Graphene-coated Suspended Metallic Nanostructures for Fast and Sensitive Optomechanical Infrared Detection

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Abstract: We investigate the effect of incorporating graphene in suspended metallic nanostructures for radiation detection. We have found enhanced absorptance resulting in increased sensitivity and faster operation owing to graphene's extraordinary plasmonic and thermal properties.

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1. Introduction

Suspended metallic nanostructures are of substantial interest for potential applications in integrated optics and plasmonic sensing. These subwavelength structures demonstrate interesting properties and phenomena owing to their larger surface to body ratio. For instance, the dominant force governing the mechanics of matters sharply changes, thus allowing us to utilize the mechanical deformation of tiny features at nanoscale [1, 2]. Based on this, we had experimentally demonstrated a plasmo-thermomechanical detector with integrated bimetallic fishbone nanowire structures facilitating optical readout [3]. We designed nanostrip antennas that absorb the free-space radiation and create a thermal gradient along the suspended beam holding the antennas. The thermal gradient causes the bimetallic nanowires to deflect according to the material thermal expansion coefficients. The deflection of metallic nanowires modulates the optical insertion loss of the underlying Si_3N_4 waveguide through the evanescent coupling between the waveguide and the lossy metals. Thus, the incoming radiation is sensed through the output of the on-chip optical waveguide.

The existing designs can be further improved by using engineered graphene layers [4]. In particular, two important parameters of consideration for detectors with integrated metallic wires are sensitivity and speed. In this paper, we analyze the graphene-coated fishbone nanostructure for improved sensitivity and speed of detection. We show that graphene can enhance the radiation-induced mechanical deflection of the metallic nanowires by two orders of magnitude, while at the same time laterally dissipating the heat that allows the nanowires to quickly go back to their initial position in less than 1μs when the radiation is withdrawn. Hence, by using graphene coated plasmo-thermomechanical oscillators, it is possible to reach detectors of over 1MHz bandwidth with optical readout.

2. Design and Numerical Analysis

We employ finite-element method (FEM) to design the improved plasmo-thermomechanical transduction and sensing that can be achieved by coating graphene on different metallic nanostructures of interest. We investigate various geometries to assess the enhancement. Here, we report the cross-shaped geometry in a unit cell (inset of Fig. 1(a) - period 660nm, L=350nm, W=100nm) due to its superior performance. In particular, we study the absorptance for silver, gold, and nickel fishbones with and without graphene sheet coated on top. For electromagnetic analysis, we consider graphene to be a 2D conductive sheet in the full-wave frequency-domain solver model. At high-frequency (near-IR, ignoring the spatial dispersion) and at room temperature (T<μ_c), graphene's conductivity can be modeled by the combination of intra- and inter-band conductivity as reported before [5].

$$\sigma(\omega) = \sigma^{intra}(\omega) + \sigma^{inter}(\omega) = i\frac{2e^2k_BT}{\pi\hbar\omega}\ln\left[2\cosh\left(\frac{\mu_c}{\mathbf{2}k_B\boldsymbol{T}}\right)\right] + \frac{e^2}{4\hbar}\left[u(\hbar\omega - 2\mu_c) - \frac{i}{2\pi}ln\frac{(\hbar\omega + 2\mu_c)^2}{(\hbar\omega - 2\mu_c)^2 + (2k_BT)^2}\right] \quad (1)$$

Here, u is a step function determining the inter-band electron transition, k_B is Boltzmann constant, $\hbar$ is reduced Planck's constant, e is electron charge, T is temperature, and we assume, chemical potential of graphene, μ_c =0.45eV, a relaxation time of ~0.5ps, Fermi velocity of 9.5x10^{5}ms^{-1}, and a mobility of 9000cm^{2}V^{-1}s^{-1}. For thermal and mechanical multi-physics calculations, the solved geometry is visualized in Fig. 2(a).

3. Absorption Enhancement

The absorptances for three common plasmonic metals – silver, gold, and nickel are shown in Fig. 1 with (dashed) and without (solid) graphene coating. The incident electric field is polarized along the antenna length (y-direction). The field distribution in localized surface plasmon (LSP) resonant wavelength is shown as the inset of Fig. 1(a). As results indicate in Fig. 1, adding graphene on top of metal nanowires enhances the absorptance in the suspended structure especially at the resonance. The coupling between the metallic structure and graphene keeps the electric field confinement mostly toward the graphene side, and the interaction is stronger for thinner nanowires. Introducing graphene, the absorptance is increased by 33% for 20nm thin silver fishbones. However, as we varied the thickness of the three different metals, our study shows consistent enhancement of absorptance especially for gold and silver. These results are also consistent with the near-field plasmonic absorption enhancement in graphene-coated metallic patterns reported before [6].

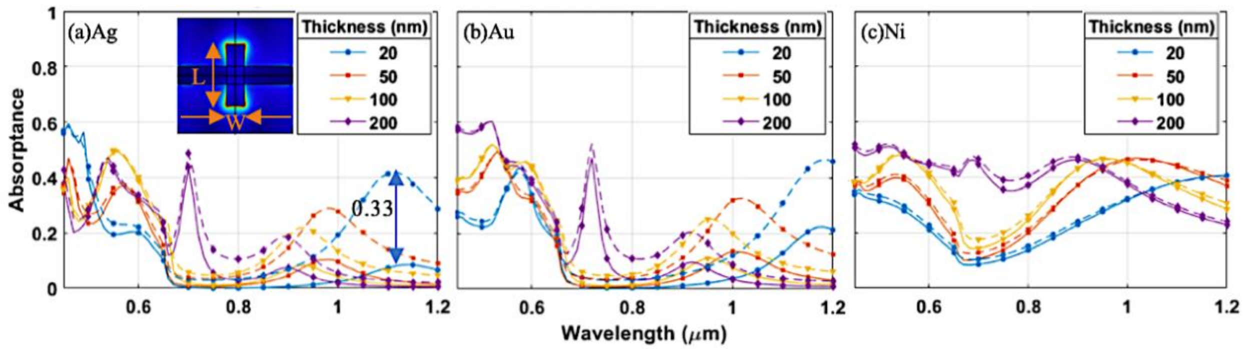

Fig 1. Absorptance of suspended fishbone nanostructures with (dashed) and without (solid) graphene coating for different metals -silver (a), gold (b), and nickel (c) of varied thickness. (a) Inset – field distribution of unit cell at resonance

4. Thermo-mechanical Analysis

The absorption enhancement reported above results in sufficient heat gradient that is required for the deformation of the suspended metallic nanowires. Previously, temperature-dependent study of bimetallic-like graphene/gold cantilevers has been done [7]. In our design, the large contrast between thermal expansion coefficients of graphene (-8x10^{-6}K^{-1}) and metals (13-18x10^{-6}K^{-1}) produces larger deflection of the beam. This in turn results in stronger modulation of the output of the underlying optical waveguide. Fig. 2(a) shows the resulting thermal gradient and mechanical displacement of suspended graphene-on-gold fishbone. The maximum deflections of 50nm-thick gold fishbone with and without graphene are found to be ~50nm and ~0.45nm, respectively, at the resonant absorption near 1μm wavelength. This shows three times improvement over previously reported gold-nickel bimetallic fishbone, which had a deflection of ~15nm [1]. It should be noted that, putting graphene on top of metals causes the suspended beam to deflect downwards when the heat gradient is created from the radiation absorption. Therefore, the metallic beam needs to be suspended high enough from the top facet of the waveguide so that any downward deflection does not result in the beam touching the waveguide.

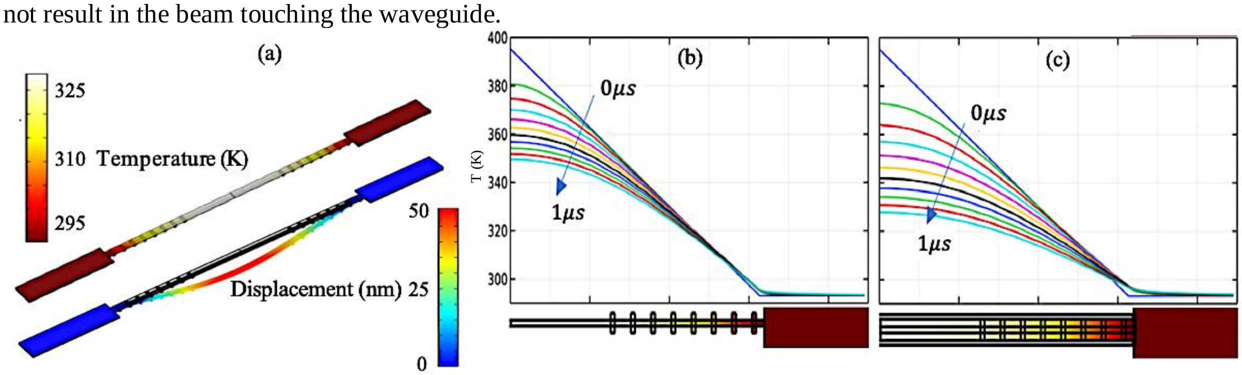

Fig 2. (a) Temperature distribution and resultant displacement of the beam due to thermal gradient. (b-c) Time-dependent cooling (half of the suspended beam is shown) of the beam without (b) and with (c) graphene sheet for a given thermal profile.

The large thermal conductivity allows graphene to quickly remove the heat from the hot-spots created by free-space radiation. This makes the integration of graphene in our device even more beneficial. The heat-spreading functionality of graphene will allow faster thermo-mechanics in the plasmo-thermomechanical detector. Fig. 2(b-c) shows the temperature distribution along the half of the suspended gold fishbone without (Fig. 2(b)) and with (Fig. 2(c)) graphene. We see that the temperature decreases much faster when graphene is coated on top of the gold. According to our simulations, bandwidth of ~1MHz and beyond could be achieved with this structure.

In summary, by coating suspended metallic nanostructures with graphene, we achieve an improvement in sensitivity caused by two orders of magnitude enhancement in mechanical deflection and a 33% increased absorption. A bandwidth of ~1MHz can be obtained using the proposed on-chip plasmo-thermomechanical infrared detector.

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