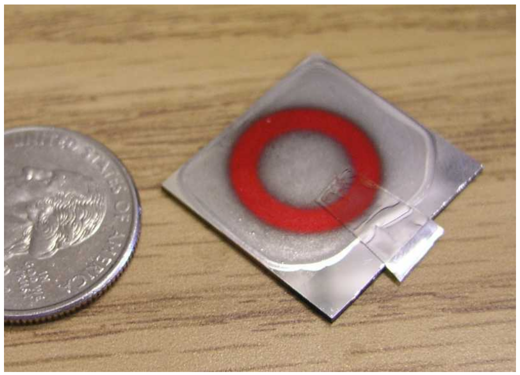
SAND2008-0167C

Microscale Nuclear Batteries: from Heterojunctions to Fuel Cells



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IDGA Tactical Power Sources Summit
January 28-30, 2008

Sandia National Laboratories

About Me

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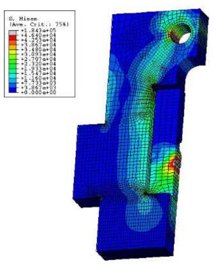
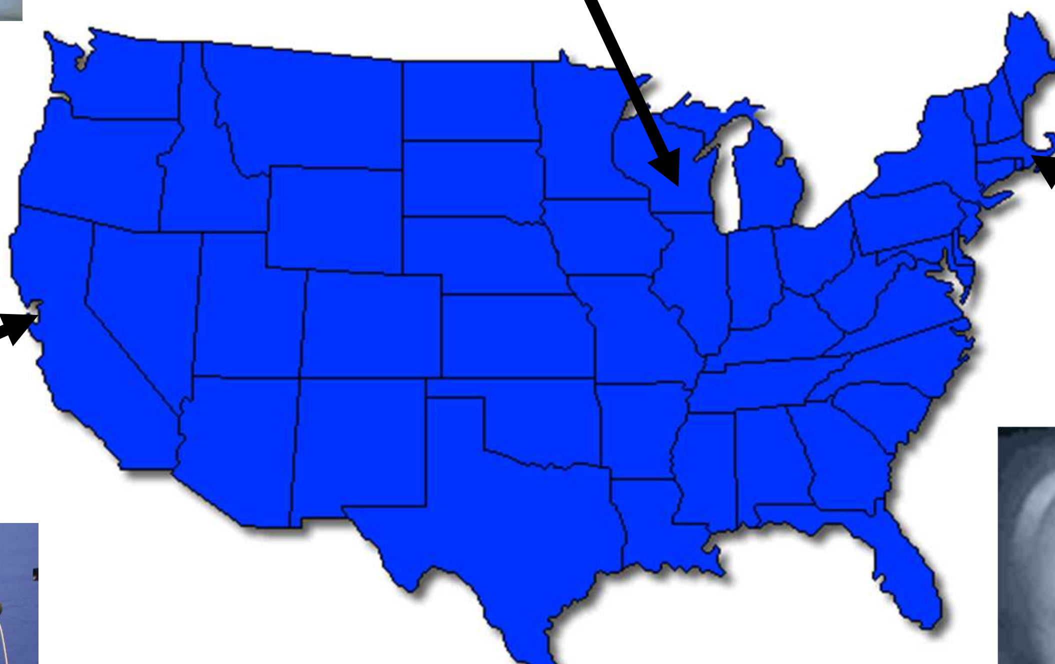
Nuclear Engineering & Engineering Physics





Tufts University
Mechanical Engineering

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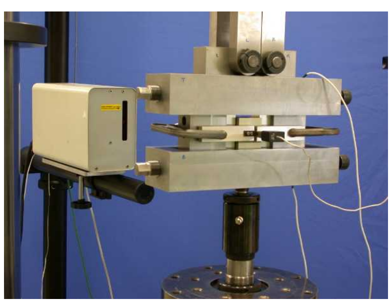

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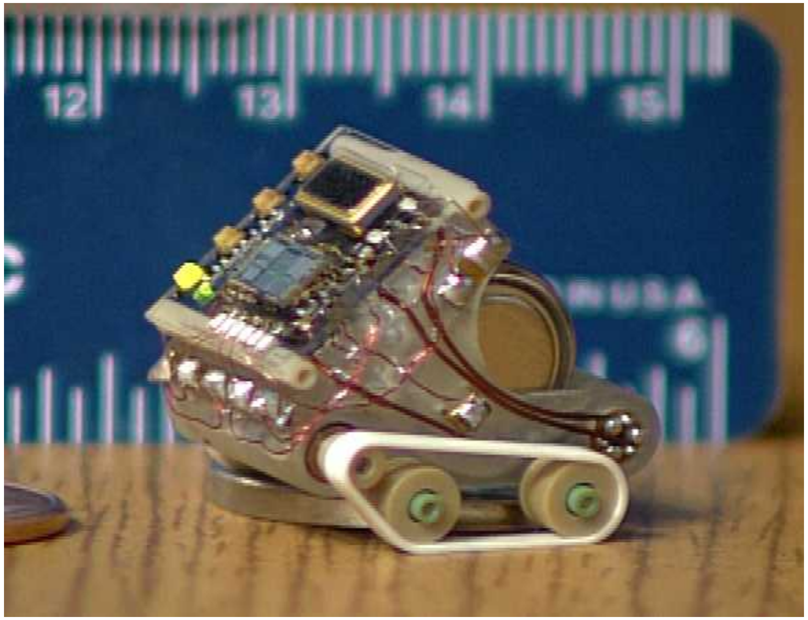
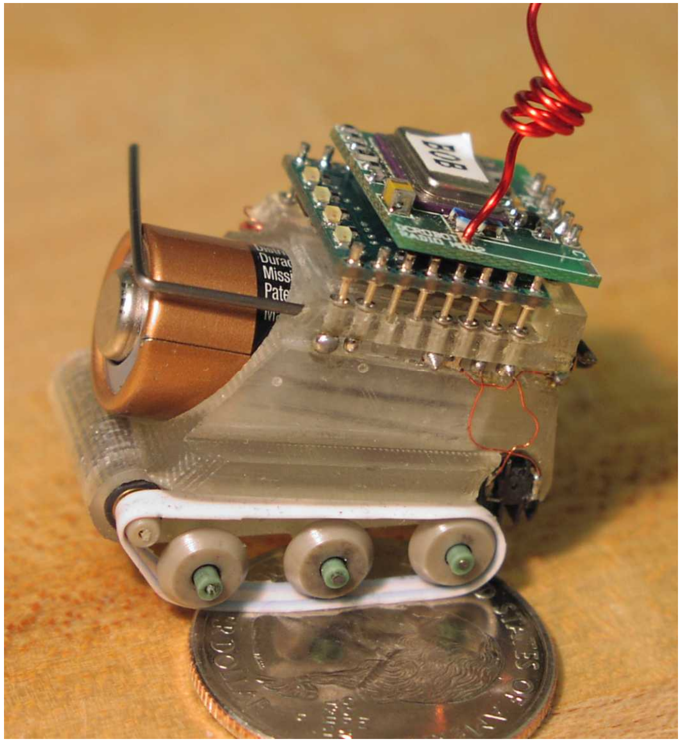
Batteries Limit Independent MEMS Devices

Batteries have not shrunk as fast as the systems they support.





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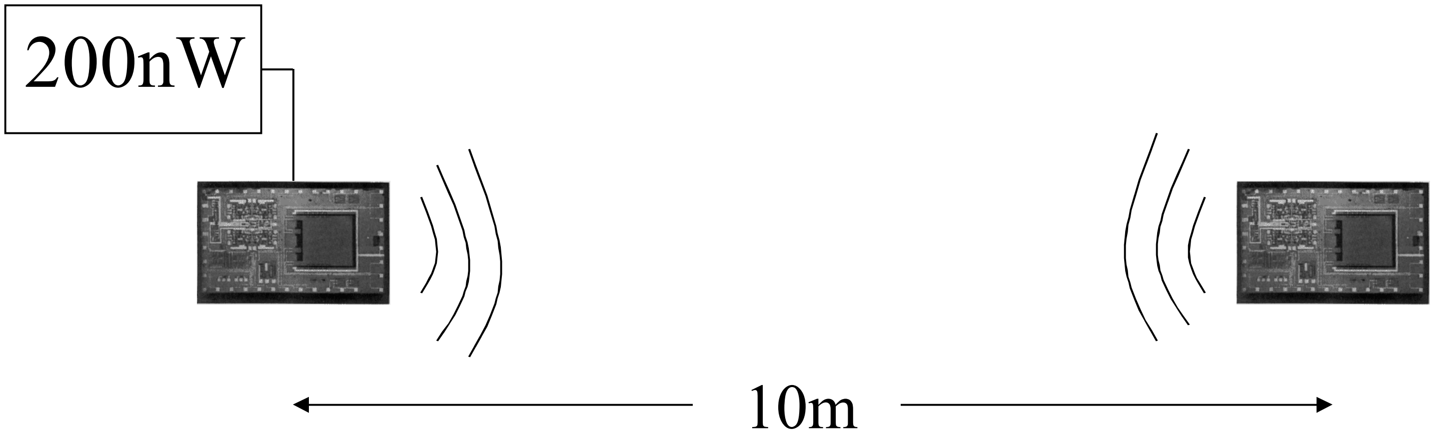
New MEMS Applications Call for On-Board Power

- Sensor arrays using wireless communications
- Mobile microsystems
- Isolated microsystems (space exploration)

Power Requirements of MEMS Devices

- MEMS devices require 100’s nW to mW



Chemical Batteries Perform Poorly When Scaled Down

- silver oxide watch batteries (mm thick)

  energy density: 2000 J/cm^3

- Ni/Zn batteries (100μm thick)

  energy density: 44 J/cm^3

- 2mm x 2mm Ni/Zn battery would provide 200nW for **1 day**

Energy from Nuclear Decay

for example, several beta emitters:

	energy density	half-life
^{3}H (tritium stored in MgT_2)	55 MJ/cm^3	12 years
^{63}Ni	281 MJ/cm^3	100 years
^{35}S	277 MJ/cm^3	88 days

- many orders of magnitude greater energy density than chemical batteries

Power from Nuclear Decay

for example:

	maximum power density	half-life
^{3}H (tritium stored in MgT_2)	0.098 W/cm^3	12 years
^{63}Ni	0.062 W/cm^3	100 years
^{35}S	25.3 W/cm^3	88 days

- comparable to chemical batteries

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Radionuclide Batteries Offer Long-Life

To produce 200nW:

	Ni/Zn battery	Ni-63 battery (5% eff) (15% fuel)
footprint	2mm x 2mm	2mm x 2mm
height	100µm	100µm
useful life	**1 day**	**decades**

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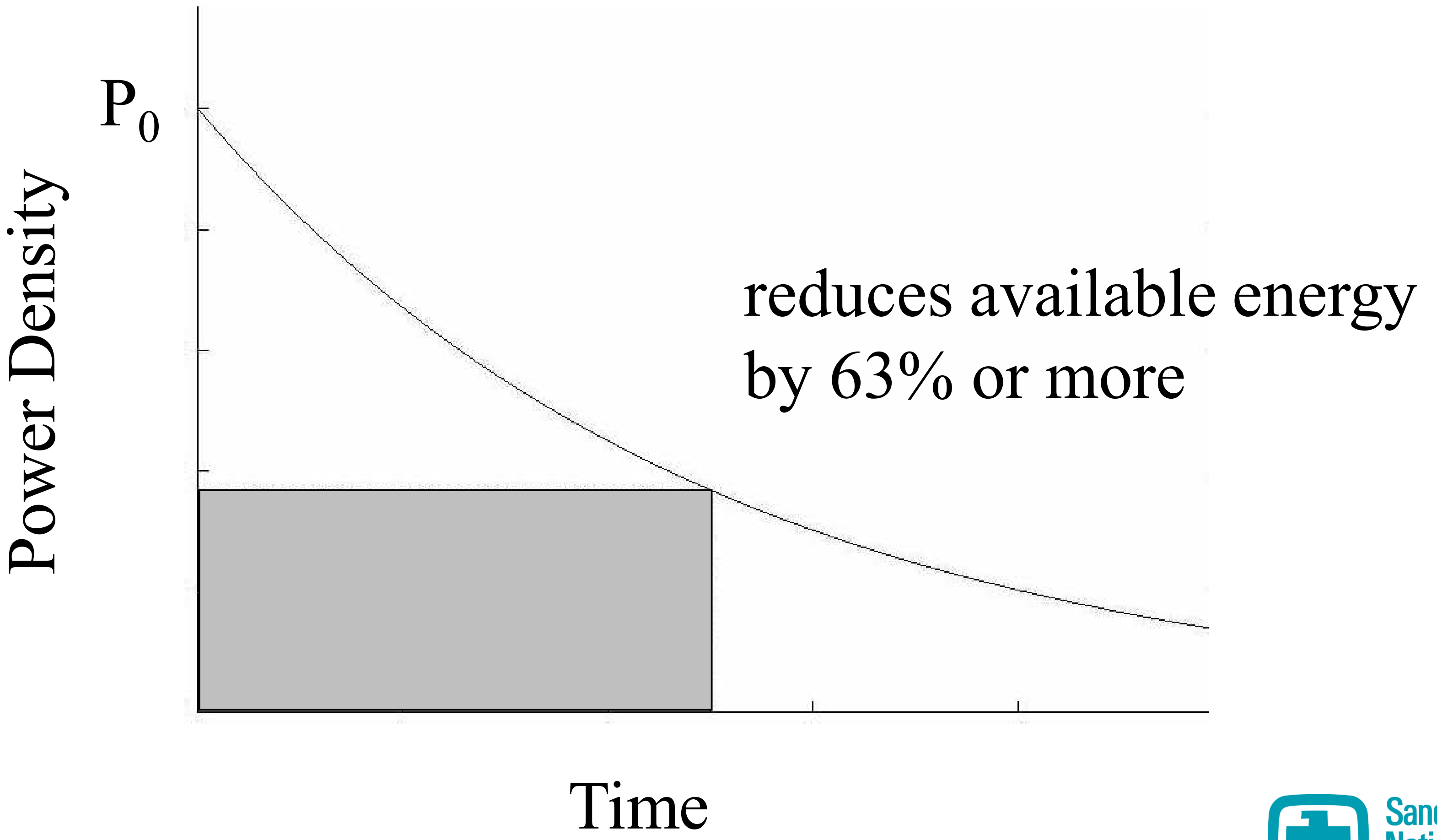
Most Applications Need Constant Power



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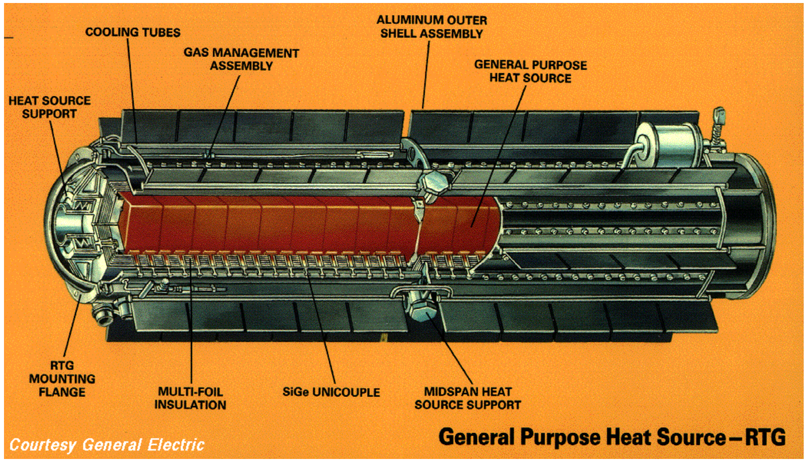
Radioisotope Thermoelectric Generators (RTGs)

- used in 41 NASA missions
- Pu-238 generates heat from alpha decay
- 114 cm long, 42 cm in diameter
- 276 W
- does not scale down well (insulation)



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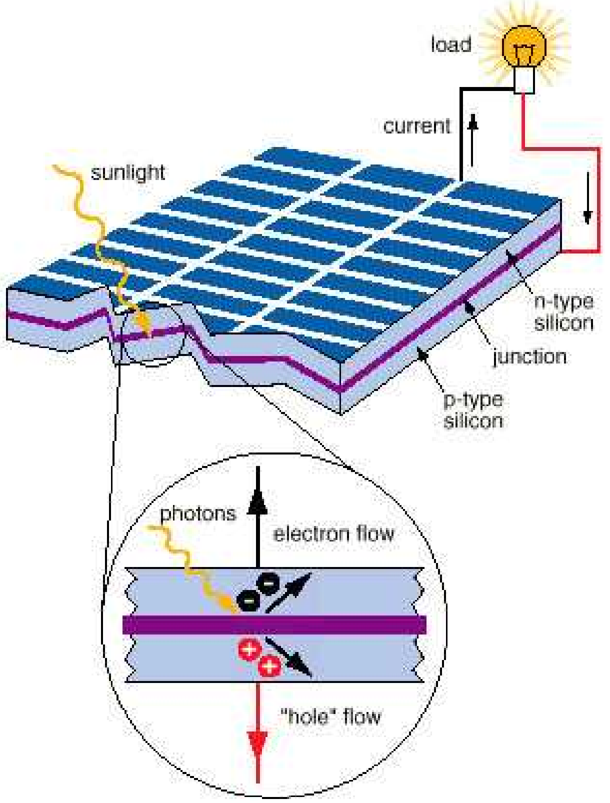
Generating Power in a Semiconductor Junction

- In photovoltaics (solar cells), each photon creates an electron-hole pair in a semiconductor junction, producing electrical power.
- A charged particle from a radionuclide can produce many electron-hole pairs.



silicon photovoltaic

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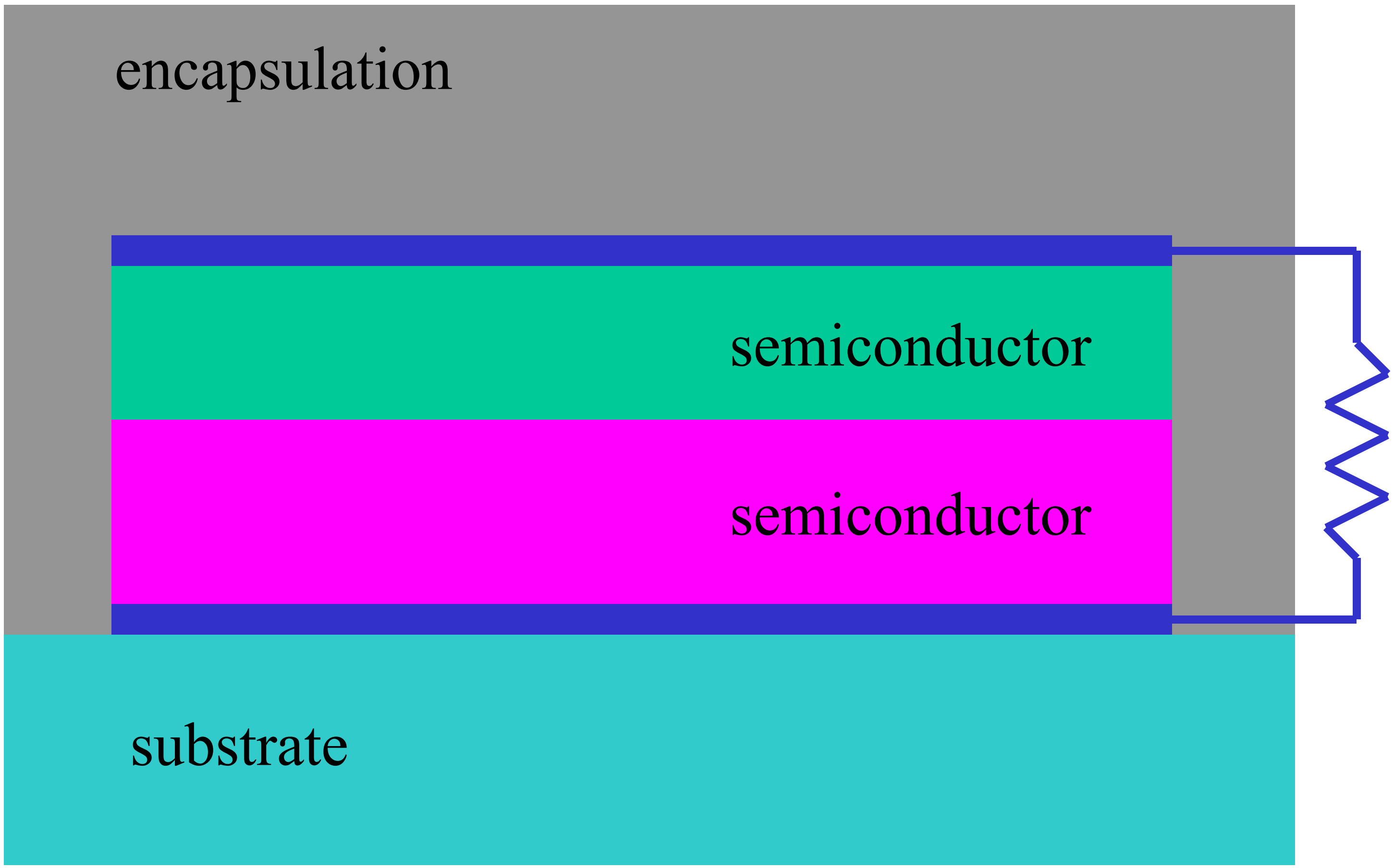
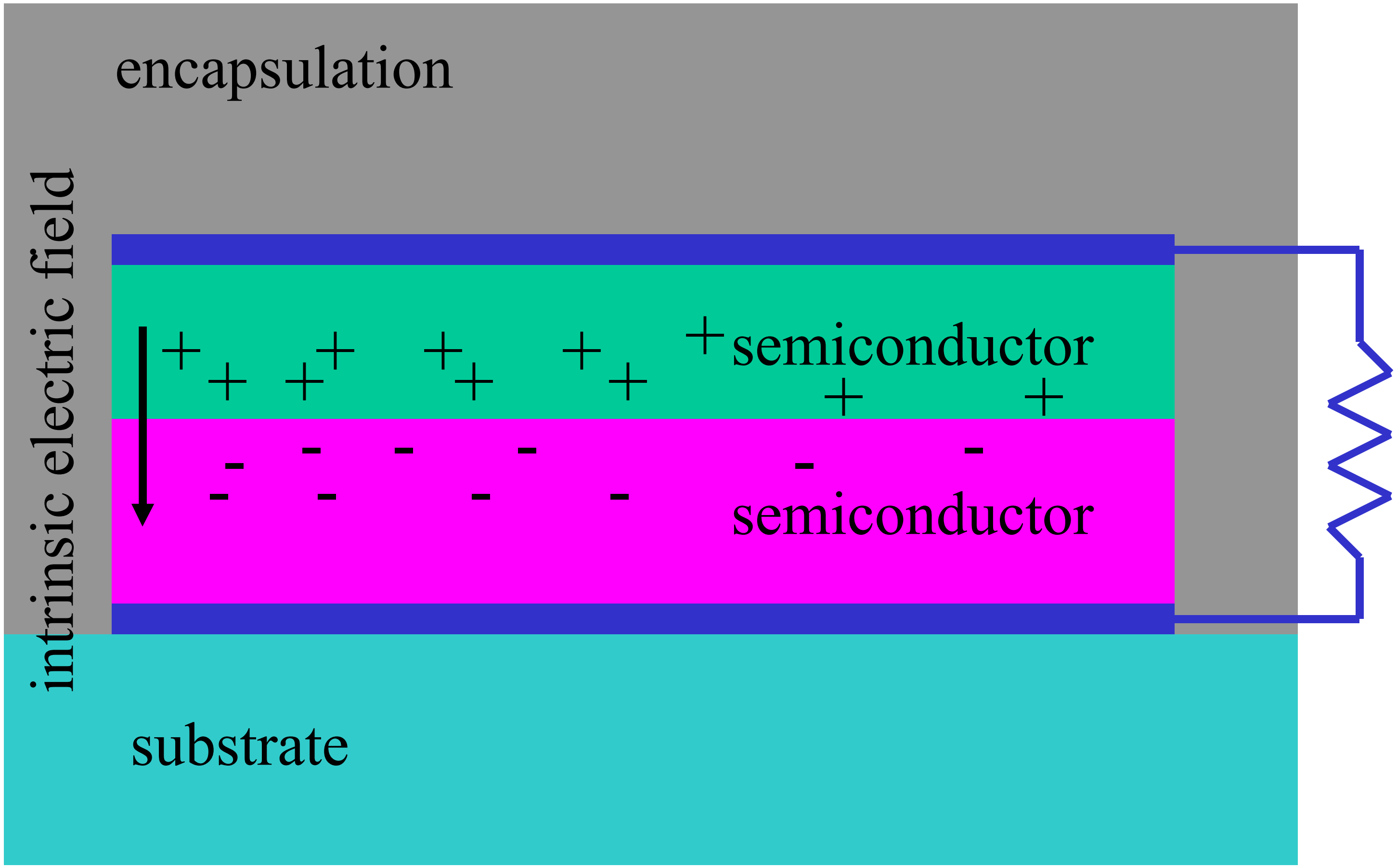
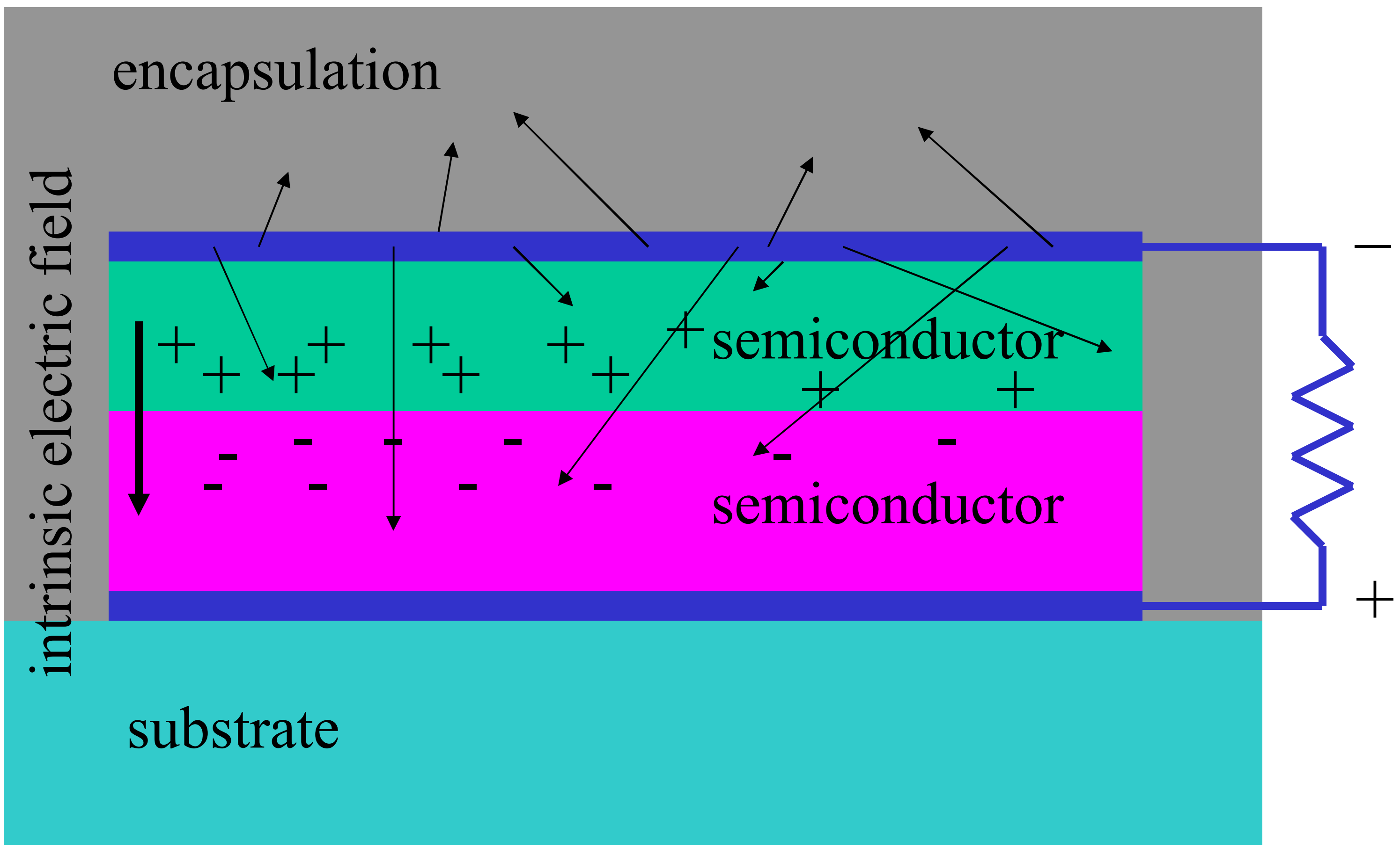
Device Layout



Doped Semiconductors Create Intrinsic Electric Field



Radioactive Source of Energetic Charged Particles



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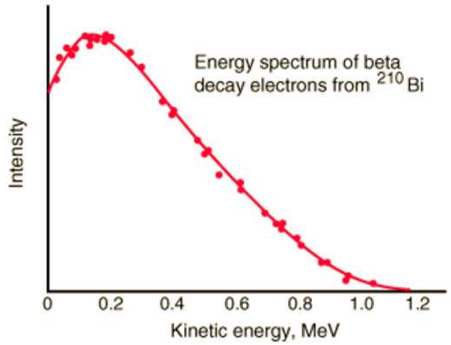
Radionuclide Selection

- Most beta emitters also release a gamma
- A few are pure beta emitters (^{3}H, ^{63}Ni, ...)
- Low-energy betas: no Bremsstrahlung can escape device
- Stable daughter ($^{3}H \rightarrow {}^{3}He$, $^{63}Ni \rightarrow {}^{63}Cu$, ...)

	half-life	max energy	average energy	max range (in polymer)
^{3}H	12 yr	19 keV	6 keV	5 µm
^{63}Ni	100 yr	67 keV	18 keV	64 µm



Not an external radiation hazard

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Safety and Licensing

- Not external radiation hazard
- Betas stopped in outer layer of dead skin cells
- Internal radiation hazard (following ingestion or inhalation)
- 200nW ^{63}Ni battery, 5% efficient → 30 mCi
- Exceeds 200 μCi ingestion limit for non-radiation workers
- NRC license? (gun sights have 12 mCi tritium, exit signs have 20 Ci tritium)

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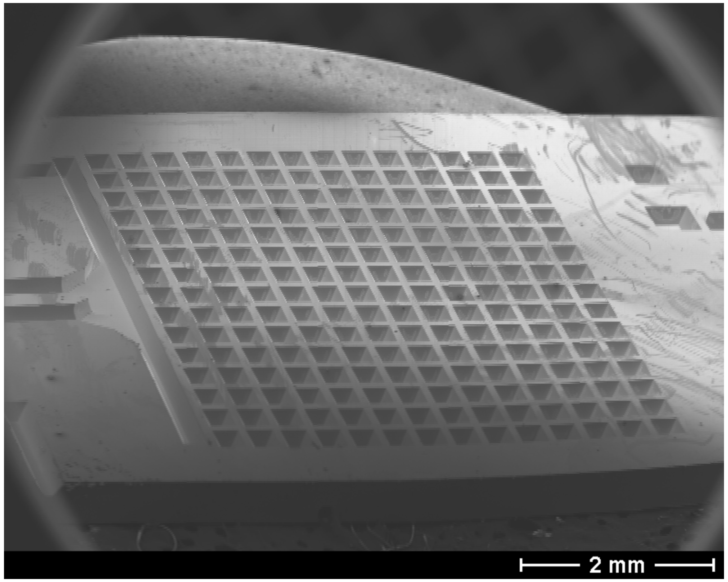
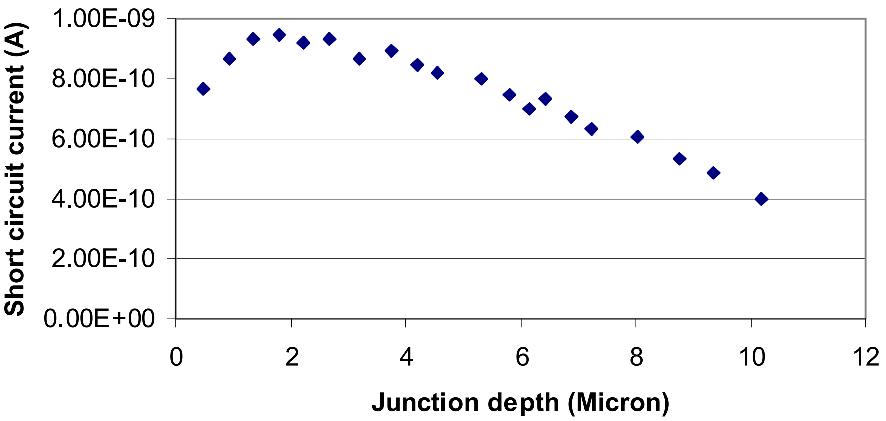
Silicon Radionuclide Battery

- work by Blanchard, et. al.
- Ni-63 source



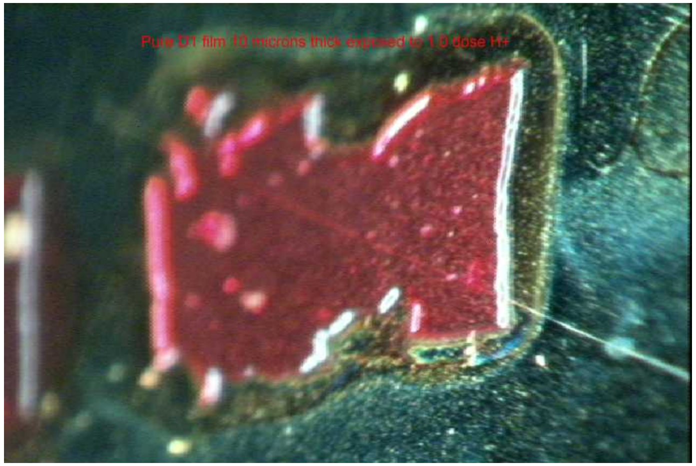
optimal depth of junction: 2 μm



Pi-Conjugated Materials

Polymeric semiconductors have advantages over silicon

- radiation damage resistance
- thousands of different materials available
- easily fabricated (amorphous)
- flexible & robust
- light weight



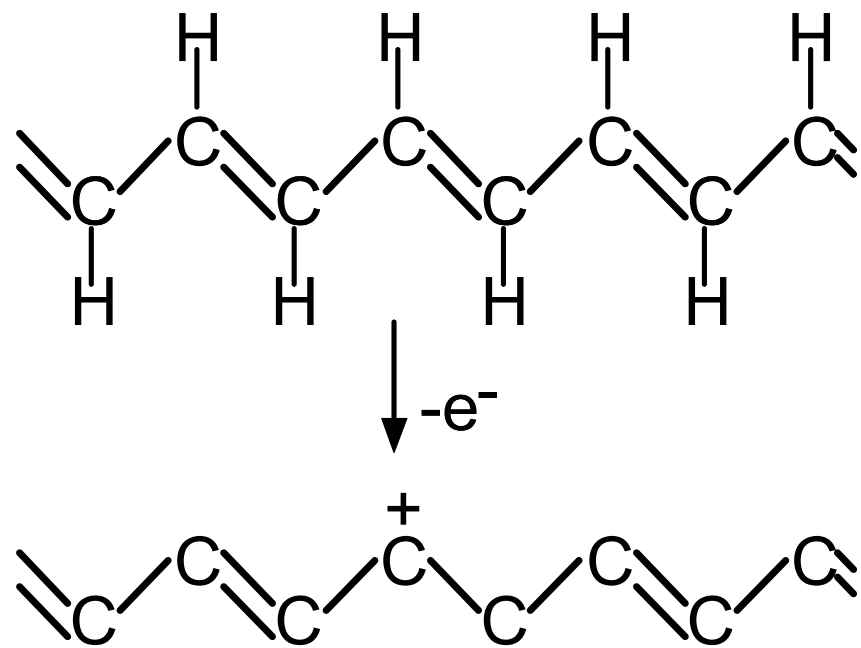
Challenges

- poor solubility
- controlling properties

What does π-conjugated mean?

- Synthetic metals, conducting polymers, organic semiconductors, organic metals
- Alternating double-single carbon-carbon bond
- The π electrons overlap
- Materials are insulators unless doped, typically with an acid

polyacetylene



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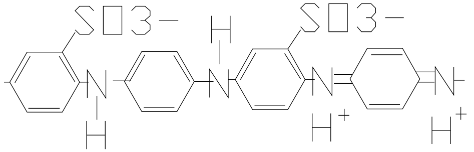
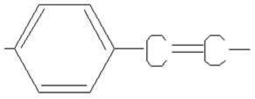
Types of π-conjugated materials

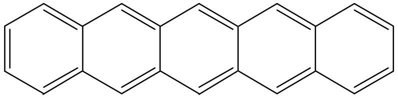
- Polymers- polyaniline, polythiophene, poly vinylene, polyacetylene, etc.
- Small molecules- anthracene, aluminum quinolate, pentacene, etc.
- Carbon nanoparticles- C_{60}, fullerenes, single walled nanotubes, multiwall nanotubes
- DNA?



Polyaniline sulfonic acid

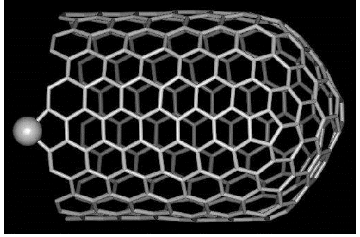


Poly para phenylene vinylene



pentacene

Carbon nanotube
From Smalley website



Properties of PCM

- Electrical
  - 12 orders of magnitude conductivity change upon doping
  - Junctions form at interfaces
- Optical
  - Electrochromism (change color with electric field)
  - Light emission, lasing
- Mechanical
  - Volume change on doping, oxidation
  - Flexible semiconductors
- Chemical
  - Chemical sensors
- Biological
  - Biocompatible?

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Ways to Deposit PCM

- Spin cast, drop cast
- Plasma
- In-situ polymerization
- Electrochemical deposition
- Ink Jet

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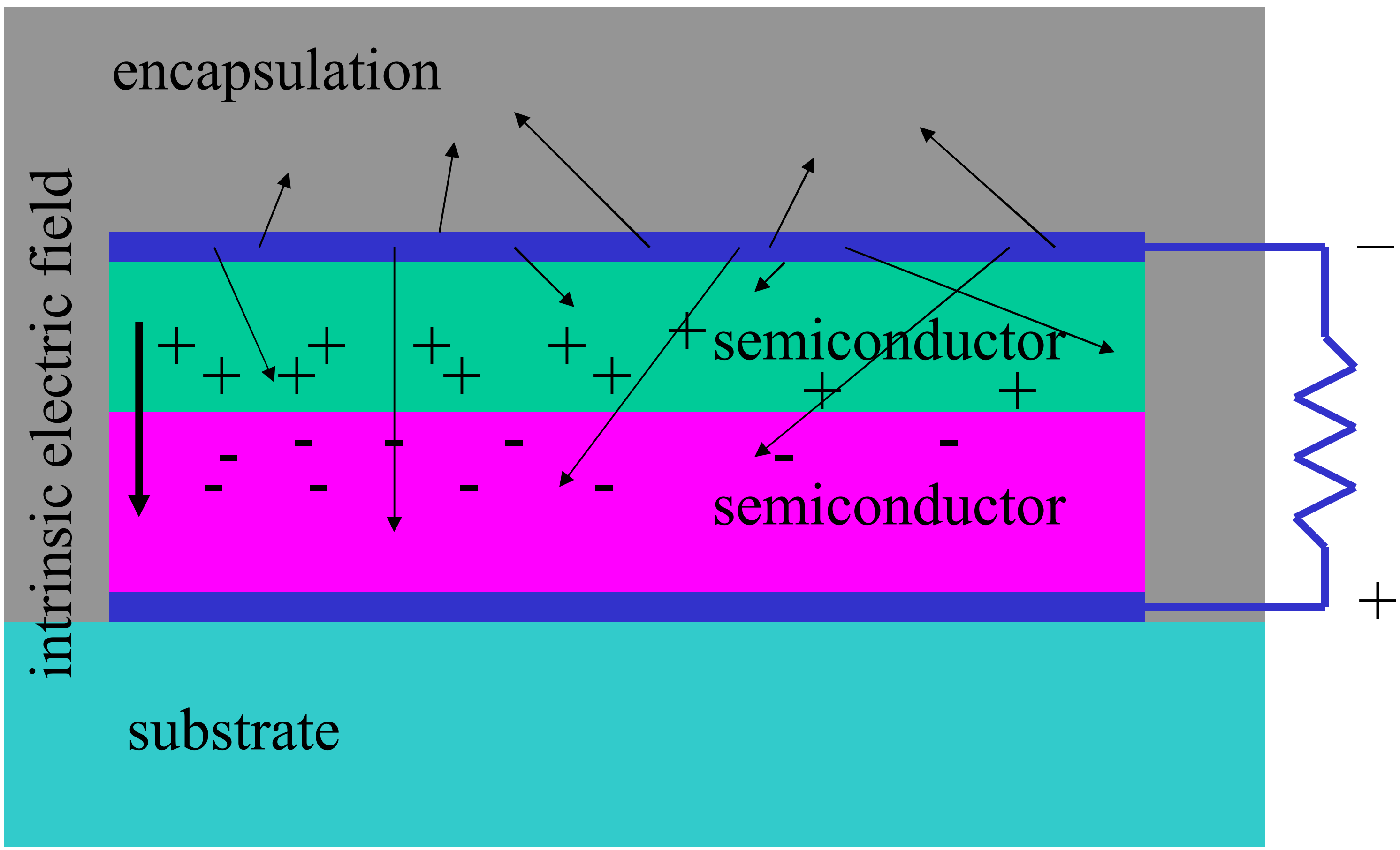
Challenges

- Poor solubility, difficult to process
- Cost
- Air stability
- Too many variables to control (more degrees of freedom than inorganic semiconductors)

Bi-layer Heterojunctions



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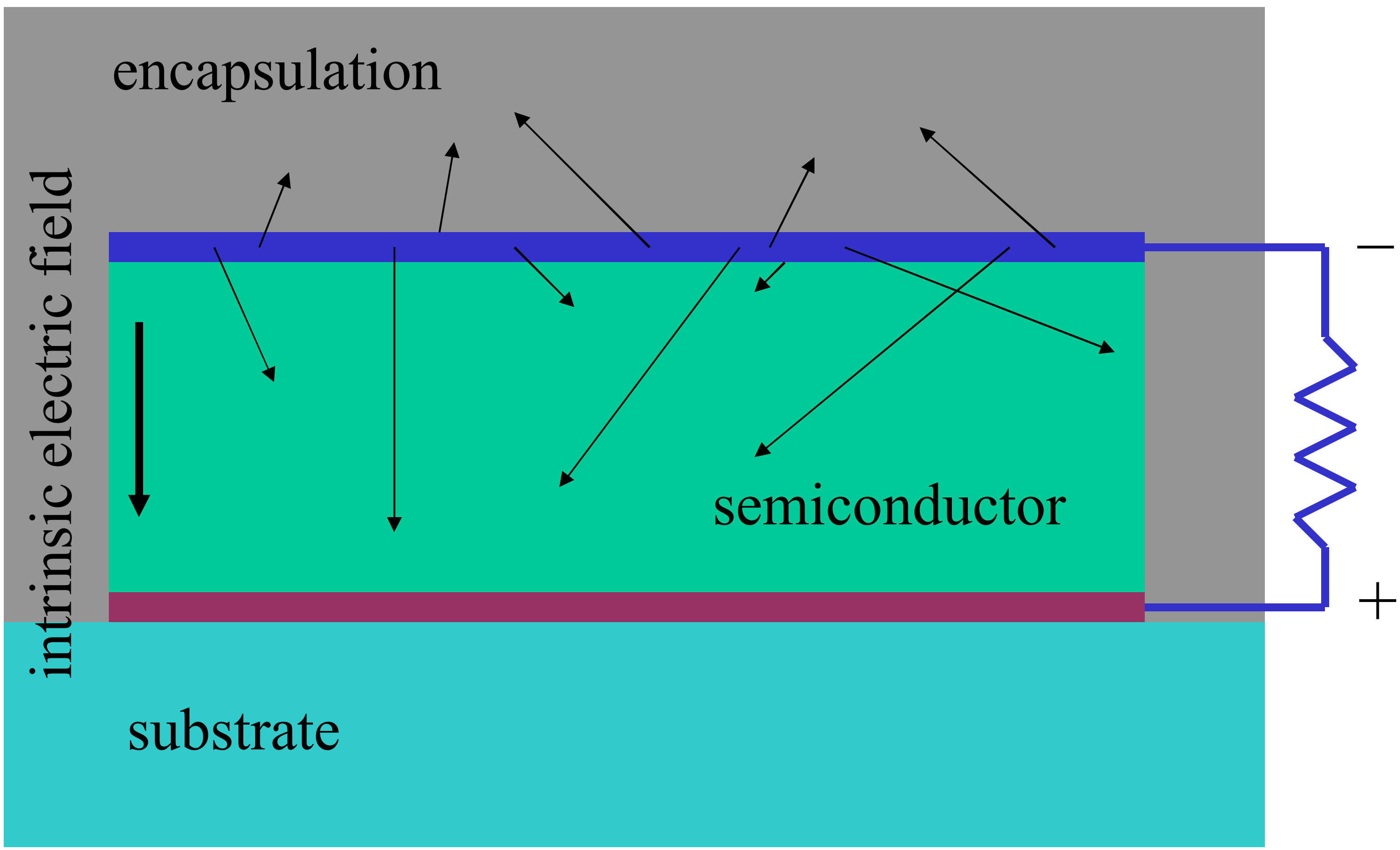
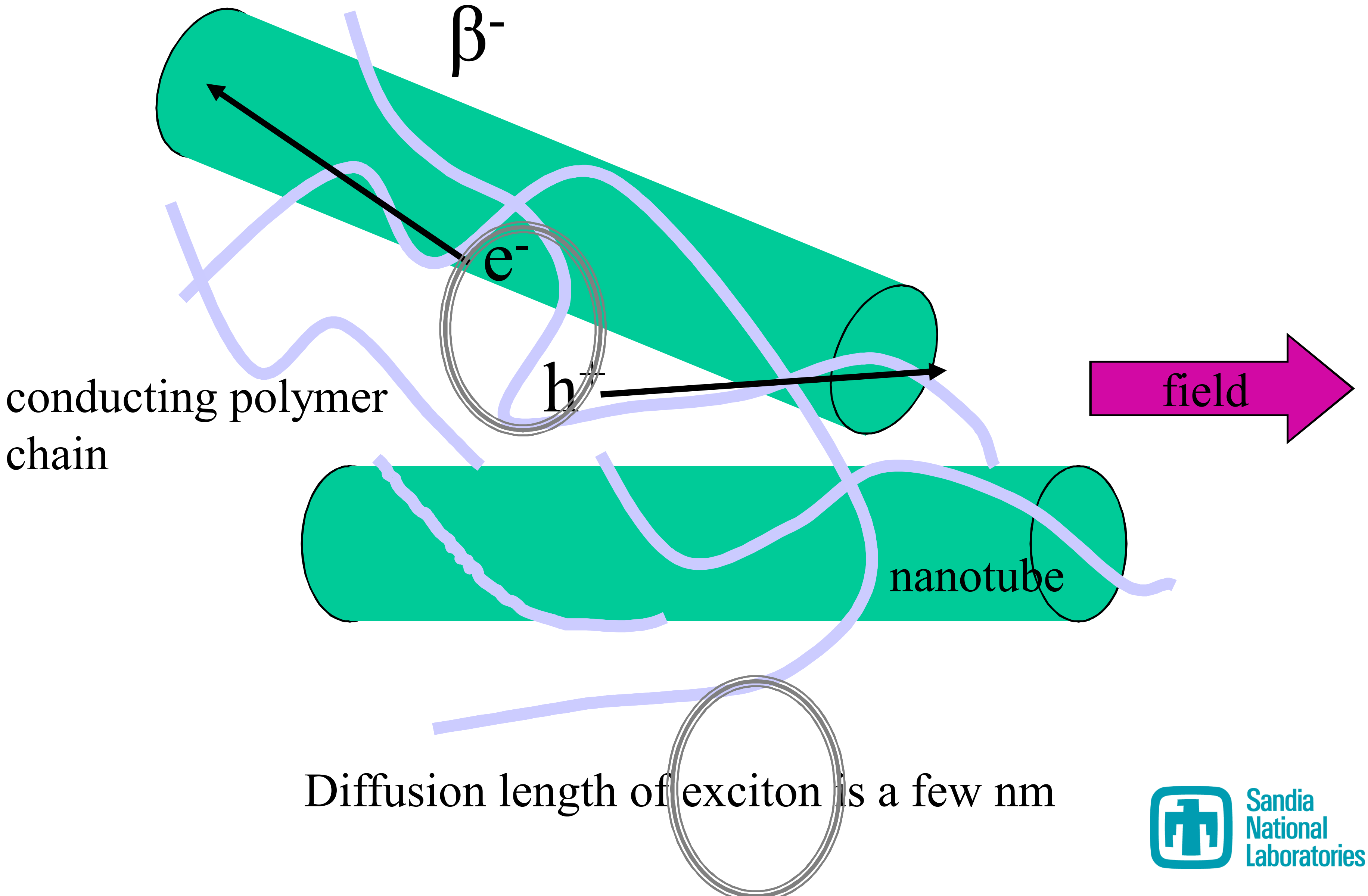
Bulk Heterojunctions



electrodes have different workfunctions

Carbon Nanotubes



Diffusion length of exciton is a few nm

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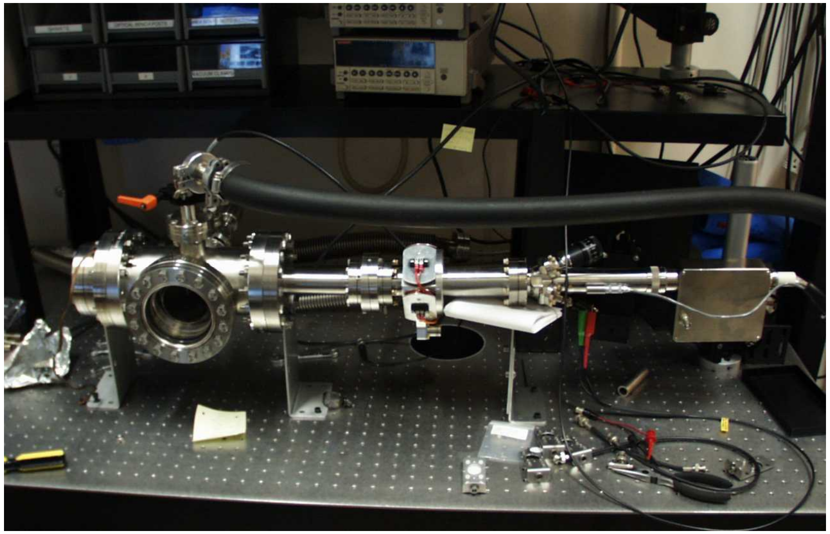
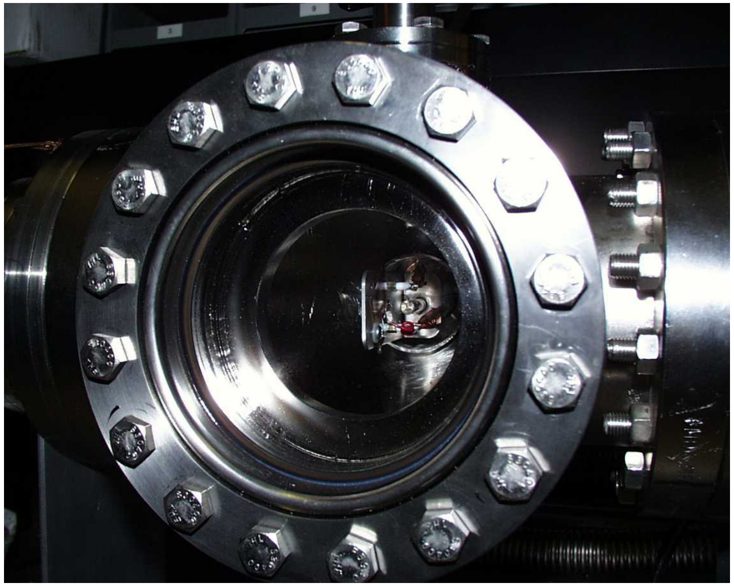
Testing with an Electron Beam

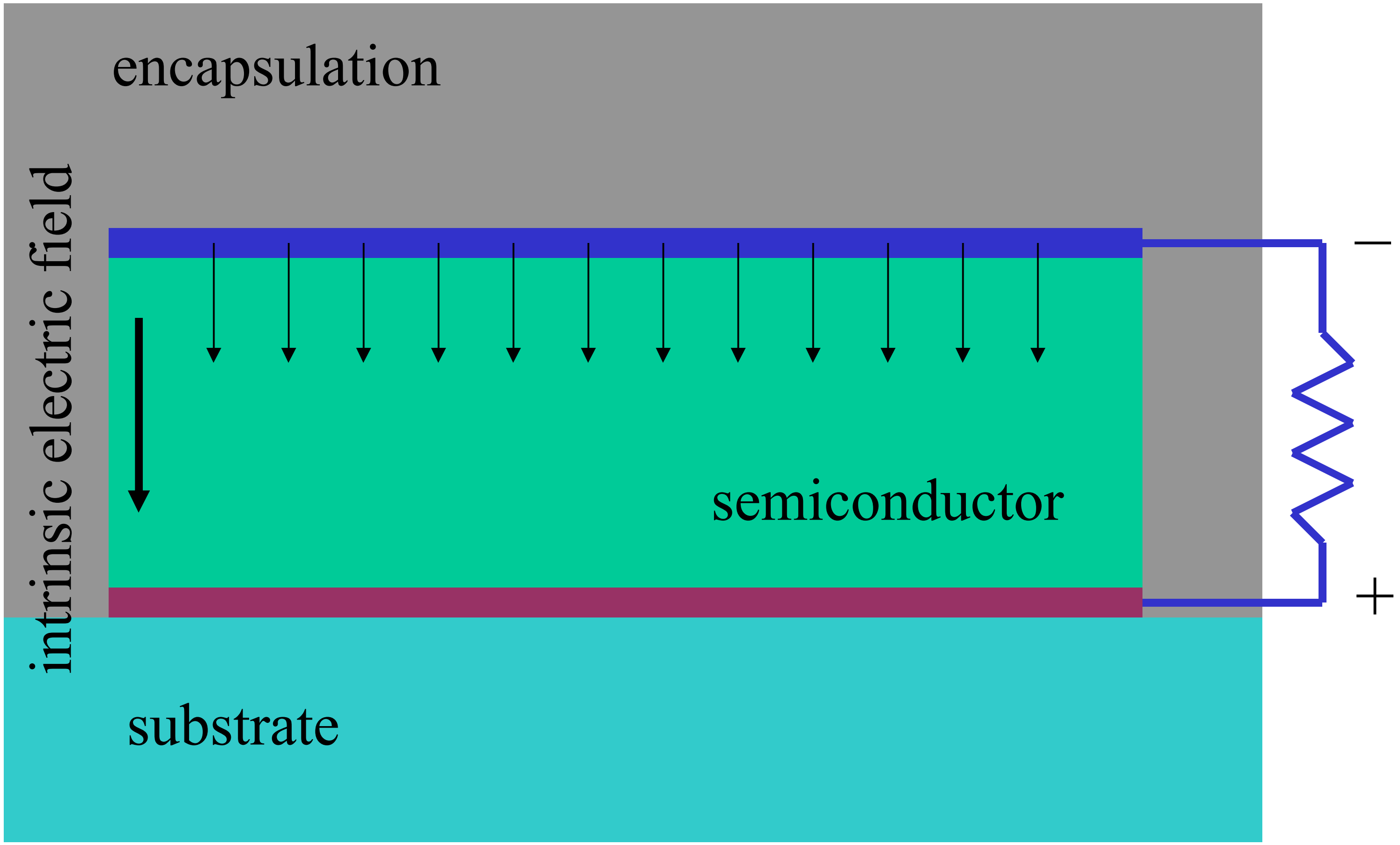
- 20 keV electron gun
- Monoenergetic
- Monodirectional





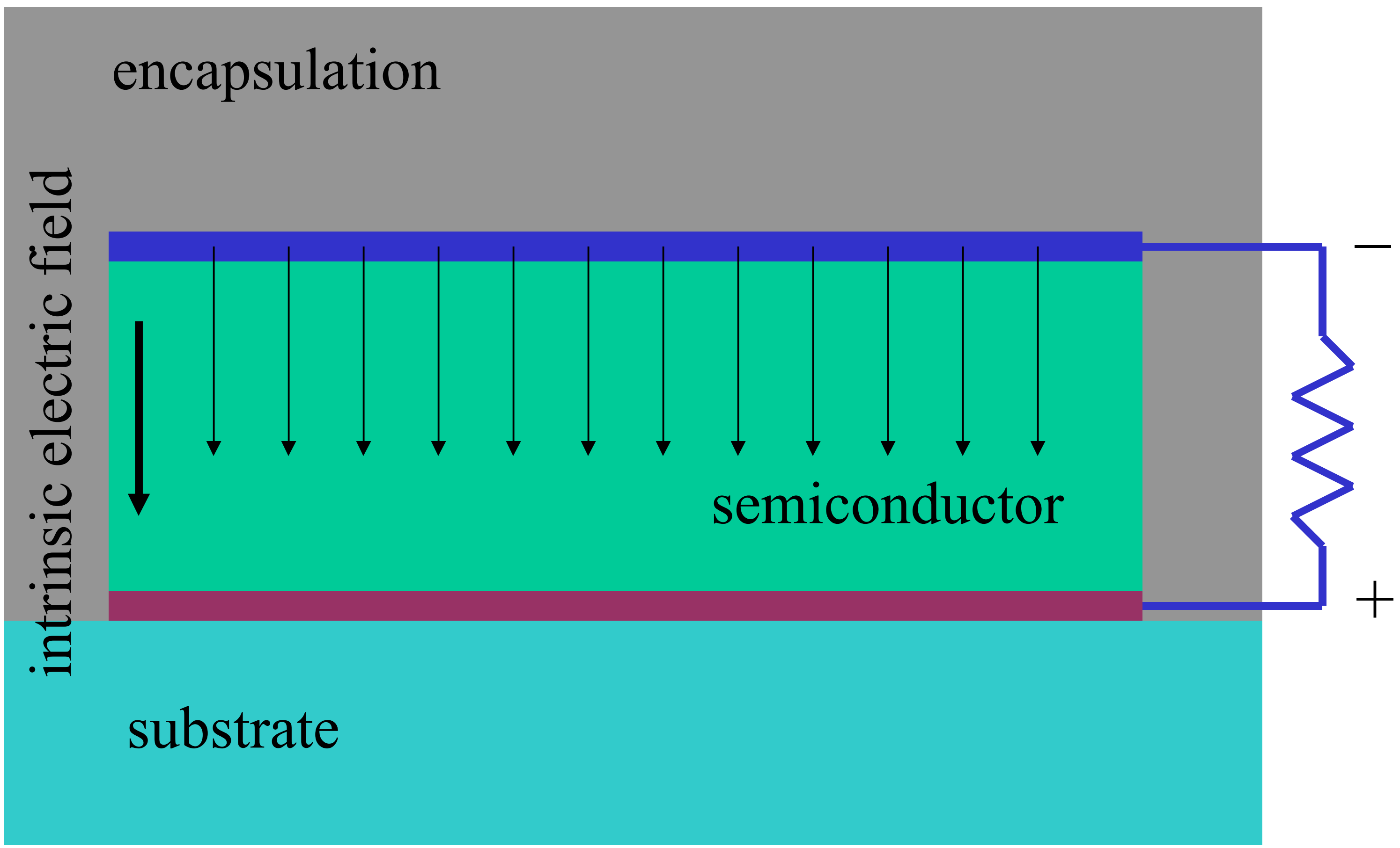
- Can adjust angle of device to beam

Bulk Heterojunctions



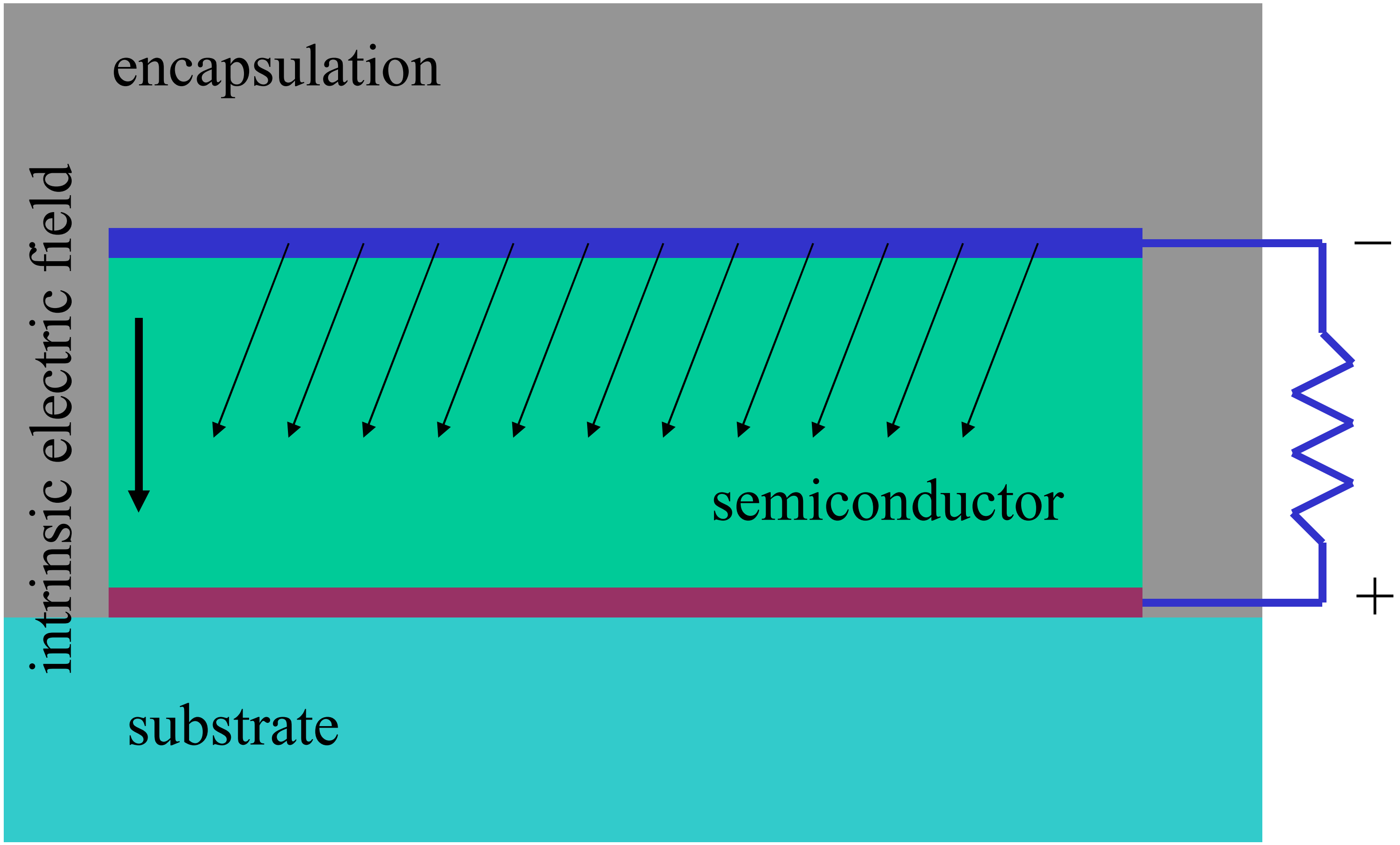
electrodes have different workfunctions

Bulk Heterojunctions



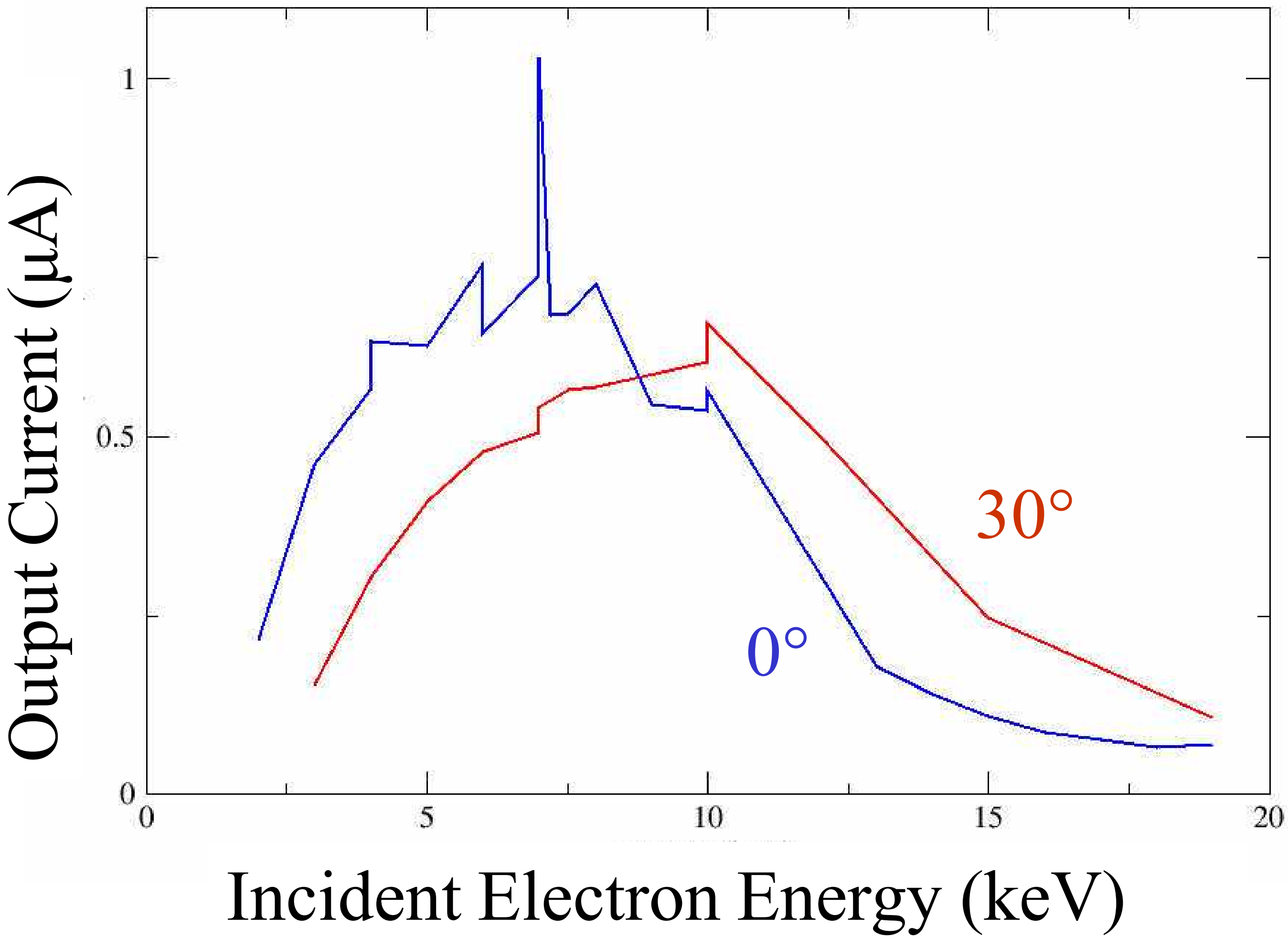
electrodes have different workfunctions

Bulk Heterojunctions



electrodes have different workfunctions

Response a Function of Incident Energy and Angle



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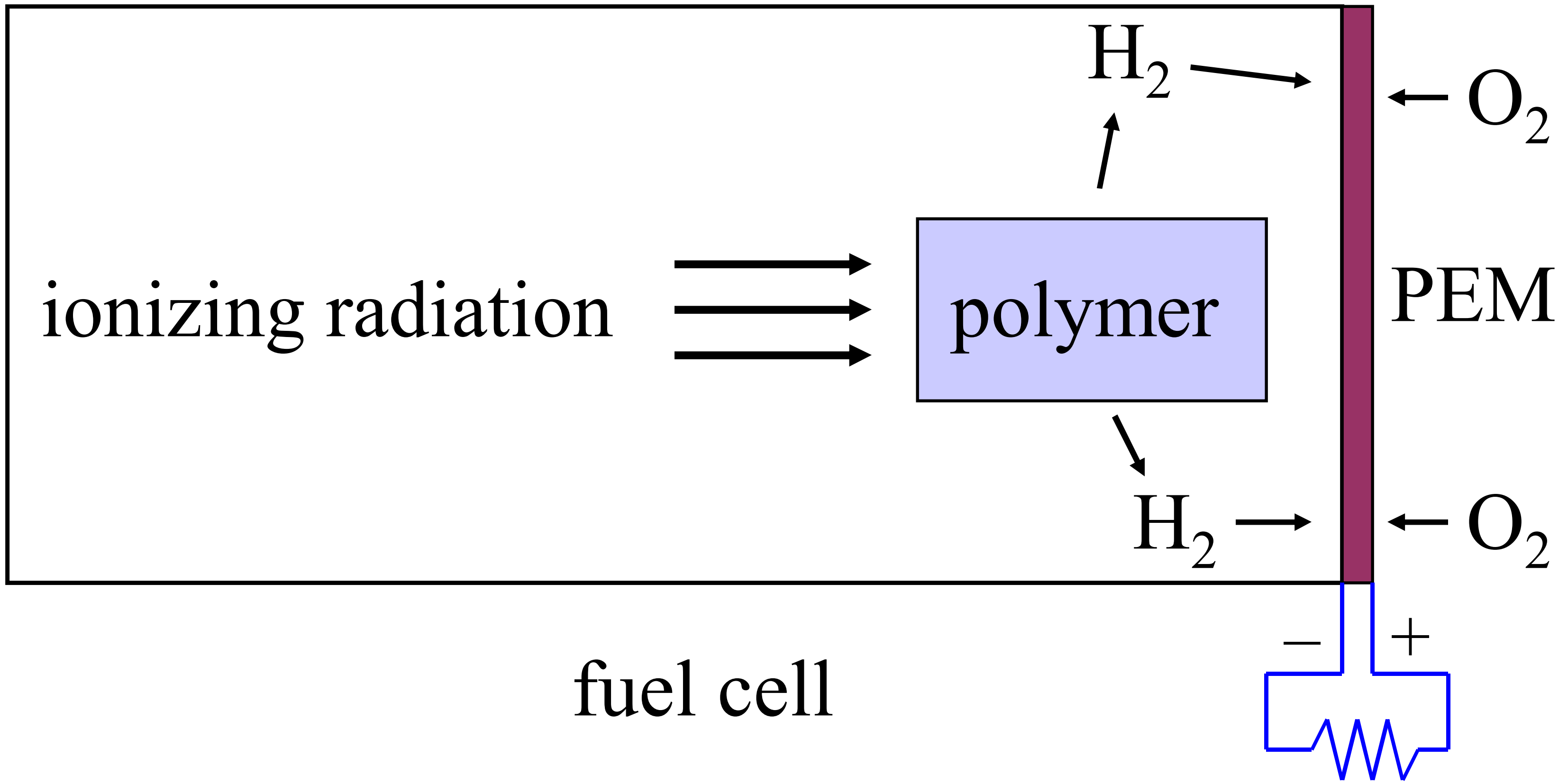
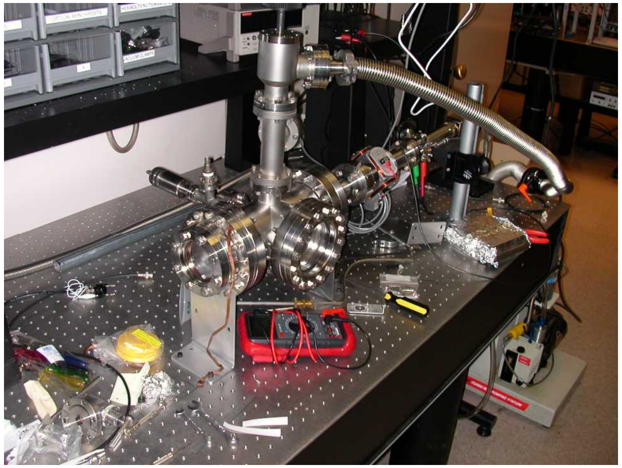
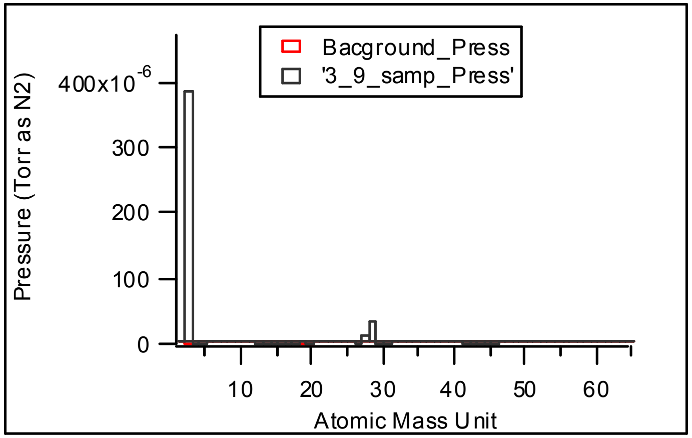
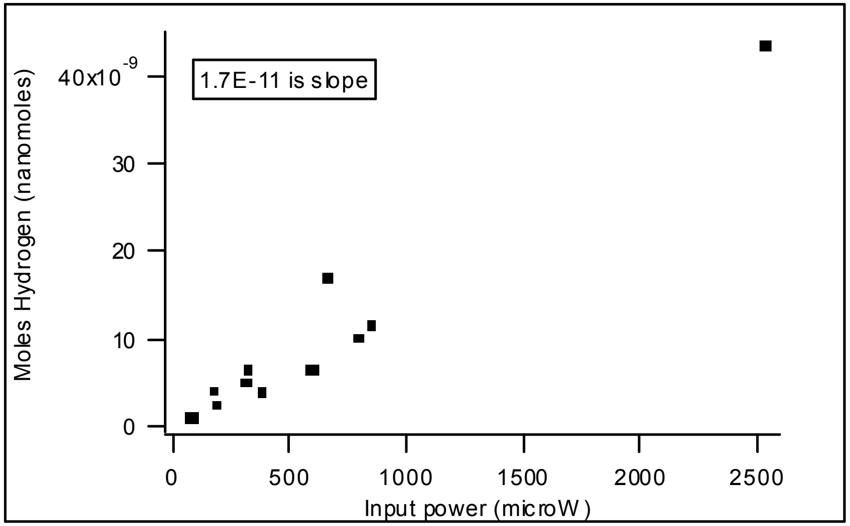
And Now for Something Completely Different...



Electron Beam Experiments







4.4% nuclear to electric
Possible to get much higher.

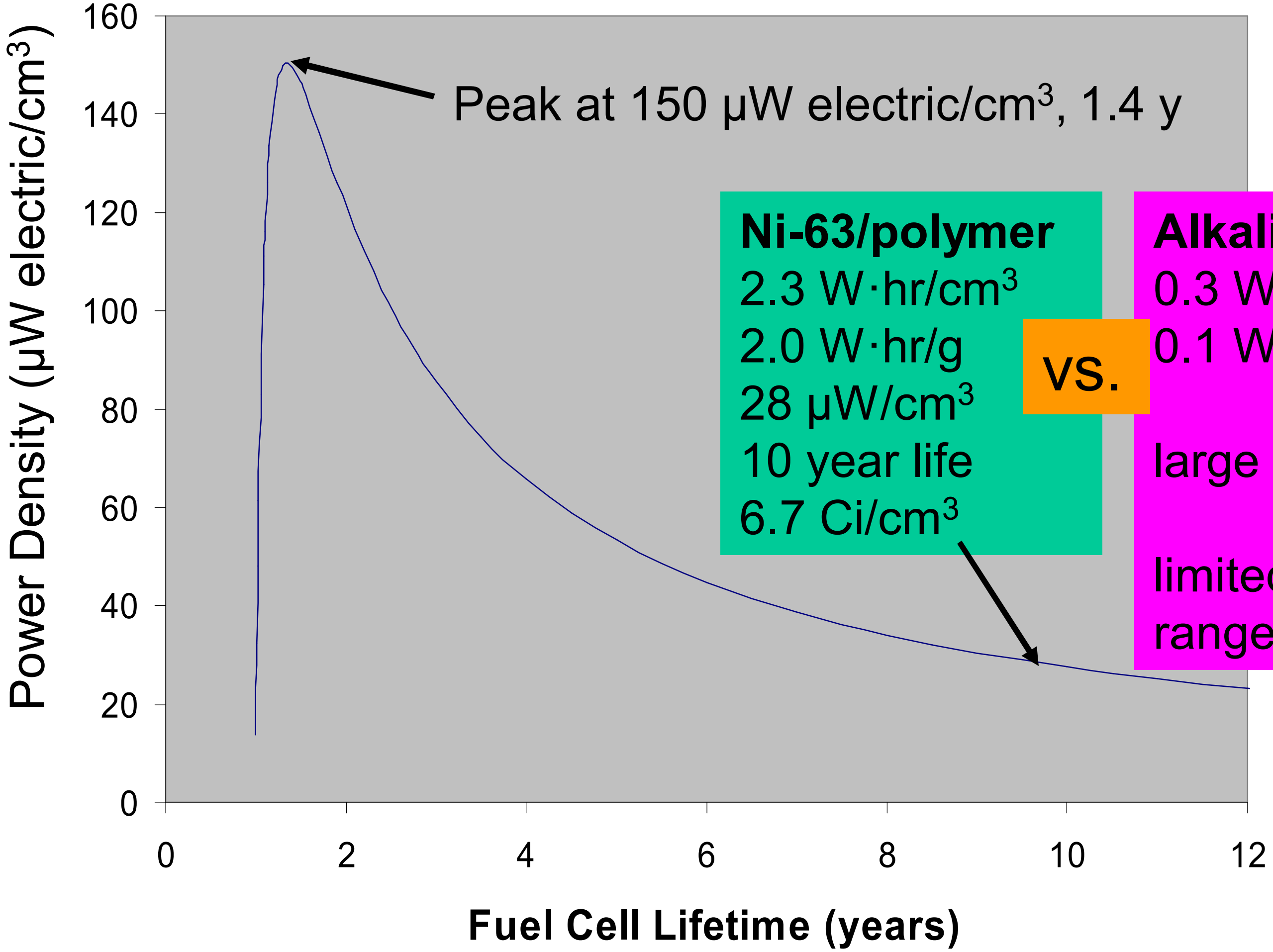
Practical dose rates are approx. 10^4 higher than in real device

Beta Range Drives Physical Design

Ni-63 Betas	Average energy	Maximum Energy
	18 keV	67 keV
range in Ni	0.6 μm	8 μm
range in polymer	5 μm	64 μm

- Two potential designs
  - Ni particles in a polymer matrix
  - alternating Ni & polymer layers (with possible H_2 diffusion layer)
- To limit self-shielding, Ni particles or layers: 0.1 μm-0.5 μm
- To limit system volume, 100s of layers
- Fabricate by automated extrusion or rolling a single layer

Power Density and Device Lifetime



Ni-63/polymer
2.3 W·hr/cm^3
2.0 W·hr/g
28 μW/cm^3
10 year life
6.7 Ci/cm^3

vs.

Alkaline-MnO_2
0.3 W·hr/cm^3
0.1 W·hr/g

large form factor

limited temperature range

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Questions?

Backup Slides

Energy Density Comparisons

	Poor	Conserv.	Optimistic	Very Optimistic	Li/Mn O_2	3V CR24320	DARPA Propr. FC
Hydrogen Recovery, wt. %*	3 (21% of avail)	6 (43% of avail)	8.5% (60% of avail.)	12% (84% of Avail)			
Fuel Cell Eff. H=> electric	45%	50%	60%	60%			
Lifetime	5 yrs.	10 yrs. max.	20 yrs.	40 yrs.	8 yrs.	8 yrs.	10 yrs.
System package wt. pkg/wt. total	40%	30%	20%	15%			
Energy Density W-hr./kg	280	740	1420	2200	180	250	900
Energy Density W-hr./L**	340	880	1700	2600	650	530	950

* Metal hydrides such as LiAlH react with water to about 7% Hydrogen by mass

** Assumes 1.2 g/l system density

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