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Plasmonics and polaritonics surpass limited in speed nanoelectronics and limited in size microphotonics

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The paper reviews the recent results concerning the new concepts and achievements in the area of plasmonics, which is defined as plasmon-polariton–based photonics and electronics and which has greatly emerged last years. The attributes of plasmonic structures to confine light to volumes significantly smaller than the diffraction limit of light are discussed and a number of important plasmonics related fields are presented, with an emphasis on structures consisting of metallic and semiconductor nanowires. The first part of the paper introduce the two major ingredients of plasmonics, interface plasmon-polaritons at metallic and semiconductor interfaces and localized plasmons in nanostructures. Some technological routs of plasmonics nanostructure fabrication are reviewed. In last part some of the most prominent applications of plasmonics are discussed: plasmonics optical nanodevices and plasmonics in thermoelectricity.

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1. General aspects of plasmonics

Replacing conventional microelectronic circuit chip components with reliable, high-speed nanoelectronic or nanophotonic circuits is one of the big challenge of nanoscience and nanotechnology. In the recent years a new approaches - plasmonics has been developed for transmitting, processing etc. optical and electronic signals through nanoscale structures [1]. The approaches is based on the ability to couple electromagnetic waves and charge carriers in solid structures through interface plasmons, are collective charge oscillations that occur at the interface between conductors and dielectrics or semiconductors. They can take various forms, ranging from freely propagating electron density waves along metal surfaces to localized electron oscillations on metal nanoparticles. Their unique properties enable a wide range of practical applications, including light guiding and manipulation at the nanoscale, detection at the single molecule level, enhanced optical transmission through sub-wavelength apertures, and high resolution optical imaging below the diffraction limit.

Planar waveguides and photonic crystal structures are being intensively investigated as primary solutions for guiding light in integrated photonic devices as well as for signal and information processing. Directing light waves at the interface between a metal and a dielectric can, under the right circumstances, induce a resonant interaction between the waves and the mobile electrons at the surface of the metal. The result is the generation of surface plasmons - density waves of electrons that propagate along the interface. There may, however, be another means of making highly integrated optical devices, with structural elements smaller than the wavelength, enabling strong guidance and manipulation of light using metallic and metallo-dielectric nanostructures. Here, plasmon-polariton waves, i.e., optical excitations coupled with collective electronic excitations, are used as information carriers. These allow to overcome some obstacles of nanoelectronics, when the laws of quantum physics that govern electron charge transport creep in, hindering device functionality as well as when the number of mobile electrons that can participate in current transport is very small when the device is reduced in size to a few nanometers.

The field of plasmonics involves the transfer of light electromagnetic energy into a tiny volume, thus creating intense electric fields—a phenomenon that has many scientists rethinking the laws of electromagnetics on a nanoscale [2]. Light beam striking a metal or semiconductor surface can generate plasmons, electron density waves, and polaritons collective semiconductor excitations, that can carry huge amounts of data.

Over the past decade investigators have found that by creatively designing the metal-dielectric interface they can generate surface plasmons with the same frequency as the outside electromagnetic waves but with a much shorter wavelength. This phenomenon could allow the plasmons to travel along nanoscale wires called interconnects, carrying information from one part of a microprocessor to another. Plasmonic interconnects would be a great boon for chip designers, who have been able to develop ever smaller and faster transistors but have had a harder time building minute electronic circuits that can move data quickly across the chip [3].

The main questions appearing in the analysis of plasmonics is: why plasmonics is so promising? Why not pure electronics or photonics? As data rates and component packing densities increase, electrical interconnects become progressively limited by RC-delay and electronics is aspect-ratio limited in speed. Indeed, since interconnect resistance $R\infty$ L/A and resistance capacitance $C\infty L$ (where L is interconnect length and A is interconnect resistance cross-section), the operational circuit speed $S \infty 1/RC\infty A/L^2$. From the last follows that $S_{max} \leq 10^{15}$ A/L^2 (bit/s), and because $A<<L^2$ the limit of the electronics speed is in the region of GHz. The bit rate in optical communications is fundamentally limited only by the carrier frequency: $S_{max} < f \sim 100$ Tbit/s , but light propagation is subjected to diffraction. Therefore, photonics being accompanied by diffraction is limited in size of the order of wave length $\lambda \sim 1$ μm. At the same time, interface plasmon-polaritons in plasmonics having wavelengths nanoscale size at optical frequencies are very suitable to overcome both problems of limited speed in electronics and limitation of packing in photonics (Fig.1).

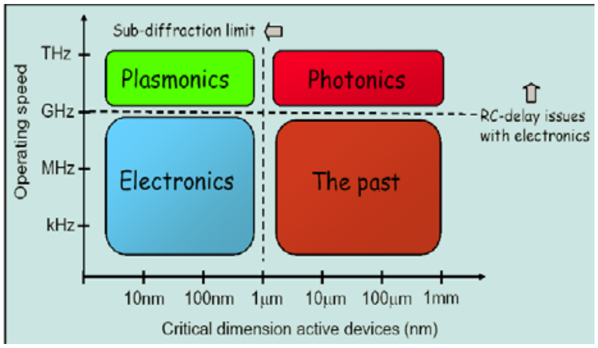

Fig.1. Graph of operating regimes of different technologies

Thus, due to abovementioned features plasmonics naturally interfacing with similar size of electronic components and similar operating speed of photonic network will enable an high improved synergy between electronic and photonic devices.

2. Design and fabrication of plasmonic nano structures

Due to emergent development of nanotechnology and growing importance in diverse applications solid-state nanostructures formation has been an active area of research during last two decades. The properties of such nanostructures can be tuned very broadly by controlling their size, shape, and composition. This has resulted in a wealth of approaches on synthetic methodologies for generating isotropic and anisotropic nanostructures with well-controlled sizes and shapes from a variety of materials. All of these are suitable to design and fabricate plasmonics nanostructures (PNS), which as all solid-state nanostructures are typically formed using either so-called top-down or bottom-up approaches [4]. Top-down approaches are involve using various forms of conventional lithographic techniques to pattern nanostructures, whereas bottom-up methods exploit the interactions of atoms, molecules, or more complex mesoscale objects, in conjunction with the controlling influences of process kinetics, to "assemble" nanostructures either on substrates or in solution.

The main approaches used for PNS fabrication include: solution-phase syntheses; stack and draw technique; top-down lithography; unconventional lithographic techniques [4]. Solution-phase synthesis, which involves the reduction of metal salts in a solution containing an appropriate stabilizer to control the growth and suppress the aggregation of the is a enough simple approach to forming PNSs. As illustration in Fig.2. nanostructured PbTe and PbSnTe obtained from hexan, tetracloretilen, chloroform etc. solutions in form of nanodot ensemble are presented.

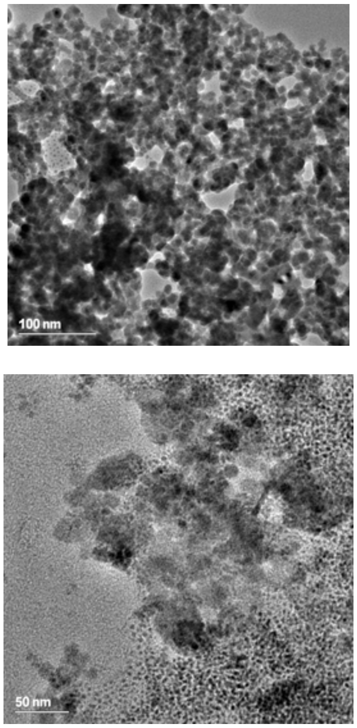

Fig. 2. Nanostructured PbTe(a) and PbSnTe (b)

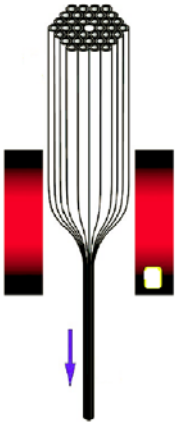

Fig. 3. Scheme of stack and draw technique

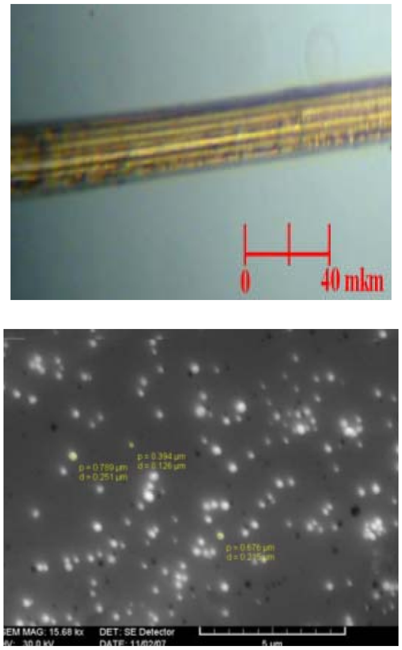

Fig. 4. Composite of glass and Bi- nanowires obtained by stack and draw approach

The stack and draw technique is the optical fiber method adapted for nanowire-like PNSs (Fig. 3). The glass composite of bismuth nanowires obtained by this method are presented in Fig. 4.

Unconventional lithographic techniques for PNS fabrication are illustrated in Fig. 5 and 6 for colloidal and soft lithographies,respectively [4].

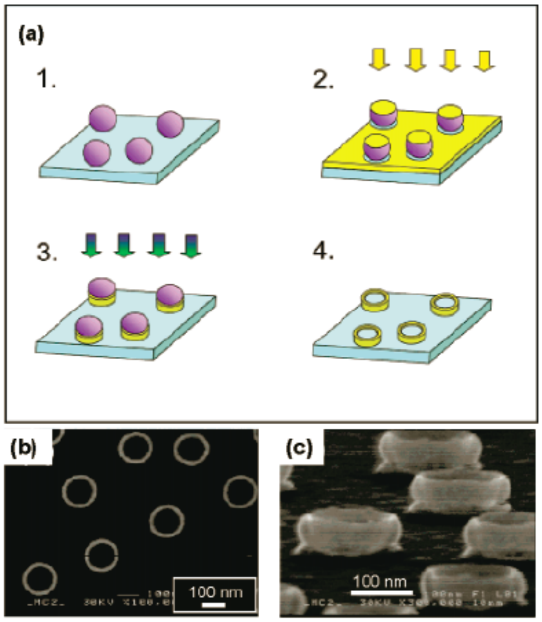

Fig. 5. Schematic depiction of nanoring fabrication by polystyrene litigraphy.

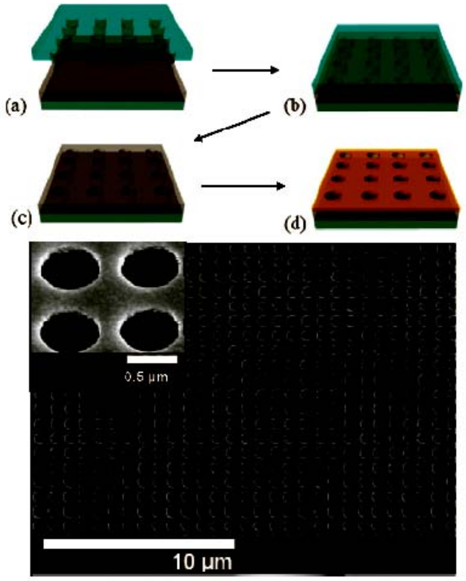

Fig.6. Plasmonic crystal fabrication process: (a) imprint, (b)cure, (c) remove stamp, and (d) Au deposition (top).

3. Interface plasmon polaritons at metal/dielectric boundariers

Interface plasmon-polaritons (IPs) are light waves that occur at a metal/dielectric (semiconductor) interface, where a group of electrons is collectively moving back and forth [5] . These waves are trapped near the surface as they interact with the plasma of electrons near the surface of the metal.

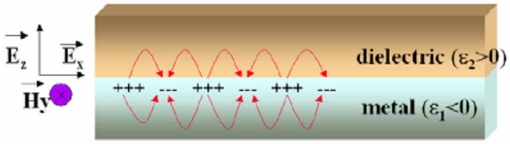

Fig. 7. Sketch of plasmonics physics at metal-dielectric (M-D) interface.

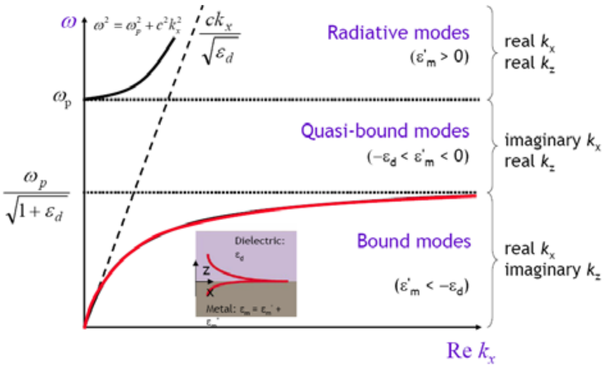

Fig. 8. Schematic behavior of plasmonic dispersion (M-D) interface.

The resonant interaction between electron-charged oscillations near the surface of the metal and the electromagnetic field of the light creates the IP and results in rather unique properties. IPs are bound to the metallic surface with exponentially decaying fields in both neighboring media. The decay length of IPs 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 feature of IPs provides the possibility of localization and the guiding of light in subwavelength metallic structures, and it can be used to construct miniaturized optoelectronic circuits with subwavelength components

The dispersion relations of the IPs always lie to the right of the respective light line, approaching $\omega_{sp}=\omega_p$ $/(1+\varepsilon_D)1/2$ for large wave vectors, the magnitude of the wave vector at ω_{sp} being limited by dissipation.

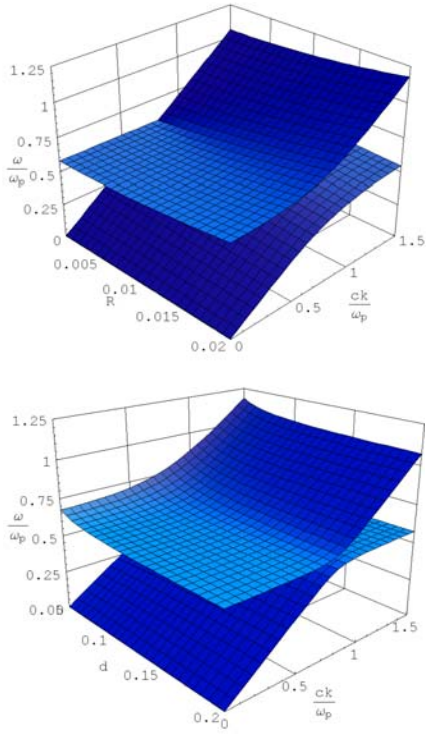

Fig. 9. Dispersion and IP frequency dependences on nanowire radius R and nanowire spacing d in PNS of metallic nanowire array in dielectric matrices.

Nanowire arrays in dielectric or semiconductor matrices are another type of PNS ,which sustain interface plasmon-polaritons modes at the boundaries [. Structuration in two dimensions as well as nanowire radius offer large possibilities to tailor the IPs characteristics and this is illustrated for ordinary IP waves of metal dielectric composite in Fig. 9. There is another advantage of nanowire geometry, when the confinement of the electrons in two dimensions leads to well defined dipole interface plasmon resonances, which open new opportunities for subwavelength plasmonic waveguides [6]. Frequency dependent dielectric properties of semiconductor $\varepsilon_c(\omega)=\varepsilon_\infty\left(\omega_L^2-\omega^2\right)\left(\omega_T^2-\omega^2\right)^{-1}$ open new opportunities [7] to design the attributes of IPs with appearance of plasmon-fonon modes (Fig. 10).

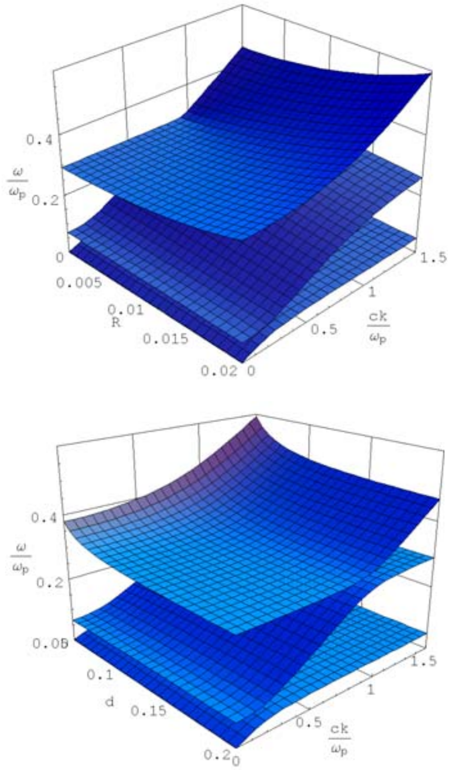

Fig. 10. Dispersion and IP frequency dependences on nanowire radius R and nanowire spacing d in PNS of metallic nanowire array in semiconductor matrices.

Typically, 10. . . 30% of IP energy scatters into free-space modes at a single boundary, severely hindering the performance of surface optical elements and essentially making it impossible to realize the 2D optics paradigm with existing isotropic plasmonic materials. Recently [8] was demonstrated that properly designed anisotropic materials can be utilized to completely eliminate this parasitic scattering by decoupling the response of plasmonic circuits to different polarizations of electromagnetic radiation, and thus opening the roadway to truly plasmonic optics. The IP is a solution of Maxwell equations that represents a transverse-magetic (TM) wave propagating at the interface between two materials. The out-of-plane scattering of IPs into free-space modes can be eliminated by meeting two conditions. First, the spatial profile of the IP mode should be independent of its refractive index. And second, the boundary between the optical elements should not support inter-polarization (TE ↔ TM) coupling. These conditions can be satisfied in uniaxial anisotropic media.

Plasmonics cylindrical nanowire structures on the basis of anisotropic materials or non-cylindricaly configurated nanowires offer also large possibilities to tailor IP characteristics [6].

4. Plasmonics optical nanoelements and nanodevices

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 electromagnetic radiation in various wavelengths from optics to microwaves. During the last years plasmonic waveguides have attracted a significant amount of research interest as potential building blocks for a nanoscale photonic infrastructure, and optical components such as straight waveguides, beamsplitters, interferometers and IP-bandgap surfaces based on modulated and textured metallic films have been demonstrated [9]. Thin metal films of finite width embedded in a dielectric can be used as plasmonic waveguides. This geometry offers the best propagation results for a interface plasmon–based waveguide, because the measured propagation length for operation with light at a wavelength of 1550 nm is reported to be as long as 13.6 mm.

At the same time, the localization for both directions is on the order of a few micrometers in this plasmonic waveguide geometry. To achieve subwavelength localization it is more suitable to use wire-like PNS and subsequently use the IPs to guide the light underneath this nanowire. However, light transport was observed along the nanowire over a distance of a few micrometers due to resistive heating within the metal nanowire.

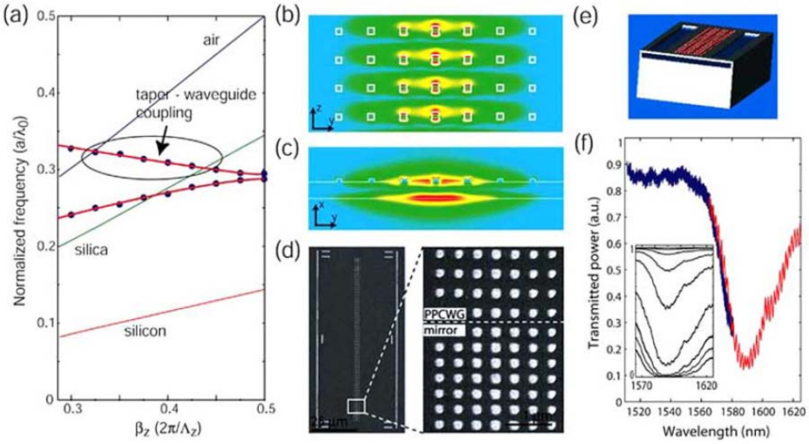

Fig. 11. Fiber-accessible low-loss near-infrared metal nanoparticle plasmon waveguide consisting of a two-dimensional array of metal nanoparticles arranged on a 500 nm square lattice on a thin silicon membrane [9].

In order to avoid the ohmic losses, one can envision using an array of nanoparticle resonators. As illustration low-loss plasmon waveguide that can be efficiently excited at a wavelength in the telecommunication window around 1500 nm is shown in Fig. 11 [9]. The waveguide consists of a two-dimensional square lattice of Au nanoparticles with a lattice period of 500 nm on a thin silicon membrane as depicted in Fig. (11d) and (11e). The electric field distribution of the optical mode calculated using finite-difference timedomain simulations is shown in Fig. (11b) and (11c) in top and lateral view, respectively.

Active control of plasmons is needed to achieve plasmonic modulators and switches. Plasmonic signals in a metal-on-dielectric waveguide containing another metal section a few microns long can be effectively controlled by switching the structural phase of the section by changing the waveguide temperature or by external optical excitation.

IPs also play a key role in the transmission properties of single apertures and the enhanced transmission through subwavelength hole arrays. By texturing the metallic surface with a subwavelength pattern, we can create IPs that are responsible for enhanced transmission observed at microwave and millimeter wave frequencies for 1D and 2D gratings with subwavelength apertures.

Plasmonics suggests new solution of the problem of low light-emission efficiencies of semiconductor-based LEDs [3]. For example, if the InGaN/GaN quantum wells are coated by nanometer silver or aluminum films, the resulting IPs increase the density of states and the spontaneous emission rate in the semiconductor. This leads to the enhancement of light emission by IP- quantum well coupling, which results in large enhancements of internal quantum efficiencies.

Plasmonics concept is involved also in the improvement of solar cell efficiency. In particular, transparent high-sheet-conductivity nanopatterned metal films are being developed for use as transparent conductors allowing parallel subcell connection, and metal nanostructures are being embedded in the active layers to enhance the photon absorption and charge separation efficiency.

5. Plasmonics in thermoelectricity

Energy conversion devices based on thermoelectricity effects rely on electron transport for energy conversion, while phonon heat conduction is usually detrimental for the energy conversion efficiency [10]. Higher energy conversion efficiency is possible if the electrons and phonons can be decoupled. Plasmonics based on interface plasmons coupled nonequilibrium thermoelectric devices offer such opportunities [11], when the energy transport from the heat source of a power generator or the cooling target of a refrigerator to the thermoelectric element is limited to electrons through the tunneling of surface-plasmons across a vacuum gap of the order of tens of nanometers. For the power generation functionality, this approach of thermal-energy coupling allows the creation of hot electrons in the thermoelectric element. In the refrigeration construction, cold electrons created in the thermoelectric element can be coupled to the cooling target through the interface-plasmons.

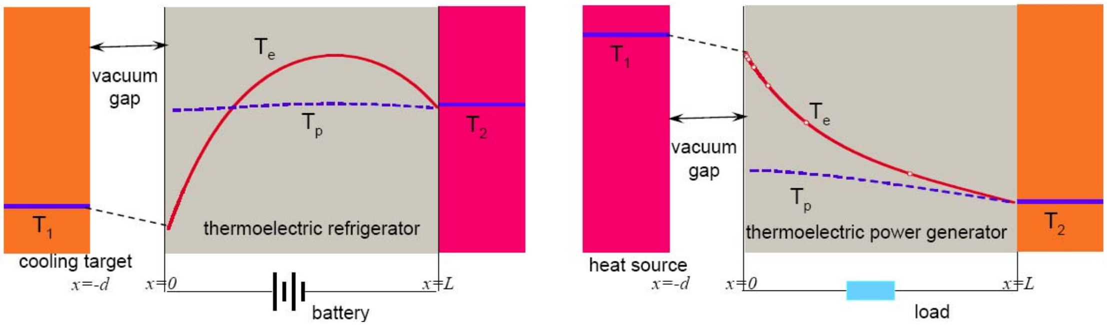

Fig. 12. Scheme of interface-plasmon coupled nonequilibrium thermoelectric devices.

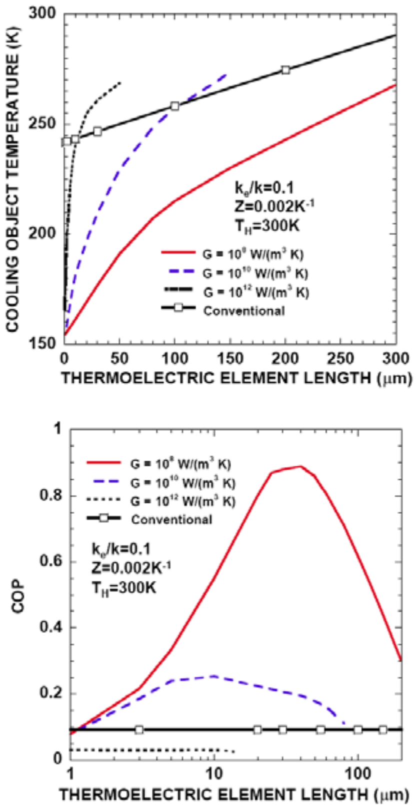

Fig. 13. (a) The cooling target temperature changes with thermoelectric element length and the electron-phonon coupling constant under a load of q=50W/cm2. (b) the COP of IP coupled nonequilibrium thermoelectric refrigerator as a function of thermoelectric element length and electron-phonon coupling constant with the cooling target temperature at 250K.

The radiative energy transfer between the heat source (or cooling target) and the thermoelectric element by surface plasmons is modeled following the same method used to model energy transfer due to interface phonon-polaritons [12]. Fig. 13 shows the performance of a surface-plasmon coupled nonequilibrium thermoelectric refrigerator under a cooling load of 50 W/cm^2, which is same as the maximum cooling power density of a L = 50 μm conventional thermoelectric refrigerator with Z = 0.002K^{-1} operating at TH = 300K and TC = 250K [12].

Clearly, much lower cooling target temperature can be obtained for a wide range of G and L combinations than the conventional device with a same given load. Figure 13 (b) compares the COP of a surface-plasmon coupled nonequilibrium thermoelectric refrigerator with conventional thermoelectric refrigerator with the cooling target temperature at 250 K. For low G value, the COP of IP coupled nonequilibrium thermoelectric refrigerator can be much higher than the maximum of the conventional thermoelectric refrigerator [12].

6. Future directions and challenges

One of the big challenge of computer electronics is that as traditional, silicon-based semiconductor devices approach the nanoscale, the laws of quantum physics take control over their performance (specifically the flow of charges—i.e. electrons) and render them inoperable.

Thus the development of all-plasmonic chip is the first main direction of plasmonics. In the near term, plasmonic interconnects may be used to address the capacity problem in digital circuits including microprocessors [3,13]. Conventional 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 information at the destination.

Another large area of plasmonics is to use plasmon technology to create the invisibility cloak for visible light. The invisibility cloak design structure is a two-dimensional pattern of concentric rings created in a thin, transparent plastic material layer on a metal film, which have different refractive properties [13]. The structured plastic on metal in different areas of the cloak creates "negative refraction" effects, which bend plasmons-electron waves generated when light strikes a metallic surface under precise circumstances-around the cloaked region. In the results the light will be guided around the cloak much as water in a stream flows around a rock, and released on the other side, concealing the cloak and the object inside from visible light.

Very important challenge of plasmonics is to develop superlens microscopy technology, which can be integrated into a conventional optical microscope to view nanoscale details of objects that were previously undetectable [3].

Interface plasmons can give rise to the intense colors of solutions of plasmon resonance nanoparticles and/or very intense scattering. While the use of plasmonic particle absorption based bioaffinity sensing is now widespread throughout biological research, the use of their scattering properties is relatively ill explored. Perhaps one of the most profound future applications of plasmon scatter, is likely to be in the measurement of distances in the range 10–300 nm for biological systems.

Recently plasmonics principles have applied to spintronics technology and created a novel way to control the quantum state of an electron's spin. The new technology, which the researchers call spinplasmonics, may be used to create incredibly efficient electron spin-based photonic devices, which in turn may be used to build, for example, computers with extraordinary capacities.

However, the current performances of plasmonic waveguides, chips etc are insufficient for the abovementioned kind of applications, and there is an urgent need for more work in this area. In particularly, some of the challenges that face plasmonics research in the coming years are [3,13]:

(i) demonstrate optical frequency subwavelength metallic wired circuits with a propagation loss that is comparable to conventional optical waveguides;

(ii) achieve active control of plasmonic signals by implementing electro-optic, all-optical, and piezoelectric modulation and gain mechanisms to plasmonic structures;

(iii) demonstrate 2D plasmonic optical components, including lenses and grating couplers, that can couple single mode fiber directly to plasmonic circuits;

(iv)develop highly efficient plasmonic LEDs with tunable radiation properties;

(v) develop deep subwavelength plasmonic nanolithography over large surfaces;

(vi) develop highly sensitive plasmonic sensors that can couple to conventional waveguides;

(vii) demonstrate quantum information processing by mesoscopic plasmonics.

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