

Near-Infrared Photothermal Therapy Cancer Treatment Assisted With Graphene-Based Materials

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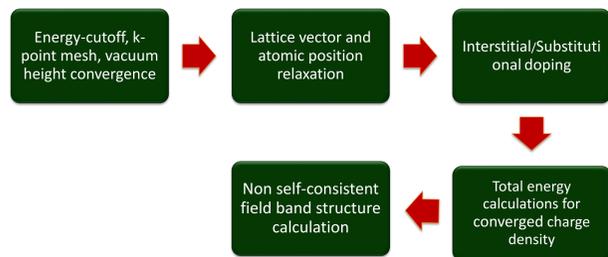
OBJECTIVE

Photothermal therapy (PTT) is less damaging and invasive among other cancer treatment methods largely due to its creative use of heat. The approach uses near-infrared light photo-absorbers as photosensitizing agents to generate heat in near-IR-irradiated cancer cells, resulting in the ablation and death of those cells. The generation of photothermal energy depends on the conversion of near-infrared light into heat by nanoscale materials. In recent studies, graphene has shown high effectiveness in in vitro drug delivery as well as in vivo cancer treatment using a near-infrared laser source. Moreover, graphene oxide can achieve better cancer cell targeting and photoablation performances at a low dosage. This indicates that graphene oxide is an effective photothermal agent with absorbance ability, comparable to that of gold nanoparticles and carbon nanotubes. However, graphene oxide's band gap is difficult to manage because the concentration and position of oxygen is difficult to control, making the efficiency of near-infrared light hard to control as well. In order to make graphene a more efficient photothermal agent, it is necessary to design new graphene based materials in accordance with the band gap of 0.3 to 0.7 eV. In this research, we used first-principles calculations to tune the band gap of graphene based materials using the method of doping with different elements. In this way, we can identify efficient graphene based materials that can be applied in photothermal therapy.

ABSTRACT

Photothermal therapy is an emerging method of cancer treatment, by which, tumors are ablated by heating agents using near-infrared light (700 to 1000 nanometers). A semiconductor with a band gap between 0.3 to 0.7 eV would efficiently emit near-infrared light. The new "magic" material graphene has zero band gap and this is advantageous to design a new material with a suitable band gap for emission of near-infrared light. In our investigations, using first-principles density functional theory calculation method, we successfully designed graphene-based materials with a suitable band gaps. This referenced material has potential to be an optimal and efficient near-infrared light source due to its narrow yet fitting band gap. The present results open up a new avenue for the application of graphene-based material to assist in photothermal therapy.

METHODS



METHODS

A. Band Structure

The 3D Bravais lattice is expressed using the real space translational vector $\vec{r}_m = m_1\vec{a}_1 + m_2\vec{a}_2 + m_3\vec{a}_3$

$$\vec{R} = n_1\vec{a}_1 + n_2\vec{a}_2 + n_3\vec{a}_3$$

where $\vec{a}_1, \vec{a}_2, \vec{a}_3$ are the real space lattice vectors.

The corresponding reciprocal space translational vector \vec{G} can be expressed using:

$$\vec{b}_1 = 2\pi \frac{\vec{a}_2 \times \vec{a}_3}{\vec{a}_1 \cdot (\vec{a}_2 \times \vec{a}_3)} \quad \vec{b}_2 = 2\pi \frac{\vec{a}_3 \times \vec{a}_1}{\vec{a}_2 \cdot (\vec{a}_3 \times \vec{a}_1)} \quad \vec{b}_3 = 2\pi \frac{\vec{a}_1 \times \vec{a}_2}{\vec{a}_3 \cdot (\vec{a}_1 \times \vec{a}_2)}$$

where $\vec{b}_1, \vec{b}_2, \vec{b}_3$ are the reciprocal space vectors.

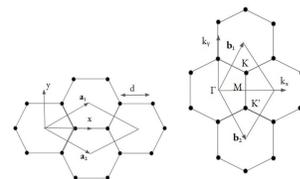


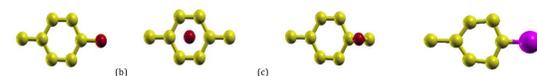
FIG. 1: (a) Real space primitive cell of graphene defined by the unit vectors \vec{a}_1 and $-\vec{a}_2$. (b) Reciprocal space primitive cell of graphene defined by the unit vectors \vec{b}_1 and \vec{b}_2 . The high symmetry k points $\Gamma(0, 0, 0)$, $K(1/3, 2/3, 0)$, $K'(2/3, 1/3, 0)$ and $M(1/2, 0, 0)$ are also shown. This shows the first Brillouin zone of graphene, along with the high-symmetry k-points.

B. Surface Calculation

We first calculated the atomic structure and band structure of pure graphene in our surface calculations with the slab model and converged vacuum height. We used 2×2 supercell to calculate graphene doped with oxygen, boron and nitrogen elements.

C. Doping

Graphene was doped using oxygen, nitrogen, boron, germanium, silicon and tin elements. Regarding the elements oxygen, nitrogen and boron, we doped on three typical doping sites, with either the doping element located directly on top of a carbon atom (T-site), at the center of a hexagonal (H-site) or the midpoint of a C-C bond (B-site). Regarding the elements germanium and tin, because of their larger size, we doped using the substitutional rather than interstitial method, substituting a carbon atom with a dopant atom.



D. Relationship between band gap and color of light

The relationship between band gap and color of light is given by the equation: $E\lambda = (hc)/\lambda$ where λ represents wavelength and c is the speed of light. For a given frequency, the band gap is represented by E_g . In near-infrared light, the wavelength is 700-1000 nanometers while the corresponding band gap is 0.34-0.73 eV.

RESULTS

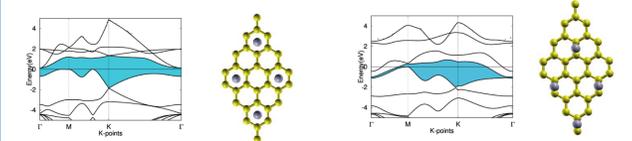


Fig. 1A Graphene doped with boron at H-site, with band structure on the left and atomic structure on the right, with a boron atom (gray) deposited in the center of carbon rings. The band gap is highlighted in blue, showing an indirect band gap of 1.3 eV.

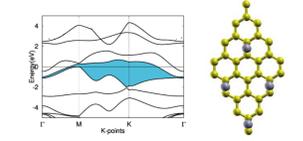


Fig. 1B Graphene doped with boron at B-site, with band structure on the left and atomic structure on the right, with a boron atom (gray) deposited on the C-B bond. The band gap is highlighted in blue, showing an indirect band gap of 0.69 eV.

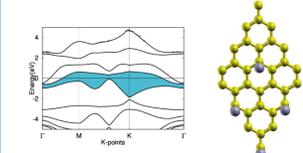


Fig. 1C Graphene doped with boron at T-site, with band structure on the left and atomic structure on the right, with a boron atom (gray) deposited on carbon atoms. The band gap is highlighted in blue, showing an indirect band gap of 0.68 eV.

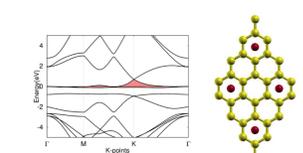


Fig. 2A Graphene doped with oxygen at H-site, with band structure on the left and atomic structure on the right, with an oxygen atom (red) deposited in the center of carbon rings. The band gap is highlighted in blue, but because the valence and conduction band intersects, there is no band gap for this material.

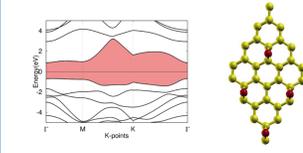


Fig. 2B Graphene doped with oxygen at B-site, with band structure on the left and atomic structure on the right, with an oxygen atom (red) deposited on the C-B bond. The band gap is highlighted in red, showing an indirect band gap of 2.8 eV.

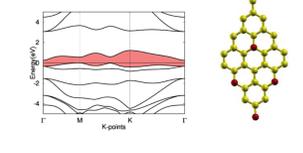


Fig. 2C Graphene doped with oxygen at T-site, with band structure on the left and atomic structure on the right, with an oxygen atom (red) deposited on carbon atoms. The band gap is highlighted in red, showing an indirect band gap of 1.22981 eV.

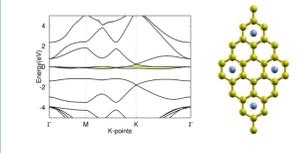


Fig. 3A Graphene doped with nitrogen at H-site, with band structure on the left and atomic structure on the right, with a nitrogen atom (blue) deposited in the center of carbon rings. The band gap is highlighted in yellow, but because the valence and conduction band intersects, there is no band gap for this material.

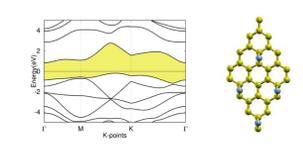


Fig. 3B Graphene doped with nitrogen at B-site, with band structure on the left and atomic structure on the right, with a nitrogen atom (blue) deposited on C-N bonds. The band gap is highlighted in yellow, showing an indirect band gap of 2.3 eV.

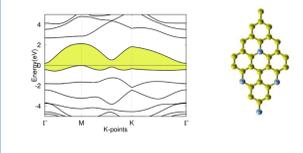


Fig. 3C Graphene doped with nitrogen at T-site, with band structure on the left and atomic structure on the right, with a nitrogen atom (blue) deposited on carbon atoms. The band gap is highlighted in yellow, showing an indirect band gap of 2.1 eV.

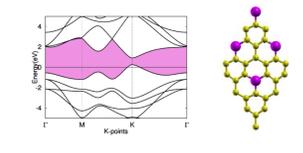


Fig. 4 Graphene doped with germanium, using substitutional doping. Left is band structure, right is atom structure, with a germanium atom (purple) replacing an atom in the graphene ring. The band structure depicts an indirect band gap of 2.5 eV.

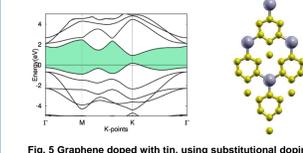


Fig. 5 Graphene doped with tin, using substitutional doping. Left is band structure, right is atom structure, with a tin atom (gray) replacing an atom in the graphene ring. The band structure depicts an indirect band gap of 1.9 eV.

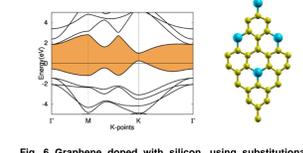


Fig. 6 Graphene doped with silicon, using substitutional doping. Left is band structure, right is atom structure, with a silicon atom (blue) replacing an atom in the graphene ring. The band structure depicts an indirect band gap of 1.82 eV.

CONCLUSIONS

The results of the research study were obtained in different stages, through convergence, relaxation and band structure calculations. During the final stage, it was found that boron doped graphene produced the most suitable band gap as a nanomaterial for near-infrared light ablation. This portrays it as a material that holds a lot of potential in photothermal therapy, offering a great deal of assistance in treatment of cancer at initial and metastatic stages. The research study discussed the practical implications of the research study in the medical field for treatment of cancer. The proposed method is quite useful among the non-invasive treatment methods of cancer. Limitations of the research work were presented in the light of the ever-evolving biotechnology and material sciences field. The domain of non-invasive cancer treatment methods is rapidly evolving and this research study provides a of the major contribution among the remedies for cancer. As stated before, as seen in our results, our selected dopants mostly outputted band gaps that were simply too large for our goal range of 0.39-0.73 eV. Because of this, we understand the necessity of small dopant material, with a low energy cutoff, able to engineer a band gap but not too big. Furthermore, in light of substitutional doping, it would be possible to increase the concentration of the dopant by replacing more carbon atoms with dopant atoms, so that the dopant has a larger possibility of engineering a goal band gap.

If we were to redo our work, it would be plausible to use a larger variety of dopants such as transition metals, halogens, etc. The research fields of nanotechnology, biochemistry, material sciences, and non-invasive cancer treatment are combined in this regime. The objective is to treat cancer cells without affecting the healthy cells as much as possible and ensure long term recovery without any side effects from the treatment and these considerations provide a lot of grounds for future research. Since, cancer causes a significant percentage of mortalities around the globe, theoretical and practical research in this field carries significant impact in practical life.

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