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# Plasmonics: Enabling functionalities with novel materials

Special Collection: Plasmonics: Enabling Functionalities with Novel Materials

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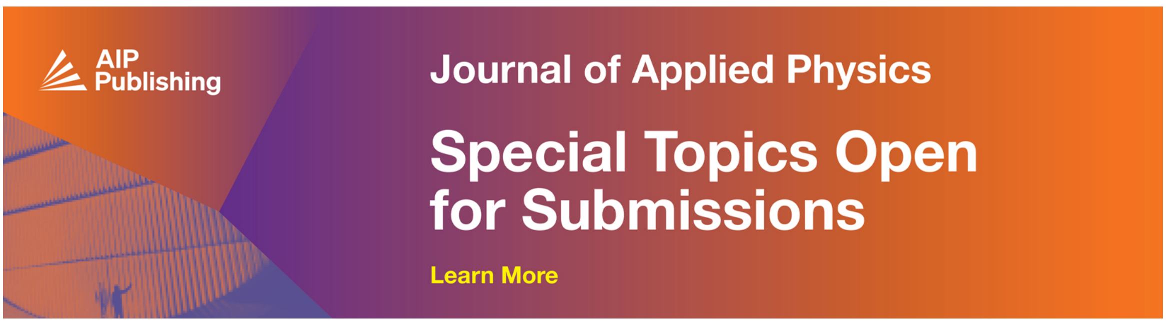

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## INTRODUCTION

The interaction of electromagnetic fields with matter and the ability to harvest and manipulate light at the nanoscale has turned the research on plasmonic nanomaterials into a booming field of study.[1] Plasmonic materials, along with their nanostructural details and hybridization, can offer new research directions in plasmonics. These can address hurdles and issues related to advancing plasmonics applications in more consolidated technologies like photovoltaics, biochemical sensors, photocatalysis, optical devices, as well as in the innovative fields of single photon sources, all-optical switches, and quantum information processing.[2]

Plasmonics is the science and technology concerned with the dielectric response of composite materials where at least one constituent has free carriers, i.e., is a metal. The free carriers enable poles in dielectric response functions (the plasmons) to be tailored by the structure instead of being dictated by the intrinsic properties of the materials themselves. A simple example is the parallel-plate capacitor, with its plasma resonance at $\varepsilon = 0$, where $\varepsilon$ is the dielectric function of the material between the plates. With current capabilities of nanoscale fabrication, these resonances enable large amounts of electromagnetic energy to be concentrated in volumes much smaller than the wavelength of the radiation used to excite them. This is of obvious interest not only for enhancing sensitivities but also for reducing sizes of logic elements, as noted above.

Traditionally, gold and silver have been the metals of choice for plasmonics research and applications due to their excellent optical and chemical properties. However, as a result of their relatively large losses and limited frequency ranges, a broad spectrum of materials is currently being explored as low-loss alternatives for expanding resonances into the UV, mid-IR, and THz regimes. These include, but are not limited to, doped oxides, ceramics, high refractive index (HRI) semiconductors, chiral assemblies,[4] and 2D materials. These developments also include new possibilities for controlling the direction of scattered light by capitalizing on coherent interactions between electric and magnetic resonances.[5] For all these possibilities, chemistry plays a major role in their synthesis, stability, and functionality, these being key issues in enabling plasmonics. A crucial tool for exploring the huge diversity of possible configurations is computational modeling, where finite-element-based methods are employed to numerically analyze the most interesting situations, thereby saving the researcher time and resources to focus on efficient experiments.[6]

Considering its multiple issues from fundamental physics to synthesis and applications, plasmonics in recent years is clearly showing its inclusive nature. Several disciplines are taking advantage of the astonishing progress in understanding and controlling the novel fundamental properties of materials on the multiple length scales explored in plasmonics. Plasmonic materials and systems are ubiquitous in diverse fields, facilitating the development of a common language even for disciplines considered just a few years ago to be very distant from plasmonics. In the last decade, plasmonics has become a multidisciplinary field, as shown in Fig. 1, where a wealth of plasmonic technologies spanning from nonlinear optics to photonics, optoelectronics, photocatalysis, photoelectrochemistry, biosensing, and medicine are already commercial realities, while others are now transitioning from the laboratory to the market.

This special topic issue provides a timely forum for highlighting emerging classes of materials that support plasmon excitation,

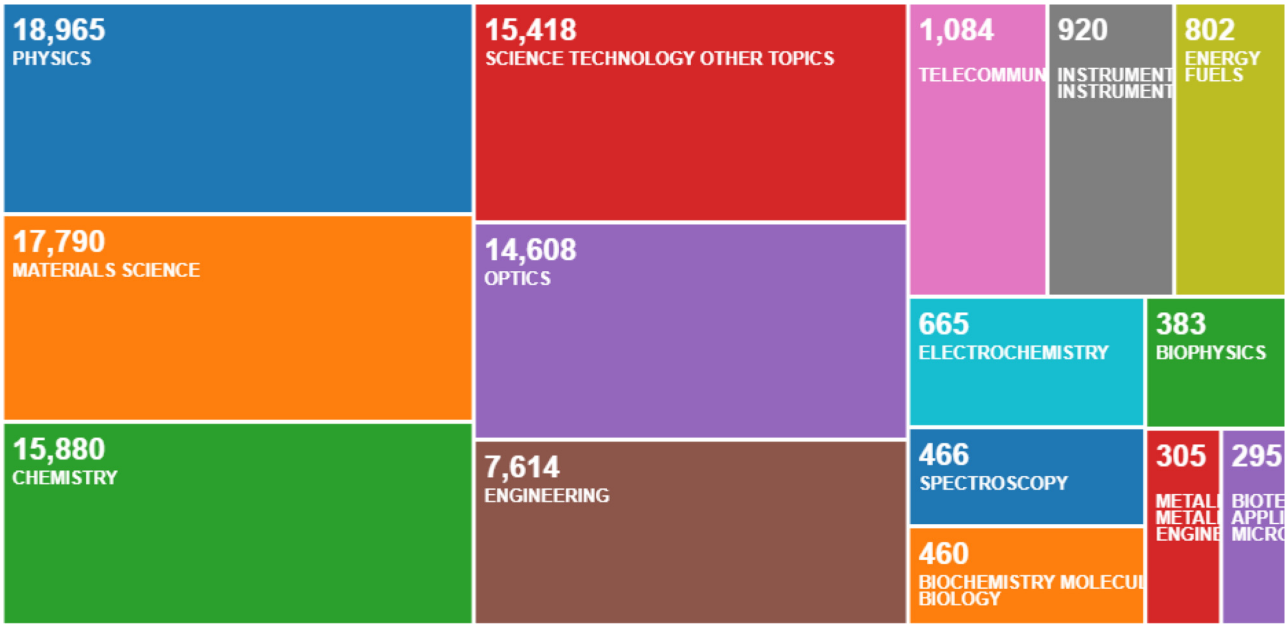


**FIG. 1.** Research areas for the search "Plasmonics" from the Isi Web of knowledge, showing the multidisciplinary of the plasmonic materials field.

sharing recent advances in their synthesis, theory, modeling, spectroscopic approaches, and fabrication methods that are advancing fundamental understanding of plasmon excitations. In addition to original research articles, invited tutorials and perspectives provide hints for future research and showcase new applications enabled by plasmonics applications.

## BACKGROUND

Plasmonics[3] is devoted to investigating and exploiting optical phenomena in nanostructured systems capitalizing on localized elementary excitations called plasmons. The planar metal–dielectric interface can be regarded as the simplest such system, where the excitations take the form of surface plasmon polaritons (SPPs) with amplitudes decreasing exponentially in both directions from the surface. Elementary excitations in three-dimensional structures such as spheres are known as localized surface plasmons (LSPs). This terminology simply highlights the fact that, unlike SPPs in extended planar systems, LSPs do not propagate due to the obvious geometric constraint imparted by the finite size of the regions. In both cases, restoring forces resulting from charge separation caused, for example, by the electric field of an incoming plane wave or fast electron result in a self-sustained collective oscillation of free carriers (the definition of an elementary excitation). In particular, plasmons can couple directly to light without the need of special techniques.

Historically, the field began with investigations of bulk and surface plasmons in thin metal films, since at the time materials science was relatively primitive and the fabrication of nanostructure to order was impossible. With material and fabrication capabilities now well under control, there has been an increasing interest in a wide variety of configurations, including metal–dielectric–metal and dielectric–metal–dielectric multilayers for SPP applications and plasmonic disks, triangles, cubes, and nanorods, among others, for LSP resonances. Together with methods of engineering dielectric functions $\varepsilon = \varepsilon_1 + i\varepsilon_2$ of materials through growth and processing, plasmonics is now a flourishing and exciting field of research.



## SUMMARY OF AREAS COVERED

In this Topical Issue, we present recent advancements, tutorials, and perspectives of non-noble-metal materials for plasmonics, novel characterization, and modeling approaches, and pave the way to plasmonic applications in life sciences, ultrafast photonics, and emerging areas of neuromorphic computing.

The design of new plasmonic materials with unique physical and chemical characteristics and outstanding optical properties plays an important role. Optimizing material properties to improve functionality and performance in plasmonic applications is a subsequent challenge to be tackled, ideally through iterative feedback from experiments. Recent advances in plasmonic materials are enabling new technological frontiers with amazing results, as described in the perspective by Gutiérrez *et al.*[1]

As an example of low-loss dielectric materials, hybridized-plasmonic high refractive index (HRI) semiconductor nanostructures of Si and Ge are discussed. They are shown to provide significant enhancement of absorption, and their use as a switch for enhanced absorbers or direction-selective devices is proposed in Refs. 7 and 8.

The blooming of emerging 2D materials in plasmonics is well emphasized by several articles. Plasmonic excitations in graphene nanostructures provide a particularly effective means to enhance light–matter interactions at THz frequencies.[9,10] A multilayer graphene metamaterial is presented that realizes an ultra-broadband absorber.[11] Operating regimes of graphene plasmonic field-effect transistors (FETs) are proposed by Zhang and Shur.[12]

The unidirectional propagation of SPP waves in a nanolaser based on a graphene–insulator–metal (GIM) platform paves the way for the future development of plasmonic circuitry using GIM platforms that can perform fast signal modulation and processing according to the recent results discussed by Li *et al.*[13]

All-epitaxial structures consisting of type-II superlattice materials quantum engineered by sandwiching a heavily doped semiconductor layer acting as plasmonic thin film are demonstrated by Nordin *et al.*[14] to support short- and long-range surface plasmon polariton (SRSPP and LRSPP) modes in the long-wave infrared region of the electromagnetic spectrum.

Among various plasmonic systems, metal–insulator–metal (MIM) waveguide structures using surface plasmon polaritons (SPPs) are widely adopted. In Ref. 15, the recent incorporation of an ordered lattice of plasmonic nanoparticles as a metal layer is proposed as a rich system of resonances, offering imaging microellipsometric investigations and a theoretical description of all-dipolar interactions in nanoparticles. Imaging ellipsometers have opened a path to recognize and interpret pattern formations and field enhancements on surfaces. To contribute to the understanding of the optical responses of patterned substrates, an explanation of the ellipsometric response using heuristic physical arguments is advanced by Hingerl.[16] In addition to more standard analysis methods, a new technique based on nanomechanical scanning absorption microscopy (NSAM) is introduced by Chien *et al.*[17]

Several articles focus on modeling and implementing characterization tools for plasmonic materials and their hybrid structures. Starting from fundamental properties, the permittivity dispersion behavior of all plasmonic materials is determined. The epsilon-near-zero (ENZ) wavelength is an important parameter to determine the plasmon characteristic frequency. The ENZ wavelengths of elemental metals are usually located in the UV–Visible range, whereas the ENZ wavelengths of transparent conductive oxides are typically located in the near-infrared region. Those of conventional narrow-gap doped semiconductors such as silicon and germanium occur in the mid-infrared region. Therefore, methods for obtaining the dielectric functions of plasmonic materials in their ENZ regions are important. Zheng *et al.*[7] show how to do this through spectral fitting. Novel combinations of organics and metals in composite films to realize ENZ metamaterials are proposed in Ref. 18.

Furthermore, it has become imperative to develop new tools to understand the absorption and scattering properties of composite nanoparticle materials. It is difficult to interpret scattering from anisotropic geometries of arbitrary shapes because an intricate interplay between material and geometric effects is involved. Insights into complex scattering mechanisms are often enabled by modal methods that decompose responses into well-understood multipolar resonances. Here, Kossowski *et al.*[19] extend the generalized normal mode expansion (GENOME) approach to lossy and anisotropic scatterers of arbitrary geometries to disentangle material and geometric contributions to scattering for any anisotropic resonator, proposing a solution to the challenges that stem from anisotropy.

Concerning applications of plasmonics exploiting different materials, those most studied include sensing, biomedical diagnostics, and identification of chemical and biological agents. In this regard, a pedagogical tutorial of the working principles of plasmonic biosensors, primary methods of fabrication, surface biofunctionalization, instrumentation, and general guidelines for their development is provided by Soler and Lechuga.[20] In Ref. 21, special focus is placed on new 3D plasmonic sensing platforms, characterization and assessment of their biosensor performance, and a procedure to develop and validate biosensors for relevant biomedical and environmental purposes. An industrial perspective of the industrial realization of plasmonic devices, especially for life science, including examples of *in vitro* diagnostics, is given by Prinz *et al.*[22]

Going beyond passive functionalities, new frontiers have recently been opened in the field by considering active, nonlinear, or dynamically tunable systems. As an example, the giant magnetoresistance (GMR) of ferromagnetic multilayers Au/Ni81Fe19 with magneto-optical (MO) activity enhanced by a plasmon resonance is exploited in spintronic–plasmonic metasurfaces. These have the peculiarity that their resonances can be modulated by an applied magnetic field (Gaspar *et al.*[23]).

Particularly enlightening is the tutorial by Gemo *et al.*[24] showing that plasmonic resonant structures are inherently capable of harnessing and focusing optical energy on sub-wavelength scales, far beyond the capabilities of conventional optical and photonic elements. They explore various approaches for combining the three building blocks of Si-photonics, resonant plasmonic structures, and phase-change materials to deliver plasmonically enhanced integrated phase-change photonic memories and computing devices and systems, underlining the inherent technical and theoretical challenges therein.

Enlightening future prospects and challenges of plasmonics for neuromorphic computing are presented by Brückerhoff-Plückelmann *et al.*[25] Here, radically new circuit technology for neuromorphic computing with plasmons is realized, enabling optimization of the computing power, size, and energy of neuromorphic chips.

## CONCLUSIONS

As research in plasmonic materials continues to expand rapidly in depth and breadth, we selected some fundamental subjects in materials for plasmonics of high and general interest. We hope that our selection reflects the past, shows the current state, and provides a glimpse into the future. We can only expect that the range of applications of these novel plasmonic building blocks will continue to grow in the coming years, opening exciting new opportunities in areas as diverse as sensing, imaging, reconfigurable photonic displays, ultrafast photonics, quantum circuitry, and many more.

This Special Topic on plasmonic materials provides researchers a timely forum to share their new materials, approaches, and perspectives. We hope that the “Plasmonics: Enabling functionalities with novel materials” Special Topic will inspire many scientists and boost the development of novel materials for plasmonics.

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