Tritium:
A MicroPower Source for On-Chip Applications

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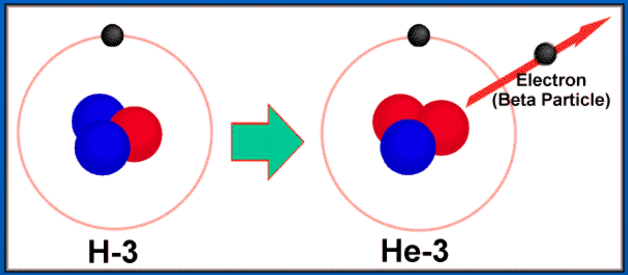
Outline

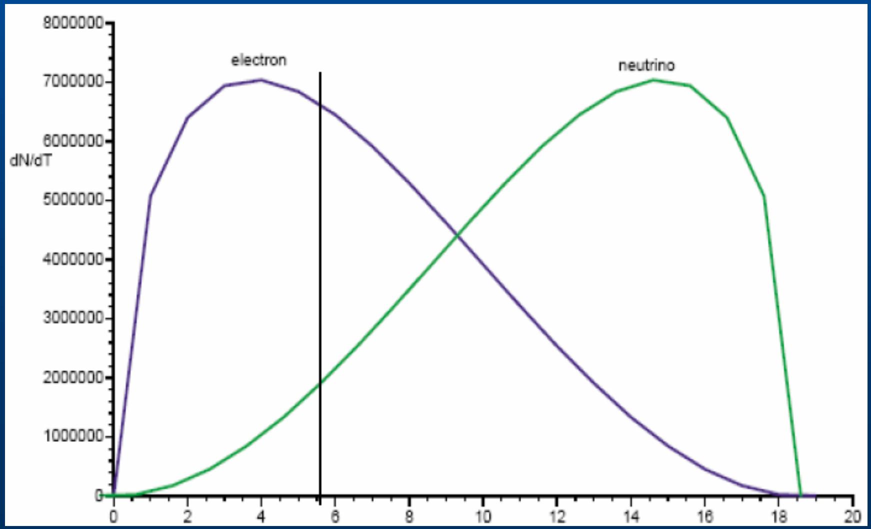
- **Tritium: Basics**
- **Tritium: A MicroPower Source**
  - **Beta-Voltaics**
  - **Beta-Powered MEMS**
  - **Beta-Luminescence**
  - **Cold Electron Source**
- **Tritium: A Characterization/Diagnostic Tool**
  - **Tritium Tracer Studies**
  - **Tritium Effusion Studies**
  - **Defect Dynamics**
  - **Particle Sensor Applications**
- **Summary**

Tritium

- Isotope of Hydrogen
- $^{3}H \rightarrow {}^{3}He^{+} + \beta^{-} + \overline{\nu}_e + 18.6$ keV
- Nuclear Half-life: $t_{1/2} = 12.32$ years
  $\lambda = 1.78 \times 10^{-9}\ s^{-1}$



- Activities: 1 Ci = 3.7×10^{10} Bq
  1 Ci = 0.39 std cc
  1 Ci = 33.7 μW
- Biological: Half-life: 10 days
  ALI*: 80 mCi
  *Annual Limit on Intake
- Chemically: Identical to ^{1}H
  Mass effect (~3amu)
  Beta catalysis
- Range (max): 4.5 – 6 mm in air
  5 – 7 micron in water

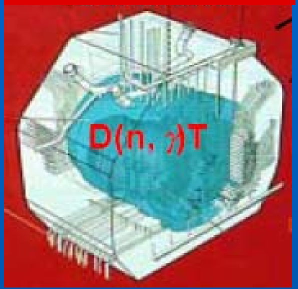


Producers & Users

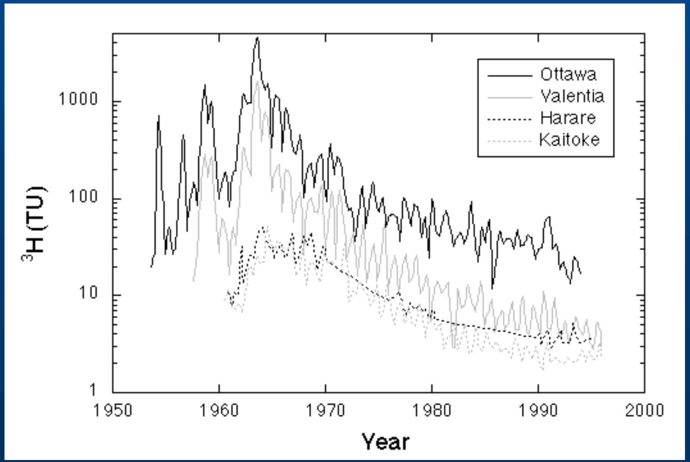
- Producers of Tritium
  - Ontario Power Generation (OPG)
    - ~1 kg/year
  - Korean Electric Power Company (KEPCO)
  - USA
    - 225 kg produced since 1955
    - 12-75 kg stockpiled
  - Russia
  - India, Pakistan

Tritium Producing Burnable Absorber Rods (TPBARs)
(Lithium Rods in a Light Water Reactor)

CANDU



- Users of Tritium
  - Pharmaceutical Research (~100g)
  - Tritium Lighting Industry (~30g)
  - Fusion Studies
    - Magnetic Confinement (ITER ~40g)
    - Inertial Confinement
  - Other



Tritium in
Natural Waterways

1 Tritium Unit (TU) = 1 T : 10^{18} H

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  - Tritium Tracer Studies
  - Tritium Outgassing & Effusion Studies
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  - Particle Sensor Applications
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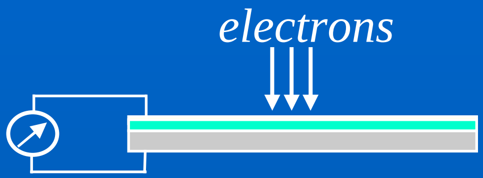
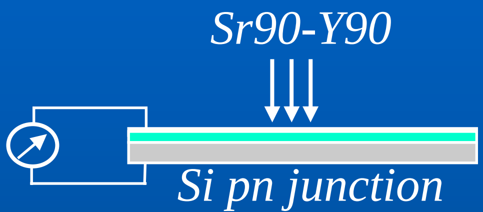
BetaVoltaics

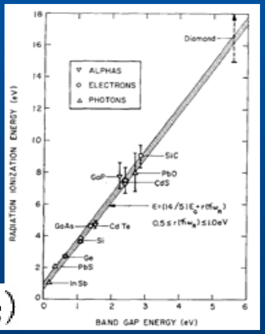
- **1951, Ehrenberg, Lang, & West:**
  - Electron-voltaic effect (on a Se device)



- **1956, Rappaport**
  - First direct conversion betavoltaic device (planar configuration, 0.4% efficiency)



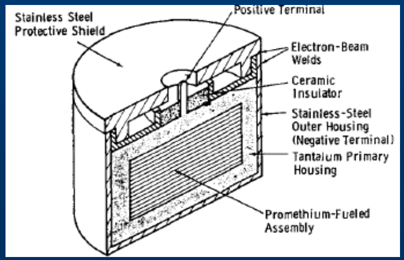
- **1968, Klein**
  - Band-gap dependence of electron-hole pair (*ehp*) generation by ionizing radiation



$$\epsilon = (14/5)\, E_G + r\,(\hbar\omega_R)$$

- **1974, Olsen**
  - Theoretical treatment of betavoltaic conversion efficiencies for a variety of semiconductor materials

- **1970s, D W Douglas Laboratories**
  - Planar silicon betavoltaics fueled with ^{147}Pm
  - Efficiencies ranged in 0.7 to 2%

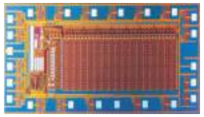


Renewed Interest in Radioisotope Batteries

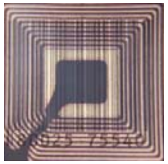
- Continual miniaturization of electronic and electromechanical systems
  - Decreased power consumption
- Integrated Power Sources (SoC)
- High energy densities compared to chemical batteries
- Operation in extreme environments
  - For example, temperatures of -100 to +150 ^{o}C

MicroPower Applications

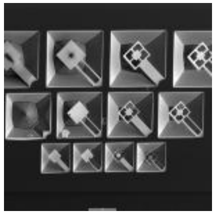
Sensor/Memory Chips
Power requirement: 1-10 μW



Non-volatile Memory



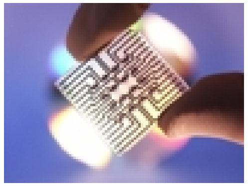
RF-ID tag



Electrostatic actuation of MEMS/NEMS

SoC Microsystem
Power requirement: 1-10 mW

Chip-scale atomic clock



Micro-gas Analyzer

Chip-scale Navigation system

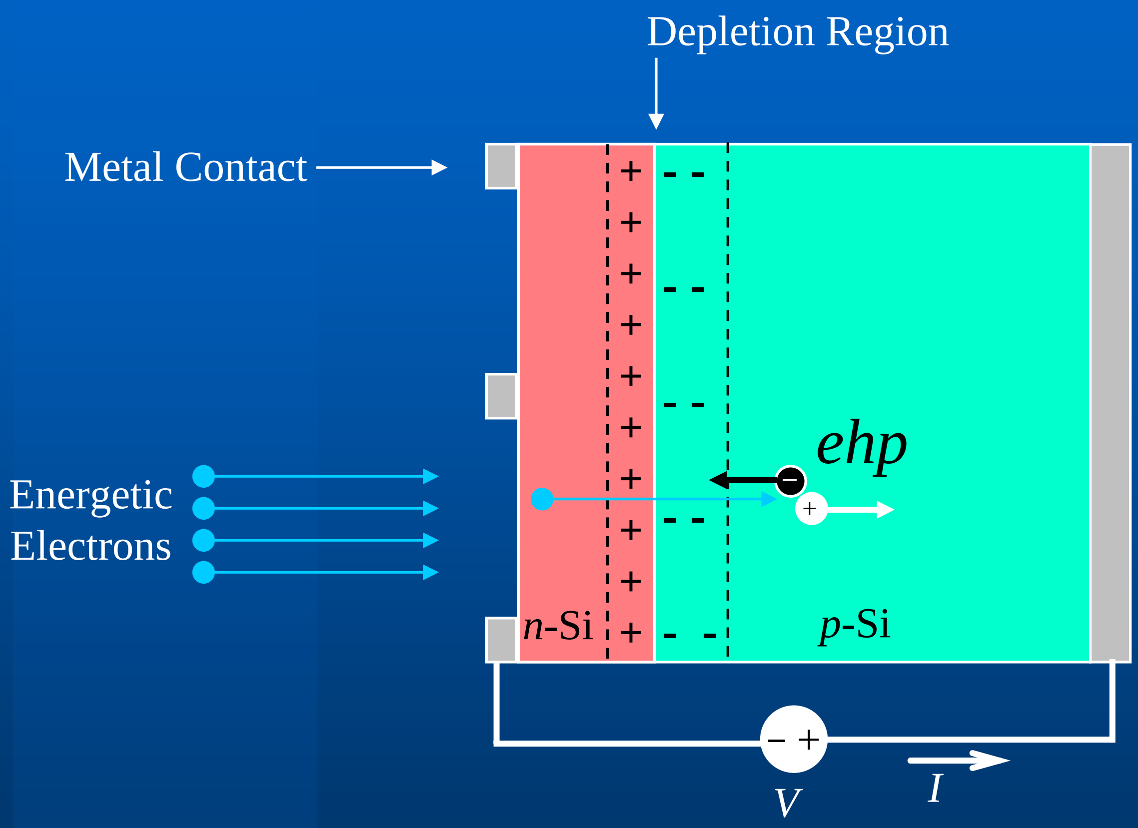
Market

- **All Batteries: $50 billion**

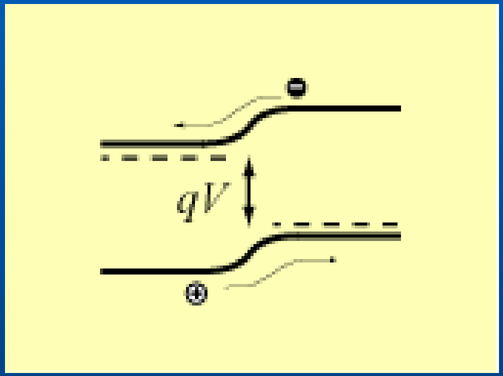
- **Target markets for betavoltaic batteries**
  - Oil, gas, and environmental
  - Military
  - Medical
  - Space
  - Emerging MEMS/NEMS

- **Market for betavoltaics $1 billion +**

Electron/Beta Voltaics



Band Diagram



ehp: electron-hole pair

Choice of Radioisotope

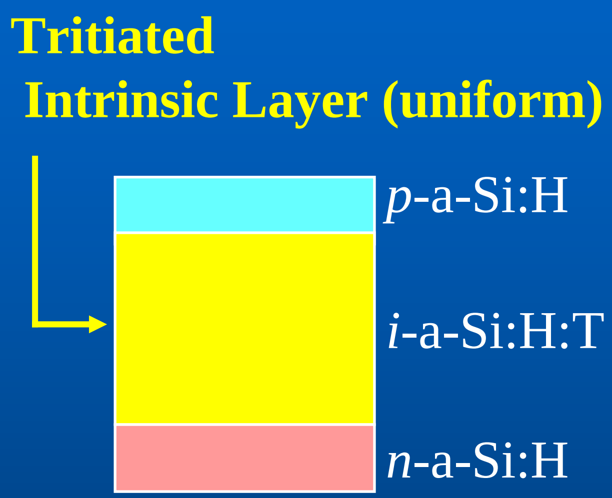
Isotope	E_{avg} (keV)	E_{max} (keV)	P (W/g)	Work (kWh/4y/g)	$T_{1/2}$ (yrs)
H-3	5.7	18.6	0.34	10.3	12.3
Ni-63	21	66	0.07	2.5	92
Sr-90	540	900	0.75	25	28
Pm-147	62	230	0.34	7.3	2.6

Tritium

- **Low energy β- emitter (benign radioisotope)**
- **Low cost**: **$2.5-$4/Ci**
- **Long enough lifetime**
- **Can be immobilized in a solid matrix**
- **On-chip integration**
- **Mature** (existing tritium lighting industry)

Intrinsic Tritiated Amorphous Silicon Betavoltaic Device

- **Substitute tritium for hydrogen in hydrogenated amorphous silicon *pin* photovoltaic devices**
- **Tritium within the energy conversion layer**
  - **In contrast to betas originating from a source external to the device**
- **Volume source battery**
  - **Attained through stacking of many cells**
  - **In contrast to a planar surface source battery**



Kherani, Kosteski, Gaspari, Zukotynski, Shmayda,,
Fusion Technol. ***28***, *(1995) 1609-1614.*

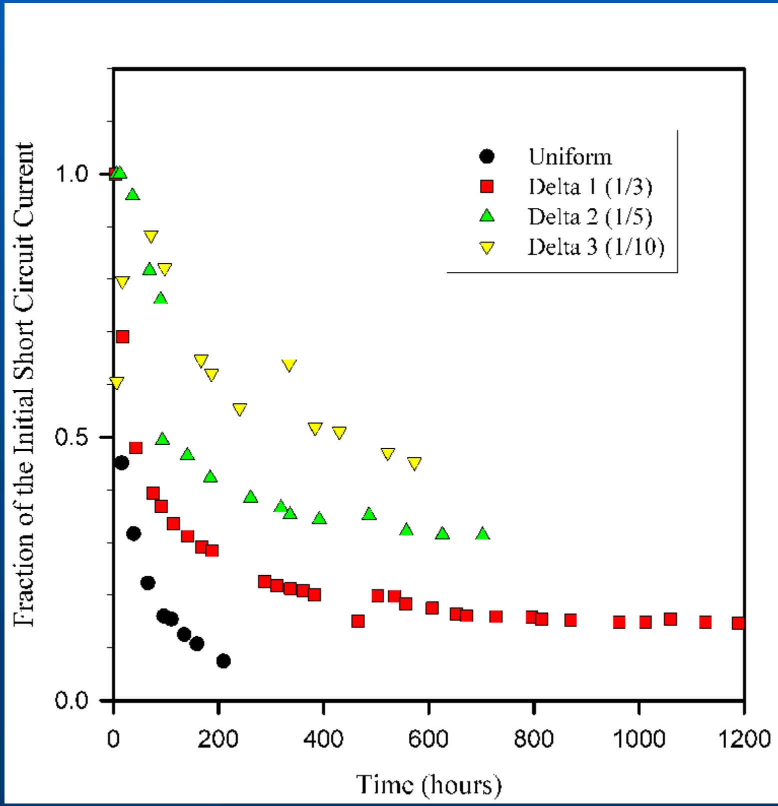
a-Si:T Betavoltaic Device

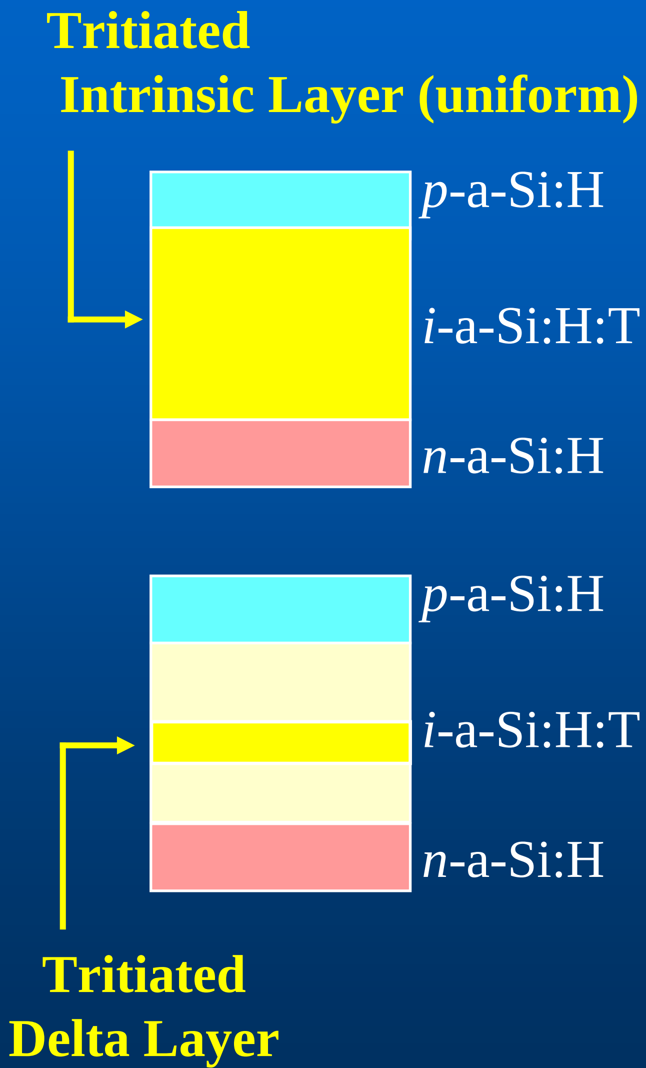
At t ~ 0

I_{sc} = 0.98 nA
V_{oc} = 21 mV
η = 0.1%

At t ~ 10 days

I_{sc} < 0.1 nA

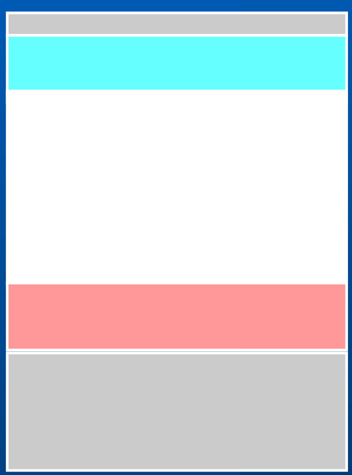




Kosteski, Kherani, Stradins, Gaspari, Shmayda, Sidhu, Zukotynski,
IEE Proc. Circuits Devices Syst. **150**, No.4, (2003) 27-281.

a-SiH Betavoltaic Cell Powered by T_2 Gas

a-SiH Betavoltaics
with ultrathin contact



Cr, 5nm
p-a-Si:H, 20 nm
i-a-Si:H,
450 nm, 10-15 % H
n-a-Si:H
SS substrate

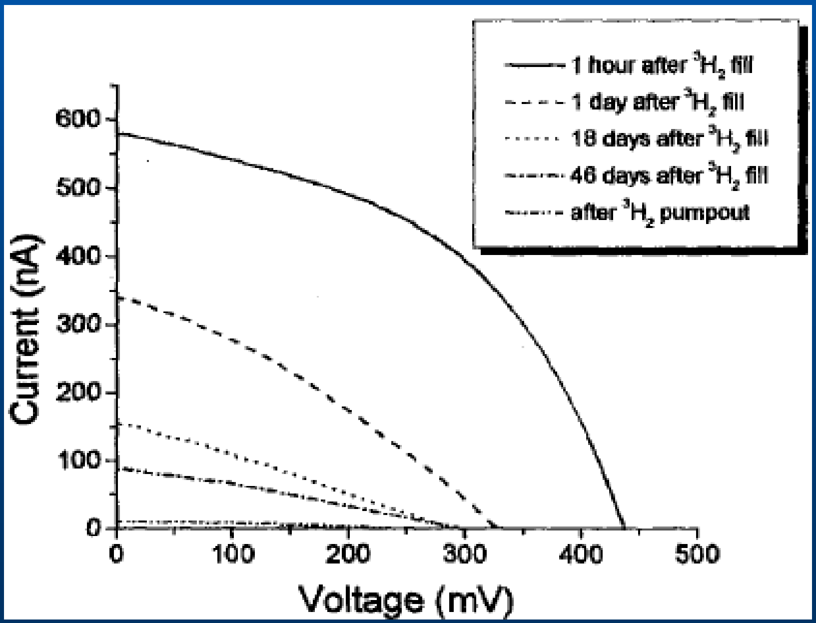
Tritium gas
pressure: 678 torr

At t ~ 0

I_{sc} = 637 nA/cm^2
V_{oc} = 457 mV
η = 1.2%

At t ~ 46 days

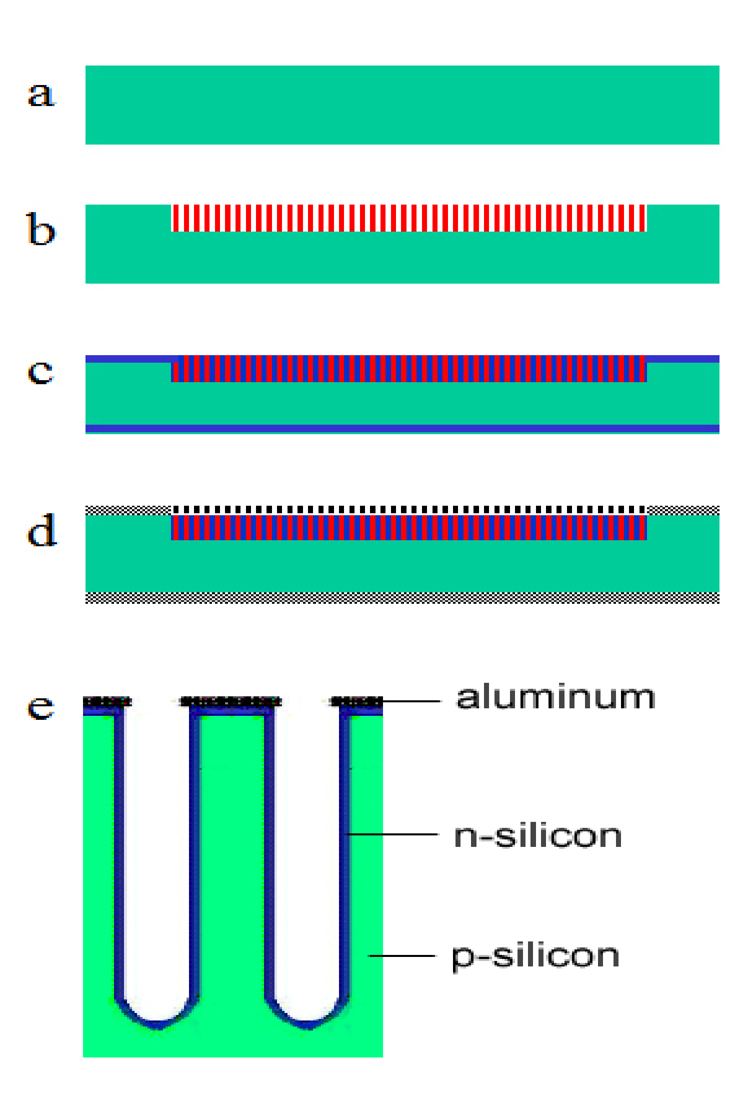
η < 0.1%



Deus, *28th PVSEC, 2000.*

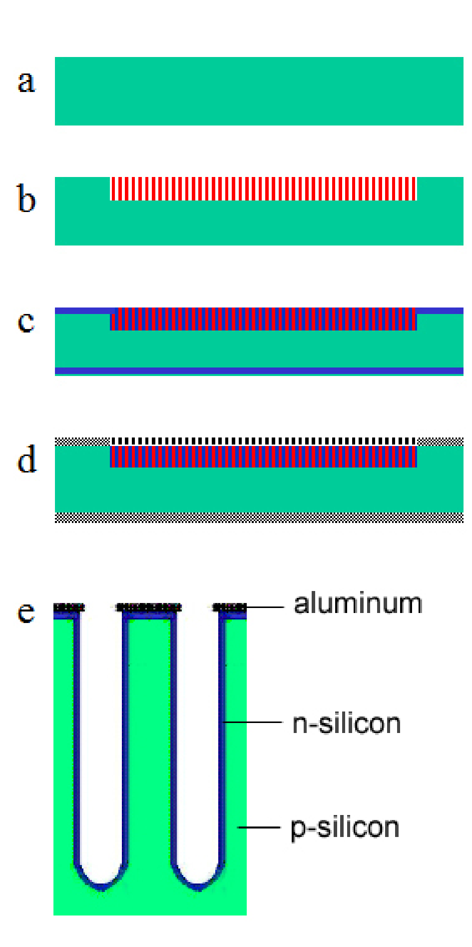
Porous Silicon 3D Betavoltaics

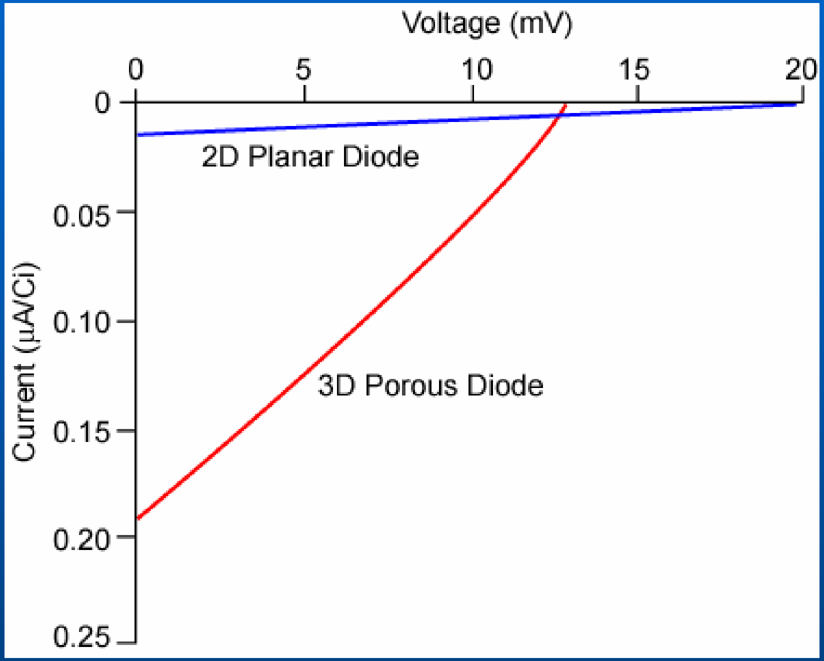
- **Introduce micropores in silicon through electrochemical anodization**
- **Create *pn* junction in the pores through diffusion of n-type dopant**
- **Introduce an appropriate radionuclide in the pores**
- **A Volume Source Battery**



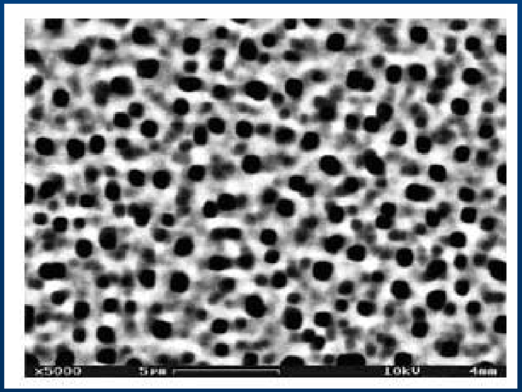
Gadeken, Sun, Kherani, Fauchet, Hirschman,
US Patent 7250323 (2007).

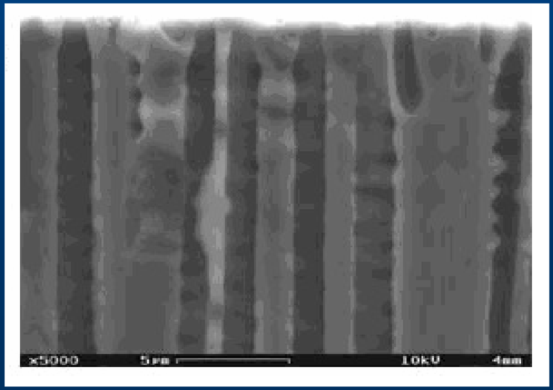
3D Versus 2D Betavoltaics





$\eta_{2D} = 0.02\%$
$\eta_{3D} = 0.2\%$

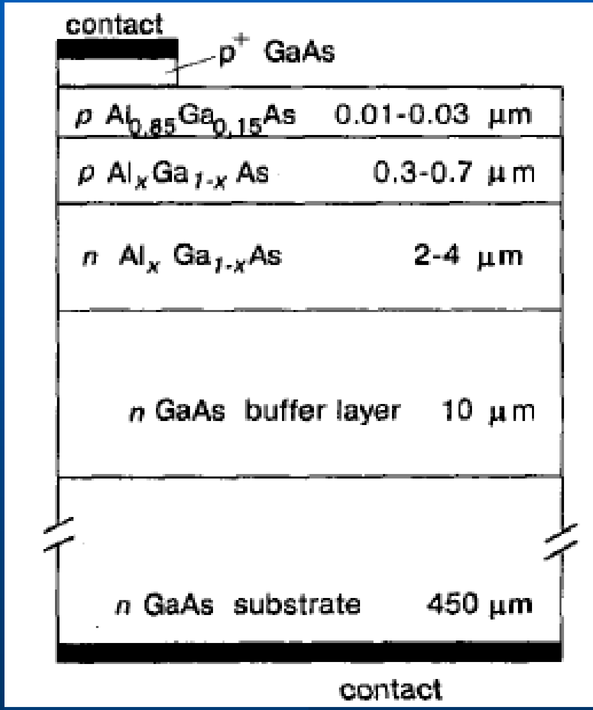




Sun, Kherani, Hirschman, Gadeken, Fauchet,
Adv Mater ***17*** *(2005) 1230-1233.*

III-V Betavoltaics

AlGaAs/GaAs Heterojunction Betavoltaics



Source of betas	Generated current density µA/cm^2	Open circuit Voltage, V	Output Power, µW/cm^2	Efficiency (%)
Tritium-titanium	0.04	0.75	0.024	5.6
Tritium gas	0.76	0.91	0.55	5.8
Tritium green lamp	0.12	0.78	0.074	---

Andreev, Kavetsky, Kalinovsky, Larionov, Rumyantsev, Shvarts, Yakimova, Ustinov, *28th PVSEC, 2000.*

Silicon Carbide Betavoltaics

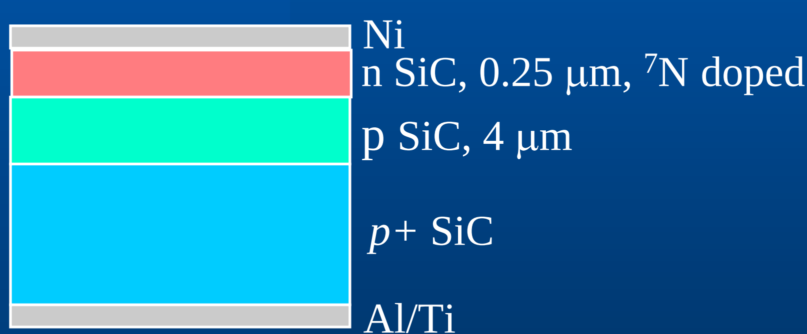
4H SiC BV Cell

1 mCi, ^{63}Ni Source (66keV)

I_{sc} = 16.8 nA/cm^2

V_{oc} = 0.72 V

η = 6%



Chandrashekhar, Thomas, Li, Spencer, Lal,
Appl. Phys. Lett., ***88*** *(2006) 033506*

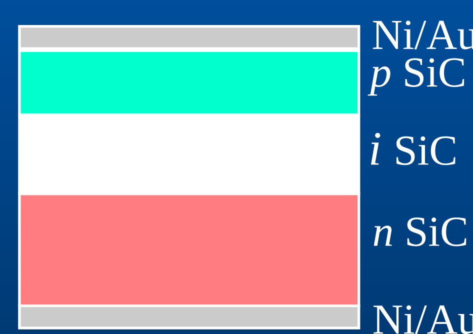
4H SiC *pin* BV Cell

8.5 GBq, ^{33}P Source (249 keV)

I_{sc} = 2.1 µA/cm^2

V_{oc} = 2.04 V

η = 4.5%



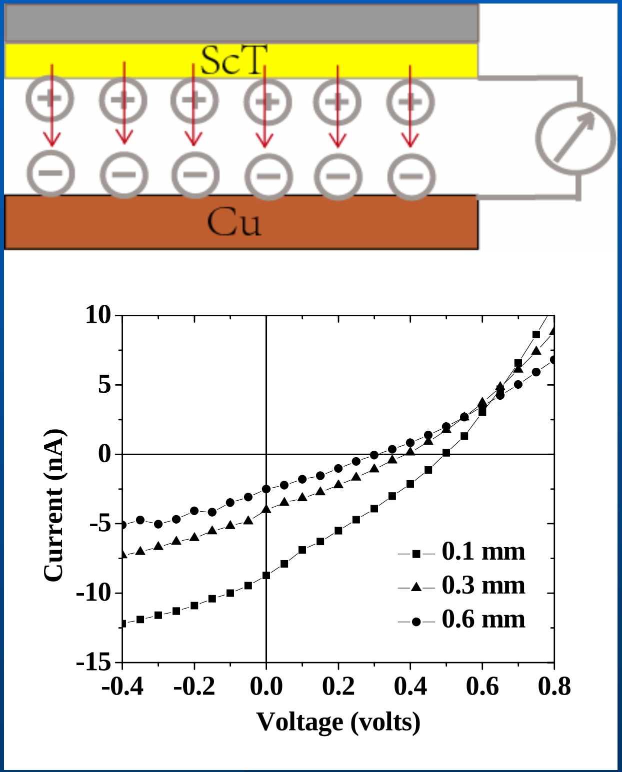
Eiting, Krishnamoorthy, Rodgers, George, Robertson,
Brockman, *Appl. Phys. Lett.*, ***88*** *(2006) 064101*.

Contact Potential Difference Betavoltaics

Air-medium CPD BV

$I_{sc} = 2.7\ nA/cm^2$

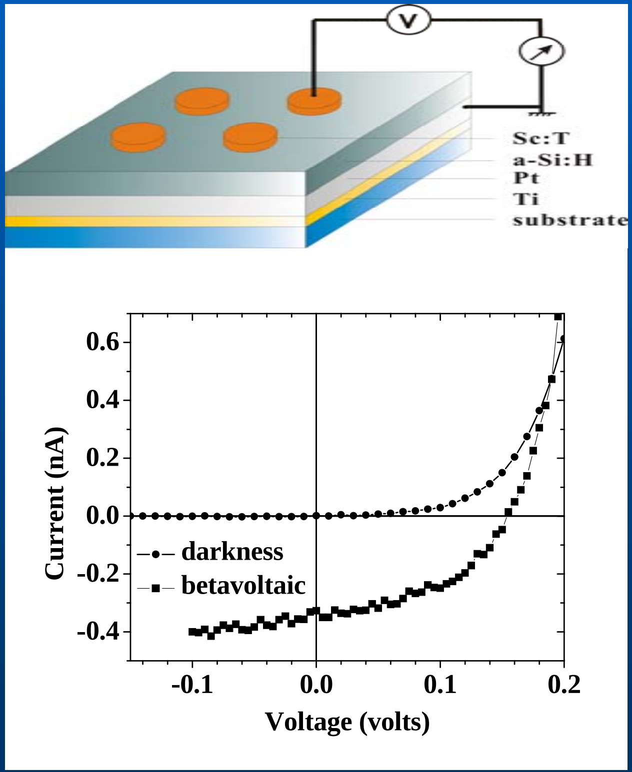
$V_{oc} = 0.5\ V$



Solid CPD BV

$I_{sc} = 5.3\ nA/cm^2$

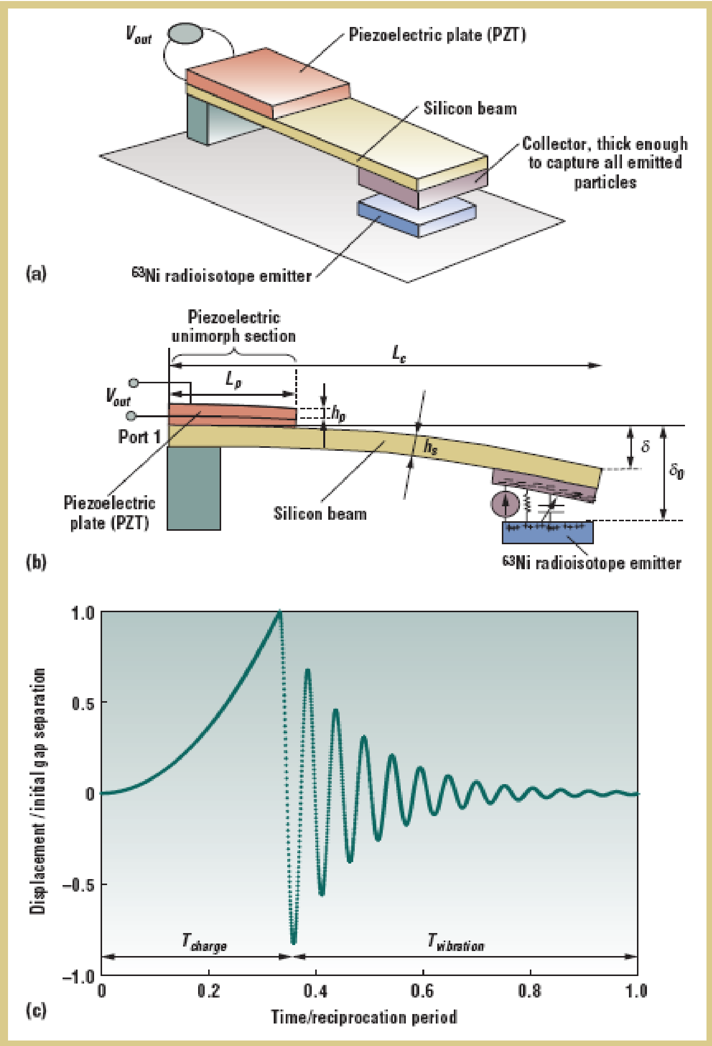
$V_{oc} = 0.16\ V$



Liu, Chen, Kherani, Zukotynski, Antoniazzi,
Appl. Phys. Lett., **92** *(2008).*

MEMS: Radioisotope-Powered Piezoelectric Generator

- Self-reciprocating direct-charging cantilever
- Direct conversion of collected-charge-to-motion energy into electrical
  - Radioisotope kinetic energy stored in the cantilever
  - Piezoelectric generator converts stored mechanical energy into electrical energy
- Overall efficiency 2.78%



Lal, Duggirala, Li, IEEE Pervasive Computing, ***4,*** *(2005), pp. 53-61.*

BetaLuminescence

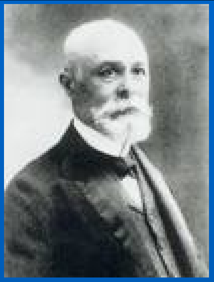
- **1898, Becquerel**
  - Radioluminescence
  - Phosphorescence material: potassium uranyl sulphate

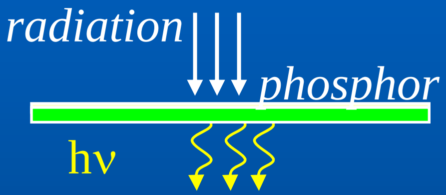
- **1920s, Elster, Geitel, and Cookers**
  - Alpha radiation induced scintillations in ZnS.

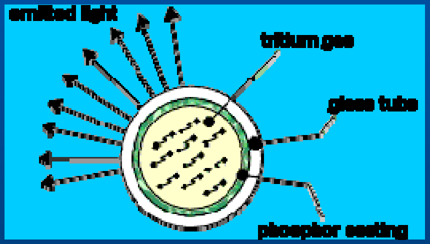
- **1967, International Atomic Energy Agency (IAEA)**
  - Standards for the use of common RL sources.
  - Most common: tritium beta-luminescence

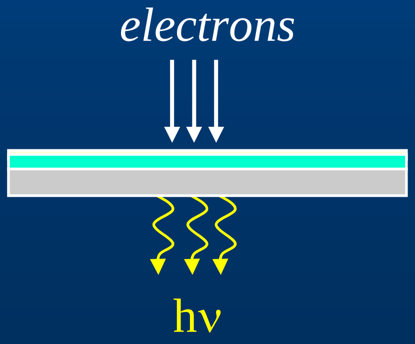
- **Present**
  - Tritium gas lighting
  - Radium ZnS:Cu paint
  - Novel materials & technologies in Betaluminescence
    - Organic
      - all-organic formulation: polystyrene and fluorescent dye
      - organic system with inorganic phosphor
    - Inorganic
      - semiconductor pn junctions
      - incorporation of tritium in solid matrix: amorphous materials, hydrides, carbon nanotubes, zeolites

Becquerel









Cold Electron Source

- Tritium immobilized in a solid
- Materials
  - Tritiated metal tritides
  - Tritiated amorphous silicon
    - Plasma enhanced chemical vapour deposition: entire film
    - Tritiation post film deposition: ~50 nm
  - Tritiated silica on Si-chip
    - High pressure tritium loading
    - Laser irradiated locked tritium
  - Tritiated silicon
    - High pressure tritium loading
    - Surface region: ~ 10 nm
  - Tritiated carbon nanotubes

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Tritium Tracer Technique

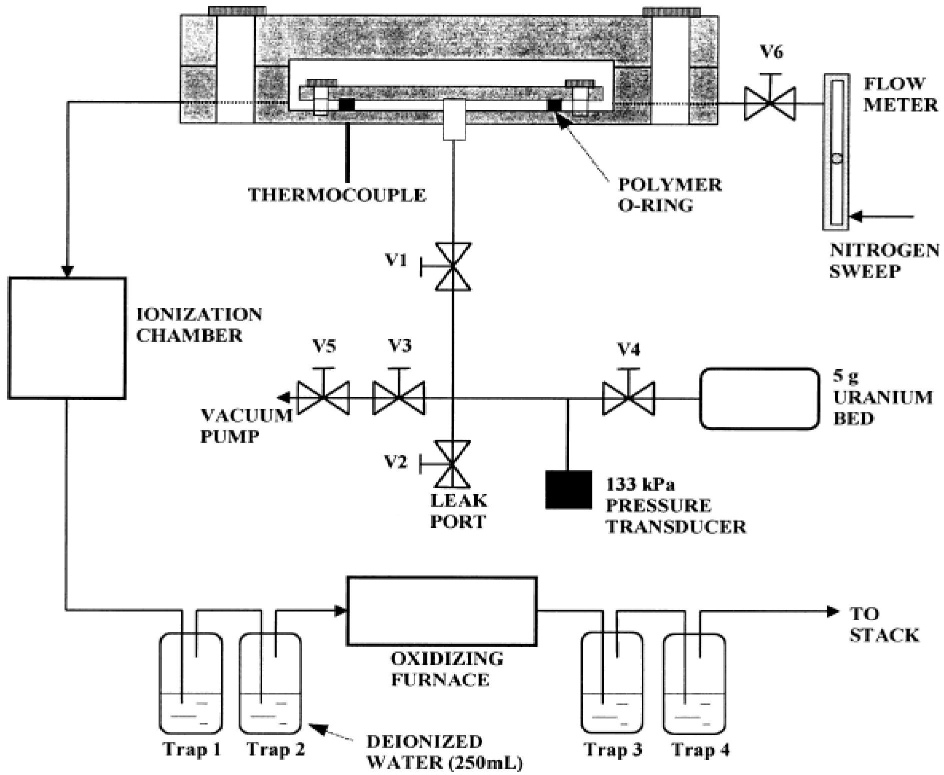
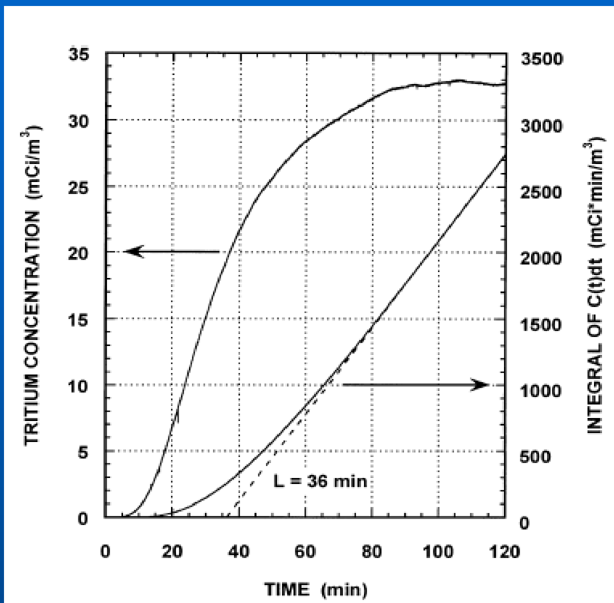


Fig. 1. Schematic of the experimental loop.

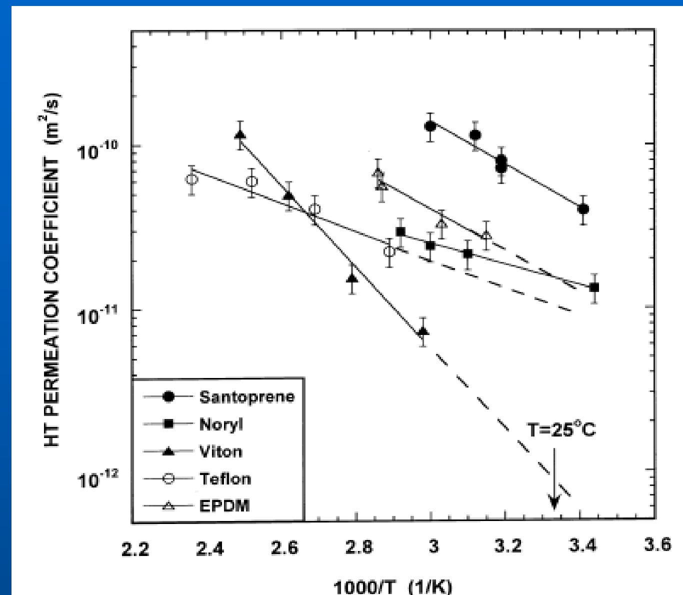
- Tritium as a tracer in measurement of hydrogen permeation in polymer for selection of new material in hydrogen fuel cell.
- Two diagnostics to trace permeating HT: an ionization chamber tritium detector and an HTO water trap/copper oxide furnace/HTO water trap system
- Tritium radiotracer method: simple, effective, reliable.

Stodilka, Kherani, Shmayda, Thorpe,
Intl. J. Hydrogen Energy ***25*** *(2000) 1129-1136*

Tritium Tracer Technique (cont'd)



Characteristic permeation curve for Noryl at 60 °C



Arrhenius plot of tritium permeation for the five polymers

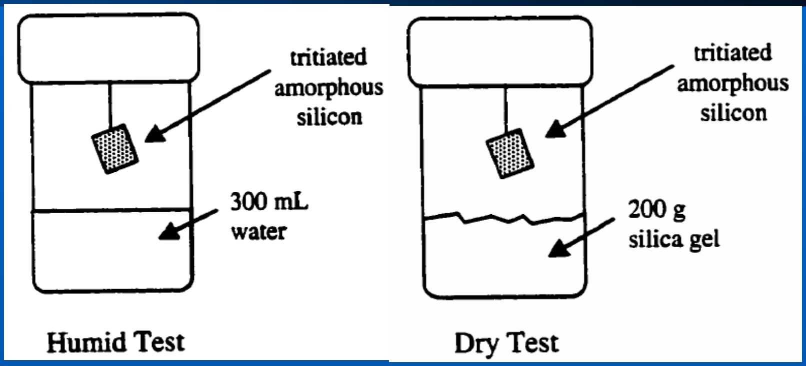
- Materials Tested: EPDM, Teflon, Viton, Santoprene and Noryl
- Permeation Parameters in reasonable agreement with referenced values of H, D, T

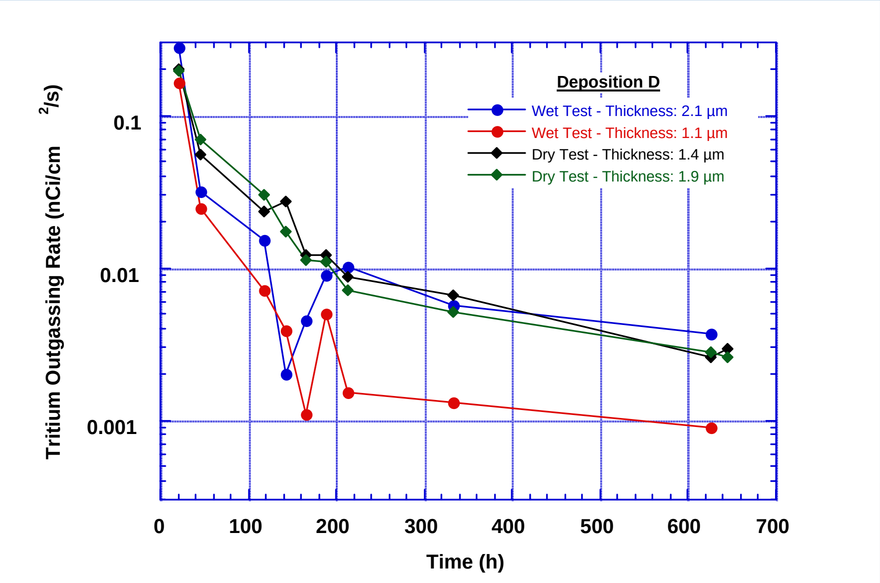
Stodilka, Kherani, Shmayda, Thorpe,
Intl. J. Hydrogen Energy ***25*** *(2000) 1129-1136*

Polymer	Temperature (°C)	P_0^{b}	E_P^{c}	D_0^{b}	E_d^{c}
Viton	63–129	1.72×10^{-4}	47.7	2.22×10^{-5}	29.1
Teflon	74–150	8.38×10^{-9}	16.7	1.39×10^{-7}	14.9
EPDM	44–76	2.74×10^{-7}	24.4	3.50×10^{-5}	27.9
Santoprene	20–60	1.21×10^{-6}	25.1	1.36×10^{-5}	21.2
Noryl	18–70	2.11×10^{-9}	12.3	4.05×10^{-7}	16.9

Tritium Outgassing Studies

- A tool to study hydrogen stability in materials
- High sensitivity
  - Difficult-undetectable for the inactive H-isotope using conventional methods
- Dry and wet test
  - Absorption of HTO desorbed from surface of a given sample
- Tritiated amorphous silicon at room temperature
  - Atomic T concentration: 9%
  - Asymptotic evolution: $2x10^{8}$atmcm^{-2}s^{-1}
  - Equivalently: Void-Network H diffusion half-life of 60 years
  - This is for a low H stability material, owing to the high void fraction of the material

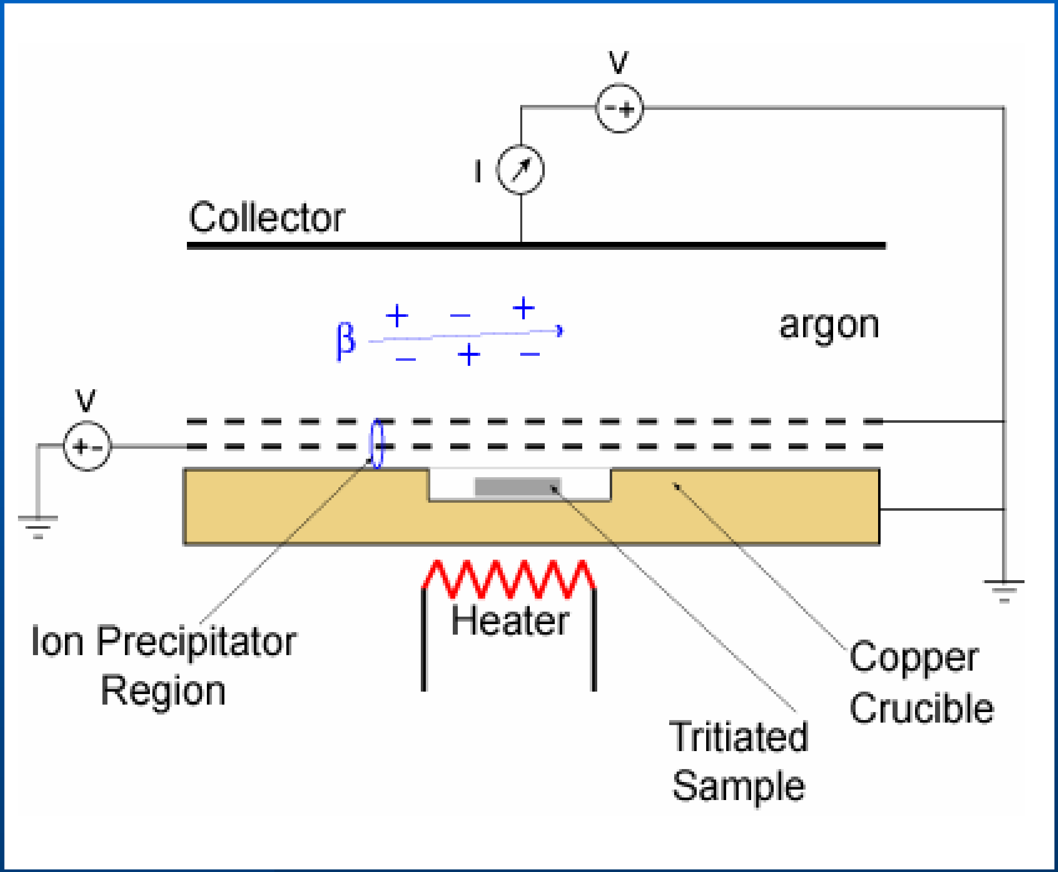


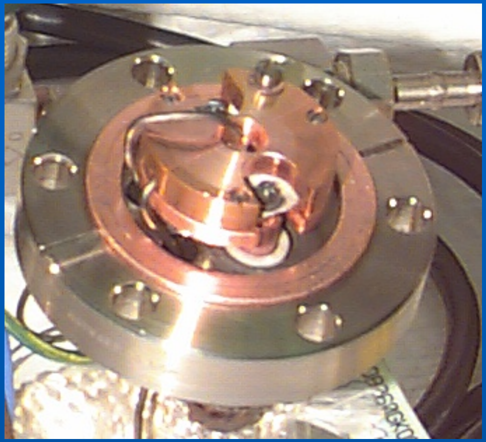


Kosteski, Ph.D thesis, Univ. Toronto. (*2001*)

Kherani, Liu, Virk, Kosteski, Gaspari, Shmayda, Zuktoynski, Chen. *J Appl Phys*, ***103***, *(2008), 024906*

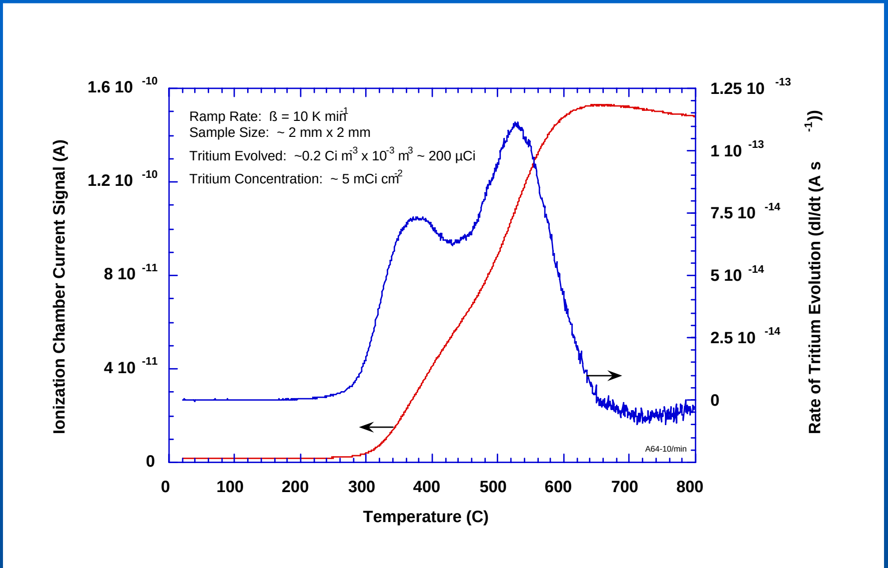
Tritium Effusion Monitor



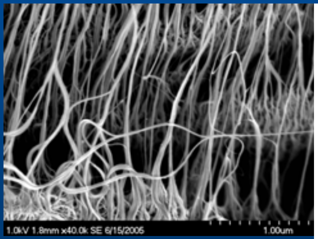


Tritium Effusion

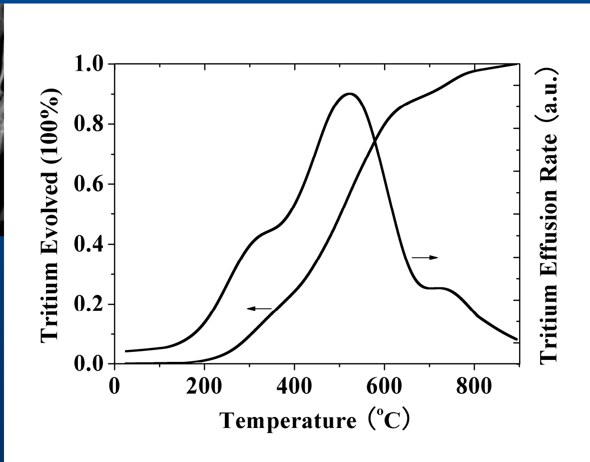
- **Tritiated amorphous silicon**
  - **No tritium evolution at room temperature**
  - **Characteristic peaks observed at temperatures above the film growth temperature**
    - **Lower temp peak: higher hydrides SiHx**
    - **Higher temp peak: mono-hydride SiH**



- **Tritiated carbon nanotubes**
  - **Tritium exposure:**
    - **100 bar at 100 ºC for 3 days**
  - **Concentration:**
    - **Atomic: 1.9%**
    - **Weight: 0.5%.**
  - **Gaussian deconvolution:**
    - **Peaks at 240 ºC and 500 ºC**
    - **High temp peak: chemisorbed T**
    - **Low temp peak: physisorbed T**



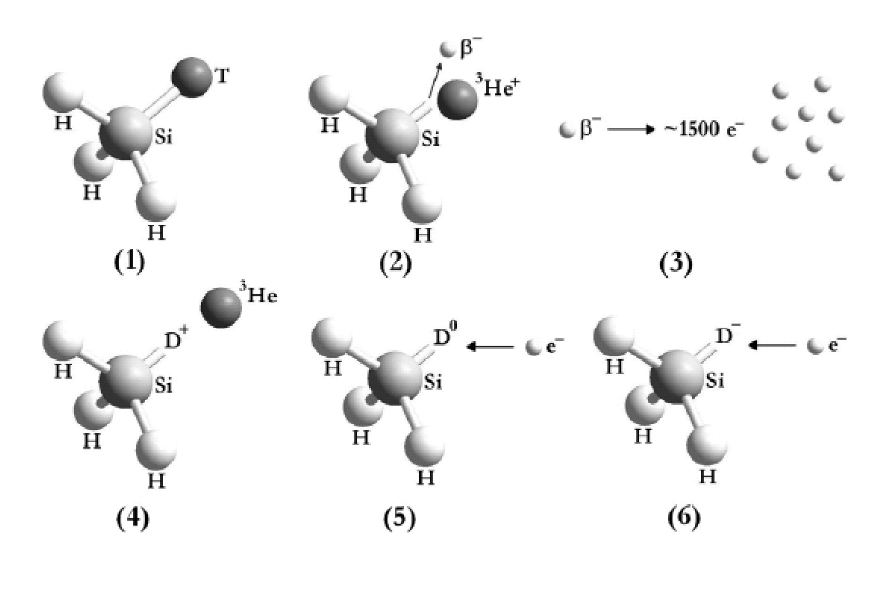
- Purified Single Walled Carbon Nanotubes (SWNT)
- ~25 µm paper-like film
- Surface Area: 1500 m^2/g
- Density: ~0.9 g/cm^3.



Kherani, Liu, Virk, Kosteski, Gaspari, Shmayda, Zuktoynski, Chen. *J Appl Phys*, ***103***, *(2008), 024906*

Defect Dynamics

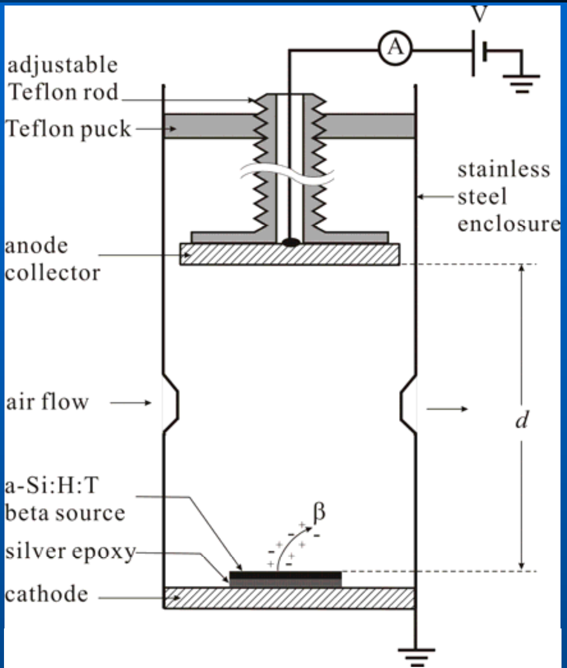
- Hydrogenated amorphous silicon solar cells
  - Staebler-Wronski effect
  - Formation of Si- dangling bonds upon light exposure
  - Drop in efficiency
- Tritiated amorphous silicon
  - Defined rate of tritium decay, hence formation of Si- dangling bonds
  - Can study samples under defined condtions (no light exposure)
- Dynamic defect model

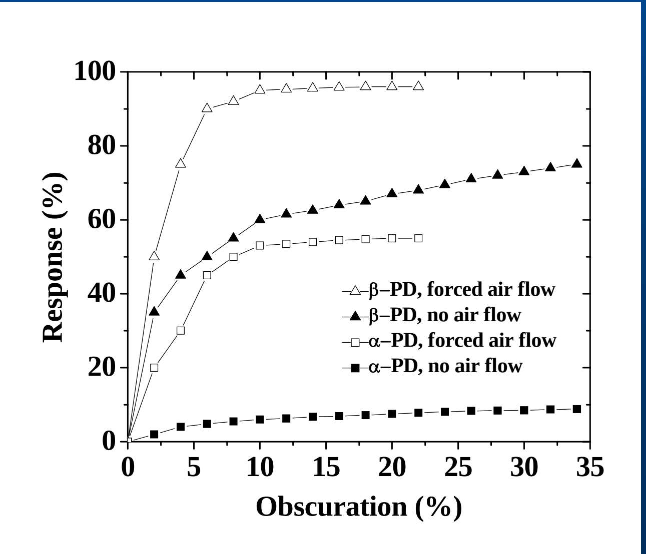


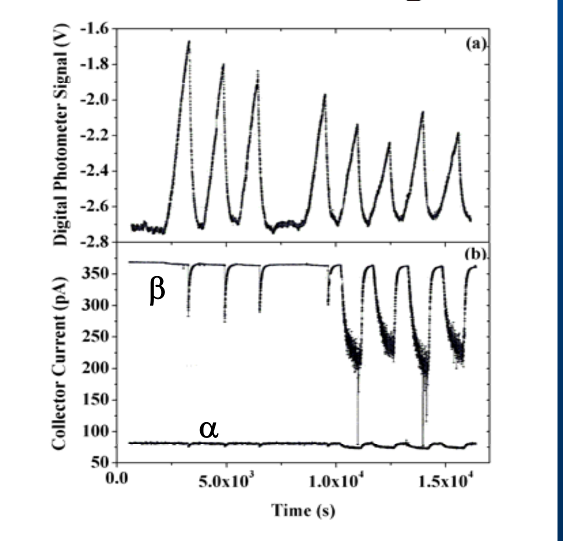
S. Pisana, S. Costea, T. Kosteski, W. T. Shmayda, N. P. Kherani, S. Zukotynski, J Appl Phys 98 093705 (Nov 2005) 1-5.; Stefan Costea, Nazir P. Kherani, Stefan Zukotynski, J Mat Sci, Vol. 18, Supp. 1, 175-182. (October 2007).

Beta Source Particle-Smoke Detector

- Tritium beta source instead of traditional alpha source
  - No gamma emission (as in Am-Be alpha source)
  - Provides bipolar and unipolar regions in the detector
  - Higher absolute current signal
  - Higher sensitivity
    - Several to forty fold more responsive than alpha based detectors
    - Functions like a dual detector (ionization and photoelectric detectors)
      - Smouldering fires
      - Open flame fires







Liu, Alvarez-Ossa, Kherani, Zukotynski, Chen, *IEEE Sensors J. 7 (2007) 917.*

Summary

- **Tritium a micro-power source**
  - **Radio-Isotope Micropower Sources (RIMS) is an active area of R&D**
  - **Renewed interest is motivated by continual miniaturization of electronic and electromechanical devices with concurrent reduction in power requirements**
  - **Tritium an amenable radioisotope given its properties and availability**

- **Tritium a powerful diagnostic for hydrogen-material studies**
  - **Ease of experimentation given hydrogen is pervasive**
  - **Unparalled sensitivity under "non-vacuum" conditions**
  - **Fundamental studies**

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