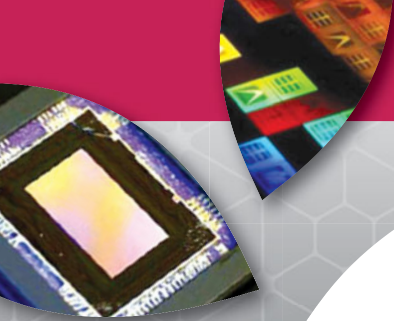

Localized fields, global impact: Industrial applications of resonant plasmonic materials

J.A. Dionne, A. Baldi, B. Baum, C.-S. Ho, V. Janković, G.V. Naik, T. Narayan, J.A. Scholl, and Y. Zhao

From the photoinduced transport of energy that accompanies photosynthesis to the transcontinental transmission of optical data that enable the Internet, our world relies and thrives on optical signals. To highlight the importance of optics to society, the United Nations designated 2015 as "The International Year of Light and Light-based Technologies." Although conventional optical technologies are limited by diffraction, plasmons—collective oscillations of free electrons in a conductor—allow optical signals to be tailored with nanoscale precision. Following decades of fundamental research, several plasmonic technologies have now emerged on the market, and numerous industrial breakthroughs are imminent. This article highlights recent industrially relevant advances in plasmonics, including plasmonic materials and devices for energy; for medical sensing, imaging, and therapeutics; and for information technology. Some of the most exciting industrial applications include solar-driven water purifiers, cell phone Raman spectrometers, high-density holographic displays, photothermal cancer therapeutics, and nanophotonic integrated circuits. We describe the fundamental scientific concepts behind these and related technologies, as well as the successes and challenges associated with technology transfer.

Introduction

Few inventions have been as ubiquitous as the incandescent light bulb. Edison's 1880 patent was born from over 40 years of effort by multiple researchers to optimize the filament materials, the bulb atmosphere, and the socket interface. The invention revolutionized society, bringing light into homes and the workplace, lengthening work and leisure time, and laying the foundation for an interconnected world. It is a technology that underscores the importance of light and light-based technologies to our world and highlights the crucial role of materials research in the optical sciences. Today, efforts continue to make lighting technologies brighter and more energy efficient.

Controlling light extends far beyond the lighting industry. It underpins the Internet, which relies on optical signal propagation, modulation, and detection for fast and long-ranging data communication. It enables new imaging technologies, from digital single-lens reflex cameras for photography enthusiasts to advanced biomedical endoscopy and microscopy. It is foundational to solar energy generation and storage—from natural photosynthesis to engineered photovoltaic and photocatalytic cells.

Whereas the diffraction limit would seemingly prohibit the development of desktop optical computers, flat camera zoom lenses, nanoscale endoscopes, or ultra-efficient nanostructured solar cells, plasmons offer a potentially transformative way to control light and enable new light-based technologies. Because plasmons can tailor light propagation from the molecular to the macroscale, they promise almost complete control of photons into and out of materials and devices. To highlight just

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a few exciting applications, plasmons have enabled brighter light-emitting diodes, smartphone-compatible molecular sensors, photothermal cancer therapies, solar-driven water purification, nanoscale lithography, subwavelength lasers, and high-density data storage and holographic displays.

Plasmonic technologies might be as revolutionary to nanoscale optics as the light bulb was for large-scale lighting. However, as for the light bulb, considerable research remains to optimize materials and performance before plasmonic devices become widespread. This article highlights the most promising societal and industrial applications of plasmons, identifies challenges in their industrial integration, and proposes potential solutions toward technology transfer. We focus on the energy, biomedical, and information-technology sectors, as these sectors not only represent some of the largest industries today, but are also industries most likely to be affected by plasmonic technologies. We speculate that the field is poised for significant industrial impact, provided that a few key materials and engineering challenges can be overcome.

Plasmonic nanoparticles: Light concentrators and converters

Plasmons are quanta of collective oscillations of free electrons. They exist in conducting materials, including metals and doped semiconductors, and can be excited by light or electrons. Whether persisting in nanoparticles, in nanowires, or on the surfaces of films, plasmons can concentrate incident radiation to subwavelength volumes. We focus in this article on resonant plasmonic materials—and, in particular, on nanoparticles—to complement a number of outstanding articles and texts discussing the properties and applications of plasmons.[1–7] As illustrated in **Figure 1**, the excitation of localized plasmon resonances gives rise to intense near fields that are sensitive to changes in the charge density and refractive index of the particle or embedding medium. Plasmonic nanoparticles can therefore be used to enhance photon absorption in adjacent materials (Figure 1a) or to accurately sense changes in the environment at the nano- and molecular-scales (Figure 1b). The locally elevated temperatures of nanoparticles can also be used in photothermally driven processes, including catalysis, medical treatments, and heat-assisted data recording (Figure 1c). Furthermore, plasmon resonances can quickly decay into hot carriers, with energies much higher than the ambient temperature provides. These carriers can subsequently be harvested and used to enable new photochemical reactions and improved energy conversion for photovoltaic and solar fuel generation (Figure 1d).[8–11]

Apart from their versatile physical properties, plasmonic nanoparticles can be readily synthesized in large quantities and with very high quality using colloidal techniques. Skilled chemists can precisely control nanoparticle size, shape, and morphology, as well as ligand coating and molecular functionalization. The bottom-up synthesis of nanoparticles is routine in laboratory settings and forms the basis for a number of current companies, including nanoComposix, Nanopartz, SkySpring Nanomaterials, Sienna Labs, and LamdaGen. The relevance of nanoparticles is further highlighted by their inclusion in the catalogues of many major chemical suppliers such as Sigma-Aldrich, Alfa Aesar, and Perkin-Elmer. The well-controlled, cost-effective colloidal synthesis of nanoparticles makes them particularly suited for industrial-scale technologies.

Plasmonic nanoparticles in energy conversion

Catalysis and chemical energy conversion

It is estimated that catalysis contributes to nearly 35% of the global gross domestic product.[12] Improving catalytic conversion rates is therefore among the most important industrial pursuits and the subject of intense investigation in the plasmonics community. Recently, visible-light excitation of reaction mixtures containing plasmonic nanoparticles was shown to drive catalytic conversions at lower temperatures and even enable reactions that cannot be activated using conventional thermal processes.[13,14] For example, Linic and colleagues demonstrated that silver nanoparticles could help drive a

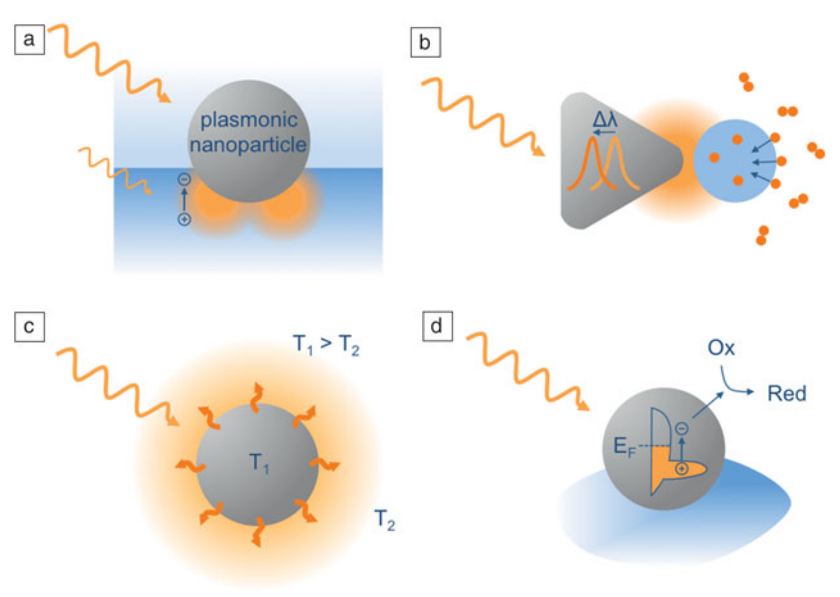

Figure 1. Four modalities of localized surface plasmon resonances (LSPRs). (a) The intense electric fields at the surface of an illuminated plasmonic nanoparticle can increase the absorption cross section of an adjacent semiconductor or dielectric. (b) LSPRs are extremely sensitive to small changes in the dielectric environment, allowing use of small shifts in their spectral positions (denoted as Δλ) to detect processes such as protein binding and ion intercalation. (c) Surface plasmons can decay nonradiatively, producing heat at the surface of a nanoparticle. (d) Surface plasmons can decay into “hot” electron–hole pairs that can be harvested to conduct nonequilibrium chemical processes at the surface of the plasmonic nanoparticles, opening new avenues for heterogeneous catalysis.

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variety of commercially important oxidation reactions, including ethylene epoxidation, CO oxidation, and NH_3 oxidation upon illumination with low-intensity visible photons.[15] The energetic electrons formed through excitation of surface plasmons were transferred to absorbed molecular O_2, inducing nuclear oxygen-atom vibration and allowing activation of the oxygen–oxygen bond at reduced temperatures. A related study indicated that plasmonic hot carriers from gold nanoparticles can dissociate H_2 molecules.[16] Further, the excitation of localized plasmon resonances on copper nanoparticles was used to reduce their surface oxide layer and increase their selectivity toward the epoxidation of propylene.[17] Together, these studies demonstrate that plasmonic nanoparticles are a new family of photocatalysts that not only reduce the energy budget of reactions, but also promise to enhance catalyst stability and product selectivity.

Beyond heterogeneous catalysis, the possibility of harvesting hot carriers in metal–semiconductor nanoparticle junctions is exciting for the conversion of sunlight into electricity and solar fuels. In analogy to the organic dyes used in dye-sensitized solar cells, metal nanoparticles can be used as efficient, tunable, and photochemically stable light absorbers in conjunction with a semiconductor. This effect was first demonstrated by Tian and Tatsuma, who reported an incident-photon-to-current conversion efficiency of 26% for a composite of porous TiO_2 and gold nanoparticles.[18,19] Recently, Mubeen et al. demonstrated a water-splitting device consisting of gold nanorods coated with TiO_2 and decorated with cobalt-based oxygen-evolving catalysts. Importantly, almost all charge carriers used in the water-splitting reaction came from hot carriers generated by plasmon resonance excitation.[20]

Apart from supporting hot-carrier generation and injection, the intense, localized electric fields of plasmonic nanostructures can also increase the absorption efficiency of semiconducting photocatalysts. This enhancement allows for the use of thinner absorbing layers, potentially reducing costs and mitigating any inherent material shortcomings, such as short exciton diffusion lengths or sluggish charge transport. For example, the introduction of gold nanoparticles embedded in or on top of hematite (Fe_2O_3) has been shown to enhance water oxidation efficiency by over 7% under AM1.5 simulated solar illumination.[21,22] As illustrated in **Figure 2**a,[23,24] such enhancements arise from increased absorption in the active layer, resulting in increased photocurrent. In another study, doped titania (TiO_2), which absorbs only weakly in the visible spectrum, was coated with silver nanospheres, resulting in a tenfold enhancement in photocurrent generation under broadband, visible irradiation.[25]

Plasmon resonances have further enabled photothermal vapor generation at relatively low illumination intensities, including outdoor solar irradiation. For example, aqueous core–shell Au@SiO_2 nanoparticles (consisting of a silica core encapsulated in gold) exposed to concentrated ambient daylight undergo a nonequilibrium process to form and release high-temperature steam within seconds of illumination.[26] This vaporization phenomenon could potentially be employed in water purification and instrument sterilization in remote locations.[27] In addition, this process can achieve improved distillation ability to generate 99% ethanol vapor from a water–vapor mixture, surpassing the 95% azeotropic concentration that conventional techniques cannot exceed.[26]

Plasmonic photovoltaics

Plasmonic light concentration and redirection have shown potential to improve the performance of thin-film photovoltaics, which have historically been limited by light absorption in the active layer (see Figure 2b–c).[24,28] Three primary geometries have been proposed for plasmonic-structure inclusion: (1) deposition of nanostructures at the top surface that preferentially scatter light into the solar cell, (2) patterning of the back electrode to redirect the incident light and create propagating waveguide modes in

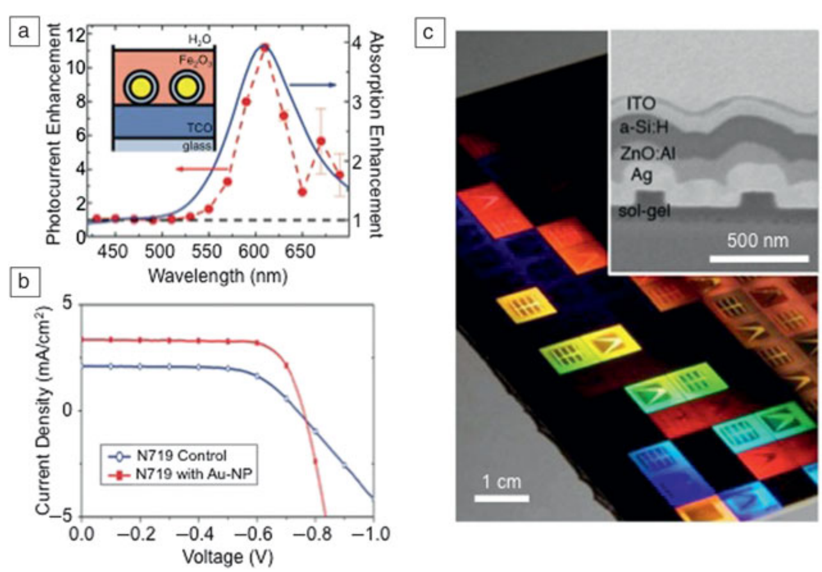

Figure 2. Plasmon-enhanced energy conversion. (a) Measured photocurrent-enhancement (red symbols) and simulated absorption-enhancement (solid blue line) spectra of a 100-nm thin Fe_2O_3 photoelectrode layer containing silica-coated gold nanoparticles (Au NPs). (b) Current–voltage characteristic for solar cells sensitized with only N719 ruthenium–organic dye (blue, open circles) and with the additional incorporation of Au@SiO_2 (15-nm Au core with 3-nm SiO_2 shell) nanoparticles under AM1.5 illumination. (c) Photograph of an array of 88 plasmonic amorphous silicon solar cells; each colored square is a separate cell with varying plasmonic particle diameter and interparticle separation. The inset shows an electron micrograph of the cross section of one solar cell. Note: a-Si:H, hydrogenated amorphous silicon; ITO, indium tin oxide; TCO, transparent conductive oxide; ZnO:Al, aluminum-doped zinc oxide. (a) Adapted with permission from Reference 22. © 2011 American Chemical Society. (b) Adapted with permission from Reference 23. © 2011 American Chemical Society. (c) Adapted with permission from Reference 24. © 2010 Optical Society of America.

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the absorbing layer, and (3) embedding nanoparticles within or near the active layer to make use of the generated high-intensity near fields.

These techniques have been used to improve the performance of thin-film silicon,[29] organic,[30] and dye-sensitized[23] cells, enabling greater light absorption in the thin active layer and increasing the short-circuit current. For example, plasmonic inclusions can enable a 30-fold reduction in silicon wafer thickness while maintaining 85% of the original efficiency.[31]

Plasmonic materials can additionally be used in the creation of next-generation electrodes to replace the traditional transparent conducting oxides. Solution-processed silver nanowires have been shown to form fused, interconnected networks through light-induced plasmonic nanowelding from localized field concentration and heating.[32] This electrode fabrication strategy requires only a tungsten-halogen lamp white-light source (30 W/cm^2), avoiding the high energy requirements of full-system, high-temperature baking.

Plasmonic nanoparticles in health and medicine

Photothermal therapy

Light-controlled localized heating of nanoparticles has been used for a number of biomedical applications, including targeted tumor ablation,[33] targeted drug delivery,[34] selective bacterial killing,[35] and single-cell nanosurgery.[36]

In the context of tumor ablation, plasmonic nanoparticles can be used to locally heat malignant cells without damaging the surrounding healthy tissues, as seen in **Figure 3**.[37,38] Tumors typically exhibit unusually porous blood vessels, which allows nanoparticles to passively accumulate in the cancerous region; once there, they remain lodged because of the diseased region's diminished lymphatic drainage. Alternatively, the surface of the nanoparticles can be functionalized with ligands that bind to receptors that are more commonly found on cancer cells, such as an epidermal growth factor receptor.[39] Nanoshells[40] and nanorods[41] have been extensively explored, in part because their near-infrared resonances match the transparency window of biological tissues.[42]

Photothermal effects can also be used to mechanically ablate cancer cells. For example, Wagner et al. used local heating of gold nanoparticles to generate vapor nanobubbles that expand and collapse within nanoseconds, creating a localized mechanical impact that leads to cell death.[43] Further, plasmonic resonances can be used to enhance the efficiency of photodynamic therapy, in which cell death is triggered by the release of cytotoxic reactive oxygen species by photosensitizer molecules.[44]

Beyond cancer therapeutics, photothermal heating can be used for controlled, local dosing, as illustrated in Figure 3b. Plasmonic nanoparticles have been used to trigger the release of drugs from various materials, including liposomes[45] and hydrogels,[46] as well as to transport and release DNA for targeted gene therapy.[47] Combined diagnostics and therapeutics is made possible by using nanoparticles as contrast agents in imaging, including magnetic resonance imaging,[48] optical coherence tomography,[49] and photoacoustic tomographic imaging.[50]

Biosensing

Plasmonic nanostructures can serve as ultraresponsive sensors, revealing slight changes in their own electronic structure, density, geometry, and temperature, or that of their surroundings, through the energies and widths of their plasmonic resonance peaks.[51,52] This property can be used for biosensing, and indeed, one of the first commercial applications of plasmonics was a home pregnancy test for detecting elevated concentrations of human chorionic gonadotropin hormone.[53]

Recently, large-area plasmonic sensors have been used to detect exosomes (vesicles released by cells into bodily fluids) for the diagnosis of some cancers, as shown in **Figure 4**a.[54,55] Additionally, solution-phase plasmonic sensors have been developed for the label-free detection of protein binding in real time.[56] Most recently, plasmonic sensing has achieved

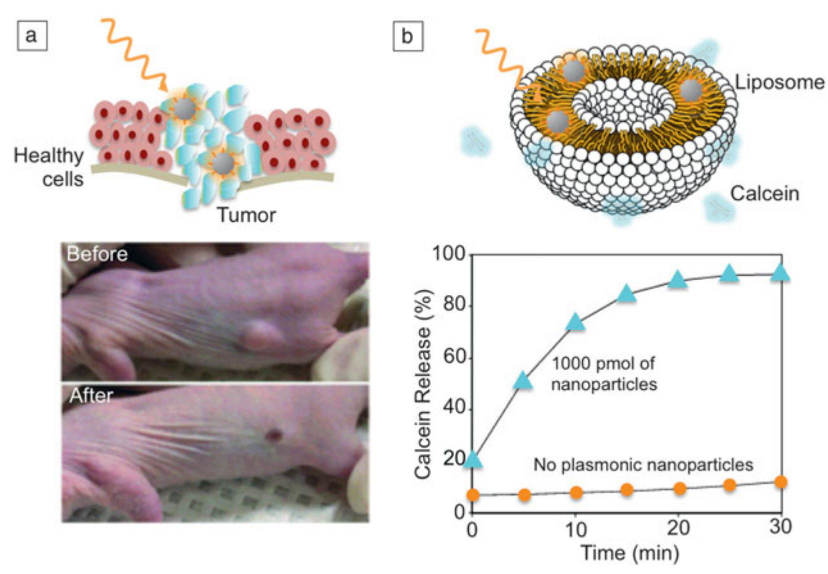

Figure 3. Cancer therapy and molecule release using plasmon resonances. (a) Top: Schematic of cancerous tumor ablation. Plasmonic nanoparticles (gray spheres) are localized in cancerous tissue. Upon irradiation, the nanoparticles release heat to the surrounding tissue, leading to cell death. Bottom: Photographs taken before and after photothermal ablation of a subcutaneous tumor, assisted by plasmon resonances in 110-nm gold nanoshells. The tumor was irradiated with a 810-nm laser at 4 W/cm^2 for 3 min. (b) Top: Schematic showing thermally induced release of small molecules from a liposome. Plasmonic nanoparticles (gray spheres) are embedded in the phospholipid membrane of the liposome. Upon irradiation, the nanoparticles produce heat, inducing a phase transition in the membrane that increases its permeability; small molecules (such as drugs or, here, the fluorescent molecule calcein) can then pass through the membrane. Bottom: UV-light-induced calcein release from liposomes at constant temperature (37°C) with nanogold-loaded nanoparticles. (a) Photographs reproduced with permission from Reference 37. © 2008 Elsevier. (b) Reproduced with permission from Reference 38. © 2010 Elsevier.

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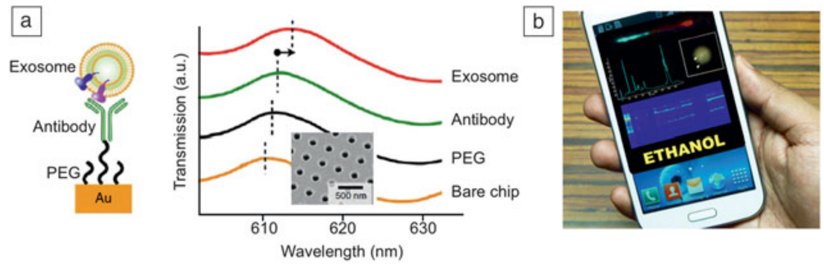

Figure 4. Plasmonic sensors. (a) Solid-state localized surface plasmon resonance-based sensor using gold hole arrays to detect binding of exosomes (vesicles released by cells). Left: The arrays are functionalized with affinity ligands for different exosomal protein markers. Upon binding, spectral shifts or intensity changes proportional to the levels of target marker proteins are observed. Right: A representative schematic of changes in transmission spectra showing exosome detection. Compared to conventional methods, this technology offers sensitive and label-free exosome analyses and enables continuous, real-time monitoring of molecular binding. (b) Hand-held surface-enhanced Raman spectrometer. This particular sensor is based on large-area silver nanoparticle films that can, in principle, detect single-molecule motion. Raman spectra are collected on the smartphone by converting the camera into a low-resolution spectrometer through the inclusion of a collimator and a grating. Note: PEG, poly(ethylene glycol). (a) Adapted with permission from Reference 54. © 2014 Nature Publishing Group. (b) Adapted with permission from Reference 55. © 2014 American Chemical Society.

monolayer protein sensitivity. For example, Altug and co-workers reported a hand-held device incorporating plasmonic arrays that sense binding of a monolayer of the bacteria-derived fusion protein A/G with immunoglobulin G (IgG) antibodies.[57] The hand-held sensor could be integrated with cell phones, as illustrated in Figure 4b, providing high-throughput and low-cost refractive-index sensing of bacteria and proteins in blood or saliva to benefit medical diagnosis in underdeveloped areas.[58]

Rather than relying on specific binding interactions (e.g., with antibodies), chemical identification can also be achieved using mid-infrared molecular vibrational resonances, which serve as "molecular fingerprints." Surface-enhanced infrared absorption spectroscopy of octadecanethiol and hemoglobin recently reached detection sensitivities in the attomolar and zeptomolar ranges, respectively.[59] Likewise, surface-enhanced Raman spectroscopy (SERS) using plasmonic substrates has achieved signal enhancements of up to seven orders of magnitude. Hand-held SERS systems[55] have been demonstrated for intraoperative detection of malignant tumors,[60] detection of food-contamination-related molecules,[61] and sensing bacteria with nanomolar sensitivity.[62] The combination of a gold-nanoparticle SERS platform with an exponential amplification reaction enabled detection of microRNAs in lung cancer cells with a sensitivity to 0.5 fM.[63] This technique therefore provided a six-order-of-magnitude improvement in sensitivity compared to existing SERS-based direct assays and a nine-order-of-magnitude improvement compared to northern blot methods for microRNA detection. Platforms need not be solid-state, and liquid-state substrate-free Raman spectroscopy is an emerging technology.[64]

By using the strongly enhanced field between two metals, tip-enhanced Raman spectroscopy (TERS) promises sub-1-nm spectral mapping.[65] At low temperature and high vacuum, the tip-to-surface distance is precisely controlled to match the nanocavity plasmon resonance with the energy of molecular vibrations, which significantly enhances the Raman signal. This remarkable technique has achieved single-molecule resolution with combined subnanometer imaging. In more recent studies, Belkin and co-workers have adapted TERS to also sense the mechanical force that molecular vibrations exert on the tip.[66] This technique circumvents the need for mid-infrared detectors and promises sensitivity down to a few tens of molecules.

Plasmonic materials for information technology

Modulators and lasers

Optical components promise faster, smarter, and more energy-efficient information technologies. In 2012, IBM announced a technology breakthrough with monolithic integration of optical modulators, photodetectors, and multiplexers into a 90-nm-base high-performance computing chip.[67] However, integration of electronics and photonics requires further miniaturization of optical components, efficient electrical or optical tuning of light propagation, dynamic access to light sources, and isolation of optical signals analogous to that in electronics.[68] One possible integrated optoelectronic circuit design is illustrated in **Figure 5**a, including an artist's depiction of nanophotonic sources, waveguides, modulators, diodes, filters, and photodetectors.[69] Localized surface plasmons are critical to many of these components.

Nanophotonic modulators based on plasmon resonances can switch optical signals with high modulation ratios and subwavelength device footprints, even when traditionally weak nonlinear media are used. For example, Dionne et al. demonstrated a silicon-based plasmonic modulator with a 10 dB/2 μm extinction ratio;[70] Volker et al. demonstrated an indium tin oxide modulator with a 1 dB/1 μm extinction ratio;[71] and Zhao and Lu demonstrated a silicon nitride modulator with a 7.7 dB/400 nm extinction ratio.[72] Submicron-scale electro-optic modulators have also been demonstrated using the metal–insulator phase transition in vanadium oxide;[73,74] the ferroelectric transition in bismuth ferrite;[75] and the tunability of novel materials such as graphene,[76,77] nonlinear polymers,[78] and thermo-optic polymers.[79]

In parallel, localized plasmon resonances have enabled coherent light generation in submicron structures, with on-chip footprints that are comparable to those of electronic devices.[80–86] For example, thresholdless continuous-wave lasing has been achieved using nanoscale plasmonic coaxial cavities,[84] and ultrafast (800-fs) pulsed emission was observed from hybrid plasmon–semiconducting nanowire lasers.[87] Further, spasers[88] promise to be next-generation sources of intense, localized,

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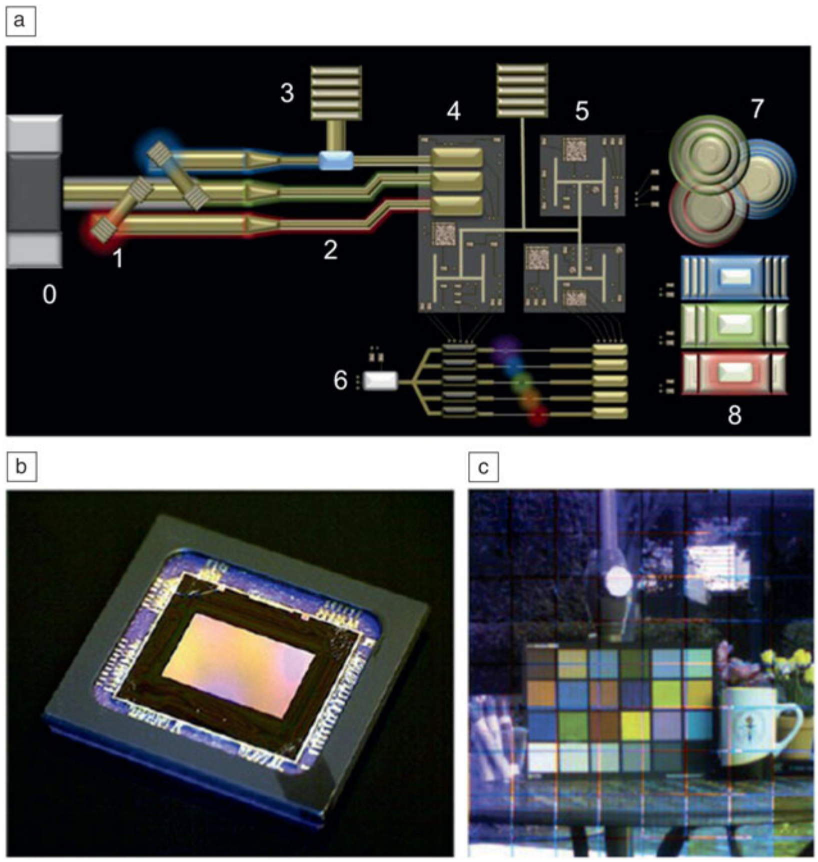

Figure 5. Plasmonics for computation and communications. (a) Schematic of a photonic and plasmonic circuit, consisting of (0) light-incoupling structures, (1) color demultiplexing in a "Z" add/drop filter, (2) bends and tapers in nanophotonic waveguides, (3) all-optical preprocessing logic, (4) integrated photodetection, (5) optical clock, (6) nano-optical subcircuit (on-chip nanoscale laser, spaser, or light-emitting diode; plasmonic modulators and diodes; and integrated photodetection), (7) collection of light by "photon sorting," and (8) integrated plasmonic filtering and beam shaping. (b) Photograph of a plasmonic complementary metal–oxide–semiconductor (CMOS) image sensor. (c) Photograph taken with the CMOS sensor, demonstrating full-color, high-resolution plasmonic imaging. (a) Reproduced with permission from Reference 69. © 2010 Institute of Electrical and Electronics Engineers. (b–c) Reproduced with permission from Reference 92. © 2013 American Chemical Society.

optical fields on the nanoscale. Unlike conventional lasers that emit photons, spasers are sources of coherent surface plasmons. Because the feedback necessary for stimulated emission is provided by surface plasmon modes instead of diffraction-limited photonic modes, the footprint can be just a few nanometers, that is, comparable to the size of the surface-plasmon wavelength.

Data storage and displays

An additional area of information processing facilitated by plasmons is data storage. For example, the intense near fields of plasmonic particles have been used in heat-assisted magnetic recording (HAMR), a magnetic data-storage technology for achieving extremely high data densities. HAMR relies on local heating of a single memory bit, with typical dimensions of 30 nm. By integrating plasmonic nanoparticles onto a magnetic write head, it is possible to address a single memory bit through photothermal effects and, hence, to write data with areal densities exceeding the 1 Tb/in.^{2} limit of conventional magnetic recording techniques.[89,90] Direct storage of information in photons has also been augmented by plasmonics. Whereas compact discs (CDs) store information in two-dimensional (2D) space using a light-sensitive glass, plasmons have been used to store optical bits in five-dimensional space:[91] three dimensions of space, one dimension of wavelength, and yet another dimension of polarization. In prototype demonstrations, plasmonic optical recording was achieved through light-dependent reshaping of gold nanorods suspended in a dielectric host. With sufficient input optical power, the rods are heated and change shape; this shape change stores information in a nonvolatile manner and is read out using low-intensity light, as with conventional CDs.

Mobile and static display technologies could also be revolutionized by plasmonics. For example, as seen in Figure 5, resonant plasmonic hole arrays have been integrated into 2D complementary metal oxide semiconductor (CMOS) image sensors, promising reduced fabrication complexity and cost compared to traditional dye-filter technologies (i.e., liquid-crystal displays).[92] Further, tunable plasmonic color filters with sizes of just a few hundred nanometers promise high-resolution displays and hyperspectral imaging.[93,94]

Beyond two dimensions, holography is an emerging technology for 3D displays. Unfortunately, rendering a 3D image with the same resolution users have come to expect from traditional 2D displays requires a monumental increase in pixel density; pixel size currently limits both the resolution and viewing angles of holograms. Recently, plasmonic metasurfaces created from arrays of gold nanorods were used to create large-field-of-view and high-density holograms. Each pixel was composed of a single 150-nm-long, 75-nm-wide nanorod, with the holographic information encoded in the nanorod's orientation.[95] The phase interference of an incoming circularly polarized beam was used to create a 3D image (330 μm × 232 μm × 48.2 μm) across a broad wavelength range. Whereas this nanorod holographic display is passive, reconfigurable holograms are under active investigation.

Emerging optical information processing: Directional and quantum plasmonics

Directionality and isolation are critical features of integrated electronic circuits, but they are challenging to realize with optical devices.[96] Recently, one-way transmission was demonstrated in nonlinear passive microrings[97] and in more exotic parity–time-symmetric microtoroids[98] and optical waveguides.[99,100] Plasmonic components can enable the same effects on smaller scales, by using highly localized magnetic circulating currents,[68] directional polarization conversion from two-layer metamaterials,[101] and plasmonic parity–time-symmetric components.[102–104]

Plasmonics has also had an impact on an emerging field of information processing: quantum computing. Single-photon sources, such as nitrogen-vacancy centers in diamond, are particularly well-suited for room-temperature quantum photonics, except for their low rates of photon emission. Plasmonics provides a means to enhance the emission of such single-photon sources without the use of bulky photonic cavities. Akimov et al.[105] demonstrated enhanced emission from quantum dots coupled to silver nanowires, and Choy et al.[106] extended the concept to diamond nitrogen-vacancy centers coupled to silver disks. Larger enhancements in emission rate can be achieved by using plasmonic hyperbolic metamaterials, which provide an enormous increase in the local density of states and, consequently, more decay channels.[107] Emission-rate enhancements from plasmonic elements can also enhance detection rates—an effect that could improve the sensitivity of single-photon photodetectors.

Outlook

The field of plasmonics is undoubtedly poised to impact the energy, biomedical, and information-technology industries. Start-up companies based on new plasmonic materials, sensors, and probes are thriving. For example, Biacore offers label-free sensing platforms for the pharmaceutical, biotechnology, and diagnostic markets; Nano-Meta Technologies develops new HAMR and thermophotovoltaic technologies; and Nanospectra commercializes plasmonic-nanoparticle-based medical therapies and is currently conducting clinical trials on photothermal ablation of head, neck, and metastatic lung tumors.

For increased industrial applicability, there is strong impetus to solve challenges related to plasmonic materials, processing, and integration. In particular, choosing materials that are CMOS-compatible and exhibit lower loss will be important for many information-technology applications.[108] High-temperature applications (e.g., in catalysis, thermophotovoltaics, photothermal treatments, or heat-assisted memory) might require plasmonic materials that are more thermally stable than noble metals. Moreover, fabrication methods beyond electron-beam lithography will be required for large-area, cost-effective device architectures. Plasmonic technologies will also have to confront the constraints imposed by current infrastructure and policy and the economies of joint cost and scale en route toward rapid commercialization.

Solutions to the technical challenges are within reach. Plasmonic devices can now be built from CMOS-compatible materials such as aluminum, copper, and titanium nitride.[109–113] Several new plasmonic materials, including transition-metal nitrides, promise high-temperature stability. Finally, self-assembly and imprint techniques are gaining momentum for large-area, engineered materials and devices with nanometer-scale features.[114–116] It will be exciting to see what the coming decades hold for plasmonic materials and applications, both in academia and on the market. Undoubtedly, the field will be successful if it can hold true to the mindset of one of the world's greatest optical-device inventors, Thomas Edison: "Find out what the world needs. Then … go ahead and try to invent it."

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