Interlayer vacancy defects in AA-stacked bilayer graphene: Density functional theory predictions

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Interlayer vacancy defects in AA-stacked bilayer graphene: Density functional theory predictions

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Abstract. AA-stacked graphite and closely related structures, where carbon atoms are located in registry in adjacent graphene layers, are a feature of graphitic systems including twisted and folded bilayer graphene, and turbostratic graphite. We present the results of \textit{ab initio} density functional theory calculations performed to investigate the complexes that are formed from the binding of vacancy defects across neighbouring layers in AA-stacked bilayers. As with AB stacking, the carbon atoms surrounding lattice vacancies can form interlayer structures with \(sp^2\) bonding that are lower in energy than in-plane reconstructions. The \(sp^2\) interlayer bonding of adjacent multivacancy defects in registry creates a type of stable \(sp^2\) bonded ‘wormhole’ or tunnel defect between the layers. We also identify a new class of ‘mezzanine’ structure characterised by \(sp^3\) interlayer bonding, resembling a prismatic vacancy loop. The \(V_6\) hexavacancy variant, where six \(sp^3\) carbon atoms sit midway between two carbon layers and bond to both, is substantially more stable than any other vacancy aggregate in AA-stacked layers. Our focus is on vacancy generation and aggregation in the absence of extreme temperatures or intense beams.

1. Introduction

Interlayer interaction in multilayered graphene, graphite and other carbon nanostructures such as multiwalled nanotubes and carbon onions, plays an important role in their mechanical and electrical properties [1]. The interlayer binding in these systems is much weaker than the covalent \(sp^2\) carbon-carbon bonding within the layers and it is this feature that leads to their highly anisotropic behaviour [2]. However, the presence of intrinsic defects that result in the formation of covalent bonds across adjacent layers can drastically alter the material properties [3]. Intrinsic defects created by atomic displacements, lattice vacancies and interstitials, can be introduced to graphitic systems under energetic particle irradiation, and this can be used to control and modify the structure and properties of these materials.

The self-interstitial and lattice vacancy represent the two most fundamental intrinsic defects in graphite, and as such, are widely studied. In multilayered graphitic systems the lowest energy configuration for an isolated self-interstitial, known as a spiro-interstitial, lies at the midpoint between adjacent layers and forms two covalent \(sp^3\)-hybridised bonds to each layer, pinning them together [3–5]. However very stable interlayer bonds can also be
formed from interaction between the under coordinated atoms surrounding vacancy defects in neighbouring layers. These interlayer divacancy complexes have very low activation energies to form (typically 0.2–0.3 eV) [6, 7], and combined with the modest activation energy for monovacancy diffusion in graphene (~1.2 eV) [8], are expected to play an important role in the response of a multilayered system to displacing irradiation. In addition to pairs of monovacancies bonding between the layers, the aggregation of additional diffusing vacancies can result in the formation of extended interlayer defects, such as the ‘ramp’ defect, which comprises a ribbon of graphene connecting adjacent layers [7]. Ab initio modelling shows that such defects should form and they have been directly observed in transmission electron microscopy images of irradiated graphite [7].

The lowest energy configuration of crystalline graphite and multilayered graphene is the Bernal structure [2] or AB stacking (Fig. 1(a)), which has a spacing between the layers of approximately 335 pm. This is by far the most common structure observed experimentally. However, owing to the relatively low strength of interlayer forces, the energetic cost of relative translation of the layers, or basal slip, is quite small. This often leads to significant regions of alternate stacking arrangements, most commonly rhombohedral or ABC stacking [9] and AA stacking. ABC stacking is where the carbon atoms in the fourth layer are located directly in registry with the first layer and the third layer is shifted with respect to the first and second layer. AA stacking is where the carbon atoms in each layer are located directly in registry (Fig. 1(b)). It is the highest energy stacking configuration, and represents a maximum on the gamma surface [10]. AA stacking has not been observed in bulk graphite; however, localised regions have been observed in many graphitic-like systems. For example, superlattices of domains close to AA stacking are formed in the Moiré patterns seen in scanning electron microscope images of rotated planes of bilayer graphene and in twist grain boundaries in graphite [11]. Recently, pure AA-stacked graphite has been produced on diamond surfaces [12] and AA stacking is also found to occur at folds of monolayer [13] and bilayer graphene [14]. Since AA stacked regions then play a significant role in many graphitic and nanostructured carbon systems, it is important to understand the nature of interlayer defects within this structure: the structures that are formed, their energetics and how they will change the material properties.

In this work, we employ ab initio density functional theory (DFT) calculations to investigate the formation of interlayer vacancy complexes in AA-stacked regions. These
demonstrate how the behaviour of populations of vacancies is dramatically different to that in AB stacked regions. In addition, to considering interlayer vacancy dimers, we also investigate the formation of larger vacancy aggregates from a stepwise addition of mobile single vacancies arriving in pairs in adjacent layers. We find two different morphologies of extended vacancy defect: ‘wormhole’ or ‘tunnel’ structures [15, 16] characterised by \( sp^2 \) bonding and ‘mezzanine’ or ‘mid-layer’ structures characterised by \( sp^3 \) bonding. We compare the formation energies of these extended defects with purely coplanar aggregates to show how they are energetically favoured over the most stable in-plane complexes.

We note that our use of \( sp^2 \) and \( sp^3 \) nomenclature indicates the number of carbon neighbours (3 and 4 respectively), and a degree of double-bond character in the case of \( sp^2 \), as demonstrated by the relatively short C-C bonds. In practice due to the local curvature, such \( sp^3 \) bonds will have a degree of \( sp^3 \) character.

2. Method

To investigate the formation of interlayer bonding between vacancy defects in a bilayer graphene structure with both good accuracy and computational efficiency, we employ the density functional theory (DFT) method implemented in the لميرو simulation package [17–20]. Valence electrons are described by a \( pdpp \) basis set possessing 22 independent Gaussian-based functions, where both the spin polarised local density approximation (LDA) [21], and the PBE96 generalised gradient approximation (GGA) [22] are used for the exchange-correlation functional. Norm-conserving pseudo-potentials are used to represent core electrons [23]. Other details of this method and its applicability to graphitic systems has been the subject of earlier work [8, 24]. The numerical integration over the Brillouin zone is performed using the Monkhorst-Pack scheme [25] and the size of the \( k \)-point mesh is \( 4 \times 4 \times 2 \). The states are occupied according to the first-order Methfessel-Paxton scheme [26] with \( k_B = 0.01 \text{ eV} \).

Neither the LDA nor PBE functionals correctly describe London dispersion interactions, which are a component of the interlayer binding in perfect graphite. Nevertheless, there is also a significant component of interlayer binding arising from orbital overlap, and overall the LDA does reproduce the interlayer interaction energy and interlayer separation quite well [27–29], whereas the GGA predicts nearly no interlayer binding. Possible reasons for this behaviour are discussed in the work previously cited in [8]. Although the GGA functional does not bind the layers, it does correctly reproduce relative stacking energies with interlayer spacing from LDA calculations. For interlayer spacing constrained at the LDA value, we find that relative energy changes are usually insensitive to the exchange correlation functional employed, which suggests that the results are not significantly affected by the omission of London dispersion forces.

The defects are constructed in a \( 6a \times 3b \times \frac{1}{2} c \) orthorhombic supercell, with \( b = a \sqrt{3} \), based on a 144-atom graphene bilayer, when no defect is present. The optimised interlayer separation, \( c/2 \), given by the \( pdpp \) basis set and the LDA for both AB stacking (325 pm) and AA stacking (352 pm) in the present work is not significantly different from that found by earlier calculations [28, 29], given that the basis sets and parameterization of the exchange-correlation functional are not identical. Thus, this geometry has an empty gap of size \( c \) separating the model structure from its images in the neighbouring supercells.

In the following sections the LDA values are given, followed by the GGA values in parentheses, both using the LDA optimized cell parameters for the perfect bilayer.
3. Results

An isolated monovacancy, formed by the removal of a single carbon atom from the graphene lattice, is susceptible to a Jahn-Teller distortion [30, 31] which results in the formation of a bond about 180–190 pm long between two of the three under-coordinated atoms [8, 32]. The formation energy of this defect is estimated to be about 7.9 eV LDA (7.4 eV GGA) [8]. The predicted activation barrier for migration of a monovacancy within the graphite layer is found to be $E_a \approx 1.2$ eV by Latham et al. [8]; however, Wadey et al. recently found a lower activation barrier in buckled graphene with a fourfold coordinated structure for the transition state [33].

3.1. Interlayer divacancy and tetravacancy

When two migrating vacancies meet within the same graphene sheet, they can coalesce to form the very stable and immobile nearest neighbour 5-8-5 divacancy structure (Fig. 2(e)) [8, 34–36] which is remarkably stable: its energy is about 7.9 eV (7.0 eV) lower than two separated monovacancies, making its formation energy approximately equal to that for a single monovacancy. However, if two vacancies in adjacent layers come into registry with each other, one or more of the under coordinated atoms surrounding each vacancy can form bonds across the interlayer gap [3]. In AB-stacked graphite, DFT calculations have shown that there are four different forms of these energetically bound cross-layer divacancy structures [8].

In the case of AA stacking, there is only one configuration, which results in stable interlayer bonding. This has one vacancy directly above the other and all the surrounding under coordinated atoms in registry (Fig. 2(a)). In this registry there are two likely bonding configurations: the first has only one interlayer bond (Fig. 3(a), (d)) while the second makes three bonds between all six under-coordinated atoms. The more stable configuration with one
Figure 3. Geometry optimised AA-stacked bilayer graphene complexes of in plane view (a) divacancy species $V_1$-$V_1$ with one $sp^2$ interlayer bond, (b) tetravacancy species, $V_2(5-8-5)$-$V_2(5-8-5)$ (no interlayer $sp^2$ bonds), (c) hexavacancy species $V_3$-$V_3$ with one $sp^2$ interlayer bond and its out of plane view in (d), (e) and (f). The red atom has an $sp^2$ interlayer bond to its counterpart in the neighbouring graphene sheet.

interlayer bond has a total energy 2.8 eV (2.4 eV) lower than two isolated monovacancies, while the configuration with three interlayer bonds is only 2.5 eV (2.0 eV) more stable than isolated monovacancies. The single-bond configuration has coplanar reconstruction within each of the two graphene sheets, similar to the pentagonal motif of the monovacancy. These are replaced in the three-bond configuration by three closely packed interlayer bonds. These bonds are highly strained and distorted, which suggests why the energy of this structure energy is higher than the first form.

Migration of additional monovacancies to this structure can result in larger multivacancy complexes. We first consider the addition of one vacancy in each layer, leading to a pair of coplanar divacancies in registry (Fig. 3(b), (e)). This leads to $V_2$-$V_2$ which is more stable than an alternative tetravacancy $V_1$-$V_1$ by 0.9 eV (0.9 eV) per vacancy. To make four interlayer bonds between two of these divacancy species, the in plane reconstructions forming the fivefold rings must be broken, which costs energy. However, even in this case the resultant species is almost energetically neutral: it is about 0.4 eV more stable for interlayer binding using the LDA, and 0.9 eV less stable using the GGA than the two in-plane divacancies.

The energy of the system can be lowered by an additional 1.1 eV (1.0 eV) per layer by rearranging the nearest neighbour $V_2(5-8-5)$ defect that is directly above the other $V_2(5-8-5)$ defect into three pentagons and three heptagons $V_2(555-777)$ haeckelite structure divacancy with a Stone-Wales type bond rotation [34]. The $V_2(555-777)$ that is directly above the other $V_2(555-777)$ can be transformed into $V_2(5555-6-7777)$ with a Stone-Wales bond rotation [34]. The $V_2(5555-6-7777)$ formation energy of 3.6 eV (3.1 eV) per vacancy is found to be between 4.0 eV (3.5 eV) for $V_2(5-8-5)$ and 3.4 eV (3.0 eV) for $V_2(5555-6-7777)$, which is in good agreement with other studies [53]. However, to reach this state relatively large barriers (∼5 eV according to DFT calculations [8]) must be crossed, which are thermally inaccessible except
at very high temperatures (above \( \sim 1900 \) K making usual assumptions of attempt frequency, \( \sim 10^{13} \text{Hz} \), and zero entropy of activation)

3.2. Interlayer hexavacancy: Wormhole and mezzanine structures

In the case of two trivacancies in registry in adjacent layers, which are formed from the addition of another migrating monovacancy in each layer (Fig. 2(c)), there are again a number of different possible configurations. A single co-planar trivacancy reconstructs to form a pair of five-membered rings and a single dangling bond (Fig. 2(f)). An alternative trivacancy can consist of a monovacancy in one layer and an in-plane divacancy in another. The \( V_1-V_2 \) is more stable than the \( V_3 \) by \( 1.5 \) eV (1.5 eV) per vacancy. When two trivacancies \( V_1-V_1 \) are in registry, a single \( sp^2 \) bond forms between the two dangling bonds releasing \( 2.0 \) eV (1.1 eV) (Fig. 3(c) and (f)). This is analogous to the interlayer bonding for the two monovacancies discussed above, with the same calculated energy release.

However, in this case the reconstructed bonds, which form the five-membered rings, are more widely spaced, and it becomes energetically favourable to break these and form additional interlayer bonds. Indeed, the formation of five interlayer bonds (by breaking the two five-membered rings in each layer) releases \( 4.8 \) eV (3.1 eV) in total (Fig. 4). This defect is more stable, by \( 0.9 \) eV (0.1 eV) than a purely in-plane \( V_6 \) loop (a structure corresponding to a hexagonal ring of carbon atoms removed from the lattice) making it the most stable \( V_6 \) species proposed in graphite to date [37, 38].

This type of reconstruction, with complete \( sp^2 \) bonding around multivacancies in adjacent layers, creates a pore in the bilayer. The chemical nature of this will be fundamentally different to holes or pores in monolayers, whose edges are unsaturated, dangling bonds. These \( sp^2 \)-bonded pores resemble the wormholes predicted by Margine et al [16]. Their wormholes arise from the rearrangement of atoms, leading to pentagons, and require an increased interlayer separation [16]. In our case the structural defect is characterised by a sequential aggregation of vacancies, and does not require a substantially increased interlayer separation to form.

However, the most stable structure for six vacancies in AA-stacked systems is not the wormhole, but another type of morphology, hereafter called a ‘mezzanine defect’. This is constructed by removing a hexagonal ring of six atoms from one sheet, then translating a ring
of six atoms from an adjacent sheet neighbouring the hexavacancy by half of the interlayer separation, and allowing the ring to expand so that it forms a symmetrical arrangement of fourfold-coordinated bonds with both nearest neighbouring graphene sheets (Fig. 5). Thus, the hexavacancy is shared or split between two neighbouring graphene sheets. Its structure is characterised by a six fold ring of \( sp^3 \)-bonded carbon atoms with a bond length within the ring of 158 pm, located midway between the two layers (a ’mezzanine’). This bonding arrangement resembles the AA-stacked zigzag prismatic edge dislocation found by Suarez-Martinez et al. The formation energy per vacancy for the mezzanine defect is calculated to be only 2.9 eV (2.9 eV). Hence, the split-hexavacancy, or mezzanine defect, has lower total energy than the alternative \( V_3-V_3 \) wormhole by 0.8 eV (0.2 eV). The mezzanine is also more favourable in energy compared with coplanar \( V_6 \) armchair and zigzag vacancy lines by 2.1 eV (0.3 eV) and 3.7 eV (1.5 eV), respectively. Two pentagones are formed at both ends of the chain of the coplanar \( V_6 \) armchair and zigzag vacancy lines, similar to the dislocation defect by Jeong et al. The mezzanine is 1.6 eV (0.2 eV) more stable than a \( V_6 \) loop, where the hexavacancy ring occupies a single layer only, without interlayer bonding. Moreover, the energy per vacancy for the mezzanine defect is significantly smaller than for the nearest neighbour \( V_2 \) defect, which costs \( E_f = 3.9 \) eV (3.5 eV) per vacancy, and substantially less than isolated \( V_1 \), where \( E_f = 7.9 \) eV (7.4 eV).

The energetics of the various structures of co-planar and interlayer vacancy complexes up to \( V_6 \) are listed in Table 1 for both the LDA and GGA functionals. Here, the total formation energy is defined relative the perfect (AA-stacked) lattice. The binding energy of an interlayer defect is defined as the energy released from the interlayer binding of the isolated defects in each layer. Where there is no label this implies no covalent interlayer bonding. The label ‘wormhole’ means all under coordinated atoms in each layer bind to form interlayer bonds, while ‘mezzanine’ refers to the interlayer \( sp^3 \) coordinated layer formation.

For the monovacancy in registry with another in an adjacent layer (\( V_1-V_1 \)), there is a small positive interaction energy (\( \sim 0.1 \) eV) without the formation of any interlayer \( sp^3 \) bonds. The formation of a single interlayer bond (by crossing a 0.3 eV barrier) releases a further \( \sim 3 \) eV. As described above, the formation of further interlayer bonds costs more energy in breaking the reconstructions than is gained from the new bonds. In the case of the coplanar divacancy, two in adjacent layers in registry (\( V_2(5-8-5) \) \( V_2(5-8-5) \)) interact very weakly (0.06 eV (0.03 eV)). However, when the reconstructions are broken and the under coordinated
Table 1. Calculated formation energies, formation energies per vacancy, and interlayer binding energies in eV for different vacancy complexes in AA-stacked bilayer graphene using LDA and GGA functionals. Formation energies $E_f$ are with respect to the perfect AA-stacked structure; interlayer binding energies $E_b$ are with respect to the energies of equivalent isolated monolayer vacancy complexes in AA-stacked bilayer graphene. The notation $V_x-V_y$ implies $n$ vacancies in top layer, and $m$ in the bottom layer. The most stable $V_x$ species are given in bold.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Interlayer bonds</th>
<th>LDA</th>
<th>GGA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_f$</td>
<td>$E_f/V$</td>
<td>$E_b$</td>
</tr>
<tr>
<td>$V_1$ (Fig. 2(d))</td>
<td>7.94</td>
<td>7.94</td>
<td></td>
</tr>
<tr>
<td>$V_1-V_1$</td>
<td>15.76</td>
<td>7.88</td>
<td>0.13</td>
</tr>
<tr>
<td>$V_1-V_1$ (Fig. 3(a), (d))</td>
<td>13.11</td>
<td>6.56</td>
<td>2.78</td>
</tr>
<tr>
<td>$V_1-V_1$ wormhole</td>
<td>13.35</td>
<td>6.68</td>
<td>2.54</td>
</tr>
<tr>
<td>$V_2$</td>
<td>7.87</td>
<td>3.94</td>
<td></td>
</tr>
<tr>
<td>$V_2-V_2$ wormhole</td>
<td>15.32</td>
<td>3.83</td>
<td>0.42</td>
</tr>
<tr>
<td>$V_2(5-8-5) V_2(5-8-5)$ (Fig. 3(b), (e))</td>
<td>15.80</td>
<td>3.95</td>
<td>-0.06</td>
</tr>
<tr>
<td>$V_2(555-777)$ $V_2(5557-777)$</td>
<td>13.51</td>
<td>3.38</td>
<td>2.23</td>
</tr>
<tr>
<td>$V_3$ (Fig. 2(f))</td>
<td>14.21</td>
<td>3.55</td>
<td>1.53</td>
</tr>
<tr>
<td>$V_1-V_2$</td>
<td>16.13</td>
<td>5.38</td>
<td>-0.32</td>
</tr>
<tr>
<td>$V_1-V_3$</td>
<td>19.39</td>
<td>4.85</td>
<td>0.24</td>
</tr>
<tr>
<td>$V_2-V_3$</td>
<td>19.74</td>
<td>3.95</td>
<td>-0.32</td>
</tr>
<tr>
<td>$V_6$ mezzanine (Fig. 5)</td>
<td>16.13</td>
<td>5.38</td>
<td>-0.32</td>
</tr>
<tr>
<td>$V_6$ armchair line</td>
<td>19.13</td>
<td>3.19</td>
<td>3.96</td>
</tr>
<tr>
<td>$V_6$ zigzag line</td>
<td>19.63</td>
<td>3.27</td>
<td>3.46</td>
</tr>
<tr>
<td>$V_3-V_5$ (Fig. 3(c), (f))</td>
<td>21.05</td>
<td>3.51</td>
<td>2.04</td>
</tr>
<tr>
<td>$V_6$ loop</td>
<td>21.23</td>
<td>3.54</td>
<td>1.86</td>
</tr>
</tbody>
</table>

Atoms form four bonds across the interlayer gap 0.4 eV (0.9 eV) is released. The contrast between this behaviour and that of the monovacancy shows that there is a very fine balance of energies in determining whether it is energetically favourable to form an interlayer bond, relating to the stability of in-plane reconstructions and the strained bonding configurations that are involved in the formation of $sp^2$ bonds across the interlayer gap. We note that there is an alternative $V_4$ structure consisting of an in-plane $V_3$ and a single vacancy, however this is 3.6 eV (3.5 eV) less stable than the ground-state $V_2-V_2$ (5-8-5) species considered above. In the case of the $V_3-V_3$ complexes ($V_6$ in total) the table shows a progression of bonding energies from one interlayer bond to five interlayer bonds to the mezzanine structure. The formation energies of co-planar $V_6$ complexes (in a single layer) are shown for comparison.

4. Magnetism

Any study of graphitic materials should always be alert to the possibility that defect structures may possess a net magnetic moment [5]. In some instances this might be due to the presence $sp^3$-hybridized carbon atoms [43, 44]. Also, it is well-established that vacancies in graphite are magnetic [8, 46]. Moreover, according to Lieb’s theorem [52], ferromagnetism can arise in the delocalized $\pi$-system of graphene sheets when the presence of point defects causes an imbalance in electronic band structure of the bipartite sublattice. In our investigation $V_1$, $V_1-V_1$ and $V_3$ appear to have one partially-occupied $sp^2$-orbital per plane, which contribute to a non-zero magnetic moment. For $V_1$ the net magnetic moment is calculated to be
Table 2. Calculated magnetic moments of the model systems. The notation $V_n$-$V_m$ represents a defect with $n$ vacancies in the top layer, and $m$ in the bottom layer.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Interlayer bonds</th>
<th>$\mu$ ($\mu_B$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$ (Fig. 2d)</td>
<td></td>
<td>~1.0 1.5</td>
</tr>
<tr>
<td>$V_1$-$V_1$</td>
<td></td>
<td>2.5 ~1.0</td>
</tr>
<tr>
<td>$V_1$-$V_1$ wormhole</td>
<td>3 $sp^2$</td>
<td>0.0 0.5</td>
</tr>
<tr>
<td>$V_3$ (Fig. 2f)</td>
<td></td>
<td>1.1 1.0</td>
</tr>
<tr>
<td>$V_1$-$V_2$</td>
<td></td>
<td>1.0 1.0</td>
</tr>
<tr>
<td>$V_2$-$V_3$</td>
<td></td>
<td>1.0 1.3</td>
</tr>
<tr>
<td>$V_1$-$V_3$</td>
<td></td>
<td>1.5 2.0</td>
</tr>
<tr>
<td>$V_6$ loop</td>
<td></td>
<td>2.0 ~3.0</td>
</tr>
<tr>
<td>$V_6$ armchair line</td>
<td></td>
<td>~2.0 ~2.0</td>
</tr>
</tbody>
</table>

about 1.0–1.5 $\mu_B$, in good agreement with earlier work [5, 45, 47–49]. Similarly, we predict that the magnetic moment for $V_3$ to be about 1.0 $\mu_B$, which is again close to earlier estimates [45, 47, 51]. Structural defects that are composed of $V_1$ or $V_3$ in one of the layers possess a magnetic moment as seen for $V_1$-$V_2$, $V_1$-$V_3$ and $V_2$-$V_3$. The divacancy wormhole, $V_1$-$V_1$ might possess a non zero magnetic moment. Structures without dangling bonds possess a zero magnetic moment. Mulliken population analysis of the defect shows that it has an unpaired electron within a $p_z$-orbital. In the case of the $V_6$ loop, conflicting results are found for the net magnetic moment: it is zero, but with antiferromagnetic ordering in [45] and non-zero (6.00 $\mu_B$) in [47]. The $V_6$ zigzag line possesses a zero magnetic moment and $V_6$ armchair line possesses a non zero magnetic moment. These are in agreement with published results; however, the armchair line can possess metallic and semi-conducting behaviour, which is dependent on the width [50].

5. Discussion

Calculations employing DFT have been used in the present work to investigate the aggregation of vacancies in AA-stacked bilayer graphene. The results show that mobile single vacancies in adjacent layers can combine to form structures composed entirely of threefold-coordinated atoms with cross-layer bonds, and that they are more stable than the corresponding forms of vacancy complexes possessing only coplanar reconstruction (i.e. pentagon and octagon rings). Thus, we have identified the most stable $V_n$ species in AA-stacked graphite for $n = 1–6$.

It is clear from these simulations that the mezzanine defect is the lowest energy structure for the hexavacancy ($V_6$) in AA-stacked regions of bilayer graphene. Although the GGA result places the mezzanine defect and wormhole very close in energy, this may well be an artefact of the functional, which yields almost no interlayer interaction, instead of giving a weak physical attraction between the graphene layers. The mezzanine defect, more than the wormhole, is penalised by its requirement to span the interlayer space with two single bonds and a distorted tetrahedral bond angle, and the GGA will tend to produce an artificial instability.

Furthermore, when viewed from the point of view of dislocation theory, each of the non-linear defects is a prismatic vacancy dislocation loop. The dislocation loop for the mezzanine defect has Burgers vector $c/2$, i.e. a partial dislocation, whereas for the wormhole it is $c$, i.e. a perfect dislocation. Elastic energies vary with the square of the Burgers vector, thus favouring the mezzanine defect, notwithstanding its increased radius compared with the wormhole.

The $c/2$ loop dislocation is of the same nature as the prismatic dislocations discussed...
by [39], except its curvature means it alternates between zigzag and armchair character around the structure. In this regard, it should be noted that [39] gave the armchair core as disconnected from any other layer; however, in this work it is connected via fourfold-coordinated carbon atoms in the same way as the zigzag core.

6. Conclusion

The process of vacancy aggregation can lead to curious structural defects, and not always the most thermodynamically stable arrangements are produced. In the case of the ground state (AB) stacking of the bilayer, the outcome of vacancy aggregation is found to be a combination of lines, prismatic loops and ramps [7]. However, there are situations where bilayer stacking is perturbed to approach AA stacking, in the limiting case of pure AA stacking, where it is found in the present work that low-energy cross-layer vacancy complexes possibly exist that are just as remarkable as those in normal AB graphite.

Even though the nearest-neighbour divacancy is a rather deep local energy minimum, it can dimerize across the interlayer space with four interlayer bonds. This binding across the graphene layers is very similar to that seen in AB-stacked bilayers, and is not inhibited by the larger interlayer separation of AA-stacked bilayer graphene.

Two new classes of structure are identified for hexavacancies. The first is a $V_6$ wormhole comprising a continuously bonded network of threefold-coordinated carbon atoms. It is expected that these pore-like structures could grow in size for larger vacancy aggregates, and are likely to exhibit unique chemical properties compared with the widely studied pores in monolayer graphene, where the pore edges are typically hydrogenated or contain dangling bonds. For larger holes these will be able to open further, closer resembling folded graphene edges. It is quite possible that such wormhole pore structures can be used as for diffusive transport of molecules such as nitrogen and water [41].

The second class is mezzanine defects, where a split vacancy loop forms a structure bounded by a ring of fourfold-coordinated carbon atoms, with bonds that span the space between adjacent graphene sheets. It is notable that the mezzanine defect is the lowest energy state for a system of six vacancies in AA-stacked bilayer graphene, and has by far the lowest formation energy per vacancy of all the systems we have studied.

The hexavacancy is already known to be a key defect structure in heavily irradiated graphite. Early positron-annihilation experiments identified $V_6$ species as a major and abundant species after heavy neutron irradiation, stable up to 1773 K [37]. The assignment was based on positron lifetime for the stable species of 350 ps, which corresponded to calculated lifetime for a stable $C_6v$-symmetry in-plane $V_6$ ring. Similarly implantation of ETU10-grade graphite with 350-keV C$^+$ ions were characterised by positron annihilation doppler broadening, and stable species tentatively ascribed to $V_6$ were observed up to 1773 K [38]. It is possible that the mezzanine structure for $V_6$ described here could also be responsible for these positron annihilation observations, since both species should be expected to have similar positron lifetimes. The smallest cavity dimension determines the positron lifetime associated with that cavity: for the mezzanine $V_6$ it is the interlayer space of 0.50 nm, whereas for an in-plane $V_6$ loop it is the diameter of the missing C$_6$ hexagon, 0.57 nm.

Careful control of temperature and nature of radiation damage could provide viable routes to new and complex nanostructures. In detail, the relative proportion of each nanostructure will be dependent on the kinetics and sequence of approach of the vacancies, which can depend on the local strain field [42] and require further investigation.
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