Thermal Infrared Plasmonics
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Abstract

We examine a new class of infrared (IR) plasmonic devices that convert thermal radiation into bound surface plasmon polaritons (SPP’s). The coupling of these SPP’s into nanometer scale metal insulator metal (MIM) channels is investigated both theoretically and experimentally. A new mechanism for detection of the IR radiation is examined that is based on direct rectification of a traveling MIM surface plasmon mode.

1 Introduction

Recently, metamaterials in the thermal IR have become an active area of research, where the goal is to control scattering or emission of thermal radiation through the use of metal/dielectric resonant subwavelength 2D and 3D structured surfaces [1,2]. Resonant scattering from these metamaterials arises directly from strong interaction of the incident electromagnetic wave with surface confined electromagnetic modes, called surface plasmon polaritons (SPP’s). Controlling the coupling to [3] and interaction with these modes can lead to new active and passive IR emissive devices [4].

The thermal or long wave infrared (LWIR) portion of the electromagnetic spectrum corresponds to a wavelength range from 8-12 microns. Many applications, such as thermal imaging, IR spectroscopy, and waste heat energy recovery exist in this spectral range and efficient detection and conversion devices can be fabricated using advanced materials and processing. As expected, the photon energies in this portion of the spectrum correspond to thermal energies that are on the order of 25 -100 meV, and photodetectors based on photon absorption often require cooling to reduce the thermal noise background. New detection schemes based on efficiently confining IR radiation to nanoscale regions may lead the way to new uncooled IR conversion devices based on rectification rather than direct absorption. Therefore, we examine the possibility of confining IR radiation into quantum scale gaps where tunnel rectification enables direct conversion of displacement currents into DC current.

Surface plasmons polaritons are bound electromagnetic modes that occur at metal dielectric interfaces and correspond to polarization waves of the free electron density in the metal that propagate along the metal dielectric interface. They strongly confine light at metal dielectric interfaces and typically are associated with the visible frequency range, where most metals have plasma frequencies in the UV-visible portion of the spectrum. At longer wavelengths, in the LWIR, the Drude model for a metal’s complex permittivity implies that the real permittivity becomes very large and negative while the imaginary permittivity is large and positive. For example, Au has a complex permittivity at a wavelength of 10.6 microns, \( \epsilon_r = -4506 \) and \( \epsilon_i = 1618 \), as compared to \( \epsilon_r = -22 \) and \( \epsilon_i = 0.75 \) at 800 nm. In this regime the surface plasmon spatial decay from the metal dielectric interface is quite large and the ability to strongly confine the light at a metal dielectric interface is reduced. Various means exist to confine the surface plasmons at the surface, one can change the plasma frequency by changing the free carrier concentration through doping, change the index of refraction of the dielectric by using a high index media, or by utilizing material resonances. Alternatively, we can confine the light well below the diffraction limit if we can couple into a metal insulator metal waveguide.

The SPP coupling of IR radiation to a nanoscale gap is shown schematically in Fig. (1) A, where we show the basic coupling geometry. Two regions are shown, a single interface region (left) and the MIM gap region (right). A single interface plasmon is incident from the left onto the MIM gap. The theoretical coupling efficiency in this geometry has been examined and can be obtained by a modal expansion in the single interface and the metal insulator metal (MIM) gap region [3]. The boundary conditions at the interface between the MIM and the single interface plasmon region
Figure 1: A) Schematic of single interface plasmon coupling to MIM SPP. B) Simulation of a planewave at 10.6 microns normally incident on a grating with a buried MIM channel with a 5 nm gap between the metal plates. C) Expansion of MIM gap region illustrating propagating MIM surface plasmon mode.

give the reflection and transmitted power in terms of mode overlaps and we can compute the conversion efficiency from the single interface plasmon to the MIM gap mode. In order to examine the coupling of IR SPP’s to a nanometer scale MIM gap mode (5 nm gap), we need to efficiently convert the incident IR radiation into single interface SPP’s. This is accomplished by using a sub-wavelength Ge grating to convert the normally incident 10.6 micron planewave into bound SPP’s propagating on the metal interface. Fig.(1) B-C) shows the electric field normal to the interface. A MIM gap SPP is clearly seen to couple into the channel. Mode matching analysis and electromagnetic simulations indicate that the coupling into the MIM gap SPP mode is between 7-10%. The coupling is very large considering the ratio of the free space wavelength ($\lambda = 10.6$ microns) to the MIM channel gap ($d = 5$ nm) is approximately 4 orders of magnitude.

Figure 2: A) Schematic of MIM gap test structure, where MIM is Pt/MgO/Al device. CO$_2$ laser spot size is overlayed on the grating. B) grating reflection versus wavelength and grating duty cycle C) SEM of thick, large area Ge grating. D) Measured FTIR of fabricated MIM grating coupler.

Fig. (2) shows the fabricated coupling test structure which consists of a large area Ge grating coupler with peripherally located MIM gap structures. The test structure is designed to operate under 10.6 micron illumination and the MIM diodes act as SPP sensors when the SPP propagates into the MIM diode channel. The launching of the single interface plasmons is readily seen in the FTIR spectrum shown in Fig. (2) D) where we see that the unpolarized FTIR reflectance drops to 50% indicating coupling of TM polarization into SPP mode.
MIM-High-resolution TEM image

Figure 3: TEM cross-section of Pt/MgO/Al MIM tunnel diode. The MgO film is seen to be conformal even over the extreme topography of the Pt metal substrate.

Figure 4: A) Schematic of FSS absorber structure. B) SEM image C) Simulated polarization averaged reflection of FSS absorber as a function of wavelength and angle of incidence. D) Measured polarization averaged reflection from FSS absorber.

The electrical detection of the MIM gap SPP mode has been seen as a weak shift in the IV characteristic as a function of the input IR power. This shift in the IV characteristics results from the MIM channel acting as a rectifying tunnel diode for the MIM gap SPP mode. Currently, the main issue with detecting this IV shift has been due to the fabricated quality and yield of our MIM channel tunnel diodes. Fig. (3) shows the TEM cross-section of a Pt/MgO/Al MIM structure. The Pt substrate is seen to have considerable topography in the form of metallic points or asperities. These asperities localize the field and become failure points for the diodes. The metal asperities also effect the MIM SPP mode propagation in the metal channels giving rise to additional loss through scattering. To address these issues, a new MIM test structure is currently being fabricated that is designed for smooth interfaces and allows for engineering of the SPP dispersion. These new MIM SPP devices will eliminate these issues and allow for a greatly enhanced electrical response to the traveling MIM SPP mode.
The conversion of IR radiation into single interface SPP modes has been performed using a simple grating coupling scheme. It is possible to improve the bandwidth, area and angular coupling using a specially designed frequency selective surface (FSS) absorber. Fig. (4) shows an example of such a large area absorber. The square loop FSS above a ground plane efficiently converts IR radiation into bound SPP modes and is nearly independent of polarization and angle of incidence.

2 Conclusions

Our main focus has been the conversion of free space IR radiation into a single interface SPP’s and its coupling into MIM gap SPP’s. The strong confinement of the single interface SPP at the metal dielectric interface enables a surprisingly large coupling of IR radiation into a 5nm gap MIM. At the gap length scales considered, $d < 10$ nm, we achieved extreme light concentration of $d/\lambda \approx 10^3 - 10^4$ in our MIM structures with power coupling efficiencies of $7 - 12\%$. Our new engineered IR plasmonic surfaces should improve the coupling by greater than $2\times$ and at gaps below 10 nm, SPP enhanced tunneling should occur in our MIM structure owing to the high electric field in the gap. Many new and interesting phenomena are expected to arise when light is confined to the quantum scales.

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4 References