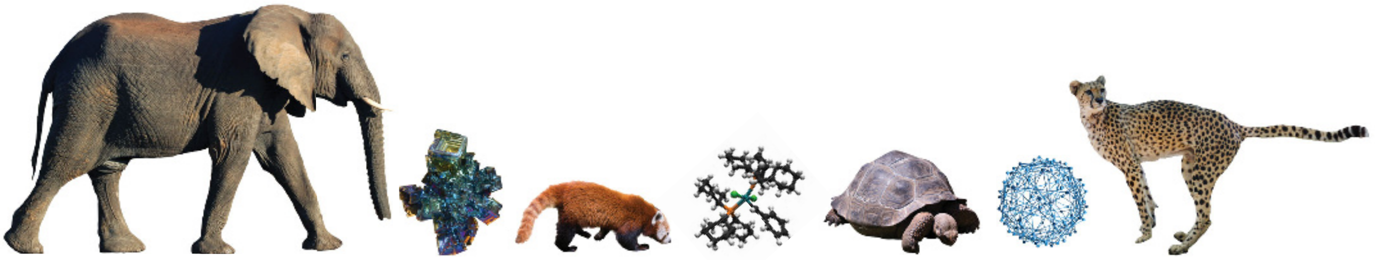

The new (old?) MATERIALS ZOO

Ah, life in the 21st century. Isn't it glorious? Every day I wake up, it seems there is a new type of material, or a new use for an old material, or a new materials process that promises to make our lives more enjoyable. We live in a wonderful world of materials, with engineered materials at the nanoscale and atomic scale, including heterostructures, quantum wells, quantum wires/nanowires, quantum dots/nanocrystals, 2D materials, and a variety of new compounds and alloys (ternary, quaternary, and quinternary materials). Some of these, such as heterostructures and quantum wells, have been around for 30 years or more. Others, such as graphene, have been known for much longer, but have recently taken on new life.

Work on a broad class of so-called 2D materials emerged in 2004 with the identification and measurement of the properties of single atomic layers of carbon in a hexagonal lattice.[1] The earliest work on record for this material involved discussions of the energy-band structure of a single hexagonal layer of graphite.[2] The more recent work, which started through exfoliation of graphite from pencil lead, has been followed by suggestions of potential applications in microelectronics, optoelectronics, flexible electronics and sensors, among others. The reemergence of graphene was followed quickly by reports of silicene, germanene, and a variety of 2D layers of transition-metal dichalcogenides (e.g., MoS_2, $MoSe_2$, $MoTe_2$, WS_2, WSe_2).[3] Developments around these include nanoribbons, nanowires, heterostructures, and quantum wells.

Other fascinating new areas of materials science include materials for spintronics[4,5] and topological insulators.[6] Spintronic materials and devices are based upon ideas of spin transport in solid-state materials. Most fundamental semiconductor transistors work on the basis of transport of charge carriers (electrons and/or holes). Channels for electrical transport are formed and then controlled by electrical biases. The movement of charge from one region of a device to another is the foundation of modern integrated circuits, including the microprocessors that drive our computers, tablets, eReaders, phones, and automobiles.

As the need for higher processing power has evolved, transistors have become significantly smaller in size. Transistors long ago reached the point where some or all of their dimensions were comparable to the wavelength of the charge carriers, which means that quantum mechanical effects have to be taken into consideration in discussing their performance. At some point, this trend in downsizing (or, as one of my friends calls it, "smallifying") has to end, as fundamental limits exist below which transistors (at least those based upon the common semiconductor-device materials) cannot maintain their performance. Intel is currently producing microprocessors with transistors with some dimensions on the scale of 14 nm. Microprocessors and other integrated circuits with transistors scaled to the 5-nm node seem to be just around the corner. The transistors in these devices may be nanowire field-effect transistors. It is not clear how much further we can go with these approaches. Spintronic structures that use materials based upon III–V semiconductors, including III-nitrides, and ferromagnetic or antiferromagnetic compounds, including Heusler compounds,[7] may offer a path forward toward higher levels of performance or lower power consumption. They may also drive solid-state approaches to quantum information applications such as quantum computing.

As is well known, surfaces have always been problematic, which has supported many of our careers.[8] There are different surface reconstructions depending on conditions. Dangling bonds yield states that enhance trapping and recombination. They are sensitive to growth of native oxides and contamination. Depending upon how the materials are produced, the surfaces may have significant roughness and other defects. Forming reproducible contacts to surfaces can be problematic. Growing other layers on top of existing layers or substrates can be problematic. Trying to extract bulk properties from measurement results can be difficult if surface processes are also interrogated (e.g., extracting bulk carrier lifetime from transient photoluminescence in the presence of strong surface recombination effects).

Now, along come topological insulators:[6] 2D topological insulators (e.g., HgTe) and 3D topological insulators (e.g., a variety of bismuth-containing compounds). In 2D topological insulators, the conductive states are edge states. Three-dimensional topological insulators are materials whose bulk properties are those of insulators, but that have surface states that can be conductive. Under some conditions, these edge or surface states are protected from disorder by their symmetry conditions. Topological insulators may have unconventional applications in spin transport, superconductivity, nanophotonics, and plasmonics. The 2016 Nobel Prize in Physics was awarded to J. Michael Kosterlitz, F. Duncan M. Haldane, and David J. Thouless for their work on these fascinating materials.

Who knew that bismuth would become so interesting? For most of my life, the only application of bismuth with which I was familiar was for Pepto-Bismol for digestive relief. Pepto-Bismol is bismuth subsalicylate.[9] Bismuth is a semimetal and has other interesting properties. Recent work has revealed a superconducting phase of bismuth at extremely low temperatures <0.53 mK that cannot be explained by the conventional Bardeen–Cooper–Schrieffer theory.[10] It has been shown that promising semiconductor materials can be made by adding small quantities of bismuth to the III–V semiconductor compounds.[11] These so-called dilute bismides (e.g., $GaAs_xBi_{1-x}$, InP_xBi_{1-x}) have potential applications in optoelectronics, including solar cells, lasers, and light-emitting diodes. Other work has demonstrated that compounds such as Bi_2Se_3 and Bi_2Te_3 are topological insulators.[6] These add to the small but growing list of applications for bismuth-related materials.[12]

Some of you may be familiar with the idea of exploiting metamaterials for optical cloaking,[13] somewhat similar to the Cloak of Invisibility invoked in the Harry Potter fantasy books, as one of the three Deathly Hallows.[14] "Meta" is a modifier to the word "materials." Many of us believe we know the definition of a material.[15] The modifier "meta" in this usage means above and beyond. In metamaterials, responses to electromagnetic radiation or sound or other stimuli are based on the structure of the objects at the mesoscale or larger, as much as they are based upon the materials properties themselves.[16] Metamaterials have mesoscale objects constructed to form artificial atoms on a mesoscale lattice.

One of the most publicized aspects of metamaterials is their ability to manifest what is apparently a negative value for the real part of the index of refraction. This means that electromagnetic radiation entering these materials will alter their paths in manners different than normal refraction. Cloaking using metamaterials appears to work somewhat differently, and in a much more limited fashion, but is being vigorously explored by the community. Metamaterial concepts have also been discussed for isolating buildings and other structures from the effects of earthquakes.[17] For those of you who have lived through a major earthquake and know how absolutely terrifying that experience is, we would appreciate anything that could isolate us from those effects.

Finally (at least for now), I recently ran across the word *metamictization*. Not knowing the meaning, I looked it up. It is an intrinsic materials response that takes a crystalline material to an amorphous phase over time.[18] Examples include crystalline materials that contain radioactive species. The emitted radiation and the recoiling nuclei can slowly amorphize the crystalline material. As someone interested in radiation effects, this process intrigued me, and I naturally wondered about the word. After all, it contains the modifier "meta," which means above and beyond. And yet, "mictization" does not seem to be a word by itself. At least, in the searches I've done, I've found no dictionary references to it, nor have I found any usage of that word. Consequently, "metamictization" is a word in and of itself, and the "meta" part of it is not just a modifier.

When I was a student, life was much simpler. We were expected to know about silicon, germanium, and a few other semiconductor materials, some simple metals, and oxides. The processing and characterization of these materials was fairly simple. We watched with trepidation and awe when some of our colleagues investigated more exotic materials such as HgCdTe. Today, the materials zoo is extremely complex and growing more so every day. We materials zoologists are expected to know these and many other materials, their synthesis, their properties, how to characterize them, and their potential applications. And I haven't even really touched Ruddlesden–Popper phases,[19,20] Heusler alloys[21] and half-Heusler alloys,[22] dilute nitrides[23] and antimonides,[24] or auxetic materials,[25] just to name a few. Isn't it great?

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