Defects and impurities in graphene-like materials

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Defects and impurities in graphene-like materials

Graphene-like materials could be used in the fabrication of electronic and optoelectronic devices, gas sensors, biosensors, and batteries for energy storage. Since it is almost impossible to work with defect-free or impurity-free materials, it is essential to understand how defects and impurities alter the electronic and vibrational properties of these systems. Technologically speaking it is more important to distinguish between different types of defects (impurities) and determine if their presence is desirable or not. This review discusses these issues and provides an updated overview of the current characterization tools able to identify and detect defects in different forms of graphene.

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Defects in materials are normally considered to be detrimental to the properties of materials and to devices based on such materials. However, defects can also be beneficial to materials in providing dopants to control both their carrier concentration and whether the carriers are n-type or p-type. Isotopic defects can also be used to probe materials’ properties by separating their electronic properties from behaviors associated with their phonon dynamics. Isotopic defects consist of defects that do not alter the electronic properties of the material. Because of the significant percentage difference between the mass of the $^{12}$C and $^{13}$C isotopic species, the graphene phonon frequencies for $^{13}$C isotopes differ sufficiently from those of $^{12}$C so that they can be used to probe related phonon phenomena in a layered compound such as graphene, without changing the electronic properties.

In this review we also consider defect-induced modifications to few-layer graphene, one of the simplest systems under current investigation in materials science, and yet informative about the effects of defects and their relevance to the functional performance of materials. In this context we consider in-plane defects, which occur ubiquitously in few-layer graphene, whether we are considering a single layer or a thin film of ten layers. In-plane defects are symmetry-breaking and can include point defects, such as vacancies, substitutional impurities, or interstitial impurities, and the impurity can be a chemical impurity or an isotopic impurity. Grain-boundary defects have been observed...
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Types of defect

In this review we consider structural defects associated with both naturally occurring imperfections and growth-induced defects on one hand, and defects introduced for enhancing the understanding of graphene-related phenomena, on the other hand. The defects include point defects, cluster defects and boundaries or edges, which also behave like defects in lowering the symmetry of the infinite crystal.

Point defects occur predominantly within the graphene plane in the form of lattice vacancies and impurity atoms. The occurrence of impurities can be either in substitutional or interstitial sites and can be in the form of isotopic impurities, which predominantly perturb the phonon spectra. Impurities in the form of foreign species (dopants) tend to mainly introduce local electric fields and strain fields associated with their local charge because of the small size of carbon atoms relative to all other species. Boron, which is even smaller in size than carbon, is a special impurity atom that constitutes a common \( p \)-type dopant for graphene. Nitrogen, being larger than carbon, does not dope graphene as readily as boron but would be more likely to enter the lattice of narrow few layer graphene ribbons than bulk graphite. However, the solubility of both boron and nitrogen in graphene is relatively low (< 2 at. %).

Hydrogen or fluorine tend to either physisorb in molecular form on specific graphene defect sites or to form graphane (hydrogenated graphene), and fluorinated graphene when added covalently and in isotopic arrangements, or different chemical arrangements that might be synthesized for the study of specific graphene-related phenomena.

In order to understand the effects of the various interesting defects, in graphene-like systems that occur or are intentionally introduced, a variety of experimental probes are used, and in this review special emphasis will be given to atomic-level structural information derived from aberration corrected high-resolution transmission electron microscopy, scanning tunneling microscopy, and spectroscopic information derived from Raman and scanning tunneling spectroscopies.

Graphene also accommodates two common types of carbon cluster defects with environments locally perturbed from the perfect sp\(^2\) hybridized carbon. The most common cluster defect is the 5-7-7-5 Thrower-Stone-Wales defect, but also frequently occurring are the 5-8-5 defects, both of which maintain an average of the six carbon planar rings of graphene, and therefore graphene can be annealed at sufficiently high temperatures to lower its defect concentration.

Since the 5-7-7-5 and 5-8-5 defects are symmetry-breaking, they can be observed spectroscopically in the Raman D-band (~1350 cm\(^{-1}\)) at 2.41 eV laser excitation, but the defects invoke other symmetry-breaking spectroscopic features, such as the D’-band at 1620 cm\(^{-1}\) and combination modes such as the Raman D+G band 2930 cm\(^{-1}\), each with a different dispersion with laser excitation energy.

At present there is no clear information available on the use of the D-band lineshape, linewidth, laser energy dependence to quantitatively discriminate between the density of 5-7-7-5 and 5-8-5 defects/μm\(^2\) in actual graphene samples, or between defects occurring in graphene samples prepared by different growth techniques. For the structural observation of individual isolated 5-7-7-5 and 5-8-5 defects, the TEM operated under high-resolution conditions, including aberration correction is especially powerful, especially for its ability to observe such individual defect clusters, or as either aggregated clusters or defect clusters in grain boundaries. In situ annealing studies of such defects in a dedicated environmental chamber under high-resolution conditions are needed to desorb such molecules. The naturally occurring vacancy concentration is determined by the growth temperature, which in turn is related to the growth method. Increasing the growth temperature reduces the naturally occurring vacancy concentration. The introduction of impurities is further discussed in connection with the chemical or electrochemical doping of graphene. Ion implantation has been another common technique used for the introduction of point defects under controlled conditions by varying the ion species dose and ion energy.

Fig. 1 Molecular models representing: (a) the 5-7-7-5 Thrower-Stone-Wales defect and (b) the 5-8-5 vacancy-like cluster defect. Because these defects maintain an average of the six carbon atoms per polygon in the graphene lattice, they can be annealed at sufficiently high temperature. Reprinted with permission from32. © 2006 by the American Physical Society.
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would be rewarding to study the effect of each symmetry-breaking mechanism. The ability to do combined tip-enhanced Raman and TEM studies on the same physical cluster defect could provide unique information about the dynamics of such defects and the changes of the different vibrational modes. Recently, highly informative combined Raman and TEM studies on the same sample have been proposed and discussed.

Characterization of defects

As explained above, defects in graphene-like materials including carbon nanotubes can naturally arise from imperfections and growth-induced defects. These systems can even show defects that are artificially introduced to fulfill some needs for technological applications. In this section, we discuss promising techniques used to characterize defects in graphene-like systems.

Micro-Raman spectroscopy

Characterization of in-plane defects

Among several characterization techniques, micro-Raman spectroscopy (MRS) has been a powerful and widely used technique to study defects in carbon-based materials. Indeed, MRS is readily accessible, fast, non-destructive and gives a wealth of information about both the electronic and phonon structures of materials. Particularly special, carbon-based materials show a very characteristic Raman feature called the D-band (the D denoting disorder-induced), which is a symmetry-breaking Raman peak that has no intensity in the absence of defects. Every time a given impurity breaks the translational symmetry of the carbon material’s lattice, D-band intensity will appear in the Raman spectrum and its Raman cross-section (MRS) has been a powerful and widely used technique to study defects and impurities in graphene-like systems.

Back in 1970, Tuinstra and Koenig showed that the ratio between the D- and G-band Raman intensities ($I_D/I_G$) is directly related to the crystallite size ($L_g$) of 3D graphite. At that time, they explained their findings for only one excitation laser energy ($E_l$), namely, 514 nm (2.41 eV). More than 30 years later, in 2006, Cançado et al. successfully extended Tuinstra and Koenig’s findings to several $E_l$ values and now the ratio $I_D/I_G$ is more fully described by the equation:

$$\frac{I_D}{I_G} = \frac{E_l^4}{560}$$

where $L_g$ is given in nm, $E_l$ is given in eV and the constant 560 is given in units of eV/nm. Although a general equation appeared through this scenario, a basic question still remained: whether the crystallite size $L_g$ is a very special characterization parameter in graphite or would other types of symmetry-breaking features also follow a similar equation? The answer is, not exactly.

In 2010, Lucchese et al. used Raman scattering to study disorder in graphene caused by low energy (90 eV) Ar$^+$ ion bombardment. By varying the ion dose, the authors studied different densities of defects induced by the ion bombardment and were able to understand the evolution of the ratio $I_D/I_G$ with ion dose (see Fig. 2). With this experiment the authors provided a Raman spectroscopy-based method to quantify the density of defects in graphene, using HOPG (highly oriented pyrolytic graphite) for calibration. In Fig. 2 the density of defects due to different ion doses is probed by $L_D$, which denotes the average distance between defects. This study revealed important information about the defect evolution by observing that $I_D/I_G$ could be fitted by a phenomenological model for $I_D/I_G$ vs. $L_D$. The model considers that the impact of a single ion in the graphene sheet causes modifications on two length scales, here denoted by $r_A$ and $r_S$ (with $r_A > r_S$), which are the radii of two circular areas measured from the impact point (the subscript A stands for “activated” whereas the subscript S stands for “structurally-defective”). Qualitatively speaking, only if the Raman scattering process occurs at distances smaller than $r_A-r_S$, will the corresponding “damaged” region contribute strongly to the D-band feature. Considering these assumptions in conjunction with statistical arguments, the $I_D/I_G$ vs. $L_D$ relation is given by:

$$\frac{I_D}{I_G} = C_A \left[ \frac{r_A^2 - r_S^2}{r_A^2 - 2r_S^2} \left( e^{-\frac{\pi L_D}{r_A^2}} - e^{-\frac{\pi L_D}{r_S^2}} \right) \right] + C_S \left[ 1 - e^{-\frac{\pi L_D}{r_S^2}} \right]$$

where $C_A$, $C_S$, $r_A$ and $r_S$ are adjustable parameters. The model is in conceptual agreement with a well-established amorphization trajectory.
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for graphitic materials$^{1,2,33,58}$. Additionally, the results show that the broadly used Tuinstra and Koenig relation between $I_D/I_G$ and $L_a$ should be limited to the measurement of 3D crystallite sizes. Recently, in 2011, Cançado et al. extended the proposed phenomenological model to be applicable to several laser lines$^{34}$.

Other types of defects are those that dope the carbon material positively ($p$-type defects) or negatively ($n$-type defects)$^{1-16}$, and those that introduce isotopic defects, the latter being neutral impurities that have only their atomic mass different from that of the pristine sample$^{17-25}$. All these impurities can be naturally introduced into the carbon lattice by their substitution in the place of some original carbon atoms or by functionalization of the sample$^{1-25}$. In the context of the MRS characterization of these functionalized impurities, a new analysis for the $I_D/I_G$ ratio as a function of dopant concentration and $E_L$ is still required in order to understand in depth the differences in connection with the use of Eq. 1. Experiments of MRS combined with x-ray photoelectron spectroscopy (XPS) to determine the amount of dopants could be carried out in order to correlate the D-band peak with the dopant concentration. Therefore, additional combined measurement techniques are awaiting development.

However, it is interesting to note that, while for graphene, these chemical doping and functionalization procedures are still under development, for single-walled carbon nanotubes (SWNTs) such chemically modified samples have been available for a much longer time so that much is already known about how to understand some of the effects of such defects on the electronic and vibrational properties of SWNTs$^2$. For substitutional $n$-type and $p$-type doping, it turns out that the $G'$ (2D) band is extremely sensitive in discriminating between these two different types of doping impurities. More recently, Maciel et al. showed that these impurities renormalize both the electronic and the vibrational structures of carbon nanotubes, and by analyzing the particular behavior of the $G'$ (2D)-band in some doped carbon nanotubes, they could both distinguish between $n$-type or $p$-type doping as well as give information about the dopant concentration, as exhibited in Fig. 3.

Regarding defects due to the introduction of isotopes into SWNTs, Costa et al. have shown how MRS also reveals special phenomena related
to isotopes, as shown in Fig. 4. The study reveals linear dependences of the Raman D-band, G-band and G'(2D)-band frequencies with an increase in the relative $^{13}$C concentration ($x$) for each of these nanotube Raman modes, and shows that the effect of the mass variation of the isotope mixture on the phonon frequencies is described through a simple harmonic oscillator model involving $^{13}$C and $^{12}$C species. The solid lines in Figs. 4a, b, and c are fittings of the experimental data to such a harmonic oscillator model for the frequency and linewidth. Finally, measurements with different $E_L$ were performed and the frequency dispersions of the D and G'(2D)-bands with $E_L$ were observed to be the same for $^{12}$C and $^{13}$C nanotubes, suggesting no changes in the electronic structure after isotope enrichment, in contrast to what happens for n-type and p-type impurities\textsuperscript{17}.

It is worth mentioning that recent advances in the Raman spectroscopy of n-doped and p-doped graphene have been reported by

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig4.png}
\caption{(a) G'(2D)-band, (b) G-band, and (c) D-band frequencies as a function of the $^{13}$C content in the sample containing a $^{13}$C:$^{12}$C ratio $x$. The circles represent experimental points and the solid lines are from model calculations. (d) The data shows a parabolic trend with its maximum at around $x = 0.5$, and its minima at $x = 0$ and $x = 1$. Reprinted from\textsuperscript{17} with permission from Elsevier. © 2011.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig5.png}
\caption{(a) Raman spectra of undoped (HG), boron-doped (BG) and nitrogen-doped (NG) graphene samples. (b) G-band frequency shifts caused by electron (N) doping (with pyridine) and hole (B) doping. From an $I_D/I_G$ analysis, it is concluded that the crystallite size is smaller for doped samples than for undoped ones. Reproduced from\textsuperscript{9} with permission from John Wiley and Sons. © 2009.}
\end{figure}
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Panchakarla et al.\(^9\). The impurities in this case are naturally introduced during the growth process and are, therefore, mainly substitutional. Their results can be summarized in Fig. 5. Basically these authors report an asymmetric phonon renormalization of the G-band feature in which defects due to \(n\)-type and \(p\)-type both result in a frequency upshift (note that the impurity concentration only changes the renormalization factor). This hardening of the G-band is explained by means of the phonon self-energy in graphene within the non-adiabatic formalism, and its broadening is due to the absence or blockage of the decay channels of the phonons into electron–hole pairs\(^83\). However the upshift rate is larger for \(p\)-doped samples in comparison to the \(n\)-doped ones. From an \(I_D/I_G\) analysis, these authors were able to find that the crystallite size \(L_a\) for doped graphene is smaller than \(L_a\) for undoped graphene, which is expected because of the extra strain introduced by the dopants compared to the strain in a pristine sample.

Characterization of armchair and zigzag edges

For graphene nanoribbons, edges can be considered to be symmetry-breaking discontinuities. Here, AC-HRTEM (aberration-corrected high resolution transmission electron microscopy) can be used directly to identify the edge type. Since the zigzag edges have a high density of electronic states relative to other edge types\(^57\), polarized Raman spectroscopy can be used to distinguish zigzag edged ribbons from ribbons with armchair and chiral edges, as shown in Fig. 6\(^53\).

Since the Raman tensor for the zigzag ribbons causes the Raman cross-section to vanish for the optical electric field polarization of light parallel to a zigzag edge, Raman spectroscopy can also be used to distinguish zigzag nanoribbons for ribbons from other edge types, as shown in Fig. 7, in which the Raman spectra were obtained for light incident with different polarization angles (\(\theta\)) with respect to the nanoribbon direction for a narrow graphene ribbon sitting on a bulk graphite substrate\(^54\).

Tip-enhancement near-field spectroscopy

Tip-enhancement Near-field spectroscopy (TES) is a technique that combines both: atomic force microscopy (AFM) and confocal optical microscopy. This special combination of techniques provides,
simultaneously, sub-wavelength and high spatial resolution of samples (determined exclusively by the diameter of the metallic tip used in the experiment) resulting in a wealth of information at the atomic scale\textsuperscript{68, 69}. Similar to MRS, TES cannot provide information regarding the type of defects that are connected to a given sample, or if the impurity atoms are substitutional or not. However, while MRS probes clusters of defects, TES allows us to determine individual impurities at near atomic resolution, which in most cases reveals the different local interactions of impurities with the pristine material.

Maciel \textit{et al.}\textsuperscript{67} also showed that TES can selectively excite regions with and without defects along individual carbon nanotube structures, as shown in Fig. 8. It is shown that TES experiments can be used to understand the local differences (in relation to the pristine material) generated by \textit{n}-type and \textit{p}-type dopants. As explained in the last section, the G'(2D) feature measured by MRS consists of two peaks: one is related to the dopants and another, related to the pristine contributions, is shifted in frequency from the first peak. Similarly to Qian \textit{et al.}\textsuperscript{69}, in the work by Maciel \textit{et al.}\textsuperscript{67} the authors could discriminate the optical responses of regions with and without impurities, and by comparing the observed Raman and photoluminescence signals, they clearly could see a localized photoluminescence emission coming from the defective site. However, the work of Maciel \textit{et al.}\textsuperscript{67} showed that every time the tip was standing over a defective region, the Raman signal from both the defect and from the pristine nanotube were observed, while only the pristine nanotube signal was observed in regions without a defect. This is an expected result because the Raman signal is strongly connected with the polarizability of the material and therefore the observed spectra will reflect both the electronic and vibrational structure of the material, while photoluminescence is sensitive basically to changes in the electronic structure.

Another application of TES is the length scale study of defect-induced Raman modes in carbon materials. Recently, Georgi and Hartschuh\textsuperscript{70}, successfully applied TES to investigate with high spatial resolution the D-band scattering near defects in metallic SWNTs. In their work, Georgi and Hartschuh found that the length scale of the D-band scattering...
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The process is about 2 nm in SWNTs, similar to this length in graphene. It is worth emphasizing that this 2 nm length is also a value for $L_D$ obtained from ion implantation studies.

High resolution transmission electron microscopy

Aberration-corrected AC-HRTEM is highly effective for studying the morphology of carbon based materials. Of course, AC-HRTEM has the advantage of high (atomic scale) resolution so that it provides valuable information about the atomic structure of pristine materials as well as the impurities in defective materials. This technique has the disadvantage of requiring expensive equipment, is time-consuming in operation and, most of time, AC-HRTEM is destructive in the sense that one cannot be assured that the sample will keep its same characteristics before and after the HRTEM analysis. Another drawback of this technique is that it relies on additional complex and dedicated equipment that is needed to extract useful information from the images. AC-HRTEM would be ideal to fully characterize, for example, 5-7-7-5 and 5-8-5 defects in nanocarbons. Because this is currently a widely discussed topic in the literature, we will restrict our attention to recent results involving HRTEM techniques.

Recently, Kotakoski et al. used electron irradiation to create a sp$^2$-hybridized one-atom-thick flat carbon membrane with a random arrangement of polygons (in other words: a graphene sheet containing heptagons, hexagons and pentagons that resembles the pentahedrite and Haeckelite-like structures). The authors demonstrate, by means of first principles calculations and AC-HRTEM experiments how the transformation occurs step by step by nucleation and growth of low-energy multivacancy structures constructed from rotated hexagons and other polygons (see Fig. 9). The observations in this work provide new insights into the bonding behavior of carbon and the dynamics of defects in graphene. It would therefore be ideal to perform in situ Raman spectroscopy measurements on the different types of defective graphenes.

Another interesting application also involving AC-HRTEM is presented by Meyer et al. They demonstrate an experimental analysis of charge redistribution due to chemical bonding in nitrogen-doped graphene membranes and boron-nitride monolayers. Namely, the electronic charge density distribution of a solid contains information about the atomic structure and also about the electronic properties, such as the nature of the chemical bonds or the degree of ionization of atoms. This work turns out to be important because the redistribution of charge due to chemical bonding is small compared with the total charge density and is difficult to measure. Although the differences are small, a full understanding of how this charge redistribution works is needed. In other words, the electron scattering by a carbon atom next to a nitrogen atom turns out to be significantly different from electron scattering by a carbon atom elsewhere in the graphene sheet.

The success of Meyer et al. relies on AC-HRTEM measurements of defective sites in graphene. In this way, they correct the spherical aberrations of the microscope and do a defocus large enough so that in the contrast transfer function (CTF), features from the nitrogen can be distinguished from the carbon atoms. In order to explain the experiment they use first principles modeling techniques, considering the charge redistribution everywhere the nitrogen atom is located. In this context, they also show that the traditional independent atom model (IAM) analysis is inappropriate to properly interpret HRTEM results in defective samples. Fig. 10 shows a comparison between the two methods of analysis and their consequences on the simulated HRTEM images. Note that in Fig. 10c it is seen that, no matter what is the defocus status, if one uses the IAM, the nitrogen atom cannot be distinguished. However, in Fig. 10f, especially for the defocus status $f_2$, it is possible to clearly observe the effects of the hydrogen atom in the graphene lattice.

With this combination of techniques, the authors analyzed the charge transfer on the single-atom level for nitrogen-substitution point defects in graphene, and they confirm the ionicity of single-layer hexagonal boron nitride. Moreover, it is possible to obtain insights into the charge distribution in general nanoscale samples and non-periodic defects can...
be clearly observed in HRTEM measurements. They have shown that HRTEM experiments when used with first-principles electronic structure calculations opens a new way to investigate electronic configurations of point defects and other non-periodic arrangements of nanoscale objects that cannot be studied by a conventional electron or x-ray diffraction analysis. Moreover, this approach is also very promising for studying vacancy cluster defects, since the existence of vacancies will also require a local redistribution of charge densities. In the future, AC-HRTEM coupled with MRS or TES need to be developed. In this way a clear understanding of the vibrational modes associated with different types of point defects can be achieved. In addition, theoretical calculations indicating the Raman modes associated with the different types of defects still need to be performed. An impressive example of the use of AC-HRTEM to resolve details of grain boundary defects in graphene is shown in Fig. 11 where pentagons (blue), heptagons (red) and distorted hexagons (green) can be seen. Here, variants of Thrower-Stone-Wales defects can be directly identified.

Finally, it is worth mentioning that layer stacking defects have also been recently investigated by both AC-HRTEM and optical techniques. In the case of trilayer graphene, the closest packed Bernal ABA stacking is most commonly observed, though ABC rhombohedral stacking has also been identified and investigated. Since the HRTEM analysis can directly distinguish between ABA and ABC stacking because of the well identified structural stacking differences, this technique is used as a primary standard for the structural identification of graphene samples. Once optical techniques that can also distinguish between these stacking arrangements are established, these more commonly available optical techniques can become secondary laboratory methods for identifying the various structural arrangements that occur commonly in few layer samples.

Other techniques
Besides the techniques presented above, it is worth mentioning that some other approaches (perhaps less well-known or even too new to be known) could be chosen to understand more about the nature of defects. In this context, scanning tunneling microscopy (STM) and spectroscopy (STS) constitute non-destructive techniques that reveal a wealth of information about the electronic structure of carbon materials as well as their impurities. An STM in its basic mode of operation will stabilize a sharp metallic tip about 1 nm above the materials surface. In this situation, an electron can tunnel from the tip to the sample and vice versa. Therefore, any tunneling current variation will be related to the density of states in the surface of the material under study, which reveals details about the material’s electronic structure. It is worth noting that transport measurements are also powerful for revealing details of the
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electronic structure of graphene-like materials. Indeed, because the electronic transport is crucial to develop industrial applications, one has to understand how devices (such as transistor and sensors) based on graphene-like materials will behave in the presence of dopants and/or structural defects.

Gate-modulated Raman spectroscopy is another technique that has been extensively used in the field of nanocarbon materials. As an important example, the isotope effect has been exploited to study the effect of the interaction of a graphene layer with a SiO2 substrate. In their work, Kalbac et al. prepared two samples containing a single 13C layer (13C 1-LG). In one case, a single 13C layer is in contact with the SiO2 substrate. The Raman spectrum of this sample is then compared with both a similarly prepared mono-layer 12C sample (12C 1-LG) on a similar SiO2 substrate and the Raman spectrum from a bilayer sample (13C/12C-LG) composed of a single layer of 12C on a SiO2 substrate on top of which a single layer of 13C is deposited to form the bilayer. Raman spectra of these three samples taken at a laser energy of 2.33 eV are shown in Fig. 12.

Here the frequency $\omega$ of the 13C Raman line is down shifted relative to that labeled by $\omega_0$ coming from 12C according to the relation $(\omega_0 - \omega)/\omega_0 = 1 - [(12 + c_0)/(12 + c)]^{1/2}$ in which $c = 0.99$ is the 13C concentration in the 13C-enriched sample and $c_0 = 0.0107$ is the natural abundance of 13C in the naturally occurring carbon material. Using electrochemical techniques these authors varied the Fermi level from −1.5 V to +1.5 V in steps of 0.1 V using a calibrated reference potential where the V = 0 potential corresponds to that of the 13C layer which is deposited on the 12C layer of the bilayer graphene sample, and electrochemical Raman results on the G band and on the G’ band were obtained. Since gating has become a very important technique for changing the Fermi level in both graphene and SWNTs, the use of electrochemistry for providing calibration standards is important. Electrochemical measurements allow calibration of frequency upshifts for positive potentials and frequency upshifts for negative potentials. That upshifts in frequency occur for both positive and negative potentials is consistent with the chemical doping experiments of Maciel et al.

The authors would like to mention that doping techniques to study the electron-phonon coupling in 12C graphene systems have been extensively used in the literature. Finally, transport measurements, optical absorption, photoluminescence, thermo-gravimetric analysis and thermal-transport measurements could also indirectly reveal and quantify defects (impurities) by scanning a structure containing a well-identified defect.

It is noteworthy that the methods to identify, quantify and detect defects discussed here, could be applied to other carbon nanosystems, but some adjustments might be necessary. For example, graphite and graphene are similar systems but their defect detection and quantification, using the techniques above, cannot be simply extrapolated. Raman spectra as well as HRTEM data would be different and defect formation due to ion irradiation needs adjustments and further research along

Fig. 11 Atomic-resolution AC-HRTEM images of graphene crystals. (a) Scanning electron microscope image of graphene transferred onto a TEM grid with over 90% graphene coverage. Scale bar, 5 mm. (b) AC-HRTEM image showing the defect-free hexagonal lattice inside a graphene grain. (c) Two grains (bottom left, top right) intersect with a 27° relative rotation angle, where an aperiodic line of defects stitches the two grains together. (d) The image from (c) with the pentagons (blue), heptagons (red) and distorted hexagons (green) of the grain boundary outlined. (b)–(d) were low-pass-filtered to remove noise; scale bars, 5 Å. Reprinted from by permission from Macmillan Publishers Ltd, © 2011.
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these lines is still needed. A similar scenario is observed for single- and multi-walled carbon nanotubes. Therefore, the present review is also intended to provide carbon researchers with valuable information related to defects and impurities that could be used and adapted to other systems including carbon foams, graphene oxide, nanotubes, etc., but significant further research would be needed to properly characterize heavily irradiated carbons and highly disordered carbons.

Conclusions and perspectives

In this review article we discussed a variety of defects and impurities in graphene-like materials, including their structure, properties, characterization and application. By envisioning real applications for these structures, one must consider that the material at the same time will somehow become degraded by defects or impurities. As discussed throughout the text, defects such as $n$-type or $p$-type dopants, isotopic substitutions and defect clusters (5-7-7-5 or 5-8-5) could be found in nano-carbons and intermolecular junctions, and are also naturally abundant. In the section Types of defect we discussed the nature of such defects and how they occur. Among the many characterization techniques currently available, our discussion in the section Characterization of defects focused on the more promising techniques now used to characterize and understand defects. Despite its limitations to distinguish between defects as well as to probe them individually, MRS remains a fast and widely accessible tool which provides a fair understanding of the electronic and vibrational properties of materials. In contrast to MRS are electron microscopy techniques, particularly AC-HRTEM. While, HRTEM is unique in several aspects, its most striking feature is its ability to probe in depth the nature of atomic bonding in crystals. Thus, HRTEM allows for a detailed identification of how specific types of defects occur in materials and how they locally change the material’s properties. Other characterization techniques were also briefly discussed, such as scanning probe microscopy (STM, AFM, and others), which greatly amplify our understanding of the electronic properties of materials surfaces.

There had been little attention given to the study of defects in nanostructures and this is because the synthesis of large-scale nanostructures with only a few naturally occurring defects has been difficult. Therefore emphasis has historically been given to promoting the synthesis of defect-free structures with high electronic mobilities and for the scale-up of such structures to the micron and even centimeter length scales for potential practical applications. Now that much progress has been made in materials preparation and characterization, it is time to take stock of where we are now, where we are going in the future, and what scientific barriers remain to be overcome. Among the scientific barriers to future progress is the controlled introduction of defects in the growth process, including point defects, cluster defects and grain boundaries, with grain boundaries arising in the growth process because of the different nucleation sites for graphene grain growth.

Finally, although the topic was not mentioned in the manuscript, the authors believe in the use of defects in applications such as for providing specific sensor sites for molecular adsorption. Enhancing the performance of the different kinds of sensor sites that can now be developed, by increasing the density of such available sites and by expanding the number of ways that such sensor sites could be used reliably and the promotion of new large-scale applications should be emphasized but special niche applications...
could also be a good strategy for developing technological tools. Carbon, like silicon, is an abundant and cheap element on our planet. Therefore its use for large scale applications is desirable and could perhaps become part of global sustainability planning if graphene and other nanocarbons could by conveniently and cheaply synthesized from CO₂ or waste CH₄.

### Acknowledgements

PTA acknowledges financial support from CNPq grant No.200616/2010-2. PTA and MSD acknowledge financial support from ONR-MURI-N00014-09-1-063. MT acknowledges support from the Research Center for Exotic Nanocarbons, Japan regional Innovation Strategy Program by the Excellence, JST.