SMART MATERIALS

Smart materials are engineered materials that sense and react to environmental conditions, and/or have one or more properties that can be significantly altered in a controlled fashion by external stimuli. These stimuli may include light, temperature, moisture, mechanical force, and/or electric or magnetic fields (Addington and Schodek 2005). All changes are reversible, as the materials return to their original states once the external stimuli expires. The reactions of smart materials vary based on their inherent properties, molecular alterations, and embedded control systems. For example, some materials perform phase changes (i.e., thermochromic) and some perform energy exchanges (i.e., photovoltaic).

Accordingly, there are three types of smart materials: (1) thermo-responsive materials; (2) light-responsive materials; and (3) stimulus (force)-responsive materials. Briefly, thermo-responsive materials undergo transformations due to the changes in temperature. Thermochromic, thermotropic, thermoelectric, and shape memory are primary examples of thermo-responsive smart materials. Light-responsive materials respond to changes in UV light. Major smart materials in this category are photochromic, photovoltaic, and photoluminescent materials. Stimulus (force)-responsive materials are the least defined and most complex among all types of smart materials. These materials undergo transformations due to external stimulants such as electricity, mechanical force, magnetic force, and kinetic energy.

Thermo-Responsive Materials

Thermo-responsive materials (TRMs) are smart materials that transform due to a change in temperature.

THERMOCHROMIC

Thermochromic materials change color in response to temperature differences. When a thermochromic material absorbs heat, its molecular structure and the consequent light reflection of the material also changes. This results in reversible color reflections.
Although there are various different thermochromic compounds, there are primarily two general types: thermochromic liquid crystals and leucodyes. The necessity for temperature precision dictates when each material should be used. When accurate temperatures are needed, thermochromic liquid crystals are used. Liquid crystal molecules are structured on separate layers so that they can change their orientation if a temperature reading differs. A temperature change triggers the molecular change on the crystal, which affects its color reflection from light.

Leucodyes paints or inks work on the same principle and are used in circumstances where precise temperature readings are not necessary. Like liquid crystals, leucodyes also have a layered molecular structure that changes its orientation due to the changes in temperature.

Today, thermochromic materials are mainly used for making: mugs that change color based on the temperature of the liquid they contain; pens that change color based on one’s finger temperature; bath toys that predict overall hotness or coolness of bath water; and clothing whose colors change according to the amount of heat generated by the body. In architecture, these materials are mostly used for interactive visual effects, although they could have additional applications for green architecture in the future.

**Thermochromic windows** In response to changes in the ambient temperature, new thermochromic window films alter their color structures as well as reduce solar heat transmission by blocking UV radiation (see Fig. 7.1). These thin plastic films are quite practical and can be incorporated into almost any window assembly.

![Thermochromic windows](image)

**Figure 7.1** Thermochromic windows provide energy savings up to 30 percent over traditional window systems.
For example, sunlight responsive thermochromic (SRT) system is developing a thermochromic film that darkens as it absorbs sunlight shining directly on a window. The tinted film has a low E layer, preventing an undesirable heat load on the building.

**Thermochromic paints** Thermochromic paints change color (and thus heat absorption) based on temperature changes in the outdoor environment. According to experimental studies done by the Group of Buildings Environmental Studies of the Physics Department at the University of Athens (Karlessia, Santamourisa, Apostolakisb, Synnefaa and Livada 2009) thermochromic applications provide thermally comfortable living environments that reduce energy consumption and help improve the urban microclimate.

**THERMOTROPIC**

In response to heat and temperature changes, thermotropic materials undergo various property transformations, including: conductivity, transmissivity, volumetric expansion, and solubility (Addington and Schodek 2005). When a thermotropic material absorbs heat its molecular structure is altered, resulting in property changes.

Although they all have similar structures, there are several different thermotropic systems, including casting resins, polymer films, hydrogels, and liquid crystals. Transparent casting resins are used in diverse types of glazing, such as windows, facade elements, and roofs. Thermoplastic polymers are used for existing windows, roof structures, or as laminates for greenhouses and solar panels. Hydrogels are particularly ideal for energy-efficient windows, as they may be used over a wide temperature range (5–60°C) (Schwartz 2008). Thermotropic liquid crystals are similar to liquids and crystalline solids. They are used for smart, efficient windows as they can provide privacy without sacrificing incoming light.

**Thermotropic windows** Thermotropic windows are one of the most popular smart window systems today because a window’s visibility is directly controlled by climatic temperature changes. If the material’s temperature exceeds a certain limit, the thermotropic layer becomes milky white, reflecting a large proportion of the incident light. However, there are no visual changes to the window at low temperatures. Therefore, during the winter these windows allow solar light and heat to penetrate undiminished into the building. For more information, see Fraunhofer website: http://www.iap.fraunhofer.de.

**THERMOELECTRIC**

Thermoelectric is the conversion of electrical energy into thermal energy, which is based on a principle called the “Peltier” or “Peltier–Seebeck” effect (see Fig. 7.2). The principle of thermoelectric energy conversion was discovered by Seebeck in 1821 (Ohta 2007). Seebeck found that an electrical volt was generated between two ends of a metal bar when there was a temperature difference at each end of the bar. In 1834,
Jean Peltier discovered that heat transfers from one metal to another occurred when an electrical current was applied across the junction of two dissimilar metals.

Thermoelectric materials are constructed from a series of connected metals. When an electrical current passes through the connections, heat is transferred. In fact, these materials are capable of transferring a large quantity of heat when connected to a heat-absorbing device on one side and a heat-dissipating device on the other.

There are three physical properties that thermoelectric materials need to efficiently turn thermal energy into electric current:

- Low thermal conductivity
- High electrical conductivity
- Large thermoelectromotive force

Thermoelectric modules are durable, reliable, silent, lightweight, and compact green materials; they do not include compressed gasses, chemicals, or toxic agents. Currently, because of their relatively high cost and low efficiency, thermoelectric devices are limited to applications in which portability, reliability, and/or small size are more important than their cost—such as for the military or aerospace industry.

### SHAPE MEMORY

Shape memory materials change their shapes from a rigid form to an elastic state when thermal energy is applied (see Fig. 7.3). When a thermal stimulus is removed, the material reverts back to its original rigid state without degradation. These effects are called “thermal shape memory” and “superelasticity” (Duerig 1990; Lagoudas 2008).

There are two classes of shape memory materials, each with different shape-changing characteristics: shape memory polymers (SMP) and shape memory alloys (SMA). When exposed to a temperature change, SMPs exhibit a mechanical property loss, as seen in releasable fasteners. By contrast, materials with SMAs provide force. As such,
they can become a lightweight, solid-state alternative to conventional actuators, such as hydraulic, pneumatic, and motor-based systems.

The application of shape memory materials spans a wide variety of sectors (automotive, biomedical, aerospace, robotics) where their superelastic properties or the shape memory effect can be best utilized. In green architecture, applications vary from self-repairing concrete beams (Kuang and Ou 2007) to deployable structures. Practical applications, such as shape memory foams that expand when exposed to higher temperatures to seal window frames, have been widely used in the building industry.

**Self-accommodating ventilation systems**  This experimental project was developed by Sergem Engineering BV, located in Leidschendam, Netherlands. In this project, shape memory alloys are used in a self-accommodating ventilation system. Changes in temperature within or outside the building activate the SMAs, operating a louver ventilation system.

**Deployable structures**  A shape memory composite is a unique material for use in dynamic structures and other applications requiring both load strength and flexibility.

Cornerstone Research Group, Inc., (CRG) has developed a structure system using shape memory composites that can be temporarily softened, reshaped, and hardened to function as deployable, flexible structures. These materials can be easily stowed for space efficiency, and then later deployed to its operational shape. The company states that the composites can be fabricated from nearly any fiber type, and that creative reinforcements permit dramatic shape changes. Applications include lightweight, rigid deployable structures (especially as an alternative or enhancement to current inflatable structures, rapid manufacturing, and dynamic reinforcement).
Flexible surface materials  In their Living Glass Project, David Benjamin and Soo-In Yang used a shape memory alloy to open and close a surface, much like the gills of a fish (Brownell 2006; Manfra 2006; McMasters 2006). Wire embedded within cast silicone contract when subjected to an electrical stimulus, causing “gills” in the surface to open and close. The system can be used for environmental control, such as circulating air within a room when high levels of carbon dioxide are detected.

Light-Responsive Materials

Light-responsive materials (LRMs) are smart materials that transform due to a change in light.

PHOTOCHROMIC

Photochromic materials change their ability to reflect color when exposed to light, and the color change is proportional to its level of UV light absorption. When a photochromic material absorbs UV light, the chemical structure of its molecules (and consequently, the light reflection of the material) changes. This results in reversible color reflections. When the light source is terminated, the material changes back to a clear state. Photochromic materials can also change from one color to another when it is combined with a base color.

Photochromic materials have numerous potential applications, such as for eye glasses, toys, cosmetics, clothing, and industrial products. They are also used in paints, inks, and casting materials. One potential application is on windows for vehicles and buildings, but currently these materials are too unstable, showing weak color change at high temperatures.

PHOTOVOLTAIC

A photovoltaic system is the process of producing an electrical current in a solid material. It was first discovered in 1839, but was not utilized for more than a hundred years. Today, photovoltaic materials are used to convert sunlight into electricity. When a photovoltaic material absorbs UV light, the photons separate the electrons from the atoms of the solar cell material, allowing the free electrons to move through the cell. This creates a new energy that can be harnessed and subsequently used for electrical energy. The physical process of this conversion is called “the photovoltaic effect.”

Currently, there are two types of solar cell technologies: (1) crystalline materials and (2) thin film materials. Single crystal silicon cells are made of thin silicon wafers, which are cut from a single silicon crystal. These are the most efficient type of silicon cells and have a long life expectancy of more than 25 years. However, the cells are fragile and must be mounted in a rigid frame. Multicrystal silicon cells are also extremely thin wafers of silicon but are cut from multiple crystals with similar life.
Stimulus (force)-responsive materials are smart materials that transform due to a change in external stimulants, such as electricity, mechanical force, and kinetic energy.

**ELECTROCHROMIC**

Electrochromic is the ability of a material to transmit light due to a change in electrical current. The optical properties are reversible, and the material reverts to its original state once the electrical current is removed. As such, electrochromic materials are the primary choice for visual devices, such as smart windows, light shutters, information displays, reflectance mirrors, and thermal radiators (Granqvist 1995) (see Fig. 7.4).

Electrochromic materials were first introduced by Deb on tungsten oxide films 35 years ago. (Deb 1973; Granqvist 1995) and became immediately popular for information displays, especially for liquid crystal devices. In green architecture, this material is mainly used in “smart windows” for its energy efficiency and thermal comfort. The transparency/opacity level is adjusted by an applied voltage.

**ELECTROSTRICITVE**

Electrostrictive materials change in size in response to an electric field and produce electricity when stretched. When an electrical current is applied, the molecular structure of
the material changes through polarization, which alters its molecular energy and produces elastic energy (Addington and Schodek 2005).

These materials are primarily used as precision control systems such as: vibration control and acoustic regulation systems in engineering, vibration damping in floor systems, and dynamic loading in building construction. They are also used as transducers for a variety of electric power generation applications, such as acoustic actuators for smart skins and microactuators for micropumps and valves.

**PIEZOELECTRIC**

Piezoelectric materials generate an electrical current in response to an applied mechanical stress. Like most electrostrictive materials, piezoelectrics are bidirectional, meaning an applied input produces a deformation. (Addington and Schodek 2005). Piezoelectric materials are used in electromechanical devices such as: microphone transducers, speakers, ceramic tweeters, buzzers, medical ultrasound imaging, and underwater sonar devices.

**Nanomaterials**

The prefix “nano” is derived from the Greek “nanos,” meaning “dwarf” or “little old man.” This term is often used to describe a particular length scale, one that typically ranges between 1 and 100 nm. All materials are composed of grains, which in turn comprise many atoms. Nanomaterials, then, are materials possessing grain sizes from 1 to 100 nm in length in at least one coordinate, and often in three coordinates (Wilson, Kannangara, Smith, Simmons and Raguse 2002).
Conventional materials have grains varying in size anywhere from hundreds of microns to centimeters. These grains are usually invisible to the naked eye. In typical nanomaterials, the majority of the atoms are located on the surface of the particles, whereas they are located within the bulk of conventional materials. Thus, the intrinsic properties of nanomaterials are different from conventional materials since the majority of atoms are in a different environment. As such, nanomaterials represent an almost ultimate increasing surface area (Wilson, Kannangara, Smith, Simmons and Raguse 2002). As such, they manifest extremely different and useful properties, which can be utilized for a variety of structural and nonstructural applications.

NANOSCALE STRUCTURES IN UNPROCESSED FORM

Fullerenes Fullerenes are formal structures of carbon atoms that can be arranged into various geometric shapes, such as cylindrical and spherical. Because of its resemblance, it was named after the geodesic domes designed by the architect Buckminster Fuller (see Fig. 7.5). Different geometrical shapes have different names; for example, spherical fullerenes are called “buckyballs” and cylindrical ones are called “nanotubes.”

Fullerenes molecules are similar to graphite and diamond but contain more carbon. This gives them unique structural properties. For example, carbon nanotubes are only a few nanometers in size but 50 percent lighter and 20 times stronger than steel alloys. They have high tensile strength, high resistance to heat, and high electrical conductivity. Because of their excellent nanoproperties, fullerenes are used in various high-end applications such as: sports gear, conductive adhesives, connectors, plastics, molecular electronics, biomedical applications, and for energy storage and thermal materials.

Figure 7.5 Fullerenes carbon molecules were named after Buckminster Fuller for their resemblance to his geodesic designs.
Nanoparticles Nanoparticles are the building blocks of nanomaterials, with diameters of 100 nm or less. Because of their nanoscale, their properties (mechanical, optical, magnetic, etc.) show molecular differences, and correspondingly, exhibit dissimilar characteristics than the bulk materials. For example, copper nanoparticles do not exhibit deformation characteristics as do bulk copper. Similarly, unlike the bulk counterpart, carbon nanoparticles demonstrate unique properties such as low density, high porosity, improved tensile strength, and thermal and chemical stability. Therefore, they are used in hybrid-specialized applications such as paint, laminating and lubricating agents, electrode materials, and semiconductors. Recent research on nanoparticles has focused on solar energy cells, biomedical applications (e.g., biosensors and imaging devices), and electronics.

Nanowires Also known as “quantum wires,” nanowires are ultrathin engineered wires (Wang 2006). Like nanoparticles, nanowires show uniquely enhanced properties over their bulk counterparts. Although most nanowire work is being done in research laboratories today, their incredible length-to-width ratio will allow these nanomaterials to replace nanotubes in the future. Potential uses are for semiconductors, transistors, and biomedical applications. For example, various nanowire-based devices (such as nanobelts and nanosprings) exhibit similar piezoelectric properties and, therefore, can replace piezomaterials for actuators and sensors.