Dynamically Responsive IR Window Coatings

2014 Building Technologies Office Peer Review

**Dynamic IR Coating – Heating**

- IR switching/visible unaffected
- IR → IR
- visible → visible

**Dynamic IR Coating – Reflecting**

- IR heats up
- IR → IR
- visible → visible

**Microscopic view**

- Pre-buckled = disordered

- Metallic nanoshell
- Template particle

- \( \omega_0 = \frac{1}{\sqrt{LC}} \)

- Coating expanded
- glass

- Thermally expanded = ordered

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Pacific Northwest National Laboratory
Project Summary

**Timeline:**
- Start date: 10/1/2013 (NEW PROJECT)
- PPG subcontract start: 1/10/2014
- Planned end date: 9/30/2015

**Key Milestones**
1. Milestone 1 (9/30/14) – Go/No Go to demonstrate lab scale dynamic IR responsive coating with 20% NIR Δ and average (visible transmittance) VT ≥ 50%, with T switch range of 30-90°C.
2. Milestone 2 (9/30/15) – Integrate buckling and subwavelength films at the 6” scale. Performance targets of 10-15% NIR Δ and average VT ≥ 50%, with T switch range of 30-90°C

**Budget:**
- Total DOE $ to date: $375K/FY14
- Total future DOE $: $375K/FY15

**Key Partners:**

| PNNL | PPG |

**Project Goal:**
To develop a low-cost, energy-saving, passively switchable dynamic IR coating by integrating a IR reflective subwavelength nanostructures in a buckling layer. Both lab scale prototypes and intermediate scale-up will be addressed.

**Target Market/Audience:**
Windows Coatings for commercial and residential. Both new and retrofit markets.
Purpose and Objectives

Problem Statement: Current electrochromic and thermochromic window technology runs as much as 16 x double glazing and blocks daylight. This significantly reduces market penetration and subsequent energy savings. This project addresses both cost and a means to allow daylighting.

Target Market and Audience: Commercial and Residential Windows – both new construction and retrofit. Technology will result in 30/20% primary heating/cooling energy savings, while allowing daylighting for potentially as low as $5-8/ft² cost (PNNL projection).

Impact of Project: If successful, switchable IR window coating technology has technical potential to save up to 2.24 Quad/yr in heating, cooling, and lighting.

1. Project will develop lab-scale prototype and address intermediate level scale-up.
2. Metrics for success
   a. Lab scale prototype film development & intermediate level scale-up
   b. R&D on durability, aesthetics, cost (1-3yr after project)
   c. Pilot scale testing (beyond current (3+yr after)
**Approach - Summary**

**Approach:** Combine a scalable nanostructured coating with a passive thermally switchable buckling coating to create a dynamic IR window film. Laboratory scale and then intermediate scale-up will be addressed.

**Distinctive Characteristics:**
- Tailorable subwavelength nanostructured coatings to control VT and IRT separately
- Buckling effect used for passive thermal switching

**Key Issues:**
- **Tailored IR response:** Subwavelength features allow for tailored IR response
- **Buckling Films:** Allows passive switching controlled by materials & processing conditions
- **Scale-up:** Intermediate level scale-up is a critical challenge and will be the major focus of Year 2
Approach – Nanostructured Coatings

Subwavelength Structures:

• Window coatings based on nanostructures smaller than wavelength of light
• Coatings contain an ordered, oriented array of the metallic nanoshells
• Open-ring resonator (ORR) nanoshells that are optically responsive
  – Resonance tuned in the visible/IR by adjusting fabrication parameters
  – Structure has intrinsic capacitance and inductance to form analogous resonant LC circuit
  – Multiple sizes will be needed for longer wavelengths (future scope)

Approach – Subwavelength Structure Design

- PNNL Numerical modeling was used to determine optimal structures
- FDTD Cad program – solving Maxwell’s eq. at each point in a mesh/
- Parameters varied: metal type, thickness, deposition angle
- Results target 70% Visible transmission and 50% NIR (750-900nm) reflection
**Template Process**

- Nanoparticle solutions

**PNNL Fabrication Approach**
- Scalable to large areas
- Wet deposition nanoparticle template
- Directional metallization to form nanoshells

**Fabrication Parameters**
- Particle diameter
- Particle separation (linked)
- Metal thickness
- Metal deposition angle

**Metal coated Nanoshell arrays**

100 nm
Approach – Reversible Buckling

**Thermally Reversible Buckling**

Room temp → 30-90°C

Buckling disorders the nanoshell array allowing IR transmission

**Buckling Geometry:**
- Stiff film/soft film stack
- Pre-buckled at room temperature gives disordered nano-array
- Heating expands and flattens film – giving ordered nano-array

**Tuning:**
- Wavelength/Amplitude tuned by choice of material modulus (E), and thickness (t) and deposition
- Temperature response set by material choice (CTE) and processing conditions

**Buckling Equation**

\[ \lambda \sim t \left( \frac{E_f}{3E_s} \right)^{1/3} \]

Integrated Film

- Microscopic view
  - IR nano-coat
  - glass
- Pre-buckled = disordered
- Thermally expanded = ordered
Approach – Scale-Up: Large Area Template Coatings

Scale-Up of Template coatings

- PPG developing process to coat large areas
- Focus on intermediate level scale-up > 6” width

Fabrication Parameters

- Coatings of polymer nanoparticles
- Size determined by PNNL modeling
- High degree of monodispersity

TEM of PPG nanospheres
PPG developing scalable directional metallization

**Standard Geometry**
- Cathode & sputtering target
- sputtered vapor flux
- direction of substrate motion
- Substrate

**Proposed Oblique-Incidence Geometry**
- Cathode & sputtering target
- sputtered vapor flux
- Substrate
Progress and Accomplishments

Lessons Learned: Metal oxidation of the nanoshells has become a potential issue upon migration to Ag. An additional protective coating was necessary, but requires adjustment to retain optimal optical properties.

Accomplishments:
- Demonstration of reversible buckling
- Demonstration of IR specific subwavelength nano-arrays
- Demonstration by PPG of 200 ft. long x 10” wide templates

Market Impact: The target markets for this dynamic window coating are new and retrofit commercial and residential buildings. Technology will result in 30/20% primary heating/cooling energy savings, while allowing daylighting for potentially as low as $5-8/ft² cost (PNNL projection). Savings in all climate zones are possible as the coating surface within the window (interior/exterior pane) may be varied based on climate and tailored to maximize energy savings.

Awards/Recognition: none at this time.
Progress and Accomplishments – Reversible Buckling

**Thermally Reversible Buckling**

- Fabricated pre-buckled bilayer film
- Demonstrated reversible buckling over multiple cycles with optical microscopy

**Reversible Buckling demonstrated >5 cycles**

18°C | 40°C | 50°C
--- | --- | ---
60°C | 90°C | 21°C

Wavelength chosen to be visible with microscope

Measured with in-situ optical microscopy heating stage
Progress and Accomplishments – Nanoshell Arrays

Demonstration of nanoshell arrays that meet milestone 50% average VT and block 53% of NIR

Metal coated Nanoshell arrays

Preliminary Transmission Data

- Demonstration of lab-scale (2” diameter) subwavelength nano-arrays via the template and directional metallization approach.
- Using Ag as optimal metal for nanoshells due to cost and optical properties – still adjusting oxidation protective layer.
- Preliminary data shows >50% average visible transmission with clear dip in NIR transmission, down to 47%.
- Additional optimization of the structures, layers, and control of defects should lead to improved performance.
Progress and Accomplishments – Scale-Up Templates

- More than 200ft of 10” wide template coating was made in first trial
- PPG synthesized optimum sized polymer nanospheres with ability to modify diameter if needed
- High degree of monodispersity
- Some defects are present – multilayer and voids in roughly equal amounts
- Opportunities for improvement by identifying and fixing source of repellencies leading to voids

![SEM of well ordered monolayer](image1)

![Optical micrograph of defects](image2)

![SEM of defects](image3)
Progress and Accomplishments – Scale-Up Metallization

- Objective: deposit partial metallic nanoshells on nano-templated substrates supplied by PNNL and PPG

- Directional Sputter Deposition Source
  - Conceptual design in-place
  - Drawings and quotation in-preparation
  - 0-45° incidence (from normal to substrate surface)
  - Possible need for mechanism to collimate vapor flux
  - Substrate rides on conveyor below source

- Preferred metal = Ag (currently used in Low-E)
- Preferred incident angle = 30°
**Project Integration and Collaboration**

**Project Integration:** This is a joint project between PNNL and PPG, which accelerates market impact. Project team communicates through frequent email, monthly telecoms, quarterly reviews with the client, and yearly site visits and/or reviews.

**Partners, Subcontractors, and Collaborators:**
- PNNL(lead): to develop laboratory scale dynamic IR films
- PPG: to develop intermediate level scale-up of the dynamic IR films

**Communications:** Alvine, *et al.* “Subwavelength Films” OSA Renewable Energy and Environment, Tucson, AZ (2013) *invited talk*
Next Steps and Future Plans:

Project Activities:
Lab scale:
- Fabricate disordered subwavelength film
- Integrate buckling and subwavelength film to demonstrate IR switching

Scale-Up
- Evaluate and optimize scaled-up templates and etching
- Complete design and build directional metallization setup
- Fabricate subwavelength films and integrate with switching layer
- Demonstrate intermediate scale IR switching coating

Tasks for Possible Expansion
- Additional work on oxide getters/barriers – potential to improve durability and increase optical performance. Requires additional modeling and lab-scale testing of nanoshells.
REFERENCE SLIDES
**Project Budget**: $750K Federal Funding, $78K cost share from PPG. Full Federal Funding of $750K was authorized on 10/1/2013.

**Variances**: N/A.

**Cost to Date**: Cumulative spent as of 3/21/2014 = $127,281.

**Additional Funding**: N/A other than cost share.

### Budget History

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Project Plan and Schedule (1 of 3)

Project Plan:
- New Start: 10/1/2014 – 9/30/2015
- 4-6 week extensions granted for FY14 Q2 milestones due to needed repairs/oversubscription on sputter chamber and longer than expected subcontract negotiations. This is not expected to impact future milestones.
- Go/no-go decision point at end of FY14 – see schedule

### Project Schedule

**Project Start:** 10/1/2013 (New Start FY14)

**Projected End:** 9/30/2015

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**Project Schedule**

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- **Projected End:** 9/30/2015

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**Go/No Go Decision Point**

- FY2014 FY2015 new start FY2014

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**Completed Work**

- **Active Task (in progress work)**

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**Milestone/Deliverable (originally planned or granted extension)**

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- **Q1 (Oct-Dec)**
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- **Q3 (Apr-Jun)**
- **Q4 (Jul-Sep)**
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