Silicon-Based Plasmonic Nanoantennas at mid-infrared for Gas Sensing Applications

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***Abstract*— Advanced nanotechnology especially CMOS technology- enables us to re-design the classic antenna in the nanoscale, which can convert propagating optical wavelengths instead of radio and microwave wavelengths into localized energy and vice versa. As a result, sensors may be designed to make sensing molecules with their characteristic vibrational transitions easier. Bowtie silicon nanoantennas are investigated in this work. When silicon with high excess carrier concentrations is used as the material of choice, the enhancement occurs in the mid-IR (MIR) spectral range, which is red-shifted when compared to the enhancement produced when gold or silver is used. Varying the substrate material and associated resonance wavelength influences the localized electric field.**

I. Introduction

Plasmonic nanoantennas have attracted the interest of researchers over the last decade due to the promising applications based on them, such as photodetection, solar cells, sensing, and integrated optical systems [1, 2]. Several plasmonic nanoantennas have been extensively investigated, including nanorod, bowtie, log-periodic, and Yagi-Uda [2-4]. Plasmonic nanoantennas may operate in both excitation (receiving) and emission (transmitting) modes [5]. When nanoantennas are excited by a light beam in the excitation mode, the incident field causes collective oscillations of electrons defined as localized surface plasmons (LSPs).

Several researchers have used (LSPR) to achieve several orders of magnitude enhancement in the localized field of metallic nanoscale structures. Doped Silicon has been used here to build nanoantennas in an attempt to mimic plasmonic phenomena reported in metallic nanostructures and achieve comparable enhancement shifted to the MIR spectral region rather than the visible range [6].

To develop a nano gas sensor employing CMOS technology, the (LSPR) and the distinctive fingerprint of each gas in the MIR range can be utilized. LSPRs are responsible for enhancing the electric field on the nanoparticle surface while maintaining the optimal conditions of a narrower resonance linewidth, allowing for the detection of even minor shifts produced by gas [7]. The MIR region gives a superior opportunity for identifying various gases that has the highest absorption on MIR. Furthermore, the absorption peaks influence the overall transmission pattern of the system, and the gas could be easy to identify.

II. Design and Material

The bowtie nanoantenna is made from silicon with a high concentration of doping which behaves similarly to plasmonics. The investigated bowtie nanoantenna depicts in Fig. 1 has the following geometry, for a bowtie pole, a square extent of 222.5 nm in the *x* and *y* directions is used, with a gap (*g*) of 30 nm. The bowtie structure is placed on top of a silicon (Palik) substrate with infinite dimensions.

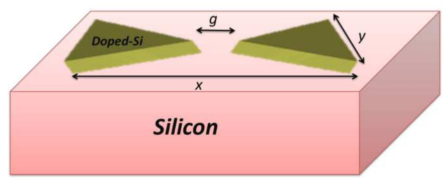

Figure 1. Doped silicon nanoantenna schematic of bowtie shape.

The most realistic high-doping concentration is selected to obtain plasmonic frequency in the MIR range, which corresponds to the shortest wavelength. The Drude model for permittivity is used to define doped silicon as in equation (1):

$$\varepsilon_m(\omega) = \varepsilon_\infty - \frac{\omega_p^2}{\omega^2 + j\omega\Gamma} \qquad (1)$$

Fig. 2 shows the material dispersion of doped silicon used in the bowtie structure that has a relative permittivity of $\varepsilon_\infty = 11.7$ F/m, the plasma oscillation frequency of $\omega_p = 2.474\times10^{15}$ rad/s, and the plasma collision frequency of $\Gamma = 9.456\times10^{9}$ rad/s for doping concentration of 5×10^{20} cm^{-3}.

III. Results and Discussion

The material dispersion of doped silicon was investigated, and the 3D Finite Difference Time Domain (FDTD) was used to predict the existence of plasmonic resonance enhancement in the case of doped Si.

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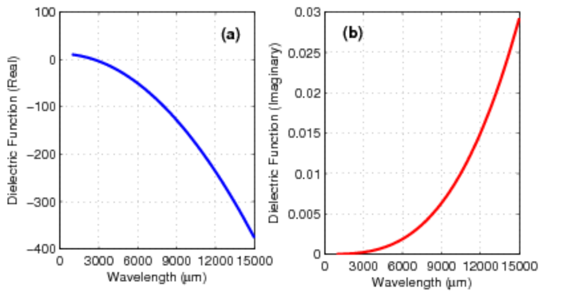

Figure 2. Material dispersion of doped silicon (5×10^{20} cm^{-3}), (a) real part and (b) imaginary part.

The normalized intensity of the bowtie nanoantenna on silicon substrate increases by approximately 16621.4 when a localized field is detected in the 30 nm gap, with a narrow peak centered at 7.57388 µm in the (MIR) region, as shown in Fig.3 (a). The XY field profile of the proposed bowtie dielectric nanoantenna at a 30 nm gap is shown in Figure 3(b). The field profile is enhanced due to the large excess electron concentrations of the doped silicon, and the highest intensity enhancement is reached at around 7.5 µm, as seen in this figure.

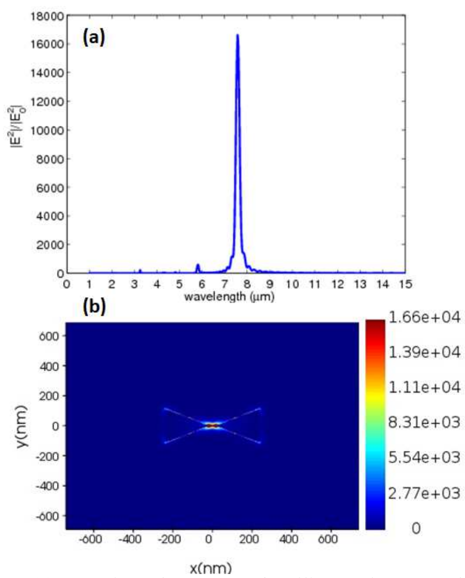

Figure 3 (a) Intensity enhancement for silicon substrate and (b) its field profile field.

Bowtie nanoantenna designs using various dielectric substrates, such as Si, SiO_2, Al_2O_3, and TiO_2, are also modeled in our calculations as in Fig. 4. The SiO_2 substrate improves field intensity and shifts the narrow peak to 4.48273 µm which is appropriate for sensing applications rather than the Al_2O_3 substrate that exhibits multiple peaks. The enhancement of the TiO_2 substrate is lower than Si, and it has two extremely close-together peaks, which might produce a sensing conflict.

Gap lengths vary from 15 nm to 35 nm, with a 5 nm increment. As can be observed in Fig. 5, such spectra obey this law: an antenna design with a narrower gap exhibits higher light intensity. Nanoantennas with a separation gap of 15 nm have a substantially higher intensity at resonance than those with gaps of 20 nm to 40 nm. This high value of around 6.5×10^4 is obtained with a gap of 15 nm. Moreover, the field enhancement curve shows two resonance peaks with a separation gap of 20 nm.

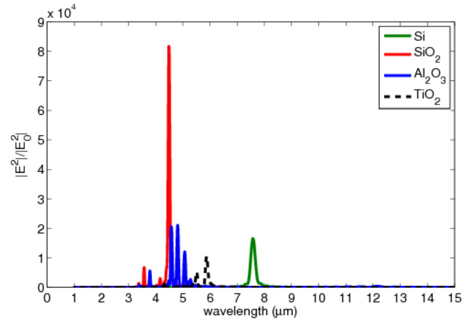

Figure 4. Gap effect on intensity enhancement of the doped Si nanoantenna.

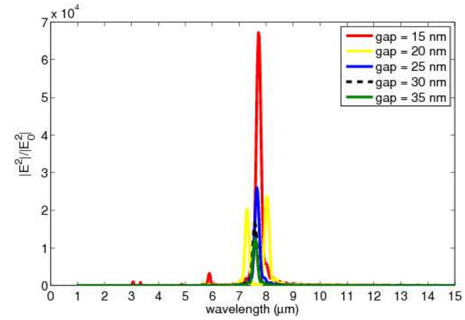

Figure 5. Gap effect on intensity enhancement of the doped Si nanoantenna.

IV. CONCLUSION

The purpose of this study is to develop silicon-based nanoantennas that exhibit Localized Surface Plasmon Resonance (LSPR) in the same manner that plasmonic metal nanoantennas operate. The material dispersion of doped Si with a 5×10^{20} cm $^{-3}$ concentration demonstrates a change in the optical response of the doped Si, allowing plasmonic resonance to occur at MIR region.

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