Periodic Black Phosphorene Nanoribbons Infrared Edge Plasmon Enhanced Absorbance

Desalegn T. Debu[1], Stephen J. Bauman[2], Joseph B. Herzog[1,2]
[1]*Department of Physics, University of Arkansas, 825 W. Dickson St., Fayetteville AR 72701*
[2]*Microelectronics & Photonics, University of Arkansas, 731 W. Dickson St., Fayetteville AR 72701*
jbherzog@uark.edu

Abstract: This work demonstrates enhanced infrared light absorption due to edge confined strong plasmon enhancement in anisotropic black phosphorene nanoribbons. The absorption spectra peak position of nanoribbon is tunable in a wide infrared wavelength range.

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The study of light and plasmon interactions has been conducted in many materials. Commonly noble metal film and nanostructures such as gold and silver support strong surface plasmon confinement [1-5]. The response of the plasmon in these metals is predominantly limited to the UV and near-infrared spectral range. There is motivation to push plasmonics into the infrared wavelengths so they can improve fiber-optic communication applications. However, in the infrared and terahertz ranges, the noble metal plasmons show weak confinement and very limited tunability due to high losses [4-8]. As an alternative the two dimensional materials can have plasmonic characteristics. Graphene, for example, has been used to generate surface plasmon resonances with weak loss attributed to its unique band structure and high carrier mobility [9-11]. Plasmon resonances in graphene range from the mid-infrared to the terahertz spectral regions [9-11]. Experimentally this has been achieved by controlling doping level, reducing structure dimensions, and applying a gate-modulation [12-14]. Typically, graphene is fabricated on a substrate; this dielectric environment couples to the substrate surface polar phonons forming plasmon-phonon coupling that have been described as surface phonon plasmon-polaritons [15] and splitting graphene plasmon mode into two distinct optical modes [16]. The coupling between the bulk phonons and the graphene plasmons causes damping that immensely hinders utilization of graphene for enhanced light absorption in the THz to mid-IR range [17–19]. Due to these limitations, there is need for investigation of other 2D materials to enable plasmonics in the infrared wavelength region. Recently black phosphorene (BP) has gained attention as an alternative for IR surface plasmon resonances due to its anisotropic optical nature, wide band gap, and higher carrier mobility [20]. The plasmonic property of BP shows a strong polarization dependence on the electric field of the incident light in IR region [21].

This work provides a theoretical mechanism and finite element simulation of periodic BP nanoribbons to explore the edge enhanced absorption and the plasmon resonances of these BP nanostructures. Fig. 1(a) shows the schematics of the periodic BP nanoribbons, with width W = 150 nm and period P = 250 nm labeled. The BP is in a dielectric medium with a gold reflector at the bottom surface. Fig. 1(b) shows a waterfall plot of the absorption spectra of the structures in the infrared range of 15 – 60 µm. We observe a red shift as a function of increasing the substrate's dielectric constant n_2 with the top dielectric medium held at n_1 = 1.00 (air). As the dielectric constant increases the absorbance spectrum of the primary peak, single mode, broadens. For n_2 > 2.0 the secondary peak emerges at lower infrared wavelength. For a silicon substrate (n_2 = 3.32) the secondary peak becomes dominant in the 15 – 30 µm range for both the absorbance and resonance plasmon modes. The primary absorption reaches a maximum value of 48% at n_2 = 1.43 and decreases as n_2 increases. This decrease shows weak coupling of the BP plasmon modes with the substrate optical surface phonons, damping the plasmons. Such effect can be overcome by altering the period or increasing the width of BP nanoribbon [21]. Fig. 1(b-c) shows the field enhancement distribution at two different wavelengths. The plasmons are confined at the edge of the nanoribbon [22]. For a given BP nanoribbon the confinement strength of the localized modes highly depends on the excitation wavelength.

Theoretically the peak resonance of the absorbance wavelengths are calculated solving Maxwell's electromagnetic equation treating BP layer as 2D surface with anisotropic conductivity obtained using semi-classical Drude model in dielectric interface considering the appropriate boundary conditions. For TM polarized periodic nanoribbon along zigzag or armchair direction in plasmonically active substrates, the resonance mode of wavelength shows strong dependent on dielectric medium, anisotropic effective electron mass and number density. Fig. 1(e) shows the finite element method simulation and theoretically calculated resonance wavelength of the primary modes based on the substrate dielectric constant. The resonance mode shifts linearly with increasing the dielectric parameter in the entire infrared spectrum considered in the study. First order resonance wavelength calculated analytically and finite element simulation results show strong quantitative agreement for different substrate dielectric constant.

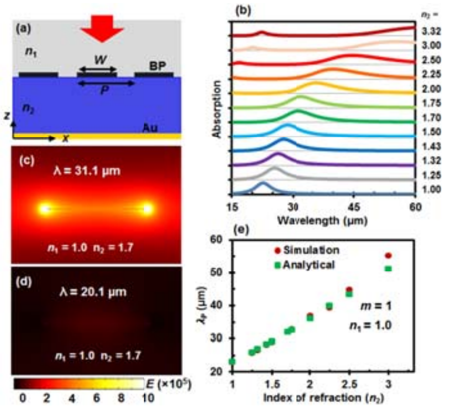

Fig. 1(a) shows schematics of the structure. The results in this figure are for a ribbon width of W = 150 nm and period of P = 250 nm. (b) Waterfall plot of the absorption spectra of the nanoribbons. (c-d) The field enhancement distribution at two different wavelengths dielectric medium with bottom surface a gold reflector. The ribbon is surrounded by air (n_1 = 1.0) on the top surface and is on a dielectric substrate (n_2 = 1.7). (e) Peak position of the plasmon resonance mode as a function of the substrate's index of refraction using both the theoretical and analytical models.

In summary, infrared light absorption is enhanced due to edge confined plasmon in anisotropic black phosphorene nanoribbons and coupling with dielectric environment. The absorption spectra peak position of nanoribbon is tunable in a wide infrared wavelength range. Findings from this study indicate black phosphorene as an alternative tunable infrared plasmonic material.

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