DIPARTIMENTO
DI FISICA E GEOLOGIA

Nanomateriali per Batterie Nucleari

Giornate di orientamento e proposte di tesi
Fisica della Materia – Dip. Di Fisica e Geologia
28/03/2025

Prof. Francesco Cottone – francesco.cottone@unipg.it

Sommario

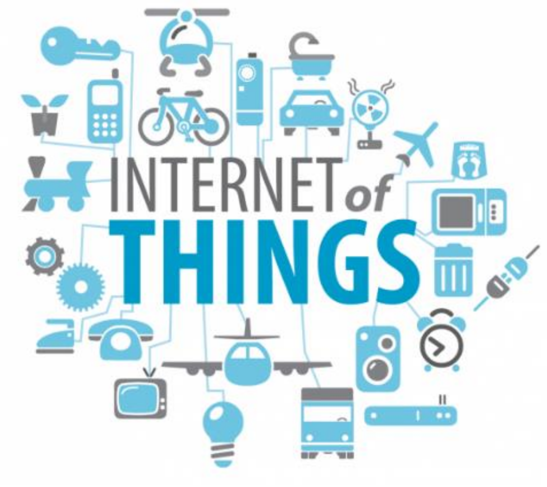
- Introduzione: micropowering, IoT e batterie nucleari nella storia
- Sviluppo di batterie nucleari alfa- e beta-voltaiche basate su nanomateriali nel nostro laboratorio
- Progetti in corso e collaborazioni internazionali
- Proposte di tesi

Micropowering, IoT e batterie nucleari

Infrastructures monitoring

Source: Wisepower s.r.l.

Internet of Things



Source: Google.

Medical/Healthcare/Body monitoring

Source: Google.

Aerospace

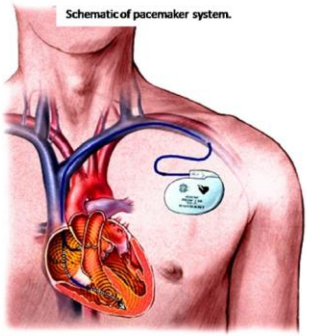
Source: google

Micro/nano robots

A. Freitas Jr., Nanomedicine, Landes Bioscience, 1999

Nanorobot **0.1 - 10uW**.

Pacemaker



D. Tran, Stanford Univ. 2007

200uW from heartbeat

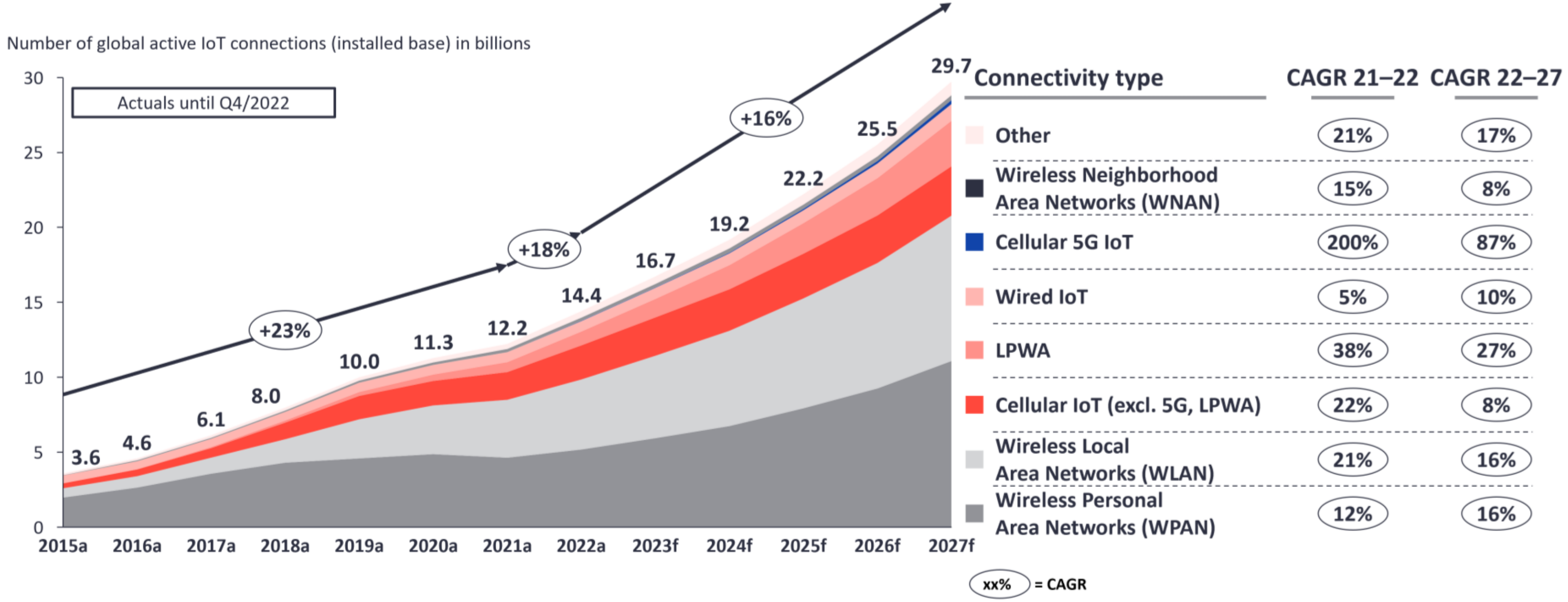
Micropowering, IoT e batterie nucleari

IOT ANALYTICS

May 2023

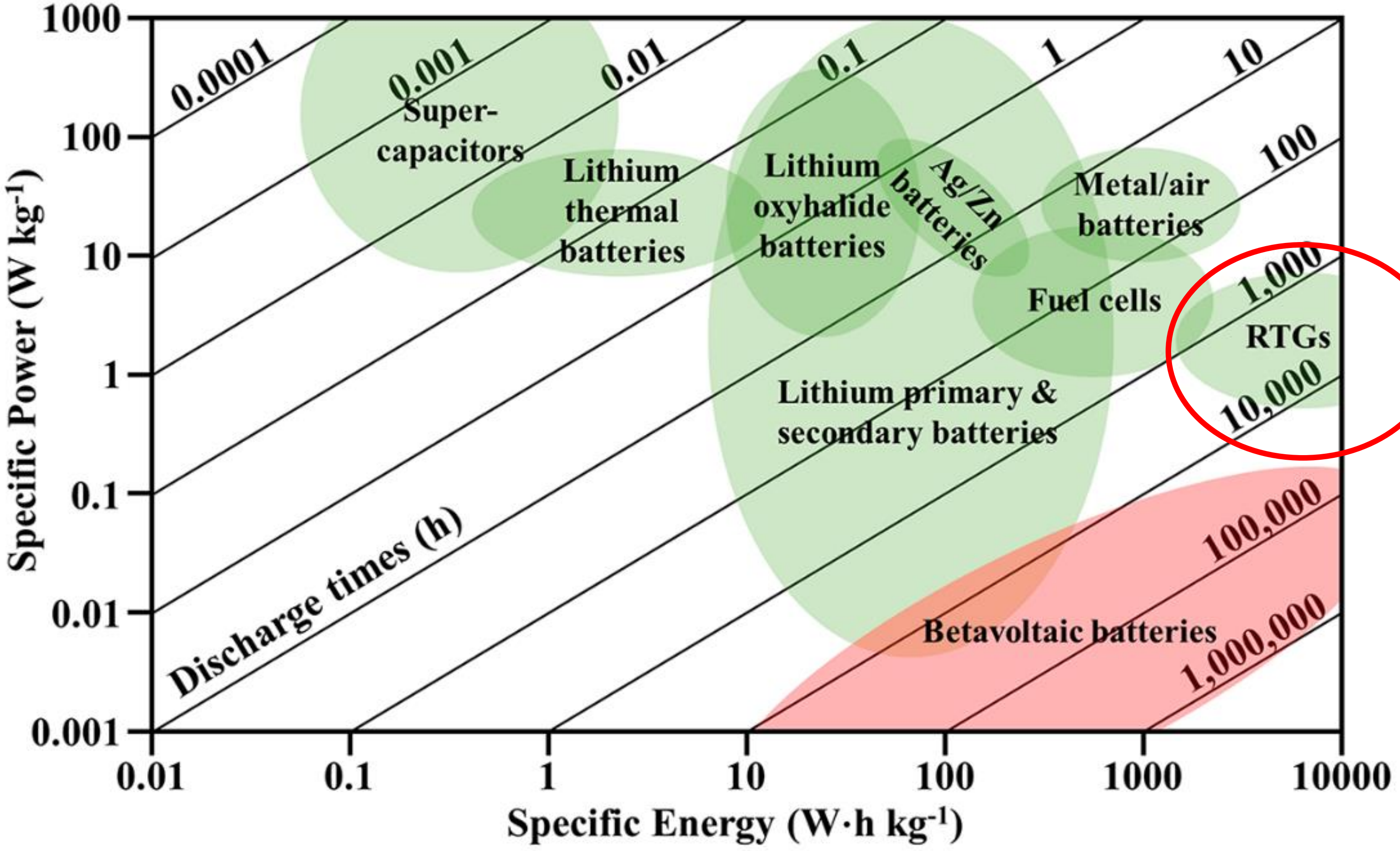
Your Global IoT Market Research Partne

Global IoT market forecast (in billions of connected IoT devices)



Note: IoT connections do not include any computers, laptops, fixed phones, cellphones, or consumers tablets. Counted are active nodes/devices or gateways that concentrate the end-sensors, not every sensor/actuator. Simple one-directional communications technology not considered (e.g., RFID, NFC). Wired includes ethernet and fieldbuses (e.g., connected industrial PLCs or I/O modules); Cellular includes 2G, 3G, 4G, 5G; LPWA includes unlicensed and licensed low-power networks; WPAN includes Bluetooth, Zigbee, Z-Wave or similar; WLAN includes Wi-Fi and related protocols; WNAN includes non-short-range mesh, such as Wi-SUN; Other includes satellite and unclassified proprietary networks with any range.
Source: IoT Analytics Research 2023. We welcome republishing of images but ask for source citation with a link to the original post and company website.

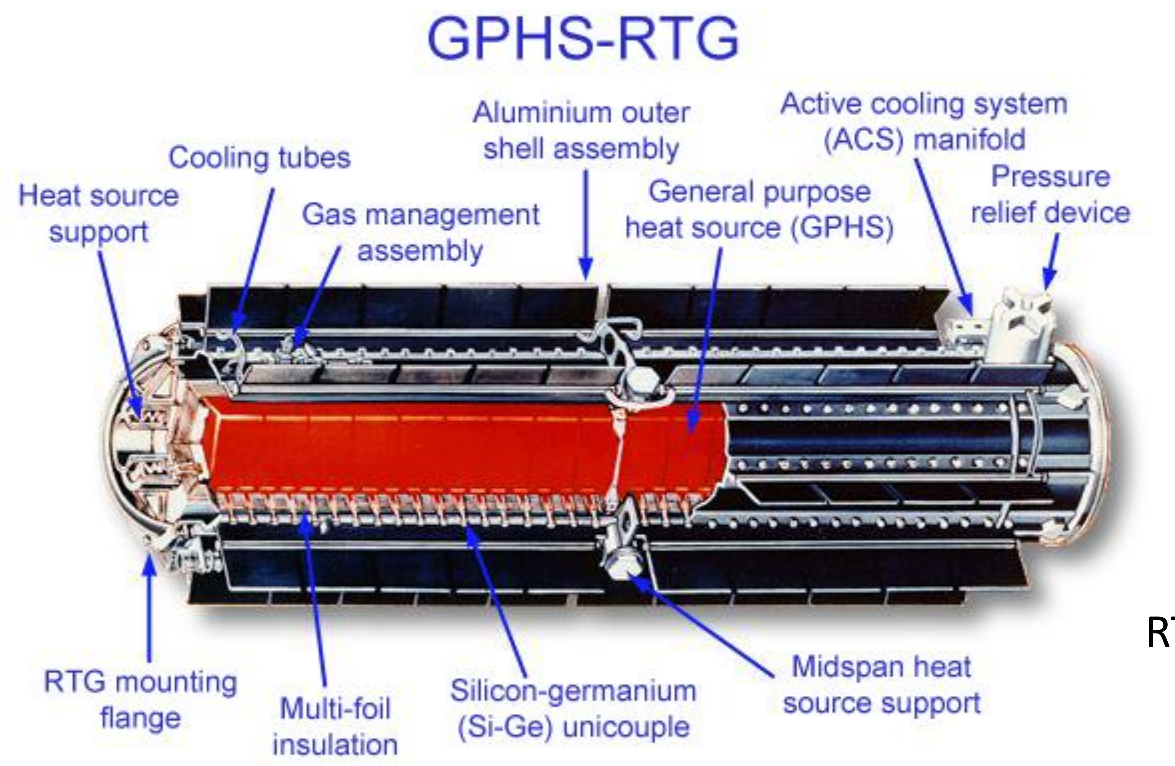
Micropowering, IoT e batterie nucleari



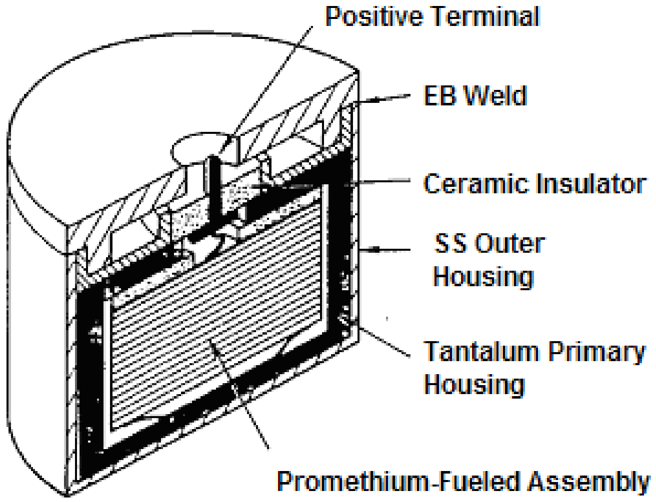
Efficiency from 0.2 to 15%

Ragone plot of the energy devices: electrochemical batteries, supercapacitors, radioisotope thermoelectric generators (RTGs), and betavoltaic batteries. – M. B. Naseem, 2023

Batterie nucleari nella storia



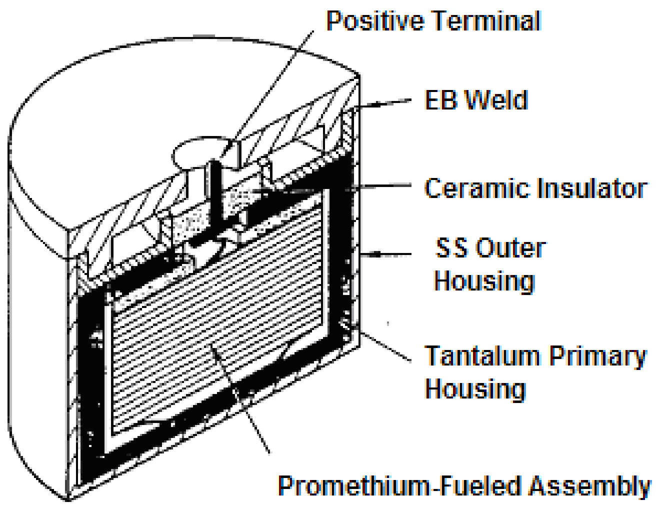
RTG

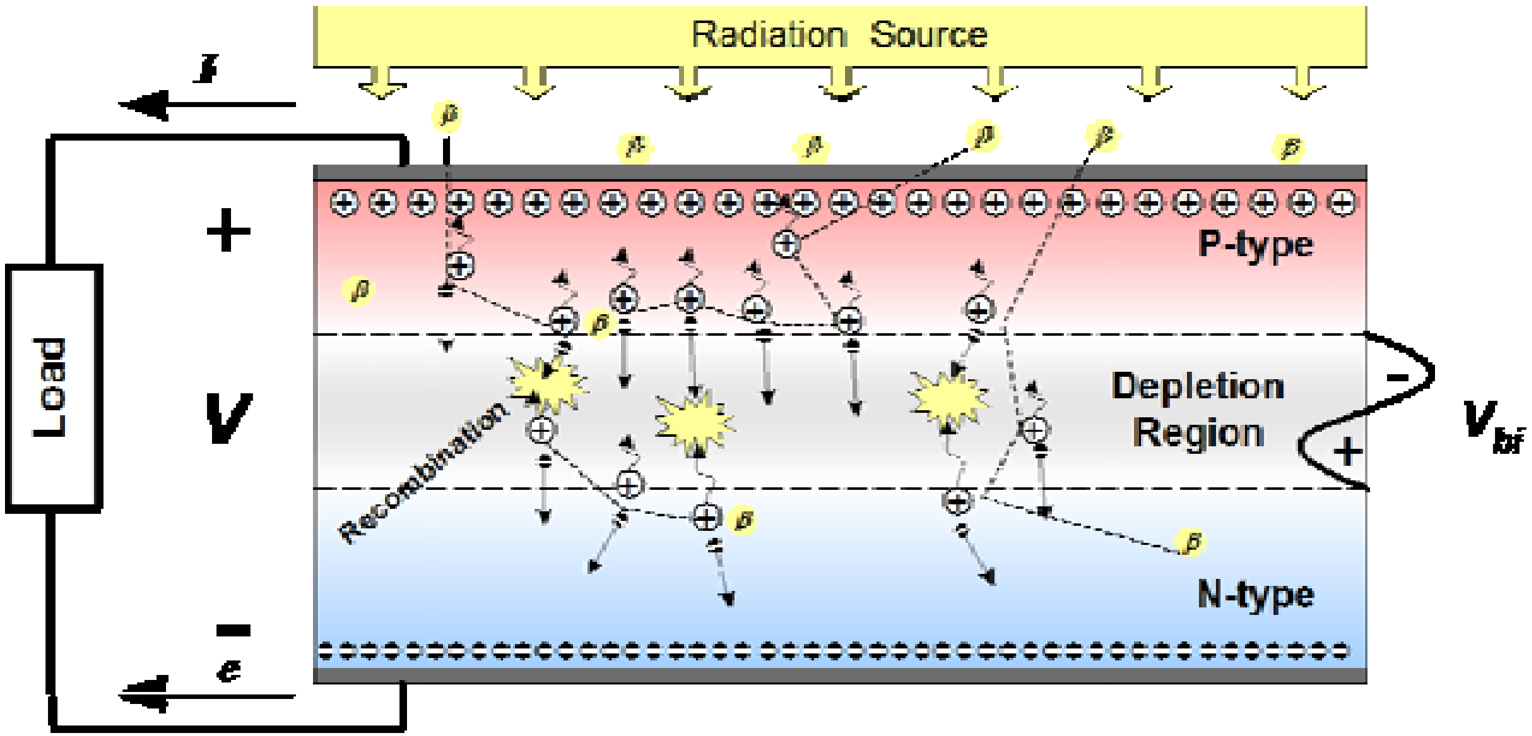


The first RTG launched into space by the United States was SNAP 3B in 1961 powered by 96 grams of plutonium-238 metal, aboard the Navy Transit 4A spacecraft

BETACEL – 1970 Pm-147

Batterie nucleari nella storia





BETACEL – 1970 Pm-147

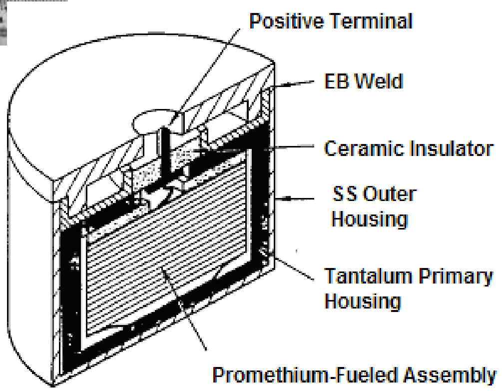
Batterie nucleari nella storia

- **1953**: Dr. **Paul Rappaport** – First to develop betavoltaics – Sr90-Y90 radioactive beta sources

- **1968-1974**: Dr. **Larry Olsen** – Betacel Model 400 – 400 µW, 4% efficient, 0.025 mW/cm3 – **Pm-147** source, 2.6 year half-life – No degradation – Successfully implanted pacemakers in over 285 patients, 60 in US.

- Lithium batteries eventually cornered the pacemaker market

- **Present**: some manufacturers – Dr. Peter Cabauy, City Labs – Dr. Chris Thomas, Widetronix , Betavolt



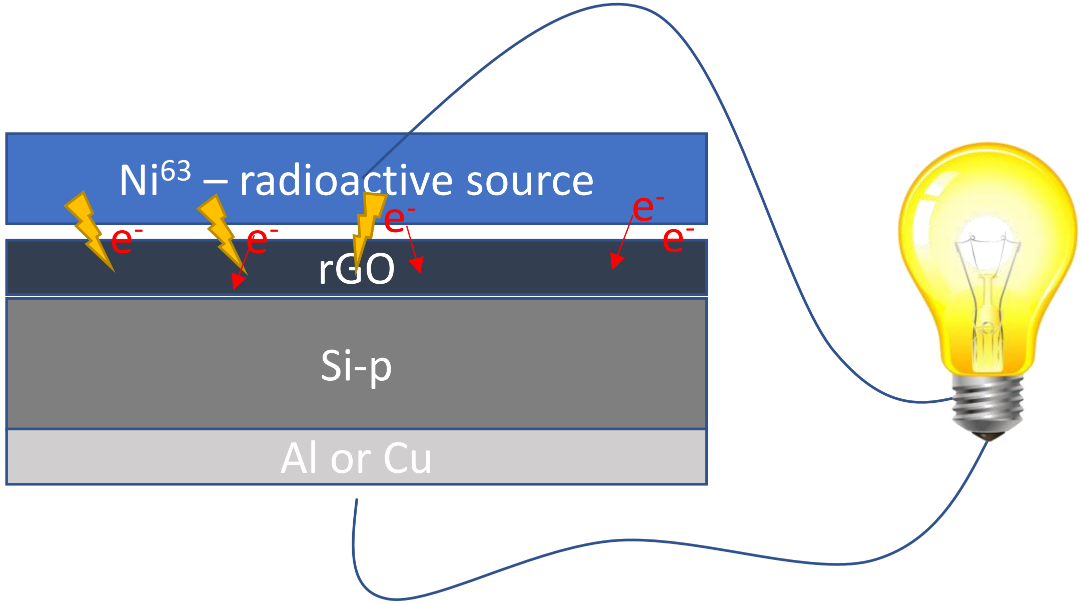
BETACEL – 1970 Pm-147

Batterie betavoltaiche – progetto Betasmart

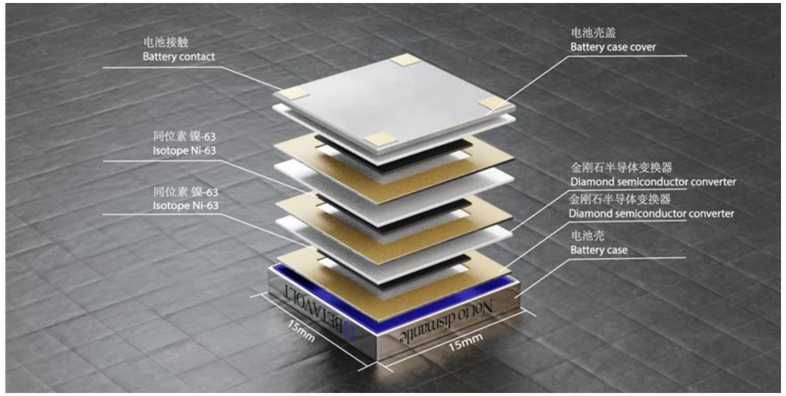
Project Collaboration with
- Prof. D. Mengoni INFN Padova
- Maddalena Pedio CNR Perugia
- Sara Dottorini (tesista)
- A. di Michele

Radioisotope	Maximum energy of β-particles (keV)	Half-life (years)	Maximum power density (W/g)	Availability
H-3	18.6	12.3	0.325	Medium
Ni-63	66.7	100.2	0.006	Low
Sr-90	545.9	28.8	0.164	High
Y-90	2,279.8	0.007	0.780	—
$^{90}Sr + ^{90}Y$	—	—	0.944	High

- **Radioactive source**
  - 3H (12.3 y half-time)
  - 63Ni (100.1 y half-time)
- **Semiconductor /semi-metal**
  - SiC, Si-p
  - Graphene/rGO



Ni decay, $_{28}^{63}Ni \rightarrow {}_{29}^{63}Cu + {}_{-1}^{0}\beta$



Betavolt-100 microwatts at 3V, 15x15x5 cubic millimeters

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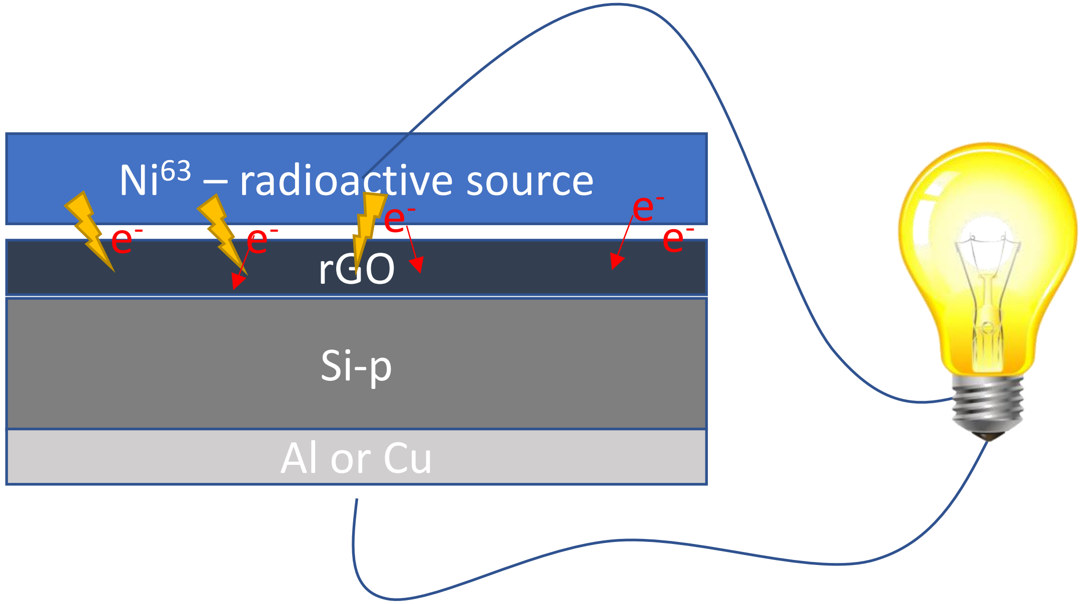

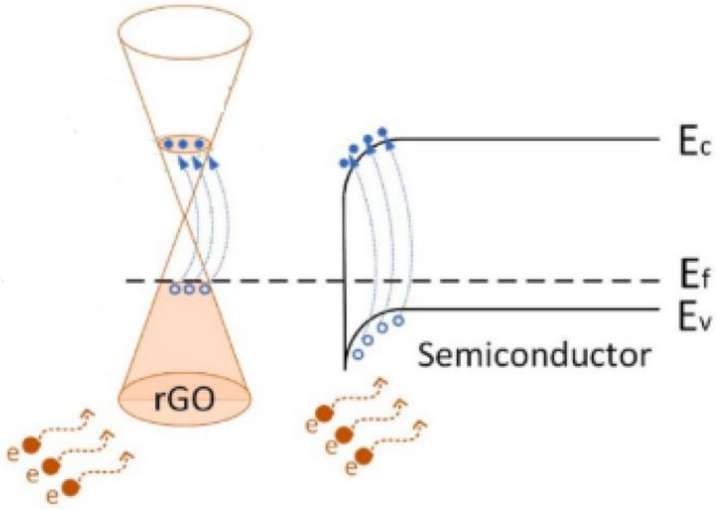

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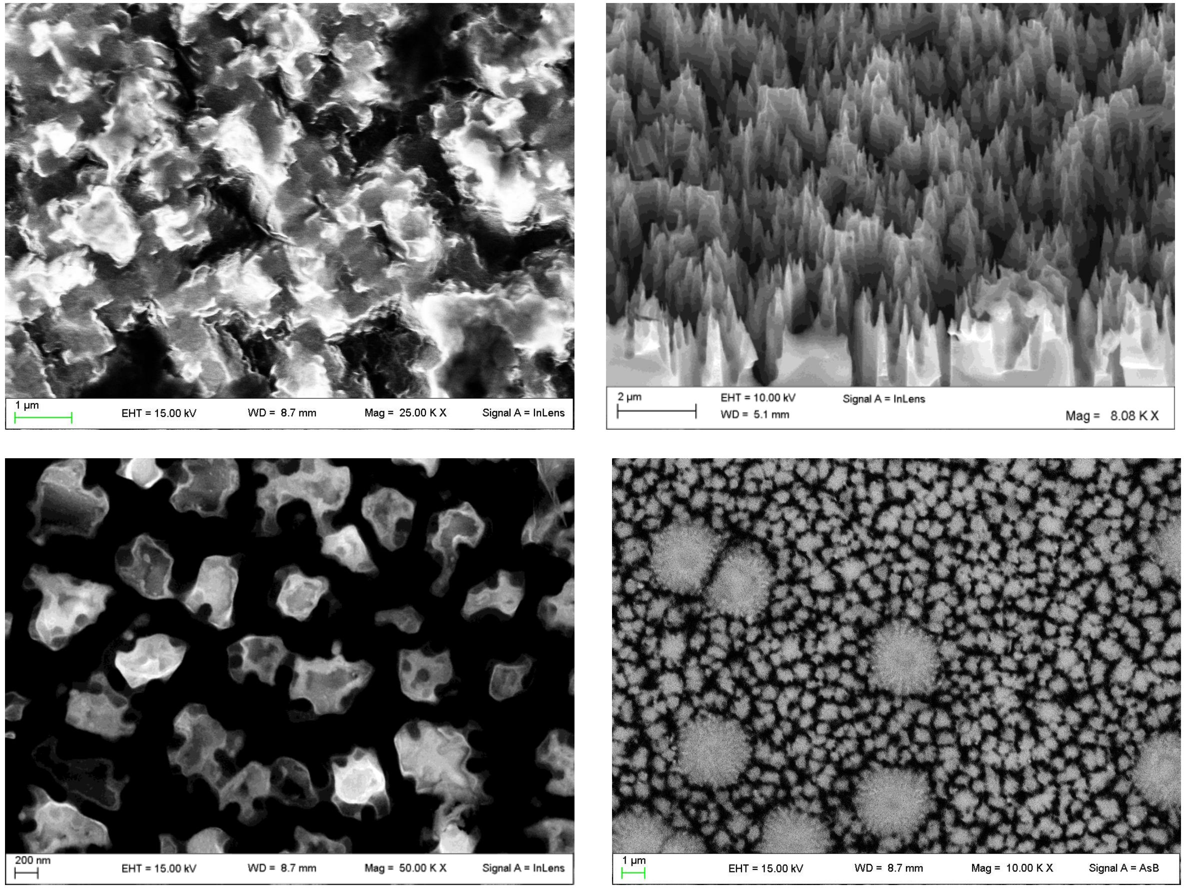
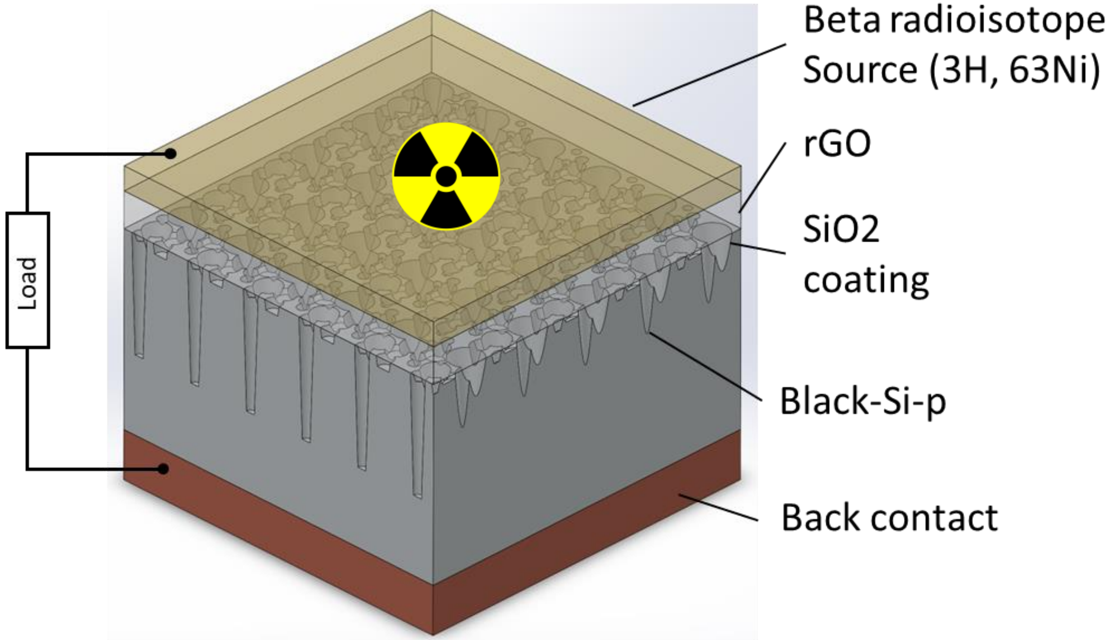
Prototipi realizzati e risultati preliminari

SEM image of Black Silicon samples



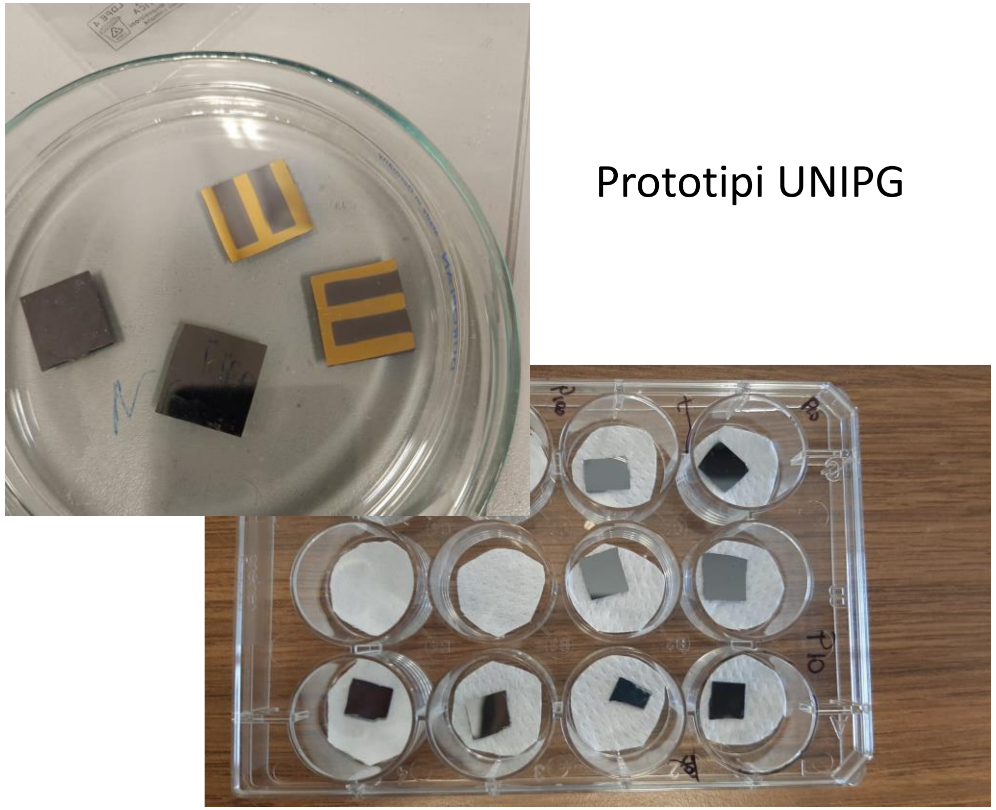
Ni, Graphene Oxide Deposition on Si-p, Black-Si



Structure of nuclear betavoltaic cell

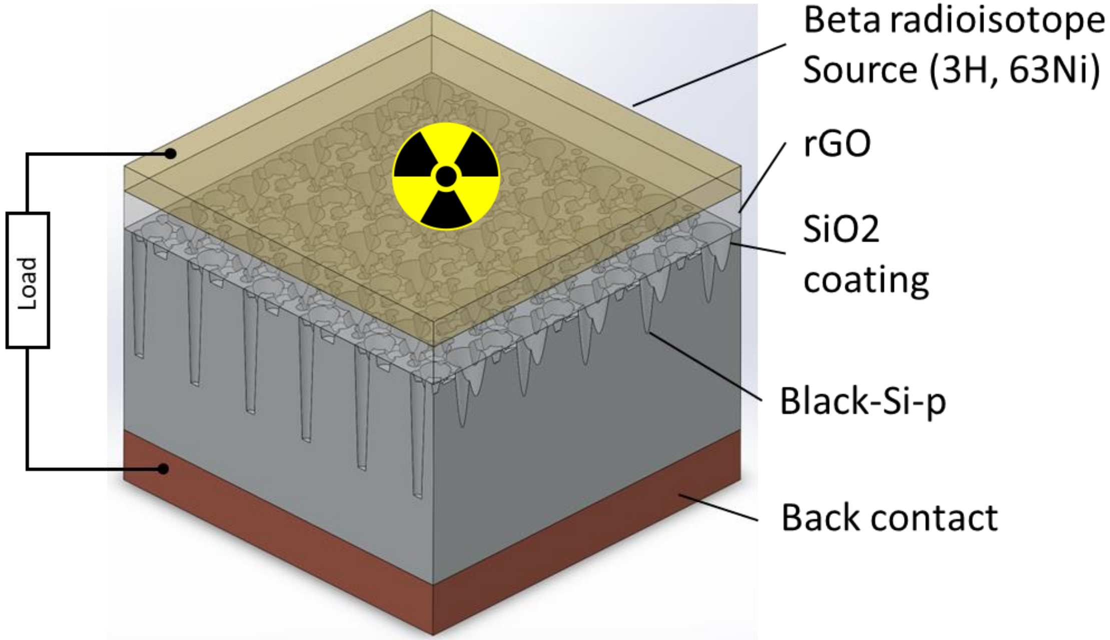
Dip. di Fisica e Geologia

Prototipi realizzati e risultati preliminari



Prototipi UNIPG

SEM image of Black Silicon samples



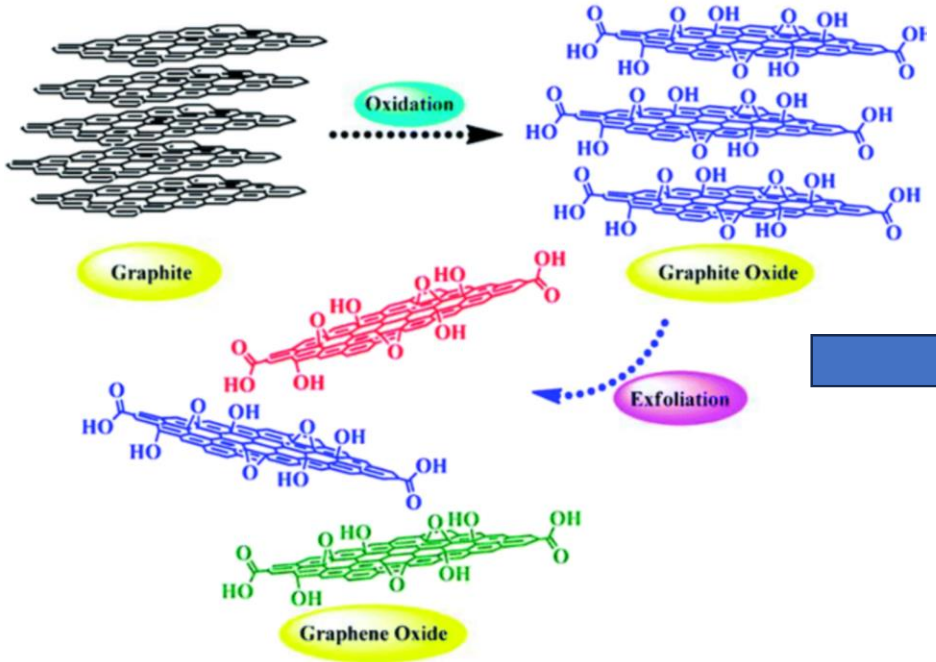
Structure of nuclear betavoltaic cell

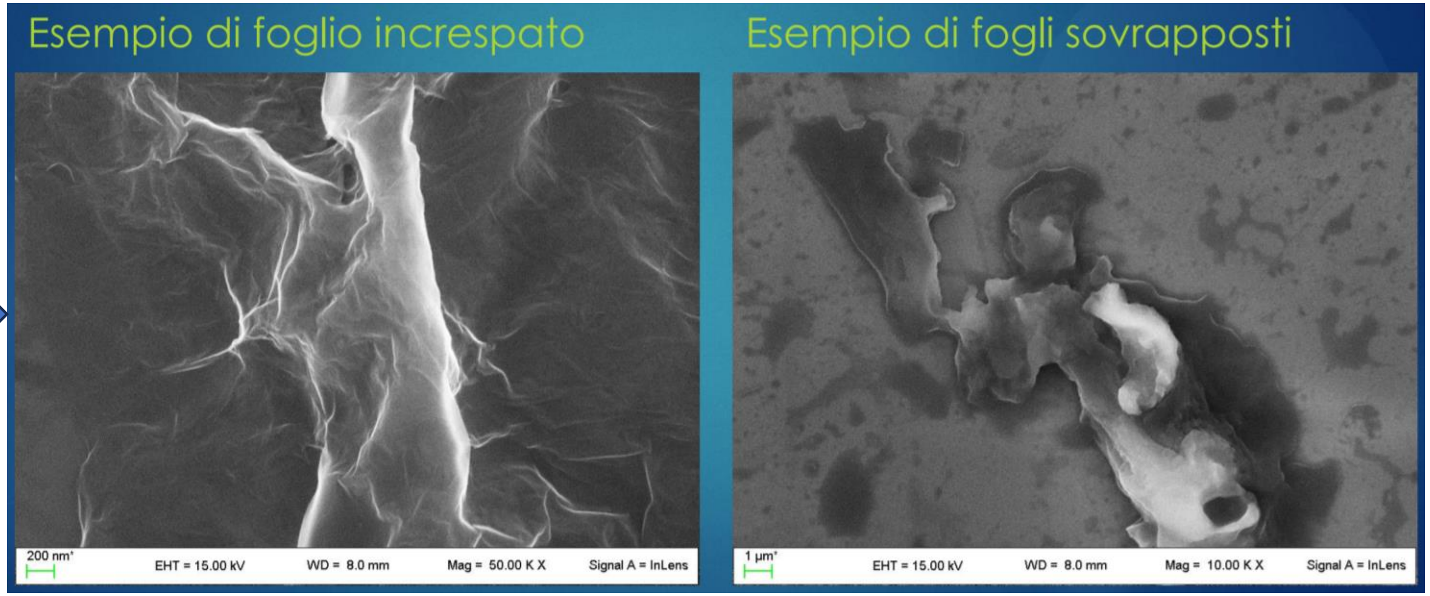
Ni, Graphene Oxide Deposition on Si-p, Black-Si

Dip. di Fisica e Geologia

Prototipi realizzati e risultati preliminari

SINTESI rGO in LABORATORIO





Marco Gaudenzi (2024). Tesi di Laurea triennale - Dip. di Fisica e Geologia

Prototipi realizzati e risultati preliminari

Ni, Graphene Oxide Deposition on Si-p, Black-Si

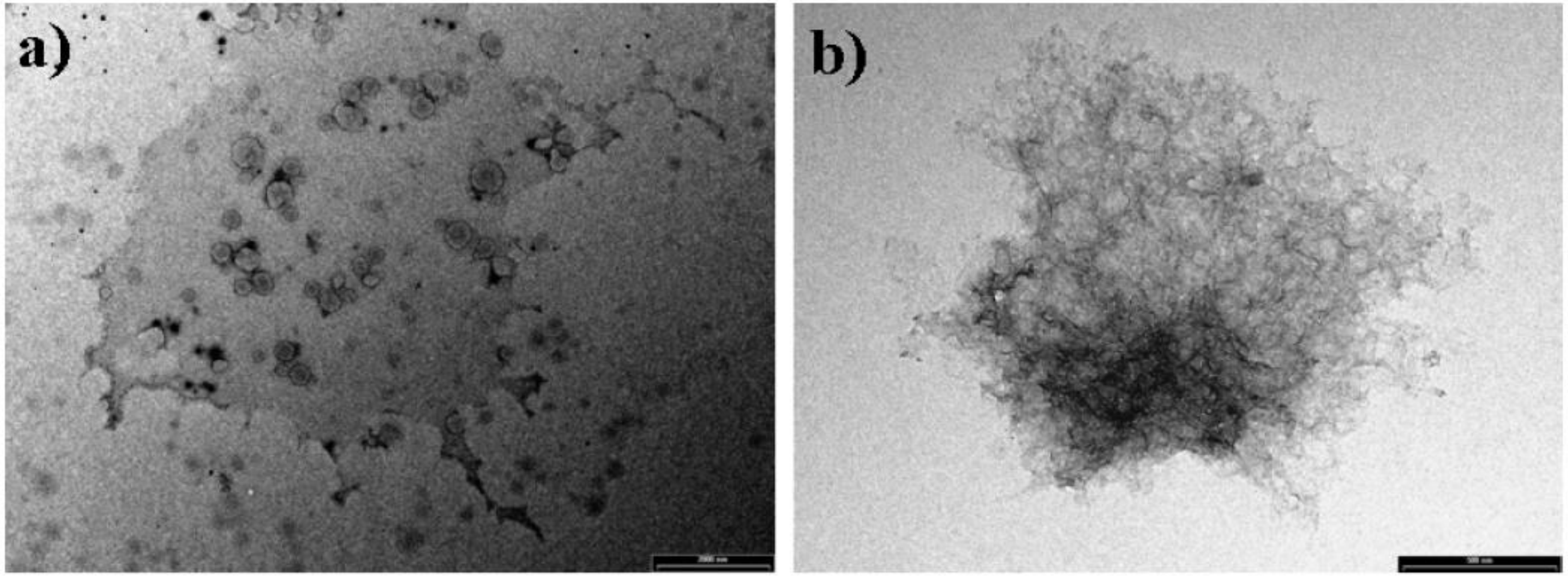
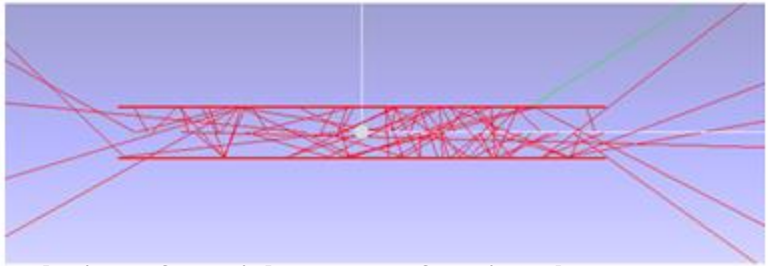


Figura 29: *Immagini TEM di GO/Si a) e rGO/Si b) (essiccati entrambi). In b) i fogli di rGO appaiono meno distesi.*

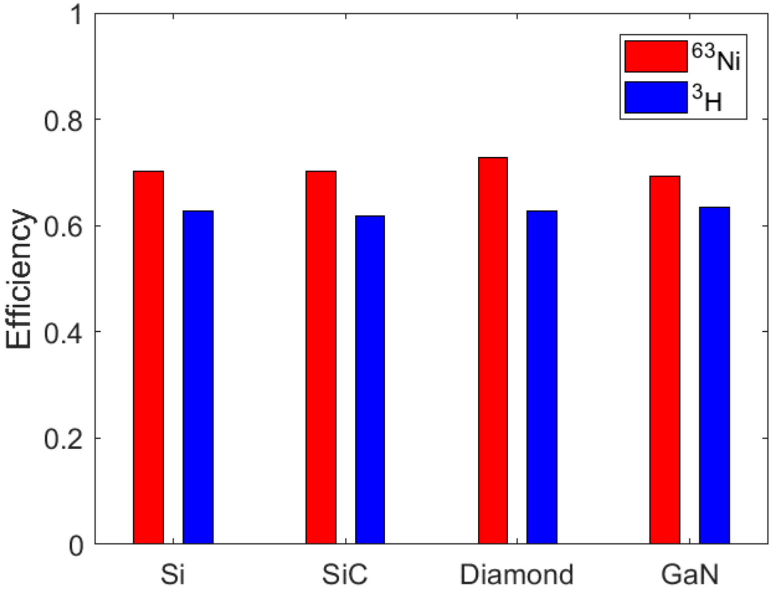
Sara Dottorini (2023). Tesi di Laurea Magistrale - Dip. di Fisica e Geologia

Generatori alfavoltaici - risultati preliminari

CONFIGURATIONS
Semiconductor
Materials
Thickness
Source
Monoenergetic electrons
Beta source
Geometry
Shape
Distance



Geant4 simulation of particles traces for Si-65 keV monoenergetic electrons betavoltaic nuclear battery in case of planar extended source

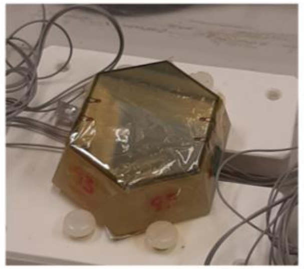


Semiconductor material and source

EXPERIMENTAL ESTIMATION OF CONVERSION EFFICIENCY WITH ALPHA SOURCE

Conversion efficiency with alpha particles was calculated by using a Silicon detector and a Source Meter

Keithley Source Meter

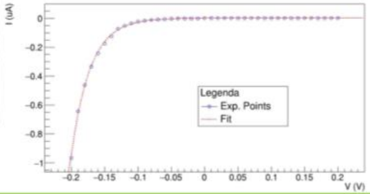


Silicon detector of 100 μm thick

The energy conversion efficiency is given by

$$\eta = \frac{P_{max}}{AqE_{avg}}$$

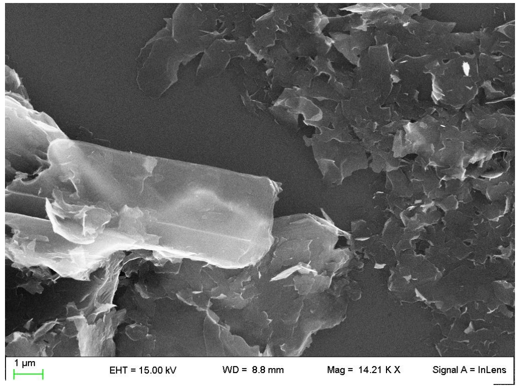
Where:
- P_{max} is the maximum output power and is estimated from I-V curves
- A is the source activity
- q is the electron charge
- E_{avg} is the average energy of the alpha particles caused by ^{241}Am decay, namely 5.486 MeV

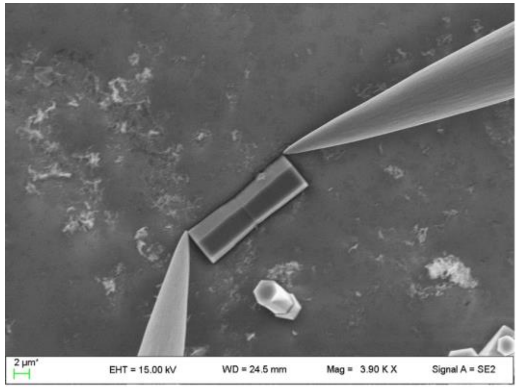


The calculated energy conversion efficiency η is 0.02%

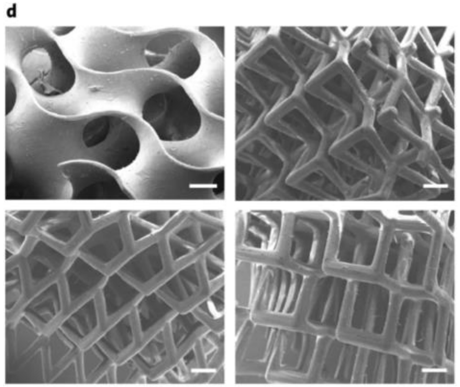
Micro generatori stampati in 3D

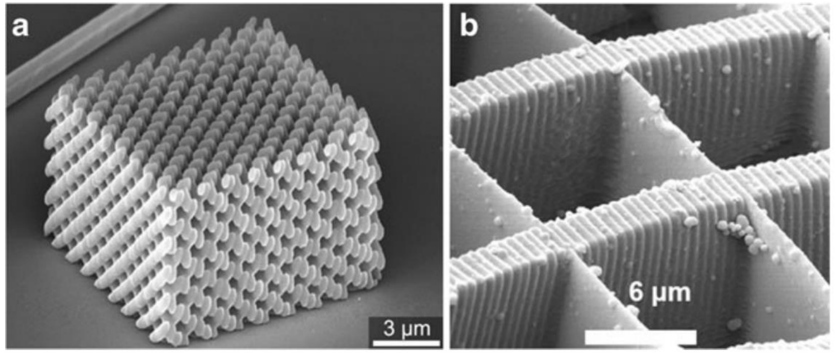
- Materiali **3D printed micro/nano strutturati** per batterie nucleari, nano-strutture custom con stampa 3D nano

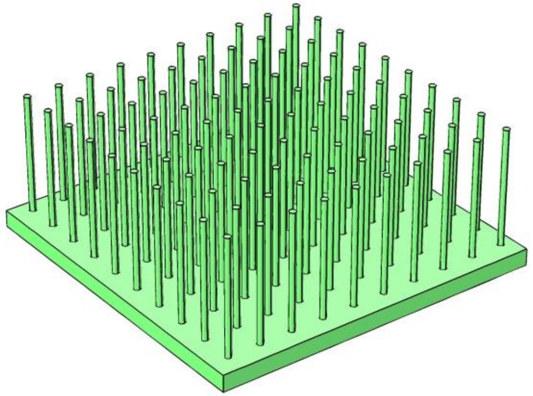




- SiC/rGO/G
- Si-pn/rGO
- Diamante
- GaN

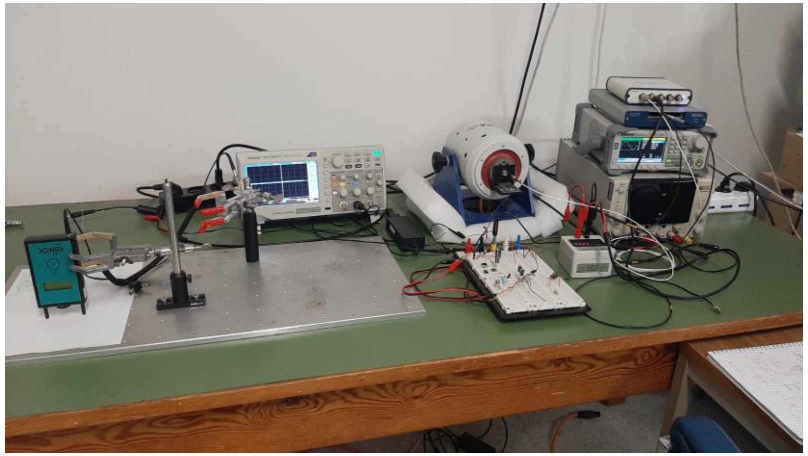


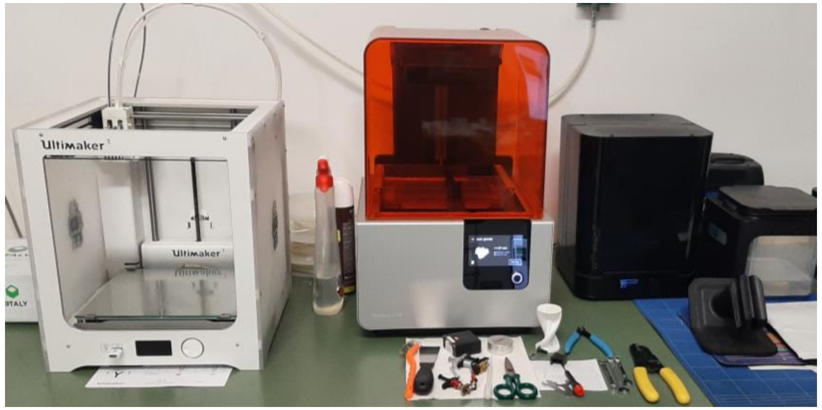


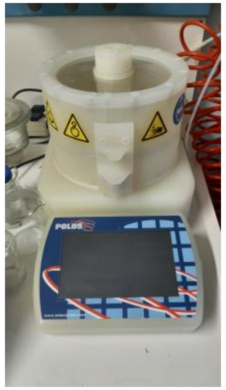


3D printed micro/nano structures (auxetic materials, photonic crystals, metamaterials)

Laboratori – MINE, NANOFAB e NIPS







A. Di Michele

Laboratory of MIcro and Nanotechnology for Energy – (MINE-LAB)

Dip. Fisica e Geologia - IV piano – edificio di Fisica.

Progetti in corso e collaborazioni

- **VITALTY** – Nanostructured and advanced materials and devices for energy harvesting
- **BETASMART** –Prof. Cottone (UNIPG, INFN), Prof. Mengoni (UNIPD, INFN)
- **NANOFAB** – Progetto Ateneo – Facility per micro e nano fabbricazione di NEMS/MEMS

COLLABORAZIONI CON AZIENDE LOCALI

COLLABORAZIONI INTERNAZIONALI

Tyndall National Institute (IRL)
Role: Access Provider (EH-Vibrational, EH-Thermoelectric, ES, MPM, SI)

CEA-Leti (F)
Role: Access Provider (ES)

CEA-Liten (F)
Role: Access Provider (EH-Thermoelectric)

Fraunhofer – Institute for Integrated Circuits (D)
Role: Access Provider (EH-Vibrational & Thermoelectric, MPM, SI)

Fraunhofer – Institute for Microelectronic Circuits and Systems (D)
Role: Access Provider (EH-Solar, EH-RF)

imec Nederland (NL)
Role: Access Provider (EH-RF, MPM, SI)

Karlsruher Institut für Technologie (D)
Role: Knowledge Hub (ES)

Politecnico di Torino (I)
Role: Knowledge Hub (ES)

Università di Bologna (I)
Role: Knowledge Hub (MPM)

NiPS Laboratory, Università degli Studi di Perugia (I)
Role: Knowledge Hub (EH-Vibrational)

University of Southampton (UK)
Role: Knowledge Hub (EH-Vibrational)

Proposte di TESI

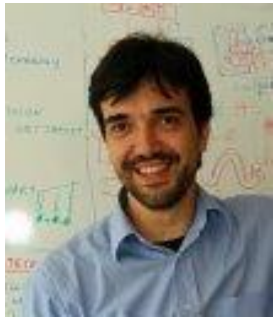
- **Betavoltaiche basate su Si/rGO → Le ricerche attuali** si concentrano sul miglioramento del processo di accoppiamento dell'rGO con i materiali radioattivi per incrementare ulteriormente l'efficienza di conversione attraverso:
  - DESIGN
  - SCELTA DEI MATERIALI: SEMICONDUTTORI NANOSTRUTTURATI (SiC, Si, rGO etc..)
  - SIMULAZIONI
  - FABBRICAZIONE
  - STUDIO SPERIMETALE

- **INFN Padova: parte della** tesi sperimentale presso INFN di Padova con varie sorgenti α e β

Gruppo di ricerca

Prof. Francesco Cottone
francesco.cottone@unipg.it

Prof. Daniele Mengoni
UNIPD- INFN Padova



Prof. Maurizio
Mattarelli

Dr. Alessandro Di Michele

Dr.ssa Maddalena Pedio CNR-IOM PG

Dr. Igor Neri

Dr. Giacomo Clementi

Prof. Luca Gammaitoni

Batterie betavoltaiche – progetto Betasmart