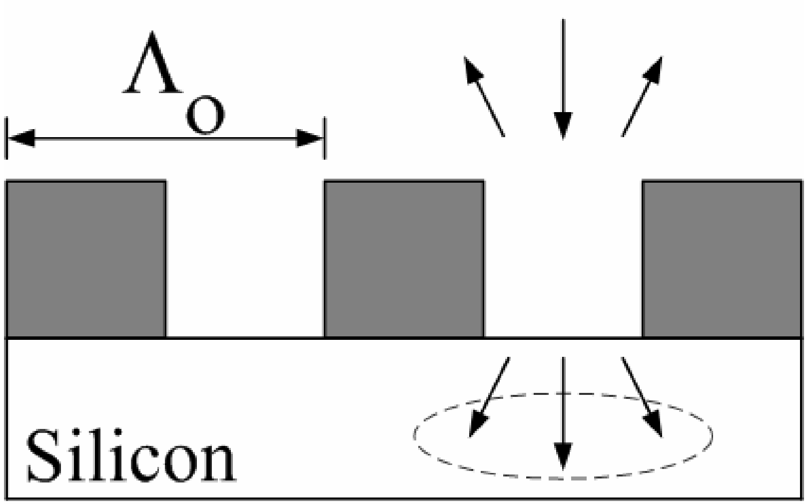
* Calculated with a junction voltage of 0.55 V, 25 °C, Area = 338 μm^2

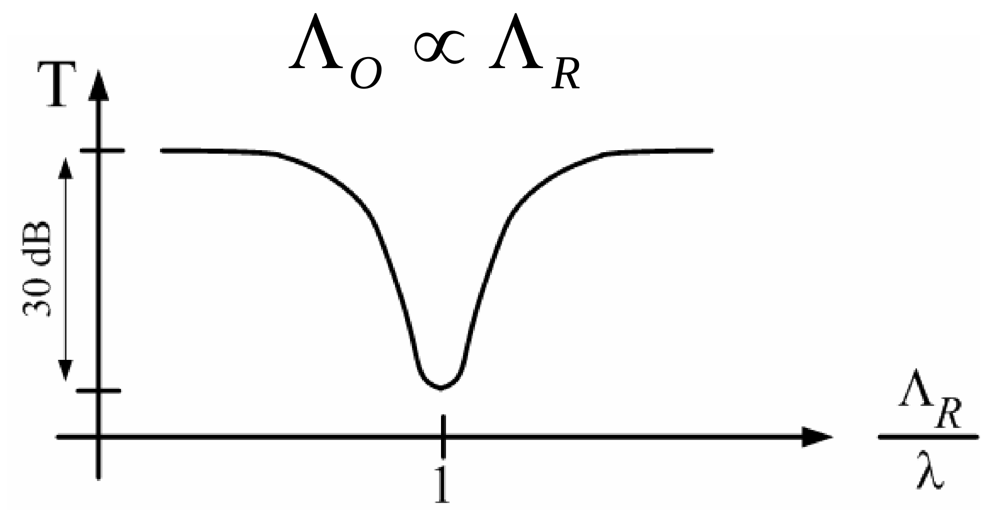
† [R. Aparicio and A. Hajimiri, "Capacity Limits and Matching Properties of Integrated Capacitors," *JSSC*, 2002]

Optical Path (Diode D2)



Diffraction Grating

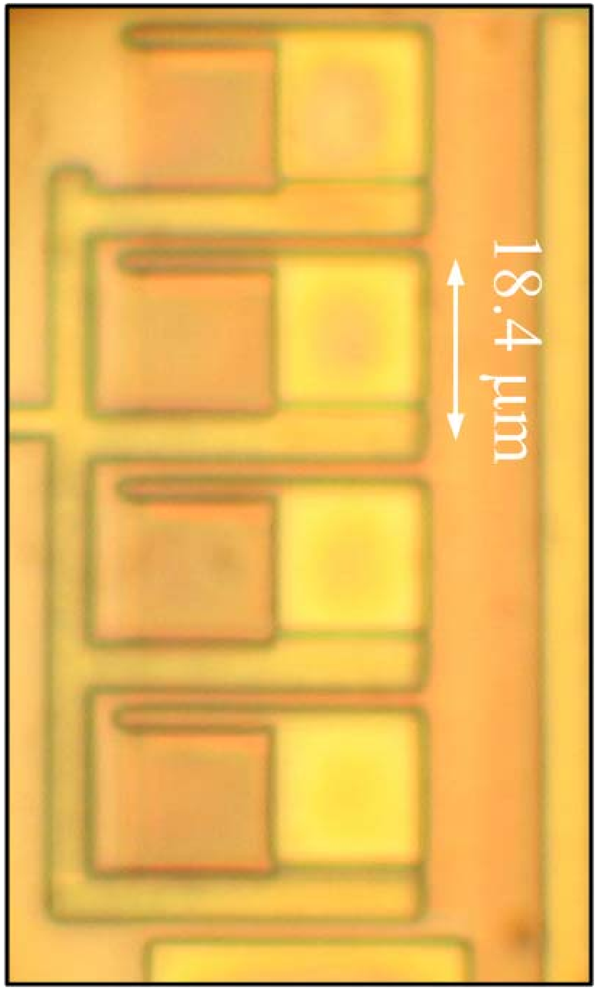




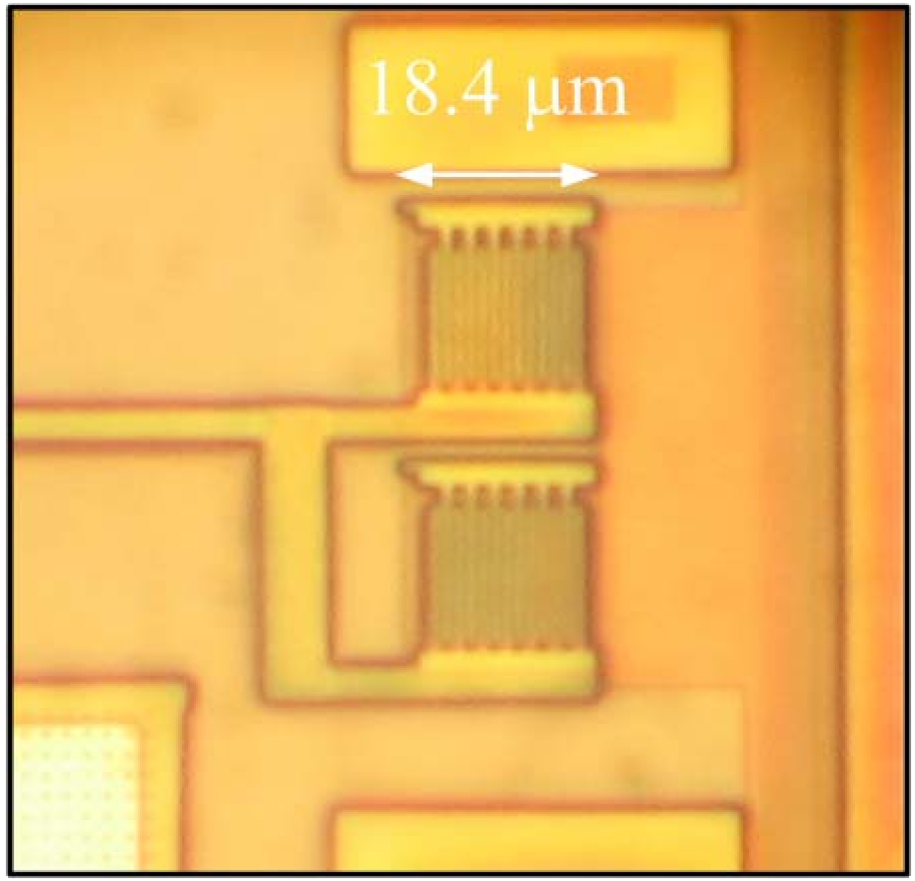
- **Metal capacitors form optical notch filter**
- **Resonant wavelength,** ***(Λ_O=950 nm $\rightarrow\Lambda_R$ =1550 nm)****
- **Vary duty-cycle, periodicity and grating depth to alter filtering effect**

***[H. Tan et al, A Tunable Subwavelength Resonant Grating Optical Filter, *LEOS*, 2002]**

Test Chip Die Photographs

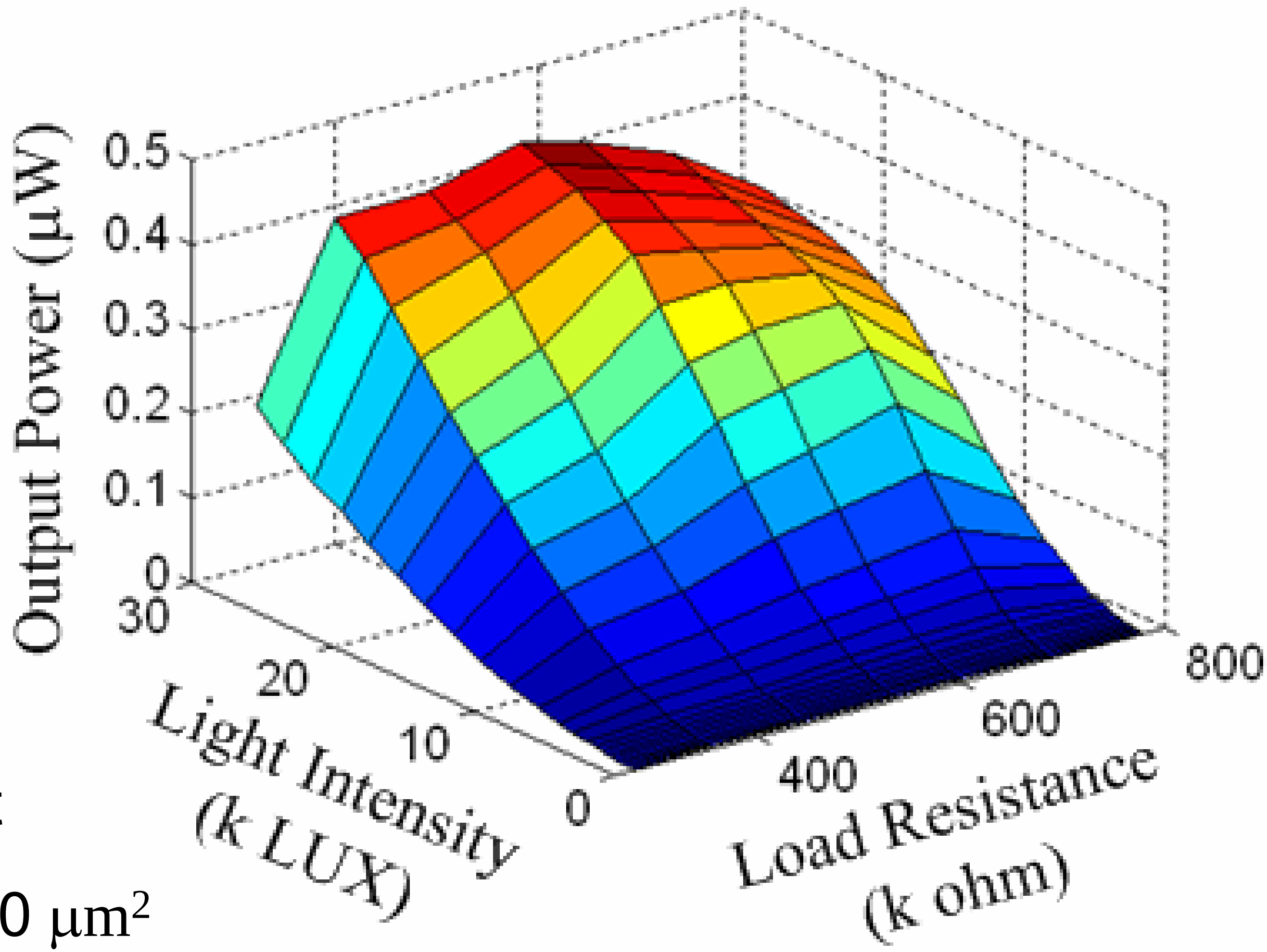


- Four Type 1 Diodes



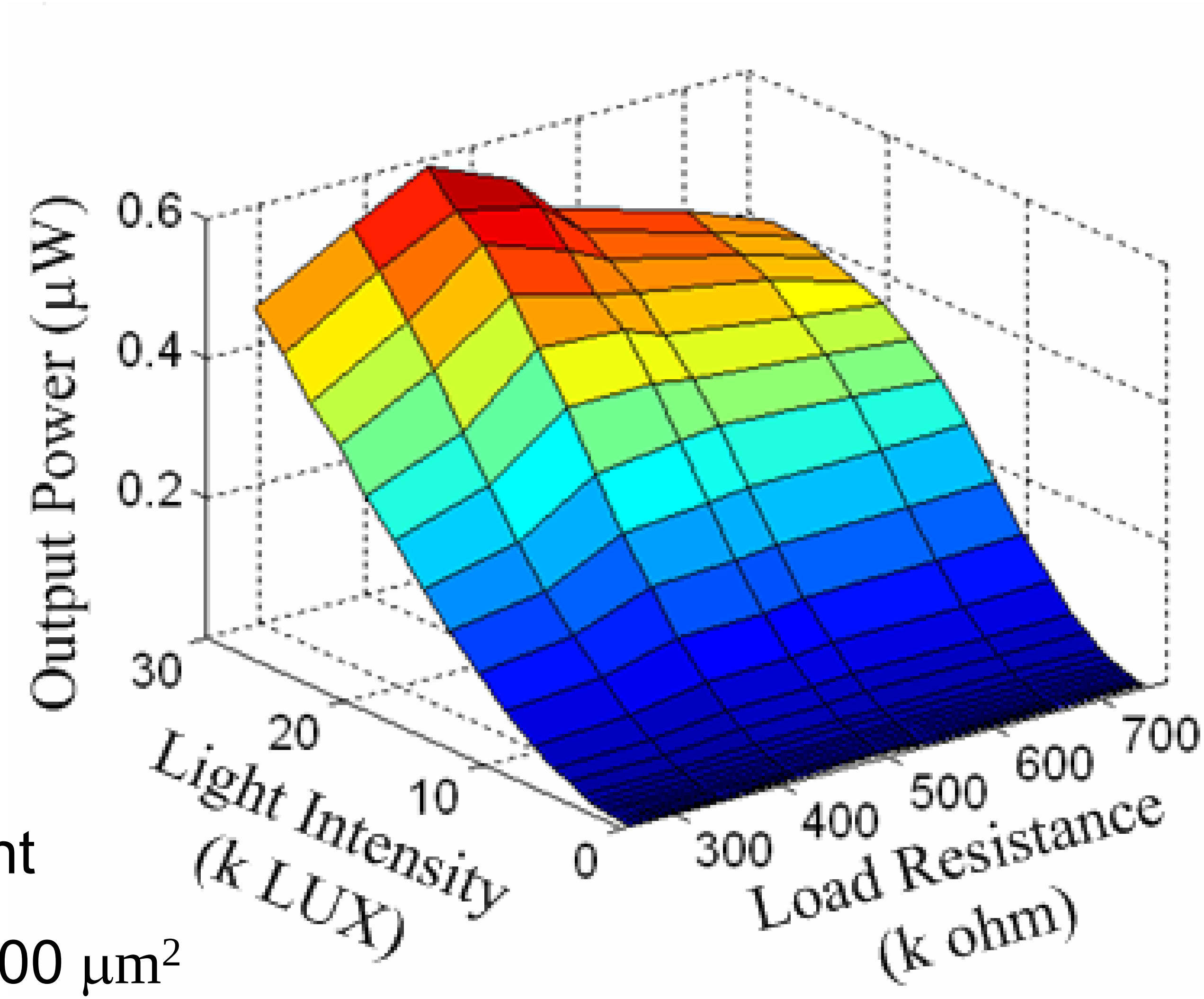
- Two Type 3 diodes

Electrical Power Generation (D1)



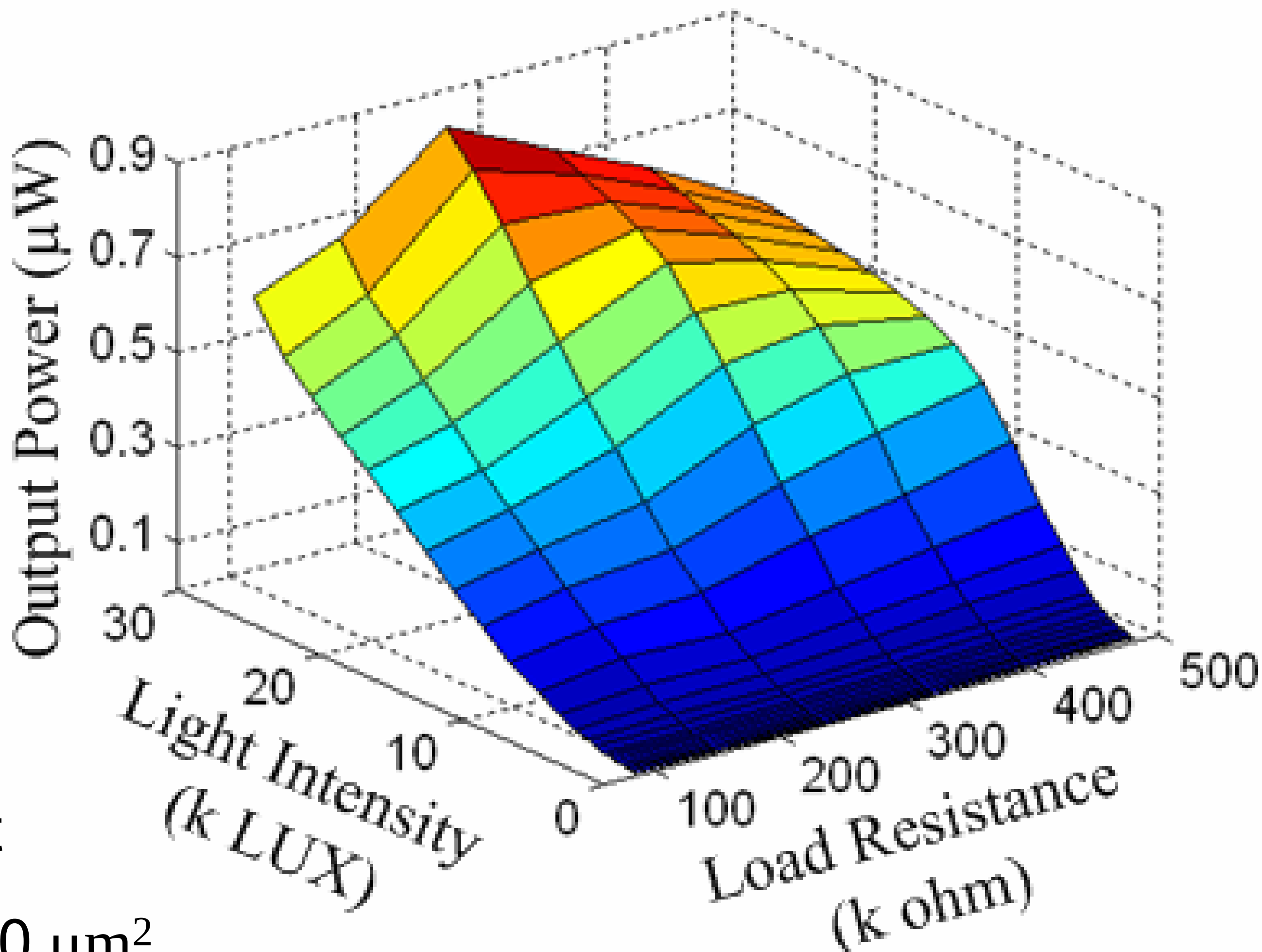
- White Light
- Area = 3000 μm^2
- 400 nW, 500 kΩ

Electrical Power Generation (D2)



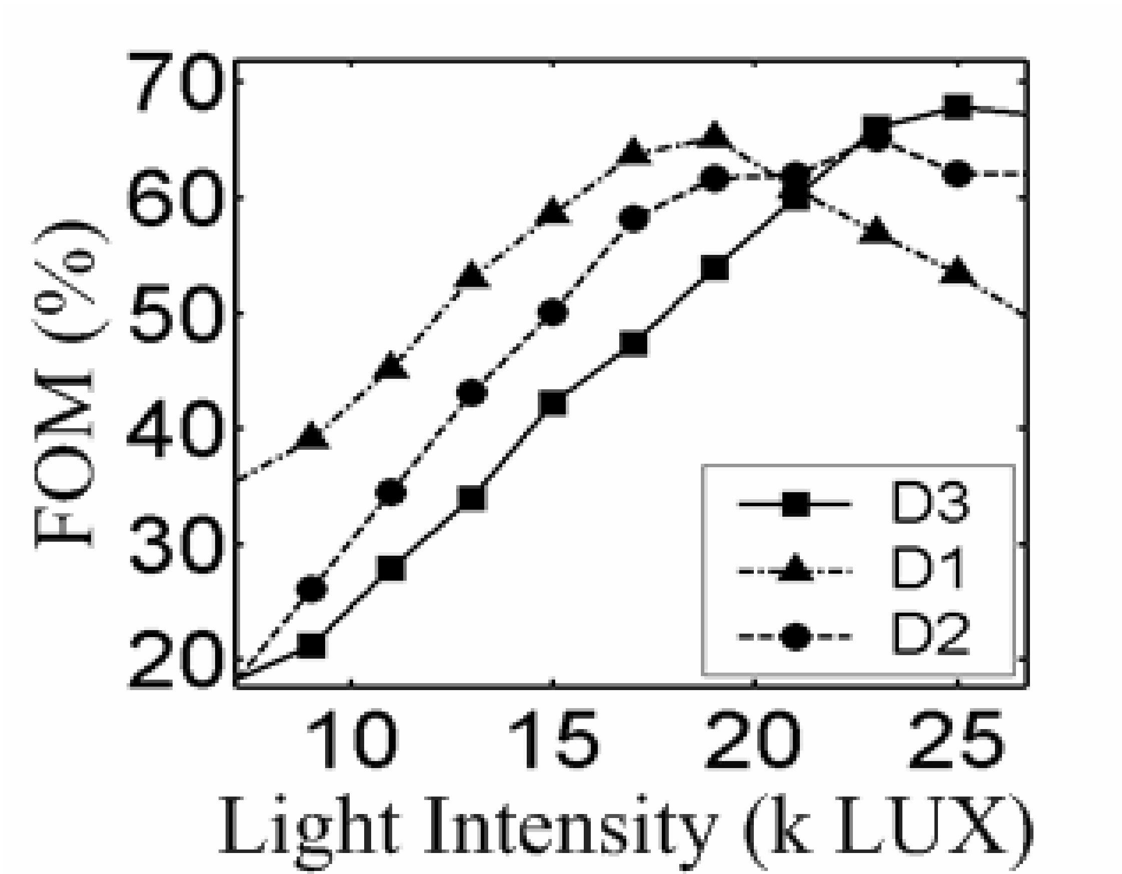
- White Light
- Area = 3000 μm^2
- 600 nW, 400 kΩ

Electrical Power Generation (D3)



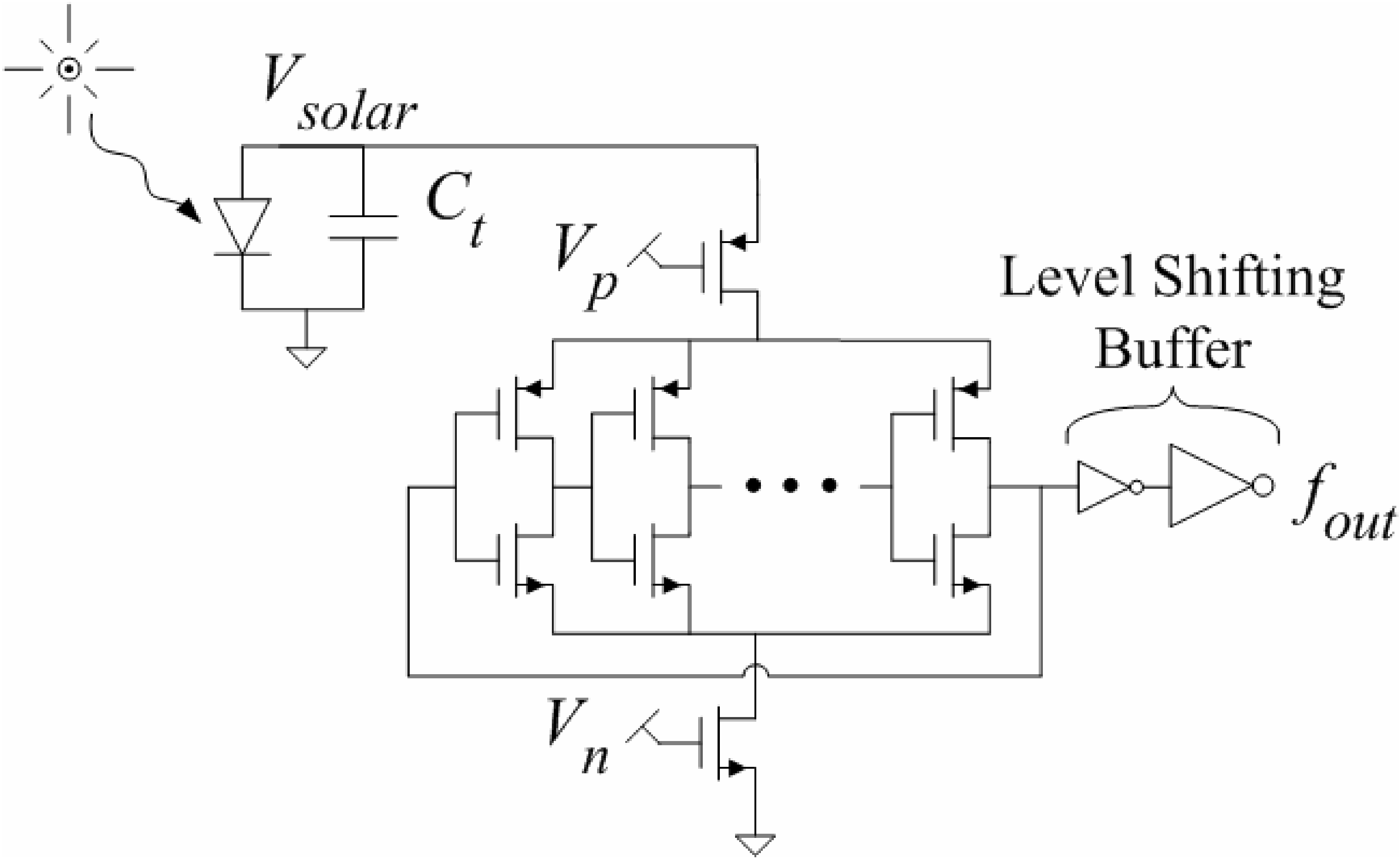
- White Light
- Area = 3000 μm^2
- 800 nW, 230 kΩ

Figure Of Merit (White Light)



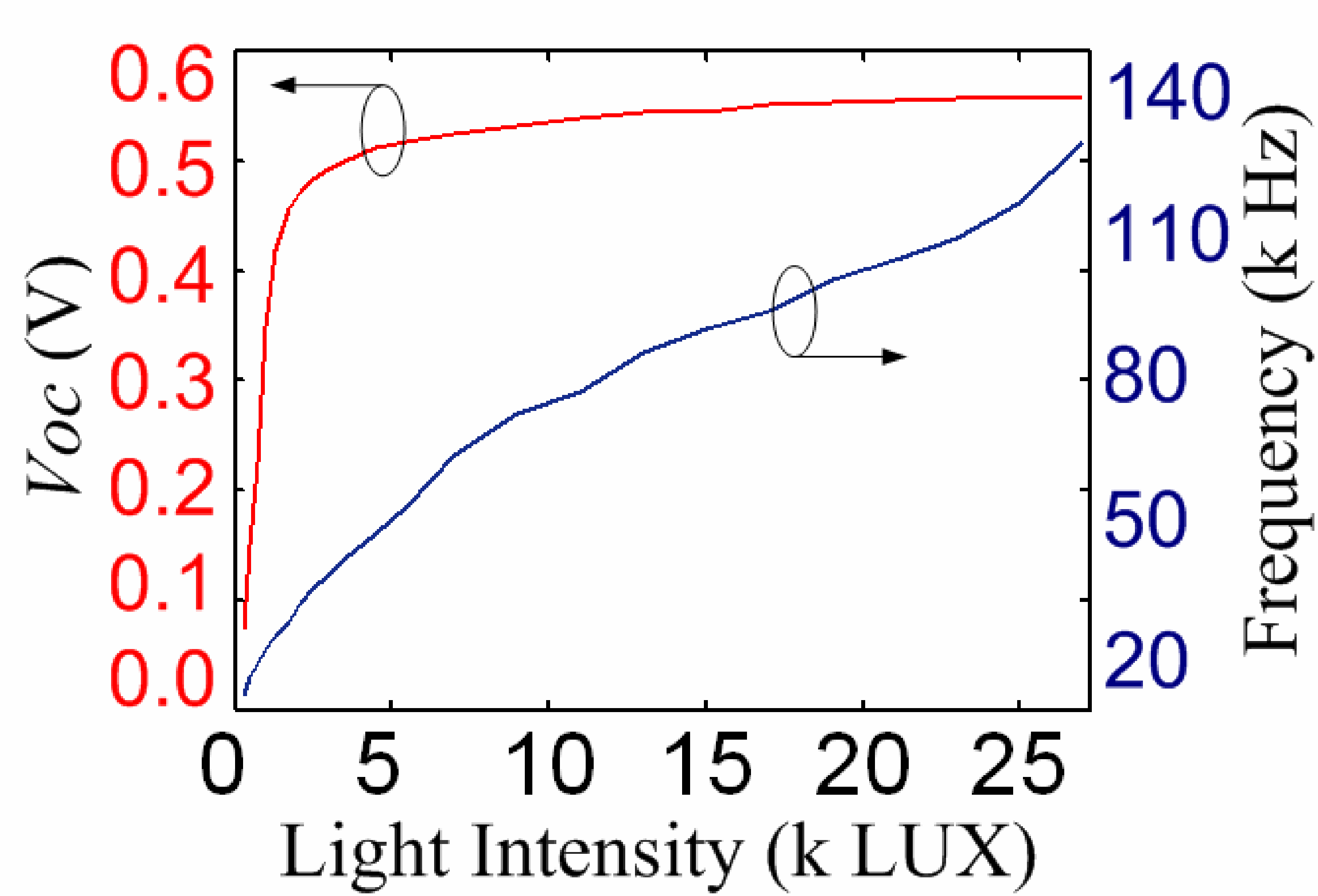
- D1 → Better at low light intensity
- D3 → Better at high light intensity

Ring Oscillator Schematic



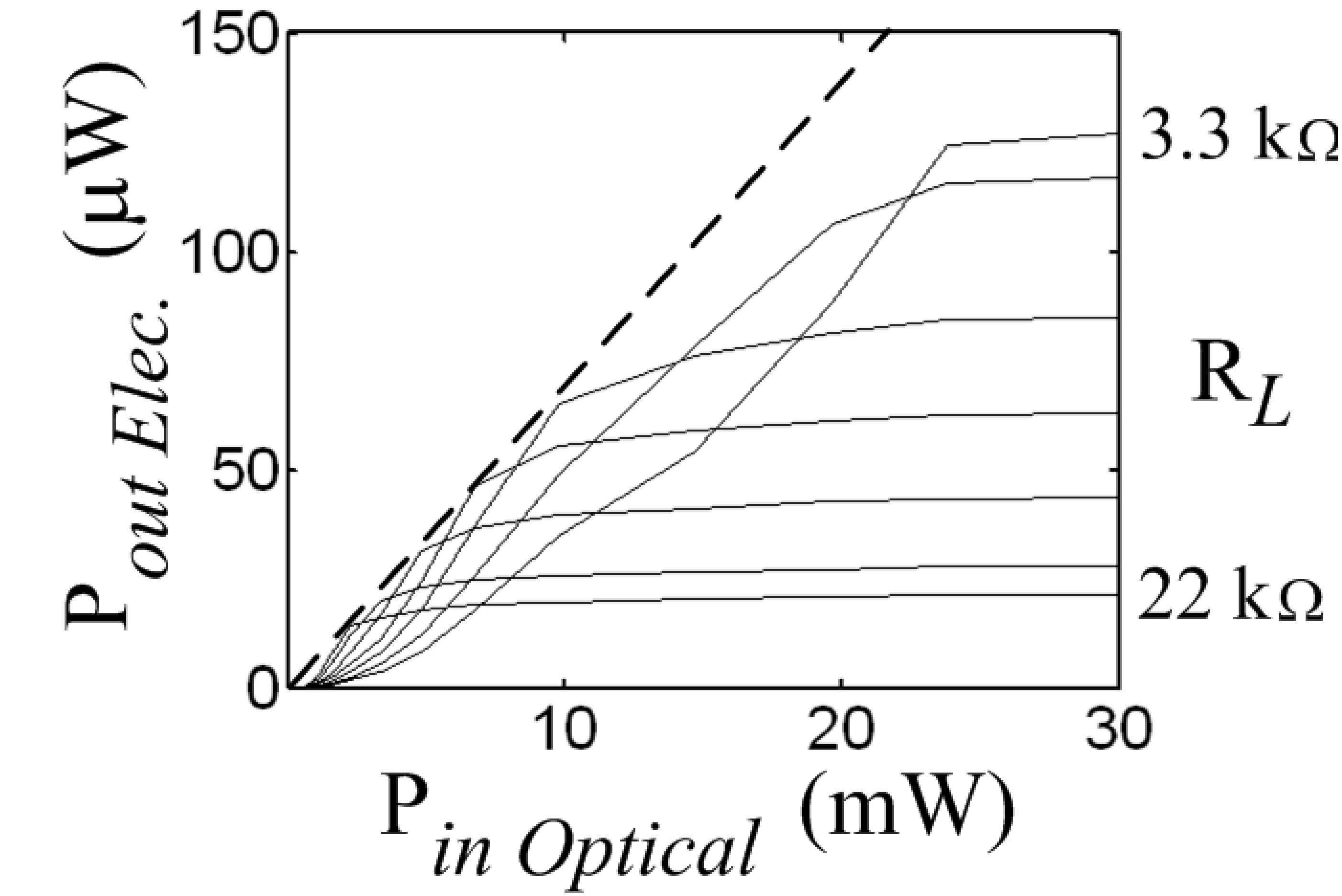
- Testing Circuitry (frequency proportional to intensity)
- Could be used to clock energy scalable system

Measured Results (White Light, D1)



- Knee in curve at 2500 (LUX) = 484 mV
- Frequency spans 40 Hz – 140 KHz

Power Generated (Green Laser)



- **Raw photodiode D3 measurements**
- **Dashed line represents linear response**
- **Lateral photocurrent included in output power**

Differential Results (Green Laser)

	D1	D2	D3
Pmax (μW)	**5.4**	**5.7**	**8.2**
Pavg (μW)	**3.3**	**3.4**	**5.3**
η (%)	**16**	**17**	**24**

- Diode area = 338 μm^2, λ = 532 nm
- Total Incident optical power = 9.75 mW (0.54 mm^2)
- Top flat approximation, P_{in} (optical) = 34.2 μW (338 μm^2)
- Differential measurements used to calibrate for nonidealities

Summary of Photodiode Results

Parameters	D1	D2	D3
Power (nW)	50	63	76
Energy Stored (fJ)	26	35	31
FOM (%)	65	66	62
Capacitance, C_m (pF)	0.245	0.254	0.216
V_{OC} (mV)	465	525	533
I_{SC} (nA)	165	182	230

Incident white light intensity = 20 kLUX (~100 mW/cm^2*), Area = 338 μm^2

*** [S. Roundy et al, "Energy Scavenging for Wireless Sensor Networks", 2004]**

System Lifetime Implications

- **Diode area required to generate 5 μW outdoors on a sunny day:**
  - D1: 184 μm x 184 μm
  - D2: 164 μm x 164 μm
  - D3: 150 μm x 150 μm
- **Number of output samples produced by a micropower DSP* using energy stored in 3 series diodes occupying 25 mm^2:**
  - D1: 687
  - D2: 745
  - D3: 903

*** [R. Amirtharajah et al, *JSSC*, 2004]**

Photodiode Summary and Future Work

- **Passive pixels can be used as integrated solar cells for energy harvesting**
  – Maximum output power is a function of light intensity and load resistance

- **On-chip interconnect can be used as integrated energy storage (0.75 fF per μm^2 in 0.35 μm CMOS)**
  – Fundamental tradeoff between energy harvesting and storage due to optical filtering
  – Exploring this tradeoff at 90nm with new test chip

- **Future polysilicon photodiodes on die surface can increase harvesting and storage capabilities**