

# Pure Spin Current Injection in Hydrogenated Graphene Structures

Reinaldo Zapata-Peña<sup>1</sup>, Bernardo S. Mendoza<sup>1</sup>, Anatoli I. Shkrebtii<sup>2</sup>

<sup>1</sup>*Centro de Investigaciones en Óptica, León, Guanajuato 37150, México and*

<sup>2</sup>*University of Ontario, Institute of Technology, Oshawa, ON, L1H 7L7, Canada*

(Dated: May 4, 2017)

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Etiam lobortis facilisis sem. Nullam nec mi et neque pharetra sollicitudin. Praesent imperdiet mi nec ante. Donec ullamcorper, felis non sodales commodo, lectus velit ultrices augue, a dignissim nibh lectus placerat pede. Vivamus nunc nunc, molestie ut, ultricies vel, semper in, velit. Ut porttitor. Praesent in sapien. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Duis fringilla tristique neque. Sed interdum libero ut metus. Pellentesque placerat. Nam rutrum augue a leo. Morbi sed elit sit amet ante lobortis sollicitudin. Praesent blandit blandit mauris. Praesent lectus tellus, aliquet aliquam, luctus a, egestas a, turpis. Mauris lacinia lorem sit amet ipsum. Nunc quis urna dictum turpis accumsan semper.

## I. INTRODUCTION

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Etiam lobortis facilisis sem. Nullam nec mi et neque pharetra sollicitudin. Praesent imperdiet mi nec ante. Donec ullamcorper, felis non sodales commodo, lectus velit ultrices augue, a dignissim nibh lectus placerat pede. Vivamus nunc nunc, molestie ut, ultricies vel, semper in, velit. Ut porttitor. Praesent in sapien. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Duis fringilla tristique neque. Sed interdum libero ut metus. Pellentesque placerat. Nam rutrum augue a leo. Morbi sed elit sit amet ante lobortis sollicitudin. Praesent blandit blandit mauris. Praesent lectus tellus, aliquet aliquam, luctus a, egestas a, turpis. Mauris lacinia lorem sit amet ipsum. Nunc quis urna dictum turpis accumsan semper. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Etiam lobortis facilisis sem. Nullam nec mi et neque pharetra sollicitudin. Praesent imperdiet mi nec ante. Donec ullamcorper, felis non sodales commodo, lectus velit ultrices augue, a dignissim nibh lectus placerat pede. Vivamus nunc nunc, molestie ut, ultricies vel, semper in, velit. Ut porttitor. Praesent in sapien. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Duis fringilla tristique neque. Sed interdum libero ut metus. Pellentesque placerat. Nam rutrum augue a leo.

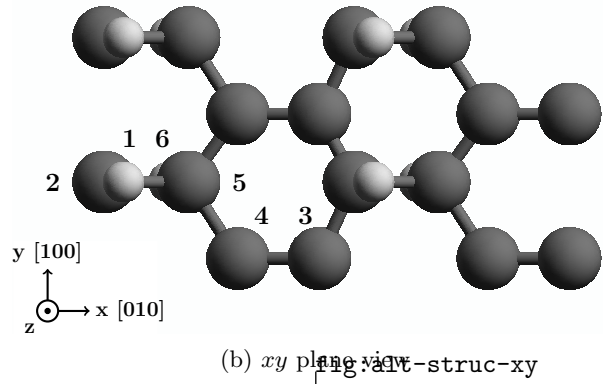
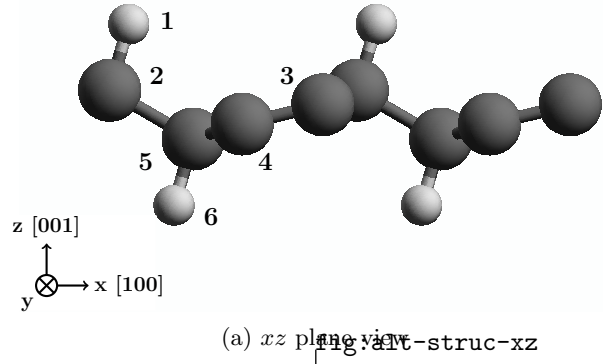


FIG. 1. Alt structure`fig:alt-struc`

Morbi sed elit sit amet ante lobortis sollicitudin. Praesent blandit blandit mauris. Praesent lec-

FIG. 2. Up structure `fig:up-struc`

tus tellus, aliquet aliquam, luctus a, egestas a, turpis. Mauris lacinia lorem sit amet ipsum. Nunc quis urna dictum turpis accumsan semper. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Etiam lobortis facilisis sem. Nullam nec mi et neque pharetra sollicitudin. Praesent imperdiet mi nec ante. Donec ullamcorper, felis non sodales commodo, lectus velit ultrices augue, a dignissim nibh lectus placerat pede. Vivamus nunc nunc, molestie ut, ultricies vel, sem-

per in, velit. Ut porttitor. Praesent in sapien. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Duis fringilla tristique neque. Sed interdum libero ut metus. Pellentesque placerat. Nam rutrum augue a leo. Morbi sed elit sit amet ante lobortis sollicitudin. Praesent blandit blandit mauris. Praesent lectus tellus, aliquet aliquam, luctus a, egestas a, turpis. Mauris lacinia lorem sit amet ipsum. Nunc quis urna dictum turpis accumsan semper.

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Etiam lobortis facilisis sem. Nullam nec mi et neque pharetra sollicitudin. Praesent imperdiet mi nec ante. Donec ullamcorper, felis non sodales commodo, lectus velit ultrices augue, a dignissim nibh lectus placerat pede. Vivamus nunc nunc, molestie ut, ultricies vel, semper in, velit. Ut porttitor. Praesent in sapien. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Duis fringilla tristique neque. Sed interdum libero ut metus. Pellentesque placerat. Nam rutrum augue a leo. Morbi sed elit sit amet ante lobortis sollicitudin. Praesent blandit blandit mauris. Praesent lectus tellus, aliquet aliquam, luctus a, egestas a, turpis. Mauris lacinia lorem sit amet ipsum. Nunc quis urna dictum turpis accumsan semper.

## II. THEORY

`sec:theory`

### A. Pure spin velocity

`sec:theory-pure_spin_current`

The spin density injection current  $\dot{K}^{ab}$  with speed along direction a and spin polarization along b is defined as

$$\dot{K} = \mu^{abcd}(\omega) E^c(\omega) E^{d*}(\omega) \quad \text{eq:dotk} \quad (1)$$

where

$$\mu^{abcd}(\omega) = \frac{\pi e^2}{\hbar^2} \int \frac{d^3 K}{8\pi^3} \sum'_{vc'} \text{Re} \left[ K_{cc'}^{ab} (r_{vc}^c r_{cv}^d + r_{vc'}^d r_{cv}^c) \right] \delta(\omega - \omega_{cv}) \quad \text{eq:mu} \quad (2)$$

is the corresponding spin density injection current pseudotensor. The ' in the sum means that

c and c' are quasi degenerate states and the sum only covers these states.

Now we define the spin velocity,  $\mathcal{V}^{\text{ab}}$  as the speed at which the spin polarized in the b direc-

tion moves along the a direction when a normal incident beam reaches the  $xy$  plane with a polarization angle  $\alpha$ . Then,

$$\begin{aligned}\mathcal{V}^{\text{ab}}(\omega) &= \frac{2}{\hbar} \frac{\mu^{\text{abxx}}(\omega)E^2(\omega)\cos^2(\alpha) + \mu^{\text{abyy}}(\omega)E^2(\omega)\sin^2(\alpha) + 2\mu^{\text{abxy}}(\omega)E^2(\omega)\cos(\alpha)\sin(\alpha)}{\xi^{\text{xx}}(\omega)E^2(\omega)\cos^2(\alpha) + \xi^{\text{yy}}(\omega)E^2(\omega)\sin^2(\alpha)}, \\ &= \frac{2}{\hbar} \frac{\mu^{\text{abxx}}(\omega)\cos^2(\alpha) + \mu^{\text{abyy}}(\omega)\sin^2(\alpha) + \mu^{\text{abxy}}(\omega)\sin(2\alpha)}{\xi^{\text{xx}}(\omega)\cos^2(\alpha) + \xi^{\text{yy}}(\omega)\sin^2(\alpha)}.\end{aligned}\quad \text{eq:vab} \quad (3)$$

For an angle  $\alpha = \frac{\pi}{4}$  this expression can be reduced to

$$\mathcal{V}^{\text{ab}}(\omega) = \frac{2}{\hbar} \frac{\mu^{\text{abxx}}(\omega) + \mu^{\text{abyy}}(\omega) + 2\mu^{\text{abxy}}(\omega)}{\xi^{\text{xx}}(\omega) + \xi^{\text{yy}}(\omega)}.\quad \text{eq:vab-90deg} \quad (4)$$

### B. Fixing spin

sec:theory-fixspin

Considering that we have 2D structures we can fix the spin direction along the  $x$ ,  $y$ , and  $z$  Cartesian coordinates and then define the magnitude of the spin velocity  $|\mathcal{V}_{\sigma^b}|$  in a fixed angle  $\gamma_b$  as

$$|\mathcal{V}_{\sigma^b}|(\omega) = \sqrt{(\mathcal{V}^{\text{ax}}(\omega))^2 + (\mathcal{V}^{\text{ay}}(\omega))^2}, \quad \text{eq:vs-mag} \quad (5)$$

$$\gamma_b(\omega) = \tan^{-1} \left( \frac{\mathcal{V}^{\text{ay}}(\omega)}{\mathcal{V}^{\text{ax}}(\omega)} \right), \quad \text{eq:gamma-ang} \quad (6)$$

where the angle is measured in the counter-clockwise direction from the positive  $x$  axis.

### C. Fixing velocity.

sec:theory-fixvel

In a similar way we can fix the velocity in the  $xy$  plane along  $x$  and  $y$  directions and define  $|\mathcal{V}^a|$  as

$$|\mathcal{V}^a|(\omega) = \sqrt{(\mathcal{V}^{\text{ax}}(\omega))^2 + (\mathcal{V}^{\text{ay}}(\omega))^2 + (\mathcal{V}^{\text{az}}(\omega))^2} \quad \text{eq:vv-mag} \quad (7)$$

and the corresponding polar and azimuthal angles  $\theta$  and  $\varphi$  as

$$\theta(\omega) = \cos^{-1} \left( \frac{\mathcal{V}^{\text{az}}(\omega)}{|\mathcal{V}^a(\omega)|} \right), \quad 0 \leq \theta \leq \pi, \quad \text{eq:polar-ang} \quad (8)$$

$$\varphi(\omega) = \tan^{-1} \left( \frac{\mathcal{V}^{\text{ay}}(\omega)}{\mathcal{V}^{\text{ax}}(\omega)} \right), \quad 0 \leq \varphi \leq 2\pi. \quad \text{eq:azimuthal-ang} \quad (9)$$

Layer No.	Atom type	Position [Å]		
		$x$	$y$	$z$
1	H	-0.61516	-1.42140	1.47237
2	C	-0.61516	-1.73300	0.39631
3	C	0.61516	1.73300	0.15807
4	C	0.61516	0.42201	-0.15814
5	C	-0.61516	-0.37396	-0.39632
6	H	-0.61516	-0.68566	-1.47237

TABLE I. Unit cell of *alt* structure. Layer division, atom types and positions for the *alt* structure. The structure unit cell was divided in six layers corresponding each one to atoms in different  $z$  positions. The corresponding layer atom position is depicted in Fig. 1 with the corresponding number of layer.

tab:alt-unitcell

### D. Layer-by-layer analysis.

sec:theory-layer

For a layered system we have that the total contribution of Eqns. (5) and (7) is given<sup>1</sup> by

$$|\mathcal{V}_{\sigma^b}(\omega)| = \ell_{\text{eff}} \sum_{\ell=1}^{N_{\text{eff}}} |\mathcal{V}_{\sigma^b}(\ell|\omega)| \quad \text{eq:vs-layer} \quad (10)$$

$$|\mathcal{V}^a(\omega)| = \ell_{\text{eff}} \sum_{\ell=1}^{N_{\text{eff}}} |\mathcal{V}^a(\ell|\omega)| \quad \text{eq:vv-layer} \quad (11)$$

## III. RESULTS

sec:results

We preset the results for  $\mathcal{V}^{\text{ab}}$  for the  $\text{C}_{16}\text{H}_8$ -alt and  $\text{C}_{16}\text{H}_8$ -up structures being both noncentrosymmetric semi-infinite carbon systems with 50% hydrogenation in different arrangements. The *alt* system has alternating hydrogen atoms

Layer No.	Atom type	Position [ $\text{\AA}$ ]		
		$x$	$y$	$z$
1	H	-0.61516	-1.77416	0.73196
1	H	0.61518	0.35514	0.73175
2	C	-0.61516	-1.77264	-0.49138
2	C	-0.61516	-0.35600	-0.72316
2	C	0.61516	0.35763	-0.49087

TABLE II. Unit cell of *up* structure. Layer division, atom types and positions for the *up* structure. The structure unit cell was divided in two layers corresponding to hydrogen and carbon atoms. The corresponding layer atom position is depicted in Fig. 2 with the corresponding number of layer.

on the upper and bottom sides of the carbon sheet, while the *up* system has H only on the upper side. We take the hexagonal carbon lattice to be on the  $xy$  plane for both structures, and the carbon-hydrogen bonds on the perpendicular  $xz$  plane, as depicted in Figs. 1 and 2.

Using the ABINIT code<sup>2</sup> we calculated the self-consistent ground state and the Kohn-Sham states using density functional theory in the local density approximation (DFT-LDA) with a planewave basis. We used Hartwigsen-Goedecker-Hutter (HGH) relativistic separable dual-space Gaussian pseudopotentials<sup>3</sup> including the spin-orbit interaction for calculating  $\mathcal{V}^a(\omega)$ .

The convergence parameters for the calculations of our results corresponding to the *alt* and *up* structures are cutoff energies of 65 Ha and 40 Ha, respectively. The energy eigenvalues and matrix elements were calculated using 14452  $\mathbf{k}$  points and 8452  $\mathbf{k}$  points in the irreducible Brillouin zone (IBZ) and present LDA energy band gaps of 0.72 eV and 0.088 eV, respectively for the *alt* and *up* structures. As mentioned in<sup>4</sup>, using DFT the LDA is only one method of many other that can be used to calculate the electronic structure of materials. Also it is known that all methods predict a different band gap than the obtained in the experiment. A correction for the band gap energy value can be calculated by other *ab-initio* methods such as the GW approximation<sup>5</sup> being this outside the scope of this paper.

The structures presented here were divided

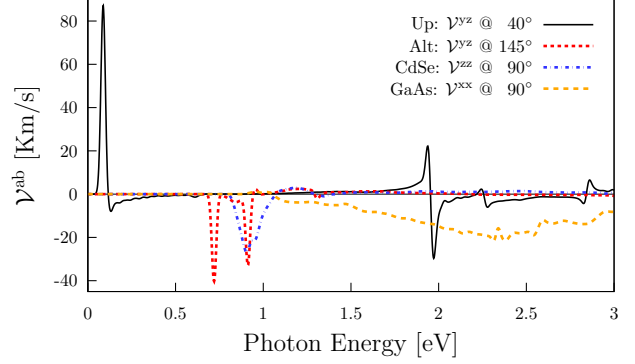


FIG. 3. Comparison of most intense responses for  $\mathcal{V}^{\text{ab}}$  for *alt*, *up*, CdSe, and GaAs structures.

into layers to analyze the layer-by-layer contribution for  $\mathcal{V}^{\text{ab}}$  response. The *alt* structure was divided in six layers corresponding the first one to the top hydrogen atoms, from the second to the forth to carbon atoms in different  $z$  positions, and the sixth and last one to the bottom hydrogen atoms. The *up* structure was divided into two layers, the first one comprised by the top hydrogen atoms and the second by the carbon atoms. The layer divisions and atom positions for the unit cells are shown in Tables I and II.

### A. Spin velocity

sec:res-pure\_spin\_current\_and\_spin\_velocity

In figure 3 we present a comparison of the most intense responses resulting from evaluate the Eq. (3) for the *alt* and *up* 2D structures vs. CdSe and GaAs bulk structures. As we can see from this figure the most intense response corresponds to the *up* structure centered at 0.088 eV corresponding to the terahertz radiation and reaching a spin velocity of 87.16 Km/s. In the other hand, for an energy range from 0.66 eV to 3.0 eV all the four structures have contributions in the same order of magnitude. Starting with the 2D structures we have that the *up* structure has other two peaks centered at 1.94 eV and 1.97 eV reaching spin velocities of 22.2 Km/s and -29.7 Km/s, respectively, and the *alt* structure has two peaks centered at 0.72 eV and 0.91 eV reaching spin velocities of -40.2 Km/s and -32.9 Km/s, respectively. Then, for the bulk structures we have that the CdSe has only one intense response centered at

Structure	Kind of system	Pol. Ang.	Energy [eV]	$\mathcal{V}^{ab}(\omega)$	
				ab	[Km/s]
<i>up</i>	2D	40	0.09	yz	87.16
			1.94	yz	22.22
			1.97	yz	-29.70
<i>alt</i>	2D	145	0.72	yz	-40.21
			0.91	yz	-32.89
CdSe	bulk	90	0.91	zz	-26.87
GaAs	bulk	90	2.31	xx	-21.62

TABLE III. Comparison of the reported maxima values of  $\mathcal{V}^{ab}$  for different structures and the corresponding polarization angle  $\alpha$  and energy values.

0.91 eV reaching a spin velocity of -26.9 Km/s, and the GaAs structure has a large and almost planar zone where the response is hold reaching the maximum for an incoming beam of energy of 2.31 eV and reaching a spin velocity of -21.6 Km/s. In table III we present the comparison of this values for the 2D and bulk structures.

### B. Fixing spin

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Etiam lobortis facilisis sem. Nullam nec mi et neque pharetra sollicitudin. Praesent imperdiet mi nec ante. Donec ullamcorper, felis non sodales commodo, lectus velit ultrices augue, a dignissim nibh lectus placerat pede. Vivamus nunc nunc, molestie ut, ultricies vel, semper in, velit. Ut porttitor. Praesent in sapien. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Duis fringilla tristique neque. Sed interdum libero ut metus. Pellentesque placerat. Nam rutrum augue a leo. Morbi sed elit sit amet ante lobortis sollicitudin. Praesent blandit blandit mauris. Praesent lectus tellus, aliquet aliquam, luctus a, egestas a, turpis. Mauris lacinia lorem sit amet ipsum. Nunc quis urna dictum turpis accumsan semper. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Etiam lobortis facilisis sem. Nullam nec mi et neque pharetra sollicitudin. Praesent imperdiet mi nec ante.

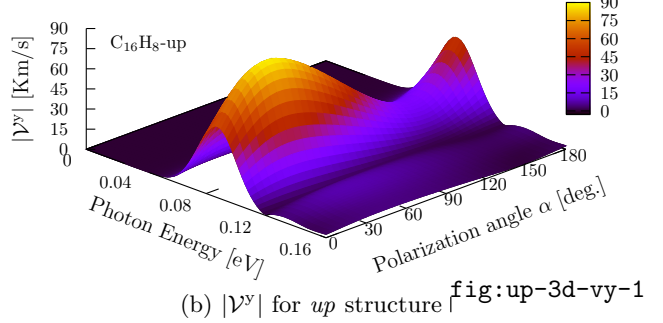
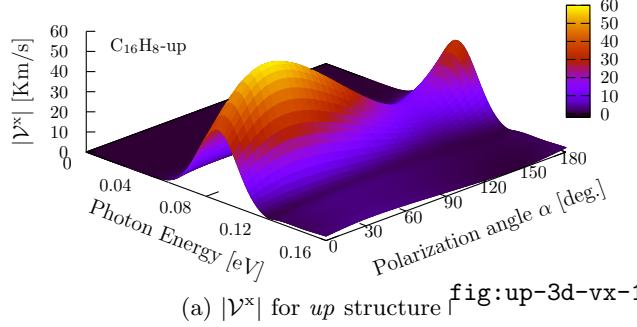


FIG. 4.  $|\mathcal{V}^x|$  response for C<sub>16</sub>H<sub>8</sub>-up structure. The maximum response zone is localized for an energy range from 0.04 eV to 0.12 eV and for a polarization angle of the incoming beam from 25° to 50°.

Donec ullamcorper, felis non sodales commodo, lectus velit ultrices augue, a dignissim nibh lectus placerat pede. Vivamus nunc nunc, molestie ut, ultricies vel, semper in, velit. Ut porttitor. Praesent in sapien. Lorem ipsum dolor sit amet, consectetur adipiscing elit. Duis fringilla tristique neque. Sed interdum libero ut metus. Pellentesque placerat. Nam rutrum augue a leo. Morbi sed elit sit amet ante lobortis sollicitudin. Praesent blandit blandit mauris. Praesent lectus tellus, aliquet aliquam, luctus a, egestas a, turpis. Mauris lacinia lorem sit amet ipsum. Nunc quis urna dictum turpis accumsan semper.

### C. Fixing velocity

#### Up structure.

For the *up* structure we first analyzed the energy range from 0.00 eV to 0.16 eV where we found the most intense response for  $\mathcal{V}^x$  and  $|\mathcal{V}^y|$ . In Fig. 4 we present the  $\mathcal{V}^a$  spectra resulting from evaluate again Eq. (7) using different polarization angles  $\alpha$  in Eq. (3) but now for the

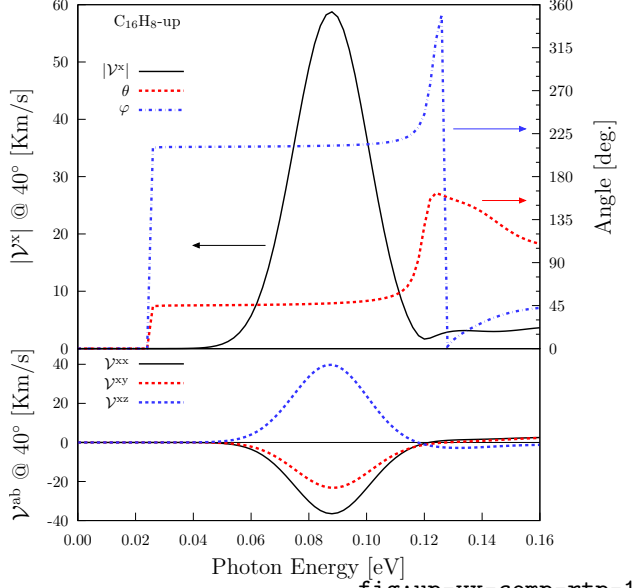
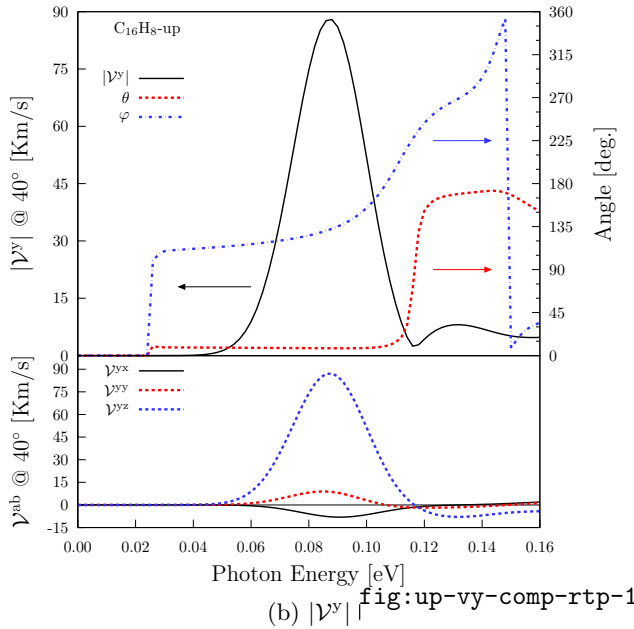
(a)  $|V^x|$  fig:up-vx-comp-rtp-1(b)  $|V^y|$  fig:up-vy-comp-rtp-1

FIG. 5. Most intense responses of  $|V^x|$  and  $|V^y|$  and the corresponding three components for the  $up$  structure. Both maxima were obtained for a polarization angle  $\alpha = 40^\circ$ .

fig:up-vab-comp-rtp-1

$C_{16}H_8$ -up structure. We can see that the onset of the response is when the energy of the incoming light is the same of the gap energy. From this picture we can see that for the zone between the energy range of 0.084 eV-0.093 eV and polarization angles between  $30^\circ$  and  $45^\circ$  is the zone where the maximum zone of response for both,

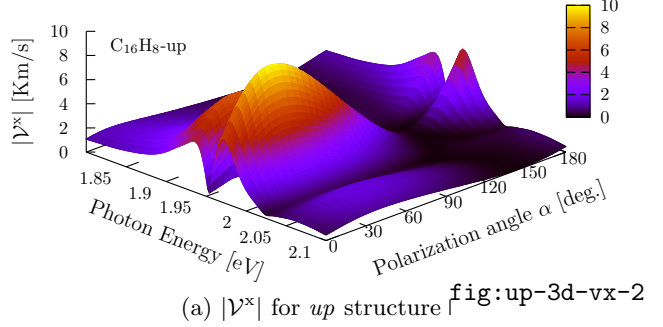
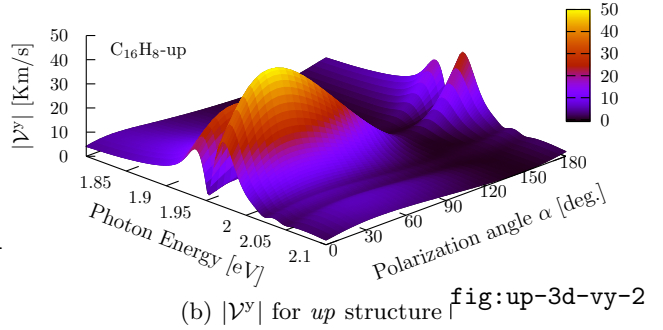
(a)  $|V^x|$  for  $up$  structure fig:up-3d-vx-2(b)  $|V^y|$  for  $up$  structure fig:up-3d-vy-2

FIG. 6.  $|V^x|$  and  $|V^y|$  response for  $C_{16}H_8$ -up structure. The local maxima responses zones are localized for an energy range from 1.95 eV to 2.00 eV and for polarization angles of the incoming beam from  $25^\circ$  to  $50^\circ$ .

fig:up-3d-2

$|V^x|$  and  $|V^y|$  is hold. We found that the absolute maximum of the response is obtained when the polarization angle is  $\alpha = 40^\circ$  and the energy of the incoming beam is 0.088 eV. In the top frames of Figs. 5(a) and 5(b) we present the results of  $|V^x|$  and  $|V^y|$  (left scale) fixing the polarization angle to  $\alpha = 40^\circ$  for the  $up$  structure vs photon energy and the corresponding polar  $\varphi$  and azimuthal  $\theta$  angles (right scale). In the bottom frames of same figures we present the decomposition of  $|V^x|$  and  $|V^y|$  in the corresponding  $V^{xx}$ ,  $V^{xy}$ ,  $V^{xz}$ , and  $V^{yx}$ ,  $V^{yy}$ ,  $V^{yz}$  components with  $\alpha$  fixed to  $40^\circ$ .

From Fig. 5(a) we have that for an incoming beam with energy of 0.088 eV the three components have similar contributions and have values of  $V^{xx} = -36.5$  Km/s,  $V^{xy} = -23.2$  Km/s, and  $V^{xz} = 39.8$  Km/s resulting in a value of  $|V^x| = 58.7$  Km/s being this value the absolute maximum obtained when the spin-velocity is fixed in the  $x$  direction. To this value corresponds a polar and azimuthal angles of  $\varphi = 47.4$  and  $\theta = 212.5$ , respectively. Now, from Fig. 5(b)



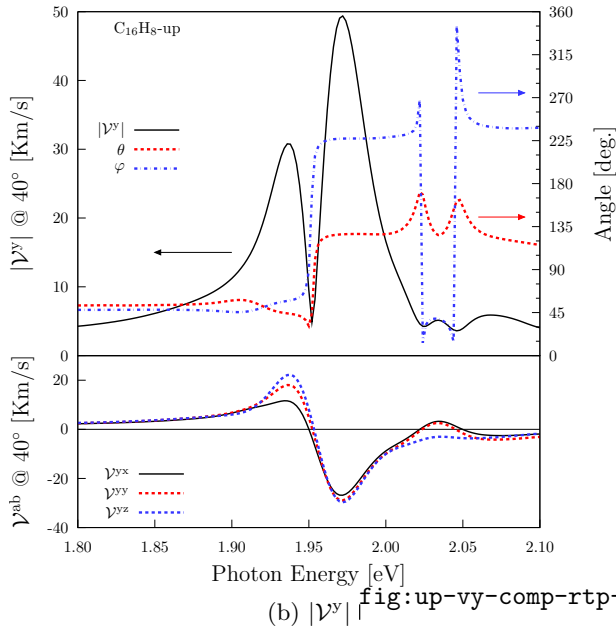
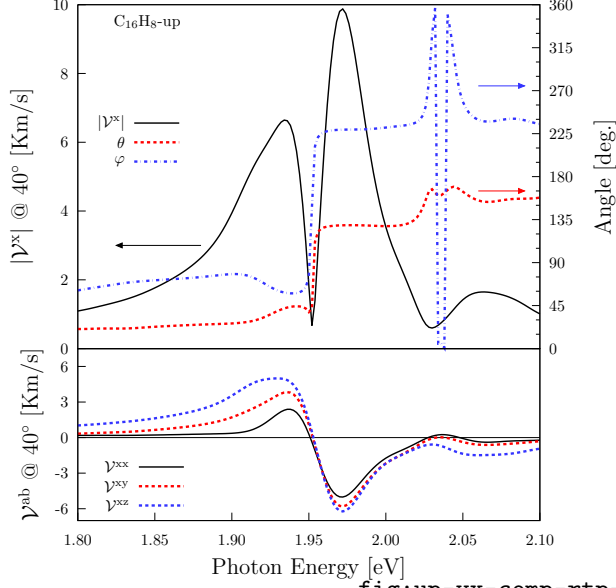


FIG. 7. Intense responses of  $|V^x|$  and  $|V^y|$  and the corresponding three components for the *up* structure. Both maxima were obtained for a polarization angle  $\alpha = 40^\circ$ .

fig:up-vab-comp-rtp-2

we have that the *yx* and *yy* components have less contributions for the total response than the *yz* and for the same incoming beam energy have values of  $V^{yx} = -7.9$  Km/s  $V^{yy} = 8.6$  Km/s, and  $V^{yz} = 87.2$  Km/s resulting in a value of the total response of  $|V^y| = 87.9$  Km/s being this value the absolute maximum obtained when the spin-velocity is fixed in the *y* direction and being 1.5

times more intense than  $|V^x|$  and corresponding spin polar and azimuthal angles  $\varphi = 7.6^\circ$   $\theta = 132.7^\circ$ , respectively. We also found that since the onset of the response till an energy for the incoming beam of 0.118 eV the components of both,  $|V^x|$  and  $|V^y|$  have no change in the spin polarization direction. Finally, after this energy value both goes to zero. Also there is another energy range of interest for an incoming energy beam from 1.80 eV to 2.10 eV presented in Fig. 6 where two local maxima of  $|V^x|$  and  $|V^y|$  are obtained for the *up* structure resulting from evaluate Eqns. (7) and (3). From this figure we have that for the zone between the energy ranges from 1.92 eV to 1.94 eV and from 1.96 eV to 1.98 eV and angles from  $30^\circ$  to  $45^\circ$  those maxima zones are hold. We found that the maxima are obtained when the polarization angle is fixed to  $40^\circ$  and the corresponding energies are 1.934 eV and 1.972 eV. Again, in the top frames of Figs. 7(a) and 7(b) we present the results of  $|V^x|$  and  $|V^y|$  (left scale) fixing the polarization angle to  $\alpha = 40^\circ$  vs the photon energy and the corresponding polar  $\varphi$  and azimuthal  $\theta$  angles (right scale) for the *up* structure. In the bottom frames of same figures we present the three components *xx*, *xy*, *xz*, and *yx*, *yy*, *yz* corresponding to  $|V^x|$  and  $|V^y|$  fixing the polarization angle to  $40^\circ$ . We found that for both cases,  $|V^x|$  and  $|V^y|$ , the corresponding components have similar contributions and for an incoming energy beam of 1.934 eV have values of  $V^{xx} = 2.3$  Km/s,  $V^{xy} = 3.8$  Km/s,  $V^{xz} = 4.9$  Km/s, and  $V^{yx} = 11.5$  Km/s,  $V^{yy} = 17.0$  Km/s,  $V^{yz} = 20.4$  Km/s resulting in a in values of  $|V^x| = 6.6$  Km/s  $|V^y| = 28.7$  Km/s being  $|V^y|$  4.3 times more intense than  $|V^x|$  for this photon energy. The responses have polar and azimuthal spin polarization angles  $\varphi = 42.0^\circ$  and  $\theta = 58.7^\circ$  for  $|V^x|$  and  $\varphi = 45.2^\circ$  and  $\theta = 56.0^\circ$  for  $|V^y|$ . Alike, for an incoming energy beam of 1.972 eV all the components of  $|V^x|$  and  $|V^y|$  have similar contributions having values of  $V^{xx} = -5.0$  Km/s,  $V^{xy} = -5.8$  Km/s,  $V^{xz} = -6.2$  Km/s, and  $V^{yx} = -26.8$  Km/s,  $V^{yy} = -28.9$  Km/s,  $V^{yz} = -29.7$  Km/s resulting in a in values of  $|V^x| = 9.9$  Km/s  $|V^y| = 49.4$  Km/s being  $|V^y|$  5.0 times more intense than  $|V^x|$  for this photon energy. The responses have

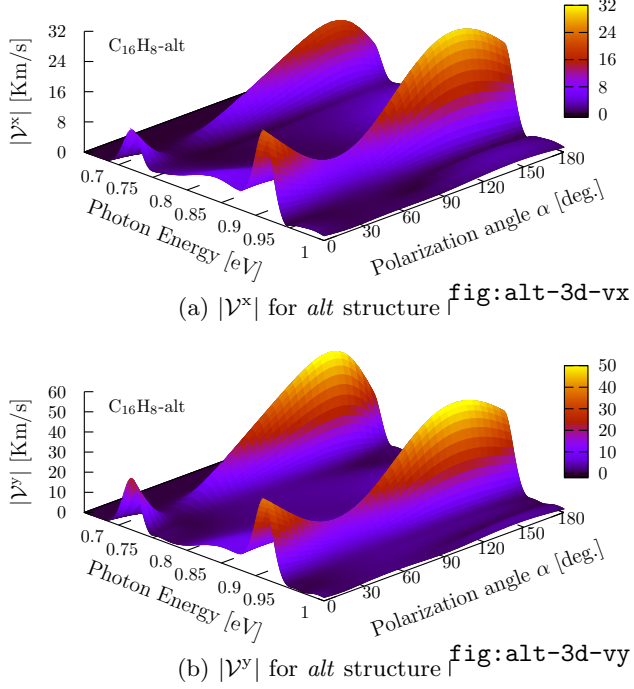


FIG. 8.  $|V^x|$  and  $|V^y|$  responses for  $C_{16}H_8$ -alt structure. The maxima responses zones are localized for an energy range from 0.90 eV to 0.93 eV and for polarization angles of the incoming beam from 120° to 150°.

polar and azimuthal spin polarization angles  $\varphi = 129.0^\circ$   $\theta = 229.1^\circ$  or  $|V^x|$  and  $\varphi = 127.0^\circ$  and  $\theta = 227.1^\circ$  for  $|V^y|$ . Finally we have that all the tree components of  $|V^x|$  and  $|V^y|$  keep the spin polarization positive till an energy of the incoming beam equal to 1.954 eV when the spin polarization changes the direction and after an energy for the incoming beam equal to 2.05 eV both responses goes to zero.

#### Alt structure.

For the *alt* structure we analyzed the energy range from 0.6 eV to 1.0 eV where we found the most intense response for  $|V^x|$  and  $|V^y|$ . In Fig. 8 we present the  $|V^a|$  spectra resulting from evaluate Eq. (7) using different polarization angles  $\alpha$  in Eq. (3) for the  $C_{16}H_8$ -alt structure. We can see that the onset of the response is when the energy of the incoming light is the same of the gap energy. From this picture we can see that for the zone between the energy range of 0.90 eV-0.93 eV and polarization angles between 120° and 150° is the zone where the maximum response for both,  $|V^x|$  and  $|V^y|$  is kept. We

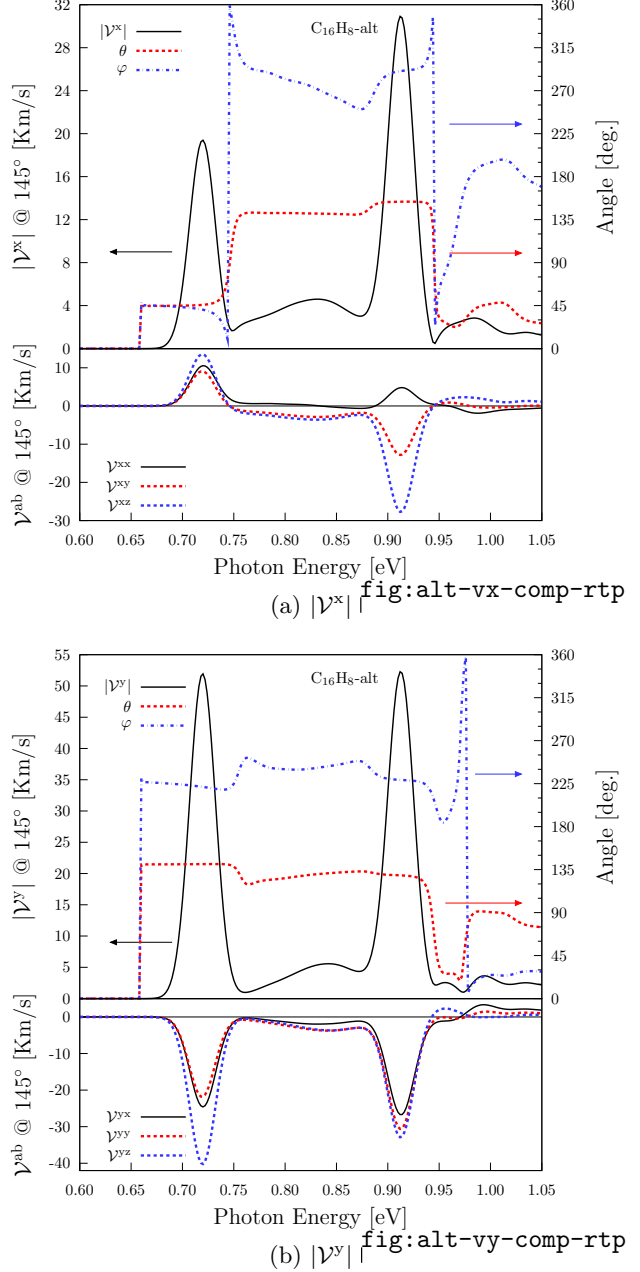


FIG. 9. Most intense responses of  $|V^x|$  and  $|V^y|$  and the corresponding three components for the *alt* structure. Both maxima where obtained for a polarization angle  $\alpha = 145^\circ$ .

also found that the absolute maximum of the response is obtained when the energy of the incoming beam is 0.912 eV and the polarization angle is  $\alpha = 145^\circ$ . In the top frames of Figs. 9(a) and 9(b) we present the results for  $|V^x|$  and  $|V^y|$  (left scale) fixing the polarization angle to  $145^\circ$  for the *alt* structure vs the photon energy and



the corresponding polar  $\varphi$  and azimuthal  $\theta$  angles (right scale). Also in the bottom frames of Figs. 9(a) and 9(b) we present the decomposition of  $|\mathcal{V}^x|$  and  $|\mathcal{V}^y|$  in the corresponding components  $\mathcal{V}^{xx}$ ,  $\mathcal{V}^{xy}$ ,  $\mathcal{V}^{xz}$  and  $\mathcal{V}^{yx}$ ,  $\mathcal{V}^{yy}$ ,  $\mathcal{V}^{yz}$  with  $\alpha$  fixed to  $145^\circ$ . Making the analysis for the components and angles for  $|\mathcal{V}^x|$  depicted in Fig. 9(a) we can see that for an incoming beam energy of 0.720 eV the components contributions are similar having values of  $\mathcal{V}^{xx} = 10.5$  Km/s,  $\mathcal{V}^{xy} = 9.1$  Km/s, and  $\mathcal{V}^{xz} = 13.5$  Km/s resulting in a total spin-velocity  $|\mathcal{V}^x| = 19.4$  Km/s and spin polar and azimuthal angles  $\varphi = 45.8^\circ$  and  $\theta = 40.7^\circ$ , respectively. In the other hand, for an energy of the incoming beam equal to 0.912 eV we found that the contribution of the components are  $\mathcal{V}^{xx} = 4.8$  Km/s,  $\mathcal{V}^{xy} = -12.8$  Km/s, and  $\mathcal{V}^{xz} = -27.7$  Km/s having a mayor response coming from the  $xz$  component and resulting in a spin-velocity magnitude  $|\mathcal{V}^x| = 30.9$  Km/s being this the absolute maximum fixing the spin-velocity in the  $x$  direction. Then, the components give us polar and azimuthal angles with values of  $\varphi = 153.8^\circ$  and  $\theta = 290.4^\circ$ . This angles and its variation with the incoming energy beam are presented in the right scale of the top frame of Fig 9(a). Finally we have that since the onset of the response till an energy of the incoming beam of 0.744 eV the three components of  $|\mathcal{V}^x|$  are positive while for the range from 0.746 eV to 0.886 eV the  $\mathcal{V}^{xx}$  component is positive but the  $\mathcal{V}^{xy}$  and  $\mathcal{V}^{xz}$  components change in direction. This is due to a change in the spin polarization direction. Finally after the energy value of 0.886 eV the response decreases and goes to zero. Making now the analysis for  $|\mathcal{V}^y|$  depicted in Fig. 9(b) we have that for an incoming energy beam of 0.720 eV the  $yz$  component have a major contribution than the  $yx$  and  $yy$  components having values of  $\mathcal{V}^{yx} = -24.6$  Km/s,  $\mathcal{V}^{yy} = -21.8$  Km/s, and  $\mathcal{V}^{yz} = -40.2$  Km/s resulting in a total spin-velocity  $|\mathcal{V}^y| = 51.9$  Km/s and spin polar and azimuthal angles  $\varphi = 140.7^\circ$  and  $\theta = 221.6^\circ$ , respectively. Also, for an energy of the incoming beam of 0.912 eV we found that the contribution of the components are  $\mathcal{V}^{xx} = -26.7$  Km/s,  $\mathcal{V}^{xy} = -30.6$  Km/s, and  $\mathcal{V}^{xz} = -32.9$  Km/s having all the three components similar contributions and resulting in a

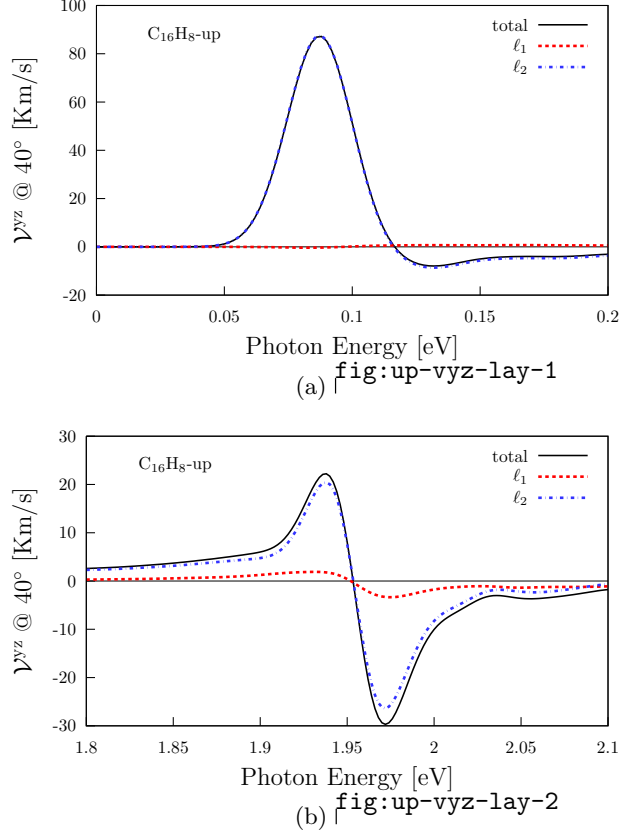


FIG. 10. Layer-by-layer contribution of  $\mathcal{V}^{yz}$  for the *up* structure.

fig:up-vyz-lay

spin-velocity magnitude  $|\mathcal{V}^y| = 52.3$  Km/s being this the absolute maximum spin-velocity for the velocity fixed to the  $y$  direction and being 1.7 times more intense than the maximum of  $|\mathcal{V}^x|$ . The components then give us the polar and azimuthal angles with values of  $\varphi = 129.0^\circ$  and  $\theta = 228.9^\circ$ , respectively. This angles and the corresponding variation is presented in the right sale of the top frame of Fig. 9(b). We also have that the three components of  $|\mathcal{V}^y|$  are negative keeping the same spin polarization since the onset of the response to a energy of the incoming beam of 0.886 eV when the response decreases and goes to zero.

#### IV. LAYER-BY-LAYER ANALYSIS

sec:res-layer\_by\_layer\_analysis

From the bottom frames of Figs. 5 and 7 we can see that for the *up* structure again the most intense component of  $|\mathcal{V}^x|$  and  $|\mathcal{V}^y|$  corresponds to  $\mathcal{V}^{yz}$  which has a value of 87.2 Km/s for an en-

ergy incident beam of 0.088 eV and -29.7 Km/s for an energy incident beam of 1.972 eV. This component and the corresponding layer by layer contribution is depicted in Fig. 10s. From this figure we have that for the energy range from 0 eV to 0.2 eV the response comes from the second layer composed by carbon atoms presented in Tab. II and denoted by the number 2 in Fig. 2. In the other hand, the response for the energy range from 1.8 eV to 2.1 eV almost all the response comes from the carbon atoms having a lesser contribution from the hydrogen layer. From the bottom frames of Fig. 9 we can see that for the *alt* structure the most intense component of  $|\mathcal{V}^x|$  and  $|\mathcal{V}^y|$  corresponds to  $\mathcal{V}^{yz}$  which has a value of -40.2 Km/s for an energy incident beam of 0.72 eV. This component and the corresponding layer by layer contribution is depicted in Fig. 11. From this figure we have that for the energy range from 0.70 eV to 0.74 eV the fifth and sixth layers corresponding to the bottom carbon and hydrogen numbered with 5 and 6 in Fig. 1 have contributions in opposite direc-

tion than the other 4 layers resulting in a total response  $\mathcal{V}^{yz} = -40.2$  Km/s for an incoming beam energy of 0.72 eV. In the other hand, for the energy range from 0.88 eV to 0.95 eV the response for the all six layers the responses are in the same direction resulting in a total response  $\mathcal{V}^{yz} = -32.89$  Km/s for an incoming beam with energy of 0.912 eV.

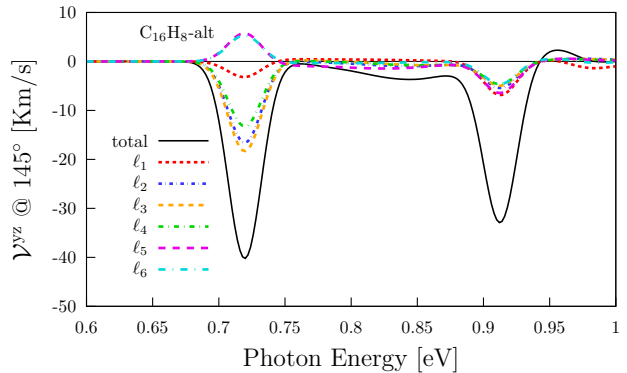


FIG. 11. Layer-by-layer contribution of  $\mathcal{V}^{yz}$  for the *alt* structure. fig:alt-vyz-lay

- 
- <sup>1</sup> N. Arzate, R. A. Vázquez-Nava, and B. S. Mendoza, Phys. Rev. B **90**, 205310 (2014).  
<sup>2</sup> X. Gonze, B. Amadon, P.-M. Anglade, J.-M. Beuken, F. Bottin, P. Boulanger, F. Bruneval, D. Caliste, R. Caracas, M. Côté, T. Deutsch, L. Genovese, P. Ghosez, M. Giantomassi, S. Goedecker, D. Hamann, P. Hermet, F. Jollet, G. Jomard, S. Leroux, M. Mancini, S. Mazevet, M. Oliveira, G. Onida, Y. Pouillon, T. Rangel, G.-M. Rignanese, D. Sangalli, R. Shaltaf, M. Torrent,

- M. Verstraete, G. Zerah, and J. Zwanziger, Comput. Phys. Commun. **180**, 2582 (2009).  
<sup>3</sup> C. Hartwigsen, S. Goedecker, and J. Hutter, Phys. Rev. B **58**, 3641 (1998).  
<sup>4</sup> R. Zapata-Peña, S. M. Anderson, B. S. Mendoza, and A. I. Shkrebtii, physica status solidi (b) **253**, 226 (2016).  
<sup>5</sup> G. Onida, L. Reining, and A. Rubio, Rev. Mod. Phys. **74**, 601 (2002).