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Tunable Surfaces and Interfaces for Radiative Control on Space Exploration Vehicles and Habitats

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Abstract

This white paper highlights the important role of radiative surfaces responsive to solar irradiation and the cosmic thermal sink of spaceflight components in the vacuum environment. Engineered static coatings consisting of temperature and electronic transition metal-oxide solids with nanoscale patterning can manage energy exchange and transport in and around spacecraft, its power electronics, and humans in space. Our decadal mission is to understand, create, and optimize vacuum surface coatings and interfaces with broad spectral response using scalable microscale-feature tunable materials.

Summary

We seek understanding of photon transport in various spaceflight environments, specifically the coupling and decoupling of optical and infrared-wavelength sources and sinks. Better fundamental understanding and future development of engineered capabilities can improve the functionality and safety of space exploration technologies and their interaction with biological elements. The working physical principles behind these coatings are based on electromagnetic wave interference, coupling, tunneling, and quantum dynamical fluctuation dissipation at the nano/microscale. The proposed technologies can benefit platforms in vacuum and variable solar irradiance, such as Low Earth Orbit, Lunar surface environment, and deep space. The proposed science is anticipated to benefit human spaceflight exploration as well as the living environment of Earth. Our decade-long objectives are to explore and harness tunable metal-oxide materials that can switch radiative emission/absorption properties via surface temperature conditions or actuated electrochromic states. Early technology development begins from materials informatics, theoretical understanding, and algorithmic optimization of device performance. Through a phase of fabrication and testing of nano/microscale components into proof-of-concept coating samples, academic researchers and industrialists can deliver scaled-up functional engineered materials on spaceflight components.

Background

The vacuum environment of objects in spaceflight eliminates energy transfer via fluid convection and conduction to heat sources or sinks. Therefore, photon radiative exchange in the ultraviolet (UV) to far-infrared/Terahertz electromagnetic wave spectrum plays the primary role in thermal management, unlike under Earth surface conditions. Heat transfer to and from spacecraft and human components are conditional on the following environments: Earth orbital flights, Lunar surface, and deep space, including far from the Sun and near the Sun. Conditions favorable to radiative exchange on the surface of Mars are not as prominent due to its atmosphere. Near-Earth objects in flight are challenged by the 1.5-2 hour cyclical Solar and shadow conditions. In Low Earth Orbit (LEO), unattenuated Solar irradiation can last up to an hour, and ~3 Kelvin cosmic sky on the other side. LEO Solar power flux can reach up to 1370 W/m^2, instead of ~800 W/m^2 within Earth's atmosphere; the dark night sky can dissipate ~800 W/m^2, not including the ~290 K Earth infrared (EIR) radiation. On the Moon, Solar and shadow period conditions are more drastic: 2 weeks each of 70 to 100 K during the Lunar night, and up to 400 K near the subsolar point at Lunar day noon. *Cyclical Sun and shadow conditions warrant radiating surfaces with tunable properties*.

Deep space or Solar missions also warrant thermal regulation via radiative coating design. For example, a Solar probe can benefit from adaptive radiators on the back side of solar cell panels to maximize collection efficiency within a narrower range of temperatures. Another use of adaptive thermal coatings is to regulate heat flow between spacecraft components. This task is critical in managing heat from computer processors, fuel cells, and batteries. Especially in small spacecraft such as CubeSats, little real estate opportunities are available for deployable panels and thermal connectors or mechanical switches. *Our mission is to create thermally managing surface coatings and interface treatments using novel tunable materials designed and fabricated at the microscale*.

The state of the art for spacecraft radiators is the quartz-on-metal optical solar reflector (OSR), with static high IR emittance. Other simple radiative treatments include white paints and silvered Teflon, especially when flexibility is needed. Tunable spacecraft radiative emitters can be achieved with mechanical louvers, both at the macroscale and at the microscale via MEMS, but they rely on a multi-component moving mechanism that may present reliability issues. Finally, an obvious thermal management technique to address components at low temperature is implementing electrical conduction heaters, but they may not be efficient in size, heat delivery, and power consumption [1]. *Overall, the technology to be developed needs to have large areal coverage yet reliable in operation across various spaceflight conditions.*

On nomenclature of radiative properties: Emittance (ε) and Absorptance (α) are the fraction of Planck blackbody radiation outward in the infrared (IR) wavelength range, and inward in the UV to near-IR wavelengths, respectively.

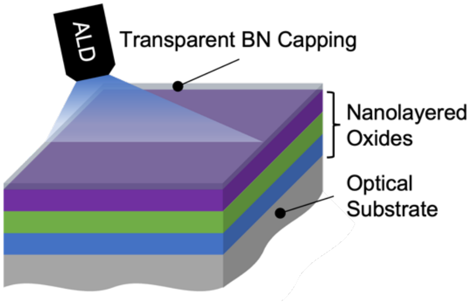
Materials Approaches

Metal-oxide materials can demonstrate variable lattice phononic and electronic phase transitions due to controllable conditions that shift its electronic band structure from an optically transparent semiconductor in broad wavelength range, to a free electron rich metal [2]. In the consideration of electrostatic discharge (ESD), metal-oxides are favorable as the typical built charge is within the conduction band.

An inert thermochromic dielectric oxide material is Vanadium Dioxide (VO_2). The key feature of VO_2 is its ability to transform electronic phases from transparent insulator at low temperatures to metallic at high temperatures. Typical VO_2 insulator to metal transition (IMT) temperature is near 70°C. The temperature transition can be adjusted via ion implantation or chemical doping. During the Vanadium deposition process, a small concentration (<2%) of Tungsten can be co-sputtered. This addition of Tungsten can drop the phase transition temperature to as low as 10°C, through post-deposition treatment in O_2/N_2-controlled 300°C furnace. Our task to grow VO_2 with various metal doping species and concentrations, and exposure to thermal annealing treatments can enable adjustment to IMT. Other stoichiometric compounds such as Vanadium Monoxide (VO) have IMT near 125 K, which may benefit components in cryogenic heat transfer. Other heavy metal-based compounds such as Iron (III) Oxide (Fe_2O_3) may also address cryogenic applications. Titanium (III) Oxide (Ti_2O_3) transitions above 400 K – this metal-oxide may address radiative switching of surfaces in proximity to propulsion structures and sources [3].

Tungsten Trioxide (WO_3) is an electrochromic transition metal-oxide that has a phase change with the application of electrical voltage, typically no more than a few Vdc. This is reversibly changed by injection of positive ions such as Li^+ and H^+ and an electron to balance the charge into the host material, i.e., WO_3. This migration changes the lattice structure significantly enough to change the optical properties to be lightening or darkening. This makes WO_3 a good candidate for tunable radiation coating that will allow control of optical force applied to a spacecraft [1]. Another electrochromic switching metal-oxide worth investigating is Niobium Oxide (Nb_2O_5). On the other hand, Niobium Dioxide (NbO_2) is a thermochromic material with IMT near 1000 K – potentially useful when integrated with spacecraft radioisotope thermoelectric generators. While these metal-oxide compounds are diverse, we plan to pool best candidate tunable optical properties using materials informatics assisted by machine learning algorithms.

Long-term aspects are critical toward reliable functioning coating materials. Spaceflight environments are harsh, from being handled during construction, launch conditions, thermal shock, and bombardment from fast atomic oxygen and gases. A protective component without affecting the oxide material thermal or electrical behavior is needed. One approach is the fabrication of thermal radiative oxide coatings with a dielectric 2D Boron Nitride (BN) capping nanolayer that exceeds thermal stability of many metal oxides. BN also



shares similar structural and mechanical properties with “miracle” material 2D carbon graphene. Unlike graphene, BN is advantageous for its optical transparency from the visible to mid-infrared. Electronic semiconducting properties of BN allows static dissipation. Highly ordered hBN(0001) has already been grown on Al_2O_3, RuO_2, TiO_2, and other oxides for applications toward battery electrode protection and heterostructure deposition for optoelectronics. Proposed new research will explore how the BN capping layer can be used to control temperature phase transition and electrochromic voltage potential changes through various substrate chemistry, strain, Fermi energy, capping layer thickness, and growth conditions. Comparable space conditions can be achieved in a laboratory setting with epitaxy-purposed vacuum and electron beam facilities [4].

Design Approaches

While many metal-oxide materials of non-doped composition have their basic thermal, electrical, and optical properties understood, the most important aspect to a functional engineered surface is its design of multiple and patterned components at the nano/microscale. A mixture of metal-oxides, insulators, metals, and other metal-oxides can be merged into a single multilayered coating. Higher level of sophistication in design includes nanopatterning of repeatable structures, such as periodic gratings, nanoparticles, and nanowires. Here, we explore various successful results of patterned structures using VO_2 and predict forthcoming capabilities of VO_2 within a configuration.

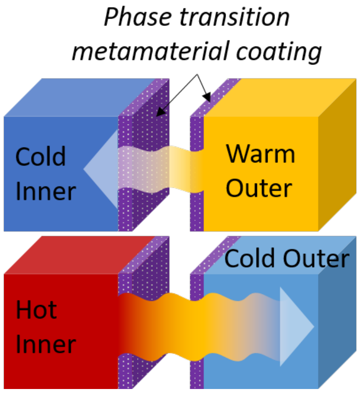
A computationally optimized design of a VO_2 surface grating was found to achieve a record low-to-high emittance enabled by Fabry-Perot étalon interference and plasmonic coupling. The high-performance switching was made possible using a surface layer of horizontally aligned VO_2 nanowires of ~100 nm diameter. The infrared emittance shifts from $\varepsilon = 0.11$ to 0.64 from temperatures below to above its IMT at 70°C. Yet, an effective externally facing switching thermal radiator must also have low absorptance of $\alpha < 0.25$. VO_2 in the visible to near-IR spectrum does not transition with temperature and stays absorbing due to bound electron oscillations. We are inspired to develop complementary gratings with VO_2 that utilize micro-biomimetic-based sunlight rejection techniques and high contrast waveguide phase shifts to minimize radiative absorption under the Sun [5].

Other multi-component structures called uniaxial multilayers can be designed to enable emission tunable to various coating conditions: Responsivity to temperature change, emission selectivity to temperature gradient, angular emission selectivity, and super-narrow or super-wide wavelength range emission or reflection. These performance-enhancing coatings depend on cleanroom fabrication processes of multi-process physical vapor deposition and oxide phase transition priming. These multilayers can demonstrate value in electromagnetic wave coupling, selective emission at oblique angles, and laser and quantum state communications. These operatives with metal-oxide-enabled tunability can offer an additional dimension of functionality.

As the counterpart of an electric diode in electronics, a thermal rectifier or thermal diode is a two-terminal device that allows heat to flow preferentially in one specific direction. The advent of concepts of thermal rectifier, thermal switch, thermal transistor, and thermal memory has spurred one of currently hottest research areas – “phononics”. Tremendous progress has been made during last decade in advancing the fundamental understanding of phonon transport at the nanoscale at the interface of dissimilar materials. The capability of manipulating heat flow has promising applications in thermal management. By modulating heat flow at speed of light, radiation-based near-field thermal devices would be potentially superior to their phononic and even electrical counterparts.

To overcome the previous limitations and achieve much stronger rectification effects, we theoretically demonstrated a vacuum thermal rectifier made of semi-infinite SiO_2 and VO_2 plates separated by a vacuum gap d. In the forward-biased scenario, SiO_2 is the emitter at 400 K, while the receiver VO_2 is maintained at 300 K as an insulator. When temperatures are reversed, VO_2 is the emitter at 400 K as a metallic material due to its phase transition at 341 K. The calculated rectification factor is as high as 0.98 at a vacuum gap of 1 μm, decreases to 0.9 at the gap of approximately 300 nm, and then increases quickly when the vacuum gap further decreases. Rectification factors can be obtained as 1.31 at a 100-nm vacuum gap, 1.67 at 50 nm gap distance, and 1.95 at 10 nm gap distance [6]. Importantly, such strong rectification is achieved when the temperatures of emitter and receiver are close to room temperature at vacuum gaps of tens or several hundred nanometers, which could be possibly realized experimentally [7,8]. Further research is required to seek a deep understanding on the underlying physical mechanism responsible for the strong rectification effect as well as to unambiguously experimentally demonstrate such a novel vacuum thermal rectifier based on near-field radiation with VO_2.

With capability to grow nano/microlayers of VO_2 separated by nano/microlayers of dielectric, metal, and other previously mentioned oxides, anisotropic permittivity multilayers – photonic metamaterials – can provide further vacuum gap rectification control [9]. With anti-symmetric multilayer designs enabled by machine learning algorithm-based optimization toward a figure-of-merit performance metric [5, 10], a near-field radiative switch can be developed that preferentially allows heat to flow directionally. Development of computational tools that can handle multi-parametric transport cases can lead to experimental tests of near-field devices *in situ*.

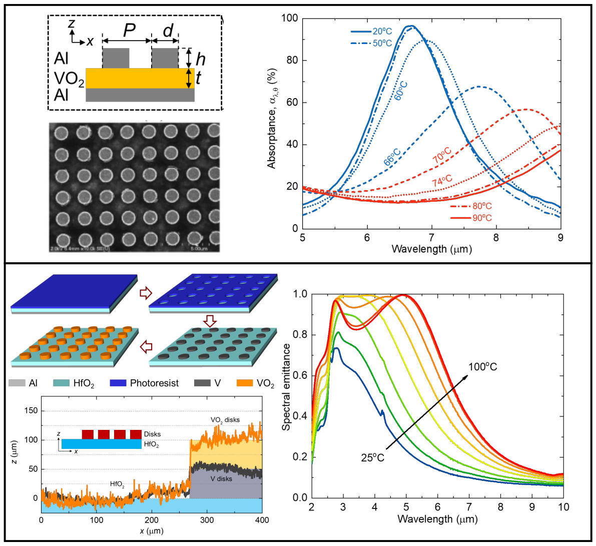


Manufacturing Approaches

Proof-of-concept chip or wafer-area tunable micropatterned coating designs have been demonstrated. 100-nm-thick VO_2 was successively grown on an opaque aluminum thin film with strong IMT behavior verified by temperature-dependent Raman spectroscopy. 2D Al disk arrays with 0.8 μm feature size was deposited on top of VO_2 layer and patterned by a stepper via a photo-lithography process. Temperature-dependent spectral reflectance measurement technique was developed and performed with an infrared spectroscopy microscope along with a sample heating stage for accurate temperature control. The measured spectral absorptance exhibits a broad spectral peak around 6.7 μm wavelength, and does not change when the VO_2 metamaterial was heated from room temperature to 50°C. With further increased temperature, IMT of VO_2 started to occur with apparent magnitude reduction and red-shifting of the spectral absorption peak until 80°C, beyond which there was no further significant change indicating completion of IMT [11].

Other work has fabricated scalable tunable metamaterial emitter with VO_2 microdisks with 1.1 μm diameter and 1.6 μm periodicity in large area on top of HfO_2 spacer and Al film. By directly shifting the MP resonance condition with the phase of VO_2 microstructures, the tunable infrared metamaterial emitter exhibits increased spectral emittance in the infrared as temperature increases to trigger the phase transition of VO_2 from insulator to metal, which is desired for enhanced radiative cooling for heat dissipation at higher temperatures [12].

Multilayered coating can be deposited over a large area, and on polymer substrates for flexibility. Vacuum deposition of metal-oxide layers is sequenced in series along a rolling sheet stock, with possibility of a backside coating. The typical manufactured sheet is 1.2 m (4 ft) wide and 3 m (10 ft) long, but the projected manufacturing capability can yield much longer sheets. A rolling-mask lithography has been developed, where a patterned UV lamp accomplishes sub-micron-scale exposure of photoresist in wide sheets [13]. This method is used to make flexible sheets with optical metasurfaces. If sheet perforation is needed for outgassing, a thin layer of germanium coat can mechanically protect and form an electrical short along the hole.



Thermally tunable infrared emitter made of metamaterials with 2D aluminum gratings on VO_2 layer (top) and with VO_2 microdisk array on HfO_2 film.

Recommendations for Transformative Science

Three research activity thrusts are sought to progress the readiness of tunable coating technology in spaceflight. The fundamental materials sciences and photon transport studies were supported by the National Science Foundation (NSF) and Air Force Office of Scientific Research (AFOSR). The next step in development of practical working coatings has yet to be supported in laboratory mock space environment. Process rollout to increase the size scale of proof-of-concept coatings need to be supported and transferred toward industrialized manufacturing.

(1) *Fundamental materials research on detectability and transmittance of photon states*

The efforts to develop fundamental material understanding and photon-phonon characterization technologies require approximately $600,000 over the emergent 3 years (2023-2026). Academic teams seek to educate and prepare professional development of research-active students or term-limited postdoctoral research associates. Tabletop vacuum cryogenic facilities are designed and constructed to begin future instrumentation of photon coupling measurement. Those supported are aided with high performance computer access and career development activities.

(2) *Design and development of proof-of-concept high performance surface treatments*

The development and testing of optimally designed coatings over the successive 3 years (2026-2029) seeks approximately $1,200,000 to address two interest areas: (a) Thermochromic coatings, and (b) Electrochromic coatings, each with additional objectives to control infrared emission or Solar absorption with selective surface normal or angular distribution. The efforts by collaborating academic research teams utilize and expand nano/microfabrication equipment or capabilities in cleanrooms. Students and researchers gain theoretical and computational proficiency. Pre-career researchers also benefit from novel semiconductor growth and patterning methods – for future domestic electronic device manufacturing.

(3) *Scaled-up nano/micromachining of tunable coatings for spaceflight environment*

Industrial-academic partnered agile processing of large-scale samples takes the final 3 years (2029-2032), covering approximately $900,000 split among academic researchers and staff, and a small manufacturing business (STTR). The shared objectives cover manufacturing methods, packaging, electronics testing, and integration with spacecraft components. Development teams interface with NASA scientists and launch structure/vehicle engineers for spaceflight studies and monitoring.

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