MPB Communications Inc.	INRS Énergie et Matériaux

4th Round Table on

Micro/Nano Technologies for Space

Dynamically-Variable Thin-film Smart Radiator Device

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Introduction

- Spacecraft are subjected to large external temperature swings (–150/ +150°C).
- Internal temperature must be regulated over 0 to 40°C.
- Efficient thermal control of spacecraft is an important issue

- Current dynamic thermal-control systems employ mechanical louvers
  Bulky (3.3 kg/m^2), and expensive (~$100K US per m^2) .

- A new approach to smart radiator devices (SRD):
  Development of a smart thin-film coating ($V_{1-x-y}M_xN_yO_n$)
  Smaller, cost-effective, lighter and simpler
  Can be applied to
    -existing thermal blankets (Kapton and Teflon FEP) (passive)
    - thermal radiators (Al), active thermal control.

- Mainly two other miniaturization methods are actually being developed.

a) Micromachined louver systems (on Si) using MEMS technologies.

b)Miniaturized heat pipes using mechanically pumped cooling system with a working fluid circulated through microchannels by a micropump.

The thin film SRD approach has significant advantages over competitive technologies:

1) Direct integration with spacecraft structure
2) Minimal added mass (<20 g/m^2)
3) Ni moving mechanical components
4) Large dynamic variation in thermal conductance and thermal emission.

Metal-Insulator Transition

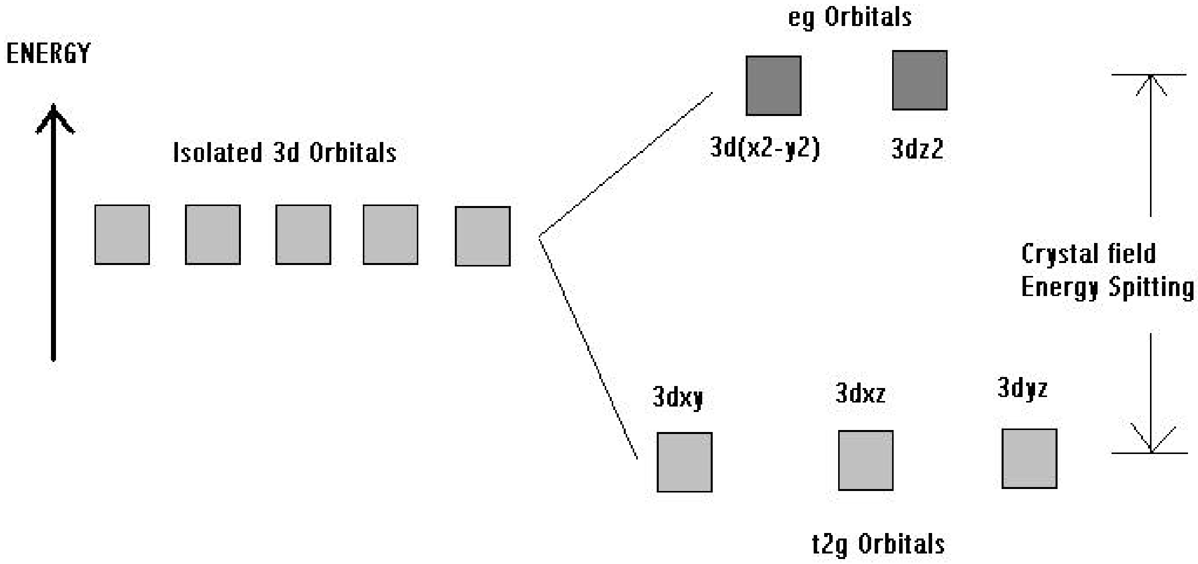
- Thin films based on **transition metal oxides** can exhibit significant changes in their crystallographic structure, and corresponding electrical and optical characteristics in response to external stimuli such as temperature, electric field and/or an optical control signal.

- Many of the transition metals such as **W, Mn, La, and V,** are characterized by partially-filled d-orbitals that contribute to the metallic bonding and electrical conduction.

- The transition metals can readily form a variety of complexes involving the d-orbitals. Chemical bonding of the transition metals to various ligands, such as oxygen, can produce an energy splitting, Do, of the d-orbitals due to electrostatic ionic and electron-electron interactions.

- Depending on the electron occupancy of the d-related orbitals in the complex, the energy splitting of the original transition metal d-orbitals can result in an effective band-gap for optical absorption and conduction, producing insulator-like behaviour.

- By increasing the effective population of conduction electrons in the complex through optical biasing, temperature or field-effect, a transition to a metallic state can be induced at a critical electron concentration.



$V_{1-x-y}M_xN_yO_n$ (M, N =Ti, W, Mo)

VO_n exhibits one of the **largest** observed variations in electrical and optical characteristics due to the metal-insulator transition.

The formation of a chemical complex with oxygen causes energy splitting of the V transition metal d-orbitals due to the electrostatic repulsion between the d-orbital electrons and the negatively-charged oxygen ions.

The small ionic radius of V^{++} allows a strong electrostatic interaction resulting in a relatively large effective band-gap, Δ_o, for optical absorption and conduction (> 2.2 eV).

At a critical electron density, electron correlation effects screen the ionic cores, reducing the d-level energy splitting.

The metal-insulator transition in V_xO_n is associated with a change in structure from a monoclinic structure below the transition temperature to a tetragonal rutile structure above the transition temperature.

The transition temperature increases with the oxygen content:

~ 126 K for VO,

~ 140K for V_2O_3

~ 341 K for VO_2.

Additional dopants, M, such as Ti and W, can be used to:

- shift the transition temperature and

-tailor the resulting dynamic thermo-optic characteristics.

VO_2 Smart Radiator characteristics

VO_2 characteristics

1) Transmittance

Highly transparent insulator below a critical electron density n_c (T> 65% between 2 and 14 µm)

2) Reflectance

Reflective semi-metal above the critical electron density

3) Electrical Conductivity

Three order of magnitude increase in electrical conductivity (σ)

4) Electrical – Thermal Conductivities (Wiedemann-Franz law)

For Temperature T above the metal /insulator transition, Related by;

$$k = p^2/3\,(k_B/e)^2 T s \quad \Leftrightarrow (k/\,s\,T) = (p^2\,k_B)\,/\,(3e^2) = 2.45\ \mathrm{x}10^{-8}\ \ (W\ ÙK^{-2})$$

(s)electrical conductivity, (k) the corresponding thermal conductivity and T is the temperature,(k_B is Boltzman constant)

5) Passive-Active control

Passive thermo-chromic device: transition controlled by thermal heat, light or a laser beam.

Active electro-chromic device: transition controlled by voltage applied to the coating

Summary of the methods of VO_2 transition control.

Physics of the transition control

A- Transition happens when the electron density (carrier) exceeds a critical threshold (Mott's Criterion)

$(n_c)^{1/3}\, r_c \approx 0.25$ **r_c is the Bohr radius**

B- The critical electron density is given as :

$$n_c = n(T) + (N_d - N_a) + N_{ph} + n(V)$$

1- Passive transition

Passively by temperature through thermal generation of carriers **(n(T)).**

2- Control the temperature transition

By doping the VO_2 with donors **(Nd)** such as Mo or W to increase the carrier concentration, that can mainly decrease the temperature of the transition

3- Tailor the temperature: smooth gradient of switching vs temperature:

Tailor the transition temperature relative to the intrinsic value of about 68°C over a wide range from below -30°C to above 70°C by adding a second dopant, for example with electron acceptor (Ti) the electron density decreases by **(Na)**

4- Voltage control

Applying a voltage that creates a field-effect to shift the Fermi level in the VO_2 to enable a metallic / insulating state transition, the carrier density increases by **n(V).**

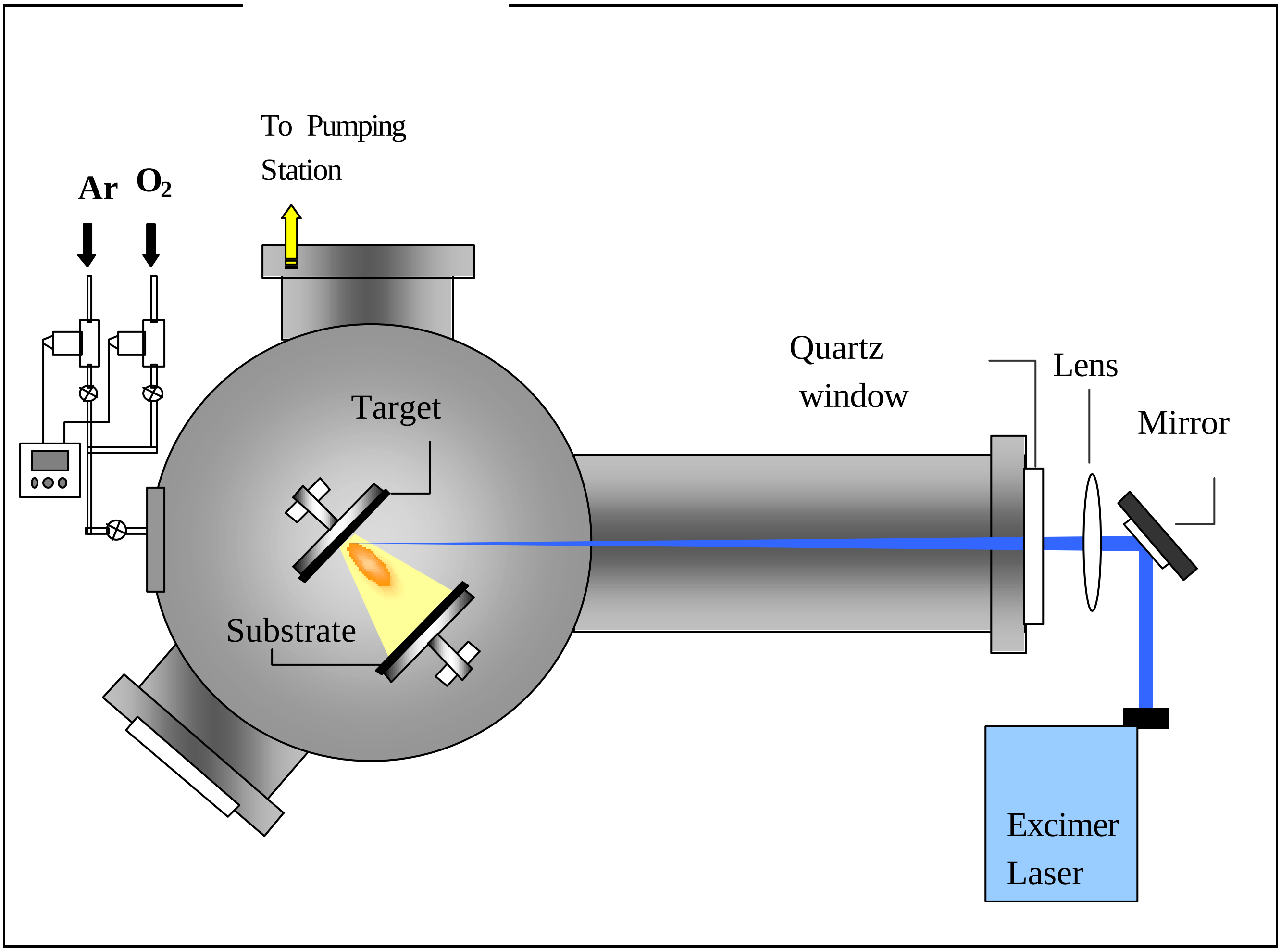
5- Laser beam excitation

The transition can be produced through a laser beam interaction; the carrier density is then Nph

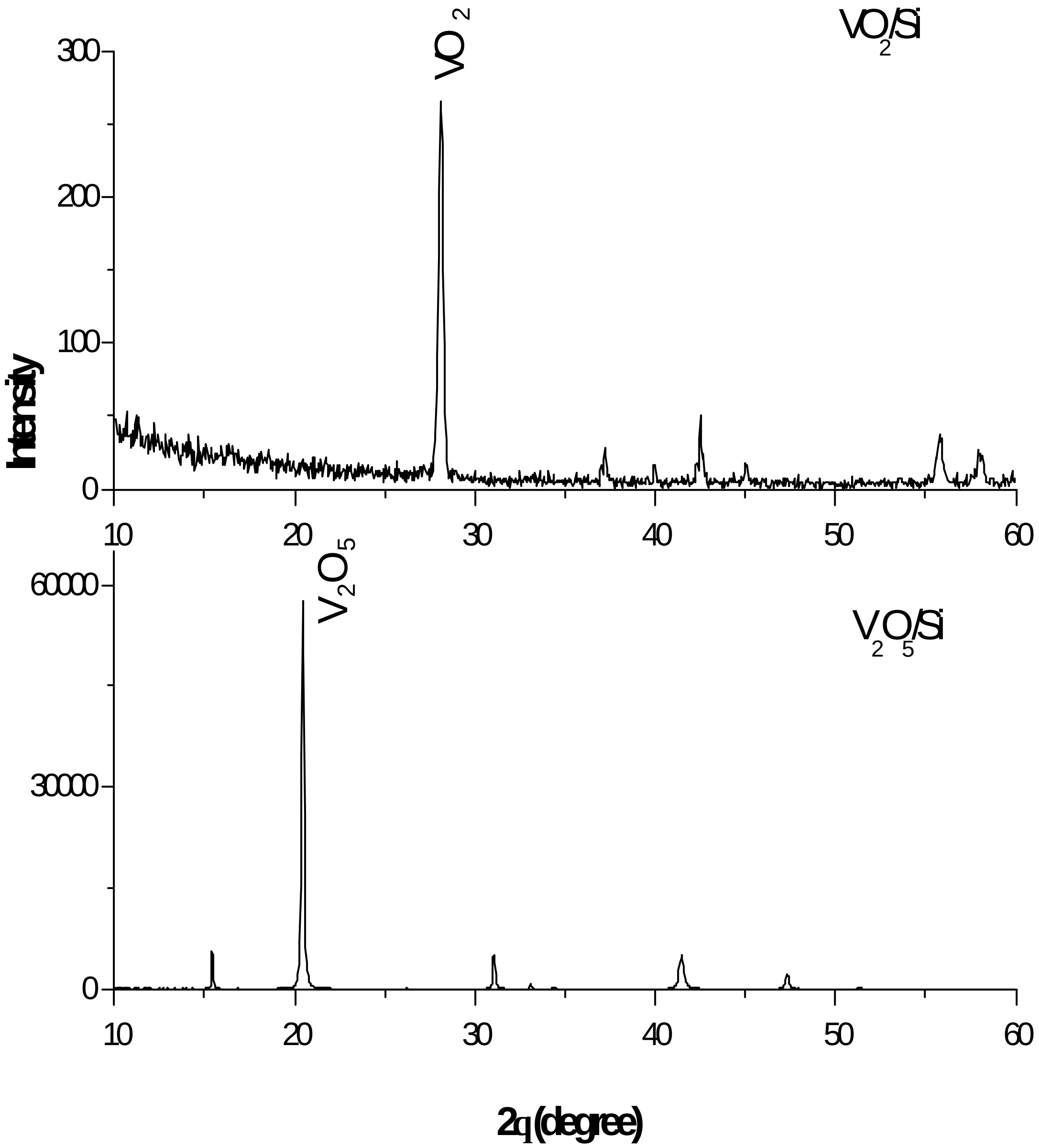
Experiment

VO_2 thin films preparation:	**Reactive pulsed-laser deposition**
Crystallographic Characterization:	**X-Ray Diffraction (Theta-2xTheta)**
Thermochromic Properties:	**- Emissiometer** **-Fourier Transform Infrared Transmittance (FTIR)** **- Temperature Reflectance spectroscopy (1 to 3 µm)**
Electrical measurements:	**Sheet resistivity as function of temperature**

Reactive Pulsed Laser Deposition Setup



Crystallographic Properties



XRD patterns of VO_2/Si and V_2O_5/Si thin films deposited at 520^{0}C.

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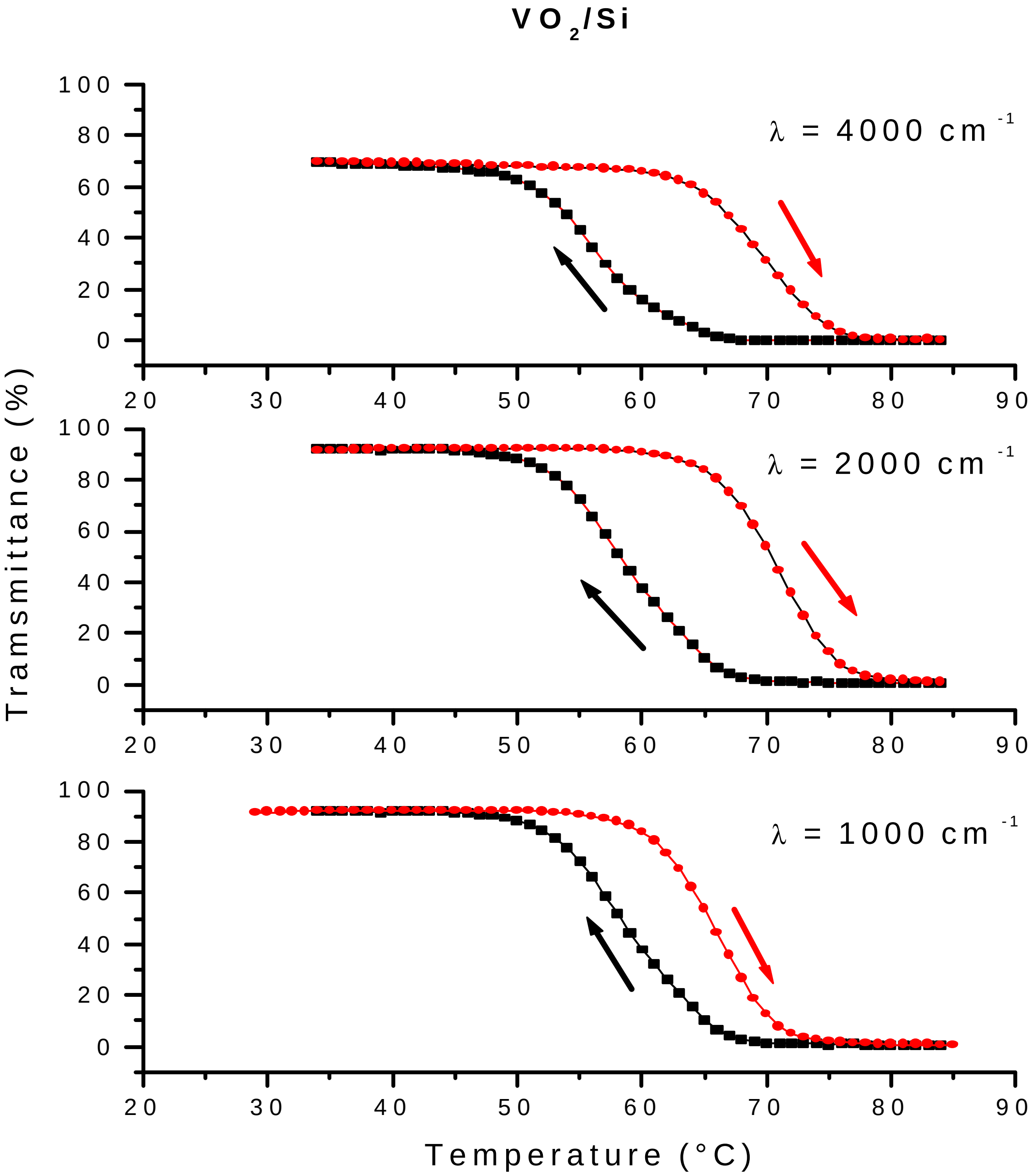
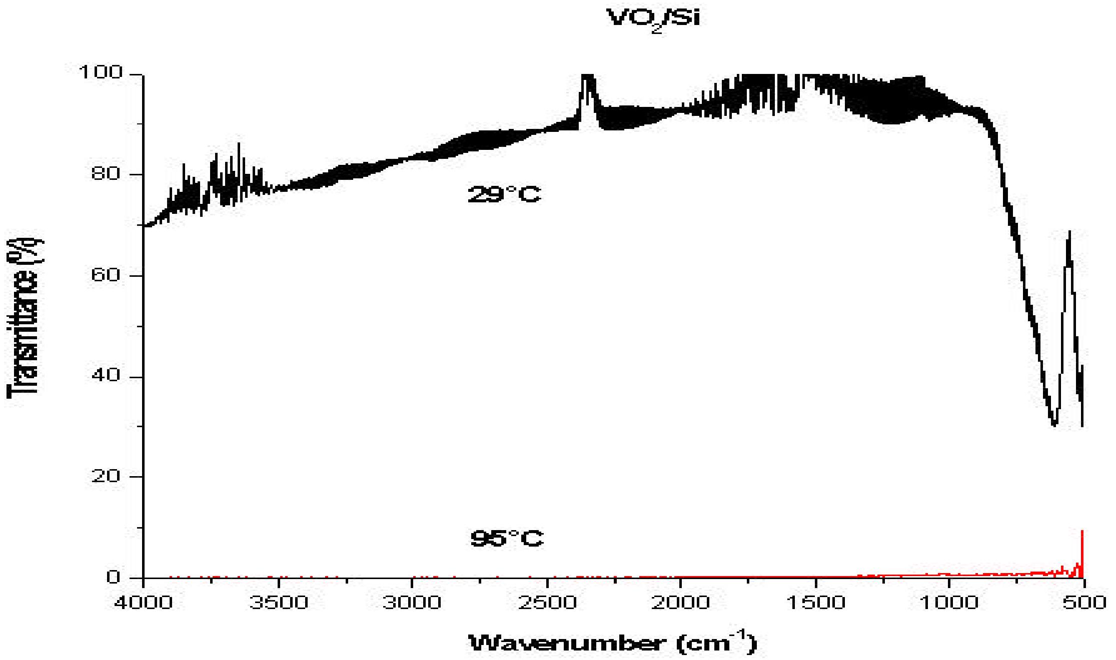
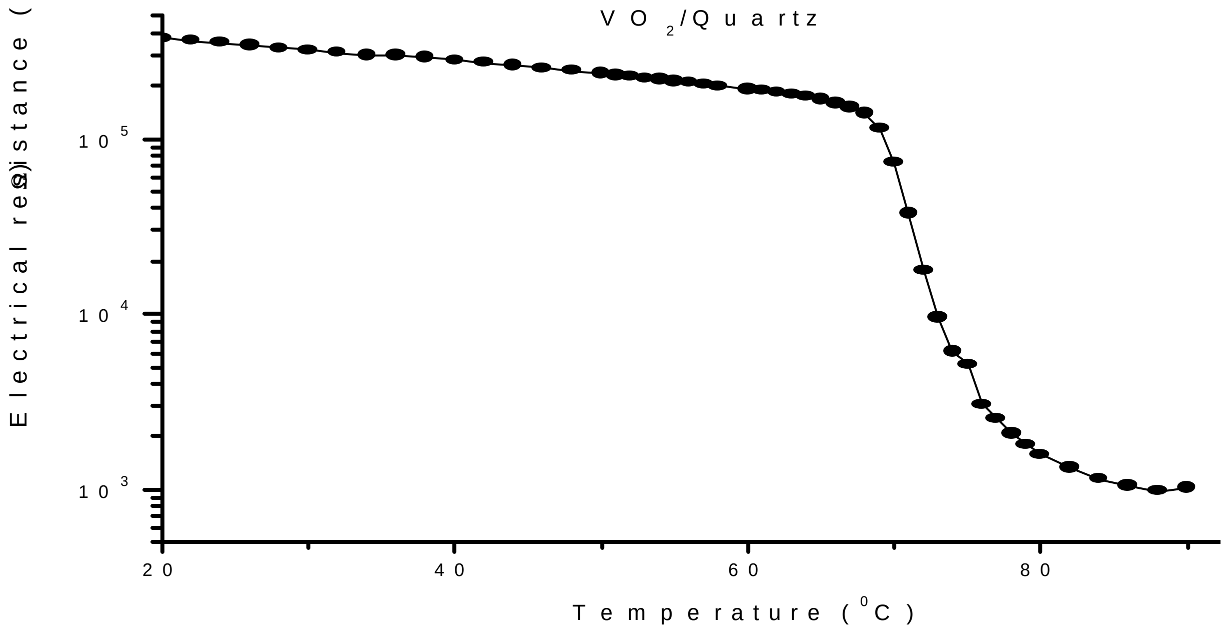
Thermochromic Properties



Temperature optical hysteresis deduced from transmittance measurements (FTIR) of VO_2 thin film onto silicon carried out at 1000, 2000, and 4000 cm^{-1}.

Transmittance measurements (FTIR) of the VO_2 thin film on Si in the semiconductor state (29^0C) and the metallic state(95^0C).

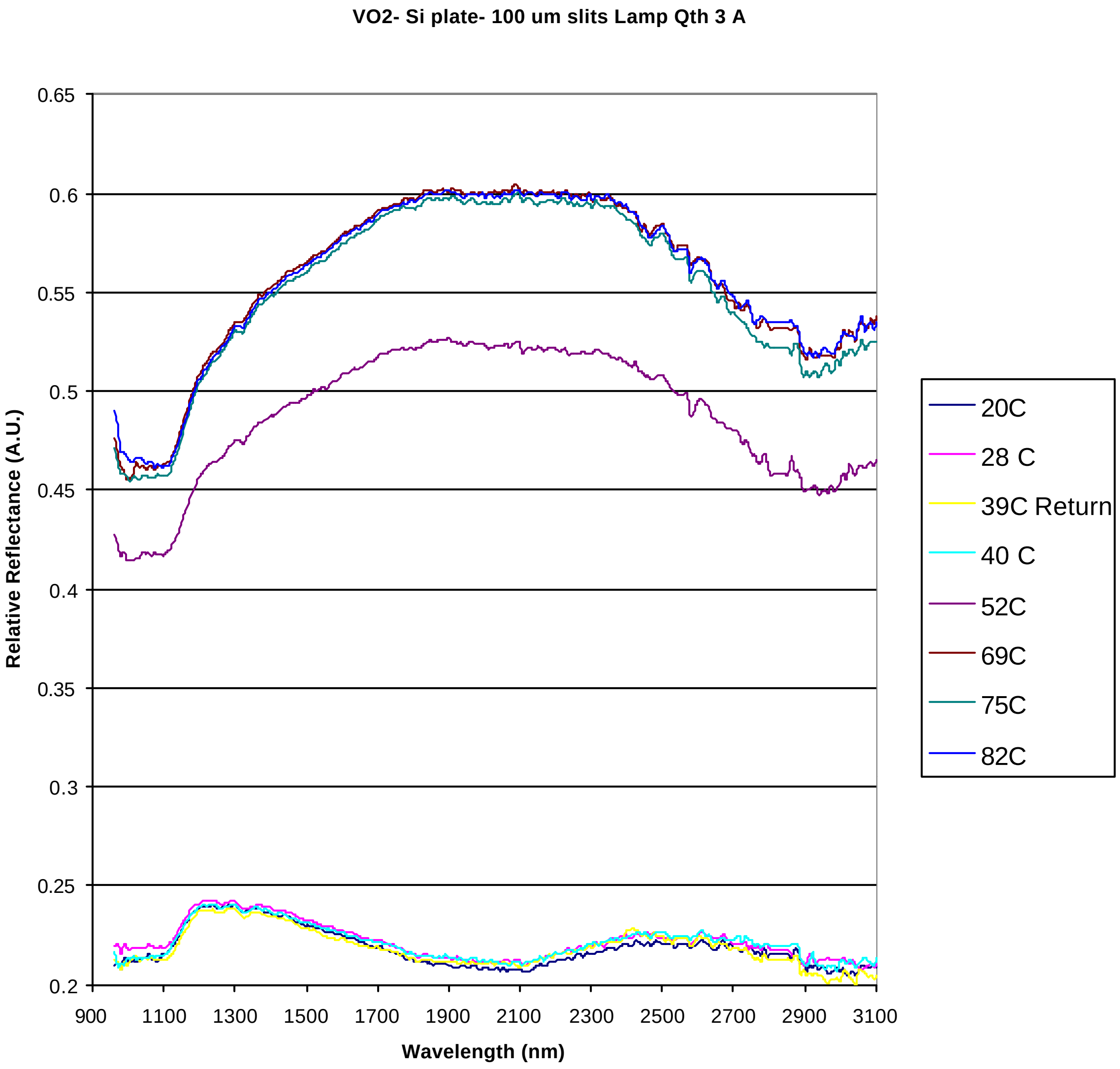




The variation of the resistance of the VO_2 on quartz, as measured using the four point probe technique (3 order of magnitude).

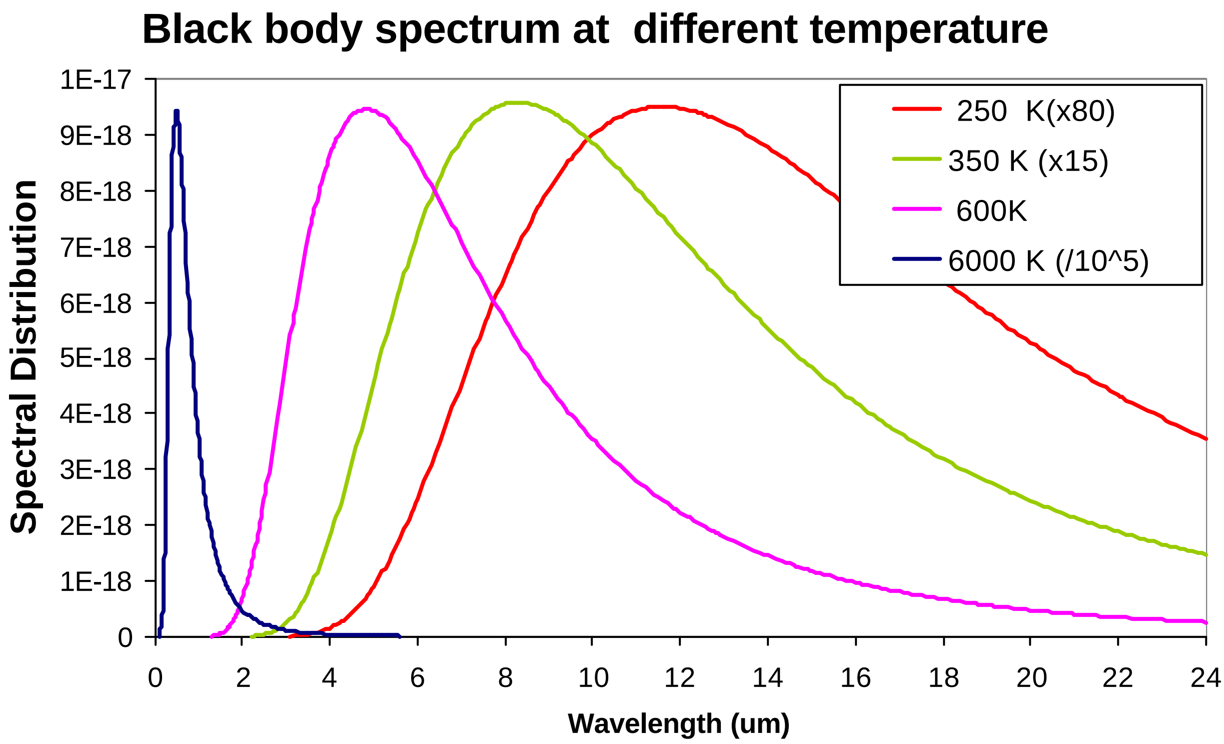
NIR (1-3μm), at 45^{o} Reflectance spectrum of VO_2/Si as deposited at 300^{o}C onto Si. The 100% reflectance is relative to an Al mirror.

Reflectance below the transition temperature is mainly the background reflectance of the underlying c-Si substrate.



Reflectance spectroscopy of the VO_2 thin film onto silicon on a semiconductor state (28^{0}C) and a metallic state (82^{0}C)

Emissivity of the VO_2 thin film



The blackbody spectral distribution function (M) is:

$$M(l,T) = \frac{2phc^2}{l^5}\frac{1}{\exp\left[\frac{hc}{lkT}\right]-1}$$

where ë is the wavelength and T temperature.
The spectrally dependent emittance is given by:

$$e(l) = [1 - T(l) - R(l)]$$

The global emissivity is given by

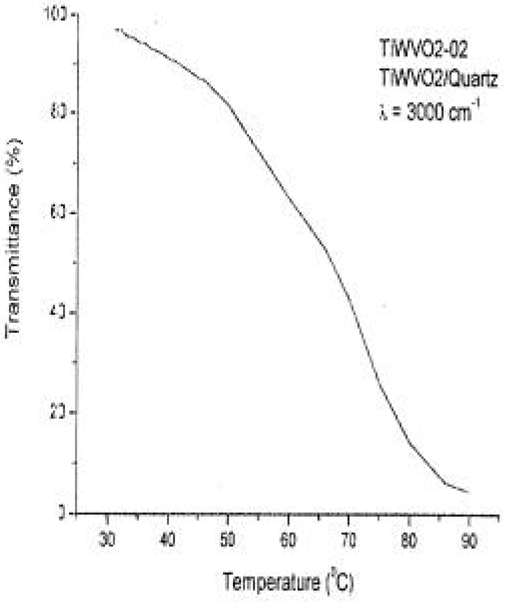
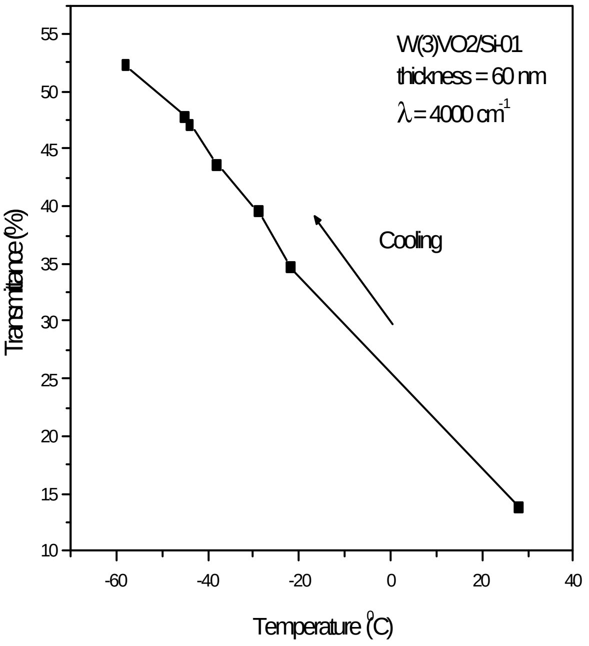
$$\mathrm{E} = \frac{\int_{l_1}^{l_2}[1 - T(l) - R(l)]M(l,T)\,dl}{\int_{l_1}^{l_2}M(l,T)\,dl}$$

Doping of VO_2

Codoping VO_2 with W and Ti produced a much broader transition region spanning over 50 °C, as shown below.

This type of characteristic is desirable for a passive SRD since it facilitates a gradual change from metallic to insulator behaviour in response to the ambient temperature.

The results indicate that there is considerable flexibility to tailor the optical characteristics and the transition characteristics of the VO_2.

VO_2 on quartz, codoped with Ti/W (Low %): Optical transmission at 3000 cm^{-1}	**VO_2 on quartz, codoped (High %) with Ti/W: Optical transmission at 4000 cm^{-1}**
	

Characteristics of the three main thin-film smart-material sytems

Parameter	$V_xX_{1-x}O_n$	WO_n	$LaSrMnO_n$
Substrate	SiO_2,Si, sapphire, Al	ITO/glass or other transparent conducter.	ZrO_2, $LaAlO_3$, $SrTiO_3$
Device Thickness	< 0.15 mm.	About 1 mm.	0.2 mm tiles, 1500 nm coating on ZrO_2.
Colorant	Metal-insulator transition Crtitical e^- density	H, Li, Na ions	Thermal electrons, composition.
Deposition Technique	- RF sputtering - laser ablation - sol –gel dip coating	- reactive sputtering - e-beam evaporation -laser ablation	- sintering powders at 1200°C - laser ablation
Switching mechanism	Thermochromic or electrochromic:	Electrochromic: (ionic colorant M):	Thermochromic Fero=>paramagnetic (metal=> insulator)
Emissivity change (De)	> 0.25 (passive) > 0.5 (active)	0.2-0.4	0.2-0.3 0
Solar Absorptance	< 0.25		0.80
Mechanical integrity	High, direct integration with radiator	Medium	Requires special ceramic substrate.
Ease of assembling	Simple structure.	More complex, more layers	Critical composition.
Mass	Lowest, can be directly applied to Al radiator.	Medium to low	Requires special ZrO_2 substrate.
Life time	> 10^8 switching cycles	Trapping of colorant (degrade reversibility)	To be tested.
Potential Failure Modes	Potential electrical shorting for electrochromic devices.	Colorant trapping. Potential electrical shorting	Composition change Mechan integration with spacecraft.
Response Time	1 ns for active 100 fs for passive	Few seconds at RT	No available data.
Tolerance to	Resistant to VUV AO.	Potential coloration by	No data available.

radiation	**Vacuum-compatible**	**energetic protons.**	

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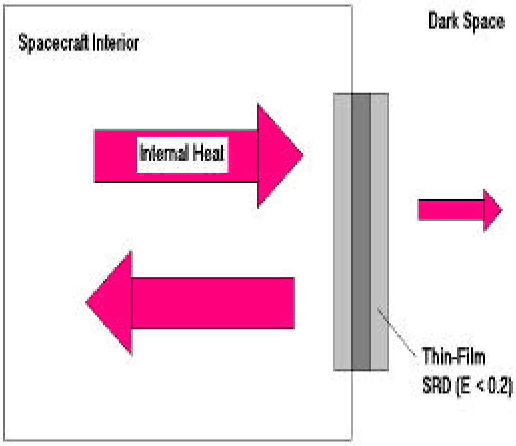
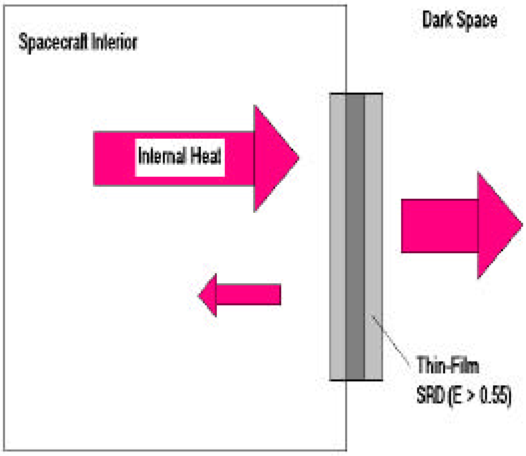
Dynamic Thermal Control of Spacecraft Using Thin-Film Smart Coating

A) Passive SRD

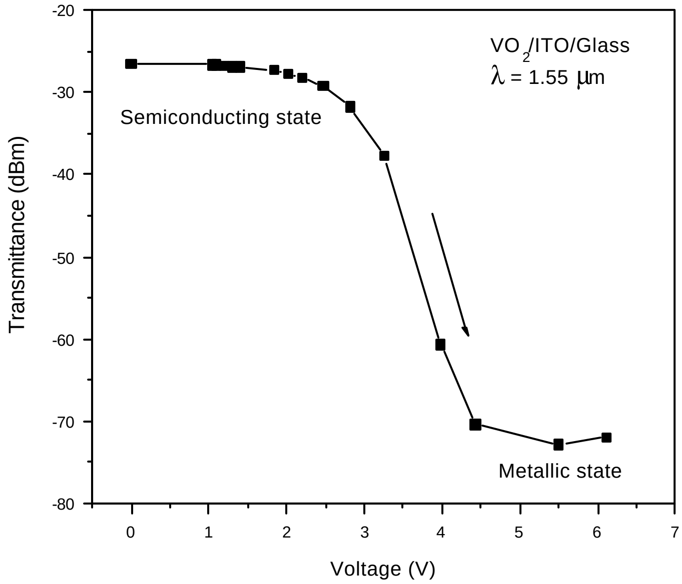
(a) Low-Temperature Case:



(b) High-Temperature Case



B) Active SRD



Simple basic structure of the active voltage-controlled SRD

1. **Al substrate**
2. **Insulator layer - thermal emitter**
3. **VO_2 semiconductor layer - emittance modulator**
4. **Electrically-conductive optical window.**

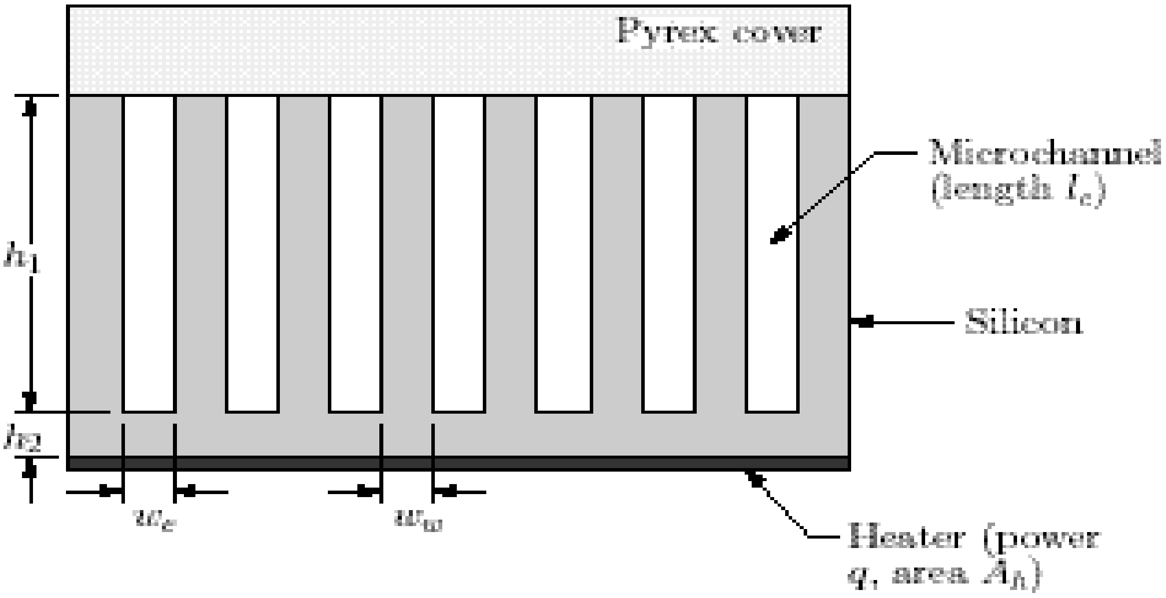
Measured Thermal Emittance

Metallic: 0.3 +/- 0.05

Insulating: 0.75 +/-0.05

Other Thermal control Miniaturized Technologies

Example of a micro louver in open position (above) and Micro heat pipes (below)



Qualitative comparison of the three miniaturization technologies

Parameter	Thin-film Smart Coating	Micro-louvers	Heat Pipes
Mechanical integrity.	Coating is covalently bonded directly to satellite materials.	Needs installation of louvers with hinges.	Easily integrated within the pumping system
Thermal coupling efficiency.	Excellent	Good	Very good
Heat rejection capability	High thermal emissivity contrast possible (factor of 4 or more).	High contrast for single louver but overall contrast reduced due to limited louver packing density.	Controlled by fluid flow rate and emitter efficiency.
Complexity	Simple structure thin-film directly applied to spacecraft structure.	Complex micro-actuator system.	Simple micromachined heat-pipes complex micro-pump mechanism
Lifetime	Long (>10^8 cycles).	Mechanical wear and stickage.	To prove.
Mass	Lowest	Low	Low
Reliability	Passive, most reliable.	To prove.	To prove.
Failure Mechanisms.	High reliability due to no moving components.	stickage, actuator failure.	Flow blockage, leakage risk
Response time	Fastest (ms to ms)	Fast (ms)	Longer time
Power consumption	Low (excellent)	Medium to high.	Medium
Relative Cost	Low	Low per microlouver, high per m^2.	Medium

No Effect of the Atomic Oxygen (Equivalent to 6 months LEO)

Atomic oxygen Parameter	Value
Fluence	10^{17} particles/ cm^{2}
Flux	10^{15} particles/ cm^{2} /min
Equivalent LEO satellite time to receive same amount AO	6 Months
Atoms energy	0.1-0.2 eV

CONCLUSIONS

- High-quality VO_2 films, about 0.1 to 0.2 mm thick, have been prepared by reactive laser ablation at deposition temperatures as low as 300°C.

- The metal-insulator transition temperature can be tailored from below -20°C ton above 70°C through doping.

- Below this transition temperature, the VO_2 films are insulating in nature and display high optical transmittance over a broad spectral range that extends from the visible to the far infrared

- Above the transition temperature, the films exhibit a sharp drop in optical transmission and a corresponding sharp increase in their electrical conductivity and reflectivity

- The VO_2 system is relatively unique in that it can be employed as the basis of both passive thermochromic and active electrochromic Smart Radiator

- A structure has been developed for a voltage-controlled VO_2-based smart-coating SRD. Preliminary results indicate that an emissivity below 0.25 is attainable in the "ON" or metallic state and an emissivity of about 0.75 is attainable in the normally "OFF" or insulating state.