mantle rheology for relating seismic wavespeed variations to temperature. Future studies will aim at making models gradually more Earth-like. A key aspect of this will be to develop more realistic models of lithospheric strength, which controls the amount of deflection that can develop due to buoyant mantle loads, and drag of the flowing mantle at the base of the lithosphere, which can lead to lithospheric deformation. Improved models of topography development must link mantle dynamics to these more realistic lithosphere models. Toward this goal, the work of Liu *et al*. is a major step in linking plate tectonics and mantle dynamics.

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APPLIED PHYSICS

Plasmonics Applied

Surface plasmons, light-induced excitations of electrons on metal surfaces, may provide integration of electronics and optics on the nanoscale.

Albert Polman

The ability to engineer metal surfaces and particles at the nanoscale has led to the rapid development of the field of "plasmonics," the optical properties of metal structures at the nanoscale. Surface plasmons are optically induced oscillations of the free electrons at the surface of a metal. Electron beam lithography, focused ion beam milling, and self-assembly have provided routes to engineer complex arrays of metal nanostructures in which plasmons can be excited, directed, and manipulated. The attractiveness of plasmons is that they can effectively confine the optical excitation in a nanoscale volume and thus mediate strong optical interactions within this volume. Also, the wavelength at which these phenomena are observed can be tuned by varying the metal shape and dielectric environment, thereby providing a broad palette from which to choose the desired optical properties for an application.

Early work in plasmonics focused on the study of resonances and electromagnetic field enhancements in individual metal nanoparticles and particle assemblies. The plasmon coupling within arrays of metal nanoparticles can lead to the formation of nanoscale hot spots in which the intensity of light from an incident beam can be concentrated by more than four orders of magnitude. This leads to a large improvement in sensing techniques that use optical radiation, such as Raman spectroscopy, with potential applications in medical diagnostics. The effect of light concentration via plasmons is most apparent in phenomena that are nonlinear in light intensity, as demonstrated recently by the on-chip generation of extreme-ultraviolet light by pulsed-laser high harmonic generation (*1*). This opens a wealth of prospects in lithography or imaging at the nanoscale through the use of soft x-rays (see the figure, left panel).

Because the plasmonic interaction between metal nanoparticles is very sensitive to their separation, precise measurements of the plasmon resonance wavelength of metal particle assemblies functionalized with biomolecules can be used as a molecular-scale ruler that operates over a length scale much larger than that in the fluorescence energy transfer metrology that is routinely used in biology (*2*). Practical applications of this concept in systems biology, such as imaging of the motion of molecular motors, are being pursued. Already, measurement of plasmonic resonance shifts is used in the detection of biomolecules (see the figure, middle left panel), and indeed standard commercial pregnancy tests are based on this principle. A potentially far-reaching application is the use of particles composed of a dielectric core and a metallic shell (*3*) in cancer treatment. These particles, when injected into the human body, are selectively bound to malicious cells, whereupon laser irradiation at a precisely engineered plasmon resonance wavelength is used to heat the particles and thereby destroy the cells. Clinical studies are showing promising results (*4*).

Suitably engineered metal nanostructures can also act as antennas in which the resonant coupling between the particles concentrates light into well-defined hot spots (*5*), enabling ultrasmall, wavelength-sensitive directional sensors or detectors. The same metal particle arrays, when coupled to optical emitters, can also act as directional emitters. Indeed, the enhanced optical density of states near the surface of metal nanoparticles can provide control over the color, directionality, and polarization of light-emitting diodes. This concept may find large-scale applications in the areas of solid-state lighting and photovoltaics (see the figure, middle right panel). Calculations and experiments (*6*) show that light scattering from metal nanoparticle arrays placed on top of a thin-film semiconductor layer can effectively fold the path of sunlight into the layer, strongly enhancing its effective absorption.

Parallel to the development of plasmonic structures based on metal nanoparticles, the propagation of plasmons along metal waveguides is also being investigated. Here too, precise control over material and geometry allows the wave-guiding properties to be controlled in ways that cannot be achieved with regular dielectric waveguides. In particular, extremely short wavelengths can be achieved at optical frequencies. It has been shown that light with a free-space wavelength of 651 nm, squeezed in a metal-insulator-metal plasmonic waveguide, has its wavelength shrunk to only 58 nm (*7*). The next challenge will be to shrink it further, into the soft x-ray wavelength regime. Similar to the coupling within nanoparticle assemblies, this effect is due to the coupling between plasmons propagating at the two metal-insulator interfaces. By further tailoring plasmonic waveguide structures, the propagation speed of plasmons can be reduced well below the speed of light (*8*). More complex geometries, in which arrays of nanoholes are integrated in a metal film, act as efficient color filters (*9*). Interestingly, in some geometries, plasmon waveguides exhibit a negative refractive index for the guided plasmon, and indeed two-dimensional negative refraction has been observed in these plasmonic waveguides (*10*).

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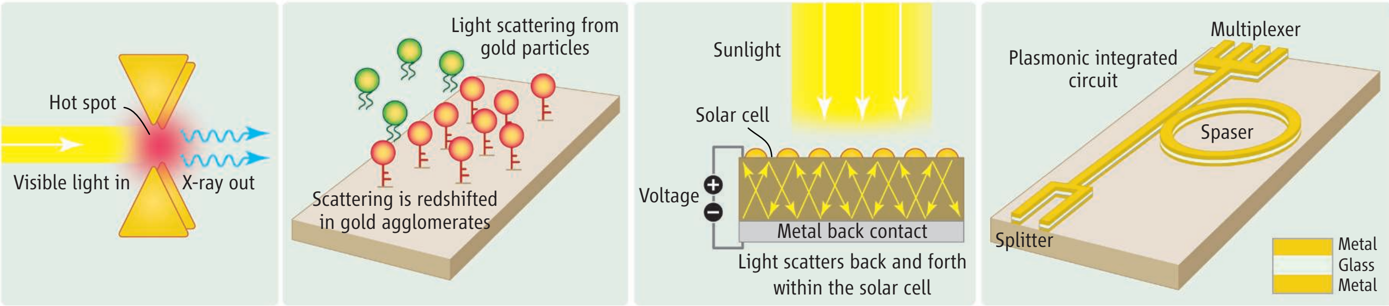

Applied plasmonics. (**Left**) A plasmonic hot spot between metal nanoparticles creates soft x-rays. (**Middle left**) Measuring the resonance shift in coupled metal nanoparticles leads to efficient sensing. (**Middle right**) Scattering from metal nanoparticles enhances light trapping in a solar cell. (**Right**) Plasmonic integrated circuit with subwavelength dimensions. A plasmonic ring laser is integrated with 50-nm-wide waveguides.

These studies on planar plasmon propagation will lead to the design of plasmonic integrated circuits (see the figure, right panel) in which optical information is generated, switched, amplified, and detected within dimensions much smaller than the (free-space) wavelength of light. This will enable the integration of optics with nanoscale semiconductor integrated circuit technology, which so far has proven impossible because of the different length scales of optics and electronics. Although plasmons decay as they propagate, it should be realized that the relatively small propagation lengths can be tolerated in devices with nanoscale dimensions. The eagerly awaited demonstration of a plasmon laser or amplifier would be a further enabler of this plasmo-electronic technology.

A recent development in plasmonics is the study of metallic nanoresonators in two- and three-dimensional arrangements, to form optical "metamaterials" with artificially engineered permittivity and permeability. Negative refraction of near-infrared light has been demonstrated in a stack of metallic "fishnet" structures (*11*). Because of the peculiar way light is refracted in a material with negative index, it is possible to achieve subwavelength optical imaging (*12*). Suitably engineered negative-index geometries may even act as invisibility cloaks for wavelengths in the visible regime.

In only a few years, plasmonics has grown from a field in which fundamental insights were developed to an area that demonstrates important applications. Many new fundamental research topics are currently being pursued, including attosecond dynamics and coherent control of plasmons (*13*), lasing spasers (*14*), cloaking using novel geometries (*15*), and quantum mechanical effects at the subnanoscale level. These studies, which are very exploratory and rich in new science, will very likely lead to new exciting applications of plasmonics as well.

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NEUROSCIENCE

Overcoming Inhibitions

Two reasons why injured neurons of the central nervous system fail to regenerate are inhibition by myelin proteins and a signaling pathway that blocks axon growth.

Woo-Yang Kim and William D. Snider

Nervous system injuries and neurological diseases often result in loss of sensation and paralysis that are irreversible. This is in part because neurons in the central nervous system are unable to regrow long cellular processes (axons) after they are damaged. Thus, neurons lose the interconnections that are vital for nervous system function. On page 967 and 963 of this issue, Atwal *et al.* (*1*) and Park *et al.* (*2*) reveal two molecular mechanisms that contribute to this failure to regenerate, pointing to new potential therapeutics.

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Until the early 1980s, there was little progress in understanding axon regeneration. One of the first breakthroughs came from Aguayo and colleagues, who showed that severed axons of mammalian central nervous system neurons could be induced to grow when placed next to a transplanted peripheral nerve, which was presumed to provide a favorable growth environment (*3*). Subsequently, Schwab and colleagues showed that glial cells (oligodendrocytes) that envelop axons with myelin inhibit axon growth, and that an antibody against myelin could reverse this effect (*4*). The glial scar that forms at the site of injury is also known to be highly inhibitory (*5*). Finally, we now know that even though axons can be induced to grow in a favorable environment, intrinsic developmental changes limit their growth capacity. Compared to neurons in the peripheral nervous system, those in the central nervous system drastically reduce their growth capacity during development (*6*).

Several groups have characterized specific components of myelin that block axon growth, including myelin-associated glycoprotein (MAG), Nogo-A, and oligodendrocyte myelin glycoprotein (OMgp) (*7*). A receptor for Nogo-A (NgR), expressed on neurons, was identified (*8*) and found to also bind MAG and OMgp (*7*). However, the