

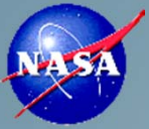
BIT's 3rd Annual World Congress of Advanced Materials-2014

Nano-Bio Quantum Technology for Device Specific Materials

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Chongqing, China



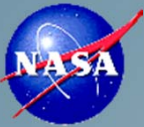
Areas to be Addressed

- **Hybrid Bandgap (HBG) Engineering**
 - SiGe Devices
 - SiGe Solar Cell

- **Thermoelectric Materials**
 - High Temperature
 - Mid Temperature

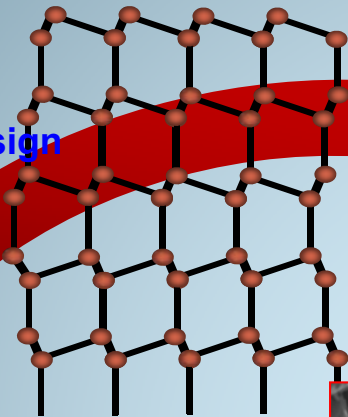
- **Smart Optical Materials**
 - Quantum Apertures
 - Micro Spectrometers
 - Light Control Ferroelectric Materials

- **Ferritin Molecules**
 - Biotemplates for Nanopartices
 - Bionanobattery

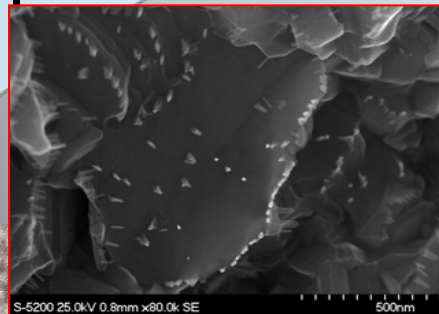


Advanced Thermoelectric Material Development

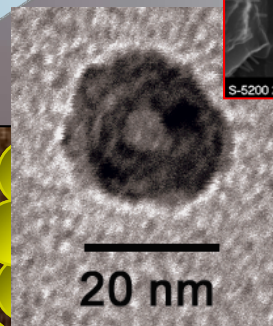
Twin Crystal with Stacking Defect:
Better Material Design
than Superlattice



SiGe



Material Prepared



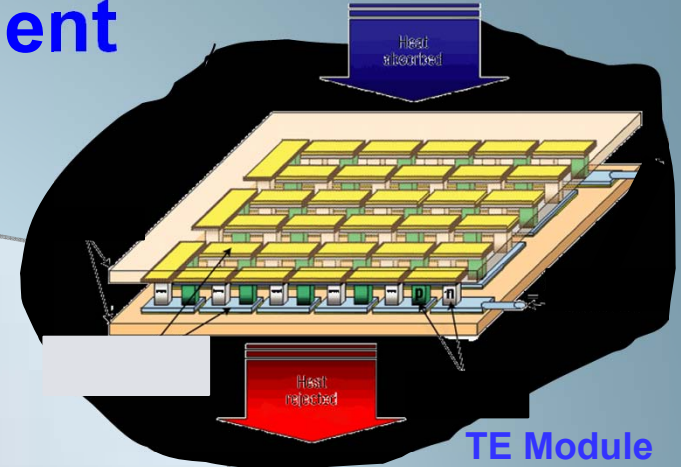
Home-grown
Voigen

High
Performance
Semiconductor



$\text{Si}_{1-y}\text{Ge}_y$
Lattice-matched
condition

Produced @ NASA LaRC

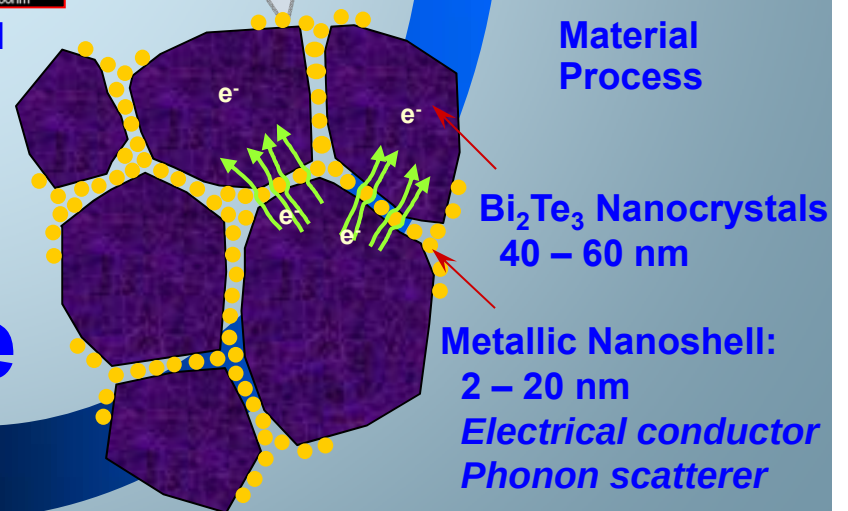


TE Module

Initial
Concept

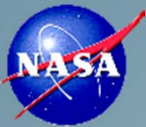
Hot Press /
Low Pressure
Material
Process

BiTe

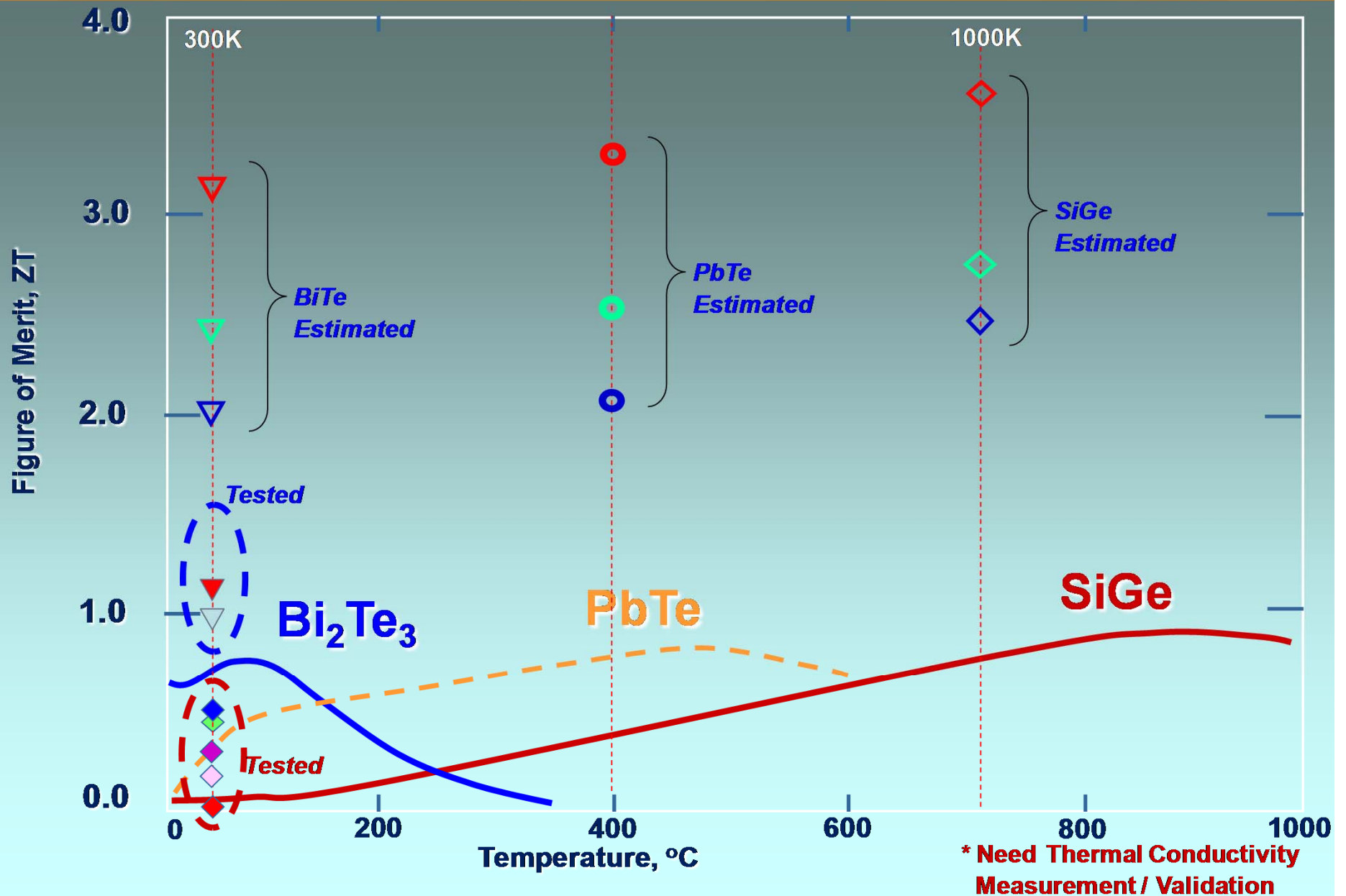


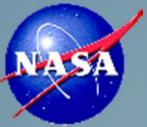
Bi_2Te_3 Nanocrystals
40 – 60 nm

Metallic Nanoshell:
2 – 20 nm
Electrical conductor
Phonon scatterer

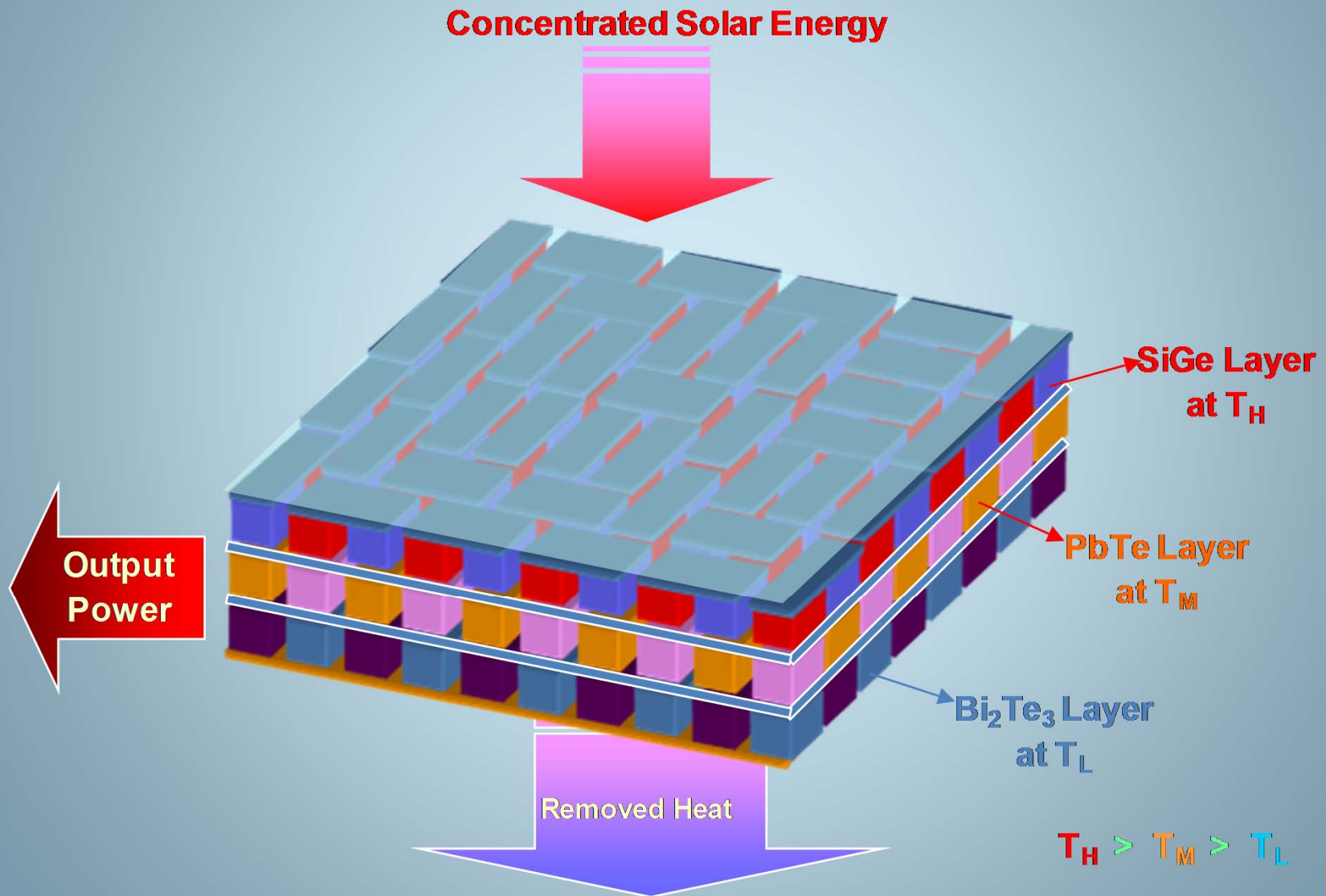


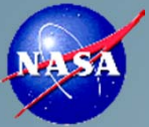
TE Performance Test Results



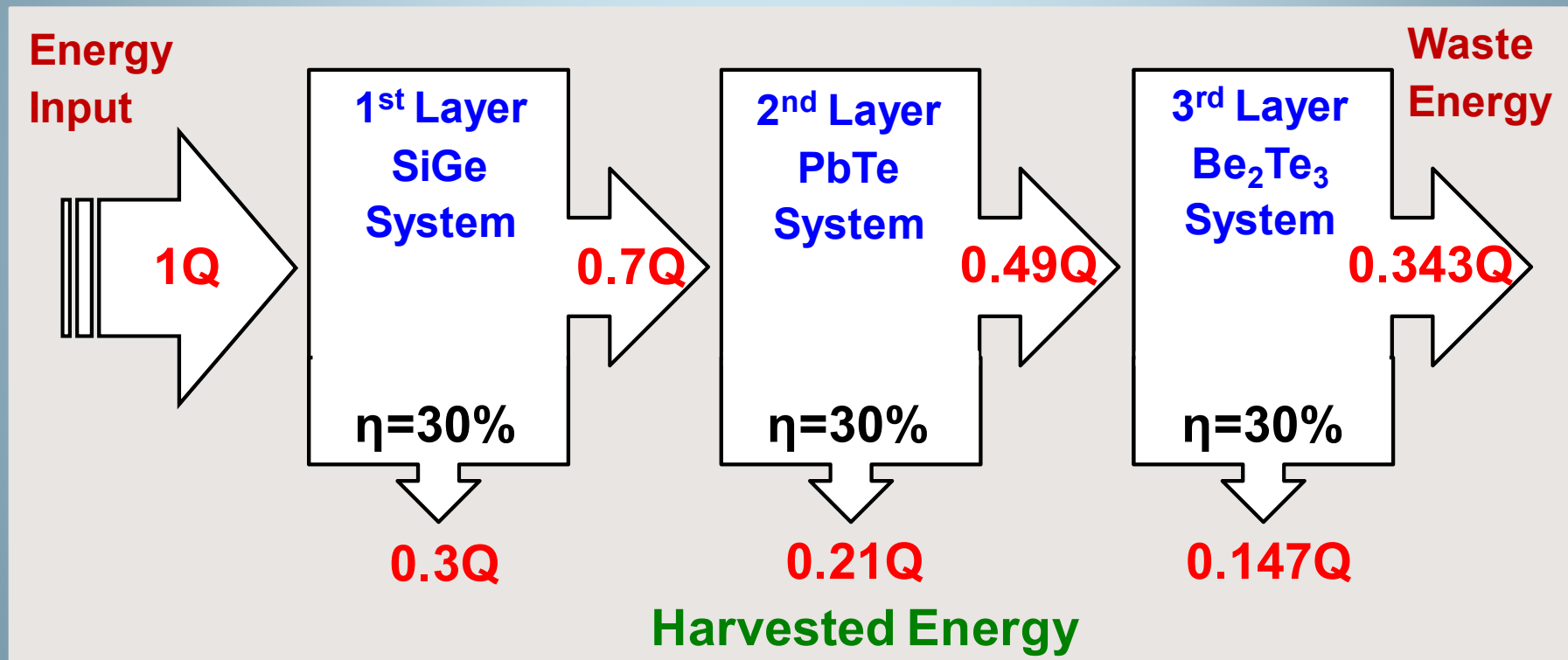


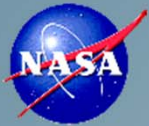
Tandem Mode of TE Generator





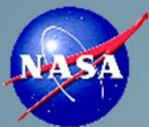
Regenerative Cycle of TE Generator





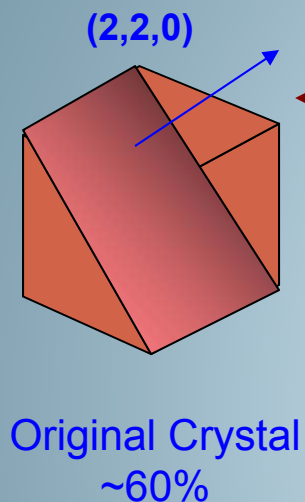
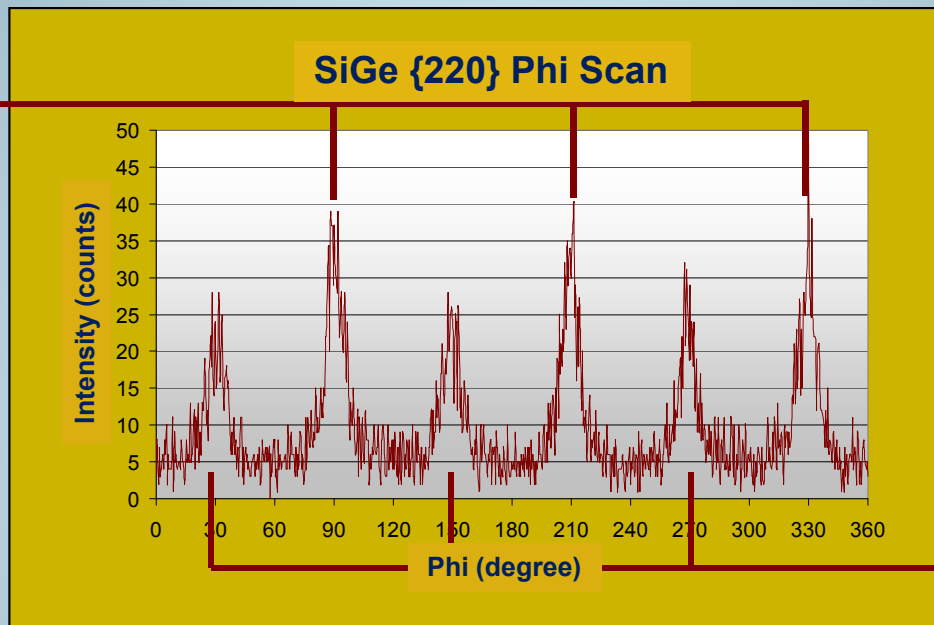
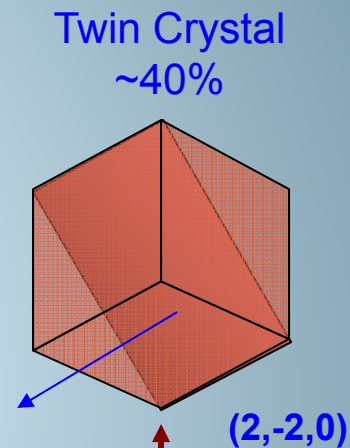
Cascade Efficiency of Tendem TE Generator

	TE FoM ≥ 1.5 $\eta = 10\%$		TE FoM ≥ 3.5 $\eta = 20\%$		TE FoM ≥ 4.5 $\eta = 30\%$		Solar Cells
TE Tandem System	Loaded Energy, Q	η	Loaded Energy, Q	η	Loaded Energy, Q	η	η
1 st Layer (Hi T)	1Q in	10 %	1Q in	20 %	1Q in	30 %	30 % (?) for membrane PV
	0.9Q out		0.8Q out		0.7Q out		
2 nd Layer (Med T)	0.9 in	10 %	0.8 in	20 %	0.7 in	30 %	
	0.81Q out		0.64Q out		0.49Q out		
3 rd Layer (Low T)	0.81Q in	10 %	0.64Q in	20 %	0.49Q in	30 %	
	0.729Q out		0.512Q out		0.343Q out		
Cascade Efficiency	0.271Q Harvested	27 %	0.488Q Harvested	48 %	0.657Q Harvested	65 %	

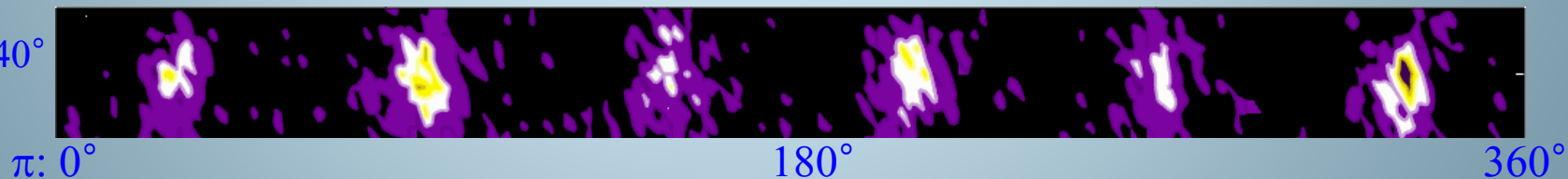


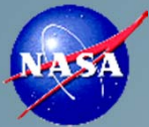
Si-Ge: Twin-Lattice Structure

Symmetry Breaking to 60:40

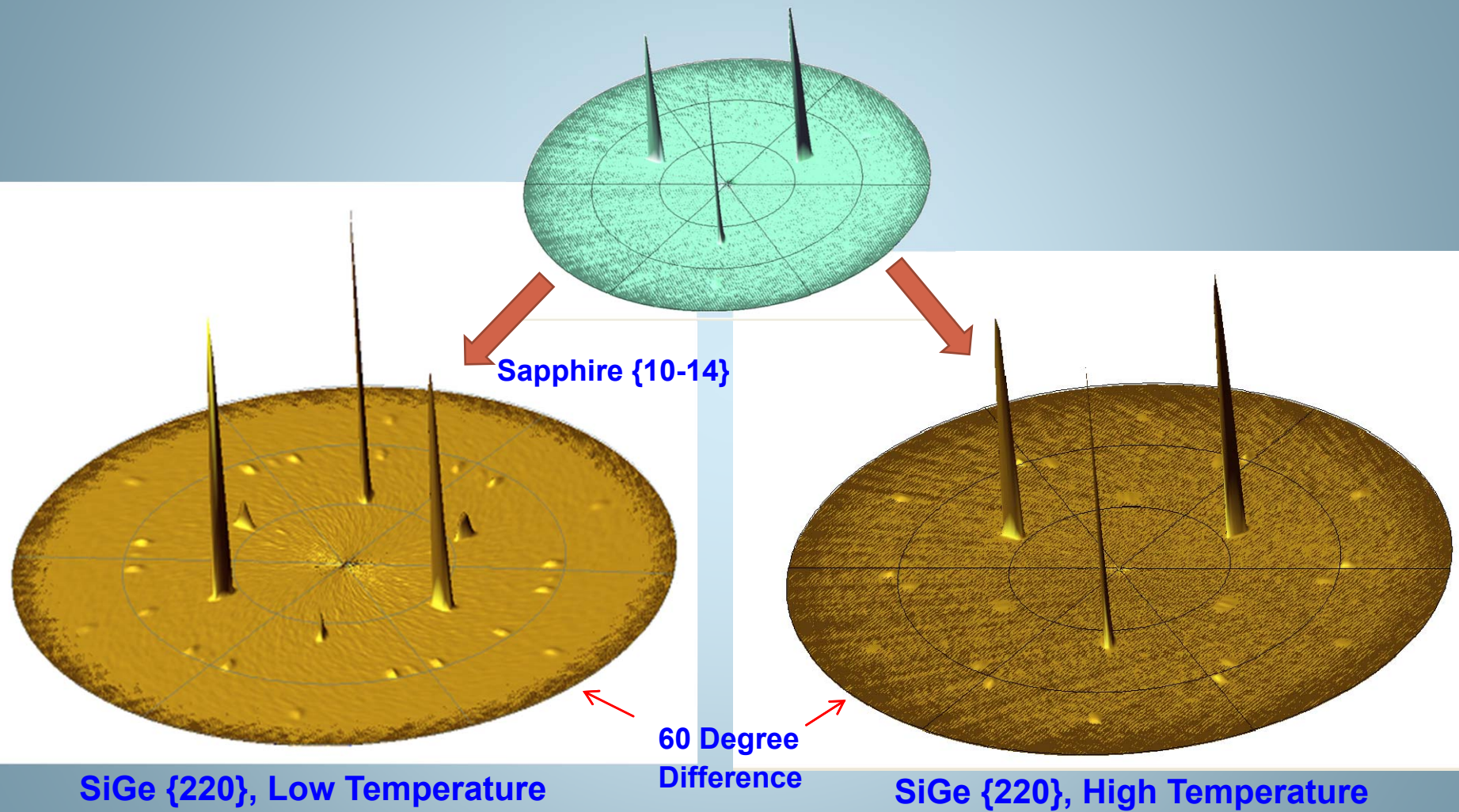


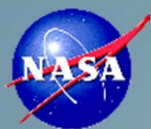
$\Psi: 32 \sim 40^\circ$





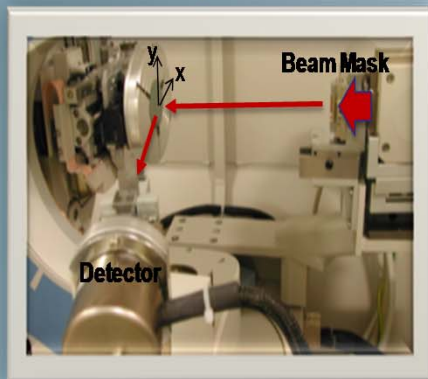
Two Single Crystalline Alignments



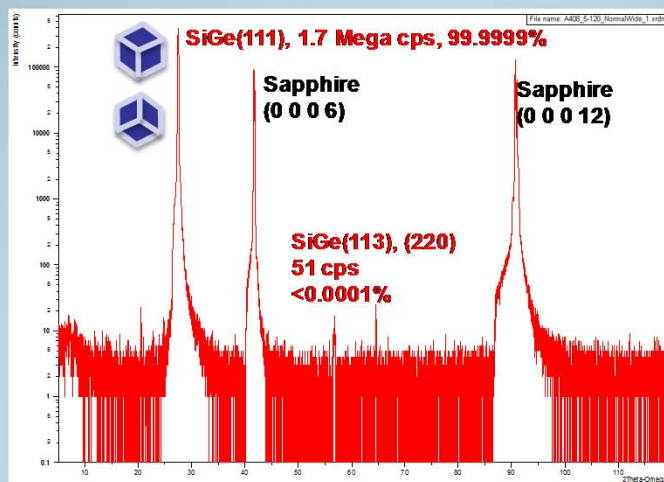


Wafer Mapping: 99.9999% Single Crystal

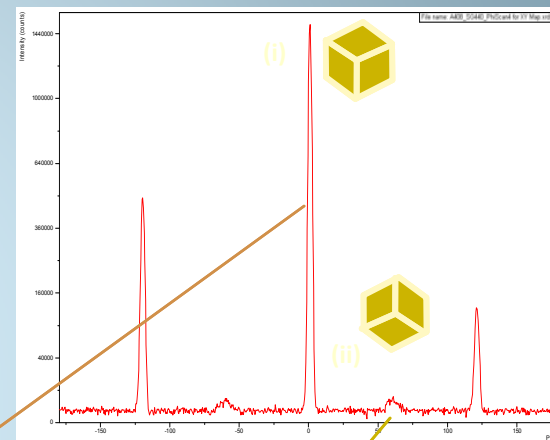
Asymmetric angles for XY mapping
with Point X-ray source



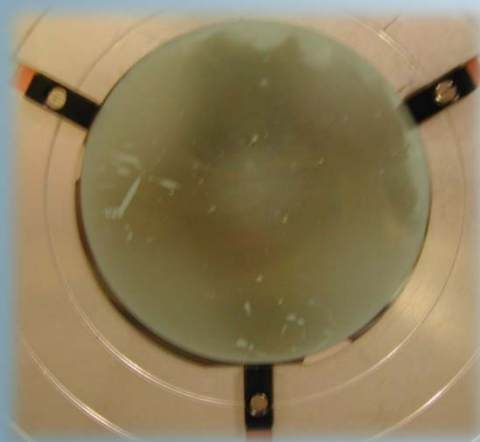
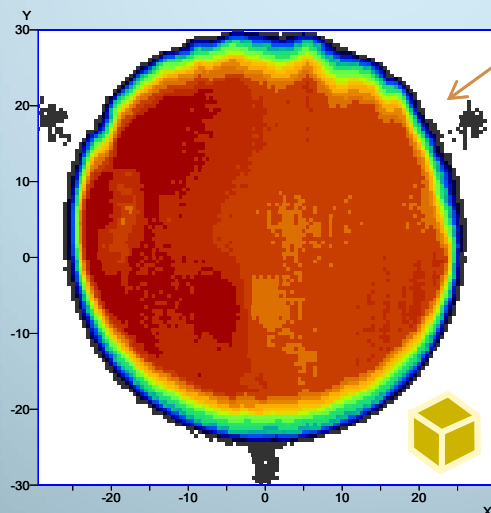
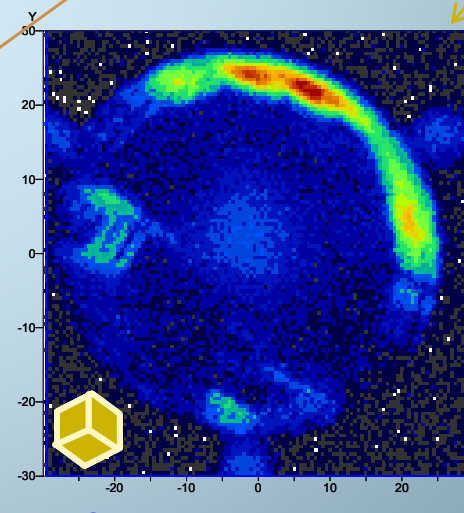
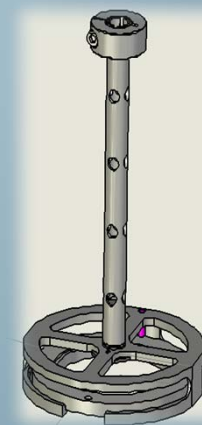
2Theta-Omega Normal Scan



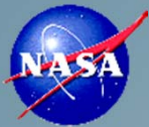
SiGe(440) Untilted Asymmetric Phi-Scan



Wafer Mapping



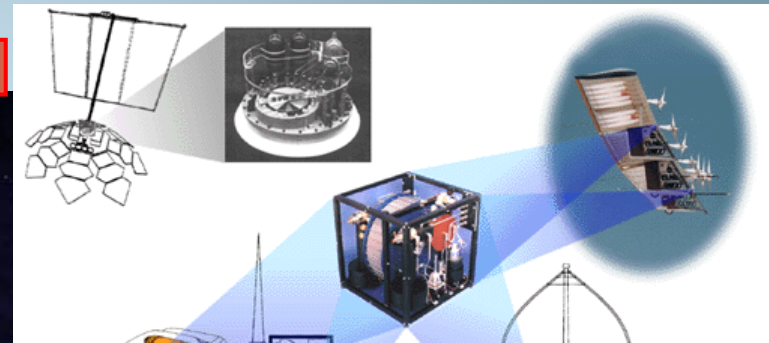
Sample Holder
Created Thermal
Shadow



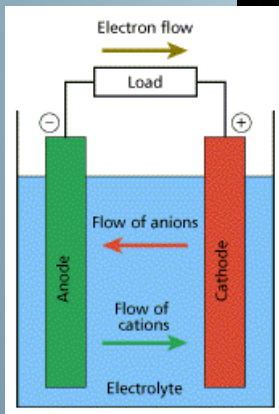
Power Sources for Spacecrafts



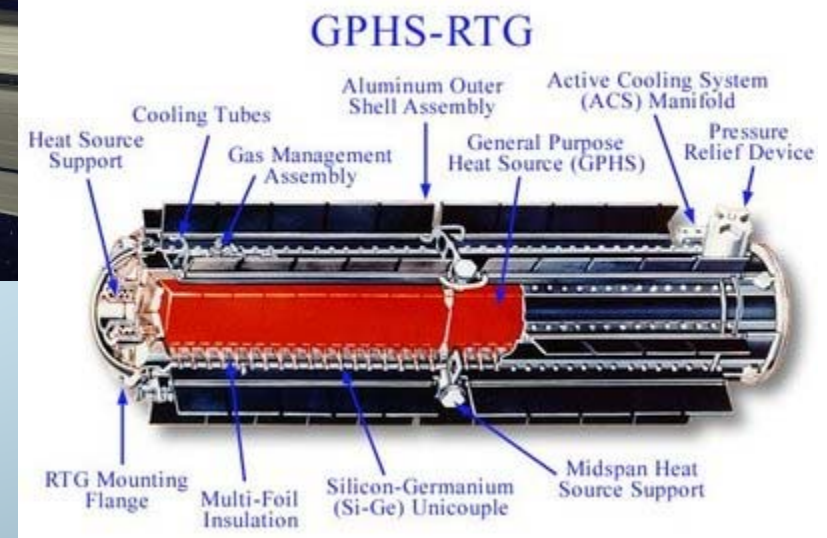
Fly-wheel Power Storage



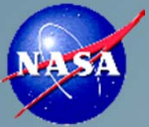
Fuel Cells



Canister-based Battery



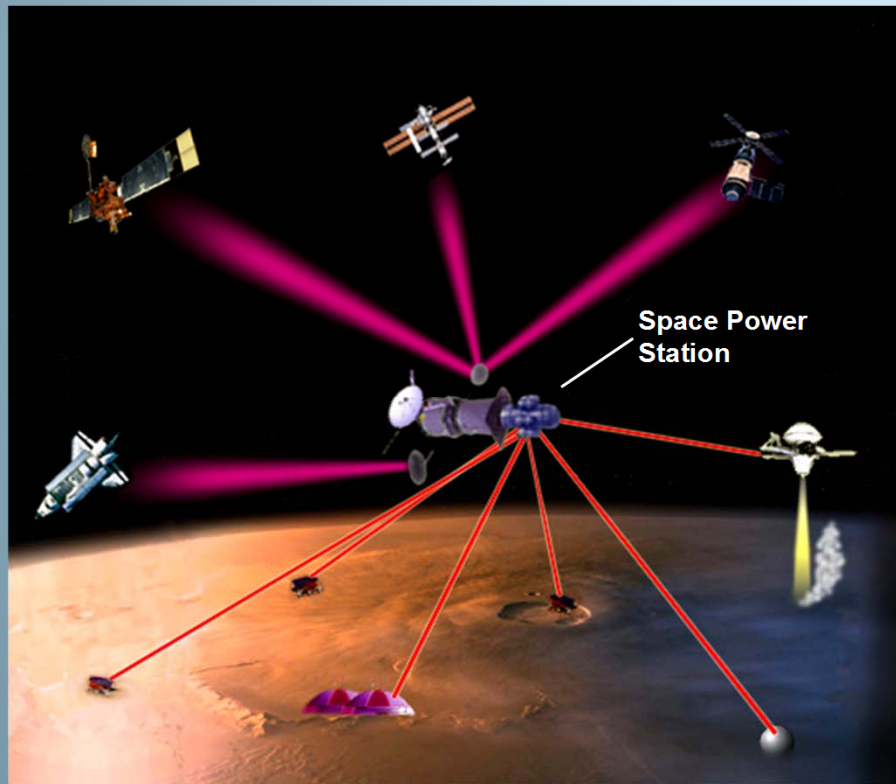
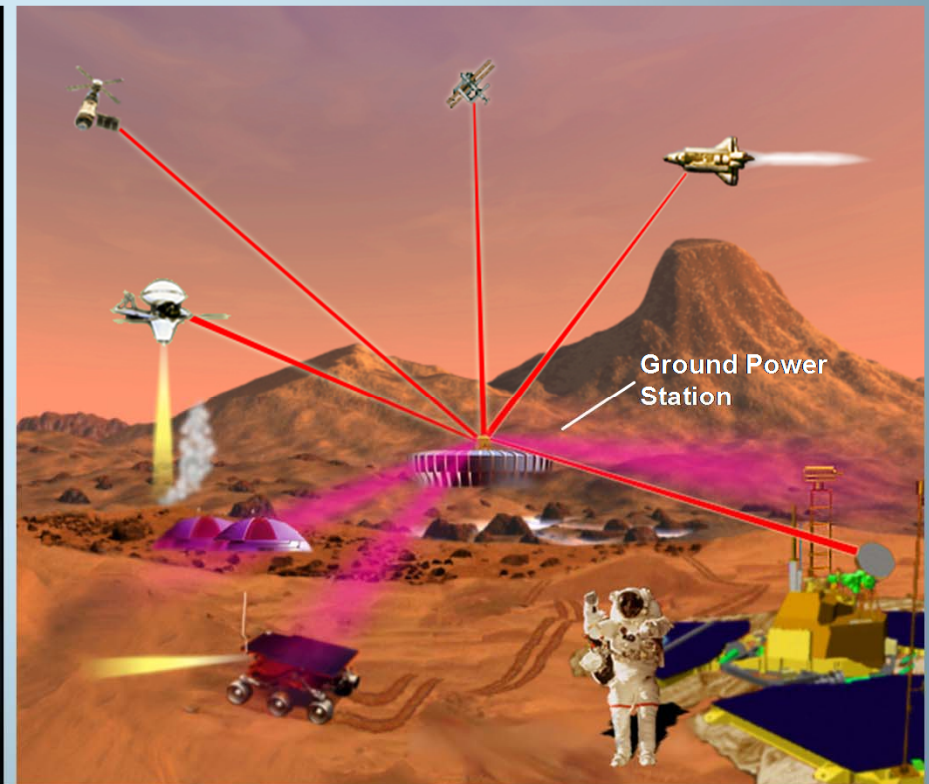
Radioisotope Thermoelectric Generators (RTG)



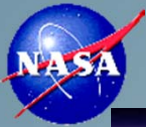
Applications of Thermoelectric Generator

The proposed system encompasses three subsystems:

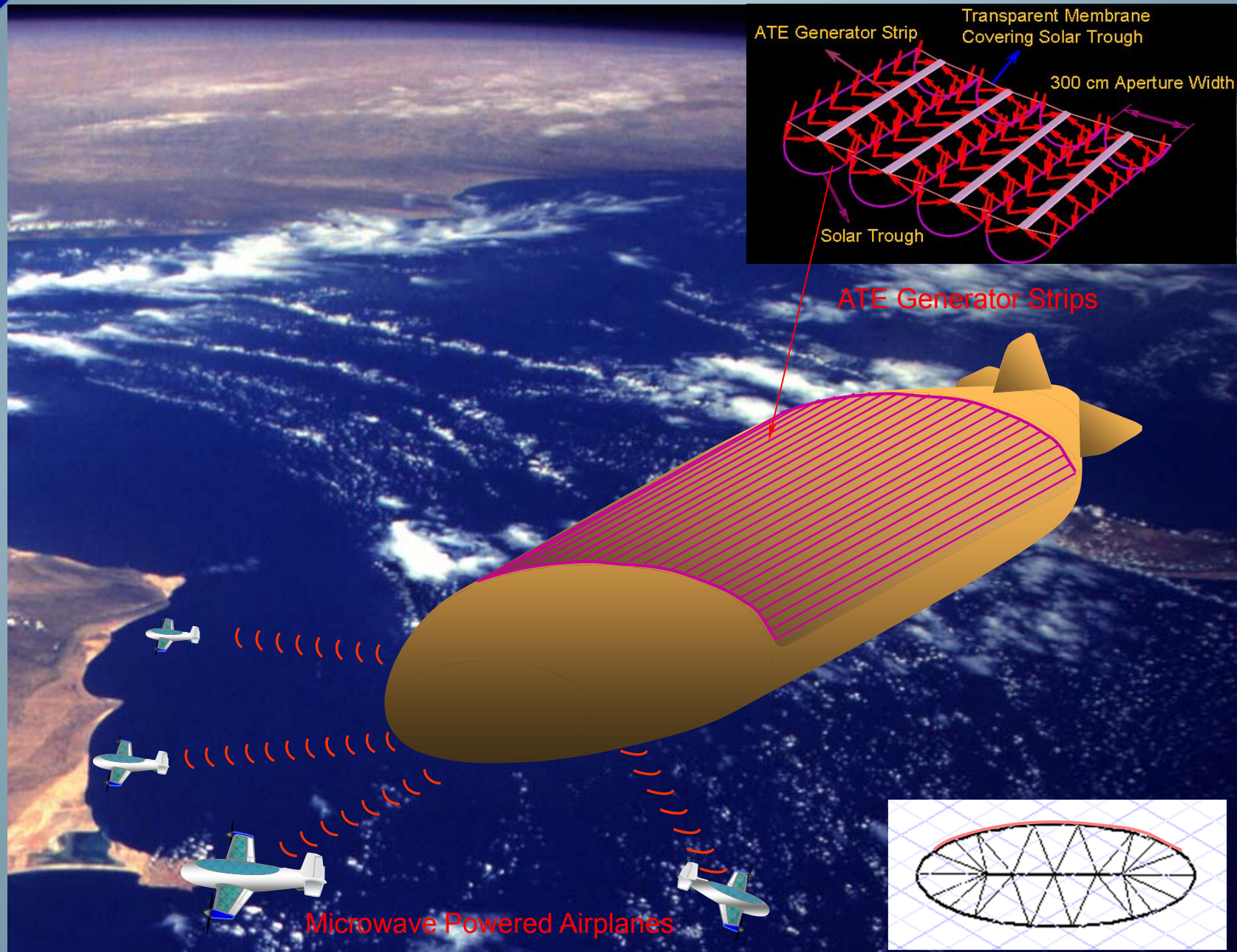
1. Radioisotope Power (RIP) Subsystem
2. Advanced Thermoelectric Generator (ATEG) Subsystem
3. Wireless Power Transmission (WPT) Subsystem

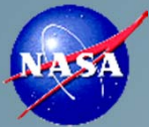


Artist's concepts of Mars space power station installed with WPT-ATEG system: space system (left) and ground system (right).



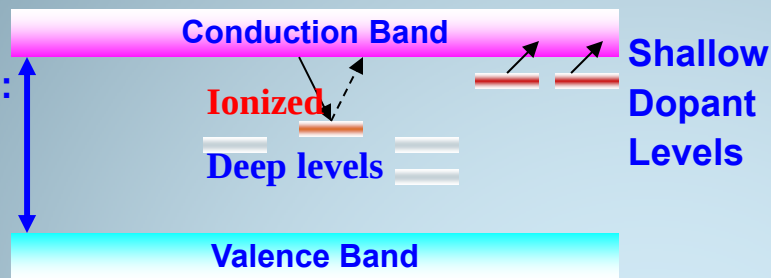
Solar Thermoelectrics Application for Airship



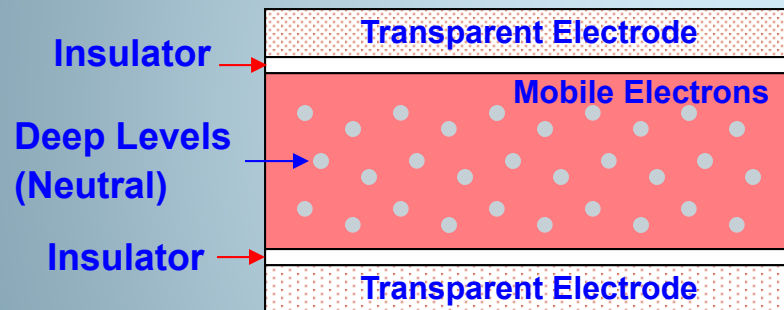


Distribution of Carriers and Ionization of Deep Levels

Wide Bandgap:
Transparent to
visible lights



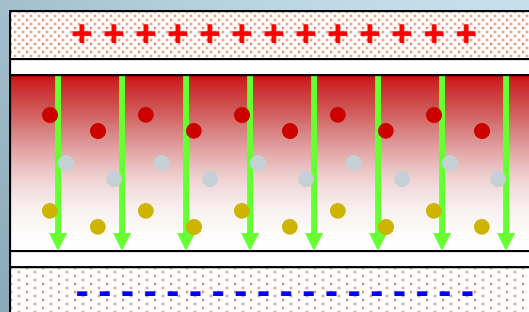
(1) Without Electric Field



(2) With Electric Field: Redistribution of Mobile Electrons

Negatively
charged
deep levels

Positively
charged
deep levels



For wide band-gap materials:

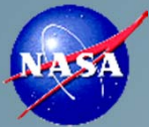
- Transparent to visible lights.
- Carriers in **shallow dopant levels** are mobile to conduction or valence band.
- Deep levels in crystal imperfection capture or emit mobile charges.
- Bandgap structure is ionized with the loss or capture of carriers.

For $|\vec{E}| = 0$,

- Mobile electrons distributed **uniformly** in media layer.
- Most of the deep levels are **neutral** in this state.

For $|\vec{E}| \gg 0$,

- Mobile carriers (electrons in the picture) are **re-distributed**.
- Deep levels are **ionized** and form **new color centers**.
- Absorption coefficient and index of refraction are changed.



Hall Effect Measurement

As Grown ScN on Al_2O_3

● RESULTS	B = 0.51 [T]	D = 0.28 [um]
Carrier Density: $\times 10^4$		
Nb = -5.7963E+20 [/cm ³]	Ns = -1.6230E+16 [/cm ²]	
μ = 11.50203 [cm ² /V·s]	Rh = -1.0769E-02 [m ² /C]	Conductivity: $\times 10^5$
ρ = 9.3631E-04 [Ω ·cm]	σ = 1.0680E+03 [1/ Ω ·cm]	
delta_R = 1.9616E-02 [Ω]	alpha = 0.12167	
Nb : Bulk concentration μ : Mobility ρ : Bulk resistivity delta_R : magnetoresistance		
Ns : Sheet concentration Rh : Hall coefficient σ : Conductivity alpha : V/H Ratio of Resistance		

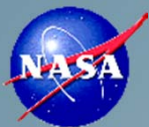
Intrinsic GaN on Al_2O_3

● RESULTS	B = 0.51 [T]	D = 0.397 [um]
Nb = -6.6835E+16 [/cm ³]	Ns = -2.6534E+12 [/cm ²]	
μ = 2.22096 [cm ² /V·s]	Rh = -93.39652 [m ² /C]	
ρ = 52.87408 [Ω ·cm]	σ = 1.8913E-02 [1/ Ω ·cm]	
delta_R = 1.5208E+04 [Ω]	alpha = 0.16824	
Nb : Bulk concentration μ : Mobility ρ : Bulk resistivity delta_R : magnetoresistance		
Ns : Sheet concentration Rh : Hall coefficient σ : Conductivity alpha : V/H Ratio of Resistance		



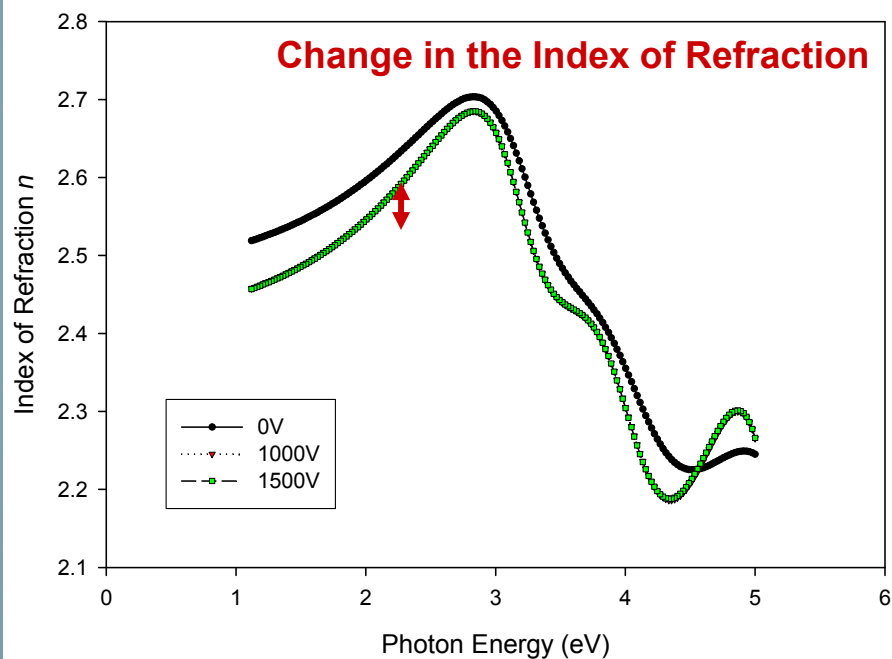
ScN grown on c-axis Sapphire (Al_2O_3) shows 10,000 times higher electron concentration than intrinsic GaN.

With the applied electric field, the redistribution of mobile charges changes the index of refraction.

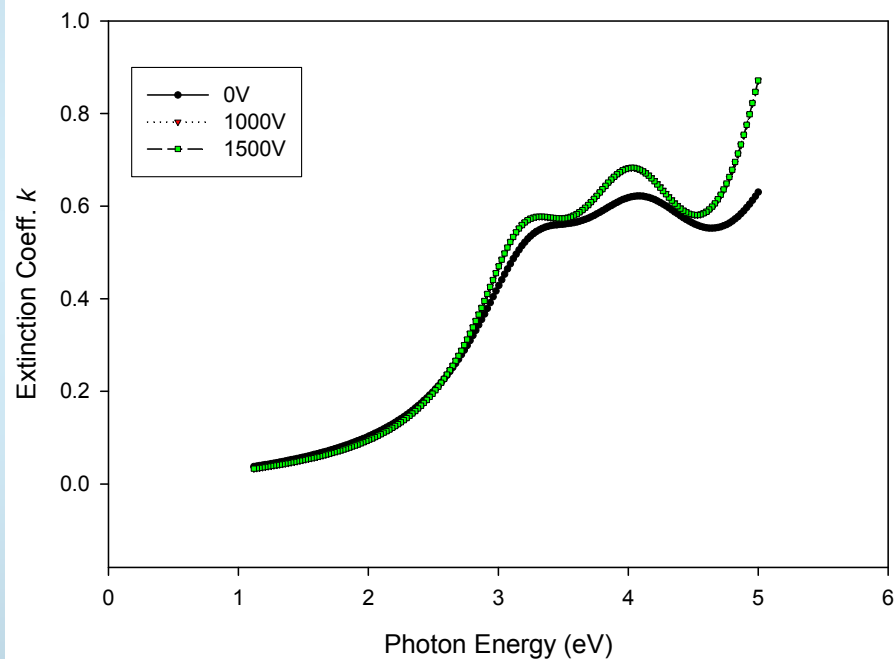


Change of the Index of Refraction in ScN

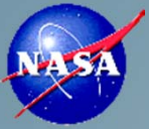
SO-009 Index of Refraction n
With Applied High Voltage



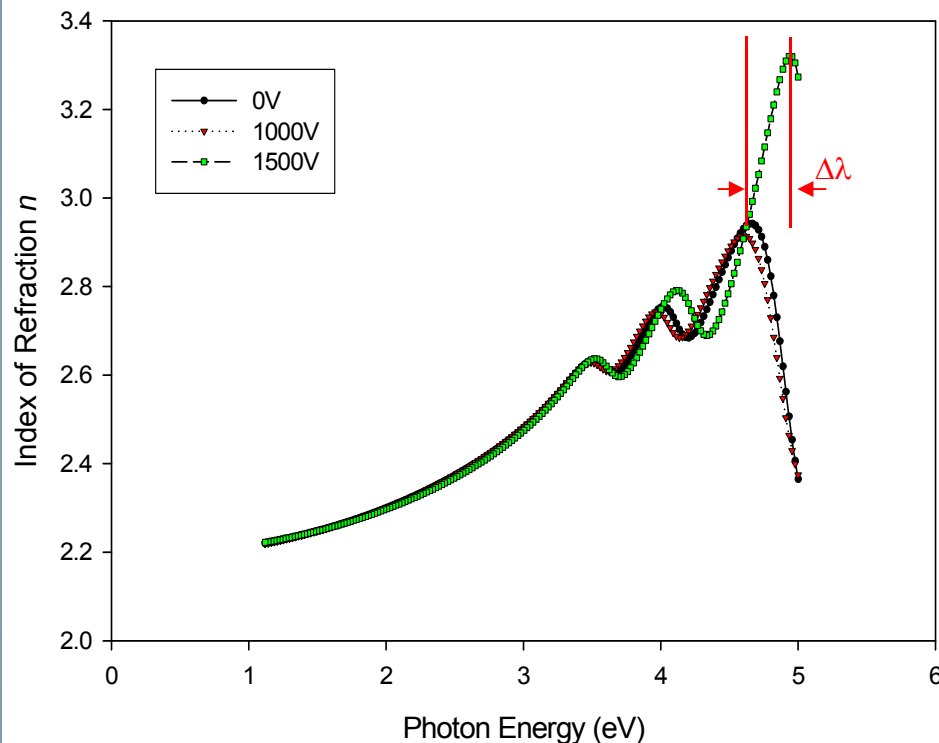
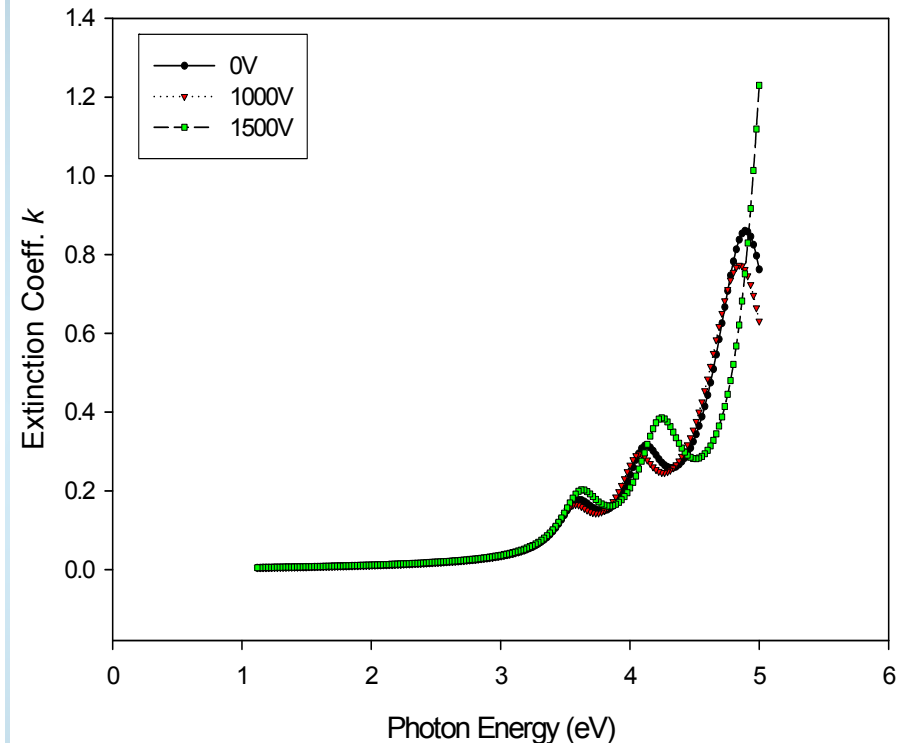
SO-009 Extinction Coeff. k
With Applied High Voltage



ScN film shows the change in the index of refraction with the applied electric field. The electric field was applied with a few mm gap. The required voltage can be reduced in the optimized structure.

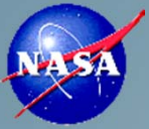


$\text{Ga}_x\text{Sc}_{1-x}\text{N}$ Alloy System

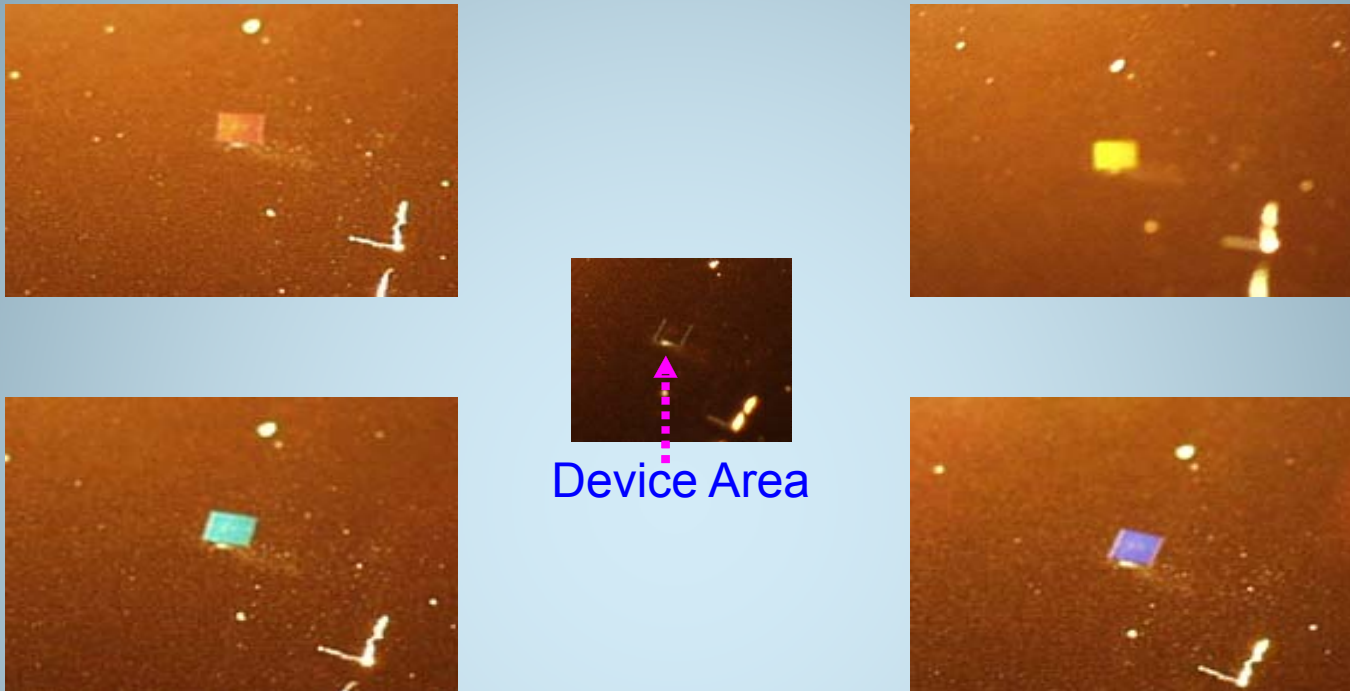


A thin-film of scandium-alloyed gallium nitride ($\text{Ga}_x\text{Sc}_{1-x}\text{N}$, $x=0.47$) shows both the spectral and refractive index shifts very clearly from 3.5 eV to higher photon energy.

Extinction coefficient data shows a similar response as refractive index shows. The shift is very clear from 3.5 eV to higher photon energy.

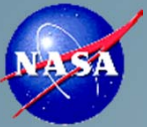


Adaptive Optical Components

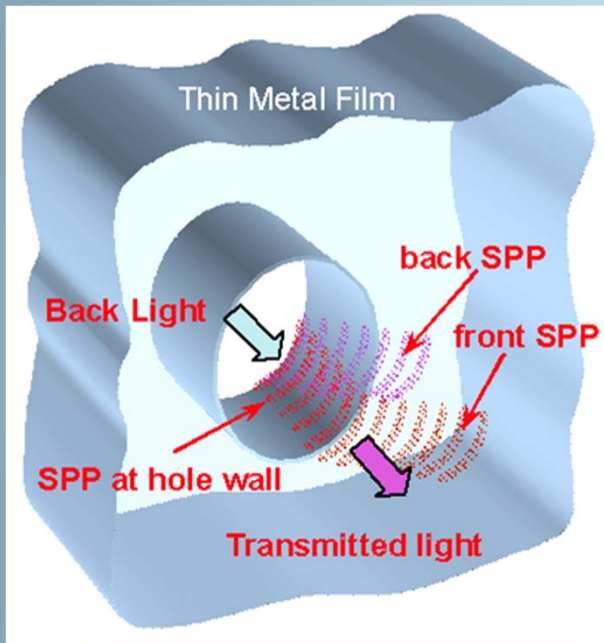


Geometric grating effect from the reflective array, fabricated at NASA LaRC.

- The goal of Adaptive Optical Components: Adding a **programmability** to the conventional optical components, including lens, grating, apertures, filters and reflectors. The same optical component can be programmed for different wavelengths and polarizations.
- It can reduce the total weight of satellites and increase the working range and **sensitivity** of device with **versatility**.

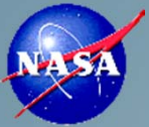


Plasmon Enhanced Transmission

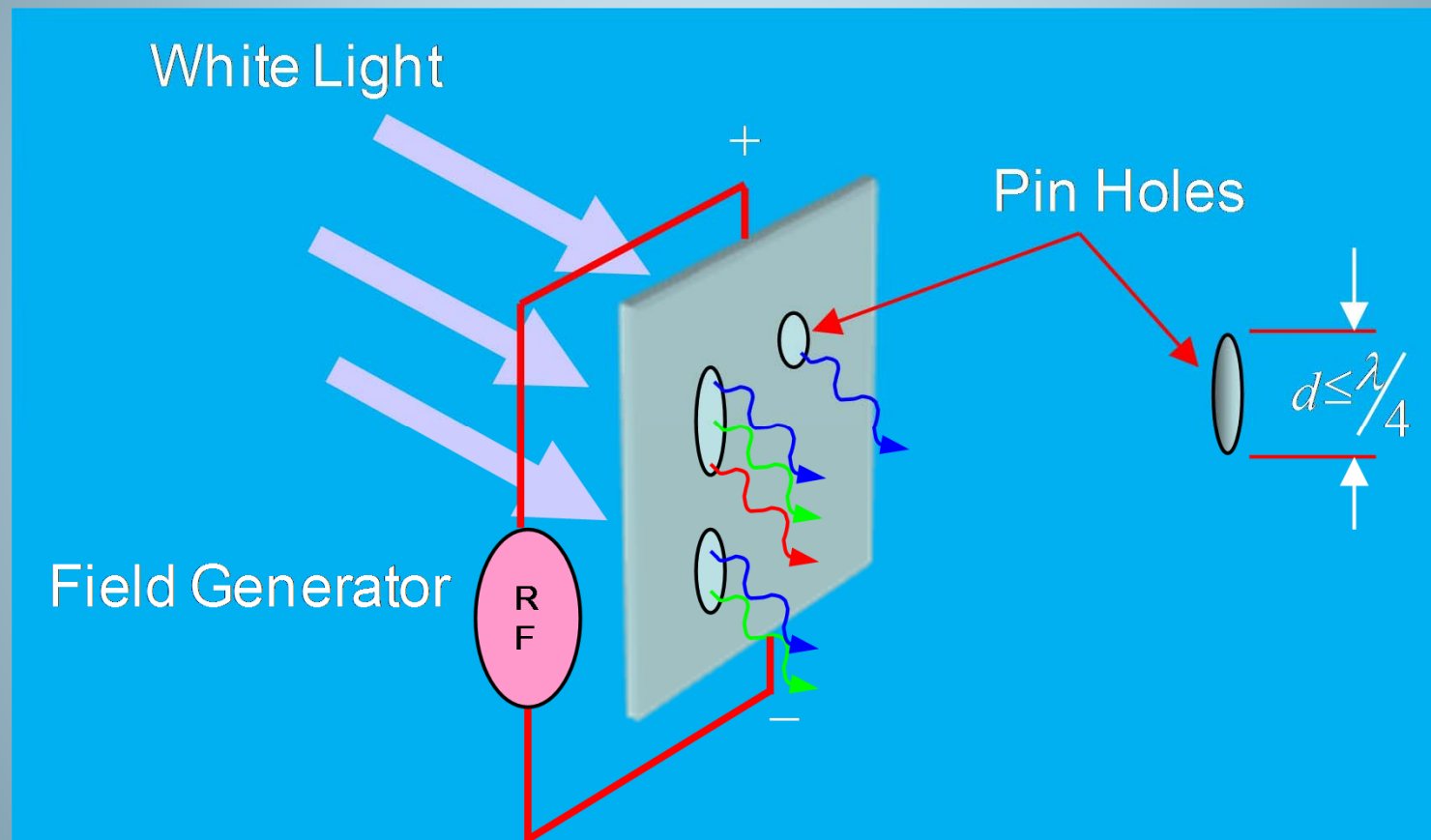


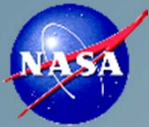
Transmission Through
a Quantum Aperture

- Metal surface has the collective movement of the electrons at the surface; it is called the surface plasmon, propagating on the surface only.
- The **skin-depth** of a good conductive metal is very shallow; a hundred nanometer metal film is enough to block the light penetration.
- The transmission of the photons through a hole smaller than $\frac{1}{4}$ of wavelength is controlled by the **surface plasmons** in the hole.
- The incident light generates the back surface plasmon. Surface plasmon **propagates through the surface** of the hole. On the front side, the surface plasmon radiates the light again.
- Other experiments indicate there is no enhanced transmission of a long wavelength light through tiny holes in Ge, where there is no plasmon. Only a good conductor surface has plasmon.

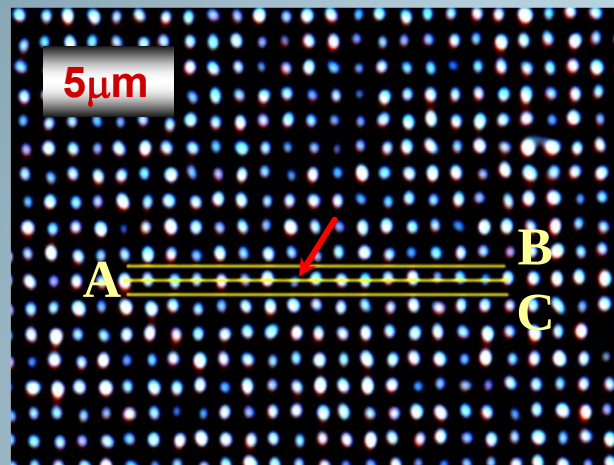


Nano Apertures

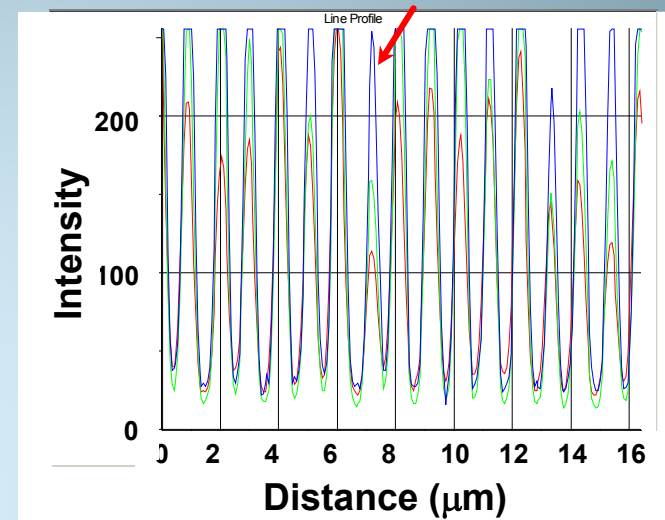




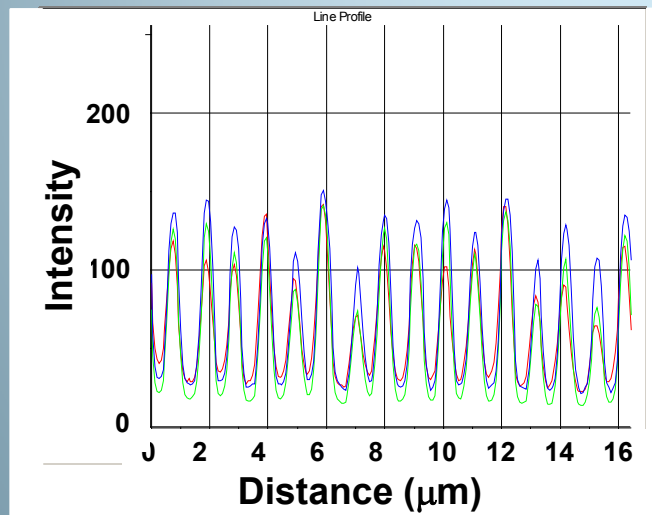
Microscopic Spectral Distribution From Individual Quantum Aperture with 200nm Diameter



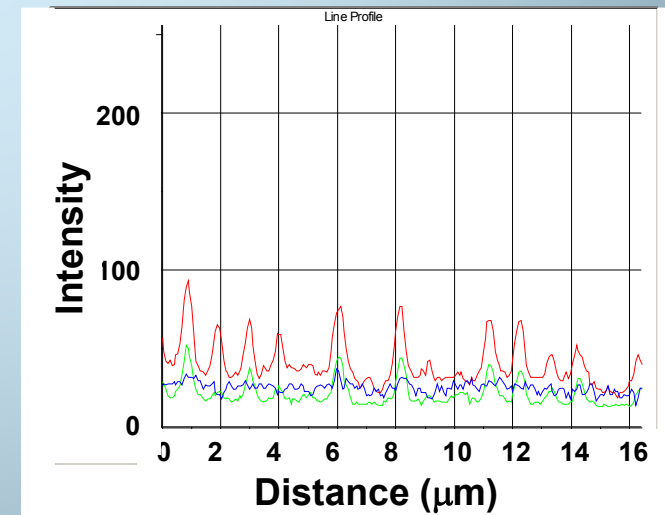
Transmitted Light



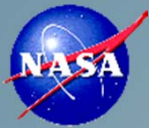
Center Line A: **Strong Blue**



Sum of Area between B and C:
Close to White Light with Blue



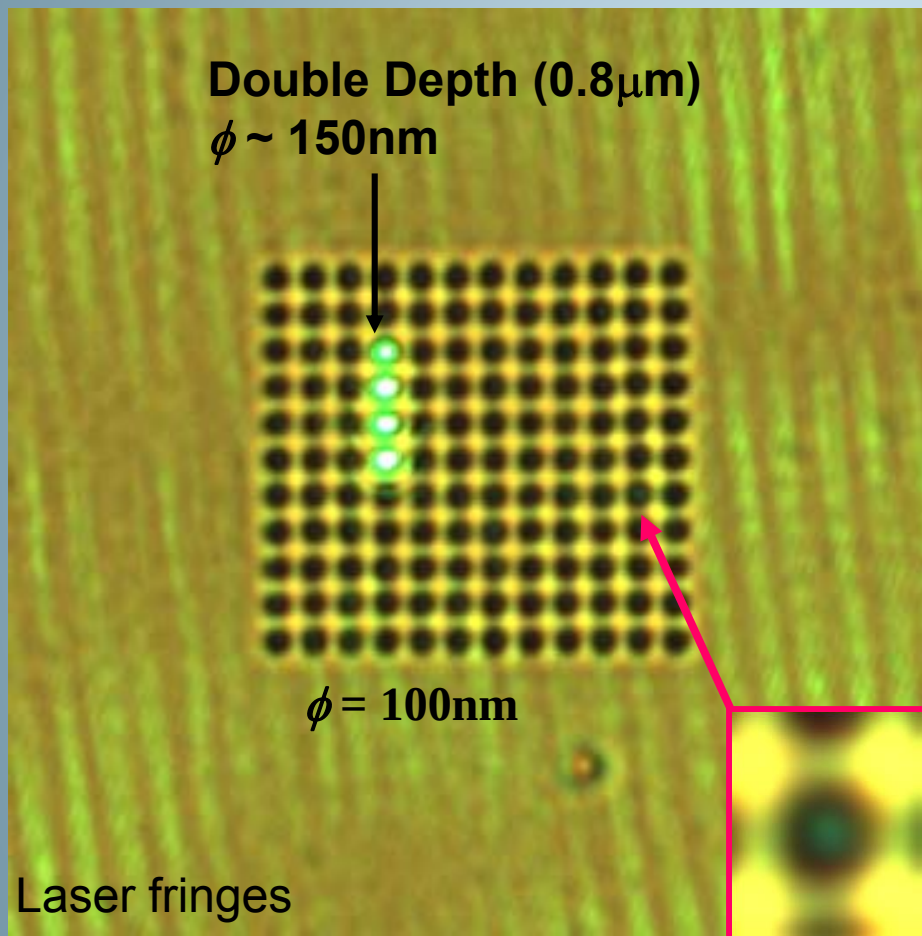
Boundary Line B or C: **Dark Red**



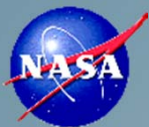
Selected Light Transmission

Laser (532nm) + Front Side Illumination

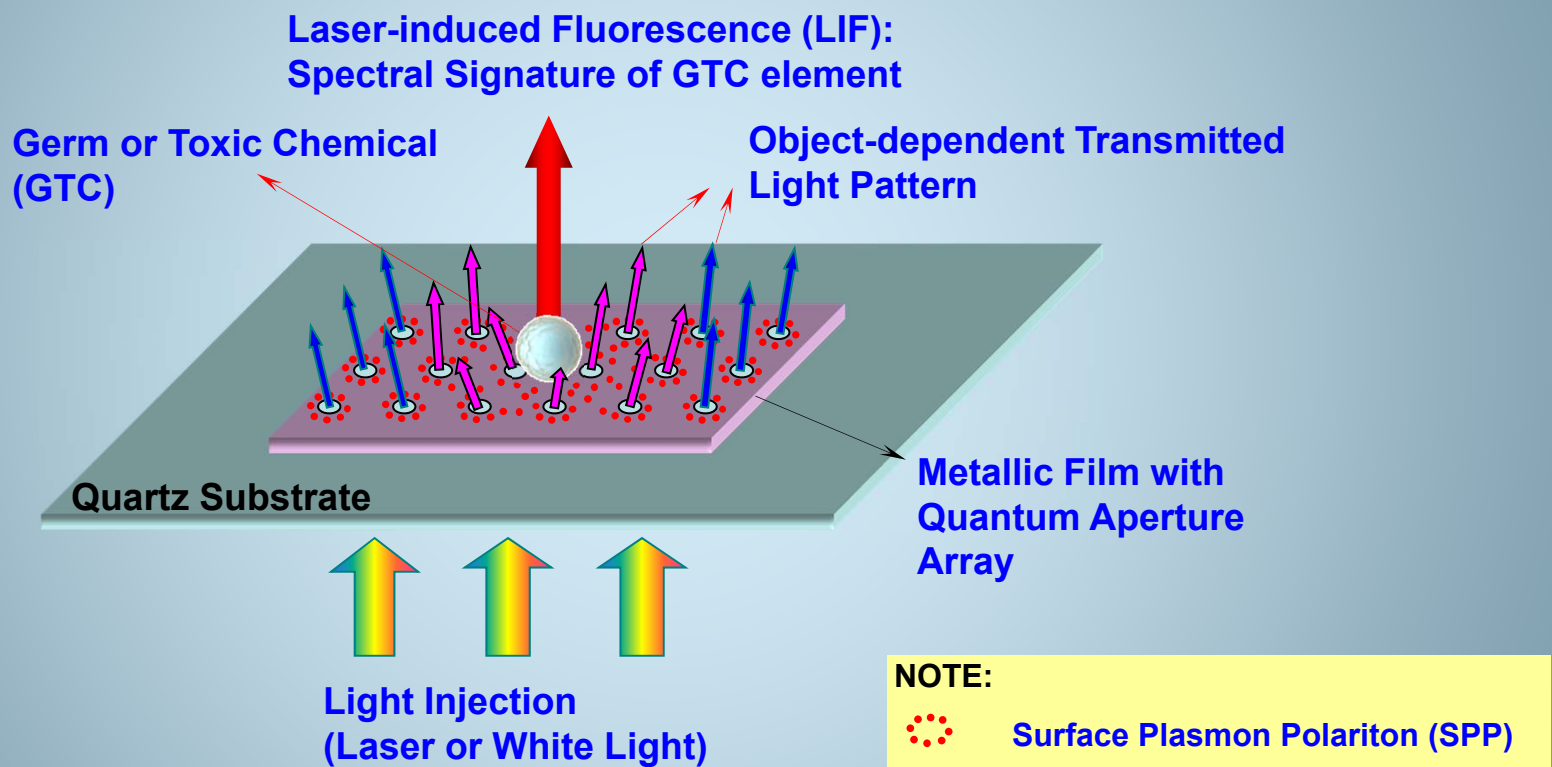
Laser (630nm) Backside Illumination only



Green Light Passes Through.

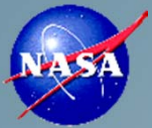


Germ or Toxic Chemical (GTC) Sensor using Quantum Aperture Array with Surface Plasmon Polariton (SPP)



NOTE:

-  Surface Plasmon Polariton (SPP)
-  Electron
-  Light Transmission by undisturbed SPP
-  Light Transmission by disturbed SPP



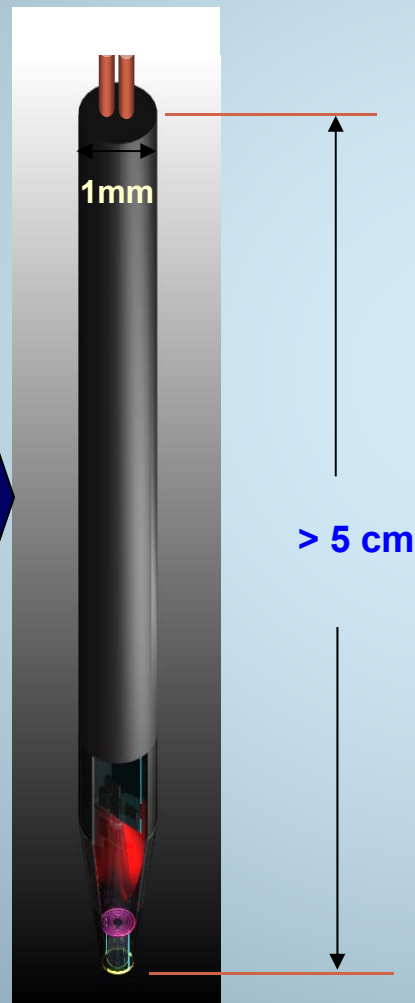
Micro Spectrometer (μ -SM) Applications

Medical Application for Neurosensing

For Space Exploration

Medical Sensors:

- Tiny Form Factor < 1 mm
- Flexible Pin
- Sensor Fusion Capable
- Power & Telemetry
- Redundancy Feature



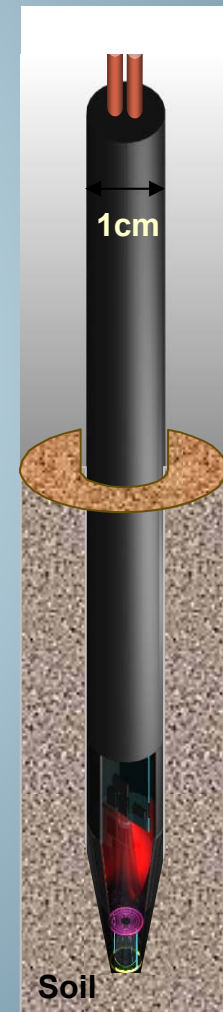
Leveraging Factors

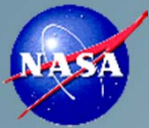
Space:

- μ -SM Imbedded Rover Tires
- μ -SM Imbedded Astronaut's Shoes
- μ -SM Imbedded Canes or Darts
- Hyperspectral Imaging

Aeronautics:

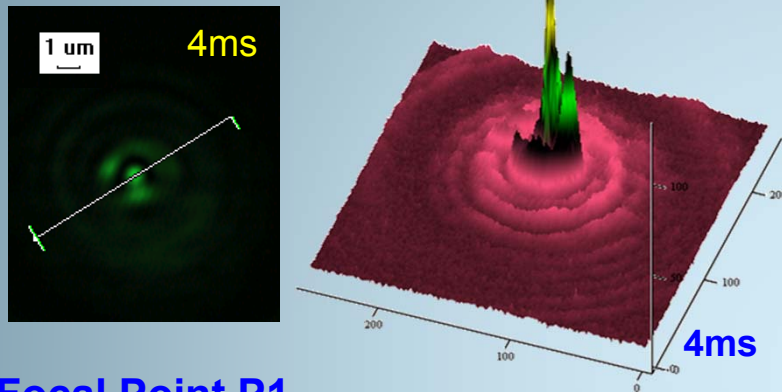
- Engine Combustion Monitoring
- Fuel Leak Detection
- Hyperspectral Lidar Imaging



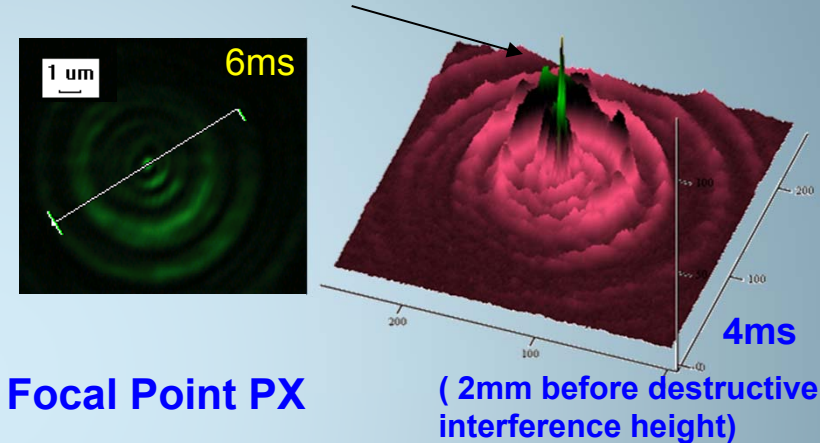


Sharpness of Focal Point P1 and PX with a Green Laser ($\lambda=532\text{nm}$)

10 mW Laser in 2mm diameter (0.3 W/cm^2) can
have a focused power density = 10^5 Watt/cm^2

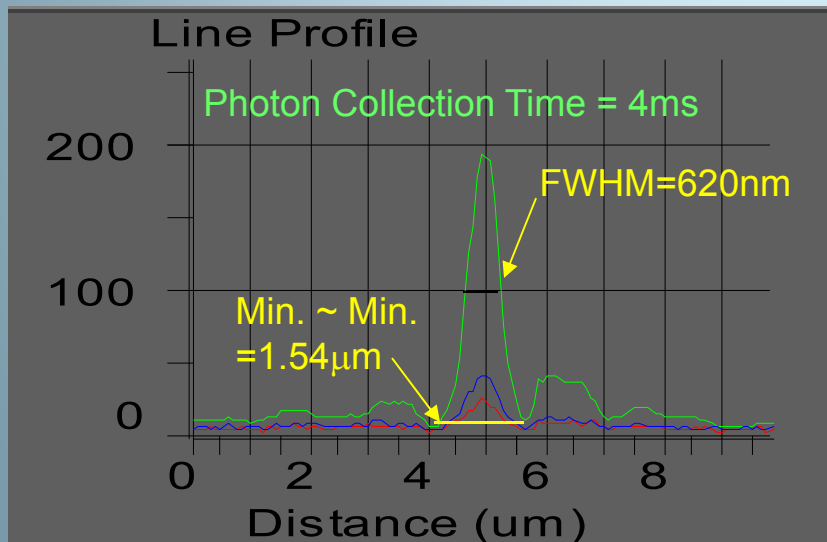
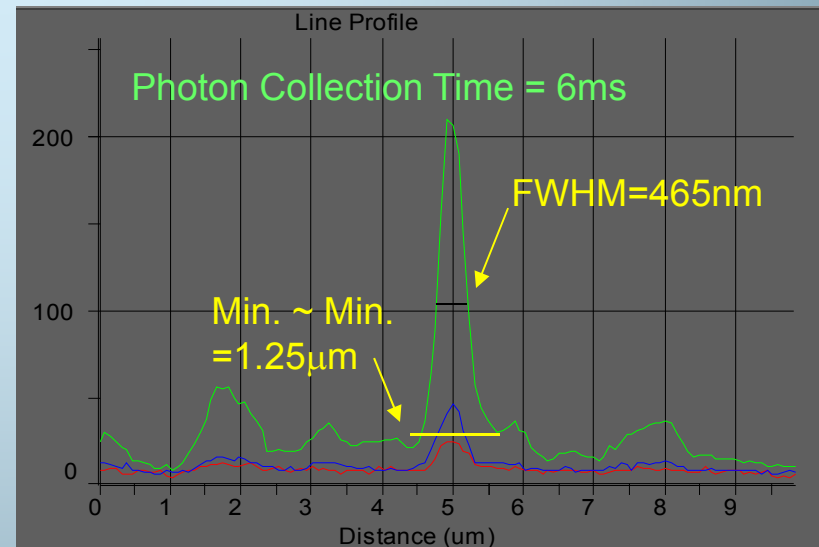


Focal Point P1

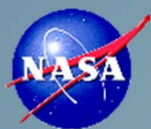


Focal Point PX

(2mm before destructive
interference height)

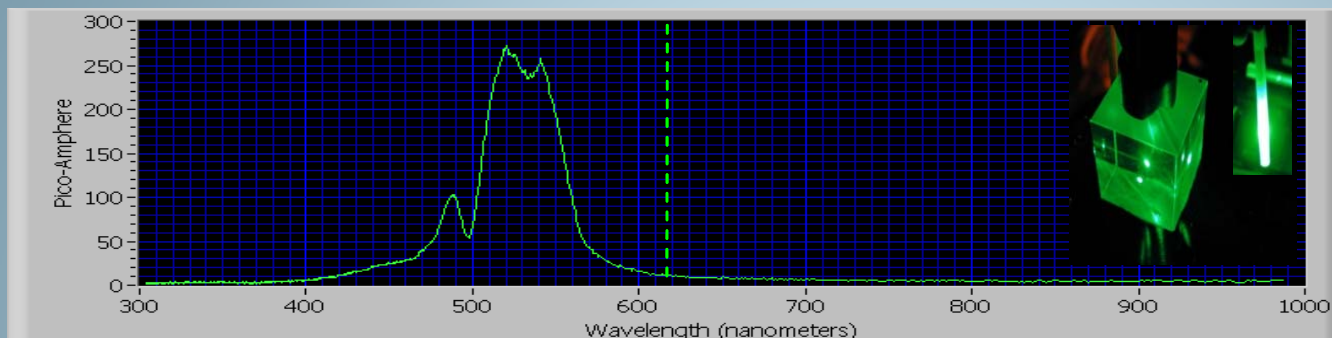
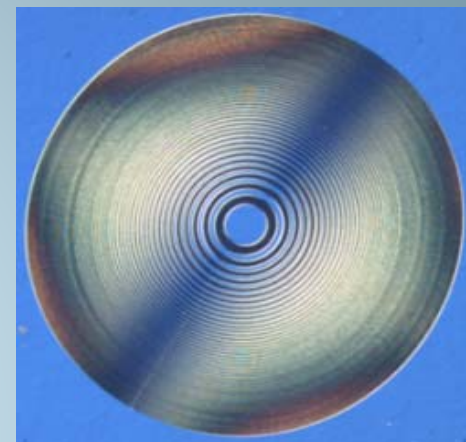


Photonic DART Technology (Densely Accumulated Ray-point by micro-zone-plaTe)

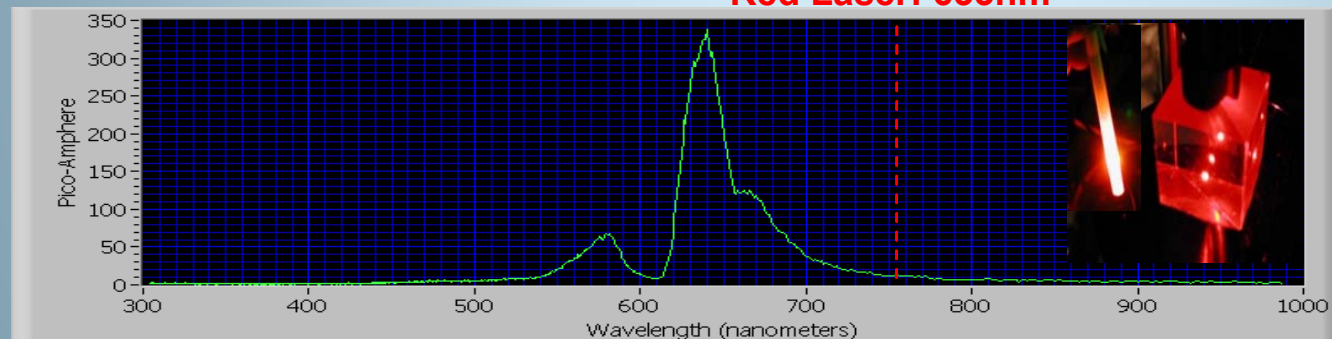


Spectral scans:

Green Laser: 532nm



Red Laser: 633nm



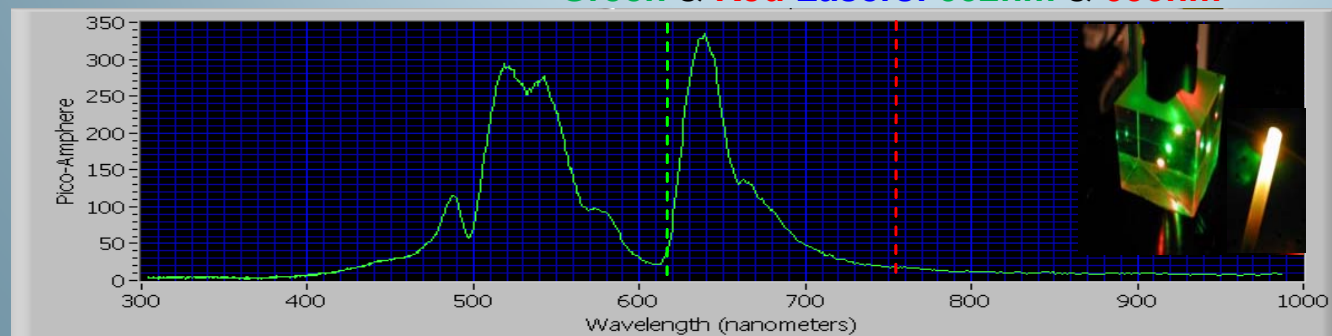
Circular Grating

Rings: 100

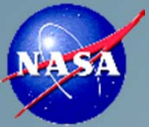
Diameter: 750 μ m

Aperture: 10 μ m

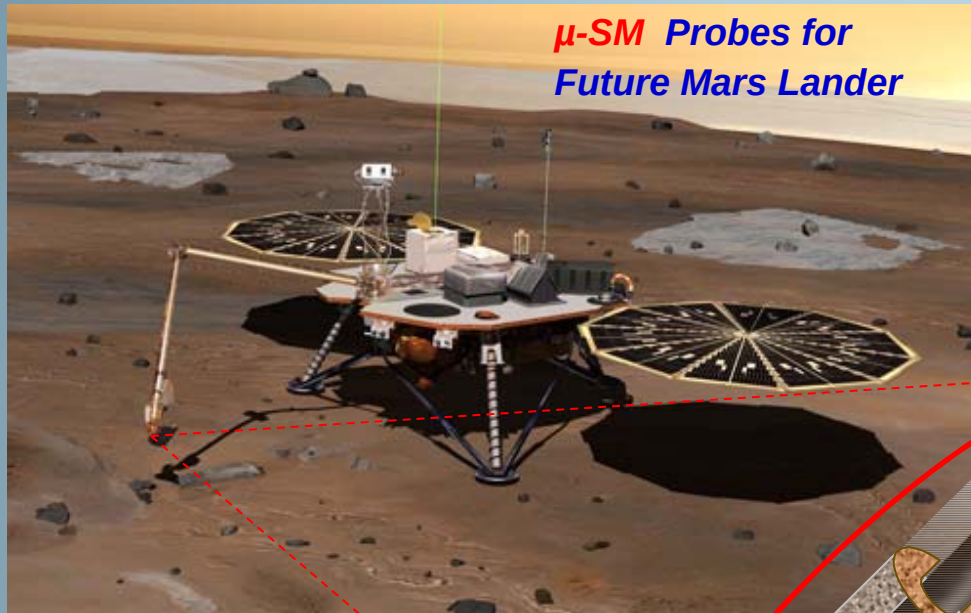
Green & Red Lasers: 532nm & 633nm



The human eye sees the yellow color, but the μ -spectrometer can distinguish the two lights, green and red.

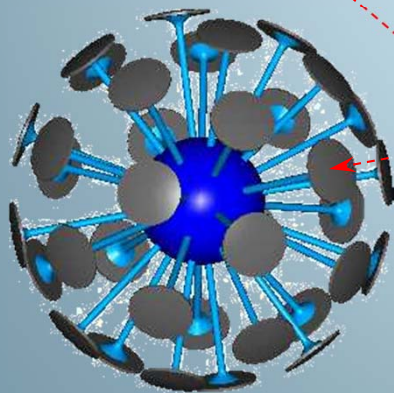


μ -Spectrometer (μ -SM) Applications Lunar & Mars Exploration

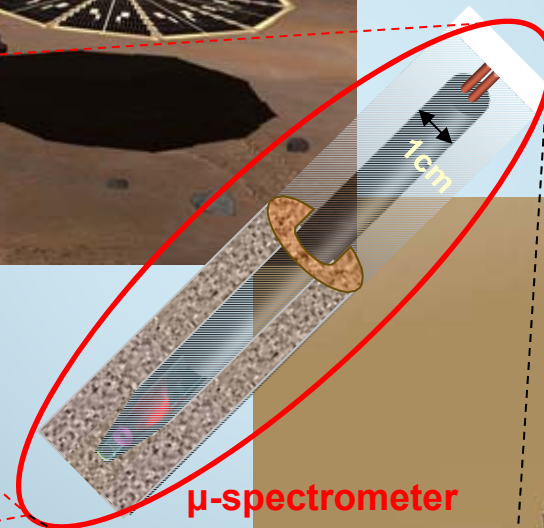


μ -SM imbedded Astronaut Shoes
and Rover Tires

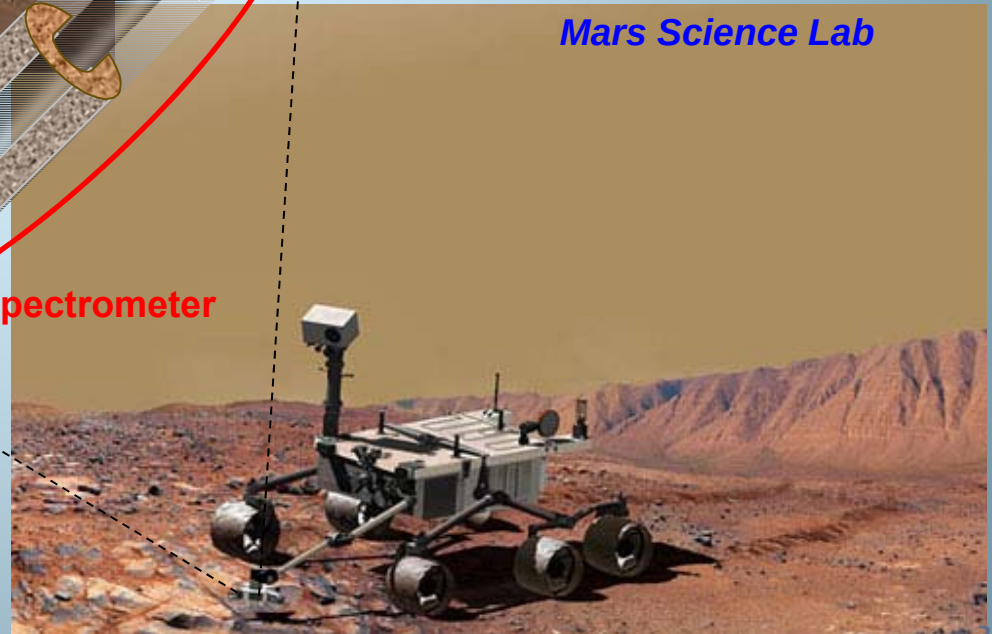
Mars Science Lab

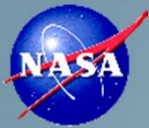


μ -SM imbedded Tumbleweed Rover

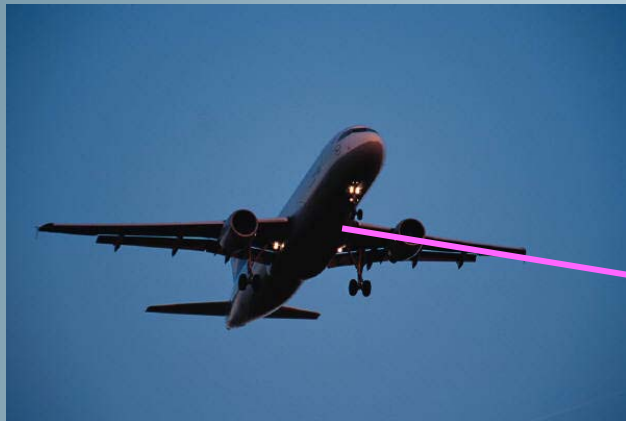


μ -spectrometer





Aero-Space Application



Laser Communication

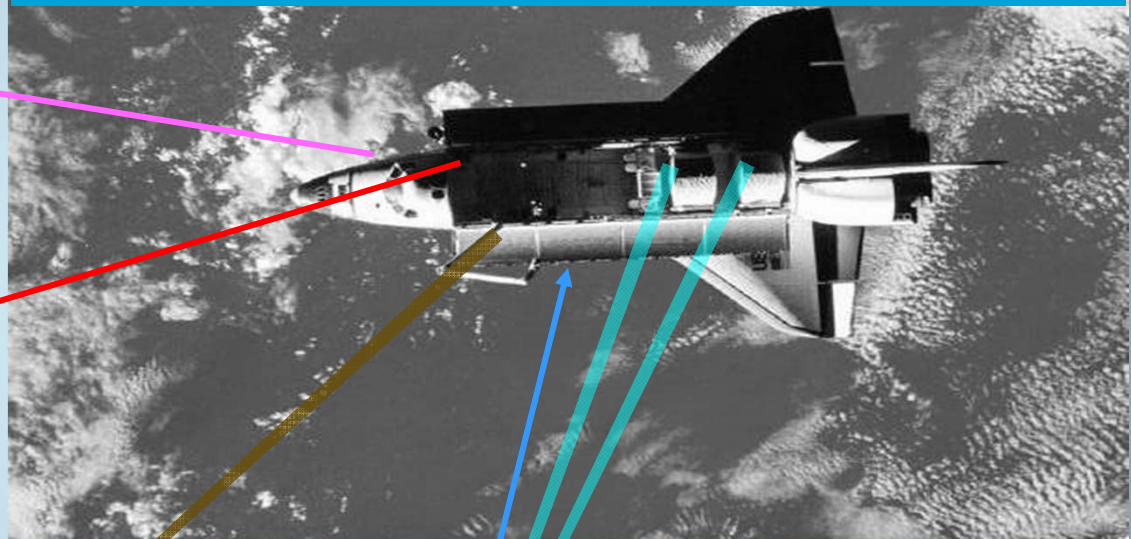


POWER for UAV

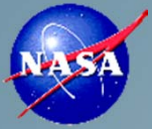


2D Measurement

Typical Mechanical Vibration: 0.1Hz ~ 100kHz
Beam scanner has to be faster than a few MHz!
We need Fast Solid State Optical Components!



3D Measurement
Interference Fringe
Two Photon Excitation

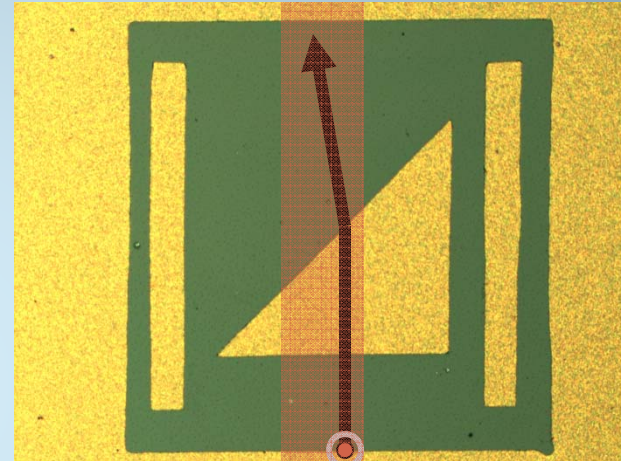


Lithography and Etched Patterns

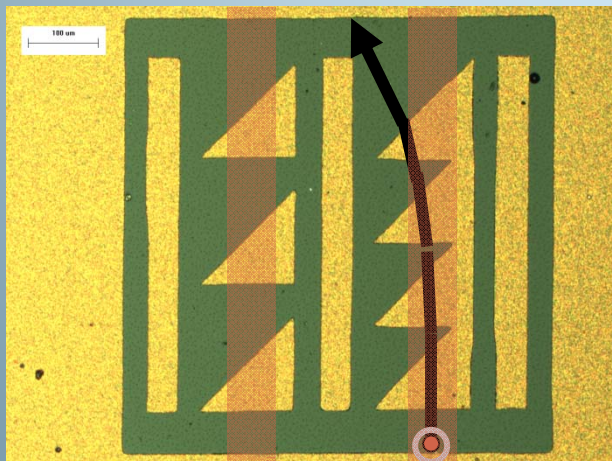
E-Beam Lithography



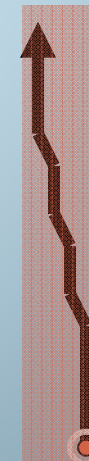
Single Beam Scanner

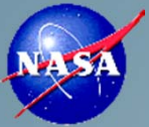


Beam Scanner Array

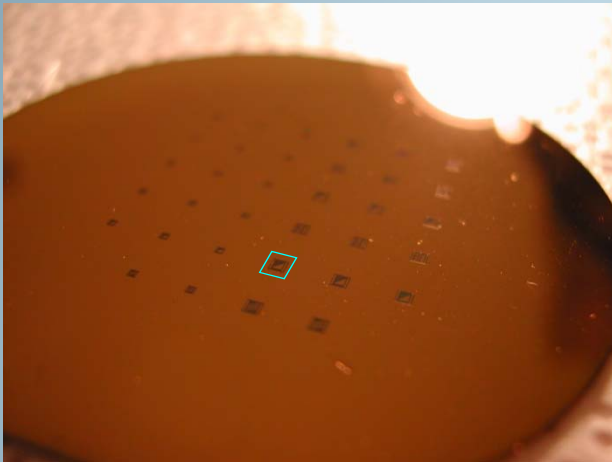


Beam Displacer

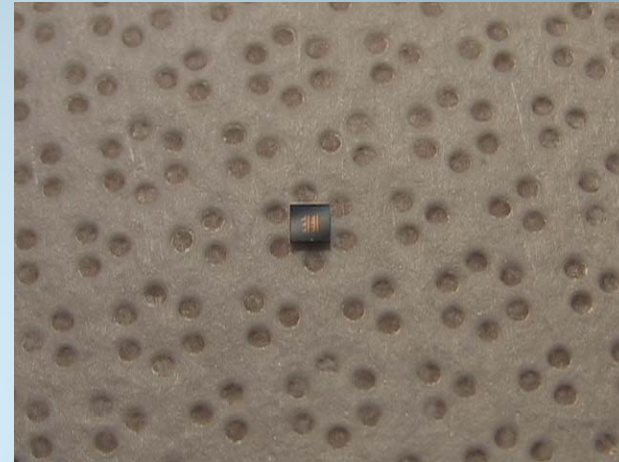




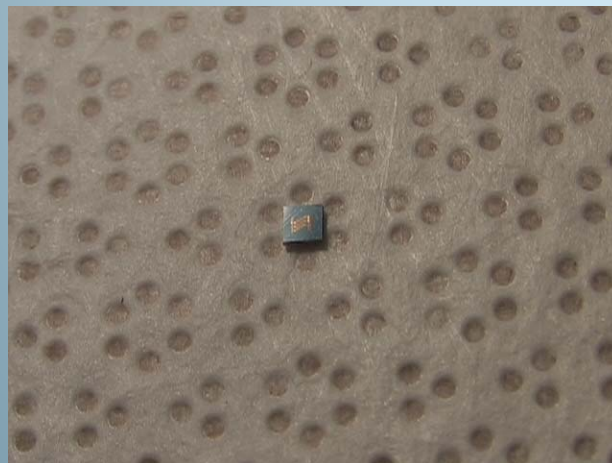
Light Control Device



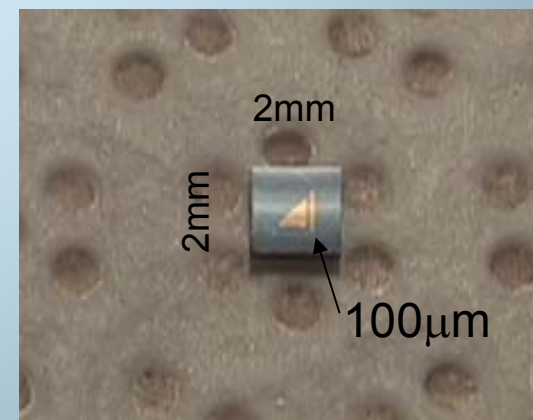
Patterns Made with E-Beam Lithography



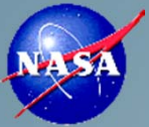
All-Solid-State Beam Scanner



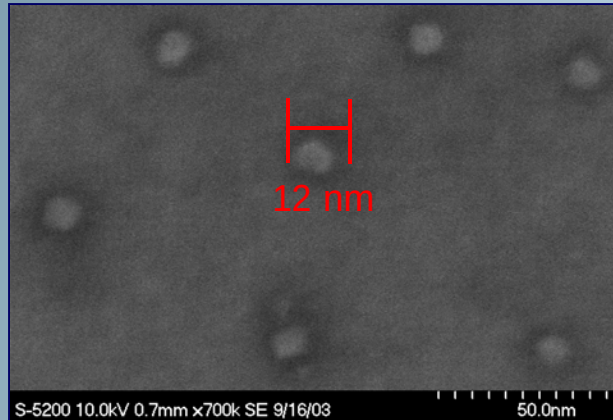
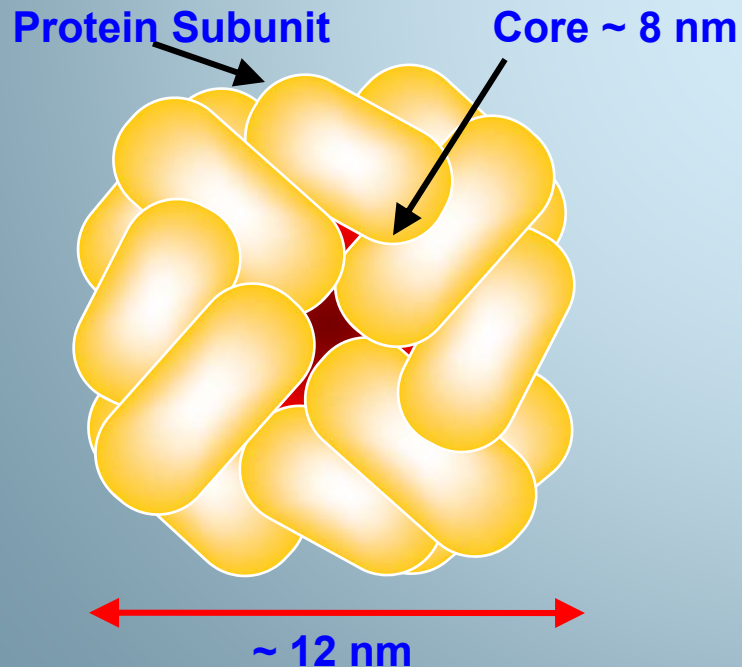
All Solid State Beam Scanner Array



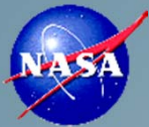
Solid State Beam Displacer



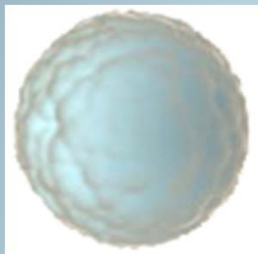
Ferritin Protein



- Iron storage protein in biological mechanisms in human, animal, and even bacteria.
- 24 subunits.
- Contains up to ~ 4500 Fe^{3+} atoms.
- Stable and robust structure to withstand biologically extremes of high temperature (up to 80°C) and pH variations (2.0-10.0).
- 2, 3, 4-fold symmetry channels for the transport of ions and molecules.
- Hydrophilic 3 fold (Fe^{2+})/ Hydrophobic 4 fold
- Electron conduction through ferritin shell is possible.
- Core materials –
 - Iron (Fe), Cobalt (Co), Manganese (Mn), Nickel (Ni), Platinum (Pt), Semiconductors (CdS, CdSe)
 - Magnetite-maghemite
 - Trimethylamine-N-oxide, etc.

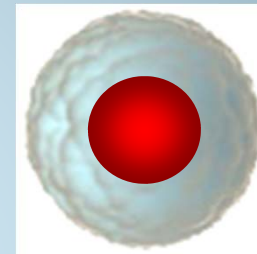


Biom mineralization & Reconstitution of Ferritin Core



Apo ferritin

M^{2+} , Oxidant



Ferritin Reconstituted
With M^{3+}



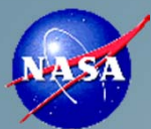
M : Core materials ---- Fe (natural)

Co, Mn, Ni, Pt, As, P, V (successful)

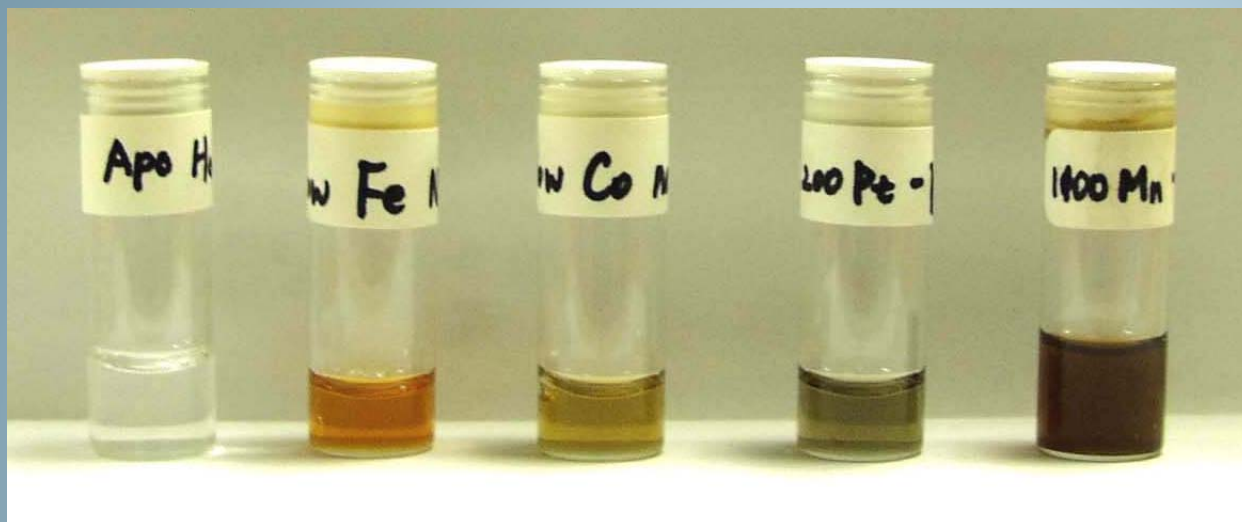
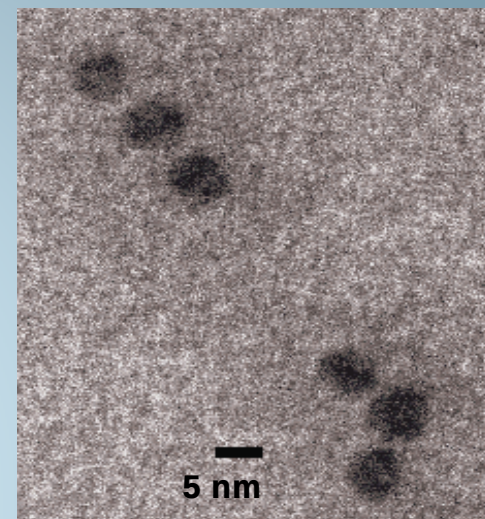
CdS, CdSe (successful)

Magnetite-maghemite (ferrimagnetic)

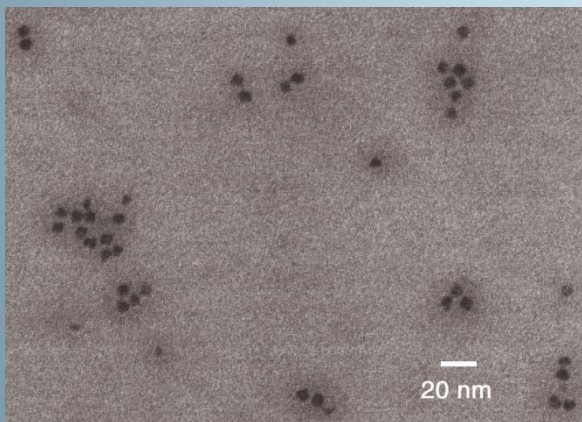
Trimethylamine-N-oxide (superparamagnetic)



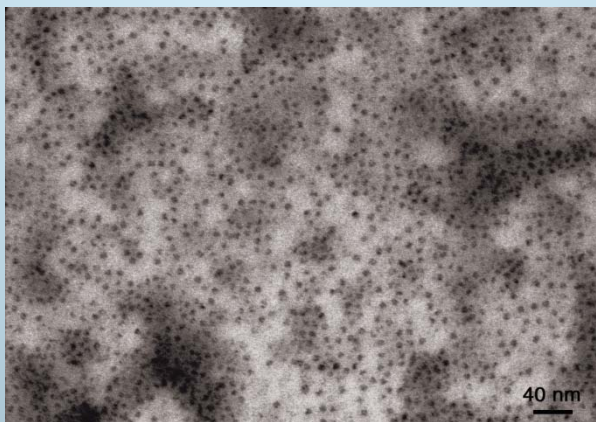
Chemically Reconstituted Ferritins



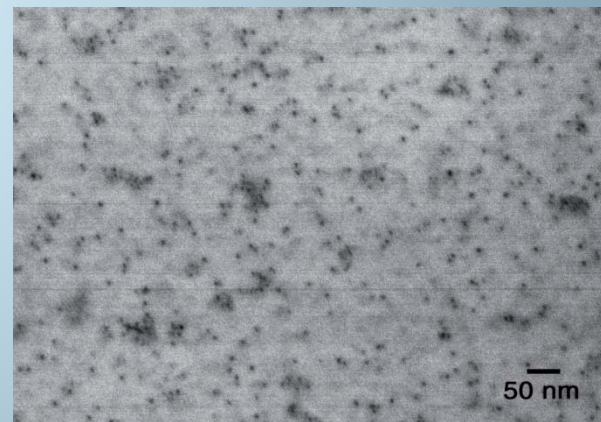
STEM Image of Fe-cored Ferritins



Fe-cored Ferritins



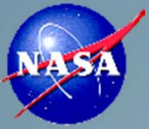
Co-cored Ferritins



Mn-cored Ferritins

Inorg. Chem., **44**, 3738-3745 (2005).

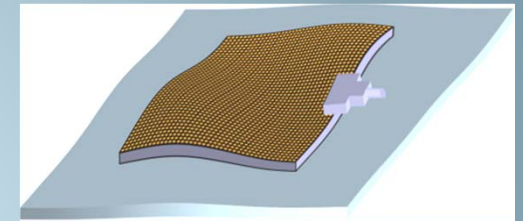
Chem. Commun., (32), 4101 -4103 (2005).



Why Bio-Nanobattery ?

What about

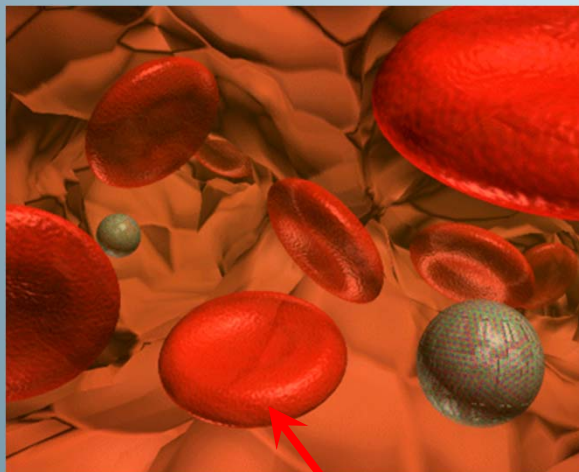
- **Distributed** power storage.
- **Flexible thin-film** battery - Designer's dream!!
- **Easy embodiment** with power harvesting devices.
- **Biocompatibility** with in-vivo nanodevices.
- **Light weight** and high energy density.
- **Chip scale power source.**
 - Intelligent and autonomous operation



Flexible Nanobattery Film



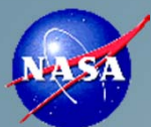
**Wearable Electronics
(Philips)**



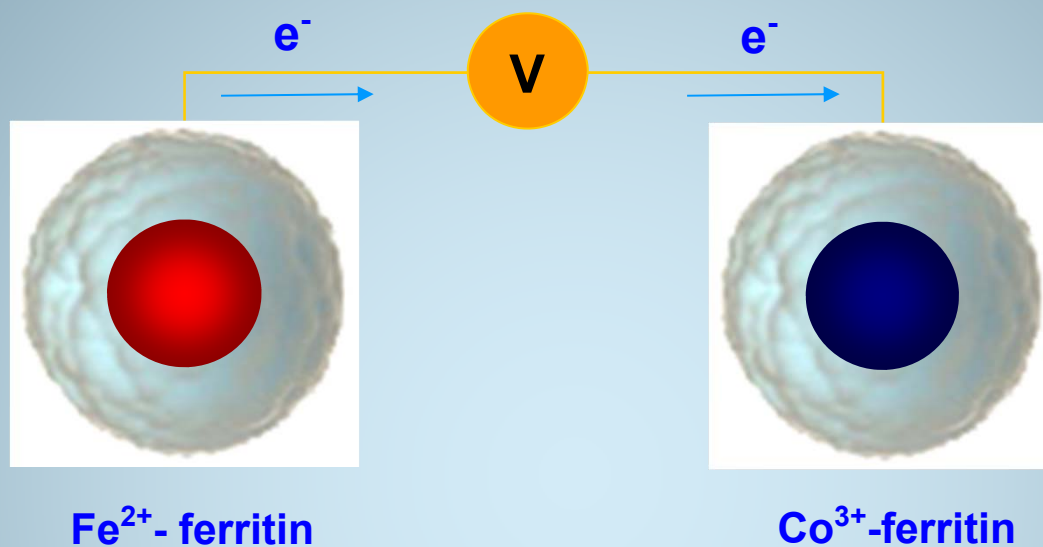
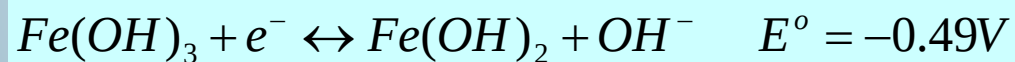
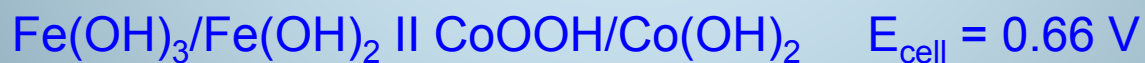
Red Blood Cell

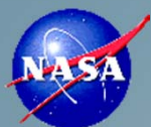


**Bio-nanobattery Patch Installed in
Autonomous Bio-nanorobot**



Bionanobattery Concept





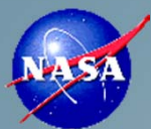
Theoretical Values of Bionanobattery

→ Anode

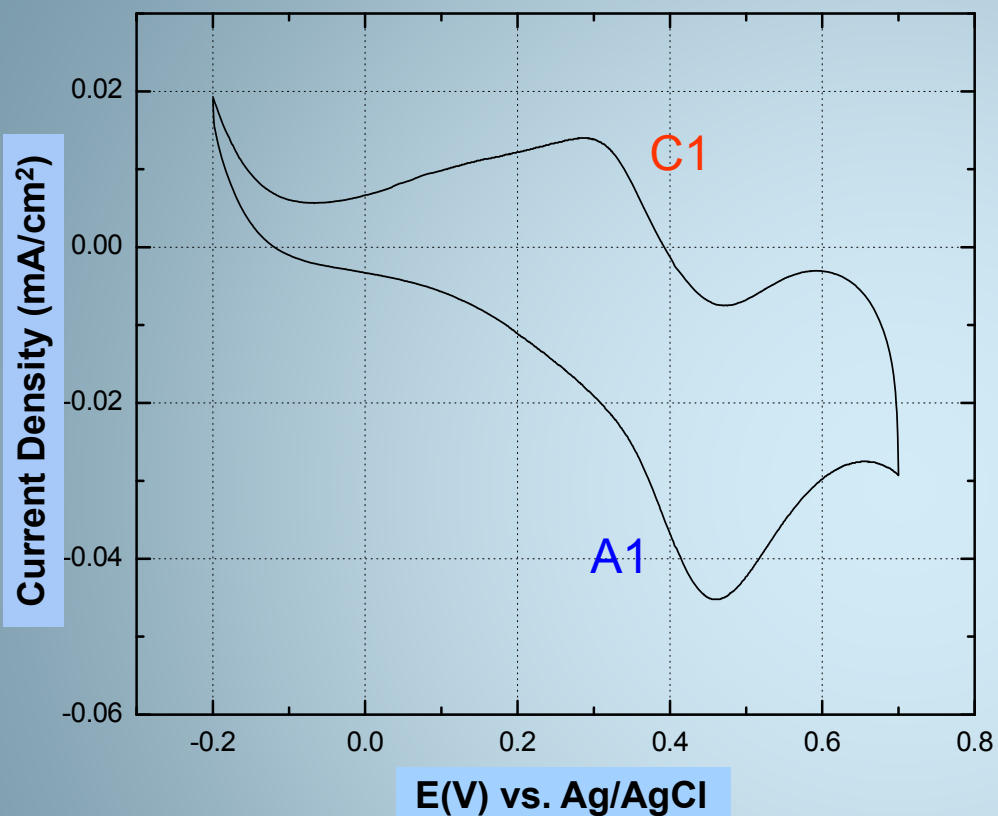
↓ Cathode

	Zn	Cd	Fe	V	Hg	Mn	Co	Ni	
Zn									$\text{Zn}^0/\text{Zn}^{2+}$: -1.246 V
Cd	0.422								$\text{Cd}^0/\text{Cd}^{2+}$: -0.824 V
Fe	0.756	0.334							$\text{Fe}^{2+}/\text{Fe}^{3+}$: -0.49 V
V	0.760	0.338	0.004						$\text{V}^{2+}/\text{V}^{3+}$: -0.486 V
Hg	1.344	0.922	0.588	0.584		0.388			$\text{Hg}^0/\text{Hg}^{2+}$: 0.098 V
Mn	0.956 (1.606)*	0.534 (1.184)	0.200 (0.850)	0.196 (0.846)	(0.262)		(0.190)		$\text{Mn}^{2+}/\text{Mn}^{3+}$: -0.29 V
Co	1.416V	0.994	0.660	0.656	0.072	0.120			$\text{Co}^{2+}/\text{Co}^{3+}$: 0.17 V
Ni	1.726	1.304	0.970	0.966	0.382	0.770	0.310		$\text{Ni}^{2+}/\text{Ni}^{3+}$: 0.48 V

(*) Mn represents as $\gamma\text{-MnO}_2$ inside Ferritin.

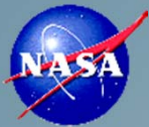


Ni-Cored Ferritin



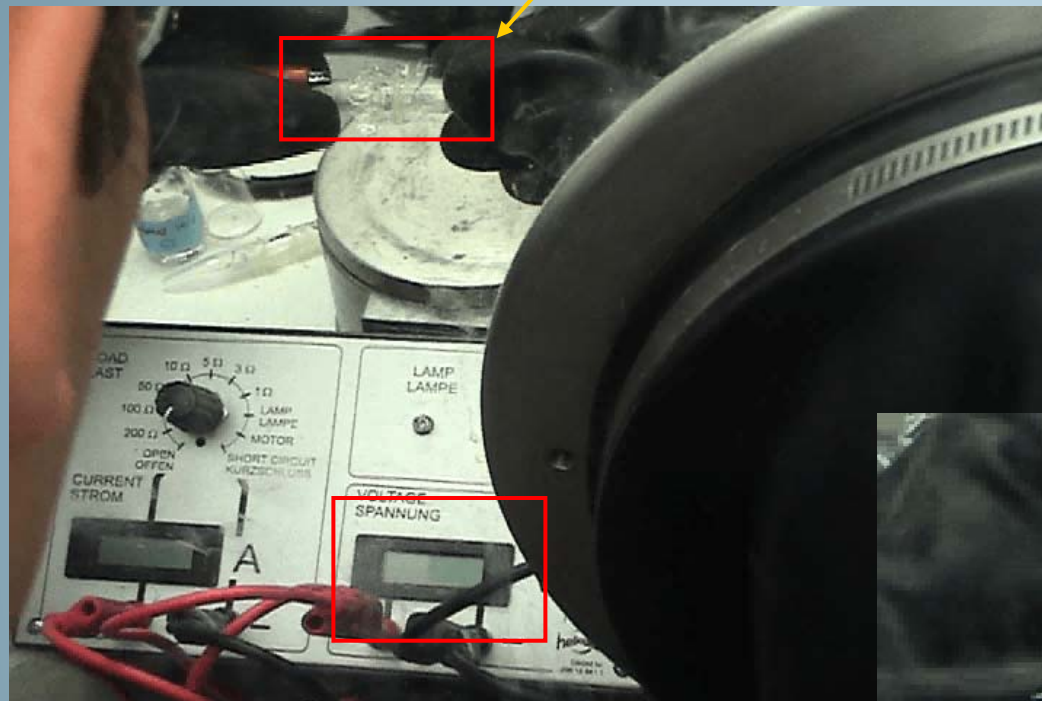
CV of physically adsorbed Ni-cored ferritin on Au electrode in 0.05 M phosphate buffer (pH 7.5 and pH 9.0) at the scan rate of 100 mV/s.

	Co	Mn	Ni
Fe	500 mV	480 mV	790 mV

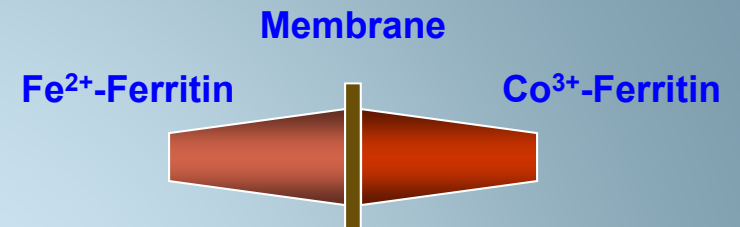


Fe-Co Bionanobattery Cell – Wet Cell

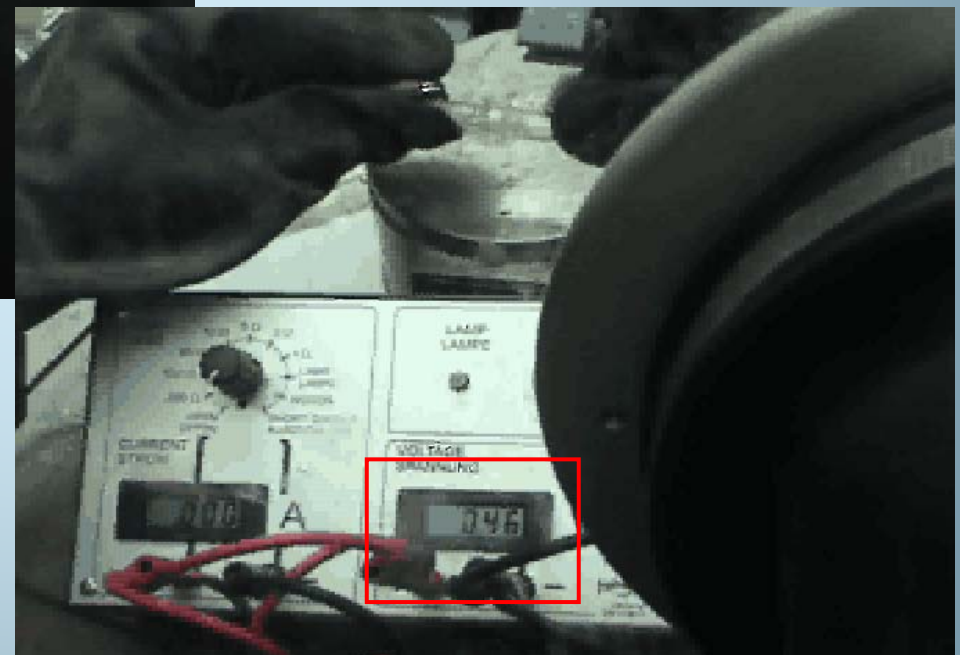
Bionanobattery Demo Cell

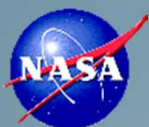


No Connection



0.46 V / Unit Cell
After Connected





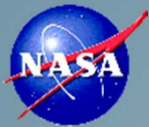
Fe-Co Bionanobattery Cell – Solid Electrodes



Thiolated Fe^{2+} $\rightarrow$ thiolated Co^{3+}

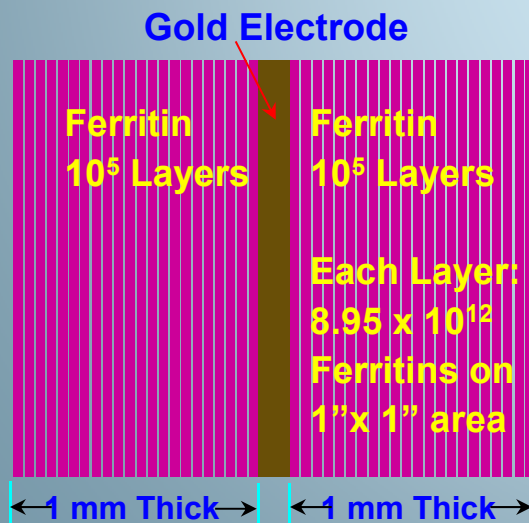
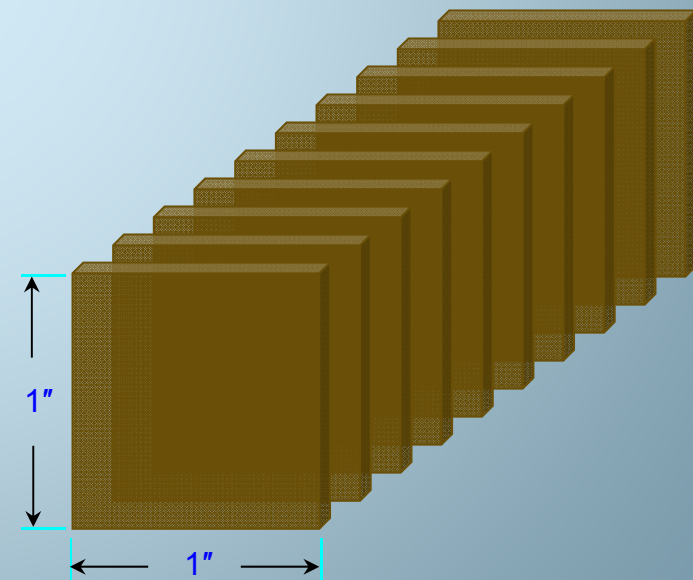
0.25 V / Unit Cell

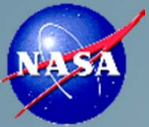




Estimation of Electrical Output

- Electrode: **1"x1"** Gold Films Coated on Both Sides of A Quartz Slide
- Total Number of Ferritin on Each Layer of 1" X 1" Area: **4.48×10^{12}**
- Total Available Electrons: 2×10^{16} per layer = **3.2×10^{-3} Coulomb**
- Charge Density per Electrode (2×10^5 layers): **640 Coulomb**
- Cell Charge Density (Array of 10 electrodes): **6400 Coulomb**
- Operational Run-time: **6400 seconds** when Fe^{2+} - Co^{3+} electrodes discharge **1 C/sec**
- If we connect 10 gold electrodes together, then
 - Parallel connection: **0.79 V, 1 A (2844 mWh)**
 - Serial connection: **7.9 V, 100 mA**

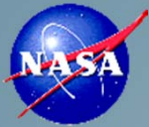




Summary

The areas discussed are still under development.

- Nano Structured Materials For TE Applications
 - SiGe and Be-Te
 - Nano Particles and Nanoshells
- Quantum Technology For Optical Devices
 - Quantum Apertures
 - Smart Optical Materials
 - Micro Spectrometer
- Bio-template Oriented Materials
 - Bionanobattery
 - Biofuel Cells
 - Energetic Materials



Team Members

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Dr. Yeonjoon Park	SiGe, TE, & SOM	National Institute of Aerospace
Dr. Jae-Woo Kim	Bionanobattery	National Institute of Aerospace
Dr. Sang-Hyon Chu	Bionanobattery	National Institute of Aerospace
Mr. Glen C. King	General Support	NASA Langley Research Center