Plasmonics: Merging Rhotonics and Electronics at Nanoscale Dimensions 4 h 37	Plasmonics: Hợp nhất photonic và điện tử học ở kích thước nano
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Electronic circuits provide us with the ability to control the transport and storage of electrons. However, the	Các mạch điện giúp chúng ta có thể điều khiển quá trình vận chuyển và lưu trữ các electron. Tuy nhiên, hiện nay

performance of electronic circuits is now becoming rather limited when digital information needs to be sent from one point to another. Photonics offers an effective solution to this problem by implementing optical communication systems based on optical fibers and photonic circuits. Unfortunately, the micrometer-scale bulky components of photonics have limited the integration of these components into electronic chips, which are now measured in nanometers. Surface plasmon-based circuits, which merge electronics and photonics at the nanoscale, may offer a solution to this size-compatibility problem. Here we review the current status and future prospects of plasmonics in various applications including plasmonic chips, light generation, and nanolithography.	hiệu suất của các mạnh điện tử tương đối hạn chế khi áp dụng trong việc gửi thông tin số từ điểm này đến điểm khác. Photonics sẽ mang đến cho chúng ta một giải pháp có hiệu quả cho vấn đề này thông qua việc triển khai ứng dụng các hệ truyền thông quang học dựa trên sợi quang và các mạch photonic. Thật không may, các thành phần cồng kền kích thước micro của photonic đã gây trở ngại cho việc tích hợp những thành phần này vào các chip điện tử, hiện nay những chip này có kích thước nano. Các mạch plasmon bề mặt hợp nhất điện tử và photonic ở thang nano cho phép chúng ta giải quyết vấn đề tương thích kích thước này. Ở đây, chúng tôi trình bày sơ lược tình hình nghiên cứu hiện tại và triển vọng tương lai của lĩnh vực plasmonic trong nhiều ứng dụng khác nhau chẳng hạn như chip plasmon, tạo ánh sáng và quang khắc nano.
oday's state-of-the-art microprocessors use ultrafast transistors with dimen- sions on the order of 50 nm. Although it is now routine to produce fast transistors, there i' a major problem in carrying digital in- formation to the other end of a microprocessor that may be a few centimeters away. Whereas copper wire interconnects carry digital infor- mation, interconnect scaling has been insuffi- cient to provide the necessary connections required by an exponentially growing transis- tor count. Unlike transistors, for which per- formance improves with scaling, the delay of interconnects increases and becomes a substan- tial limitation to the speed of digital circuits (1) . This limitation has become more	[redacted] [redacted]

evident over the past 1 to 2 years, as the annual in- crease rate of the clock speed of microproces- sors slowed greatly.

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Optical interconnects such as fiber optic cables can carry digital data with a capacity >1000 times that of electronic interconnects. Unfortunately, fiber optic cables are ~1000 times larger compared with electronic com- ponents, and the two technologies are diffi- cult to combine on the ’ame circuit.

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External optical interconnects that can connect differ- ent parts of the electronic chips via air or fiber cables have also been proposed. However, the resulting bulky configuration has limited the implementation of thi’ idea. The ideal ’olution would be to have a circuit with nanoscale fea- tures that can carry optical signals and electric currents. One such proposal is surface plasmons, which are electromagnetic waves that propagate along the ’urface of a conductor. The interac- tion of light with matter in nanostructured metallic structures has led to a new branch of photonics called plasmonics. Plasmonic circuits offer the potential to carry optical signals and electric currents through the same thin metal circuitry, thereby creating the ability to com- bine the superior technical advantages of pho- tonics and electronics on the same chip.

Plasmonic Chips: Light on a Wire

What limits the integration of optical and elec- tronic circuits most is their respective sizes. Electronic circuits can be fabricated at di- mensions below 100 nm. On the other hand, the wavelength

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of light used in photonics cir- cuits is on the order of 1000 nm. When the dimensions of an optical component become close to the wavelength of light, the propaga- tion of light is obstructed by optical difírac- tion (2), which therefore limits the minimum size of optical structures including lenses, fi- bers, and optical integrated circuits. Although the introduction of photonic crystals brings a partial solution to these problems, the pho- tonic crystal itself has to be several wave- lengths long, because the typical period is on the order of half of a wavelength (3).

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Surface plasmon-based photonics, or ‘‘plas- monics,’’ may offer a solution to this dilemma, because plasmonics has both the capacity of photonics and the miniaturization of electronics. Surface plasmons (SPs) provide the opportunity to coníine light to very small dimensions. SPs are light waves that occur at a metal/dielectric interface, where a group of electrons is collect- ively moving back and forth (4). These waves are trapped near the surface as they interact with the plasma of electrons near the surface of the metal. The resonant interaction between electron-charged oscillations near the surface of the metal and the electromagnetic field of the light creates the SP and results in rather unique properties. SPs are bound to the metallic surface with exponentially decaying fields in both neighboring media.

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The decay length of SPs into the metal is determined by the skin depth, which can be on the order of 10 nm—two orders of magnitude smaller than the wavelength of the light in air. This

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feature of SPs provides the possibility of localization and the guiding of light in subwavelength metallic structures, and it can be used to construct miniaturized optoelec- tronic circuits with subwavelength components (5). Such plasmonic optoelectronic circuits, or plasmonic chips, will consist of various compo- nents such as waveguides, switches, modulators, and couplers, which can be used to carry the optical signals to different parts of the circuit.

Plasmonic waveguides are used to guide the plasmonic signals in these circuits and can be configured by using various geometries (6). Thin metal films of finite width embedded in a dielectric can be used as plasmonic wave- guides. This geometry offers the best propa- gation results for a surface plasmon-based waveguide, because the measured propaga- tion length for operation with light at a wave- length of 1550 nm is reported to be as long as 13.6 mm. However, the localization for both directions is on the order of a few micrometers in this plasmonic waveguide geometry (7). To achieve subwavelength localization, one can reduce the width of the wire and subsequently use the SPs to guide the light underneath this nanowire. In nanowires, the confinement of the electrons in two dimensions leads to well- defined dipole surface plasmon resonances, if the lateral dimensions of the wire are much smaller than the wavelength of the exiting light. By using this method, a 200-nm-wide and 50-nm-high gold nanowire was fabricated. This plasmonic waveguide was then locally excited at a light wavelength of 800 nm (8). By direct

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imaging of the optical near field with subwavelength-resolution photon scanning tunneling microscopy, light transport was ob- served along the nanowire over a distance of a few micrometers. Although this is a clear dem- onstration of subwavelength guiding, the losses associated with the resistive heating within the metal limit the maximum propagation length of light within these structures. In order to avoid the ohmic losses, one can envision using an array of nanoparticle resonators. The resonant structure of the nanoparticles can be used to guide the light, whereas the reduced metallic volume means a substantial reduction in ohmic losses. Stefan Maier and co-workers (9) used such a structure (Fig. 1A), in which nanoscale gold dots were patterned on a silicon-on- insulator wafer to define the plasmon propaga-tion path.

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Figure 1B shows scanning electron micrographs (SEMs) of the fabricated plas- monics waveguides designed for operation at a wavelength of 1500 nm. The waveguide struc- ture is not uniform across its width where the size of the metal dots is reduced from 80 nm X 80 nm at the center to 50 nm X 50 nm at the edges. This has the effect of confining the energy more intently to the middle of the guide (Fig. 1A). This structure has been shown to have a decay length longer than 50 mm, where-as theoretical simulations predict a decay length in the order of 500 mm. Figure 1A shows that although the

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localization along the x direction is subwavelength, the localization extends a few periods along the y direction, which corresponds to localization on the order of a wavelength. Therefore, the subwavelength localization of SPs is limited only to the x direction.

To achieve localization in both directions, a new type of highly localized plasmon has been analyzed and experimentally demon- strated in metals with V-shaped grooves (10). The major features of plasmons in V grooves include a combination of strong localization, single-mode operation, the possibility of nearly 100% transmission (truyền qua, hệ số truyền qua, trong một số ngữ cảnh có thể có nghĩa là khả năng lan truyền) through sharp bends, and a high tolerance to structural imperfections. For the localization and guiding to occur, the wedge angle (0) of the V groove should be smaller than a critical angle. For V grooves made from silver with a vacuum wavelength of 0.6328 mm, this critical wedge angle is found to be 102°. The measured lateral localization of a structure with a 40° wedge angle is ~300 nm, which is superior to the nanoparticle-based plasmonic waveguides. However, the reported experimen- tal and theoretical decay lengths for the same V groove-shaped plasmonic waveguide are 1.5 mm and 2.25 mm, respectively, which are obviously too short for any application of these plasmonic structures. The propagation distance performance of the V groove-shaped SP wave- guides has been recently extended to 250 rnm (11). By using focused ion-beam milling tech- niques, 460-mm-long V groove-shaped plas-

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monic waveguides were fabricated on gold layers that were deposited on a substrate of fused silica. Scanning near-field optical micro- scope measurements of these structures were made at optical communication wavelengths (1425 to 1620 nm). For a structure with a 0.6-mm-wide and 1.0-mm-deep groove wedge (corresponding to a ~17° wedge angle), the SP propagation lengths were measured to be within 90 to 250 mm. The mode was well confined along the lateral direction, and the measured mode width was 1.1 mm.

Thus there is a basic trade-off in all plas- mon waveguide geometries between mode size and propagation loss. One can have a low propagation loss at the expense of a large mode size, or a high propagation loss with highly confined light. A hybrid approach, where both plasmonic and dielectric waveguides are used, has been suggested as a solution to this trade- off (12). These waveguides are designed for 1500-nm operation and exhibit losses on the order of-1.2 dB/mm, and they can guide light around 0.5-mm bends. Light can also be ef- ficiently coupled between more convention- al silicon waveguides, where these plasmon waveguides with compact couplers and siiríace plasmon optical devices can be constmcted by using planar circuit fabrication techniques.

Introduc- ing gain to the plasmonic waveguides can also bring a solution to the limited propagation distances. This situation is theoretically investigated by consider- ing the propagation of SPs on metallic waveguides adjacent to a gain medium (13). The analytic analysis and

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numeric simulation results show that the gain medium assists the SP propagation by compensating for the metal losses, making it possible to propagate SPs with little or no loss on metal boundaries and guides. The calculated gain requirements suggest that lossless, gain-assisted surface plasmon propagation can be achieved in practice for infrared wavelengths.	[redacted]
Recently, a new kind of SP geometry has been suggested to solve theoretically the issue of confinement versus propagation length (14). The new mechanism for confining much more field in the low-index region rather than in the adjacent high-index region is based on the rel- ative dispersive characteristics of different sur- face plasmon modes that are present in these structures. The structures have a subwavelength modal size and very slow group velocity over an unusually large frequency bandwidth. Simulations show that the structures exhibit ab- sorption losses limited only by the intrinsic loss of the metal.	[redacted]
Currently, there is no experimen- tal data that supports these simulations. How- ever, the new suggested SP structure is quite promising and deserves attention from the experimental research groups that are working on plasmonic waveguides.	[redacted]
Plasmonic chips will have optical input and output ports, and these ports will be optically connected to conventional diffraction-limited photonic devices by	[redacted]

plasmonic couplers (8). The couplers should have high conversion efficiency, along with a transmission length that is longer than the optical wavelength to avoid the direct coupling of the propagating far-field light to the nanophotonic devices inside the plasmonic chip. A promising candidate for this feature can be fabricated by combining hemispher- ical metallic nanoparticles that work as a plas- monic condenser and a nanodot-based plasmonic waveguide (15). When the focused plasmons move into the coupler, the transmission length through the coupler is 4.0 mm. Nanodots can also be used for focusing SPs into a spot of high near-field intensity having a subwave- length width (16). Figure 2A shows the SEM image of such a sample containing 19 200-nm through-holes arranged on a quarter circle with a 5-mm radius. The SPs originating from these nanodots are coupled to a metal nanostrip wave- guide. A near-field scanning optical microsco- py (NSOM) image of this structure was taken at 532-nm incident wavelength with horizontal polarization. The near-field image (Fig. 2B) shows that the focused SPs propagate along the subwavelength metal guide, where they par- tially penetrate into the 100-nm-wide bifurcation at the end of the guide, thus overcoming the diffraction limit of conventional optics. The measured propagation distance is limited to 2 mm, and the propagation distances are expected to be much longer with improved fabrication processes and by using properly designed metal-dielectric hybrid structures. The combination of focusing arrays and nano- waveguides may serve as a basic element in planar

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plasmonic circuits.	[redacted]
Active control of plasmons is needed to achieve plasmonic modulators and switches.	[redacted]
Plasmonic signals in a metal-on-dielectric wave- guide containing a gallium section a few mi- crons long can be effectively controlled by switching the structural phase of gallium (17). The switching can be achieved by either chang- ing the waveguide temperature or by external optical excitation. The signal modulation depth can exceed 80%, and switching times are expected to be in the picosecond time scale. The realization of an active plasmonic device by combining thin polymer films containing molecular chromophores with thin silver film has also been reported (18). The molecular plas- monic device consists of two polymer layers, one containing donor chromophore molecules and the other containing acceptor fluorophore molecules. Coupled SPs are shown to provide an effective transfer of excitation energy from donor molecules to acceptor molecules on op- posite sides of metal film up to 120 nanometers thick. The donors absorb incident light and transfer this excitation energy by dipole-dipole interactions to the acceptors. The acceptors then emit their characteristic fluorescence. These re- sults are preliminary demonstrations for active control of plasmonic propagation, and future research should focus on the investigation of electro-optic, all-optical, and piezoelectric mod- ulation of subwavelength plasmon	[redacted]

waveguide transmission (truyền qua, trong một số ngữ cảnh có thể có nghĩa là khả năng lan truyền).

Extensive research efforts are being put forth in order to achieve an all-plasmonic chip. In the near term, plasmonic interconnects may be used to address the capacity problem in digital circuits including microprocessors. Con- ventional electronic interconnects may be used to transfer the digital data among the local arrays of electronic transistors. But, when a lot of data need to travel from one section of a chip to another remote section of the chip, electronic information could be converted to plasmonic information, sent along a plasmonic wire, and converted back to electronic informa- tion at the destination. Unfortunately, the cur- rent performance of plasmonic waveguides is insufficient for this kind of application, and there is an urgent need for more work in this area. If plasmonic components can be suc- cessfully implemented as digital highways into electronic circuits, this will be one of the ‘‘killer applications’’ of plasmonics.

Plasmonic Light Sources

The emerging field of plasmonics is not only limited to the propagation of light in structures with subwavelength dimensions. Plasmonics can also help to generate and manipulate electro- magnetic radiation in various wavelengths from optics to microwaves. Since their introduction by Nakamura in 1995 (19), InGaN-based semi- conductor light emitting diodes (LEDs) have become promising candidates for a variety of solid-state lightning applications (20). How- ever,

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semiconductor-based LEDs are also notorious for their low light-emission efficiencies.

Plasmonics can be used to solve this efficiency problem (21). When InGaN/GaN quantum wells (QWs) are coated by nanometer silver or aluminum films, the resulting SPs increase the den- sity of states and the spontaneous emission rate in the semiconductor. This leads to the enhance- ment of light emission by SP-QW coupling, which results in large enhancements of internal quantum efficiencies. Time-resolved photoluminescence spectroscopy measurements were used to achieve a 32-fold increase in the spon- taneous emission rate of an InGaN/GaN QW at 440 nm (22). This enhancement of the emission rates and intensities results from the efficient energy transfer from electron-hole pair recom- bination in the QW to electron vibrations of SPs at the metal-coated surface of the semi- conductor heterostructure. This QW-SP cou- pling is expected to lead to a new class of super bright and high-speed LEDs that offer realistic alternatives to conventional fluorescent tubes.

Similar promising results were obtained for organic LEDs (OLEDs), which are now becoming popular as digital displays. In an OLED, up to 40% of the power that can be coupled into air is lost due to quenching by SP modes. A periodic microstructure can be used to recover the power that is normally lost to SPs. Using this approach, strong photo- luminescence has been reported from a top- emitting organic light-emitting structure, where emission takes place through a thin silver film (23). The results indicate that the addition of

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a nanopatterned dielectric overlayer to the cath- ode of top-emitting OLEDs should increase light emission from these structures by two or- ders of magnitude over a similar planar struc- ture. The dielectric layer acts to couple the surface plasmon-polariton modes on the two metal surfaces, whereas its corrugated morphol- ogy allows the modes to scatter to light. An OLED using a p-conjugated polymer emissive layer sandwiched between two semitransparent electrodes was also reported (24). One of the electrodes was an optically thin gold film anode, whereas the cathode was in the form of an optically thick aluminum (Al) film with pat- terned periodic subwavelength two-dimensional (2D) hole array that showed anomalous trans- mission in the spectral range of the polymer photoluminescence band. At similar current densities, a sevenfold electroluminescence ef- ficiency enhancement was obtained with the patterned Al device compared with a control device based on imperforated Al electrode, demonstrating that the method of patterning the electrodes into 2D hole arrays is efficient for this structure. Plasmonics can also be used to enhance the performance of lasers (25). A metal nano-aperture was fabricated on top of a GaAs vertical cavity surface emitting laser (VCSEL) for subwavelength optical near-field probing. The optical near-field intensity and the signal voltage of nano-aperture VCSELs exhibit record high values because of the lo- calized surface plasmons in metal nanostruc- tures. The enhancement factors of the optical near-field and voltage signal are 1.8 and 2, respectively. Reducing the nano-

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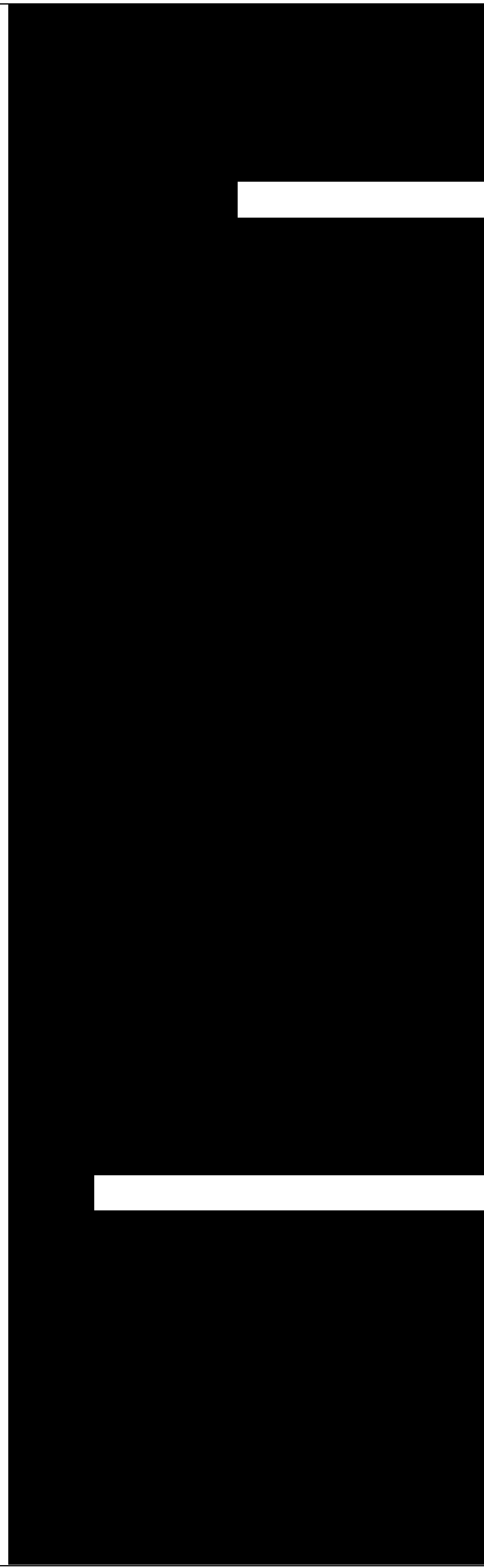
aperture re- duces the optical resolution of the VCSEL probe from 240 nm to 130 nm. These results show that plasmon enhancement will be helpful for real- izing high-resolution optical near-field VCSEL probes. SPs also play a key role in the transmission properties of single apertures and the en- hanced transmission through subwavelength hole arrays (26, 27). There has been intense controversy on the physical origin of the en- hanced transmission in these structures (28). Recent theoretical and experimental analyses suggest that the enhanced transmission can be explained by diffraction assisted by the enhanced fields associated with SPs (29, 30). Although SPs are mostly studied at optical frequencies, they can also be observed at the microwave, millimeter-wave, and THz frequencies (31). By texturing the metallic surface with a subwave- length pattern, we can create SPs that are re- sponsible for enhanced transmission observed at microwave and millimeter wave frequencies for 1D and 2D gratings with subwavelength aper- tures (32, 33). A subwavelength circular aper- ture with concentric periodic grooves can be used to obtain enhanced microwave transmis- sion near the surface plasmon resonance frequency (34). These results show that enhanced transmission from a subwavelength circular annular aperture with a grating is assisted by the guided mode of the coaxial waveguide and coupling to the surface plasmons. A 145-fold enhancement factor is obtained with a subwave- length circular annular aperture surrounded by concentric periodic grooves. The same structure	[redacted] [redacted] [redacted]

also exhibits beaming properties that are similar to the beaming effects observed from a subwavelength aperture at optical wavelengths (35). Figure 3 shows the electromagnetic waves from a subwavelength circular annular aperture surrounded by concentric periodic grooves. The radiated electromagnetic waves have a very strong angular confinement around the sur- face mode resonance frequency, in which the angular divergence of the beam is ±3°. En- hanced transmission at THz wavelengths is also reported for a freestanding metal foil per- forated with periodic arrays of subwavelength apertures (36). The peak transmission at the lowest frequency resonance is ~0.6 for each aperture array, which is a factor of ~5 larger than the fractional area occupied by the aper- tures. Doped semiconductors exhibit a behavior at THz frequencies similar to that of metals at optical frequencies, thus they constitute an op- timal material for THz plasmonics (37). Enhanced transmission of THz radiation is observed by using arrays of subwavelength apertures struc- tured in n-type Silicon. This enhancement can be explained by the resonant tunneling of SPs that can be excited at THz wavelengths

Fig. 3. Calculated (A) and measured (B) electric field distribution from a subwavelength circular annular aperture with a grating at the resonance frequency. The measured electric field intensity is confined to a narrow spatial region and propagates without diffracting into a wide angular region, which is in good agreement with the simulations.

Fig. 4. The images of an arbitrary object obtained by different methods. (A) FIB

image of the object. (B) The image obtained on photoresist with a silver superlens. (C) The image obtained on photoresist with conventional lithography. (D) Comparison of both methods. [Adapted from (40)]



falls within the sensitivity range of a photo- resist, the resulting enhanced optical field that is close to the metal surface can locally cause increased exposure of a thin layer of resist directly below the mask. Because the tech- nique is not diffraction limited, it can produce subwavelength structures using broad beam illumination of Standard photoresist with vis- ible light. Using this technique, sub-100-nm lines have been patterned photolithographically at a wavelength of 436 nm (38). Theoretical simulations of plasmonic nanolithography pre- dict even better performance (39). Finite dif- ference time domain (FDTD) simulations of isolated silver particles on a thin resist lay- er show that broad beam illumination with p-polarized light at a wavelength of 439 nm can produce features as small as 30 nm, or 1/14, where 1 is the wavelength. Depending on the exposure time, lateral spot sizes ranging from 30 to 80 nm with exposure depths ranging from 12 to 45 nm can be achieved.

The performance of plasmonic nanolithog- raphy can be boosted by using the ‘‘superlens’’ concept introduced by Pendry (40). A superlens can be used to enhance evanescent waves via the excitation of surface plasmons. The gain obtained from plasmonic excitation inside the superlens compensates for the loss of the eva- nescent waves outside of the superlens. The reconstructed evanescent waves can then be used to restore an image below the diffraction limit on the other side of the lens. This unusual lens can be constructed by using a thin slab of material with negative permittivity or perme- ability, or both. By using silver as a natural optical superlens, sub-diffraction-limited imag- ing with 60 nanometer half-pitch resolution, or one-sixth of the illumination wavelength, was demonstrated (41). By proper design of the work- ing wavelength and the thickness of silver, which allows access to a broad spectrum of subwave-length features, arbitrary nanostructures can also be imaged with good fidelity. Figure 4 com- pares the performance of this superlens-based plasmonic nanolithography to conventional nano-lithography. A 365-nm exposure wavelength was used for both nanolithography experiments. The word ‘‘NANO’’ was printed as a mask by a focused ion beam (FIB) system (Fig. 4A). Figure 4B was obtained with the superlens, and the resulting image on the resist is almost perfect. Figure 4C shows the diffraction limited image obtained from the conventional lithography. Figure 4D numerically compares both methods. Although the resolution achieved by convention- al methods is limited to ~320 nm, the plasmonic nanolithography method was able to generate an image with ~four times better resolution. Super-resolution imaging using the same method was also reported for a 50-nm-thick planar silver superlens at wavelengths around 365 nm (42). Gratings with periods down to 145 nm can be resolved, which agrees well with the FDTD simu- lations. These are the

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preliminary demonstrations of superlens-based plasmonic nanolithography, and additional research for further improvements in subwavelength resolution, aerial coverage, and uniformity is needed. After these improvements, plasmonic nanolithography may be a viable al- ternative to other nanolithography systems.

Future Directions and Challenges

The field of plasmonics offers several research opportunities. These include plasmonic chips that function as ultra-low-loss optical inter- connects, plasmonic circuits and components that can guide light within ultracompact op- tically functional devices, nanolithography at deep subwavelength scale, superlenses that en- able optical imaging with unprecedented resolu- tion, and new light sources with unprecedented performance. To fulfill the promise offered by plasmonics, more research needs to be done in these areas. Some of the challenges that face plasmonics research in the coming years are as follows: (i) demonstrate optical ũrequency sub- wavelength metallic wired circuits with a prop- agation loss that is comparable to conventional optical waveguides; (ii) develop highly efficient plasmonic organic and inorganic LEDs with tunable radiation properties; (iii) achieve active control of plasmonic signals by implementing electro-optic, all-optical, and piezoelectric modu- lation and gain mechanisms to plasmonic struc- tures; (iv) demonstrate 2D plasmonic optical components, including lenses and grating cou- plers, that can couple single mode fiber di- rectly to plasmonic

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circuits; and (v) develop deep subwavelength plasmonic nanolithography over large surfaces. Conclusion The research on plasmonics has made major advances in the past few years. Besides creating new photonics devices, which are considerably smaller than the propagating light’s wavelength, plasmonics is expected to be the key nanotech- nology that will combine electronic and photo- nic components on the same chip.	[redacted]