Novel materials

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Materials have central roles in all fields of engineering; they define, through structures and devices, our interfaces to the physical and the virtual world. The emergence of new materials catalyzes transformative advances in civilizations, to an extent that eras of human development are often defined by the prevailing materials used in engineered systems, from the Stone, Bronze, and Iron Ages to the present times, aptly referred to as the Silicon or the Polymer Age. From an academic standpoint, the fundamental phenomena that define complex relationships between chemical compositions, structures, and properties in advanced materials serve as the basis for some of the most intellectually stimulating and dynamic areas of research in the physical sciences. This work has additional appeal because it is intrinsically interdisciplinary and combines essential aspects of traditional fields of study in physics, chemistry, and even biology, to an increasing extent, together with engineering processes and control strategies. Progress in materials science and in the engineering application of new materials is essential to the pursuit of solutions to societal grand challenges. Examples span those related to the development of sustainable sources of energy, from high-power magnets for wind turbines to designer semiconductors for solar cells; to the invention of technologies that improve human health, from metal alloys for lightweight prosthetics to polymer matrices for controlled drug release; to progress in intra- and interplanetary travel within realms of objective and virtual reality alike, from high-efficiency batteries for emissions-free vehicles, to carbon composites for fuel-efficient spacecraft, to atomically thin films for high-speed integrated circuits.

This Special Feature on Novel Materials presents a collection of perspectives articles, short reviews, and original research papers designed to capture some of the breadth and excitement in recent materials research. This representative set of topics intersects critical areas in electronics, biology, advanced manufacturing, and chemical synthesis, with interdisciplinary foci that combine scientific discovery with engineering applications.

The issue begins with three articles on materials for classes of biomedical devices that offer capabilities with direct benefits in human health. The first article, by Ailianou et al. (1), describes fundamental studies of biodegradable polymers used in advanced vascular scaffolds designed for the treatment of coronary heart disease. These devices, known as stents, deploy into blood vessels where they provide structural reinforcement following procedures to remove obstructive plaques. Traditional metal stents, used on more than a half-million patients annually, remain in the body, where they present lifelong risks, most significantly because of their tendency to nucleate the formation of blood clots. Biodegradable polymers provide an alternative, in the form of stents that dissolve and disappear gradually after their function is no longer needed, thereby eliminating unnecessary device load on the patient. Such types of stents are rapidly replacing conventional counterparts. The findings reported in the Ailianou et al. article provide important insights into the morphological characteristics of the constituent polymers that confer the mechanical strength necessary for these and related applications. In particular, the authors discover that deformations caused by deployment of these stents align the polymer chains in a manner that increases their strength and prevents the formation of fractures. Such understanding has important practical implications for the engineering design of ultrathin, low-profile devices.

The second article focuses on materials designed to prevent the formation of clots and biofilms on the surfaces of stents and other implants. Specifically, Sunny et al. (2) introduce a composite coating that consists of a porous solid matrix filled with a liquid, to yield a repellent surface that prevents fouling. This system, as demonstrated in transparent coatings on endoscopes through a comprehensive set of animal trials, involves a design inspired by the slippery surfaces of the carnivorous pitcher plant, in which the liquid-infused material spontaneously forms a bio-compatible, lubricating, “nonstick” overlayer. For endoscopes, the result is significantly enhanced antibacterial...
and antifouling properties, with an associated reduction in the
need for time-consuming processes to clean the imaging lenses.
The consequences include decreased time and cost for endo-
scopic procedures, with reduced risks to the patient and the
ability to visualize previously obscure regions unobstructed and
uninterrupted. Potential uses extend beyond camera-guided in-
struments, surgical tools, and biomedical implants, to icophobic
surfaces that can improve the safety of aircraft, clog-resistant oil
pipelines that can reduce the probability of spills, and marine
antifouling hulls that can increase the fuel efficiency of ships.

The third article in this area, by Fang et al. (3), reports a mate-
rials solution to a long-standing challenge in classes of implant-
able devices that, unlike endoscopes or biodegradable stents,
must provide reliable electronic functionality over the lifetime of
the patient. In established technologies of this type, such as car-
diac pacemakers and cochlear implants, the electronics reside in
metal or ceramic housings. Interfaces to the body occur through
point contacts established via electrode pads at the terminal ends
of connecting wires. Recent research establishes materials strate-
gies and device designs for flexible, conformal devices that can
integrate directly with the curved, moving surfaces of critical in-
ternal organs, to provide qualitatively more sophisticated modes
of operation in which the integrated electronic systems them-
selves, rather than wired electrodes, establish the biotic/abiotic
interface. A key challenge in achieving stable, long-term function
with such systems is in the development of thin, flexible coatings
as structurally perfect, impermeable barriers to prevent penetra-
tion of surrounding biofluids into the active electronics. Results
presented by Fang et al. (3) demonstrate that pristine, thin films of
silica, thermally grown on the surfaces of device-grade silicon
wafers and then physically integrated on top of flexible electronics
platforms, can satisfy these demanding requirements, with pro-
jected operational lifetimes of many decades. This advance in
materials science leverages a long history of innovations in crystal
growth, purification, cleaving, and polishing techniques that un-
derpin the capacity to manufacture silicon wafers with a nearly
complete absence of impurities or crystal imperfections and with
surfaces that have roughness measured at the atomic level. Silica
that forms by oxidizing the surfaces of such wafers yield thin,
electrically insulating layers of water-proof glass with similar levels
of perfection and uniformity. Large-area films produced in this
manner can reliably and reproducibly integrate with the most ad-
vanced forms of flexible electronic devices to yield impenetrable
biofluid barriers. The outcomes enable long-lived biomedical im-
plants that can bend and conform to the surfaces of critical organs,
such as the heart or the brain, to provide clinically relevant modes
of operation in stimulation and electrophysiological mapping that
cannot be achieved with rigid, sealed electronic platforms and
wired point contact interfaces that are available today.

The next two articles involve additional classes of materials
with relevance to these and other types of advanced electronic
systems. In the first article, Kang et al. (4) report methods for
creating and purifying microscale sheets composed of phospho-
rous atoms chemically bonded together in a 2D construct, with
thicknesses as small as a single atomic diameter. This material,
known as phosphorene, has excellent semiconducting characteris-
tics and remarkable mechanical properties. These features suggest
potential uses in advanced electronic components, including tran-
sistors that might find roles in the types of flexible devices de-
scribed in the previous paragraph. The methods introduced by
Kang et al. rely on aqueous solution dispersions and centrifuga-
tion techniques to yield phosphorene with unmatched materials
quality. The resulting high-performance “inks” can be delivered
by low-cost printing techniques to substrates of interest for the
construction of various types of electronic devices. Demonstrations
include field-effect transistors with key properties that ex-
ceed those of devices formed with phosphorene synthesized in
other ways.

The second article on electronic materials, by Kim et al. (5),
summarizes recent progress in the development of light-emitting
devices (LEDs) that have the potential to enable displays with
brighter, more vivid colors and lower materials costs compared
to those of technologies that currently dominate the consumer
electronics market. The active materials include both organic
and inorganic constituents, combined in ways that provide great
versatility in their chemical compositions, crystalline structures, and
associated properties. Although many of these so-called hybrid
materials are historically old, rapid advances over the last three
years in methods for chemical modification and physical deposition
in forms optimized for operation in LEDs position these technolo-
gies as leading candidates for displays of the future, including
those with paper-thin geometries and bendable mechanics. The
materials and approaches for flexible and printable electronics em-
body in the preceding pair of articles could be relevant in this
context, as backbone driver circuits for these hybrid LEDs.

In any complex system, such as a display, materials-processing
strategies and fabrication schemes are critically important. Al-
though solution printing approaches such as those used for the
phosphorene electronic inks in the paper by Kang et al. (4) are
valuable, they are best suited for forming patterns of thin films in
largely planar formats. Research over the last decade has estab-
lished a broad range of materials and methods for printing 3D
objects. The article by Janusziewicz et al. (6) reports progress on
one of the most powerful and newest of these techniques. Here,
specialized photosensitive polymers enable a process in which
continuous exposure of a liquid precursor material to programmed
patterns of light yields—in a continuous manner—3D objects in
complex geometries, without the rough, layered morphologies that
characterize parts formed using traditional methods. The resulting
levels of uniformity in physical properties and degrees of precision
in surface finish significantly exceed those of any alternative. The
materials insight that underpins this technique is that the presence
of oxygen can inhibit certain light-initiated reactions that cure
liquid monomers into solid polymers. Janusziewicz et al. exploit
this behavior by using an oxygen-permeable optical window that
prevents growth of polymers directly on the window, where the
oxygen concentration is high, but allows it to proceed unimpeded
in adjacent regions where the concentration is low. Passing a se-
quence of patterns of light through this window in a coordinated
fashion as it continuously moves through a liquid bath of monomer
yields 3D parts with user-definable geometries. The high-speed
nature of this process has the potential to expand the use of 3D
printing beyond its traditional realm in prototyping, into high-
volume, cost-effective manufacturing where the polymer materials
will continue to play key roles in tailoring the resulting parts to
satisfy application requirements.

In the article by Haines et al. (7), the authors demonstrate an
interesting application of unusual, 3D polymeric structures formed
by techniques of spinning and weaving rather than by 3D printing.
Here, helical coils of oriented polymer fibers generate large and
reversible changes in length as a result of thermal expansion under
this type of geometric constraint, even with mild levels of heating/
cooling. The underlying process involves winding/unwinding of
these helical constructs such that actuators can be engineered as
a kind of artificial muscle composed of individual strands, linear arrays of them, or 2D woven fabrics. Motion in such cases occurs through processes associated with intrinsic changes in the constituent materials, as a solid-state alternative to mechanical machines that rely on gears, pulleys, and motors for similar purposes. These materials-based actuators can deliver levels of specific work that exceed those of natural muscle by 50 times, and they offer the ability to create torsional actuation for rotational motions that can reach speeds of over 100,000 revolutions per minute. Such capabilities are of additional interest when considered in the context of the biomedical materials systems discussed in the first three papers (1–3).

The final article in this Special Issue provides perspectives on a strategy to produce 3D materials that is radically different from the 3D printing schemes and winding/weaving processes described above. In this piece, O’Brien et al. (8) outline fundamental considerations in the formation of systems by hierarchical organization, where structures that develop at one length scale are used as building blocks for a larger length scale. The corresponding processes range from formation of nanoparticles from atomic precursors, the organization of molecules on the surface of these nanoparticles, and eventually on materials built from nanoparticles, where the structure is guided by the results from the preceding length scales. This interconnected description reveals how the uniformity and control of one length scale profoundly impacts what can be achieved at each subsequent length scale. A goal of this work is to develop foundational concepts in materials science that can address the unique challenges associated with structural and compositional control in these unusual systems.

Our hope is that this overview and the associated collection of articles in this Special Issue can convey some of the vibrancy and excitement associated with modern research in advanced materials. The topics presented here are of interest not only for their basic scientific content in issues related to the growth of materials and structures, their intrinsic mechanical, chemical, and electrical properties, and the nature of interfaces between materials and biological systems, but also for their core relevance to engineering applications in areas ranging from biomedical devices to consumer electronics. The topical breadth, interdisciplinary content, and direct linkages to societal grand challenges suggest a bright and essential future for research on novel materials.