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Comparative analysis of metals and alternative infrared plasmonic materials

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Abstract

In the last decade or two the field of nanophotonics has seen rapid development empowered by introducing the concepts of plasmonics and metamaterials. The enabling feature behind this progress has been the use of noble metals that exhibit negative dielectric permittivities over a wide spectral range of visible and infrared wavelengths which allowed for manipulating the light on the sub-wavelength scale. Consequently, numerous interesting phenomena that otherwise do not exist in nature have been demonstrated in laboratories, but their transitions to practical applications have been painfully slow due to the large ohmic losses that are inherent in all metals. Doped semiconductors with lower losses have been proposed as new plasmonic materials to replace noble metals. Because the electron densities that are introduced with the artificial doping are always a few order of magnitude lower than what naturally available in metals, their plasma frequencies are shifted considerably towards longer wavelengths to the infrared (IR). This work compares these two categories of plasmonic media in structures that support either localized or propagating surface plasmon polaritons (SPPs) in mid IR. We have found that in both cases new plasmonic materials underperform noble metals in terms of enhancing optical field in localized SPPs and reducing SPP propagation loss in plasmonic waveguides. The cause
of this subpar performance is the inherently low electron density that yields significantly reduced plasma frequency compared to noble metals. This fundamental property associated with all new plasmonic materials dictates that while new materials do hold a number of advantages, including tunability and ability to withstand high temperatures, noble metals even with their ohmic losses are not likely to be replaced in the foreseeable future.

Fueled by the rapid advancement in nanofabrication technology, optical metamaterials, defined as artificial materials possessing properties that do not exist in nature, have been in the focus of attention around the world in recent decades. The driving force behind these efforts has been the promise of engineering advanced optical devices capable of performing functions unattainable with conventional optical media. The most desired property associated with the metamaterials that brings about most novel functions has been the negative refractive index made possible by the negative values of both permittivity $\varepsilon$ and permeability $\mu$ with properly engineered constituents. The most commonly used constituent of metamaterials is metal because of its intrinsic negative permittivity and ability to exhibit negative permeability when engineered into special shapes with subwavelength dimensions. A unique feature of these subwavelength metal nanostructures is the extreme localization of the electromagnetic fields in the modes known as the surface plasmon polaritons (SPPs). A wide range of applications have been proposed for these plasmonic metamaterials including bio- and environmental sensing, light harvesting, and nonlinear optical processing. Light sources and detectors among others can benefit from the strong localized SPP fields that often improve either efficiency or speed, preferably both. Tightly confined propagating SPPs have long been promoted to achieve subwavelength waveguides for future on-chip optical interconnects. In addition, novel functionalities made possible by metamaterials and metasurfaces relying on SPPs have been envisioned such as super lenses, optical cloaks and other transformational optics schemes.

With all the effort committed to bringing these promises into reality over the past decade, few have made inroads in real world applications. The plasmonics community has slowly come to the consensus that the ohmic losses of the metals including the noble ones which are the mainstay of plasmonics and metamaterials are simply too high. The free electrons in metal that
yield the negative real part of the frequency-dependent dielectric function also give rise to the
imaginary part that is responsible for the loss because of the momentum scattering as
\[
\varepsilon_m = \varepsilon_\infty \left[ 1 - \frac{\omega_p^2}{\omega^2 + i \omega \gamma} \right]
\]  
(1)

where \(\varepsilon_\infty\) is the “background” dielectric constant of the bound electrons and ions in the metal,
\(\omega_p = (ne^2/\varepsilon_\infty e_m)^{1/2}\) is the plasma frequency, \(m\) is the electron effective mass, and \(\gamma\) is the
momentum scattering rate which is the origin of the loss. The plasma frequency is typically in
the ultraviolet region on the order of \(\omega_p \approx 10^{16} \text{s}^{-1}\) for noble metals, while the momentum
relaxation rate is on the scale of \(\gamma \approx 10^{14} \text{s}^{-1}\), because of strong electron-phonon and electron-
electron scattering.

It is not difficult to argue that had the imaginary part of the dielectric function vanished by
eliminating electron scattering in the metal, majority of the envisioned novel functionalities and
impressive enhancement would have been materialized by now. This can be easily understood
from the point of view of energy conservation for SPP oscillation. In any optical cavity made of
dielectric in which electromagnetic modes are supported, the mode energy oscillates between
electrical and magnetic forms that are exactly balanced. But when the characteristic dimension of
such a cavity becomes subwavelength, the mode energy can no longer be balanced because the
magnetic field begins to diminish and the system enters the so called quasi-static regime. In other
words, the potential form of the electrical energy has no matching kinetic counterpart in the form
of magnetic energy, as a result, no optical mode can be confined in a subwavelength dielectric
cavity, which is the well-known diffraction limit\(^9\). The following question then arises: how does
a subwavelength metal nanostructure support SPP modes? The answer can be found in the
collective kinetic motion of the free electrons in metal that simply does not exist in dielectrics
except the relatively narrow Reststrahlen region in far IR. As the magnetic energy continues to
decrease when the plasmonic structure is being shrunk deep into subwavelength dimensions, the
kinetic energy of the free electrons becomes increasingly dominant to make up for the
diminishing magnetic energy in order to balance the electrical potential energy, so at some well-
defined frequencies the self-sustaining SPP modes can be supported. But as soon as the energy is
stored in the form of electron kinetic motion, it becomes subject to loss as electrons get scattered
in metal\(^9\). While the electron kinetic energy loss should be twice as fast as its momentum loss at
because the SPP energy is stored half of the time in the kinetic form, the SPP mode decays roughly at the rate $\gamma \approx 10^{14}s^{-1}$ depending on the actual ratio of the kinetic energy stored in electron motion to that stored in the magnetic field. It is not hard to see the deeper the subwavelength of the metal structure, the stronger the SPP confinement and therefore the higher the SPP mode loss $^{10}$.

The frustration with the inherent metal losses has eventually led the plasmonics/metamaterials community to the idea of finding alternative plasmonic materials with a negative real part of the dielectric function but considerably smaller loss. Recognizing the need for significant density of free electrons, much attention has been directed towards strongly doped conventional semiconductors such as InAs $^{11}$, InP $^{12,13}$, transparent oxides such as AlZnO and ITO $^{14}$ as well as nitrides (TiN, ZrN) and others $^{15,16,17}$. The reason for looking into these alternative materials is that they could have lower rate of momentum scattering $\gamma$ than metals, while their free electron densities can be controlled for frequency tuning of the SPP resonances. Indeed, $\gamma$ is lower in some of the proposed alternative materials compared to the noble metals as listed in Table I, most notably, $\gamma \approx 10^{13}s^{-1}$ for highly doped ($2 \times 10^{19} \text{ cm}^{-3}$) In$_{0.53}$Ga$_{0.47}$As. This fact stems partially from the intrinsic properties of InGaAs $^{18}$ (lower effective mass) and partially from the advanced growth methods perfected for this material widely used in electronics (high mobility transistors) and photonics (lasers and detectors).

The lower scattering rates in doped semiconductors can be explained primarily by the much smaller number of states into which the electrons can be scattered because of the smaller density of states around the Fermi level in these materials in comparison to the situation in metals where the Fermi level is much higher in the conduction band as illustrated in Fig. 1. In other words, the smaller scattering rate is also the result of smaller free electron density. A direct consequence of this is, of course, lower plasma frequency. In other words, the ratio $\omega_p / \gamma$ cannot be increased (as witnessed from Table I) and this state of affairs cannot be altered much even with the reduced electron effective mass in a semiconductor because smaller effective mass is typically associated with a material of smaller bandgap that has larger background dielectric constant $\varepsilon_\infty$. This set of circumstances precludes the alternative materials with scattering rates lower than metal from
being employed for visible and near IR applications and therefore doped III-V and II-VI semiconductors cannot really be considered a viable alternative for metals in this spectral range. However, they do appear to be the promising candidates for mid IR plasmonic metamaterials as has been argued in\textsuperscript{11,14,15,16}, assuming that their smaller loss can indeed translate into stronger field confinement in subwavelength structures. Unfortunately, no experimental data support such claims as the quality factors of the SPP resonances in highly doped semiconductor nanostructures have always been broader than what have been observed from metal nanostructures\textsuperscript{11,12}. While part of the problem could be attributed to fabrication difficulties, numerical studies\textsuperscript{19} have shown that most “alternative” materials are still inferior to noble metals over wide range of wavelength and more recent theoretical analysis has revealed something more fundamental that ultimately limits the achievable optical field enhancement with the alternative plasmonic materials, namely, their low plasma frequencies\textsuperscript{20}. In this work, we briefly present the underlying physics that supports this point of view, and test it by performing numerical simulations of plasmonic structures made of doped InGaAs and Au for comparison. Two types of structures are studied, subwavelength particles that support localized SPP modes and waveguides that confine propagating SPPs. The SPP resonance in InGaAs and Au nanoparticles can be tuned to the same wavelength by varying the doping density and aspect ratio respectively. Our simulation results support the conclusion that noble metals consistently deliver better figure of merit even in the mid IR range with lower effective SPP mode loss in both subwavelength particles and waveguides are always superior to doped semiconductors when loss is the only concern. The argument for alternative plasmonic materials can still be made in areas of other considerations such as cost, availability, compatibility with existing technology, melting point, optical damage threshold, etc., but, when it comes to the ability to sustain low loss tightly confined SPP modes metals appear to be the materials of choice in the foreseeable future.

\textbf{Results and Discussion}

\textbf{Scaling of Effective SPP Loss}

While noble metals have their plasma frequencies up in the ultraviolet, the SPP resonances supported by the subwavelength particles made from them can be tuned to lower frequencies. In
the case of the mid IR, the structures of interest may not need to be in tens or even hundreds of nanometers in order to support SPPs so long as they are subwavelength which could be on the order of a micrometer. They should therefore not be referred to as nanostructures or nanoparticles. Let’s now consider an Au ellipsoidal particle with a length $l$ and cross-section of diameter $a$ as shown in Fig. 2(a) whose aspect ratio can be adjusted to obtain SPP resonances from visible to mid IR. As has been discussed above, the SPP mode oscillates between the “potential” or “in-phase” and “kinetic” or “quadrature” energy and the loss occurs when the energy is stored in the collective motion of the free electrons which is a part of the quadrature energy that also includes a non-dissipative magnetic component. The actual or effective SPP loss should therefore depend on how the total kinetic energy is divided between free electron motion $E_k$ and magnetic component $E_m$ as

$$\gamma_{\text{eff}} = \gamma \frac{E_k}{E_k + E_m}.$$  

Upon the optical excitation, the electric field permeates into the particle by a skin depth, roughly $\lambda_p / 2\pi$ where $\lambda_p = 2\pi c / \omega_p$ is the plasma wavelength that is ~150nm for Au. The electric current as a result of the collective motion of the free electrons under the influence of this electric field is contained near the particle surface in the effective cross section area that can be approximated as

$$S_{\text{eff}} = \frac{\pi a^2}{4} \left[1 + \left(\frac{\pi a}{2\lambda_p}\right)^2\right]^{1/2}.$$  

It is important to realize that because the skin depth is determined only by the plasma wavelength, $S_{\text{eff}}$ does not depend on the excitation or SPP wavelength, but rather only on the plasma wavelength $\lambda_p$ and the characteristic dimension $a$. Clearly, if the diameter of the particle is much smaller than the skin depth, $a << \lambda_p$, then the current permeates the entire particle and $S_{\text{eff}} = \pi a^2 / 4$, but in large diameter particles $a \gg \lambda_p$, the current flows in the region of skin depth with $S_{\text{eff}} = a\lambda_p / 2$.

If we model SPPs in terms of LC oscillations, the cycle when energy is stored in the form of electron kinetic motion and magnetic field is equivalent to that of energy being stored in the
inductor in a LC circuit. Both the free-electron kinetic energy \( E_k \) and magnetic energy \( E_m \) can therefore be expressed in terms of the induced current \( I \) through their respective inductance \( L_k \) and \( L_m \) as \( E_k = L_k I^2 / 2 \) and \( E_m = L_m I^2 / 2 \). The kinetic inductance \( L_k = l / e_0 \varepsilon_0^2 S_{eff} = \mu_0 \lambda_p^2 / 4 \pi^2 S_{eff} \) has a strong dependence on the ratio between the plasma wavelength \( \lambda_p \) and the mode dimension \( a \), in the case of \( a << \lambda_p \), \( L_k \propto \lambda_p^2 / a^2 \) while for \( a >> \lambda_p \), \( L_k \propto \lambda_p / a \). The magnetic inductance \( L_m = \mu_0 l / 2 \pi \left[ \log \left( \frac{4l}{a} \right) - 1 \right] \), on the other hand, shows a very weak dependence on \( a \). Since the expression in the square brackets varies only from 1 to 2 as the ratio \( (l / a) \) increases from 1.5 to 5 and thus can be dropped in our order-of-magnitude analysis, we obtain a very simple relation between the effective loss rate and the ratio of \( a / \lambda_p \) as

\[
\gamma_{eff} \approx \gamma / \left( 1 + 2x^2 / \sqrt{x^2 + 1} \right)
\]

where \( x = \pi a / 2 \lambda_p \). This expression is obviously valid for both Au and doped InGaAs, but for Au \( x \) can be significantly larger than 1, while for doped semiconductor with its longer plasma wavelength \( x \) is typically less than 1, which should lead to large effective loss.

This expression for effective loss can actually be generalized to describe other subwavelength structures, such as a split ring resonator (SRR)\(^2\) illustrated in Fig. 2(b) with the circumference \( l \) and the cross-section of the wire \( \pi a^2 / 4 \). The SRR resonance frequency can always be adjusted by properly choosing the SRR gap \( d \). The magnetic inductance of the SRR loop \( L_m = \mu_0 l / 4 \) once again does not depend on the cross-section, and the effective loss rate of the SRR is almost identical to Eq. (4), \( \gamma_{eff} \approx \gamma / \left( 1 + \pi x^2 / \sqrt{x^2 + 1} \right) \), signifying its generality.

Note that one can extend the analogy with the RLC circuit further by noting that the resistance of the particle is related to its kinetic inductance as \( R = \gamma L_k \) and one can always write for the effective damping of RLC circuit near resonance \( \gamma_{eff} = R / L \) from which Eq. (2) immediately follows. In other words, while semiconductors have higher mobility (lower momentum damping rate), the only characteristics affecting the effective damping rate of SPP is conductance which
is actually higher in metals with large density of free electrons. Furthermore, one can use the circuit analogy to obtain an estimate of the resonant frequency of the SPP in the limit of small particles as $\omega_r \sim \omega_p S_{\text{eff}}/l$.

The dependence of the effective loss normalized to the electron momentum scattering rate $\gamma_{\text{eff}}/\gamma$ on the ratio of $a/\lambda_p$ is shown in Fig. 3(a). This dependence works for all subwavelength plasmonic structures including those made of Au or doped InGaAs, albeit for different materials the effective SPP loss appears on a different part of the curve for the same SPP wavelength $\lambda_p$ because of the order-of-magnitude difference in their plasma wavelength $\lambda_p$. For instance, for Au in visible, say $\lambda = 500 \text{ nm}$, with subwavelength dimension of $a \approx \lambda/5 = 100 \text{ nm}$, the ratio $a/\lambda_p < 1$ and the effective loss $\gamma_{\text{eff}} \approx \gamma_{\text{Au}} \approx 10^{14} \text{ s}^{-1}$ stays on the left side of the curve. In mid IR, however, say $\lambda = 10 \mu\text{m}$, $a \approx \lambda/5 = 2 \mu\text{m}$ is already subwavelength, but still much larger than the plasma wavelength $a/\lambda_p \approx 13$, so the effective loss moves to the right side of the curve with $\gamma_{\text{eff}} \approx \gamma_{\text{Au}}/20 \approx 5 \times 10^{12} \text{ s}^{-1}$. For InGaAs with $2 \times 10^{19}/\text{cm}^3$ doping, its plasma wavelength $\lambda_p = 5 \mu\text{m}$, the same subwavelength dimension $a \approx \lambda/5 = 2 \mu\text{m}$ in mid IR still has the ratio $a/\lambda_p < 1$, so $\gamma_{\text{eff}} \approx \gamma_{\text{InGaAs}} \approx 10^{13} \text{ s}^{-1}$. It is conceivable therefore that metal with larger $\gamma$ and smaller $\lambda_p$ can have smaller effective loss than a doped semiconductor. To illustrate this, we have plotted the effective loss of subwavelength ellipsoid with a diameter of $a \approx \lambda/5$ made from either Au or InGaAs doped to $2 \times 10^{19}/\text{cm}^3$ in Fig. 3(b). As follows from Table 1, because the Au plasma frequency is about 37 times of that in InGaAs, in order to tune the SPP resonance to the same wavelength, the length of Au ellipsoid will be longer than that of InGaAs since their cross section diameters are chosen to be identical. As one can see from Fig. 3(b), the aspect ratio of the Au particle can be tuned to obtain SPP modes over a much wider spectral range than that of the doped InGaAs which does not support SPPs when $\lambda < 5 \mu\text{m}$. We can push SPPs to somewhat shorter wavelength with higher doping in semiconductors, but this usually causes their scattering rate to go up and approach metal loss, defeating the purpose of using them as alternative plasmonic materials. The effective loss of Au particle asymptotically reduces from its bulk value of $\gamma_{\text{eff}} \approx \gamma_{\text{Au}} \approx 10^{14} \text{ s}^{-1}$ with the increase of SPP wavelength as the size of the subwavelength
The cross section fixed to \( a = \lambda / 5 \) is allowed to get larger relative to its plasma wavelength \( \lambda_p \). The increase of the ratio \( a / \lambda_p \) in Au is eventually responsible for the smaller effective loss than the doped InGaAs despite the fact that the bulk scattering rate in the semiconductor is about ten times smaller than in the metal, because the cross section in InGaAs is still smaller than its plasma wavelength, \( a = \lambda / 5 < \lambda_p \), and the electric current permeates the entire semiconductor particle. At very long wavelengths the dimension approaches \( a \gg \lambda_p \), the effective loss can be simply expressed as \( \gamma_{\text{eff}} \approx \frac{\gamma \lambda_p}{\pi a} = \frac{\gamma}{\omega_p} \frac{2c}{a} \), hence the proper figure of merit (FOM) for plasmonic structure should be \( \omega_p / \gamma \) and not \( \text{Re}(\varepsilon) / \text{Im}(\varepsilon) \approx \omega / \gamma \) or \( \omega_p^2 / \omega \gamma \) often used in the literature. According to Table I the proper FOM is always higher for metals than for any of the doped semiconductors.

**SPP Field Enhancement Comparison**

Having analyzed the scaling of the effective loss, we shall now examine the SPP field enhancement in plasmonic structures numerically. The comparison is made between subwavelength structures of either Au or doped InGaAs for field enhancement in mid IR. SPP resonances are tuned in two distinct ways. We use doping in InGaAs sphere to adjust its SPP resonance. As one can see from the extinction spectra in Fig. 4(a), the resonance can be continuously tuned to cover a broad (nearly an octave-wide) range from about 7 to 13 µm by reducing doping in InGaAs from \( 1.2 \times 10^{19} \) to \( 4 \times 10^{18} \) cm\(^{-3} \) while fixing its diameter at 1.4 µm. The range of SPP resonances is by no means limited and can be extended by exploring wider range doping levels and aspect ratios. For Au, however, we use the length of a rod with a fixed cross section of 0.6 µm-diameter to tune its resonance. Figure 4(b) shows that the same mid IR spectral range of 7 to 13 µm can be covered by varying the Au rod length from 3 to 6 µm. Again, a wider range can be obtained by adjusting the aspect ratio of the Au rod. This range is chosen solely for comparative purpose.

We have taken care to round the ends of the Au rod to avoid special localization effect that takes place at the sharp edges. We then used Lumerical numerical FDTD software to simulate the SPP
field distributions in the two plasmonic structures made of either doped InGaAs or Au that are tuned over the same spectral range as shown in Fig. 5(a). Using the scattering rate of $10^{14}$ s$^{-1}$ for Au and $10^{13}$ s$^{-1}$ for doped InGaAs, we have obtained the SPP fields around doped InGaAs and Au rod as illustrated in inset of Fig. 5(b). The maximum achievable field enhancement for both structures is compared in Fig. 5(b) where the SPP field near the ends of the Au rod is consistently stronger than that near the poles of the InGaAs sphere throughout the mid IR range of 7 to 13 µm, despite the fact that Au has an-order-of-magnitude larger scattering rate than InGaAs. This seemingly surprising outcome is a direct result of what we have just demonstrated analytically in the previous section, namely that the effective loss does not depend on the light wavelength, but scales according to the ratio of the characteristic dimension of the plasmonic structure to the material plasma wavelength. In the mid IR range, we have this favorable condition that the characteristic dimension of the Au structure sits in between the plasma and light wavelengths: $\lambda_{p,\text{Au}} < a < \lambda$, where the effective loss scales towards the right side of curve in Fig. 3(a). But in the doped InGaAs sphere, because of the low free carrier density (relative to any metal) and thus small plasma frequency, we actually have $a \leq \lambda_{p,\text{InGaAs}} < \lambda$ where the electric field and thus current permeate the entire InGaAs structure, and the effective loss is closer to the highest value $\gamma_{\text{eff}} \approx \gamma_{\text{InGaAs}}$ on the scaling curve in Fig. 3(a).

**SPP Propagation Length in a Plasmonic Waveguide**

Another purported benefit of the doped semiconductors as alternative plasmonic materials is their ability to support SPPs traveling in sub-wavelength plasmonic waveguides and having reduced loss. With the lower losses in doped semiconductors by about one order of magnitude relative to noble metals, the expectation has been that plasmonic waveguides made of these alternative materials can support low-loss SPPs that can travel much longer distance than those of metals before being dissipated. This expectation appears to be logical at first glance, but the already-mentioned recent theoretical analysis, as well as other recent works has shown that similar to the disappointing SPP field enhancement with the alternative plasmonic materials, the much anticipated benefit in doped semiconductor waveguides remains elusive. Unlike the localized SPPs around a subwavelength plasmonic structure exhibiting resonance behavior, the
gap SPP in a plasmonic waveguide exists over a broad range of frequencies and can be confined in subwavelength dimensions, e.g. the gap thickness can be made much less than the SPP wavelength \( a \ll \lambda \), when sandwiched between two plasmonic layers either of metal or doped semiconductor as shown in Fig. 6(a). The gap SPP confined in such a waveguide is a TM mode and its propagation constant can be approximated as

\[
\beta = k_d + \frac{k_d}{k_a} + j\frac{k_d}{2\omega k_p a} = \frac{2\pi n}{\lambda} + \frac{\lambda_p}{\lambda_d a} + j\frac{n\gamma\lambda_p}{2\pi ca}.
\]

(5)

The real part is slightly larger than the wavevector in the dielectric core, \( k_d = \frac{2\pi n}{\lambda} \), where \( n \) is its index of refraction. The propagation length can be obtained from the imaginary part as

\[
L_{\text{prop}} = \frac{1}{2\beta} = \frac{\pi ca}{n\gamma\lambda_p} = \left( \frac{\omega_p}{\gamma} \right) \frac{a}{2n}.
\]

(6)

As expected, SPP propagating in thinner waveguide suffers more loss. The ratio \( a / \lambda_p \) once again appears in the loss (imaginary part) of the propagation constant and the FOM for the waveguide is still the same \( \omega_p / \gamma \) as previously obtained for the localized SPP. It can be argued that noble metals with higher FOM should also have lower SPP loss than doped semiconductors. To put this to test, we shall compare two plasmonic waveguides, one of Au/MgF\(_2\)/Au and the other InGaAs/MgF\(_2\)/InGaAs doped to \( 1.2 \times 10^{20} \) cm\(^{-3}\). The waveguide width is fixed at \( w = \lambda / 2 \).

We used the Lumerical mode solver to calculate the SPP propagation constant for different gap thicknesses and wavelengths. The real and imaginary part of the propagation constant are shown in Fig. 6(b) and (c), respectively, as a function of gap thickness for several wavelengths. The simulation result agrees well with that of Eq. (5). The real part for the doped InGaAs is always greater than that of Au simply because \( \lambda_{p,\text{InGaAs}} > \lambda_{p,\text{Au}} \) as described in Eq. (5). The imaginary part for the doped InGaAs is also greater than that of Au, indicating that the doped InGaAs waveguide is indeed lossier, which has been explained by comparing the proper FOM \( \omega_p / \gamma \) between the two materials. Finally, the simulation results for propagation loss and length are shown in Fig. 7(a) and (b), respectively, as a function of the gap thickness for a few wavelengths. Consistent with the predication from Eq. (5), the SPP propagation length in Au waveguide always exceeds that in doped InGaAs with lower propagation loss despite the fact that Au has higher scattering rate than InGaAs. In addition, the propagation length increases linearly with the
gap thickness for both waveguides as expected from Eq. (6). The propagation length for Au has a weak dependence on wavelength in agreement with Eq. (6), but that of InGaAs does decrease for shorter wavelength because as the wavelength approaches plasma wavelength, the field permeates deeper into InGaAs, incurring larger loss.

**Conclusions**

We have performed a comparative study of plasmonic structures made of doped semiconductors and noble metals. By doing so, we have put to test the claim of new plasmonic materials such as doped semiconductors with lower material losses being a better alternative to noble metals that are currently widely used in plasmonics and metamaterials. We have compared doped InGaAs with Au for their optical field enhancement and SPP propagation length in mid IR for which the claim was made. Tuning of SPP resonances supported by an InGaAs subwavelength sphere was obtained by varying its doping density, for Au rod, it was achieved by adjusting its length while fixing its cross section, effectively changing its aspect ratio. For the waveguides, we compared plasmonic structures that have MgF$_2$ dielectric core of subwavelength thicknesses being sandwiched by either doped InGaAs or Au as confining layers. The findings support an earlier theoretical study that predicts noble metals to outperform doped semiconductors even with their larger ohmic losses because of the inherently higher plasma frequencies in the metals. The proper FOM that characterizes the ability of SPP to achieve high degree of field confinement with small loss should be the ratio of plasma frequency $\omega_p$ to the scattering loss $\gamma$, $\omega_p / \gamma \approx |\text{Re}(\varepsilon)^{3/2}|/|\text{Im}(\varepsilon)|$, instead of other commonly used FOMs. While the intrinsic loss in doped semiconductors can be an order of magnitude lower than in metals, their electron densities and thus plasma frequencies are at least 30 times smaller. The subpar performance of the new materials is a direct consequence of this and cannot be improved much because the doping levels cannot be made comparable to those of metals, and any attempt to increase doping to remotely approach the electron densities in metals, the scattering losses in these new materials will rise up quickly with the high defect densities associated with the dopants, diminishing the motivation to employ these materials in the first place.
Using the electrical engineer’s vocabulary, one can simply state that while the **mobility** of a doped semiconductor easily exceeds that of a metal, the **conductivity** is always less in doped semiconductor and since it is the overall resistance determines the energy dissipation, this dissipation is always higher in semiconductors.

It is also important to mention that lower effective loss in metal leads to stronger absorption of light in metallic nanoparticles than in semiconductor ones. As shown in recent works\textsuperscript{26,27} the maximum absorption attainable in plasmonic nanoparticles is proportional to $\omega_p^2 / \gamma$ i.e. the electrical conductivity of the material which is always large in the metals. Hence metals probably hold advantage in the applications where localized heating is required, especially in biomedical ones.

As a parting thought, this short study should in no way be interpreted as a declaration of ineffectiveness of all novel plasmonic materials. While the propagation loss and ability to concentrate the field are definitely among the most important characteristics of plasmonic and metamaterial structures, they are not the only ones and for a number of applications doped semiconductors may indeed be an answer. One salient feature of doped semiconductors is their ability to tune their response by changing the carrier concentration in them and thus modulate the light. Furthermore\textsuperscript{26}, in order to shift the response of metallic structures to longer wavelengths (Fig.4a) requires very large aspect rations which may be difficult to fabricate, while semiconductors in general, depending on specific applications\textsuperscript{28,29,30,31} these materials can offer superior mechanical and/or thermal properties, better compatibility with existing technology, e.g., CMOS, affordability, or availability, among other considerations, as long as their limitations are recognized.

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Table 1. Parameters of plasmonic materials – metals and doped semiconductors (From Refs.9,11,14,15,16,17)

<table>
<thead>
<tr>
<th>Material</th>
<th>$\omega_p$ (eV)</th>
<th>$\gamma$ (eV)</th>
<th>$\omega_p / \gamma$</th>
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<tbody>
<tr>
<td>Ag</td>
<td>9.2</td>
<td>0.02</td>
<td>460</td>
</tr>
<tr>
<td>Au</td>
<td>8.9</td>
<td>0.07</td>
<td>127</td>
</tr>
<tr>
<td>Al</td>
<td>12.7</td>
<td>0.13</td>
<td>98</td>
</tr>
<tr>
<td>AZO(2%)</td>
<td>1.74</td>
<td>0.045</td>
<td>40</td>
</tr>
<tr>
<td>ITO(10%)</td>
<td>1.78</td>
<td>0.15</td>
<td>12</td>
</tr>
<tr>
<td>TiN</td>
<td>8</td>
<td>0.188</td>
<td>45</td>
</tr>
<tr>
<td>In$<em>{0.52}$Ga$</em>{0.48}$As (doping 2x10$^{19}$ cm$^{-3}$)</td>
<td>0.24</td>
<td>0.014</td>
<td>17</td>
</tr>
</tbody>
</table>

Figures

Figure 1. Illustration of the electronic transition with the absorption of a SPP from an occupied state below the Fermi level $E_f$ to an empty state above in the conduction band of either metal or semiconductor along with their respective final density of states.
Figure 2. Schematics of (a) the induced electric current (red arrows) permeating the skin depth of an ellipsoid with diameter $a$ and (b) the geometry of a SRR.

Figure 3. (a) Dependence of the effective loss normalized to the electron momentum scattering rate $\gamma_{\text{eff}} / \gamma$ on the ratio of $x = a / \lambda_p$ and (b) comparison of effective loss between Au and doped InGaAs ($2 \times 10^{19} / \text{cm}^3$) subwavelength ellipsoid ($a = \lambda / 5$) with aspect ratio tuned to a range of SPP resonant wavelength $\lambda$. Dotted circles indicate where mid IR subwavelength structure of
either doped InGaAs or Au resides on the curve. SPP resonance in InGaAs ellipsoid doped to $2 \times 10^{19} / \text{cm}^3$ only exists for $\lambda > 5 \mu\text{m}$ (solid curve).

![Figure 4](image)

**Figure 4.** Tuning of the SPP resonance of (a) InGaAs sphere of 1.4 µm-diameter doped to various carrier concentrations and (b) Au rod with aspect ratio adjusted with different lengths at fixed cross section of 0.6 µm-diameter.

![Figure 5](image)

**Figure 5.** (a) Tuning of SPP resonant wavelength obtained by adjusting doping in InGaAs sphere or the length of the Au rod with fixed cross section of 0.6 µm-diameter. (b) Maximum achievable field enhancement for both structures.
Figure 6. (a) Illustration of the SPP waveguide with MgF$_2$ core of height $a$ sandwiched between either doped InGaAs or Au. (b) Real and (c) imaginary part of the effective index of refraction for InGaAs/ MgF$_2$/InGaAs and Au/ MgF$_2$/Au waveguides as a function of MgF$_2$ core height for SPP wavelengths of 3, 5, and 7 µm.
Figure 7. Comparison of (a) propagation length and (b) loss between InGaAs/MgF$_2$/InGaAs and Au/MgF$_2$/Au waveguides as a function of MgF$_2$ core height for SPP wavelengths of 3, 5, and 7 µm.

References


Field enhancement vs. resonant wavelength (μm)

Gold rod

InGaAs sphere

44x34mm (240 x 240 DPI)