Non resonant Raman spectra of homogeneous and inhomogeneous individual dimers of Single-walled Carbon Nanotubes (SWNTs)

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Abstract. We study the effects of the coupling between single-walled carbon nanotubes (SWNTs) on the phonons in homogeneous (identical nanotubes) and inhomogeneous (different nanotubes) dimers of SWNTs. Bond polarization theory and the spectral moments method (SMM) are used to calculate the non-resonant Raman frequencies of the breathing-like modes (BLMs) and tangential-like ones (TLMs). The dependence of the phonons on different structural parameters such as diameter and chirality is investigated. We focus on the dependence of the so-called Breathing-Like Modes (BLMs) of dimers originating from the van der Waals coupling of the Radial Breathing Modes (RBMs) of each individual tube forming the dimer. On the other hand, the TLM of dimer is reported and discussed. Distinct behaviors of the TLM are evidenced. The calculated of spectra are compared with the few experimental Raman data obtained on individual dimers.

1. Introduction.

Many researchers have devoted their efforts to study carbon nanotubes [1] and graphene [2] due to their various remarkable chemical, physical and mechanical properties [3]. These characteristic properties allow great potential applications [1, 4] of carbon nanotubes (CNTs) in many fields, such as photocatalysis [5], medicine [6], nanoscale electronics [7], optoelectronic devices [8], hydrogen storage [9, 10], mechanical systems [11], electrochemical devices [12], composites [13], SEM probes [14] and field emission devices [15, 16]. Carbon nanotubes exist in a wide variety of forms, such as single-walled carbon nanotubes (SWNTs), double-walled carbon nanotubes (DWNTs) and dimer of SWNTs.

For long time, it has been theoretically demonstrated a one-to-one correspondence between the atomic structure of a SWNT, especially its diameter, and the frequency of a low-frequency Raman active mode, the so-called radial breathing mode (RBM).
Recently, it was stated theoretically, and confirmed experimentally, that the RBM frequency vs Diameter (d) relationship can be expressed as: $\omega_{RBM} = \frac{228}{d} \sqrt{1 + Cd^2}$ with $C = 0$ for individual environmental-free SWNTs (isolated SWNT) [21], and $C \neq 0$ for SWNTs in interaction with an environment such as SWNTs sitting on a substrate, surrounded by different surfactants, or in bundles (Ref. [22] and references therein). In SWNT bundles, the origin of the $C$ term mainly results from competition between the intertube interactions leading to an upshift of the radial breathing mode (called radial breathing-like mode (RBLM) in SWNT bundle) of about 8-16 cm$^{-1}$, depending on the tube diameter, with respect to the RBM of individual isolated SWNTs [17, 18, 19]. In SWNT bundles, in addition to the RBLM, a second mode is predicted in the low-frequency breathing mode range [18, 19, 20]. It originates from a double degenerate mode (E mode) in individual SWNT. Both bundle modes are fully-symmetric and can have mixed vibration patterns [18]. The most small bundle: the dimer of SWNTs, is characterized by weak van der Waals interactions between the neighboring carbons of its two constituting SWNTs. Dimer of two identical (non-identical) SWNTs, the so-called homogeneous (inhomogeneous) dimers, have three electronic configurations, namely: SC-SC, SC-M and M-M, where SC (resp. M) stands for semiconducting (resp. metallic) SWNT.

Individual carbon nanostructures, such as double-walled carbon nanotubes (DWNTs) and dimers of SWNT provides unique model systems for the study of van der Waals coupling at the nano scale [24]. Raman spectroscopy is known as a powerful tool for studying the vibrational properties of such carbon nanostructure [25], (other references have to be added) especially the dependence of these properties as a function of the diameters [26].

In a previous paper, using the spectral moments method (SMM) [27, 28, 29, 30], and in the framework of the bond-polarization theory, the polarized Raman spectra of DWNTs have been calculated. The dependence of the Raman spectrum of DWNTs, with the diameter and chirality of each constituting SWNTs, was investigated.

In the present work, the Raman spectra of other van der Waals-coupled carbon nanostructures, the homogeneous and inhomogeneous dimer of SWNTs, are calculated. The dependence of the Raman active modes on the diameters, chirality and length of each constituting SWNT is investigated. The results of calculations concerning the low-frequency breathing like modes (BLMs) of dimers of SWNTs are compared with the few available experimental Raman data.
2. Models and computational method.

The force constant model FCM model we employ involves a fourth nearest neighbor approximation. The force constant tensor describes the coupling between the $i^{th}$ and the $j^{th}$ carbon atom, which are $N^{th}$ nearest-neighbor of each other[31].

A Lennard-Jones potential $U_{LJ}(r) = 4\varepsilon \left( \frac{\sigma}{r} \right)^{12} - \left( \frac{\sigma}{r} \right)^{6}$ is used to describe the van der Waals interactions between the two constituting SWNTs of the dimers, with parameters $\varepsilon = 2.964$ meV and $\sigma = 0.3407$ nm.

We calculate the Raman spectra of dimers of SWNT using the spectral moment's method (SMM). For SWNT, the SMM method is described in detail in Ref[29]. And the same approach is used in this work. Raman tensor of each vibrational mode is calculated in the framework of non-resonant bond-polarizability model[32]. The frequencies of Raman-active modes are derived from the position of the peaks in the calculated Raman spectra the intensity of the Raman spectrum is normalized with respect to the number of carbon in the sample under consideration. In our calculations, the common axis of the two tubes is along the Z axis.

3. Results.

In this section, the calculated Raman spectra of infinite homogeneous and inhomogeneous dimers of SWNTs are reported. The dependence of the Raman spectrum as function of diameter and chirality of the constituting SWNTs is investigated.

3.1. Infinite homogeneous Dimer of SWNTs.

We now turn to the study of For each investigated dimer, the Lennard-Jones intertube energy was minimized. The optimal intertube gap is found around 3.4Å.

In a first time, we focus on the Raman spectra of armchair-armchair dimers, identified as (n,n)-(n,n). In order to illustrate our approach, the breathing-like modes (BLM) (figure1-(A)) of the Raman spectra of (5,5)-(5,5), (10,10)-(10,10), (15,15)-(15,15) and (20,20)-(20,20) dimers are discussed.

The Raman spectrum of the (15,15)-(15,15) dimer displays two intense peaks located at 110 (BLM2) and 115 $cm^{-1}$ (BLM3), and a weak peak at 82 $cm^{-1}$ (BLM1). All these modes result from the coupling of all the breathing modes of isolated tubes. For infinite dimers, the eigenvector of each mode modes is easily obtained from the direct diagonalization of the dynamical matrix. By this way, we found that BLM2 mainly corresponds to the coupling of the radial breathing mode (RBM) of isolated (15,15) tube. The frequency of the RBM in isolated (15,15) armchair tube is calculated at 108$cm^{-1}$.
and, as expected, the calculations show a slight upshift of the frequency of the BLM2 in (15,15)-(15,15) dimer. The BLM1 and BLM3 peaks are assigned to hybridation between radial breathing modes and the $E_n$ modes of individual (15,15) SWNT [18]. Notice that hybridation between the breathing modes increases with increasing the diameters of the tubes.

In figure1-(B) we discuss the dependence with the diameter of the breathing-like modes, in low diameter (0.5-1.2nm), one RBLM mode is found (full circle). at diameter 1.35nm another RBLM mode appear resulting to the coupling mode of both tubes(open star) due to the van der Waals interactions between the tubes. these interactions become more intersting when the diameter increases. Notice that as in SWNT, the BLM’s are not significantly dependent on the chirality of the tube, that’s the reason why we calculate only for armchair-armchair dimer(smaller unit cell than for chiral and therefore faster calculations).

We examine now the TLM range starting by Armchair-Armchair dimers. the corresponding spectra are shown in the figure2-(A) for different systems. As clear from figure2-(A), we observe here one peak of the tangential modes (TM’s) of both systems. From calculations the Raman spectrum of (10,10)-(10,10) dimer displays TLM’s at 1586 $cm^{-1}$. When the tube diameter increases, an upshift of TLM’s modes

![Figure 1.](image-url)

(A) The ZZ calculated Raman spectra of infinite (5,5)-(5,5), (10,10)-(10,10), (15,15)-(15,15) and (20,20)-(20,20) dimers in the BLM range. (B) Diameter dependence of the Raman-active mode frequencies for armchair-armchair dimers.
Figure 2. The ZZ calculated Raman spectra of infinite armchair-armchair (A), zigzag-zigzag (B) and chiral-chiral (C) dimers in the TLM ranges.

around 1589 cm\(^{-1}\) of large diameter. In the Zigzag-Zigzag dimers the corresponding spectra are shown in the figure2-(B). Also the Raman spectra displays one peak of the tangential modes (TLM’s) of both systems. The TLM frequency of (10,0)-(10,0) dimer is 1598 cm\(^{-1}\). But on the contrary of Armchair-Armchair dimer when the tube diameter increases, a downshift of TLM’s modes around 1592 cm\(^{-1}\) of large diameter. On the other hand the Raman spectrum of a chiral-chiral systems displays two bands of the tangential modes (TLM’s)(figure2-(C)). We deduced as in SWNT, the Raman spectrum in the TLM region is very sensitive to the chirality of the tubes.

In contrary to the breathing like modes range, the coupling modes don’t exist in the TM region. For example, TLM of (10,10)@(10,10) is centered at 1586 cm\(^{-1}\). In isolated (10,10) SWNT, Raman line is calculated at 1585 cm\(^{-1}\). Also in a chiral-chiral systems like (12,10)-(12,10) one, the Raman spectrum presents two peaks (1586 and 1590 cm\(^{-1}\)). In isolated (12,10) SWNT, Raman lines are calculated at (1585 and 1591 cm\(^{-1}\)). The comparison between the calculated Raman spectra shows that the Dimer spectra are a superposition of the two Raman spectra of the corresponding isolated tubes in this range.
3.2. Infinite inhomogeneous Dimer of SWNTs.

We report the calculated Raman spectrum for infinite inhomogeneous dimers of SWNTs, the calculations are performed on infinite systems, we applied periodic boundary conditions on unit cells of the considered nanotubes forming the system.

In a first time, we focus on the Raman spectra of chiral-chiral dimers as function of diameter. In order to illustrate our approach, the breathing-like modes (BLM) (figure 3) of the Raman spectra of (7,3)-(8,4), (11,7)-(12,8), (15,11)-(16,12) and (19,15)-(20,16) dimers are discussed.

The Raman spectrum of the (19,15)-(20,16) dimer displays four peaks located at 88 (BLM1), 92 cm\(^{-1}\) (BLM2), 98 cm\(^{-1}\) (BLM3) and 107 cm\(^{-1}\) (BLM4). All these modes result from the coupling of all the breathing modes of isolated tubes. For infinite dimers, we use the same method (direct diagonalization) to obtain the eigenvector of each mode. By this way, we found that BLM2 (resp.BLM3) mainly corresponds to the coupling of the radial breathing mode (RBM) of isolated (20,16) (resp.(19,15)) tube. The BLM1 and BLM4 peaks are assigned to hybridation between radial breathing modes and the E\(_n\) modes of individual SWNTs. Notice that hybridation between the breathing modes increases with increasing the diameters of the tubes as shown in figure 3, in the small diameter ((7,3)-(8,4)) the Raman spectrum displays two peaks located at 268 cm\(^{-1}\) and
Figure 4. The ZZ calculated Raman spectra of different chirality of dimers in the BLM range.

318 cm\(^{-1}\), these modes correspond to the coupling of the RBM of isolated (8,4) and (7,3) tubes. The hybridation modes are not appear. When the diameter increases the hybridation modes increase.

In figure 4 we present the ZZ polarized Raman spectrum of four configurations of dimers. Zigzag-Chiral dimer ((17,0)-(15,4)), Armchair-Zigzag dimer ((10,10)-(17,0)) , Armchair-Chiral dimer ((10,10)-(15,3)) and Chiral-Chiral dimer ((15,3)-(14,5)) in the BLM range. All diameters of the tubes close to 1.35nm. The dependence of chirality is discussed.

In Armchair-Zigzag dimer ((10,10)-(17,0)), the Raman spectrum shows three peaks located at 163(BLM1), 167(BLM2) and 170 cm\(^{-1}\)(BLM3), the lower-frequency pair of peaks (163 cm\(^{-1}\) and 167 cm\(^{-1}\)) is assigned to vibrations of the (10,10) tube and the higher-frequency (170 cm\(^{-1}\)) to the vibrations of (17,0) tube. To compare with the (10,10)-(10,10) dimer we found that the two peaks corresponding to (10,10)-(10,10) dimer is found in (10,10)-(17,0) dimer. In the (10,10)-(15,3) the Raman spectrum displays four peaks located at 163(BLM1),
165(BLM2), 170(BLM3) and 176 cm$^{-1}$(BLM4), the lower-frequencies pair of peaks (163 cm$^{-1}$ and 165 cm$^{-1}$) is assigned to vibrations of the (10,10) tube and the higher-frequency (170 cm$^{-1}$ and 171 cm$^{-1}$) to the vibrations of (15,3) tube.

The BLM1 and BLM4 are a hybridation modes of both tubes, BLM2 corresponding to a radial breathing mode to (10,10) and BLM3 is a radial breathing mode to (15,3). We found a systematic upshift of the frequency of the BLM2 with respect to the frequency of the breathing mode in (10,10) SWNT by 3 cm$^{-1}$. This upshift of the radial-breathing mode of (10,10) tube in dimers is controlled by the chirality of the other tube that forms the dimer with (10,10) tube.

In the TLM region, the Raman spectrum of different dimers presented in figure 5 show four peaks are called TLM1, TLM2, TLM3 and TLM4. The first two frequencies correspond to the Transverse-Optical modes (TO), the second two modes correspond to Longitudinal-Optical modes (LO) modes of the semiconducting carbon nanotubes. For instance, the (7,3)-(8,4) dimer displays four bands located at 1576, 1580, 1594 and 1596 cm$^{-1}$, the two pair of peaks (1576 and 1594 cm$^{-1}$) correspond to the vibrations of (7,3) tube and (1580 and 1596 cm$^{-1}$) those of (8,4) tube. While the frequencies of the tangential modes in isolated (7,3) and (8,4) tubes are respectively calculated at (1584 and 1595 cm$^{-1}$) and (1586 and 1593 cm$^{-1}$). We notice that as in homogeneous dimers the calculated Raman spectra shows that the Dimer spectra are a superposition of the two Raman spectra of the corresponding isolated tubes in this range. In addition, our calculations state a changes of the tangential-like modes in Dimer, caused by intertube van der Waals interactions, with respect to SWNTs.

In figure 6 the Raman spectrum of four systems are presented, the diameter of the tubes close to 1.35 nm. We found two modes in armchair-zigzag ((17,0)-(10,10)) dimer, one mode of each tube 1586 cm$^{-1}$ for (17,0) and 1592 cm$^{-1}$ for (10,10). Three modes in armchair-chiral ((10,10)-(15,3)) 1586 cm$^{-1}$ for (10,10) tube and two pair peaks (1585 and 1592 cm$^{-1}$) for (15,3) tube, also three bands in zigzag-chiral ((17,0)-(15,4)) 1592 cm$^{-1}$ for (17,0) tube and two pair peaks (1586 and 1593 cm$^{-1}$) for (15,4) tube. In the chiral-chiral ((15,3)-(14,5)) dimer, four modes are found two pair peaks (1576 and 1592 cm$^{-1}$) for (15,3) tube and two pair peaks (1583 and 1591 cm$^{-1}$) for (15,4) tube. We notice that the TLM region is very sensitive to the chirality of the tubes in the TLM range as we found in homogeneous systems.

4. Discussions.

The (15,11)-(16,12) is an inhomogeneous dimer and the distance between them is close to d=3.4 Å. Their chiral angles are boths close to 25°. In figure 7 the Raman spectra displays the four peaks corresponding to $A_{1g}$ modes for (15-11)-(16-12) dimer, we found four bounds (called BLM) located at 102 cm$^{-1}$ (BLM1), 118 cm$^{-1}$ (BLM2), 125 cm$^{-1}$ (BLM3) and 128 cm$^{-1}$ (BLM4).
The presence of additional modes as compared to the two expected radial-breathing modes (RBM) is attributed to the lowering of the symmetry in dimers [34, 35]. It is tempting to assign the lower-frequency pair of peaks (102 cm$^{-1}$ and 118 cm$^{-1}$) to vibrations of the (16,12) tube and the higher-frequency pair (125 cm$^{-1}$ and 128 cm$^{-1}$) to the vibrations of (15,11) tube.

To analyze the experimental data in the light of the calculated features of our work, we consider some given experimental frequency from reference [36]. Recent Raman measurements on (15,11)-(16,12) Dimer, obtained by direct synthesis method, performed by [36], showed that RBM Raman spectrum is dominated by four peaks around 124, 131, 138, 146 cm$^{-1}$.

Débarre et al [37] have reported the Raman spectrum of (8,6)-(18,4) dimer with two peaks at 150 cm$^{-1}$ (BLM2) and 245 cm$^{-1}$ (BLM3). From our calculations the BLM2 and BLM3 are found around 140 and 235 cm$^{-1}$. We notice that in the last system ((8,6)-(18,4)) the BLM1 and BLM4 (hybridation modes) are very weak because the diameter of the tubes are small (0.95nm for (8,6) and 1.59nm for (18,4)).

We examine now the TLM range of Raman spectrum of the (15,11)-(16,12) dimer. The corresponding spectra is shown in the figure 7. The TM frequencies are 1577(TLM1), 1580(TLM2), 1588(TLM3) and 1590 cm$^{-1}$(TLM4). The first two frequencies correspond...
Figure 6. The ZZ calculated Raman spectra of different chirality of dimers in the TLM range.

Figure 7. (top) experimental Raman spectrum (bottom) ZZ polarized Raman spectrum of (15,11)-(16,12) dimer.
to the TO modes, the second two to LO modes of the constituent semiconducting carbon nanotubes. As was shown in the figure2-(C), the TO mode’s frequency show a strong dependence on the nanotube’s diameter, while LO modes do not have a big change. In this system we assign the 1577, 1588$cm^{-1}$ to a (15,11) nanotube and 1580, 1590$cm^{-1}$ to a (16,12).

The frequencies of TO modes predicted for isolated individual SWNTs (15,11) and (16,12) are 1588$cm^{-1}$ and 1589$cm^{-1}$ respectively. These frequencies are upshifted with respect to the corresponding TO modes in the bundle (1577$cm^{-1}$ and 1580$cm^{-1}$). We observe also that the difference between the frequency of the TO mode in (16,12) and (15,11) individual SWNTs is around 1$cm^{-1}$, that is slightly smaller than the difference calculated in the dimer (around 3$cm^{-1}$). In this assumption, for TO modes, the interaction between the tubes leads a downshift of frequency of the both TO modes and to an increase in their frequency separation. In this framework these two features could be considered as the signature of the coupling between the TO modes of SWNTs in dimer.

Finally, a careful examination of the LO modes lead to a a weak evidence of the coupling between SWNTs in this dimer. Indeed, there is a small deviation of the LO frequencies of the dimer from those found in isolated individual tubes. assuming the frequencies of the LO mode in isolated individual SWNTs (15,11) and (16,12) as (1590$cm^{-1}$ and 1591$cm^{-1}$ respectively). These frequencies are downshifted by 1$cm^{-1}$ with respect to the corresponding LO modes in the bundle (1588$cm^{-1}$ and 1590$cm^{-1}$).

In table 1 we compare our calculations with the experimental BLM and TLM measured in Ref[38]. This values gives the best agreement between experimental and our calculations.

|       | our works ($cm^{-1}$) | ref[38] ($cm^{-1}$) |
|-------|------------------------|---------------------|
| BLM1  | 102                    | 124                 |
| BLM2  | 118                    | 131                 |
| BLM3  | 125                    | 138                 |
| BLM4  | 128                    | 146                 |
| TLM1  | 1577                   | 1568                |
| TLM2  | 1580                   | 1571                |
| TLM3  | 1588                   | 1586                |
| TLM4  | 1590                   | 1596                |
5. conclusion

In this article, we investigated the non-resonant Raman study of Van der Waals coupled carbon nanostructures, namely, a bundle of two identical and non-identical SWNTs (Dimer). We showed that Van-der-waals coupling between the tubes lead to collective radial breathing-like modes (RBLM). The dependencies of these RBLMs as a function of diameter and chirality were discussed. Also we discussed the TLM region of dimer of two SWNTs we found two distinct behaviors of TLM: i) A clear shift of TLM frequencies of constituent tubes in comparison with those of SWNTs. ii) The spectrum of dimer was just a simple sum of TM of corresponding SWNTs. In order to compare with the experimental data we calculated the Raman spectrum of (15,11)-(16,12) dimer. We found that our calculations are in good agreement with experimental data.

6. ACKNOWLEDGMENT

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7. references

[1] Lijima S Helical microtubules of graphitic carbon Nature 1991 354,56-58.
[2] Novoselov K S Geim A K Morozov SV JiangZhang Y D Dubonos S V Grigorieva I V Firsov A A (2004) Science 306 666.
[3] Scheibe B Pulen E Kalenczuk R (2010) J Alloys Compd 500 117.
[4] Endo M Kim C Nishimura K Fujino T Miyashita K (2000) Carbon 38 183.
[5] Chen C Liang Y Zhang W (2010) J. Alloys Compd 501 168.
[6] Cheung W Pontoriero F Taratula O Chen A M He H (2010) Adv. Drug Deliv. Rev. 62 633.
[7] Hermann S Pahl B Ecke R Schulz S E Gessner T (2000) Microelectronic. Eng 87 438.
[8] Yao Z Postma H W Balents L Dekker C (1999) Nature 402 273.
[9] Rather S Naik M Hwang S Kim A Nahm K (2009) J. Alloys Compd 475 17.
[10] Jain I P Jain P (2010) J. Alloys Compd 503 303.
[11] Kuo-Jung Lee, Mao-Hsiang Hsu, Huy-Zu Cheng, Jason Shian-Ching Jang, San-Wo Lin, Cheng-Ching Lee, Sang-Chaur Lin, (2009) J. Alloys Compd 483 389.
[12] Baughman R H Cui C Zakhidov A A Iqbal Z Barisci J N Spinks G Mazzoldi A De Rossi D Rinzier A G Jaschinski O Roth S Kertesz M (1999) Science 284 1340.
[13] Thostenson E T Ren A Chou T W (2001) Compos. Sci. Technol 61 1899.
[14] de Jonge N (2009) Adv. Imag. Electron. Phys 156 203.
[15] Darbasi S Abd Y Mohajerzadeh S Asl Soleimani E (2010) Carbon 48 2493.
[16] Shim M Javey A Kami N W S Dai H J Am J (2001) Chem. Soc 123 11512.
[17] Dresselhaus M S Eklund P C (2000) Adv. Phys 49 p.705
[18] Henrard L Popov V N Rubio A (2001) Phys. Rev. B 64 p.205403
[19] Sbai K Rahmani A Chadi H Sauvajol J L J. Phys.: Condens. Matter 21 (2009) p.045302
[20] Popov V N Henrard L (2001) Phys. Rev. B 63 p.233407
[21] Lin X K Wang W Wu M Xiao F Hong X Aloni S Bai X Wang E Wang F (2011) Phys. Rev. B 83 p.113404
[22] Araujo P T Maciel I O Pesce P B C Pimenta M A Doorn S K Qian H Hartschuah A Steiner M Grigorian L Hata K Jorio A (2008) Phys. Rev. B 77 p.241403.
[23] Blancon J -CPaillet M Tran H NThan X T Abarber M Ayari A San Miguel APanas A -M Zahab A -Sauvajol J -LDelFatti NVallée F (2013) Nat.Commun 4 2542.
[24] Dresselhaus M S Dresselhaus G Saito R Jorio A (2005) Phys. Rep 409 47.
[25] Kavan L Rapta P Dunsh L Bronikowski M J Willis P Smalley R E (2001) J. Phys. Chem. B 105 10764
[26] Astakhova T Yu Vinogradov G A Menon M (2003) Chem. Ball Int. Ed. 52 823.
[27] Rahmani A Sauvajol J L Cambedouzon J Benoit C (2005) Phys. Rev. B 71 125402.
[28] Rahmani A Junid P Benoit C Jullien R (2001) J. Phys: Condens. Matter 13 5413.
[29] Rahmani A Sauvajol J L Rel S Benoit C (2002) Phys.Rev.B 66 125404.
[30] Benoit C Bey R Poussigue G (1992) J.Phys. Condens. Matt 4 3125.
[31] Wirtz L Rubio A (2004) Solid State Commun 131 141.
[32] Guha S Menendez J Page J B Adams G B(1996) Phys. Rev. B 53 13 106.
[33] Lu J Wang S (2007) Phys. Rev.B 76 233103.
[34] Sbai K Rahmani A Chadi H Sauvajol J-L (2009) J.Phys: Condens.Matter 21 045302.
[35] Henrard L Popov V Rubio A (2001) Phys. Rev. B 64 205403.
[36] Levshov D Michel T Paillet M Than X T Tran H NAREN R Rahmani A Boutahir MZahab A -A Sauvajol J L (2014, January) In MRS Proceedings Vol. 1700 pp. mrss14-1700. Cambridge University Press.
[37] D´ebarre A Kobylko M Bonnot A M Richard A Popov V N Henrard L Kociak M (2008) Physical review letters 101(19) 197403.
[38] Levshov D (2013) Raman modes in index-identified individual single-walled and multi-walled carbon nanotubes. Unpublished PhD thesis. University of Montpellier 2.