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Refractory Plasmonics

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Refractory materials are defined as those with a high melting point and chemical stability at temperatures above 2000°C. Applications based on refractory materials, usually nonmetallic, span a wide range of areas including industrial furnaces, space shuttle shields, and semiconductor technology. Metals have also been studied as refractories; however, the optical properties of those metals that have been tried for high-temperature applications were not good enough to be used in plasmonic applications (these are almost entirely based on noble metals, which are not good refractories). Refractory materials that exhibit reasonably good plasmonic behavior would undoubtedly enable new devices and boost such existing applications as heat-assisted magnetic recording (HAMR) (1), solar/thermophotovoltaics (S/TPV) (2), plasmon-assisted chemical vapor deposition (3), solar thermoelectric generators (4), and nanoscale heat transfer systems (5).

The field of plasmonics offers the potential to greatly enhance the efficiencies of existing technologies, such as electronics and photonics, as well as to create new technological opportunities (6). Although several proof-of-concept studies have been reported, the realization of practical devices has been hindered by the challenges associated with the properties of noble metals—in particular, poor chemical and thermal stability and high losses (7, 8). Usually listed as a problem for plasmonic applications, resistive losses result in heating of the plasmonic material, enabling a temperature rise in a confined volume around the nanostructure. Several plasmonic applications with a great potential for practical use, such as photothermal treatment (9) and HAMR (1), rely on the heating effects. Because of the local temperature rise, the mechanical and chemical stability of plasmonic nanostructures are of paramount importance; refractory plasmonic materials are therefore indispensable.

S/TPV technology is based on the idea of absorbing solar irradiation with a broadband absorber, which results in heating of an intermediate component and the subsequent emission of this thermal energy in a narrow spectrum for efficient absorption by the photovoltaic cell. Such devices can theoretically achieve energy conversion efficiencies up to 85% (2). However, the operational temperatures required for high-efficiency devices are estimated at ~1500°C, and emitter materials that can withstand prolonged exposure to such temperatures have not yet been developed. Engineered absorber and emitter photonic crystals can be fabricated with refractory metals (10, 11), but achievable operational temperatures are still far below 1500°C.

A handful of alternatives. The low melting point and softness of metals pose problems when real-world applications are considered, especially in nanostructures in which the melting point is reduced. Refractory plasmonic materials would provide a solution for high-temperature applications where corrosion and wear resistance are desired. Refractory metals exhibit plasmonic resonances mostly in the near-infrared region with relatively higher losses. Transition metal nitrides mimic the optical properties of gold and provide the superior material properties of the refractory materials. It is above the “crossover wavelength” that a material becomes plasmonic.
the desired values, and adequate durability cannot be obtained even with protective layers made of refractory dielectric materials (11). One-dimensional photonic crystal emitters based on Si/SiO$_2$ layers, although they are more vulnerable to degradation at high temperatures, have demonstrated the highest S/TPV efficiency when integrated with a carbon nanotube broadband absorber that has limited spectral selectivity and back-emission at longer wavelengths (12). Refractory plasmonic materials could be the solution for most of the major limitations, thus advancing the existing S/TPV technology. Ultrathin metamaterial absorbers and emitters made of the same refractory plasmonic material could be integrated as a narrow intermediate spectral converter that can be easily heated, owing to the increased surface-to-volume ratio (13). The absorber could be spectrally engineered so that back-emission is minimized at longer wavelengths and a reduced absorber area ratio is no longer a problem. Larger absorber areas would enable higher temperatures and much higher efficiencies, also eliminating the need for light collection optics. More important, thinner structures achievable with metamaterials would reduce the mechanical load on the nanostructures, thus enabling high-temperature durability. Another field with a potential near-term impact in industry is HAMR. The demand for larger data storage capacity has resulted in a need for larger areal densities, and consequently smaller grain sizes, which in turn may lead to thermal instabilities. One promising approach is to use high-coercivity materials (which have greater stability at room temperature) and to locally heat the material with a plasmonic nanoantenna, lowering its coercivity for a short time to write data. This idea was demonstrated in an experiment in which local heating on a 70-nm track was achieved with a gold nanoantenna (1). However, efficient heating of the high-coercivity material results in self-heating of the plasmonic component. Local temperatures reaching 400°C, along with tough operation conditions, impose an extra load on the antenna, which is located very close to a disk spinning at a high speed. Under these conditions, deformation of the nanostructure is unavoidable, especially for noble metals (14). In contrast to S/TPV, studies on HAMR have yielded some findings on the advantages of using plasmonic nanostructures, but have lacked materials with the required refractory properties. The solution for potential high-impact refractory plasmonic applications lies in material building blocks. Finding the proper constituent materials could open up a new avenue for high-temperature applications of advanced plasmonic and metamaterial devices, analogous to recent advances in silicon and silica fiber technologies. One example is transition metal nitrides, such as titanium nitride and zirconium nitride, that exhibit plasmonic properties comparable to those of gold in the visible and near-infrared spectrum (15) (see the figure). Coupled with their refractory properties, these materials can boost the performance of many heat-assisted plasmonic devices, thus replacing the traditional noble metals or refractory materials with poor plasmonic properties. Materials research has been at the center of the most recent studies in the field of plasmonics and metamaterials. Among the alternative materials with desirable optical performance, those with complementary metal–oxide semiconductor compatibility, biocompatibility, chemical stability, tunability, and low losses have attracted attention (16). High-temperature stability is the next desired feature to develop in the field of plasmonics.

References and Notes

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Myelin—More than Insulation
R. Douglas Fields

Myelin is often compared to electrical insulation on nerve fibers. However, nerve impulses are not transmitted through neuronal axons the way electrons are conducted through a copper wire, and the myelin sheath is far more than an insulator. Myelin fundamentally changes the way neural impulses (information) are generated and transmitted, and its damage causes dysfunction in many nervous system disorders including multiple sclerosis, cerebral palsy, stroke, spinal cord injury, and cognitive impairments. A detailed understanding of myelin structure is therefore imperative, but is lacking. On page 319 of this issue, Tomassy et al. (1) provide a high-resolution global view of myelin structure spanning the six layers of mammalian cerebral cortex. The findings are likely to spark new concepts about how information is transmitted and integrated in the brain. New techniques of automating collection of electron microscopic images taken in series through layers of tissue are becoming available to analyze neuron ultrastructure in large volumes (2). Using such methods, Tomassy et al. reveal myelin structure in the mouse cerebral cortex along individual nerve fibers, providing a coherent picture.

Unusual features of myelin in the mammalian cerebral cortex permit more complex forms of network integration.

Myelin is a coating of compacted cell membrane that is wrapped around the axon by non-neuronal cells called oligodendrocytes. These multipolar cells extend slender cellular processes to grip axons and spin up to dozens of layers of membrane around it like electrical tape. Many oligodendrocytes grasp a single axon to span its full length. The tiny space exposed between each grasping “hand” corresponds to a node of Ranvier, where voltage-gated sodium channels are concentrated. When the electrical potential across the axon membrane depolarizes by about 20 mV, these channels allow rapid influx of sodium ions that discharges the transmembrane potential, creating a voltage transient of ~0.1 V—the action poten-