International Workshop on Glass for Harvesting, Storage & Efficient Usage of Solar Energy

Sheraton Station Square Hotel, Pittsburgh Nov. 16 -18, 2008

Windows of the Future:
Materials Solutions to Global Energy Challenges

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This work was supported by the Assistant Secretary for Energy Efficiency and Renewable Energy, Office of Building Technology, State and Community Programs, Office of Building Research and Standards of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

Outline

- Higher level energy considerations of buildings envelope & windows
- Vision: The zero net energy building
  - Role of façades, windows, & glass
- Evolution of modern windows:
  - Low-e glass
  - Solar control coatings
  - Switchable windows
- The window as a switchable device: approaches and materials
  - Liquid crystal and suspended particle devices
  - Gasochromic
  - Electrochromic (absorbing versus reflecting)
- Challenges:
  - The intelligent façade
  - The window as multifunctional device – “window of the future”

US Window-Related Energy Consumption

(Quads)

	Residential	Commercial
Heating	1.65	0.96
Cooling	1.02	0.52
Total	*2.67*	*1.48*

Daylight: +1 Q

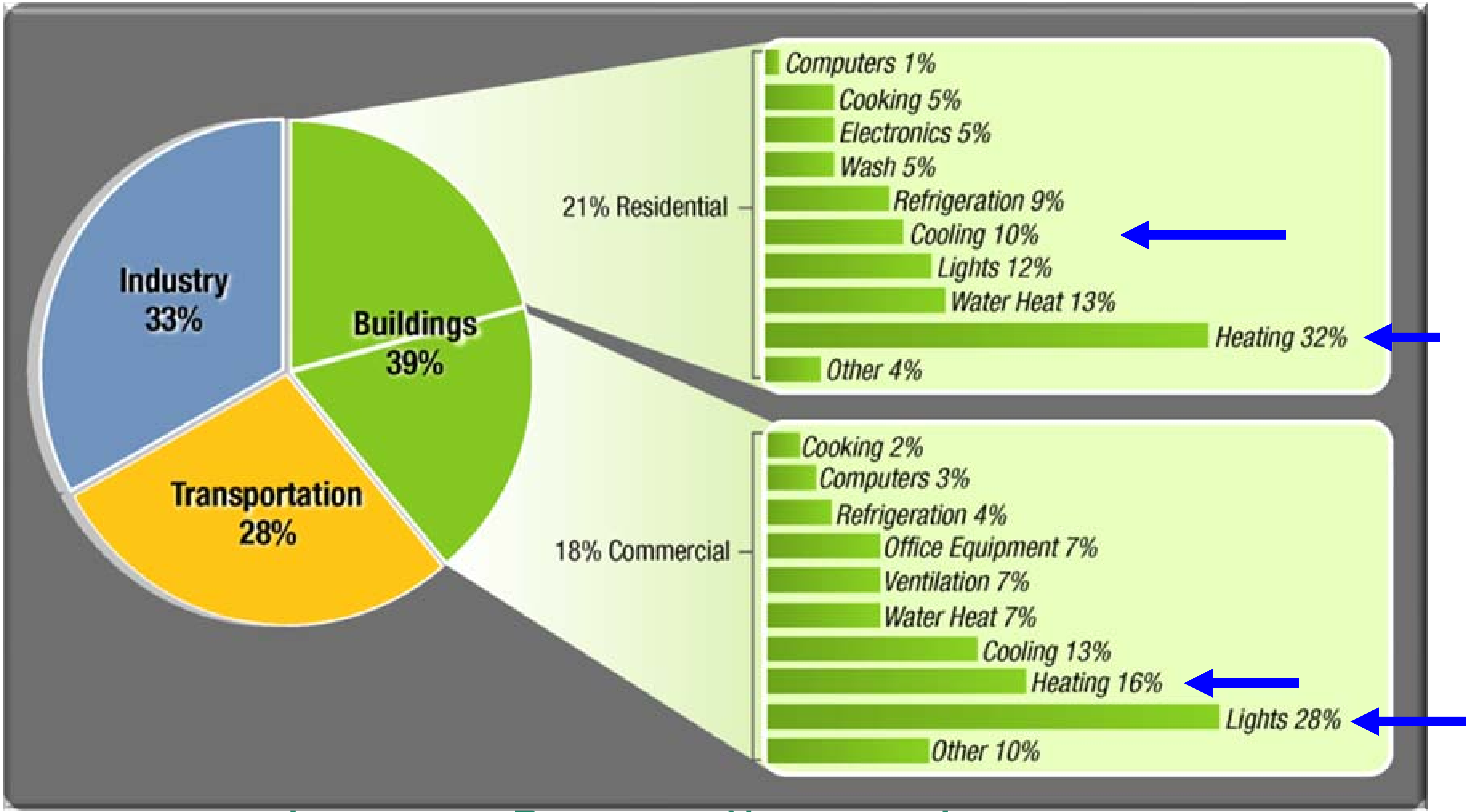
- ☐ Total Building Energy Use: ~ 40 Quads
- ☐ **Window-Related: 4.1 Quads***

***Quad:** 1 quadrillion BTU ≈ 1 EJ ≈ 1% of annual US Energy Consumption

Stephen Selkowitz and André Anders, Windows Group (EETD), 2008

Fenestration Impacts on Residential End Use Energy Consumption

Buildings consume 39% of total U.S. energy
71% of electricity and 54% of natural gas

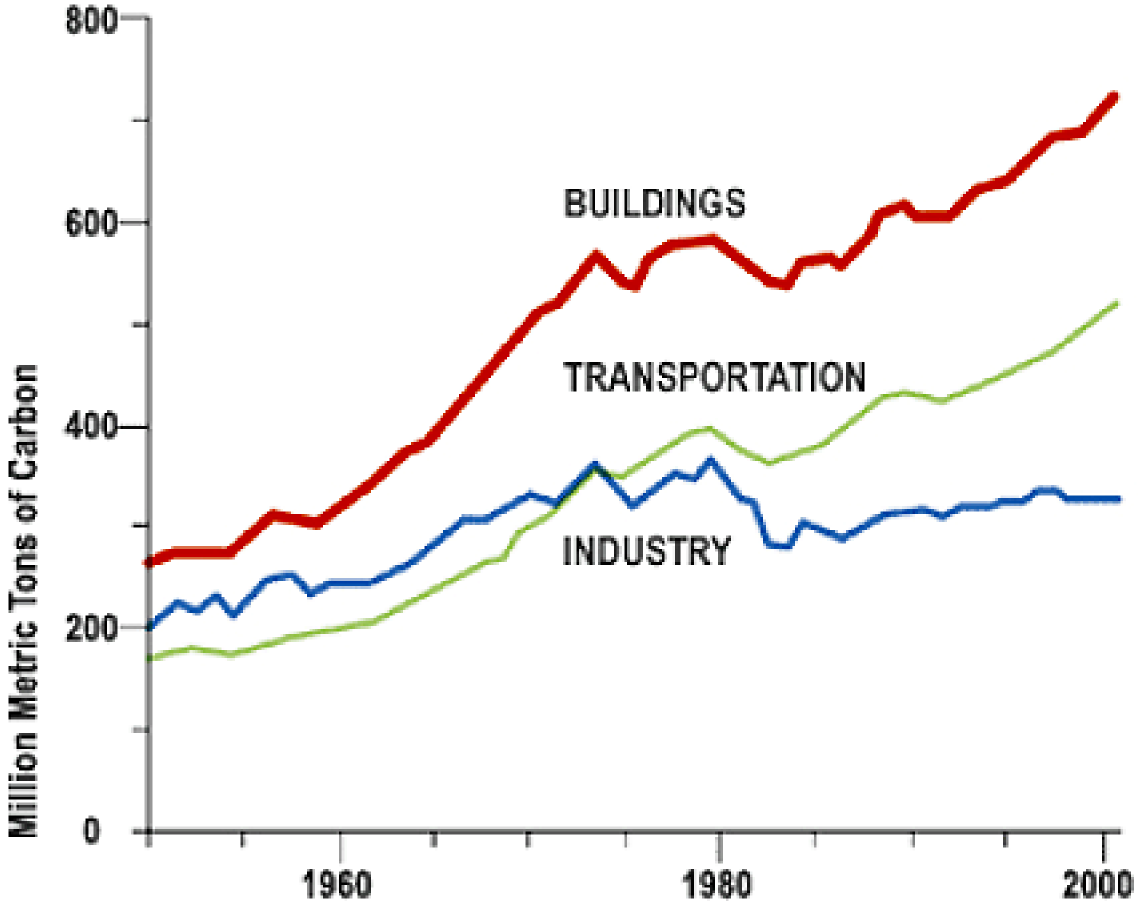


Stephen Selkowitz and André Anders, Windows Group (EETD), 2008

Zero Net Energy (ZNE) Buildings "Grand Challenge"

- Focus on Life Cycle of the Building
  - Design → Construction → Operations with BIM (building information model) - a CAD model with details of the building including energy info
- Focus on Integrated Smart Building Systems
  - Materials → Devices → Integrated Systems → Buildings
- Focus on Intersection of Technology and Policy
  - Innovative, disruptive technologies
  - Occupant behavior, life style, satisfaction, comfort
  - Investment and Decision making
- Focus on Measurable, Documented Energy Impacts
  - Make buildings performance measurable, visible and understandable

U.S. End-Use Energy/Carbon Split



<u>Building Energy Use:</u>

39% total U.S. energy

40% of carbon emissions

71% electricity

54% of natural gas

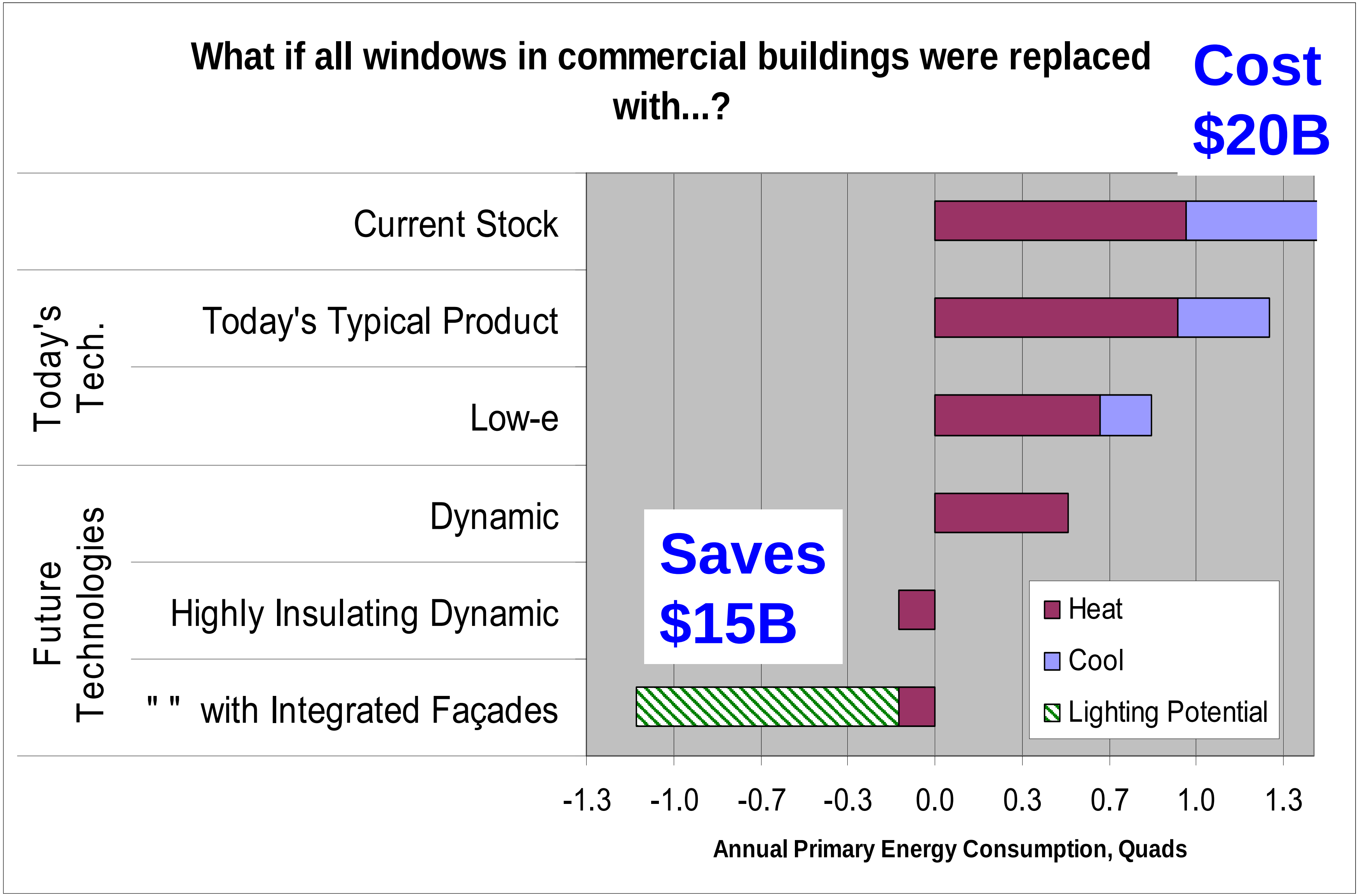
<u>Fastest growth rate!</u>

Two Contrasting Views of Energy Efficiency

**1976 Perspective:
Code Official's View of the Ideal Windows**

**2008 Perspective:
Architect's View of the Ideal Windows**

National Energy Savings



Progress in U.S. Residential Window Markets

- 1973: Typical Window:
  - clear, single glazed,
  - double or storm window in north,
  - $U_{average}$ = 0.85 BTU/hr-F-sq.ft.

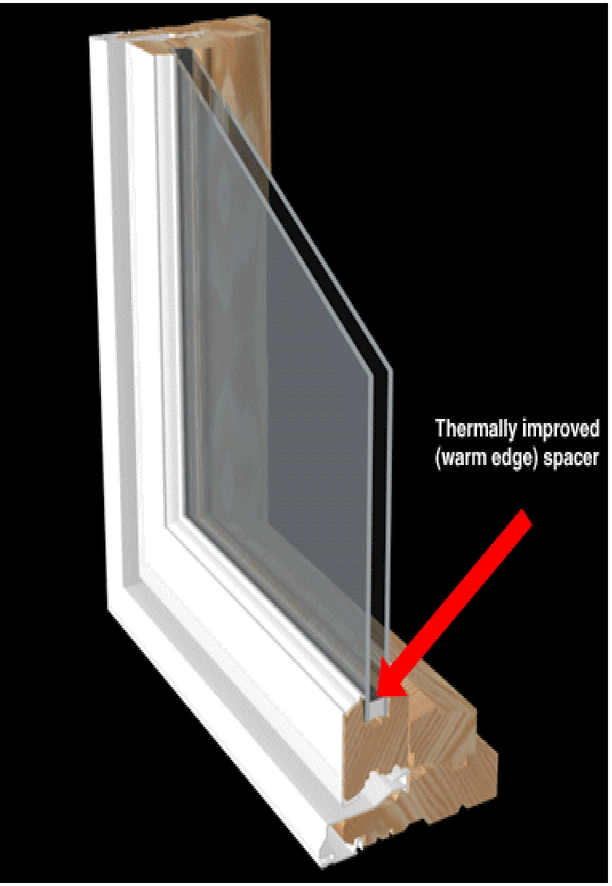
- 2006: Typical Window:
  - 95% double glazed
  - 60% have a low-E coating
  - 30-65% energy savings vs. 1973
  - $U_{average}$ = 0.45 BTU/hr-F-sq.ft.

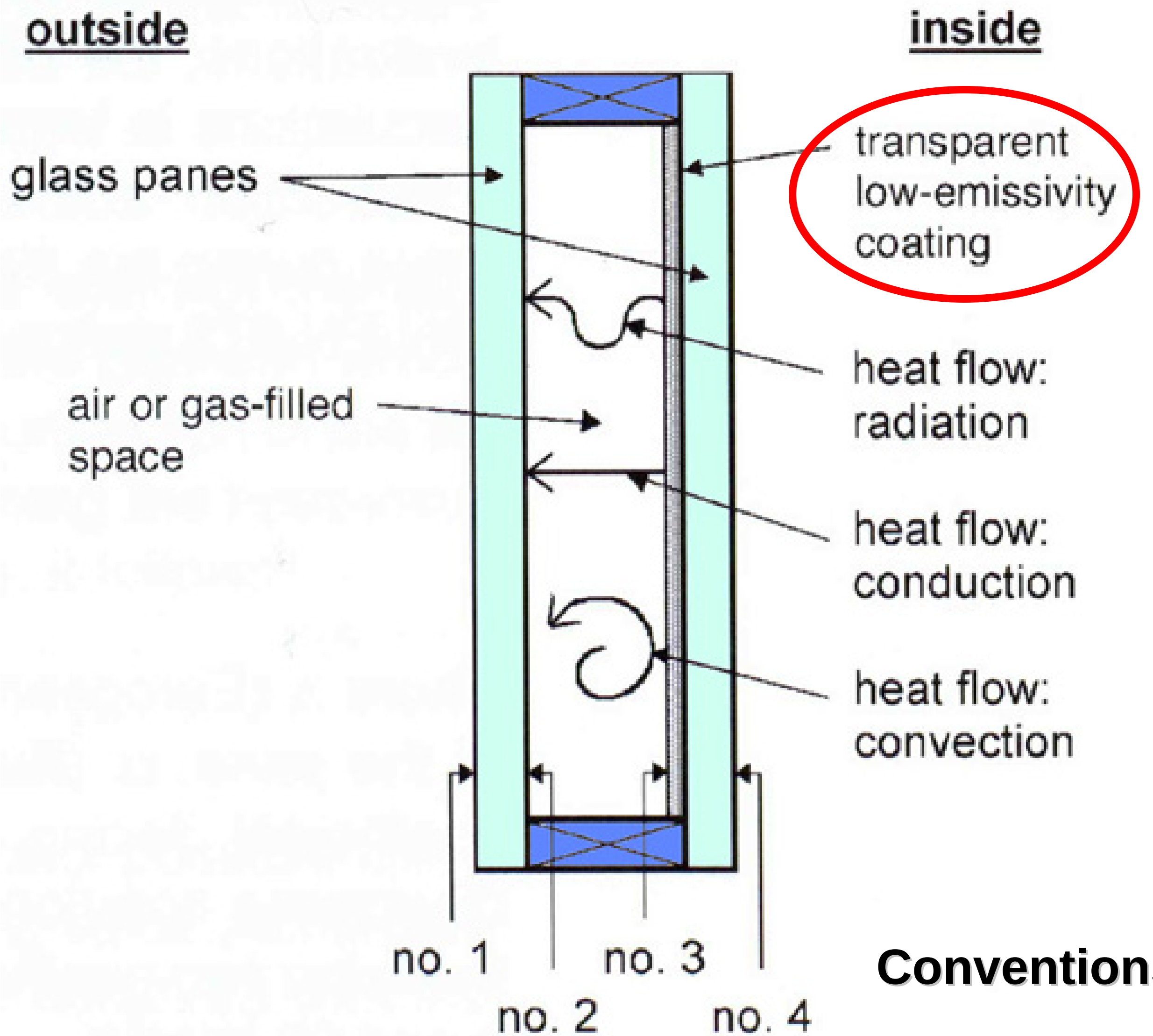
- 2020: Zero Energy Building “ZEB” Window:
  - Zero net energy use (typical)
  - Net winter gain; 80% cooling savings
  - **$U_{average}$ = 0.10 BTU/hr-F-sq.ft.**
  - **Dynamic solar control**

goals

Stephen Selkowitz and André Anders, Windows Group (EETD), 2008

Insulated Glass Unit - IGU



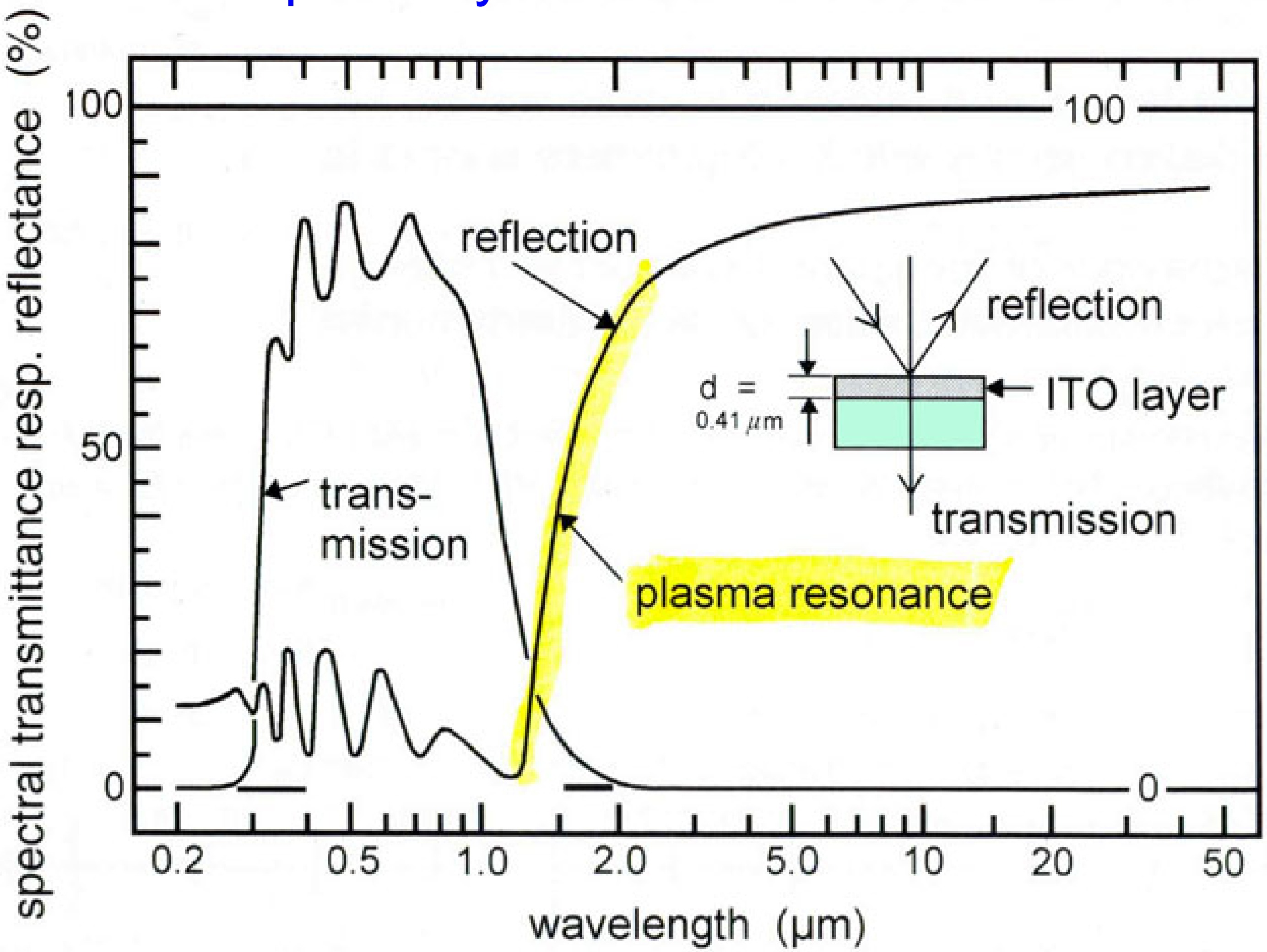


Conventions

H. J. Gläser, Large Area Glass Coating, Von Ardenne, Dresden, 2000

Low Emissivity (Low-E)

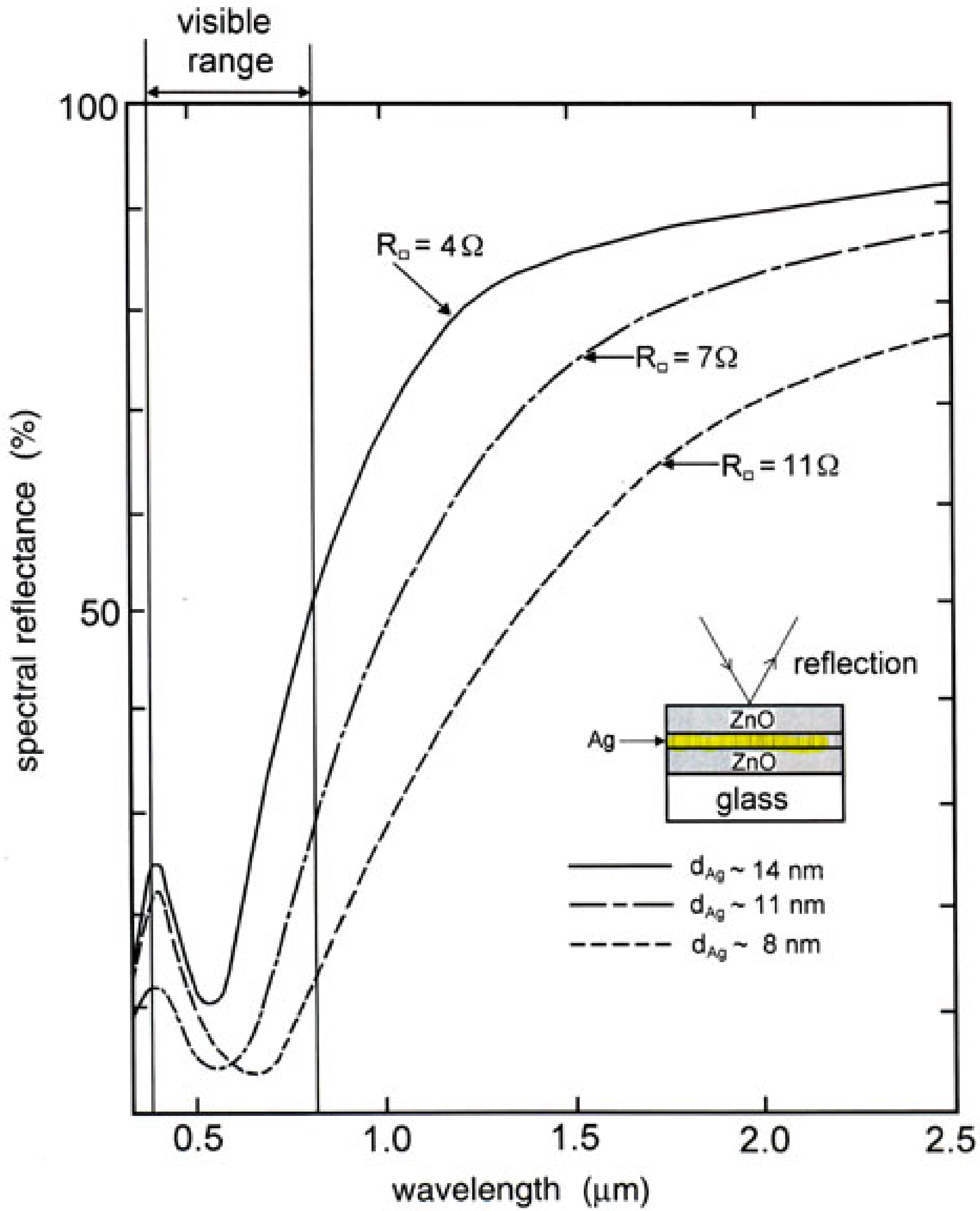
Spectrally selective transmission



H. J. Gläser, Large Area Glass Coating, Von Ardenne, Dresden, 2000

Spectral Selectivity

- Sheet resistance determines reflection in IR
- high sheet resistance → high SHG
- low sheet resistance → low SHG and coloration in visible



H. J. Gläser, Large Area Glass Coating, Von Ardenne, Dresden, 2000

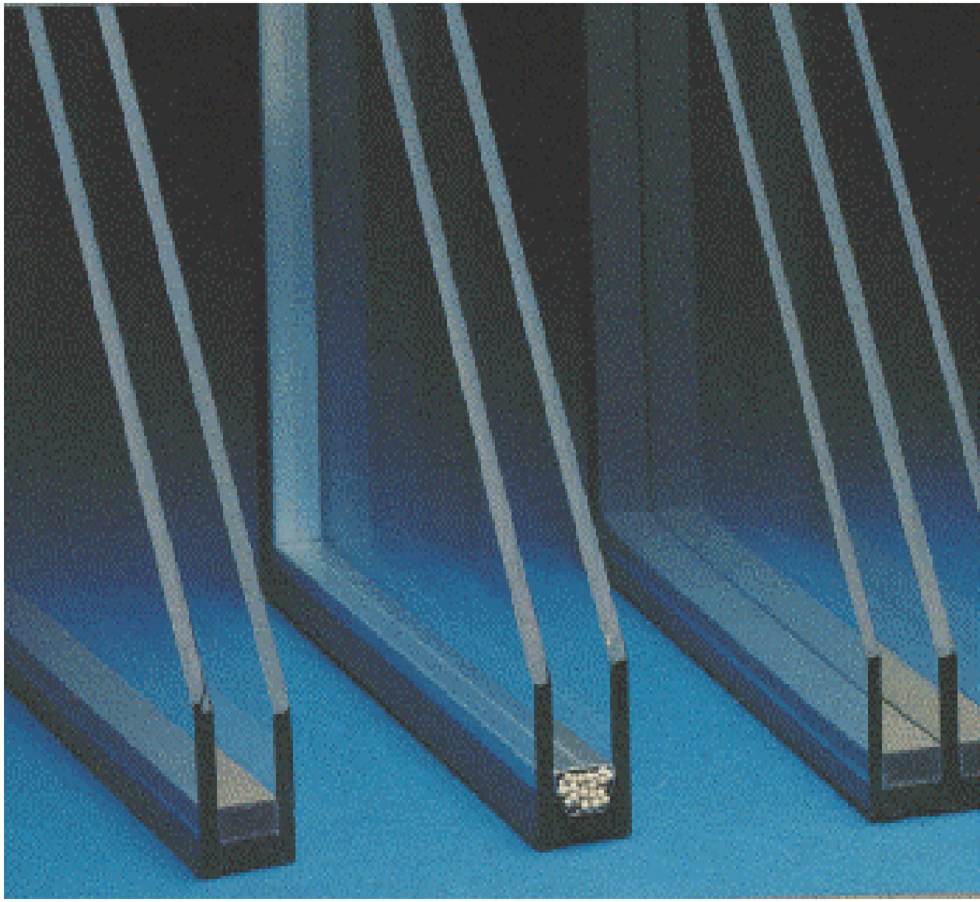
Zero Net Energy Window Objectives

Nearer term objective: U-value < 0.8 W/m^2-K

Long term target: U-value < 0.5 W/m^2-K "Super-Window"

Approaches:

- Low-E coatings
- Low conductance gas fills
- "Warm edge" low conductance spacers
- Insulated frame systems
- Recently: investigate use of a very thin, third pane in the center



Stephen Selkowitz and André Anders, Windows Group (EETD), 2008

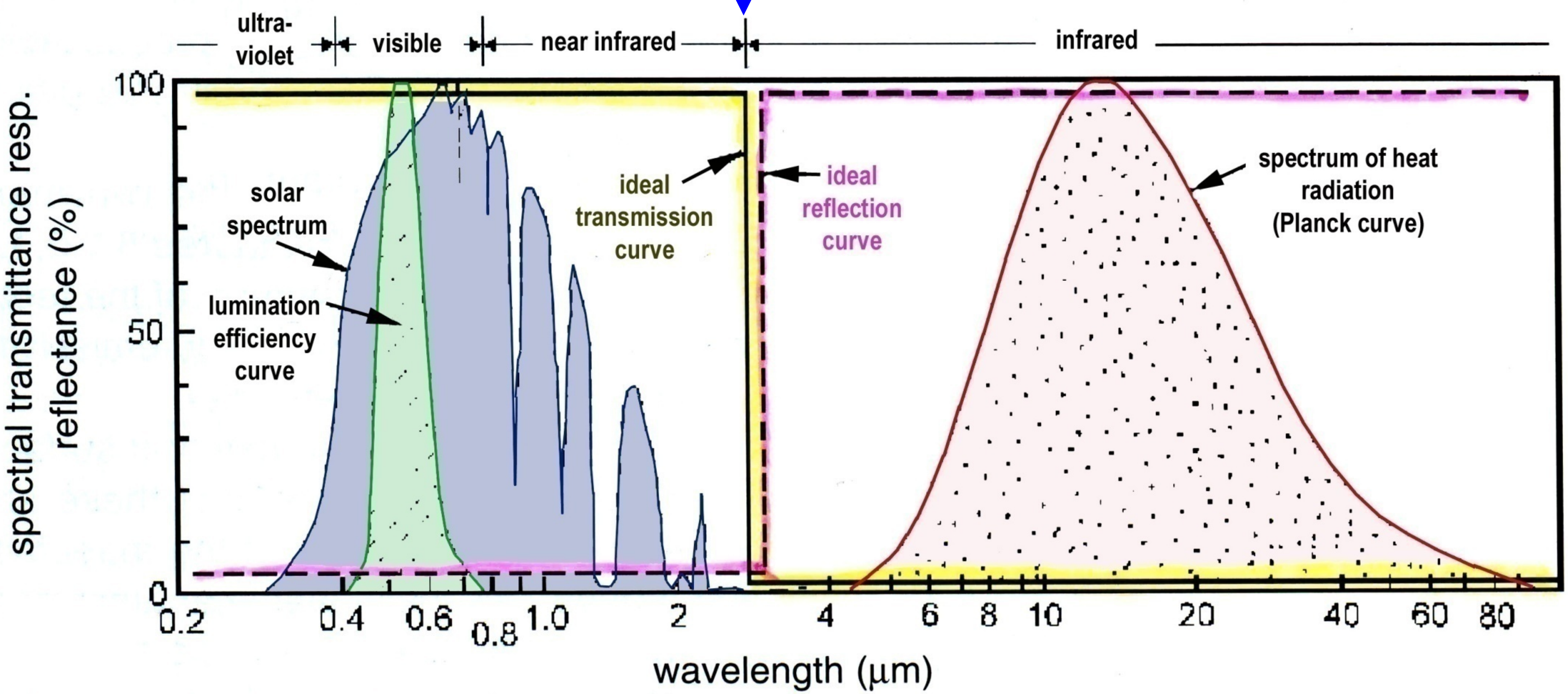
Advanced Window Technologies for Zero Net Energy Buildings

- Five main approaches:
  1. **Highly Insulating Windows**
  2. **Glazings that reduce Solar Heat Gain but admit daylight**
  3. **Dynamic Glazings (variable transmittance)**
  4. **Daylight/sunlight redirecting systems**
  5. Future: Lighting + HVAC (heating, ventilation, air conditioning) are integrated and optimized via **intelligent, integrated façades.**

Stephen Selkowitz and André Anders, Windows Group (EETD), 2008

The Ideal Energy-Saving Window: low-U plus low-E plus switchable SHG

Goal: make curve step switchable for optimized SHG!

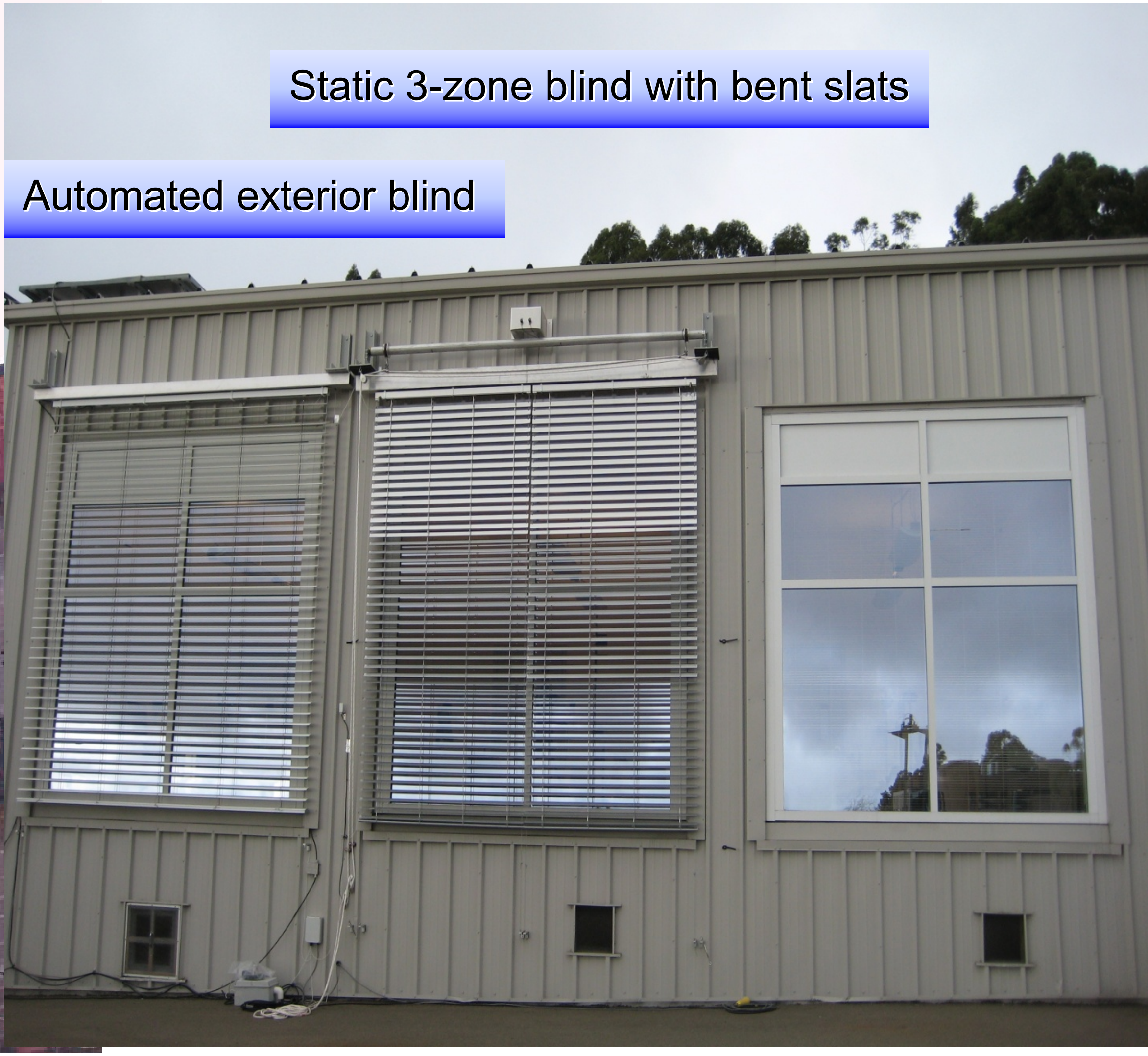


H. J. Gläser, Large Area Glass Coating, Von Ardenne, Dresden, 2000

Switchable, Dynamic Windows

- Mechanical shades (manual → automated)
- Suspended Particle Devices (SPDs)
- Liquid Crystal Devices
- Thermochromic
- Gasochromic
- **Electrochromic**
  - Absorbing (a.k.a. first generation)
  - Reflecting (a.k.a next generation)
- …

Exterior Shading Systems



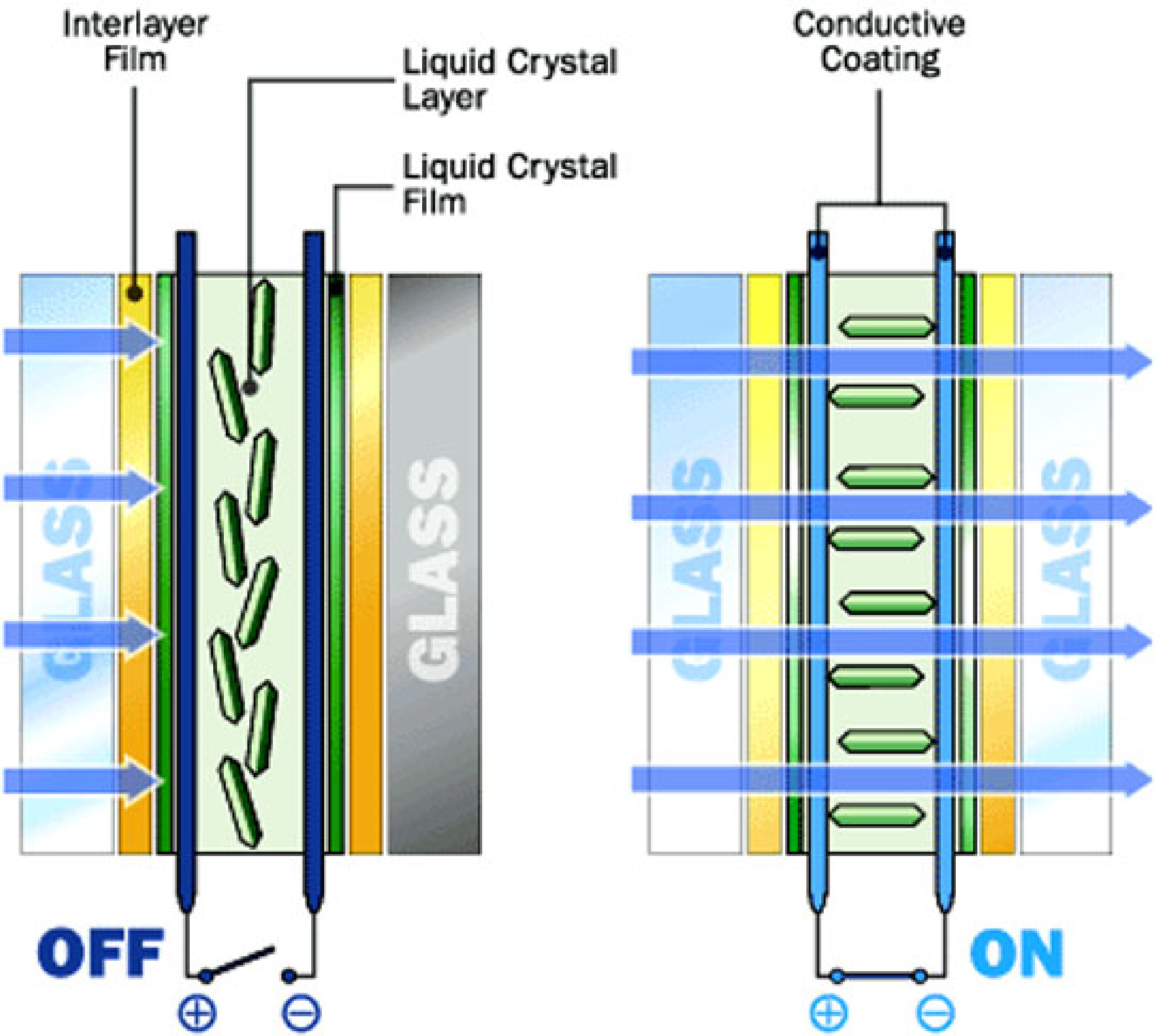
Suspended Particle Devices - SPDs

- Suspended particles align in response to an electric field between transparent thin films
- Transmission can be switched faster than with other chromic techniques (seconds)
- Can be integrated in smart window solutions
- Energy efficiency and lifetime not (yet) proven

Raytheon Aircraft Company Offering Electronic Dimmable Window Shades for King Airs (video clip)

http://www.spdcontrolsystems.com/

Liquid Crystal Window



- Intriguing mostly because this could lead to a multifunctional device
- Not (yet) established as an energy savings device
- Not (yet) proven to have wide-angle, low glare properties

http://www.consumerenergycenter.org/

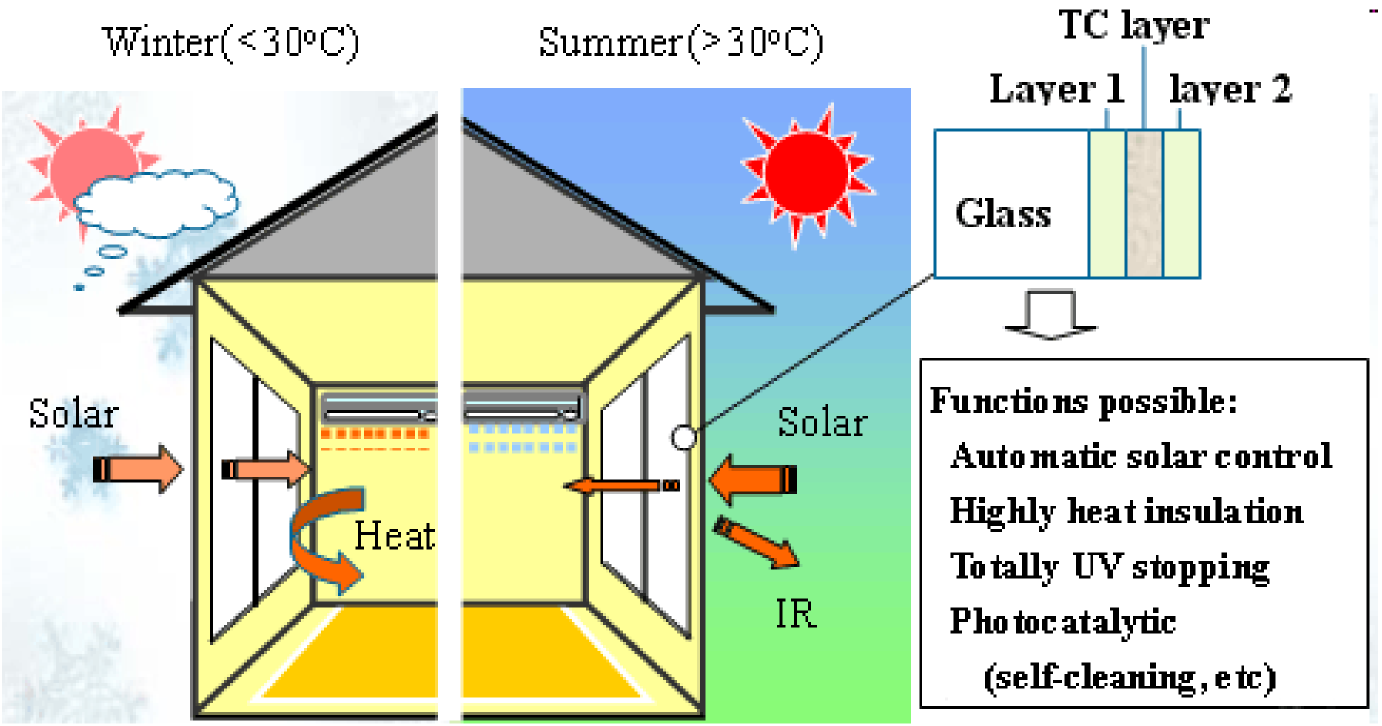
Thermochromic Windows

- Thermochromic materials respond automatically and reversibly to heat:
  1. Organic materials: patented **polymers**
  2. Inorganic materials: **VO_2 doped with Mo or W**

Example 1: "Cloud Gel," a water-soluble polymer that is transparent when cool and that turns white when warmed; has durability issue with UV.

Example 2: VO_2 and VO_2:Mo,W or $V_{1-x}M_xO_2$: the temperature at which the optical property changes can be freely set from the room temperature to 68°C by adjusting the dopant dosage.

Thermochromic Windows



- Current sizeable, government-backed research activities in Europe and Japan, not in the US.
- Disadvantage: since transition is automatic, no controlled integration into a larger, “smart” system possible

http://www.aist.go.jp/aist_e/latest_research/2005/20050614_2/20050614_2.html

Gasochromic Windows

- Very simply layer structure: WO_3 with Pd/Pt
- Gas between panes is switched, e.g. Ar $\leftrightarrow$ Ar+H_2
- Pioneered by Interpane, and FHG, Germany, within the SWIFT program of the European Union
- Prototypes max. 1.5 m x 1.8 m used in experimental façades
- Integrated gas cycling system

Photo: Interpane

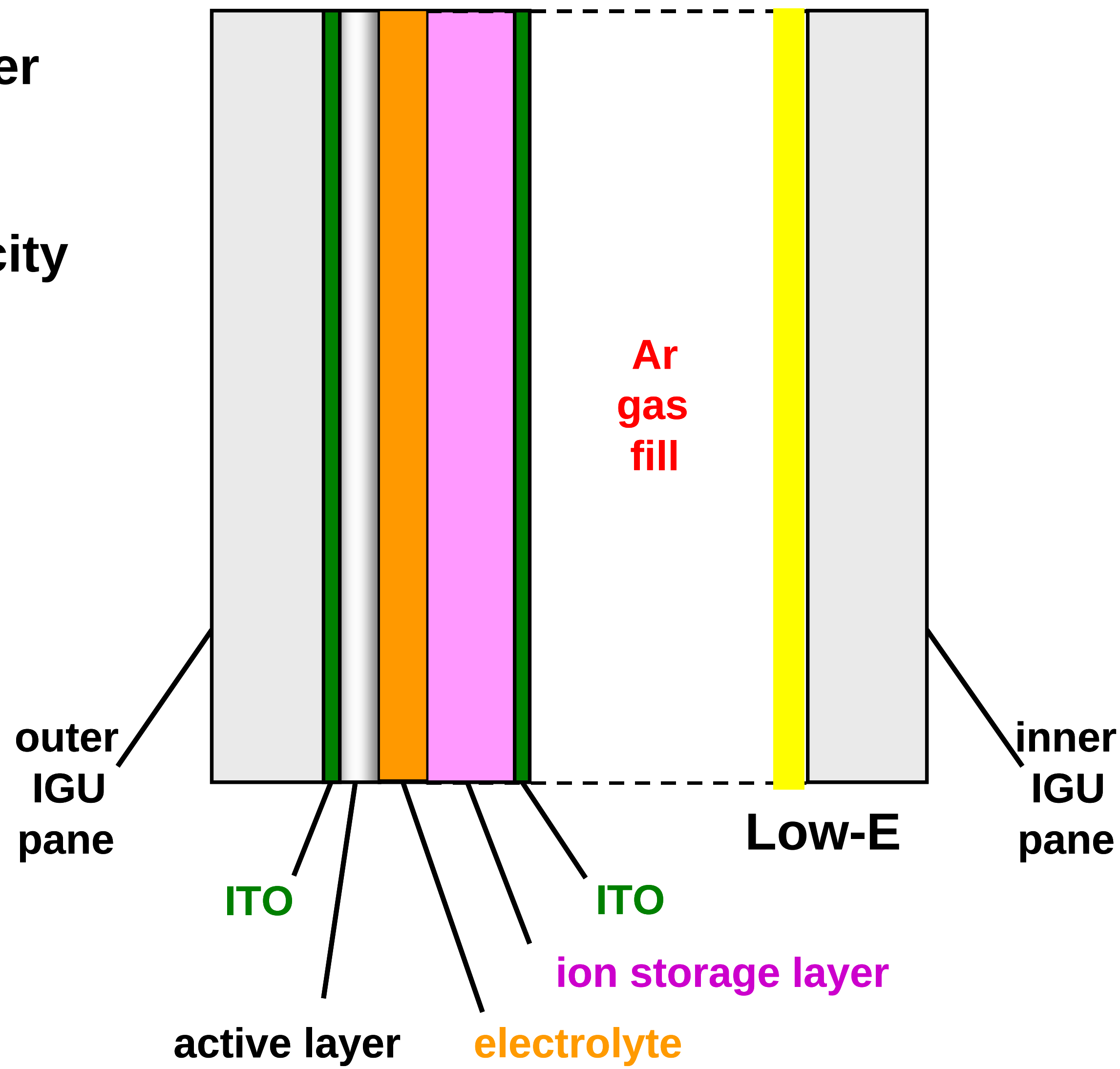
Conventional Electrochromic Windows

- transmission 50% - 13%
- Blue in transmission (WO_3-based)
- Minimal reflectance control
- Complex multilayer design
- Still expensive

LBNL – Oakland test room with Flachglass windows

Conventional Electrochromic Windows

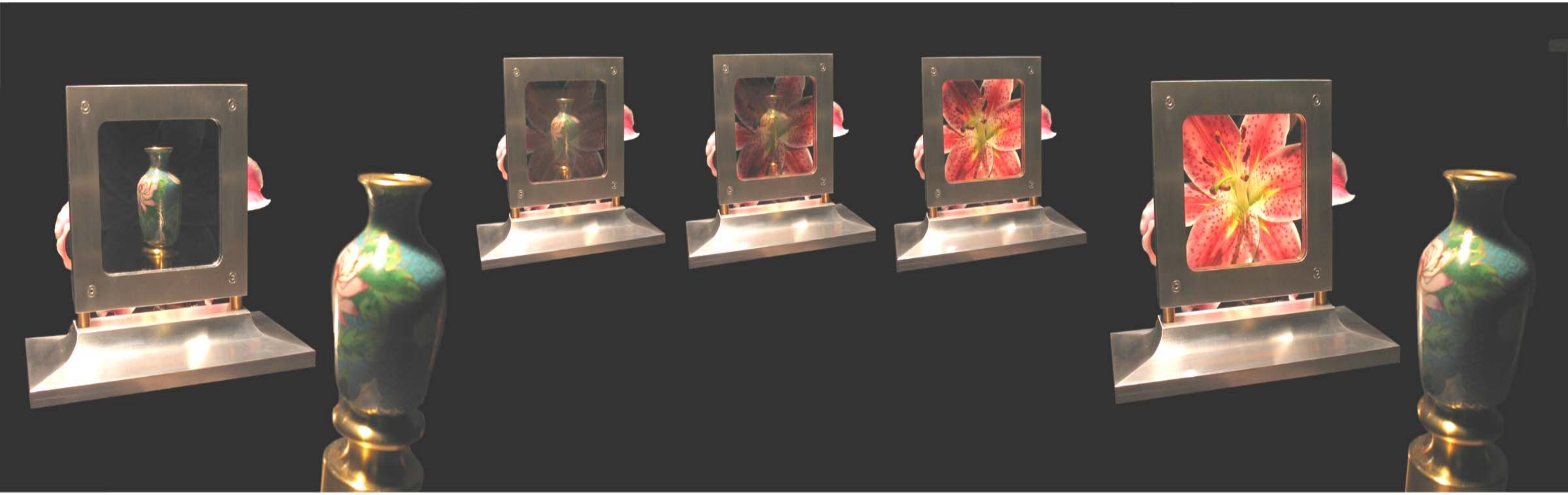
- ✓ Metal oxide active layer and ion storage layer
- ✓ Limited storage capacity
- ✓ Many coatings, thick layers



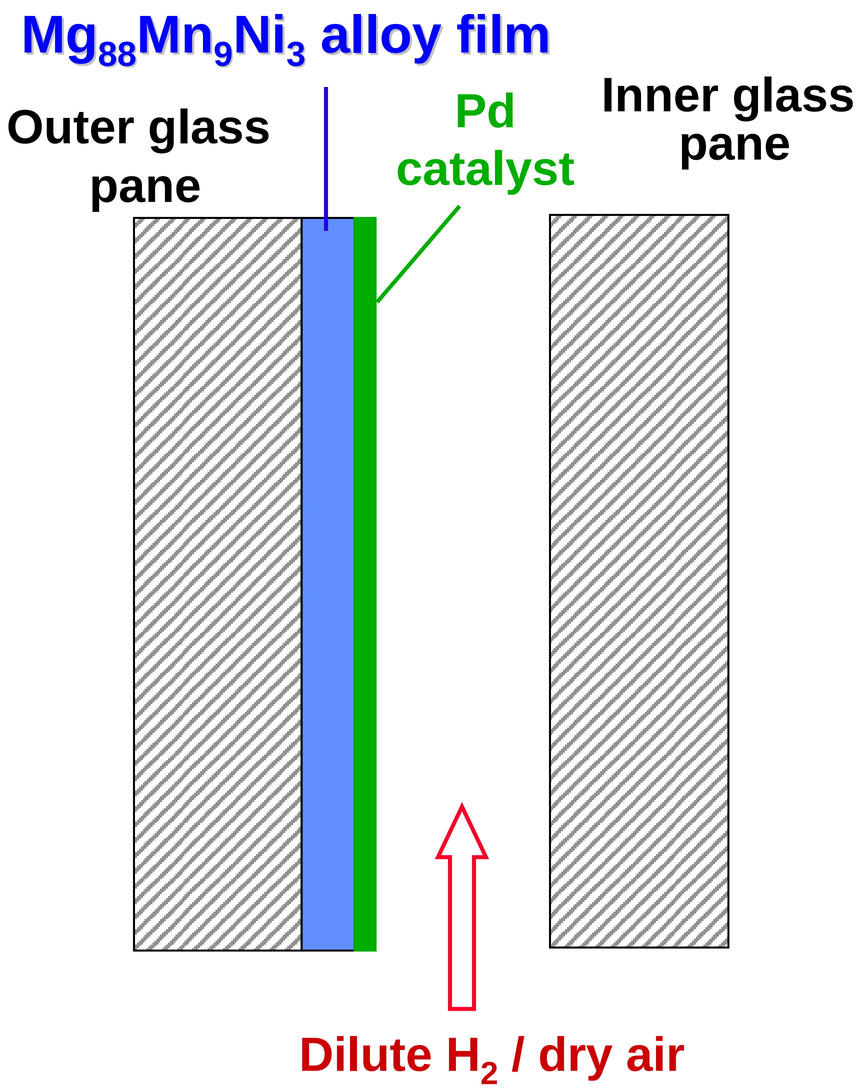
Switchable Mirrors

- “Switchable Mirrors” were invented based on Rare Earth Hydrides in 1995 by Prof. Griessen's group, Amsterdam
- Since then, other classes of materials have been invented, including transition metal hydrides (LBNL)

(Video clip)



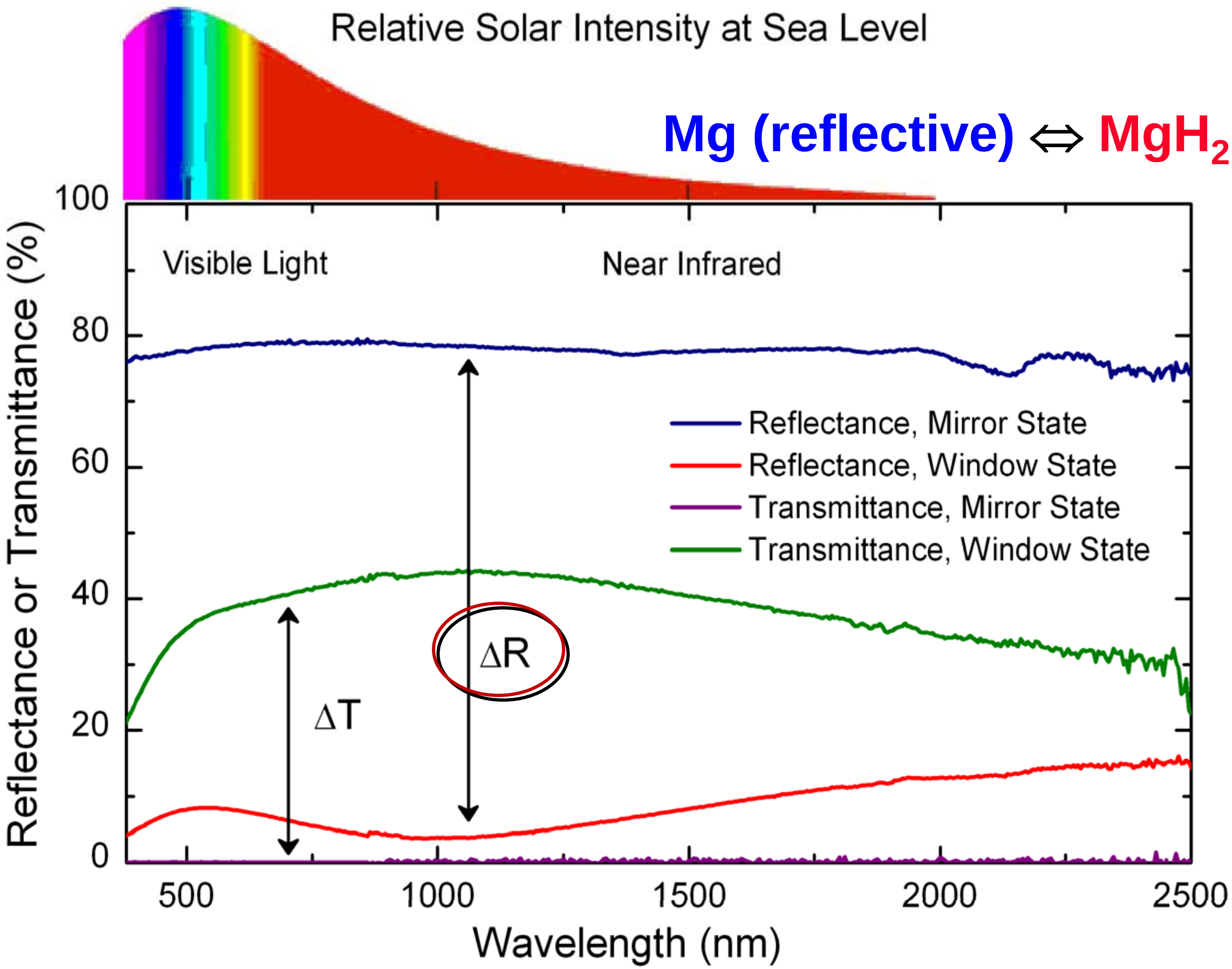
Gasochromic Reflective Windows



R&D100 in 2005

Reflective Electrochromics

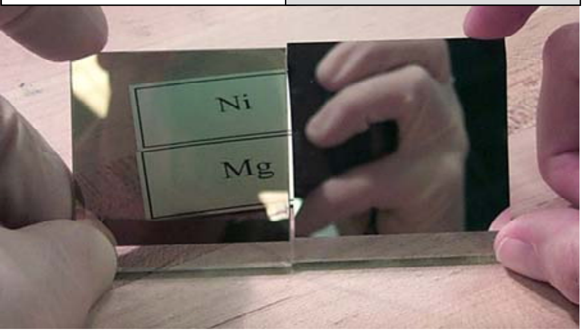
Mg (reflective) ⇔ MgH_2 (clear)

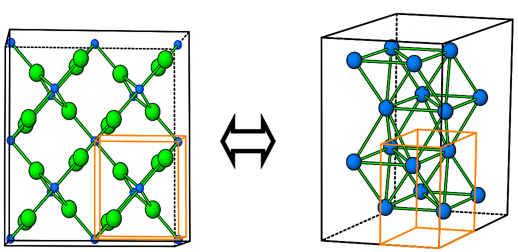


Various Switchable Mirror Concepts (LBNL)

Metal Hydrides

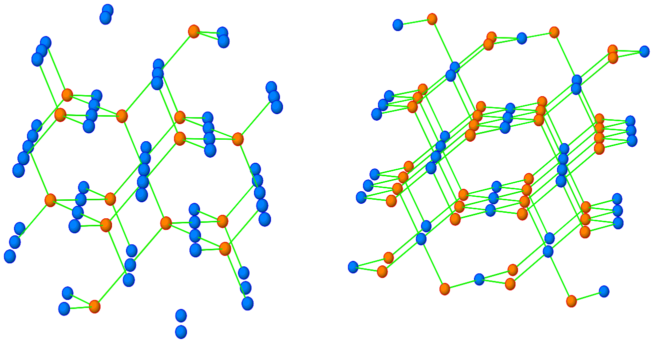
Semiconductor | Metal





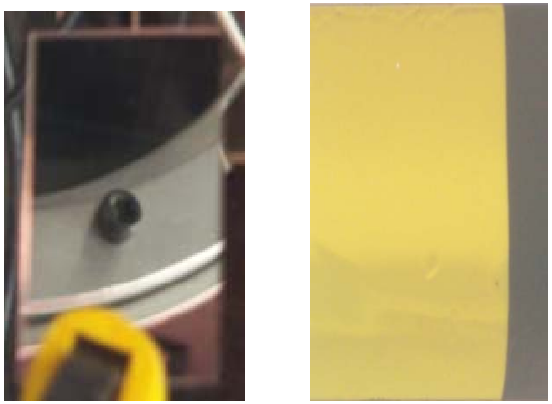
MgH_2 ⇔ Mg

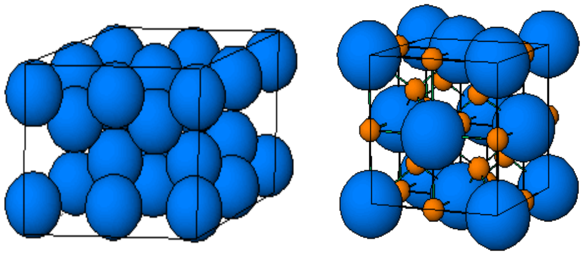
Copper Oxides



Cu_2O CuO

Lithium Pnictides





Sb $SbLi_3$

Patents of T. Richardson, LBNL

Stephen Selkowitz and André Anders, Windows Group (EETD), 2008

Goals of Research at Berkeley Lab

- Develop 2nd generation, reflective electrochromic windows that have:
  - greater potential of energy savings than conventional, absorbing EC windows
  - Lower manufacturing cost than conventional device designs

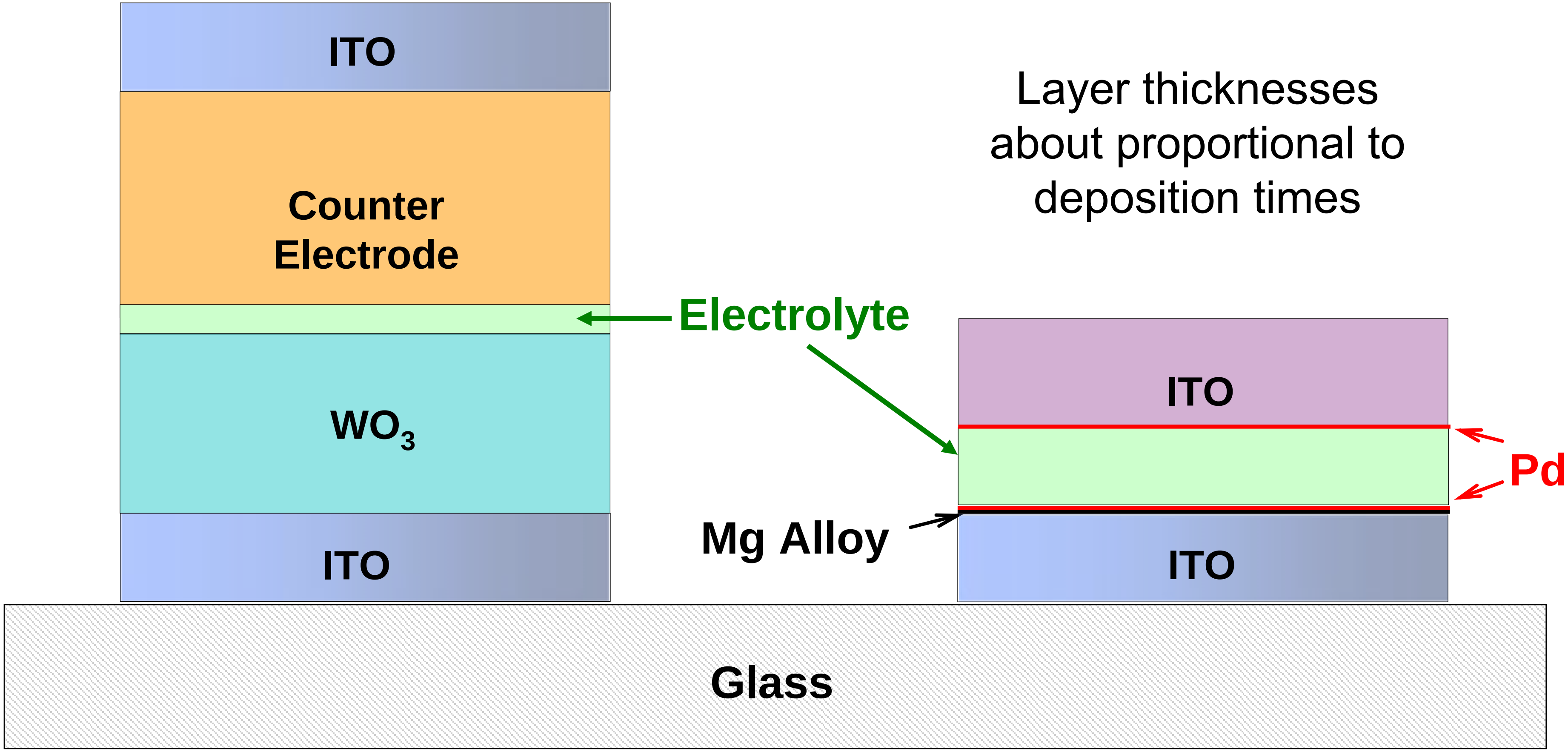
- In recent couple of years: develop a reflective metal-hydride electrochromic insulating glass unit employing a novel gas reservoir design

Electrochromic Window Concept with H_2 (3%) gas reservoir

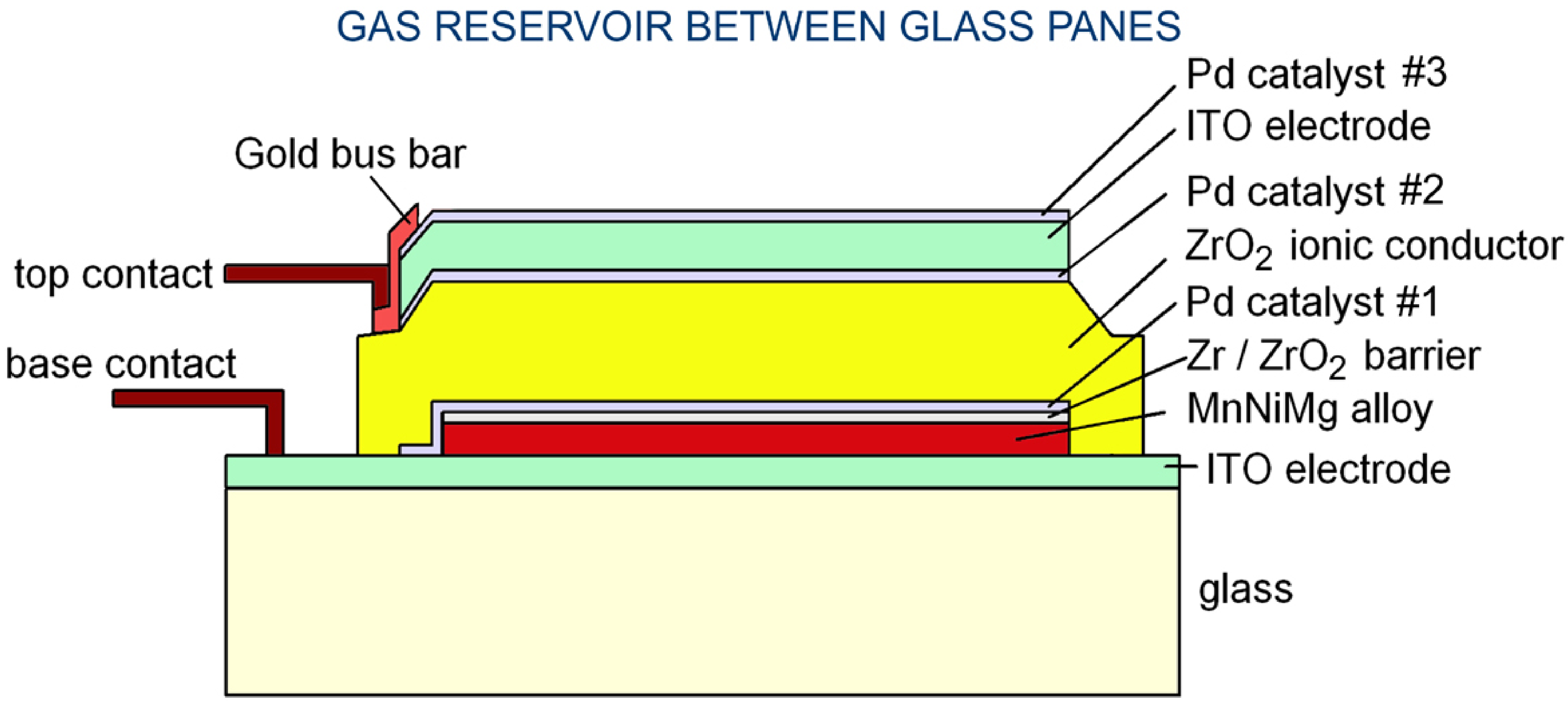
Absorbing Ion Storage

Gas Reservoir switchable mirror

Layer thicknesses about proportional to deposition times



Gas-reservoir Electrochromic Mirror



Challenge:

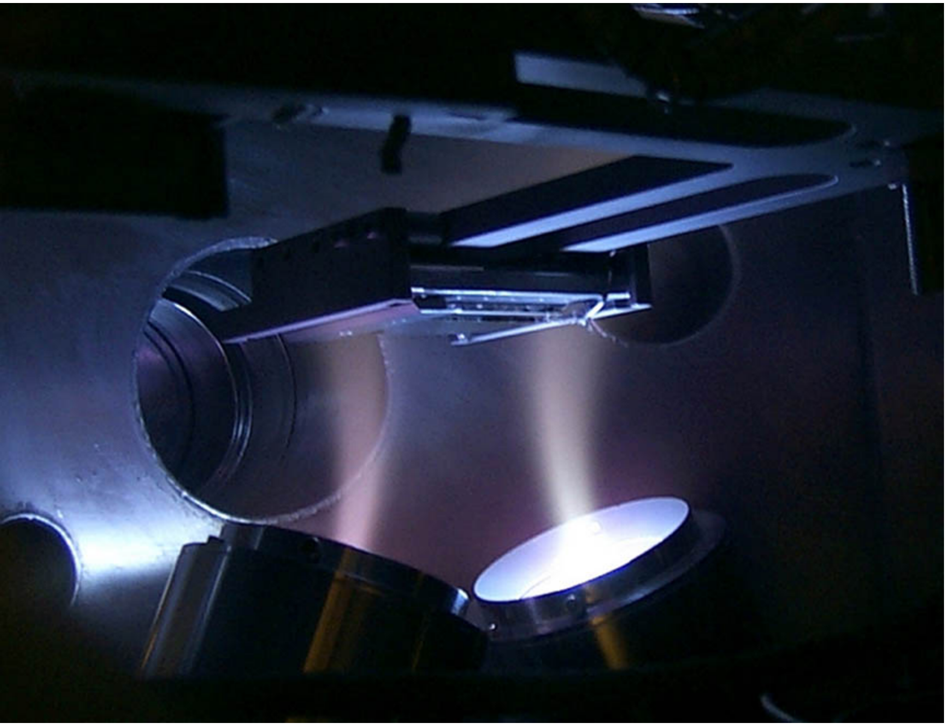
from proof-of-principle of switching to durable working prototypes and beyond

A. Anders, et al., Thin Solid Films, online 6/23/08

Sputtering:
A preferred technology, proven for large areas

Co-Sputtering to Fabricate the Metal Alloy Films

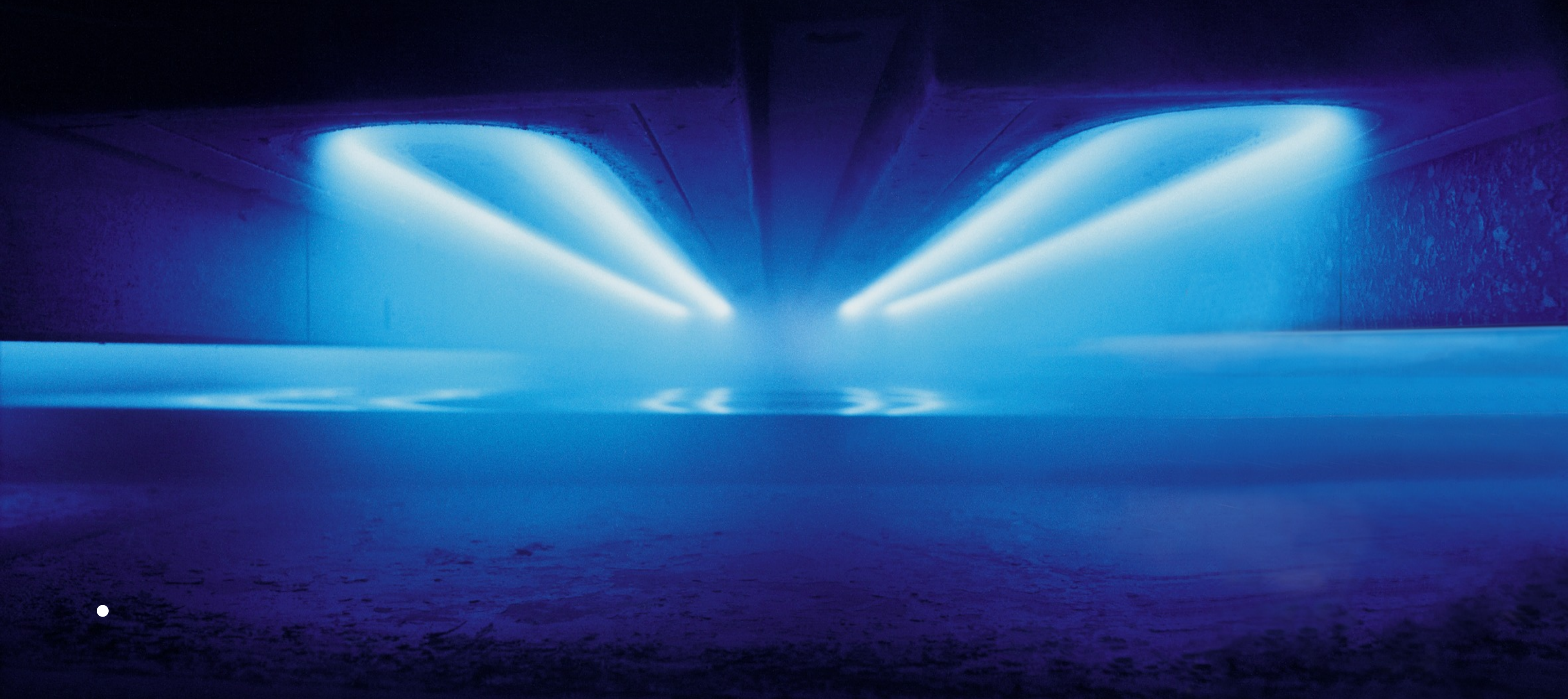
Dual-Magnetron Sputtering to Fabricate ZrO_2 Electrolyte Film



Stephen Selkowitz and André Anders, Windows Group (EETD), 2008

Very Large Area Pulsed Sputtering

- Magnetrons serving alternatingly as cathode and anode
- Medium frequency sputtering (up to 350 kHz)



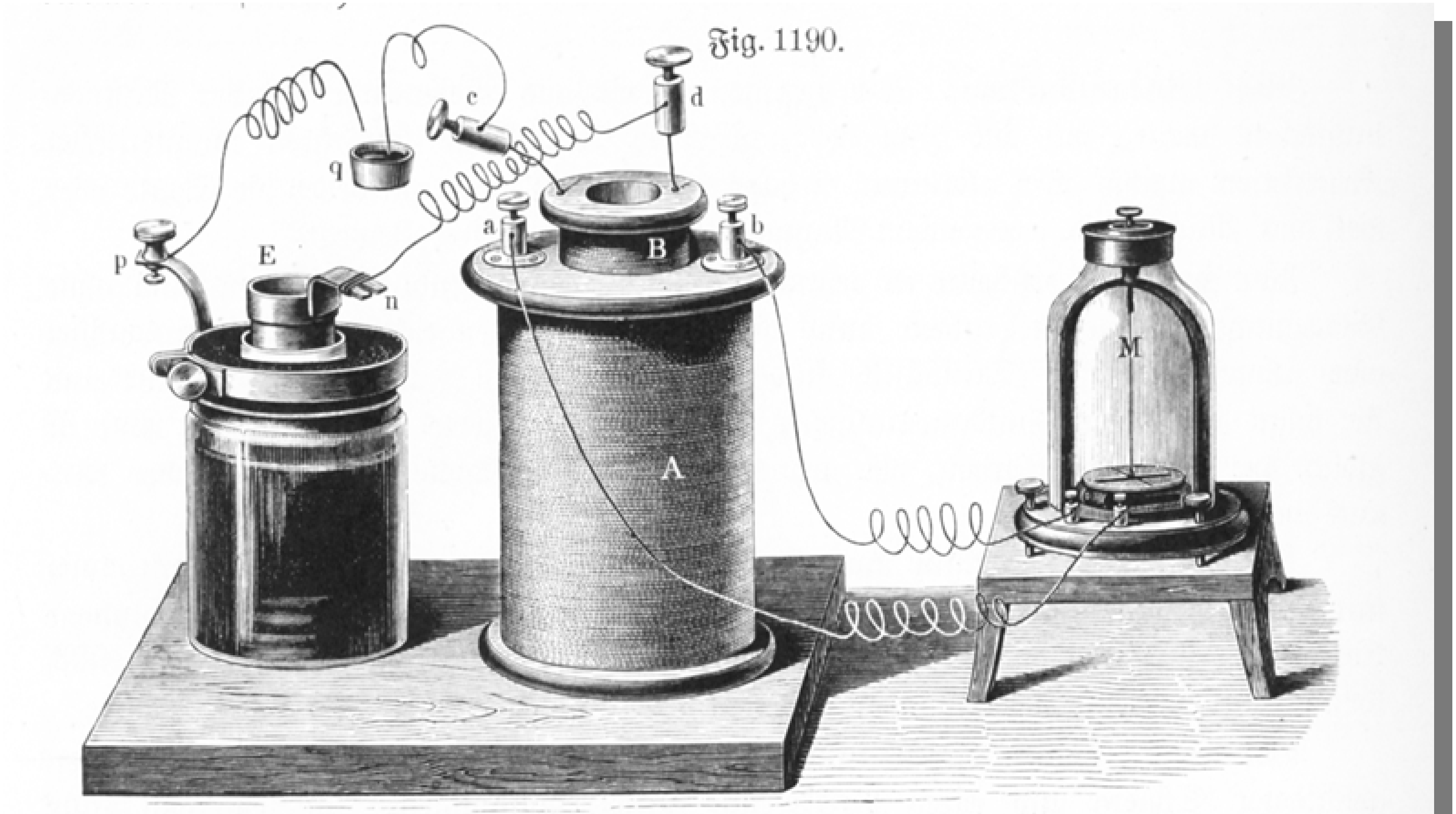
- high throughput for on-line coaters, up to 3.5 m wide

Photo courtesy of

VON ARDENNE

Glass Coating
by 19th Century Pulsed Sputtering

…has already many elements of modern pulsed processing: latest is "high power impulse magnetron sputtering"



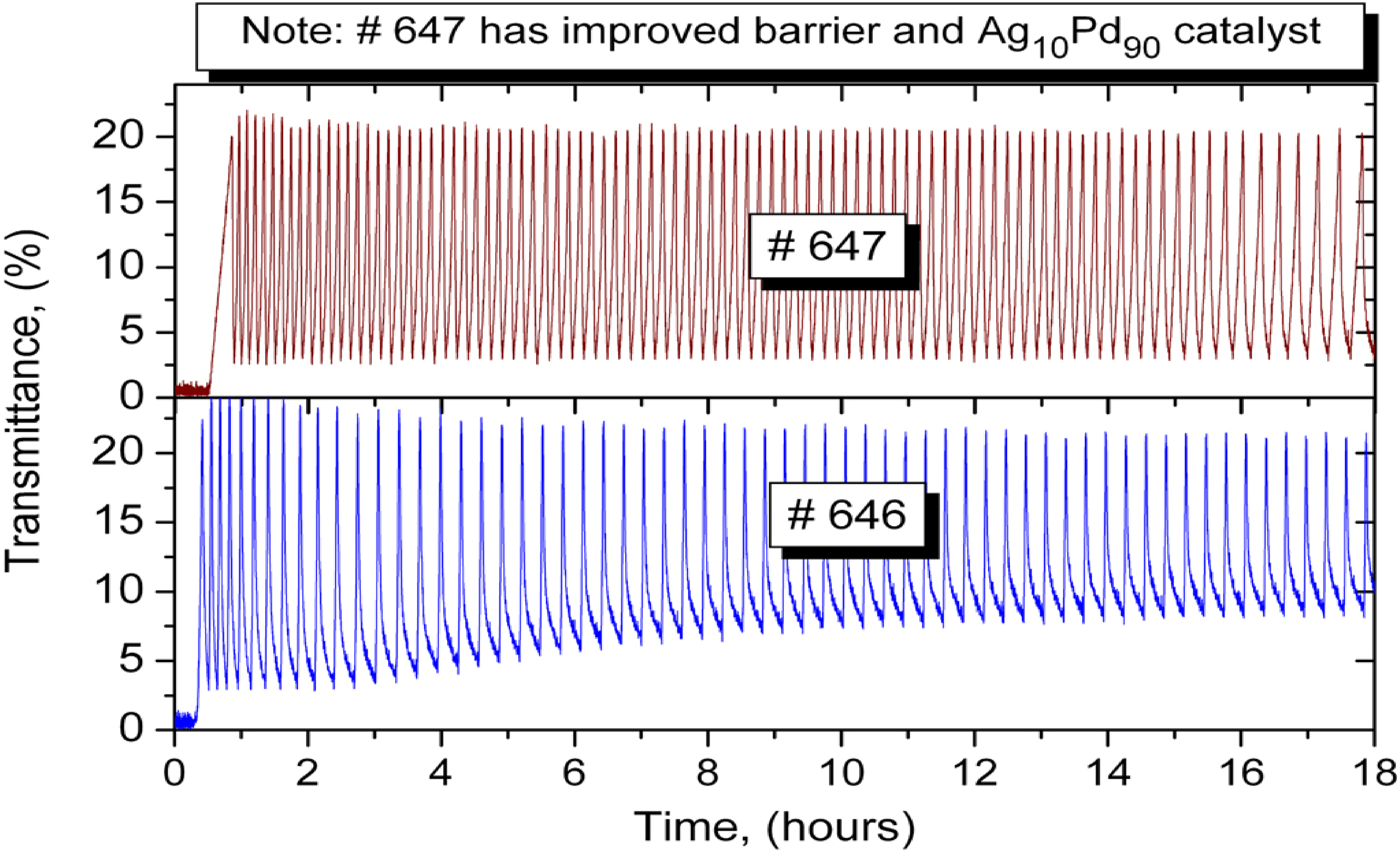
Energy storage — *Pulse transformer* — *Vacuum chamber*

Metal Hydride Switchable Mirror

Small Window Prototype: Video

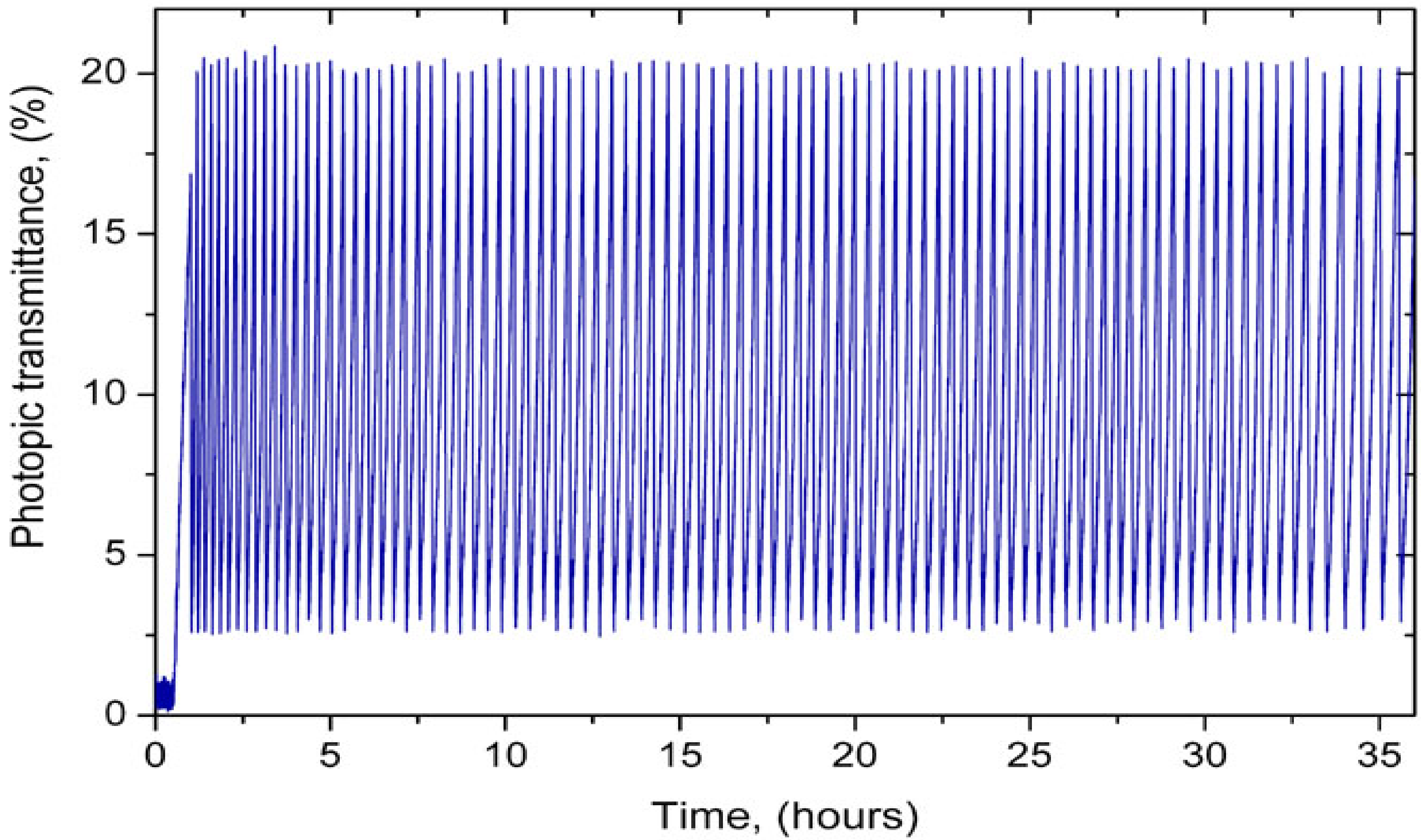
longcut highres.mpg

Improvements by Barrier Layers and Catalyst Alloying



A. Anders, et al., Thin Solid Films, online 6/23/08

Best device so far: > 100 full cycles



> 10^3 full cycles needed for prototype
> 10^5 cycles needed for commercial windows

A. Anders, et al., Thin Solid Films, online 6/23/08

Switchable Mirror Research in Japan

Advance Industrial Science and Technology (AIST) press release of Dec. 21, 2006:

• A research group at the Lawrence Berkeley National Laboratory of the U.S.A. developed a thin-film switchable mirror made of a magnesium-nickel alloy. This has a *dark brown color, even in its transparent state…"….*(not true! – close to neutral, absorption by Pd)

•*"By using magnesium-titanium alloy, we reduced the degree of tinting considerably, and we developed a thin film that is almost color-neutral in its transparent state.*"

Impressive size: 60 cm x 70 cm

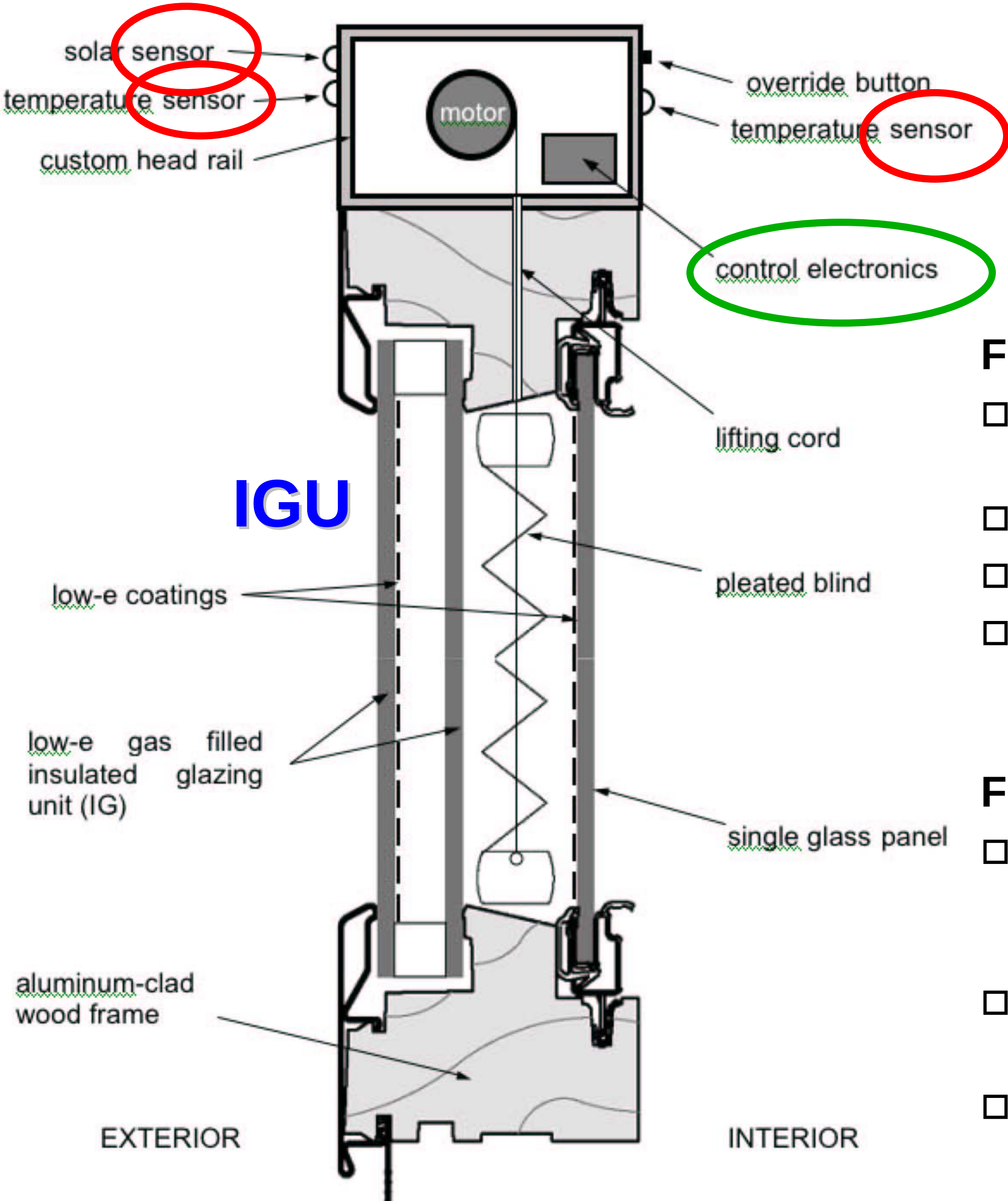
"Scientists at the AIST are currently working on maximizing the durability of the switchable glass, and overcoming the deterioration that arises due to repeated switching."

http://www.aist.go.jp/aist_e/latest_research/2007/20070129/20070129.html

http://www.engadget.com/2007/02/01/aist-turns-transparent-glass-into-mirrors-to-conserve-energy/#comments

Window Integration and Windows as Multifunctional Devices

Near-Term Dynamic Window Concept Addressing Energy and Comfort



Features

- Automated shade within glazing system
- Built-in sensors
- Automated or manual control
- Links to home energy management system

Functions

- Homeowners will employ shading systems for privacy, aesthetics
- Automate shading for peak demand control
- Permits solar heat gain during winter season

E. S. Lee, et al., *Energy and Buildings* 36, pp. 503-513, 2004

Integration of Dynamic Windows with Daylighting Technologies and Systems

- **Potential: 100% increase in potential perimeter savings**
- Improve visual comfort in perimeter zone -> greater acceptance
- Improve uniformity of daylight in perimeter zone
- Extend the impact of daylight from 5m deep to 10-15m

Existing solutions need improvement:

e.g. Using 19th century reflective and refractive optics

Dynamic Systems: Operable Shades with *Smart Controls* Exist Today

Future:
Integration of all Adjustable / Switchable Functions

- Intelligent Façades take into account numerous conditions
  - Automatic, software-controlled
  - But also adjustable by occupant, the user, for comfort
  - Dynamic, based on continuous input from sensors
    - Temperature (outside / room)
    - Illumination (outside / room)
    - Current occupancy
    - Load on grid (energy demand, instantaneous cost-based)
- Integrated, intelligent façades include (dynamic) glazing, shades, lighting functions, HVAC, …
- Power-grid independent

Window as Large Area Light Emitter

- Large area, low intensity emitter of white or colored light
- Possible approaches:
  - OLED with transparent electronics
  - ZnO transparent electronics
  - …
- Many issues, incl.
  - Durability
  - “haze” by electronic components
  - Cost

Much anticipated: Window as Switchable Transparent Display

- Issues:
  - Preserving the window function!
  - Durability
  - Cost

Addressable pixels need to be transparent (without haze) and meet energy performance requirement and …

http://electronics.howstuffworks.com/enlarge-image.htm?terms=oleds&page=5

Summary:
The Window of the Future *needs* …

1. **… to stay a *Window*: i.e., a means for outside view and comfort.**
2. … to become a part of the net zero energy building by addressing
   - ✓ Thermal insulation
   - ✓ Daylighting
   - ✓ Spectrally selective energy control.
3. … to achieve the necessary performance: it needs to be switchable, adjusting for season and time of day.
4. ...to be durable and affordable.

Summary:
The Window of the Future *should*…

1. …address energy and comfort by separately switching the visible and IR
2. …be grid independent
3. …be multifunctional
   - Source of artificial daylighting
   - Display / Picture
   - Include shutter (mechanical/ absorbing / reflecting) for complete privacy
   - Energy source, at least to become self-serving and grid independent
4. …be part of an integrated, smart façade, equipped with
   - Sensors
   - Communication channels
   - Receptors for response.

…towards intelligent facades, incl. dynamic windows with integrated daylighting systems!

LINKS FOR FURTHER INFORMATION

- http://windows.lbl.gov
- http://windows.lbl.gov/software
- **Commercial Windows Website:**
- http://www.commercialwindows.org
- **Advanced Facades Project Website**
- http://lowenergyfacades.lbl.gov
- **New York Times project**
- http://windows.lbl.gov/comm_perf/newyorktimes.htm
- **Electrochromics project**
- http://windows.lbl.gov/comm_perf/electrochromic