Highly sensitive gas sensor using plasmonic antennas

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Introduction

Localized Surface Plasmon Resonance (LSPR) is used for chemical gas sensing. In this technique, we measure the change in the resonance frequency of the dipole w.r.t change in the concentration of the gases. Propagating SPR has been used in the past for gas sensing purpose but it involves moving parts and so it is difficult to make a portable device based on propagating SPR.

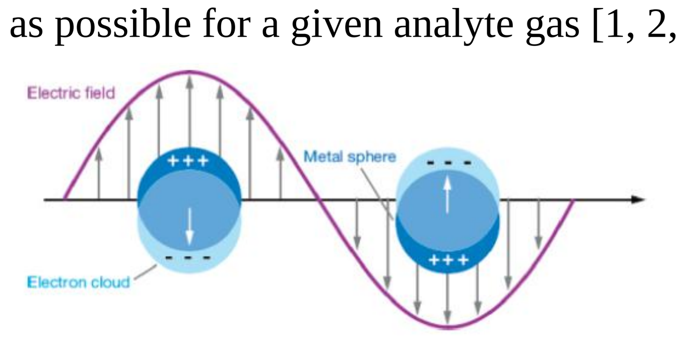
Background

Presently used sensor, face the challenge of successfully exhibiting high sensitivity, selectivity, ease of operation and portability. They need on chip heater for operation or need external stimulus like UV exposure for operation. This makes the device design and operation complicated.

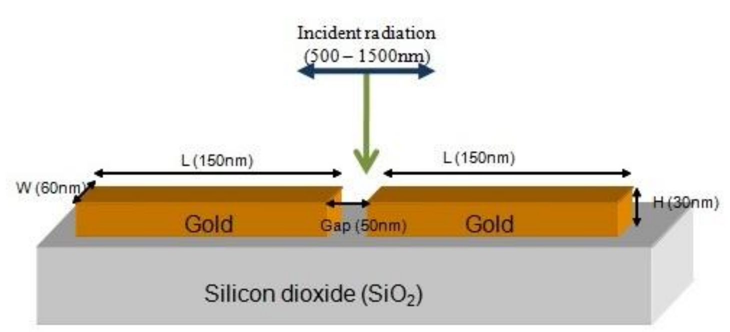
However, in this work, we use metal nano particles (MNP) exhibit plasmonic behavior at visible frequencies. The plasmonic resonance frequency is dependent on the shape, size, material and the dielectric constant surrounding , the MNP. Shift in the resonance wavelength is dependent on the characteristics of the device such as the bulk sensitivity (m) and the exponential field decay (l_d).

$$\Delta\lambda = m(n_{analyte} - n_{air})\left(1 - e^{-2d/l_d}\right)$$

By increasing the bulk sensitivity, m, to be as high as possible and exponential field decay length, l_d, to be as small as possible, we can the shift to be as high as possible for a given analyte gas [1, 2, 3].



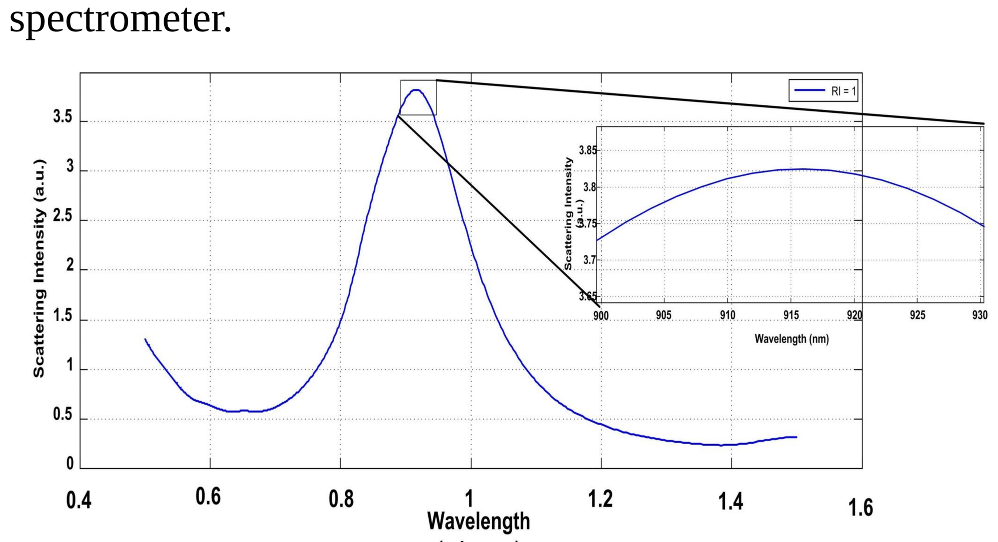
Device structure used



Dipole structure used for simulation

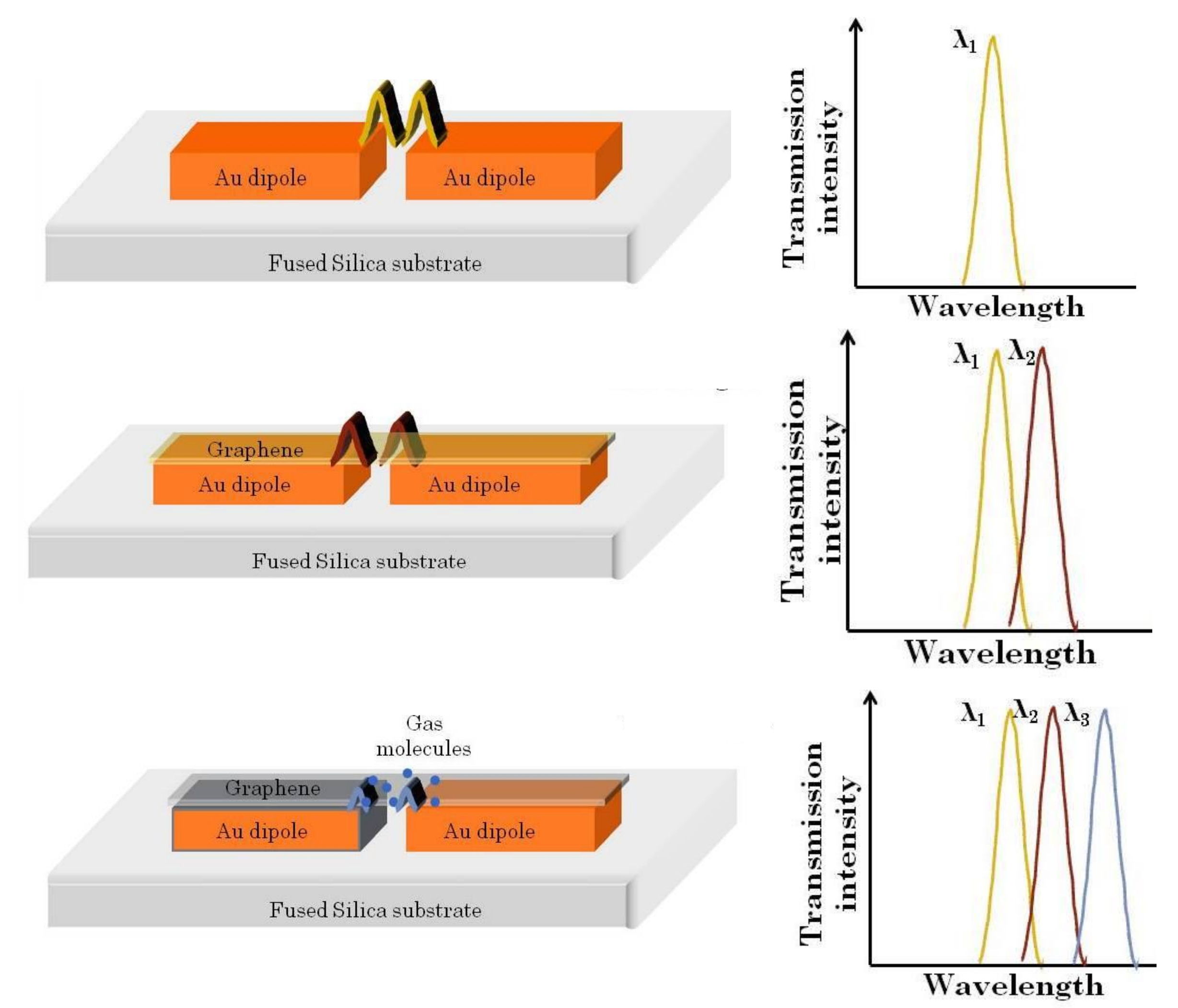
A dipole nano antenna structure. The cavity between the the two dipole arms makes the electric field stronger and more confined. Any changes in the electric field within the cavity of the dipole nano antenna results in the shift in the resonance frequency of the dipole nano antenna.

Gold was the most suitable material with the length, width, thickness and gap of 150nm, 60nm, 30nm and 50nm respectively. The bulk sensitivity calculated for the above structure is 450nm/RIU (Refractive Index Units). This value is more than any other plasmonic sensors used presently. Additionally, the resonance frequency lies in the range of the optical spectrometer.



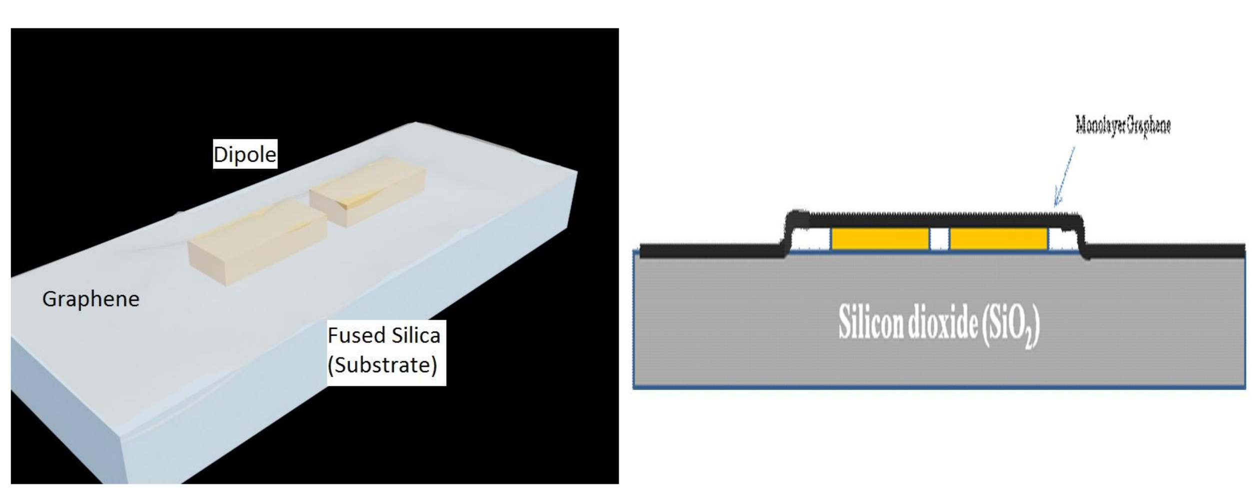
Graphene loaded dipole nano antennas

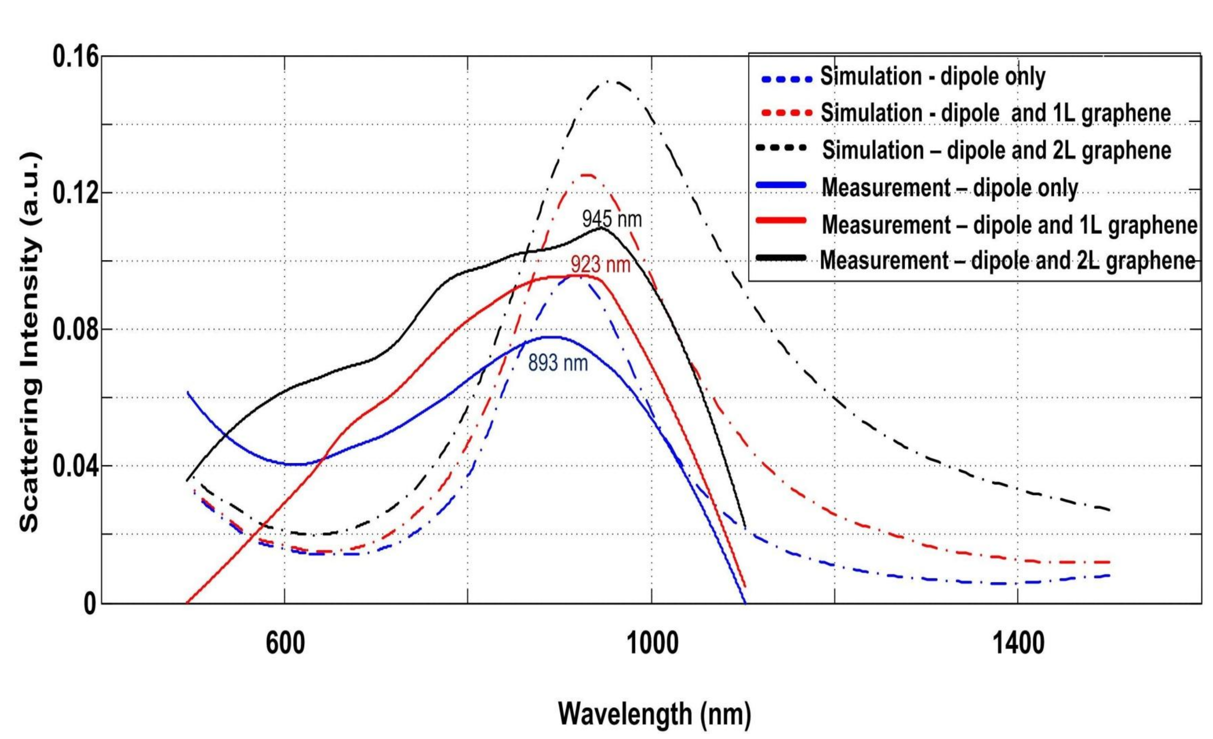
Graphene is a 2D one atom thick sheet of carbon and has a very high surface to volume ratio. It absorbs only 2.3% of the incident light and does not generate plasmons in the visible spectrum. Graphene model is used from ref. [4]. Carbon based sensors (CNT and graphene) have demonstrated very high sensitivity in sensors (in the range of .1-10ppb) for different molecules using conductance change. However, when selectivity is introduced by functionalization, sensitivity drops down in the ppm range. In the proposed sensor, this challenge is overcome because no conductivity measurements are performed [5, 6] .



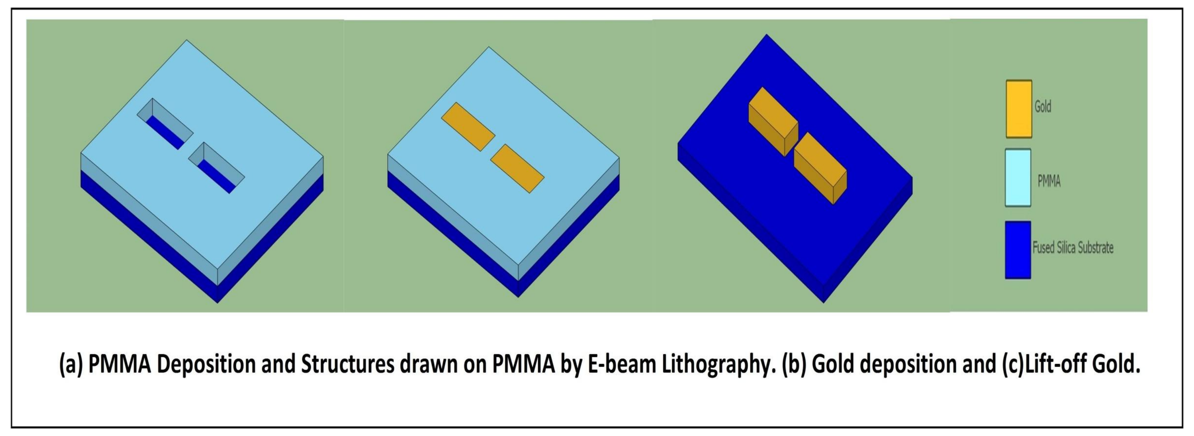
Simulation and Experimental Results

Simulations for the device model were performed using the Finite Difference Time Domain (FDTD) tool from Lumerical Inc. Simulation were performed for bare dipole, dipole loaded with monolayer graphene and with bilayer graphene.

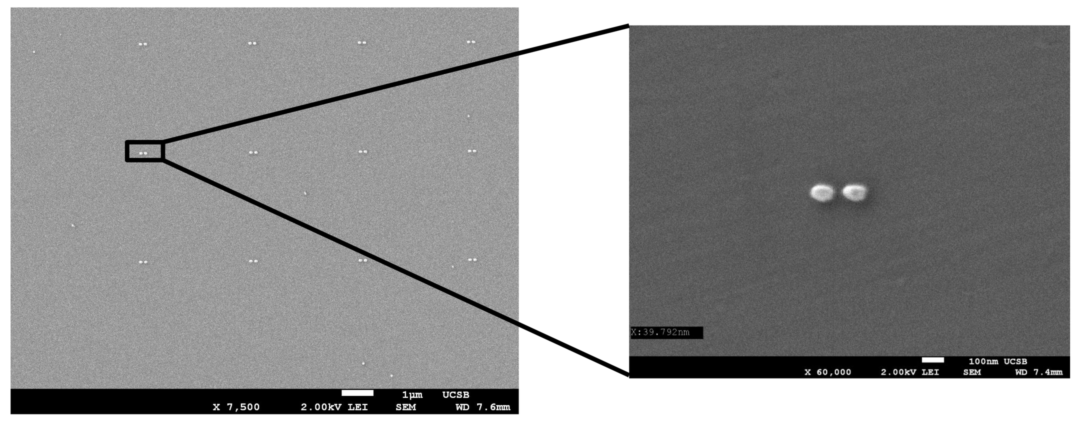




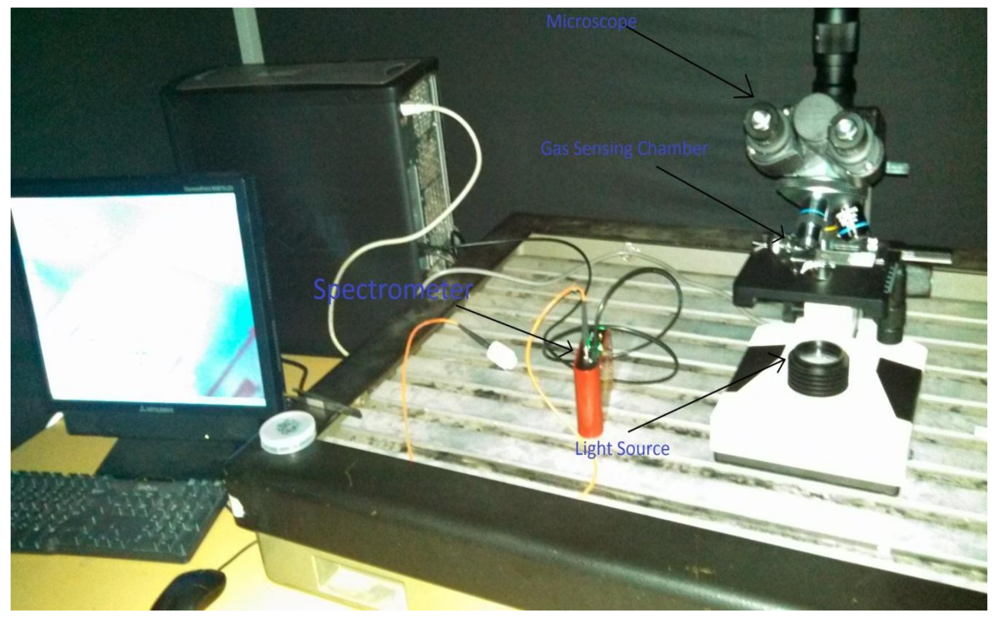
Fabrication Process



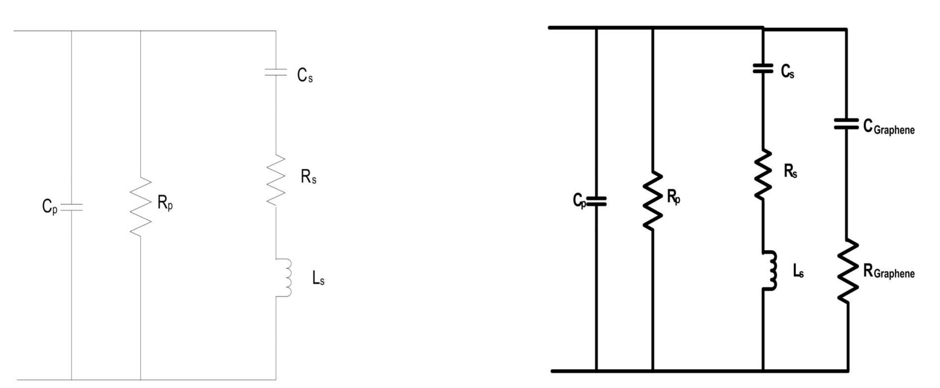
(a) PMMA Deposition and Structures drawn on PMMA by E-beam Lithography. (b) Gold deposition and (c)Lift-off Gold.



Measurement setup and Results



Equivalent Circuit



(a) Equivalent Circuit for bare dipole

(b) Equivalent circuit for graphene covered dipole

Equivalent circuit is based on the concepts discussed in [7, 8]

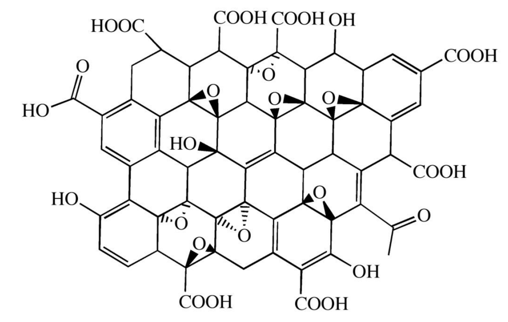
Sensitivity and Selectivity

Sensitivity for the device is dependent on the bulk sensitivity (m) and the exponential field decay length (l_d). In order to determine the sensitivity of the device, we compare it with the recently studied in the literature [9].

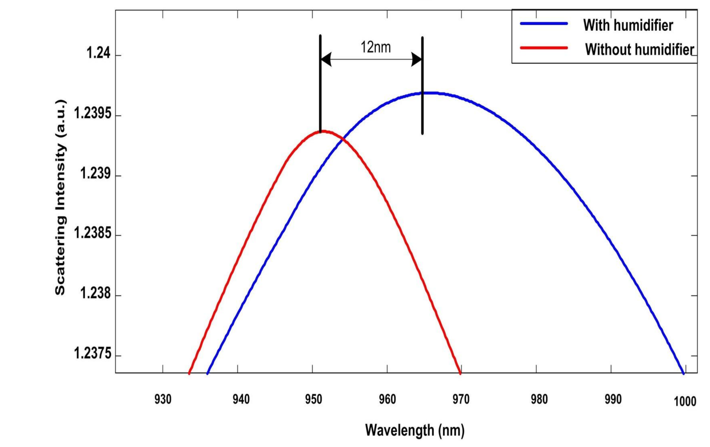
	Literature	Proposed dipole
Bulk Sensitivity (nm/RIU)	185 – 275	**460-700**
Exponential field decay length (nm)	6	**8**
Sensor sensitivity (for ethanol)	10ppb	**<2ppb (Expected)**

Selectivity can be introduced by functionalization of the graphene/graphene oxide. Graphene oxide has –OH and –COOH molecules, which can be replaced with other functionalized molecules. Sensitivity can be further improved by in-situ UV cleaning of the graphene/graphene oxide [10].

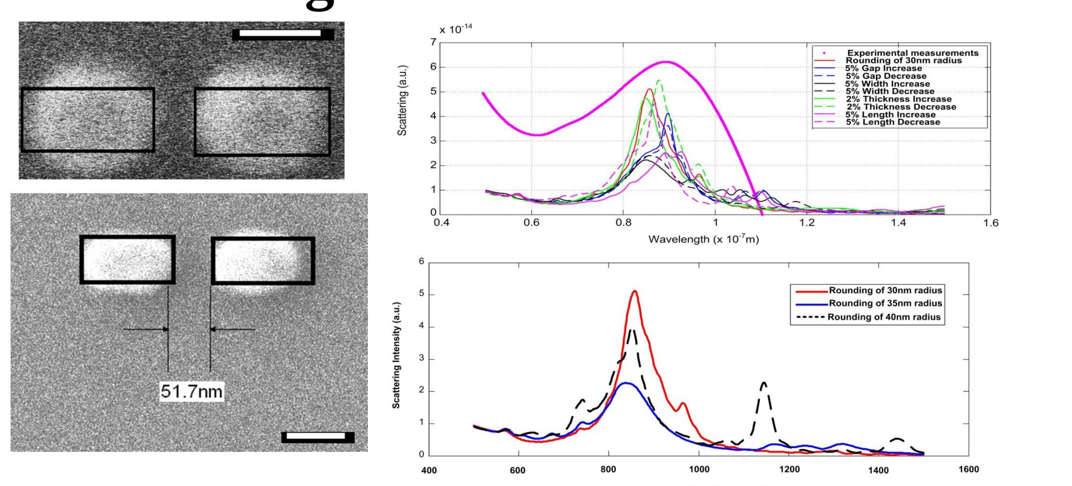
The sensor can be functionalized for different analytes. As no conductance measurements are involved, functionalization does not affect the sensitivity.



Water Vapor test



Rounding and fabrication effects



Summary

In this work, a highly sensitive gas sensor with sensitivity in the range of .1-10ppb is proposed. This sensor has ultra-sensitivity along with very high selectivity because of the functionalization of graphene/graphene oxide and also because of the intrinsic selectivity characteristic of plasmonic nano antennas. This device can be packaged as a portable device and needs minimum components for operation (Regular white light LED and a photodiode). The fabrication cost of the device is very low.

Publications

1. Mehta, B.; Zaghloul, M.E., "Tuning the Scattering Response of the Optical Nano Antennas Using Graphene," *Photonics Journal,IEEE*, vol.6, no.1, pp.1, 8, Feb.2014 doi:10.1109/JPHOT.2014.2300501
2. Mehta. B, Zaghloul. M; "Plasmonic Antennas based Gas sensor using Graphene", ISDRS 2013.
3. Mehta. B, Zaghloul. M; "Tuning Nano antennas with Graphene", IEEE International Symposium on Antenna and Propogation 2013, Orlando USA. (**Best student paper finalist**)

References

1. Stewart, M. E., Anderton, C. R., Thompson, L. B., Maria, J., Gray, S. K., Rogers, J. A., & Nuzzo, R. G. (2008). Nanostructured Plasmonic Sensors, 494–521.
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3. Mario Agio and Andrea Alu. Optical antennas. Cambridge University Press, 2013.
4. Ergun Simsek. A closed-form approximate expression for the optical conductivity of graphene. Optics letters, 38(9):1437-1439, 2013.
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6. Wenjing Yuan and Gaoquan Shi. Graphene-based gas sensors. Journal of Materials Chemistry A, 1(35):10078, 2013.
7. A Alu and N Engheta. Tuning the scattering response of optical nanoantennas with nanocircuit loads. Nature Photonics, 2(5):307-310, April 2008. ISSN 1749-4885.
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