Localized and resonant guided elastic waves in an adsorbed layer on a semi-infinite superlattice

D. Bria, E. H. El Boudouti, and A. Nougaoui
Laboratoire de Dynamique et d'Optique des Matériaux, Département de Physique, Faculté des Sciences, Université Mohamed I, Boîte Postale 524, 60000 Oujda, Morocco

B. Djafari-Rouhani
Laboratoire de Dynamique et Structure des Matériaux Moléculaires, Unité 8024 associée au Centre National de la Recherche Scientifique, Université de Lille 1, 59655 Villeneuve d'Ascq, France

V. R. Velasco
Instituto de Ciencia de Materiales, CSIC, Cantoblanco, 28049 Madrid, Spain

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The pseudoguided acoustic modes associated with an adlayer deposited on a substrate may become very weak resonances, difficult to detect experimentally, due to their interaction with the substrate modes. In this paper, we show that the observation of these modes can be made possible, or at least facilitated, when the substrate is a superlattice instead of being a homogeneous medium. This is essentially due to the existence of minigaps, and also of two types of polarizations for the minibands, which may prohibit the propagation of the guided modes of the adsorbed layer into the superlattice and therefore increase the degree of localization of these guided modes. These features are especially relevant at high acoustic velocities (in particular around and above the longitudinal velocity of sound in the adlayer) or in the case of a hard layer where the resonances may become very weak if the substrate is made of a homogeneous material. The purpose of this paper is to demonstrate theoretically this new phenomenon with a few illustrations. The localized and resonant modes associated with the adlayer are obtained from a calculation of the total and local density-of-states by means of a Green's function method. The existence and behavior of the guided modes are discussed as a function of the nature and thickness of the adsorbate, the nature of the layer in the superlattice that is in contact with the adlayer, and the wave vector $k_{\parallel}$ (parallel to the layers).

I. INTRODUCTION

In the past years, interest has turned to acoustic waves in adsorbed layers.[1] For this purpose, homogeneous materials (substrates) are commonly used as supports for the adsorbates, and the propagation of surface acoustic waves in these systems depends on the relative magnitudes of the transverse and longitudinal velocities of sound in these two materials.[1–3] These studies[4–12] have been performed mostly in the vicinity of the transverse threshold of the adsorbate and below the transverse velocity of sound in the substrate and therefore these modes become guided waves of mainly transverse character in adsorbed layers. Some years ago,[13–23] much attention was devoted to the propagation of acoustic modes lying above the substrate velocity of sound and in the vicinity of the longitudinal threshold of the adsorbate, the so-called longitudinal guided modes (LGM's). The LGM's are resonances (also called leaky or pseudomodes) with a displacement field having mainly a longitudinal character and propagating in the film. These pseudomodes are polarized in the sagittal plane, defined by the wave vector $k_{\parallel}$ (parallel to the surface), and the normal to the surface. LGM's in one adsorbed layer[14–17] were investigated by Brillouin light scattering, and the experimental results were found to be in agreement with a Brillouin scattering cross-section theory.[16] Similar investigations were performed for two adsorbed layers[13,19,20] and for finite superlattice[24,25] considered as effective homogeneous media. Let us notice that the measure of surface modes and pseudomodes by Brillouin spectroscopy helps one to characterize the elastic properties of thin films[17,21] and superlattices.[24,25]

However, as mentioned above, in all these studies, the adsorbed layers are deposited on a homogeneous substrate; therefore the guided modes in these layers fall inside the substrate bulk bands. This is, in particular, the case for LGM's that lie at high velocity range in the vicinity of the longitudinal velocity of sound in the adsorbate, and thus partial waves of these modes can propagate into the substrate. Consequently, the LGM's may strongly interact with the substrate modes giving rise to weak resonances or pseudomodes, which are not usually easy to detect experimentally.[14–17] After the completion of our paper, two papers[26,27] appeared dealing with the experimental observations of high velocity acoustic modes of a hard layer deposited on a substrate. Although they show the possibility of detecting some resonances in a few systems, these works again emphasize the general difficulty of observing the guided modes of adlayers when their velocities fall inside the substrate bulk bands.

The object of the present paper is to put forward a new idea for making possible, or at least facilitate, the observation of the guided modes in an adlayer, namely, to use a superlattice, instead of a homogeneous medium, as the substrate (see Fig. 1). This opens the possibility of finding true guided modes in the adsorbed layer, when these modes fall inside the minigaps of the superlattice (SL). Indeed the

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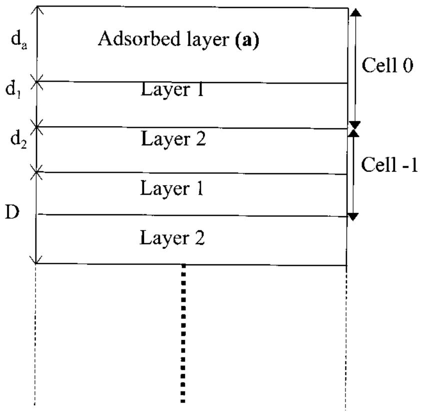

FIG. 1. A schematic representation of a semi-infinite two-layer SL ($i=1,2$) with an adsorbed layer ($i=a$). d_a, d_1, and d_2 are, respectively, the thicknesses of the adsorbed layer and of the two different slabs out of which the unit cell of the SL is built. D is the period of the SL.

SL acts as a barrier for the propagation of these modes that remain well-defined guided waves of the topmost layer. Some of the modes of the adlayer fall inside the minibands of the SL, giving rise to pseudoguided modes; however, even these resonances may still remain very sharp, in particular due to the existence of two types of polarization of the waves in the SL minibands. The advantage of using a SL rather than a homogeneous medium as the substrate is especially relevant in the high acoustic velocity range. To the best of our knowledge, this phenomenon has not been addressed in any previous work.

The above physical idea is demonstrated here by calculating the total and local density-of-states (DOS) associated with an adlayer deposited on a superlattice, where the true (or localized) and resonant surface modes appear as well-defined peaks of the DOS. The calculation is performed within a Green's function formalism, which is quite suitable for studying the spectral properties of composite materials. We have previously applied such a formalism to the case of one[18] and two[22,23] adsorbed layers deposited on a substrate. In the present paper, we are interested in calculating both local and total DOS of sagittal acoustic modes associated with an adsorbed layer on a semi-infinite superlattice (Fig. 1). The knowledge of the DOS in these structures enables us to determine the spatial distribution of the modes and, in particular, the possibility of localized and resonant guided modes that appear as well-defined peaks of the DOS inside the minigaps and inside the bulk bands of the SL, respectively. One can compare the sharpness of these peaks when the adlayer is deposited on a SL or on a homogeneous substrate. The latter structure is obtained from the former one by taking the two layers constituting the SL (Fig. 1) of the same material.

From the theoretical point of view, this paper generalizes our previous calculation of Green's function for a semi-infinite SL with a stress free surface[28] and for the interface between a semi-infinite SL and an homogeneous substrate;[29] to the best of our knowledge, the SL/adsorbed layer Green's function associated with sagittal modes has not been calculated before.[30] However, the main object of this paper is to discuss the physical behavior of the guided modes associated with the adlayer and the details about the theoretical method will be given elsewhere.[31]

The paper is organized as follows. A brief presentation of the formalism is given in Sec. II. Section III contains the study and discussion of the behavior of the guided modes associated with an adlayer deposited on a SL, with the emphasis on the advantage of using a SL, rather than a homogeneous medium, as the substrate. The conclusions are presented in Sec. IV.

II. METHOD OF CALCULATION

Consider a slab of material $i=a$ adsorbed on a semi-infinite SL formed from a semi-infinite repetition of two different slabs $i=1$, 2. We call d_i ($i=1,2,a$) the thickness of each type of slab. All the interfaces are taken to be parallel to the (x_1,x_2) plane. A space position along the x_3 axis in medium i belonging to the unit cell n is indicated by (n,i,x_3), where $-d_i/2 \leqslant x_3 \leqslant d_i/2$ (see Fig. 1). The period of the SL is called $D=d_1+d_2$. All the three media are assumed to be isotropic elastic media, each characterized by its mass density ρ and its elastic constants C_{11} and C_{44}. The squares of the bulk longitudinal and transverse velocities of sound in each medium are, respectively, given by

$$C_l^2=C_{11}/\rho, \quad C_t^2=C_{44}/\rho. \tag{1}$$

Due to the isotropy within the (x_1,x_2) plane, the shear horizontal vibrations are decoupled from those polarized within the sagittal plane, for any value of the propagation vector $\mathbf{k}_\parallel$ parallel to the interfaces.

In this paper we calculate the DOS by using the theory of interface response in composite material.[32] In this theory, the Green's function $\mathbf{g}$ of a composite system can be written as

$$\mathbf{g}(DD)=\mathbf{G}(DD)+\mathbf{G}(DM)[\mathbf{G}^{-1}(MM)\mathbf{g}(MM) \times\mathbf{G}^{-1}(MM)-\mathbf{G}^{-1}(MM)]\mathbf{G}(MD), \tag{2}$$

where D and M are, respectively, the whole space and the space of the interfaces in the composite material. G is a block-diagonal matrix in which each block $\mathbf{G}_i$ corresponds to the bulk Green's function of the subsystem i. In our case, the composite material is composed of a SL built out of alternating slabs of materials i ($i=1,2$) with thickness d_i, in contact with an adsorbed layer of material $i=a$. In Eq. (2) the calculation of $\mathbf{g}(DD)$ requires, besides $\mathbf{G}_i$, the knowledge of $\mathbf{g}(MM)$. In practice, the latter is obtained[32] by inverting the matrix $\mathbf{g}^{-1}(MM)$, which can be simply built from a juxtaposition of the matrices $\mathbf{g}_{si}^{-1}(MM)$, where $\mathbf{g}_{si}^{-1}(MM)$ is the interface Green's function of the slabs i ($i=1,2$) and of the adsorbed layer alone. Let us emphasize that, in the geometry of the SL/adsorbed layer structure, the elements of the Green's function take the form $g_{\alpha\beta}(\omega^2,k_\parallel|n,i,x_3;n',i',x_3')$, where ω is the frequency of the acoustic wave, $k_\parallel$ the wave vector parallel to the interfaces, and α, β denote the directions $x_1(\equiv 1)$, $x_2(\equiv 2)$, and $x_3(\equiv 3)$. For the sake of simplicity, we shall omit in the following the parameters ω^2 and $k_\parallel$, and we note as $g(n,i,x_3,n',i',x_3')$ the 3×3 matrix whose elements are $g_{\alpha\beta}(n,i,x_3,n',i',x_3')$ $(\alpha,\beta=1,2,3)$.

By assuming that $k_\parallel$ is along the x_1 direction, the components g_{22} decouple from the components $g_{11},g_{13},g_{31},g_{33}$

TABLE I. Transverse and longitudinal velocities and mass densities for W, Al, and Si.

	C_t (m/s)	C_l (m/s)	ρ(Kg/m^3)
W	2860	5231	19300
Al	3110	6422	2700
Si	5845	8440	2330

(i.e., $g_{12}=g_{21}=g_{23}$, $g_{32}=0$); the former corresponds to shear horizontal vibrations whereas the latter are associated with the vibrations polarized in the sagittal plane.

The knowledge of the response function g in the SL/adsorbed layer system enable us to calculate the local density-of-states for a given value of the wave vector $k_\parallel$:

$$n_\alpha(\omega^2,k_\parallel;n,i,x_3)=-\frac{\rho^{(i)}}{\pi}\mathrm{Im}\,g_{\alpha\alpha}(\omega^2,k_\parallel|n,i,x_3;n,i,x_3),$$

$$(\alpha=1,2,3) \tag{3a}$$

or

$$n_\alpha(\omega,k_\parallel;n,i,x_3)=-\frac{2\omega}{\pi}\rho^{(i)}\mathrm{Im}\,g_{\alpha\alpha}(\omega^2,k_\parallel|n,i,x_3;n,i,x_3),$$

$$(\alpha=1,2,3). \tag{3b}$$

The total density-of-states for a given value of $k_\parallel$ is obtained by integrating over x_3 and summing over n,i, and α the local density $n_\alpha(\omega^2,k_\parallel;n,i,x_3)$. More particularly we are interested in this total density-of-states from which the contributions of the infinite SL have been subtracted. This variation $\Delta n(\omega^2)$ can be written as the sums of the variations $\Delta n_1(\omega^2)$, $\Delta n_2(\omega^2)$ in the DOS in layers 1 and 2, and the DOS $n_a(\omega^2)$ in the adsorbed layer (a), respectively.

$$\Delta n(\omega^2)=\Delta n_1(\omega^2)+\Delta n_2(\omega^2)+n_a(\omega^2), \tag{4}$$

where

$$\Delta n_1(\omega^2)=-\frac{\rho^{(1)}}{\pi}\mathrm{Im\,tr}\left\{\sum_{n=-\infty}^{0}\int_{-d_1/2}^{d_1/2}[\mathbf{d}(n,i=1,x_3;\, n,i=1,x_3)-\mathbf{g}(n,i=1,x_3;n,i=1,x_3)]dx_3\right\}, \tag{5}$$

$$\Delta n_2(\omega^2)=-\frac{\rho^{(2)}}{\pi}\mathrm{Im\,tr}\left\{\sum_{n=-\infty}^{-1}\int_{-d_2/2}^{d_2/2}[\mathbf{d}(n,i=2,x_3;\, n,i=2,x_3)-\mathbf{g}(n,i=2,x_3;n,i=2,x_3)]dx_3\right\}, \tag{6}$$

$$n_a(\omega^2)=-\frac{\rho^{(a)}}{\pi}\mathrm{Im\,tr}\left\{\int_{-d_a/2}^{d_a/2}\mathbf{d}(n=0,i=\mathbf{a},x_3;\, n=0,i=\mathbf{a},x_3)dx_3\right\} \tag{7}$$

where $\mathbf{d}$ and $\mathbf{g}$ are the Green's functions of the coupled (SL/adsorbed layer) system and of the infinite SL, respectively.

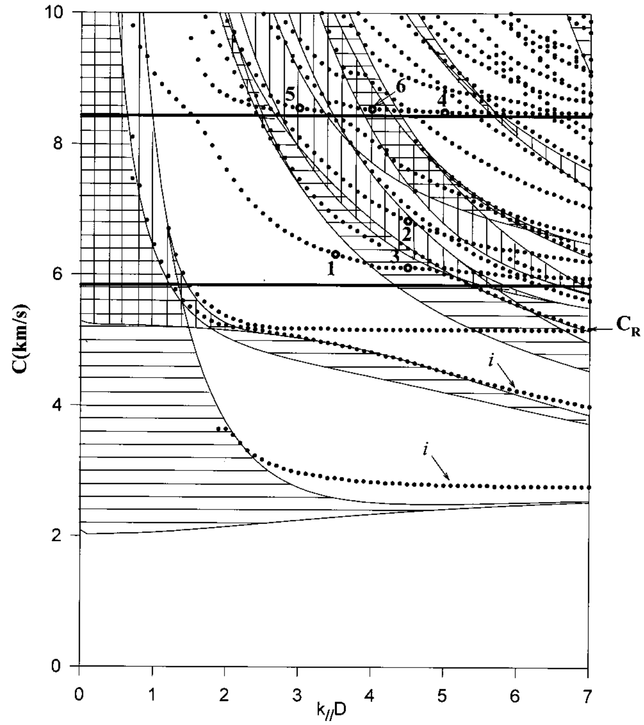

FIG. 2. Dispersion of localized and resonant sagittal modes (full circles) induced by an adsorbed layer of Si material of thickness $d_a=3D$ deposited on the top of the Al-W SL with a W termination. The resonant and localized modes are falling, respectively, in the bulk bands (shaded areas) and the minigaps (separating the shaded areas) of the SL. The horizontally- and vertically-shaded areas correspond to bulk bands associated with each of the two polarizations of the waves. C is the velocity, $k_\parallel$ the propagation vector parallel to the interfaces, and $D=d_1+d_2$ the period of the SL. The heavy-straight lines indicate the transverse and longitudinal velocities of sound of the Si adsorbed layer. The branches labeled (i) correspond to modes localized at the SL/adlayer interface.

The trace in Eqs. (5)–(7) is taken over the components 11 and 33, which contribute to the sagittal modes we are studying in this paper. The integration over x_3 and the summation over n can be performed very easily because the Green's function elements are only composed of exponential terms.[31]

III. RESULTS AND DISCUSSION

This section contains a discussion of the dispersion curves and behaviors of sagittal acoustic waves induced by an adsorbed layer on a semi-infinite SL. These localized and resonant modes appear as well-defined features of the local or total density-of-states. We compare these results with the corresponding results when the adlayer is deposited on a homogeneous substrate.

In our study, the SL is made of Al and W, while the adsorbed layer is assumed to be Si material. The thicknesses of the layers are taken such that $d_1=d_2$ and $d_a=3D$, where $D=d_1+d_2$ is the period of the SL. Table I gives the numerical values of the transverse and longitudinal velocities of sound and mass densities of the materials. We shall focus our attention on the different localized and resonant guided waves induced by the adsorbed layer inside the minigaps and inside the bulk bands of the SL as a function of the wave

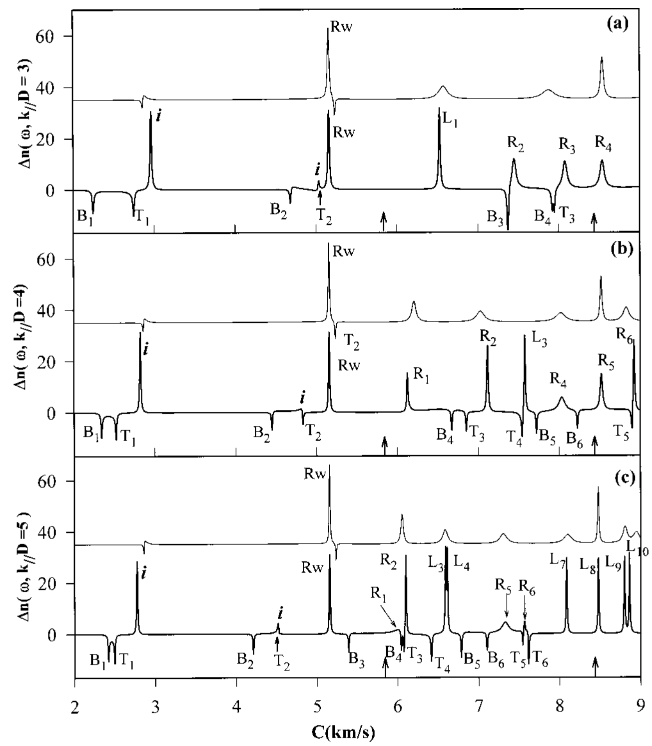

FIG. 3. Variation of the DOS due to the adsorption of the Si layer on an Al-W SL (heavy-solid curves) at $k_{\parallel}D=3$ (a), 4(b), and 5(c). As a matter of comparison, we have also plotted (thin-solid curves) the DOS due to the adsorption of the Si layer on a homogeneous W substrate (Si/W). The arrows on the velocity axis indicate the transverse and longitudinal velocities of sound in the Si layer. B_i and T_i refer to δ peaks of weight-1/4 at the edges of the different bulk bands, L_i and R_i indicate localized and resonant modes induced by the SL/adsorbed layer.

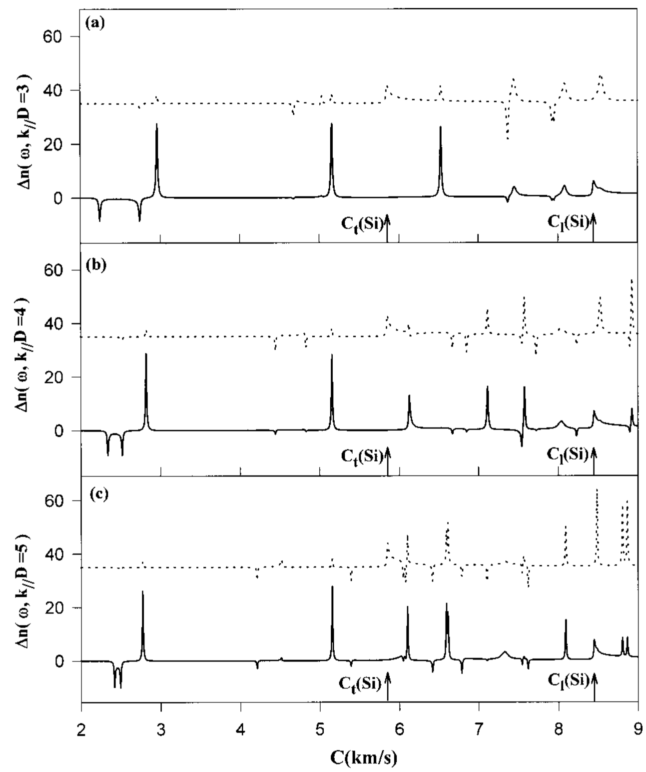

FIG. 4. Same as in Fig. 3, where the contributions of shear vertical (full curves) and longitudinal (dotted curves) components in the DOS are separated.

vector $k_{\parallel}$ (parallel to the interface) and the nature of the layer in the SL that is in contact with the adsorbed layer. We show in particular that, though the velocities of sound in the Si adlayer are higher than those in the (W, Al) layers constituting the SL, both transverse and longitudinal guided waves with velocities lying in the range of transverse and longitudinal velocities of sound may be confined in the topmost layer in such a way as to produce an acoustic waveguide.

Figure 2 gives the dispersion curves (velocity C versus the reduced wave vector $k_{\parallel}D$) of sagittal acoustic waves for a Si slab on a semi-infinite W-Al SL (Si/W-Al) terminated with a W layer. The shaded areas in Fig. 2 represent the bulk bands of the SL. Due to the coupling of two degrees of freedom for vibrations, the bulk structure involves two regions of frequencies, represented by horizontally- and vertically-dashed lines, associated with each polarization of the waves.[28] One can distinguish also the ranges of frequencies belonging simultaneously to both types of bands (horizontally-plus vertically-dashed lines) and the regions separating the different shaded areas corresponding to minigaps. The dotted curves in Fig. 2 correspond to localized and resonant guided modes induced by a Si adsorbed layer of thickness $d_a=3D$. The full horizontal lines in Fig. 2 represent the values of transverse and longitudinal velocities of sound for the Si material. The branches lying above the transverse velocity of sound in Si[C_t(Si)] represent localized and resonant modes induced by the Si adsorbed layer; these modes move to the Si transverse sound velocity in the limit $k_{\parallel}D\rightarrow\infty$. The horizontal branch (labeled C_R) lying below C_t(Si) corresponds to the Rayleigh or pseudo-Rayleigh mode on the Si adsorbed layer depending on whether its velocity lies inside a minigap or inside a bulk band of the SL. The other branches (labeled *i* in Fig. 2) represent interface modes localized at the SL/adlayer interface. The different modes in Fig. 2 are obtained from the maxima of the DOS, illustrated in Fig. 3 (heavy solid curves) for a few values of the wave vector $k_{\parallel}D$. For the sake of clarity and despite the analytical nature of our calculations, the δ peaks in the DOS are broadened by adding a small imaginary part to the velocity C (i.e., $C\rightarrow C+i\epsilon$). L_i and R_i, respectively, indicate the localized and resonant modes induced by the Si adsorbed layer in the minigaps and in the bulk bands of the SL. B_i and T_i, respectively, represent δ peaks of weight $-1/4$ (antiresonances) located at the bottom and the top of the minibands.[28–30] The positions of the modes in Fig. 2 are, in general, almost the same as those corresponding to a Si adsorbed layer on a homogeneous W substrate (Si/W); this can be observed in Fig. 3 where we have plotted together the DOS for the Si/W case (thin-solid curves) and the Si/SL case (heavy-solid curves). However, because of the existence of the SL minigaps in Fig. 2, the guided modes falling in these minigaps do not propagate in the SL and remain well-defined guided waves in the adsorbed layer (see below); therefore, they appear as true δ peaks in the DOS of the Si/SL system (labeled L_i in the heavy-solid curves of Fig. 3). On the contrary, they appear, in general, as weak resonances in the DOS associated with the Si/W case (thin-solid curves of Fig. 3) because in this case these modes are falling in the continuum of the

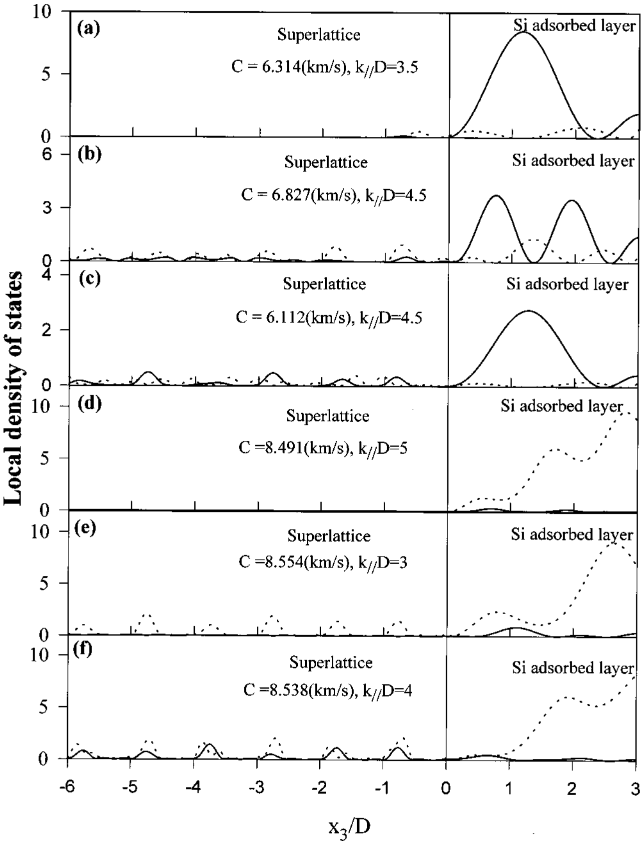

FIG. 5. Spatial representation of the local DOS for the modes labeled 1–6 in Fig. 2. The first three modes (a), (b), and (c) lie in the vicinity of C_t(Si) and fall, respectively, at $[k_\parallel D=3.5,\ C=6.314\,\mathrm{km/s}]$; $[k_\parallel D=4.5,\ C=6.827\,\mathrm{km/s}]$, and $[k_\parallel D=4.5,\ C=6.112\,\mathrm{km/s}]$. The next three modes (d), (e), and (f) lie in the vicinity of C_1(Si) and fall, respectively, at $[k_\parallel D=5,\ C=8.491\,\mathrm{km/s}]$; $[k_\parallel D=3,\ C=8.544\,\mathrm{km/s}]$, and $[k_\parallel D=4,\ C=8.538\,\mathrm{km/s}]$. The full (dotted) curves correspond to shear vertical (longitudinal) components of the local DOS, respectively. The space position at the SL/adsorbed layer interface ($x_3=0$) is marked by a vertical line.

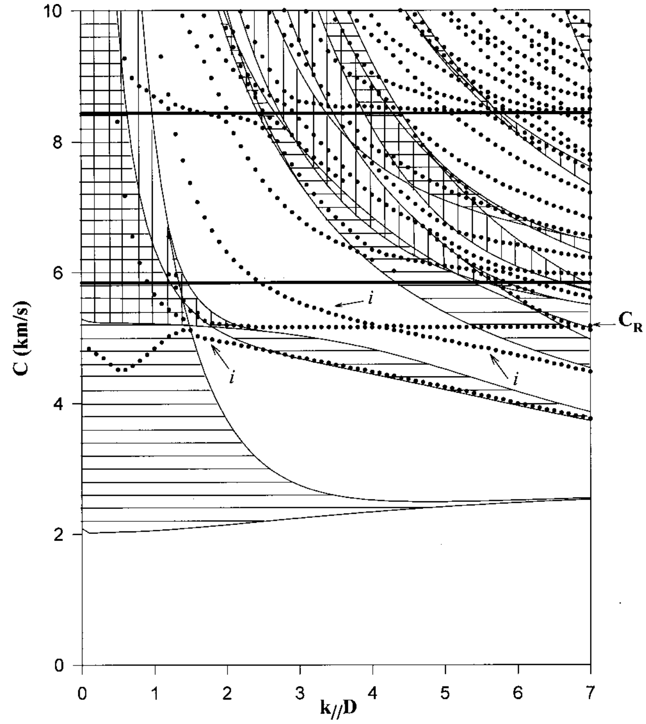

FIG. 6. Same as in Fig. 2 for the case of a Si adsorbed layer deposited on the top of an Al-W SL terminated with a full layer of Al material.

substrate bulk bands. Therefore, the experimental observation of such localized modes should be easier when the substrate is a SL instead of a homogeneous material; indeed, the confinement of these modes in the adsorbed layer becomes more pronounced in the former case than in the latter. One can also notice in Fig. 2 an important coupling and anticrossing of the modes induced by the adlayer in the vicinity of transverse and longitudinal velocities of sound in Si.

Among the above guided waves, one can distinguish the modes in the vicinity of C_t(Si), which are predominantly of shear vertical character and the branches in the vicinity of C_l(Si), which are predominantly of longitudinal character. However, the branches falling between C_t(Si) and C_l(Si) are of mixed transverse and longitudinal character. This is shown in Fig. 4 where we have separated in the DOS the contribution of shear vertical (full curves) and of longitudinal (dashed curves) components. An analysis of the local DOS as a function of the space position x_3 (Fig. 5) clearly shows the localization properties of the different kinds of modes belonging to various velocity ranges. The local DOS reflects the spatial behavior of the square modulus of the displacement field. Figures 5(a)–5(f) correspond to the modes, respectively, labeled 1–6 in Fig. 2, showing that these modes are confined in the Si adsorbed layer. However, the first three modes are predominantly of shear vertical

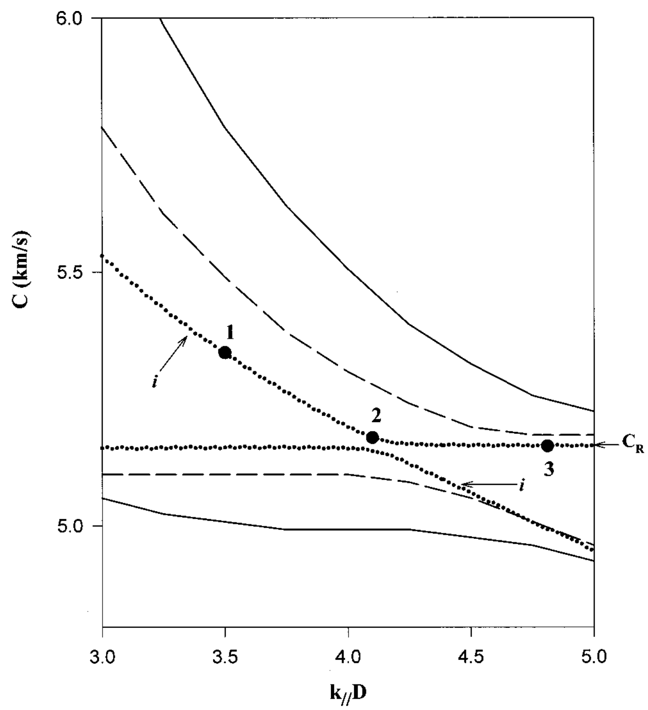

FIG. 7. The interaction between the Rayleigh surface and interface modes near $k_\parallel D \approx 4.2$ in Fig. 6, is emphasized for several values of the thickness d_a of the adsorbed layer: $d_a=D$ (——), $d_a=1.5D$ (— — —), and $d_a=3D$ (· · · ·).

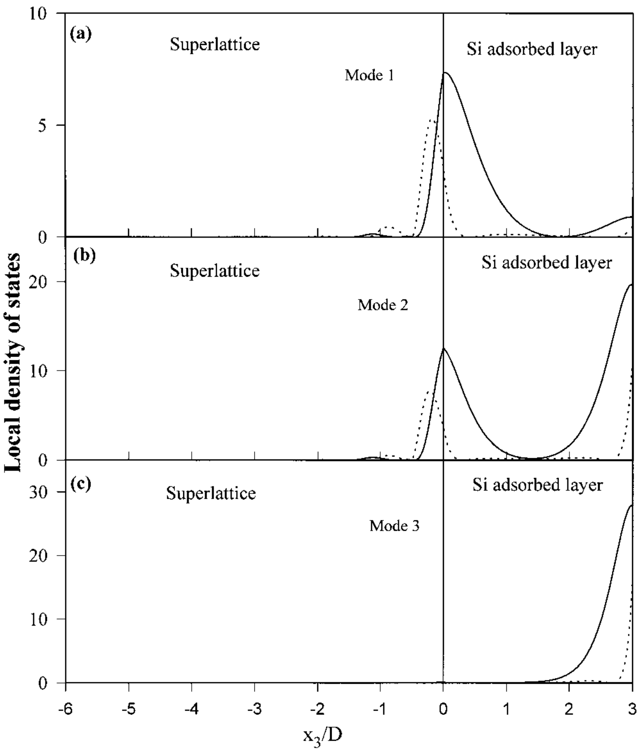

FIG. 8. Spatial representation of the local DOS for the modes labeled 1, 2, and 3 in Fig. 7 and corresponding, respectively, to $[k_{\parallel}D=3.5,\ C=3.5\,\mathrm{km/s},\ d_a=3D]$ (a),$[k_{\parallel}D=4.1,\ C=5.163\,\mathrm{km/s},\ d_a=3D]$ (b) and $[k_{\parallel}D=4.8,\ C=5.1686\,\mathrm{km/s},\ d_a=3D]$ (c). The full and dotted curves correspond to longitudinal and shear vertical components of the local DOS, respectively.

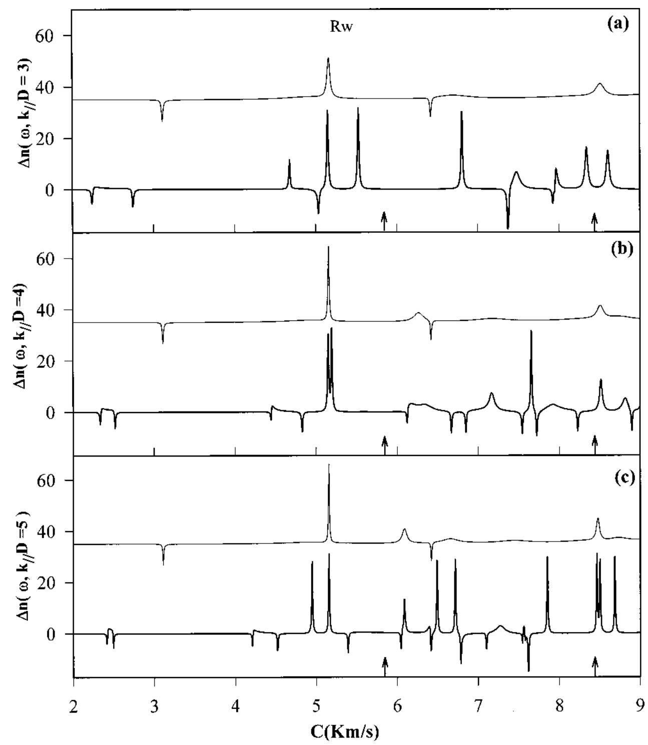

FIG. 9. Variation of the DOS due to a Si adsorbed layer deposited on the top of an Al-W SL terminated with a full layer of Al material (heavy-solid curves) or on top of a homogeneous Al substrate (thin-solid curves).

character as their velocities lie in the vicinity of C_t(Si), while the latter three modes are mostly of longitudinal character as their velocities lie in the vicinity of C_l(Si). Furthermore, among the different modes cited above, one can distinguish the modes falling inside the SL minigaps (called localized modes and labeled 1 and 4 in Fig. 2); therefore, these modes do not propagate into the SL and remain well-confined in the topmost layer [Figs. 5(a) and 5(d)]. Indeed, in Figs. 5(a) and 5(d), the SL plays the role of a barrier that prevents the penetration into the SL of the phonons propagating in the Si adsorbed layer. The other modes (called resonant or pseudomodes and labeled 2, 3, 5, and 6 in Fig. 2) fall either inside one of the two types of bands of the SL (as it is the case for the modes 2, 3, and 5) or inside both types of bands of the SL (as it is the case for the mode 6). These modes still remain well-confined in the Si adsorbed layer even though they are in resonance with the bulk bands of the SL. However, the resonances are stronger for the modes falling inside one type of bulk bands, since these waves are composed of one propagating and one evanescent component inside the SL.

Concerning the modes falling between C_t(Si) and C_l(Si) (not presented here), they exhibit a mixed shear vertical and longitudinal character. Let us mention that longitudinal guided modes with high velocities of sound are usually difficult to detect experimentally, and therefore using a SL as a support instead of a homogeneous substrate presents a very useful device for the detection of these kind of modes.

In the same manner, we have studied (Fig. 6) localized and resonant modes induced by a Si adsorbed layer deposited on the same SL but terminated with an Al layer instead of a W one. The results in Fig. 6 are quite different from those presented previously (Fig. 2); they show the dependence of the modes induced by the adsorbed layer on the nature of the topmost layer in the SL. In particular, besides the transverse and longitudinal guided modes (similar to those in Fig. 2), one can notice, for increasing $k_{\parallel}D$, an interaction between interface branches (localized at the SL/adlayer interface and labeled i in Fig. 6) and the Rayleigh surface branch (localized at the surface of the Si adsorbed layer), which is independent of $k_{\parallel}D$. This interaction gives rise to the lifting of the degeneracy at the crossing points around $k_{\parallel}D\approx 4.2, 6.9$, etc, as it is emphasized in Fig. 7, around $k_{\parallel}D\approx 4.2$. One can notice, in particular, a decrease in the coupling between the modes by increasing the thickness d_a of the adsorbed layer. Before the anticrossing point, the higher (resp. lower) mode is essentially localized at the SL/adlayer interface (resp. at the surface of the adlayer); the opposite situation occurs after the anticrossing point. This smooth evolution of the character of the two branches is illustrated in Fig. 8. Let us stress that the different modes induced by the Si adlayer deposited on a homogeneous Al substrate present very small features in the DOS as compared to the case of Si/SL system as it is illustrated in Fig. 9.

Finally, we have also studied the case when the adsorbed layer is of the same nature (W or Al) as one of the layers constituting the SL but with a different thickness. The velocities of the modes in the case of the W/SL and Al/SL systems are, respectively, almost the same as in the case of the W/Al(substrate) and Al/W(substrate) systems.[18] However, the modes falling in the SL minigaps appear as true δ peaks instead of being weak resonances in the case of a homogeneous substrate.[31] Moreover, because of the low velocities of sound in W and Al (in comparison with Si), only one interface branch appears below the transverse velocities of sound in these materials, the so-called Stoneley branch. The details of these calculations will be presented in Ref. 31.

IV. SUMMARY AND CONCLUSION

In this paper, we developed the idea that the observation of the guided modes of an adlayer can be made possible or at least facilitated if the substrate is a SL instead of being a homogeneous material. For this purpose, we studied the localized and resonant modes confined in the topmost layer and compared their behaviors in the DOS with those obtained when the adlayer is deposited on a homogeneous substrate. We studied both localized and resonant guided modes that have, respectively, their velocities lying in the minigaps and in the minibands of the SL. Indeed, in the first case, the SL plays the role of a barrier for phonons in the adsorbed layer leading to their confinement in the topmost layer; while in the second case, phonons may still remain well-confined in the topmost layer, in particular due to the existence of two types of polarizations of the waves in the SL minibands. Moreover, the well-confined guided waves do not depend on whether the velocities of sound in the adsorbed layer are lower or higher than those of the materials constituting the SL. This phenomenon is without analog in the usual case where the substrate is made of a homogeneous material.

Due to the SL/adlayer interaction, different localized and resonant modes were obtained and their properties investigated. These modes appear as well-defined peaks of the DOS, with their relative importance being strongly dependent on the wave vector $k_{\parallel}$, on the thickness and the nature of the adsorbed layer, as well as on the nature of the layer in the SL that is in contact with the adsorbed layer. The experimental observation of the guided modes predicted here can be performed with the Brillouin scattering technique.[19,20,26,27,33]

The results presented in this paper are based on an analytical calculation of the Green's functions of acoustic waves of sagittal polarization in an adsorbed layer deposited on a semi-infinite SL.[31] Besides the calculations of local and total density-of-states and the determination of the dispersion relation presented in this paper, these response functions can also be helpful in the calculation of all eigenvectors[32] (for instance the displacement field associated with multiple reflection and transmission at the different interfaces) and in the study of light scattering by acoustic phonons.[34]

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