Extraordinary transmission in the ultraviolet range from subwavelength slits on semiconductors

M. A. Vincenti, D. de Ceglia, M. Buncick, N. Akozbek, M. J. Bloemer, and M. Scalora

1AEgis Technologies Group, 410 Jan Davis Drive, Huntsville, Alabama 35806, USA
2Charles M. Bowden Research Center, AMSRD-AMR-WS-ST, RDECOM, Redstone Arsenal, Alabama 35898-5000, USA

(Received 11 November 2009; accepted 11 January 2010; published online 1 March 2010)

In this paper, we describe a way to achieve the extraordinary transmission regime well into the UV range using subwavelength slits carved on semiconductor substrates. Unlike metals, the dielectric permittivity of typical semiconductors like GaAs or GaP is negative beginning in the extreme UV range (λ ≤ 270 nm) and is characterized by large absorption. We show that the metallic response of bulk semiconductors exhibits surface plasmon waves that lead to extraordinary transmission in the UV and soft x-ray ranges, in spite of the large absorption. The importance of realistic material response versus perfect conductors is also discussed. We show that the use of perfect conductor boundary conditions can lead to field amplitudes that may be underestimated by several orders of magnitudes. These findings may be important in high resolution photolithography, near-field optical devices, and ultra-high density optical storage in wavelength ranges, where it may not be possible to utilize more traditional plasmonic materials like noble metals.


I. INTRODUCTION

The propagation of light through small apertures has fascinated scientists for centuries. As the size of the aperture approaches the wavelength it behaves like a point source. Bethe calculated the transmission through subwavelength apertures located on a perfectly conducting, infinitely thin screen. In this case, the transmission is greatly reduced when the size of the aperture is much less than the incident wavelength. However, the reduction in aperture size may trigger novel physical phenomena, like extraordinary transmission. The demonstration of extraordinary transmission in metallic subwavelength arrays of two-dimensional (2D) holes by Ebessen in 1998 has received renewed interest in this field particularly for its applications in near-field optics and nanoplasmonics. This peculiar phenomenon has been studied widely from the optical to the microwave regime in an attempt to shed light on the physical mechanisms that contribute to it. It has been demonstrated both numerically and experimentally that the choice of the geometrical parameters is crucial to the enhanced transmission process. On the other hand, the excitation of surface waves inside and outside the holes or apertures is indeed necessary for the process. Several theoretical studies have reported on the transmission and reflection of light through subwavelength holes on perfect electric conductor (PEC) screens, showing that the calculation of the propagation constant and the wavelength of the Fabry–Perot resonance inside the slit reduces to an arithmetical exercise. However, as predicted by surface plasmon theory, the introduction of a negative real part of the relative permittivity of the metal allows the formation of surface modes, leading to efficient coupling of the incoming light inside the subwavelength holes imprinted on the substrate. Since a negative value for the permittivity is achieved only if the operating wavelength is tuned below the plasma frequency of the chosen metal, the applications that exploit the extraordinary transmission regime for linear and nonlinear optical applications are mostly limited to the visible and infrared ranges.

As calculations on silver substrates have demonstrated, cavity effects relying on the formation of surface plasmons are indeed simultaneously important in both linear and nonlinear processes like second harmonic generation from slits/apertures on metal substrates. As a representative example, in Fig. 1 we plot a 2D map of the transmission from a single

![Figure 1](http://example.com/figure1.png)

**FIG. 1.** (Color online) 2D map of the transmission coefficient evaluated by varying the substrate thickness and the aperture size. The presence of two resonances for the same substrate thickness (~200 nm) confirms the Fabry–Perot-type behavior of this structure (Ref. 9).
A beam tuned to a wavelength of 800 nm is approximately without slits or apertures of any kind, the transmittance of a resonance phenomenon makes it possible to achieve the extraordinary transmission regime without the need for additional surface texturing or grating to excite transverse surface waves, as is generally thought; the mere coincidence of longitudinal cavity resonance phenomena with appropriate slit size causes the energy to become localized inside the cavity and to be efficiently reemitted on the opposite side of the substrate. We remark that for a 200 nm thick silver substrate without slits or apertures of any kind, the transmittance of a beam tuned to a wavelength of 800 nm is approximately \(-75\) dB. For practical purposes we therefore normalize the transmittance with respect to the total energy incident on the geometrical area that coincides with the aperture.

We now extend the extraordinary transmission regime to semiconductors, and make some practical consideration in the process. Unlike metals, where the plasma frequency is in the UV-visible range, in semiconductors the plasma frequency is usually found deep in the UV range. A first superficial glance at the problem might lead one to underestimate the importance of this attempt because it may seem that we are merely reducing the wavelength below a certain threshold in order for the dielectric constant to become negative. One might thus conclude that the expected results are well understood within the ambit of enhanced transmission in metalic substrates in the optical range. In reality, there are significant issues that must be overcome, chief among them is the huge linear absorption present in semiconductors near resonance (i.e., where the dielectric function becomes negative), in sharp contrast to metals. Without prior study it is not at all obvious to know whether or not it is possible to excite longitudinal or transverse surface waves of the type discussed in Ref. 9 for metals, under the resonant conditions that are necessary to achieve either enhanced transmission or the enhancement of nonlinear frequency conversion, especially without additional surface texturing. To comfort the reader further, it is sufficient to say here that it is extremely difficult to excite a surface plasmon on a uniform semiconductor layer or half-space in the range of interest; a simple calculation will show that absorption makes it unlikely (if not impossible) for any kind of surface wave to propagate any meaningful distance on a single absorbing semiconductor layer or substrate. However, it has been shown that surface plasmons and evanescent modes can be excited and propagated through a semiconductor/dielectric multilayer stack precisely in this wavelength range. These considerations should make it clear that while we are certainly dealing with metal-like materials, semiconductors are not metals, and results that may apply to the former do not necessarily apply to the latter.

We now come to the specifics. The dielectric constant of GaAs and other semiconductors becomes negative just below 270 nm and has a large imaginary part due to the absorption resonance (see Fig. 3). At \(\lambda = 250\) nm and normal incidence, the transmittance of a single GaAs layer 40nm thick is \(-0.01\%\). In this article we demonstrate that by choosing proper slit size and layer thickness the extraordinary transmission regime can be achieved, despite the presence of large absorption. Extraordinary transmission is thus achieved through a combination of surface waves that converge toward the aperture and field localization inside the nanoslits that give us a glimpse of a new useful wavelength regime in semiconductors for both linear and nonlinear processes. In this regard, in contrast to metals, which do not have an intrinsic quadratic nonlinear term, nonlinear interactions in semiconductors are mostly driven by a \(\chi^{(2)}\) contribution, although under the right circumstances surface phenomena may compete and acquire some importance. It follows that the bulk nonlinear response of semiconductors has a different behavior relative to metal apertures, as the geometrical parameters of the slit are varied. We will explore the nonlinear optical properties of apertures on semiconductor substrates separately.
II. LINEAR RESPONSE OF A SINGLE SUBWAVELENGTH SLIT CARVED ON A GaAs SUBSTRATE

We consider a single layer of a GaAs having the linear dispersion profile taken from Palik’s handbook of optical constants,13 and having thickness $w$ and an aperture of size $a$ (Fig. 4). The variation in these two geometrical parameters is examined in order to enhance or maximize linear transmittance. All calculations reported below were performed using two different techniques to make sure the physics is modeled correctly, by solving directly Maxwell’s equations using an in-house finite-difference time domain (FDTD) method and a time-domain fast Fourier transform beam propagation method (FFT-BPM).14 For both numerical methods we considered a Gaussian-shaped incident field tuned at $\lambda$ = 200 nm. As depicted in Fig. 5, we considered three different values of $a$, which are smaller than the operating wavelength ($\lambda/12$, $\lambda/8$, and $\lambda/6$), and varied the thickness of the substrate from $w=\lambda/10$ to $w=\lambda$. By normalizing the transmitted field to the energy that impinges on the geometrical area behind the slit, we observed how the resonances form in nearly the same positions by increasing aperture size; at the same time the value of the transmission increases with aperture size, approaching a value of 40% when $a=32$ nm and $w=40$ nm. It is worth noting that performing the same analysis for wider slits does not alter the longitudinal Fabry–Perot-type behavior of the nanocavity, but the process becomes less interesting when the value of $a$ becomes comparable to $\lambda$; the influence of aperture size on the enhanced transmission phenomenon is relevant only if the size of the aperture is much smaller than the operating wavelength, allowing the efficient formation of longitudinal surface modes inside the hole. Once we fixed the geometrical parameters to $a=32$ nm and $w=40$ nm, we varied the incident wavelength to investigate the relationship between the extraordinary transmission regime and the dispersion peculiarities of GaAs. As Fig. 6 shows, the single slit system exhibits strong resonant behavior as a function of wavelength. The magnitude of the transmittance (blue curve - no markers, left axis) increases as the magnitude of the real part of the permittivity decreases (red curve - square markers, right axis), reaching a maximum value of $\sim102\%$ when $\lambda=240$ nm. That is to say, a little more of the energy that falls directly on the slits is transmitted, garnered via surface waves that are channeled inside the slit by resonant conditions. Figure 6 demonstrates quite clearly that the enhancement of transmission is proportional to $\varepsilon_r$ and somewhat independent of absorption (black curve, right axis). These results are counterintuitive and have no counterparts for metals. They also prove that the extraordinary transmission regime is achieved in spite of the large absorption that typically characterizes semiconductors in the UV range; in Fig. 6 maximum transmission occurs practically at the absorption resonance. As Fig. 7 shows, the slit exhibits a Fabry–Perot extraordinary transmission regime in

FIG. 4. (Color online) Sketch of the simulated structure: A subwavelength slit $a$ wide is carved on a GaAs layer $w$ thick.

FIG. 5. (Color online) Transmission coefficient of a single slit carved on a GaAs substrate; results are plotted varying the thickness of the substrate layer with slits widths $a=16$, 24, and 32 nm.

FIG. 6. (Color online) Spectral response of a single 32 nm aperture carved on a 40 nm thick GaAs substrate (blue curve - no markers); the figure reveals a resonant behavior and the dependence of the transmission process on the permittivity values of the semiconductor (red - square markers and black - triangle markers curves).
semiconductors similar to metals (compared to Fig. 2), despite the presence of large absorption. The maxima and minima of the transmission spectrum nearly correspond to the theoretically predicted values obtained using surface plasmon theory. Once the operating wavelength is determined, the geometrical analysis helps to further optimize the device in boosting the transmission well above 100% in a multislit environment. For the incident wavelength \( \lambda =240 \text{ nm} \), the effective index for the surface plasmon that propagates at the GaAs/Air interface is \( n_s \approx 1.05 \), which means that the surface wave propagates at \( \lambda_s/2 \approx 123.6 \text{ nm} \). By simply considering the slit as a Fabry–Perot cavity, one can expect the maxima of the transmission at \( \lambda_s/4 \approx 61.8 \text{ nm} \) and \( 3\lambda_s/4 \approx 185.4 \text{ nm} \). At the same time, the minimum of the transmission must occur at \( \lambda_s/4 \approx 114 \text{ nm} \). These values are obtained by neglecting the imaginary part of the dielectric permittivity of the semiconductor, which results only in a small shift in the resonant positions by less than 5 nm.

III. THE CONTRIBUTION OF SURFACE PLASMONS TO THE ENHANCED TRANSMISSION REGIME: REAL SUBSTRATES VERSUS PERFECT SCREENS

Another nontrivial aspect of the linear response depicted in Fig. 6 refers to the treatment of the material. Although metals are often treated as perfect conductors, significant differences exist between nanocavities modeled either as PECs or with realistic, causal parameters. PECs are usually reported in the literature as being a good reference point. The reality is that an accurate analysis of transverse and longitudinal field profiles inside the resonant nanoslit reveals that in the wavelength range of interest, field amplitudes can vary by several orders of magnitudes. The large discrepancies and their different nature via specific boundary conditions can give rise to the formation of hot spots inside the aperture that would go unobserved were one to use a PEC model. The Fabry–Perot-type behavior of these nanocavities may be altered significantly by introducing a realistic dielectric permittivity; by imposing a PEC condition one artificially forces a certain dynamics and boundary conditions that void the formation of surface waves that penetrate inside the material, changes the effective dispersive properties that the wave experiences along with field localization properties inside the nanoslit, and may ultimately render the enhanced transmission regime unachievable. Conditions that force the fields to
zero at the surface of an ideal conductor may be appropriate for metals in the microwave regime but quite unrealistic and inappropriate for both metals in the visible and near IR ranges and semiconductors in the UV range in both linear and nonlinear contexts. So serious questions can arise about qualitative and quantitative aspects of the interaction for a PEC compared to the realistic conditions that one should instead examine, and that may culminate with significant field enhancements near and around the nanoslit and the enhanced transmission process. Moreover, the smaller the aperture is, the stronger the contribution of surface plasmons will be to the transmitted fields and to the differences between a real material and a PEC; as depicted in Fig. 8, plotting the transmission value for a slit of variable size in GaAs (blue curve, left axis) and in a PEC (red curve, left axis) is quite evident that the enhancement factor (black curve, right axis) decreases when the aperture size is increased, yielding a value of $\sim 1.5$ for apertures comparable to the incident wavelength. By looking at Fig. 8 one could also infer that an enhancement of $\sim 1.5$ is guaranteed by the formation of surface waves on the wall alone, while this enhancement could be boosted significantly when field penetration is allowed to take place and for close walls to interact (apertures smaller than 60 nm or so). As proof of the fact that fields are pushed to assume different shapes and amplitudes inside the nanocavity, thanks to the contribution of the actual permittivity data; in Figs. 9 and 10 we report the calculated magnetic and electric fields, and the transverse Poynting vector for both screen types. These figures highlight how the formation of surface waves inside the slit not only contributes to their shape but also to their intensities, which is more than three times larger for the magnetic field (Fig. 9) and two order of magnitude greater in the real material for both transverse components of the Poynting vector and electric field (Fig. 10).

IV. MULTIPLE APERTURES

As it was demonstrated for resonant silver substrates, the overall transmittance can be much higher in a multislit system, thanks to a combination of the formation of surface waves that can constructively interfere between neighboring apertures and properly chosen substrate thicknesses. However, given the highly absorbing nature of GaAs, similar enhancement is not guaranteed a priori in our present system. Since slit size and substrate thickness are fixed to maximize the transmission process, for simplicity here we report only the dependence of transmittance as a function of slit separation. As depicted in Fig. 11, for $\lambda = 240$ nm, two similar slits having a center-to-center distance of $\sim \lambda / 3$ (to be contrasted with $\lambda / 2$ for silver) yields a transmittance of $\sim 147\%$. However, unlike silver, the improvement is not preserved for large number of slits. While silver shows a small increase and saturation in the transmission coefficient beyond a few apertures, the large imaginary part of the dielectric function of GaAs frustrates the transmission process as the number of slits increases (Fig. 12).

V. CONCLUSIONS

We have demonstrated that it is possible to achieve extraordinary transmission of light in the UV and soft x-ray ranges by exploiting the negative value of the dielectric per-
mittivity of semiconductors, in spite of large absorption values. For certain geometrical parameters and excitation wavelengths we demonstrated the possibility of achieving a transmittance of $\sim147\%$ for a double slit system, thanks to the coupling of surface waves inside subwavelength sized apertures. For GaAs we find a transmission maximum near the absorption resonance, at $\sim240$ nm. Together with the improvement of the linear process we also predict (but will report separately) direct correlations to the enhancement of nonlinear interactions, just as occurs for the metal substrates, albeit with different qualitative aspects with respect to the metal, in this case due to the presence of a bulk nonlinearity.

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