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Optical Antenna Design for Nanophotodiodes

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Abstract: Guidelines for designing an optical antenna for optimizing the performance of a nanophotodiode are proposed. A nanopatch design is simulated with over 70% absorption efficiency using germanium as the absorber.

I. Introduction

Nanoscale photodetectors offer many benefits for optical interconnect applications [1]. The low capacitance increases the photovoltage and reduces the amount of gain required, reducing the overall energy consumption of the receiver, in addition to higher bandwidth. Traditional photodiode designs are limited to micrometer-dimensions due to both the diffraction limit for focusing light and the absorption length of the semiconductor material [2]. In recent years nanostructured metal has been used to greatly enhance optical intensity orders of magnitude larger than that of the incident light [3]. While there have already been several attempts to utilize optical antennas for enhancing the efficiency of normal incidence nanophotodiodes, the reported efficiency has been below 0.1% in all reported cases [4-6].

In this paper, we have derived a systematic approach to optimize optical antenna design and achieve high efficiency nanophotodetectors. Using coupled mode theory (CMT) for antennas [7], we show that maximum absorption efficiency as high as 72% can be achieved in a germanium absorber embedded in a nanopatch antenna.

II. Antenna Design

In the CMT picture of the antenna-coupled photodiode, there are several sources of radiation loss including re-radiation via the antenna, Q_{rad}, absorption by the metal structure of the antenna, Q_{metal}, and absorption by the semiconductor itself, Q_{semi}. From the theory we learn that maximum power transfer occurs when $Q_{rad} = Q_{abs}$, or when the absorption and re-radiation rates are equal. We can also calculate the expected efficiency of the power absorbed by the semiconductor over the power absorbed by the entire structure, and get the following.

$$\eta = \frac{P_{Semi}}{P_{Abs}} = \frac{1}{\frac{Q_{Semi}}{Q_{Metal}} + 1}$$

This states that the efficiency can approach 100% given the appropriate ratio of Q values in metal and semiconductor. These Q values depend on both material Q and the confinement of electromagnetic energy within each material in the structure. To optimize absorption in the semiconductor, the radiation and absorption Q values should be matched and the electric field should be strongly confined within the semiconductor away from the metal.

III. Analysis of Dipole and Patch Geometries

Both the previously reported dipole antenna and our nanopatch geometry are simulated using FDTD software CST Studio. The geometries are seen in Fig. 1a-2a, were simulated using both gold and silver Drude models with parameters taken from Johnson and Christy [9], and using germanium as the absorbing material for the photodiode. Both structures were made to be resonant at 1.5µm wavelength. The Q values for radiation and absorption were calculated by fitting the ringdown curve of the cavity, and by successively adding material loss into the system. There are two important factors to achieve high efficiency nanophotodetectors: (1) Q_{abs} and Q_{rad} should be matched to achieve maximum power transfer; (2) $Q_{semi} << Q_{metal}$ to minimize optical loss in metals. We have simulated two optical antenna structures in detail. With the dipole structure (Fig. 1), Q_{abs} (=26.6) and Q_{rad} (=14.9) are not well matched, meaning the antenna does not provide good power transfer to the semiconductor. Secondly the metal Q (=26.5) is much lower than the germanium Q (=344.5) meaning much of the absorbed light is being absorbed by the gold than by the germanium, leading to the calculated efficiency of 5%. The poor ratio of gold to germanium Q values is due largely to the amount of electric field in the metal compared to the amount in the germanium. Even with a lower loss metal such as Ag, the maximum absorption efficiency in Ge is still limited to 19%. An ideal structure should have high confinement factor in the semiconductor. Comparatively the nanopatch antenna shown in Fig. 2 has much better efficiency with gold, 45%, due to improvements in both factors. Although the nanopatch antenna is not completely matched (Q_{rad}=34.7 and Q_{abs}=22.3), due to better field confinement in the germanium region the ratio of gold (Q_{Au}=44.3) and germanium (Q_{Ge}=44.9) Q values is much more favorable for power transfer into the germanium. The absorbing efficiency can be further increased to 75% by replacing Au with lower loss Ag. With further optimizations in the dimensions and thicknesses of the nanopatch structure this could approach even higher efficiency.

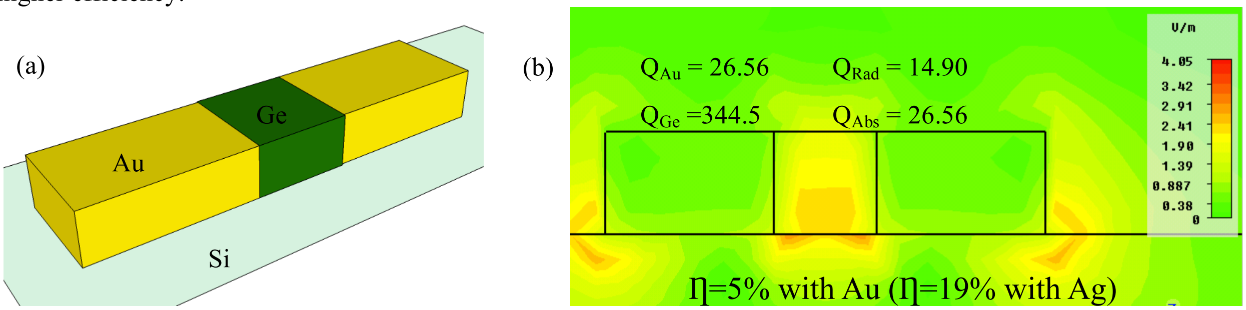

Fig. 1 (a) Schematic of dipole antenna. Gold arms are 50nm x 50 nm x 80 nm each. The germanium region is 50 nm x 50 nm x 50 nm. The structure is sitting on a silicon substrate. (b) Peak electric field and Q values from simulation.

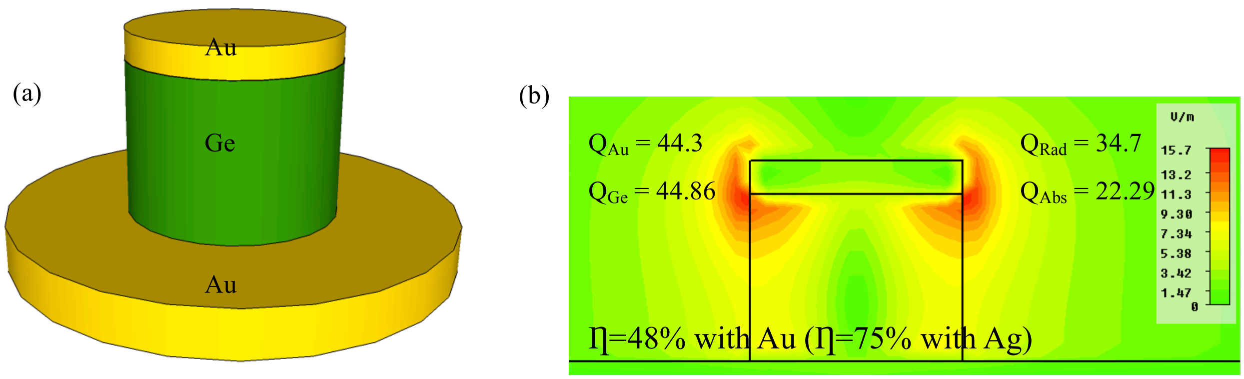

Fig 2 (a) Schematic of nanopatch antenna. The gold cap is 30 nm thick. The germanium region is 180 nm in diameter and 150 nm thick. The structure is sitting on a 100 nm thick gold film. (b) Peak electric field and Q values from simulation.

IV. Conclusion

We have used antenna CMT and applied it towards the specific case of optical antenna coupled nanophotodiodes, showing that given proper consideration of the antenna design, high theoretical efficiencies can be attained. Using the silveer nanopatch antenna geometry and germanium absorber, simulations show a photodiode with dimensions of 150 nm by 200 nm in diameter with an efficiency of 75%.

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