Low-energy vibrations at the InSb(110) surface

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We present a study of low-energy vibrations at the InSb(110) surface along the $\overline{\Gamma Y}$ direction. Surface phonons have been measured by He inelastic scattering and a theoretical analysis has been performed by means of first-principles calculations. We have been able to distinguish the surface acoustic mode above the Rayleigh wave and to identify a surface resonance and an optical surface mode at higher energy. Theoretical calculations are shown to be in agreement with the detected phonon dispersion curves except for the surface resonance which is found 1 meV higher than calculated.

I. INTRODUCTION

Compound semiconductors with the zinc-blende structure are extensively studied because they are basic materials for technical applications. Notwithstanding the large interest in this class of materials there are not many experimental data on the vibrational properties of their surfaces and these are mainly concentrated on the GaAs(110) surface as the prototype of nonpolar cleavage surface of III-V compounds. Phonon dispersion curves on this surface have been mapped by means of He atom scattering^{1,2} (HAS) and electron energy-loss spectroscopy^{3,4} (EELS) for the lower- and higher-energy parts of the phonon spectrum, respectively.

Semiempirical models based on the tight-binding approach^{5,6} and bond charge model^{7,8} were used to describe the interatomic force constants and the dynamical matrix, which gave substantial insight into the interpretation of the surface dynamics. A preliminary study based on Car-Parrinello molecular dynamics gave consistent results for a few selected phonon modes;⁹ while a major step toward a full description of the surface vibrations was the recent application of the density functional perturbation theory¹⁰ (DFPT) to the calculation of GaAs(110) phonon dispersion curves.¹¹ These first-principles calculations, based on density functional theory,¹² have the great advantage of giving a unified description of the structural, dynamical, and electronic properties of the system under study. In the case of GaAs(110) a substantial agreement of calculations with both experimental data and previous theoretical analysis was obtained. The method was shown to determine quite well the surface phonons, while a more detailed analysis was required for the surface resonance of the bulk vibrations. Moreover, a true surface optical mode was calculated to lie flat along the two principal symmetry directions at about 15 meV, which was observed neither by HAS experiments nor by EELS studies.

In the present work we report on a combined experimental and theoretical study of low-energy vibrations of the InSb(110) surface where, to our knowledge, sur-

face phonons were never measured. This surface is expected to present dynamical behavior quite similar to that of GaAs(110), but due to its softness all the phonon modes should lie at lower energies. Thus a more complete mapping of the surface dispersion curves can be obtained with the HAS technique we used, since this experimental method is particularly suited for measuring surface vibrations of the lowest energies.¹³⁻¹⁵ In fact we have been able to detect also the optical mode, which lies at 8 meV. In order to interpret the experimental data, first-principles calculations have been performed within the framework of DFT and both the equilibrium geometry of the relaxed InSb(110) surface and its low-energy vibrations have been calculated. Moreover, DFPT gives directly the atomic displacements for the topmost layers, making easier the interpretation of the experimental phonon spectra.

II. EXPERIMENT

The He atom scattering apparatus, described in detail elsewhere,¹⁶ has a fixed scattering geometry with $\theta_i + \theta_o = 110^\circ$ where θ_i and θ_o are the angles formed by the impinging and outgoing He beams with the surface normal, respectively. The sample is mounted on a six degrees of freedom manipulator. The overall angular resolution of the apparatus is 0.135° [full width at half maximum (FWHM)] which, together with an angular reproducibility of 0.005° , allows the transfer width to exceed 1200 Å. The He beam energy can be selected in the range 19–70 meV, which corresponds to a 6–11.3-Å⁻¹ range for the He wave-vector modulus. Time of flight (TOF) spectra have been taken by chopping the beam into 5-μs pulses at a rate of 1000 Hz. The data are collected by a multichannel analyzer with time resolution of 1 μs. In the present experiment we used two beam energies of 19 and 30 meV. At both energies used, the elastic peak results to be 11.5 μs wide (FWHM), which corresponds to an energy spread of 0.4 and 0.9 meV for the lower and higher beam energy, respectively.

The InSb(110) surface was obtained by cleavage in air and the sample was fixed to the holder by silver paste. Subsequently the surface was prepared in ultrahigh vacuum conditions by repeated cycles of sputtering and annealing. It has been shown that this nonpolar surface can be sputtered with 150–250-eV Ar^+ ions with neither changing the surface stoichiometry with respect to the bulk nor damaging the bulk beneath.^{17,18} Then the sputtered surface is rapidly heated up to 790 K (a few degrees below the melting point) and, after quenching down to room temperature, a well-ordered and clean surface is obtained. The corresponding diffraction patterns are shown in Fig. 1. The average terrace width can be

FIG. 1. Upper panel: diffraction patterns taken along the $[1\bar{1}0]$ ($\Gamma\bar{X}$) and $[001]$ (ΓY) directions with He energy of 19 meV. Lower panel: (i) side view of the InSb(110) surface structure across the (100) plane; the relaxation parameters are labeled; (ii) top view of the InSb(110) surface structure; the unit cell (dashed line) is labeled with its dimensions related to the lattice parameter a_0 .

easily estimated from the angular FWHM of the specularly reflected peak, which is in antiphase condition for monatomic steps at the energy of 19 meV; i.e., the amplitudes of He waves scattered from two terraces separated by a monatomic step add destructively in the specular direction. In this case the peak broadening beyond the instrumental profile reflects the step distribution.^{19,20} We obtained average terrace width exceeding 1200 and 600 Å along the $[001]$ (ΓY) and $[1\bar{1}0]$ ($\Gamma\bar{X}$) directions, respectively. The excellent quality of the surface is also witnessed by the very low intensity of the diffuse elastic peak taken away from the Bragg diffraction peaks (see Figs. 2, 3, and 4), meaning that the concentration of defects is very low. We also observed that the surface after the preparation remained unchanged for several days at room temperature with a base pressure of 5×10^{-11} mbar. A drop of about 20% of the initial signal intensity is eventually observed after a week, but in this case the surface quality is easily recovered by simply heating the sample at 470 K. This means that the surface defects are possibly due to water adsorption without any other contamination or impurity diffusion from the bulk.

III. RESULTS AND DISCUSSION

All phonon measurements have been taken at room temperature and along the ΓY direction. Because of the high corrugation of the InSb(110) surface the elastically scattered He intensity is distributed over many diffraction channels (see the envelope of the Bragg peaks in Fig. 1). Therefore phonon spectra can be observed also at large scattering angles corresponding to momentum transfers outside the first surface Brillouin zone (SBZ). As a consequence at any angle the absolute scattered intensity is low compared to that from close-packed metal surfaces and time measurements longer than 1 h were required for a single TOF spectrum.

Apart from the Rayleigh wave (RW) dispersion curve we observed another acoustic branch at slightly higher energies. This is evident in the energy converted TOF spectra shown in Fig. 2 taken at four negative values of the polar angle $\theta_{is} = 55^\circ - \theta_i$, between the (0,2) and (0, $\bar{1}$) diffracted peaks. In the lower panel of the same figure we report the corresponding energy scan curves and data points on the extended SBZ, where the calculated dispersion curves are superimposed. For these scattering conditions, phonon peaks with higher intensities are observed in the gain part of the TOF spectrum (phonon annihilation) in the second SBZ, where the scan curves intercept the dispersion curve of an acoustic wave. Notwithstanding the presence of a deception peak,²¹ two distinct acoustic branches are evident in the loss part of the spectra, where the scan curves enter the third SBZ. We note a quite large intensity of the upper branch phonons (hereafter labeled A2) at large phonon wave vector; close to the zone boundary they are much more intense than Rayleigh phonons (see the loss part of the spectra at $\theta_{is} = -9.5^\circ, -9.4^\circ, -9.3^\circ$). We also observe that the Rayleigh phonons close to the zone boundary are only detected in the third SBZ.

In Fig. 3, energy spectra taken at three small positive angles close to the specular peak are shown. Together with the acoustic phonons, the presence of a low dispersive vibration at about 5 meV is evident. These phonons (labeled O1) are observed close to the $\bar{\Gamma}$ point and the corresponding dispersion curve has been followed up to about the half zone, where it reaches the energy of 6 meV. In the same spectra of Fig. 3 there are also traces of a faint vibration between 7 and 8 meV (labeled O2). In order to obtain a more detailed mapping of this last phonon mode we have taken TOF spectra with beam energies between 30 and 32 meV. In fact, notwithstanding the reduced energy resolution, a higher inelastic cross section for the higher-energy phonons is expected by increasing the beam energy.^{14,22} Due to the Debye-Waller attenuation, the spectra taken in this condition show fainter phonon peaks than those taken at 19 meV, and longer measurement times were required. The most intense phonon peaks have been detected at positive angles between the (0,0) and (0,1) peaks. Three of these spectra are reported in Fig. 4. The high-energy phonons

are found to correspond to an optical mode that departs from the zone boundary at 8 meV and almost reaches the $\bar{\Gamma}$ point at 7 meV. It is to be noted that the intensity of the corresponding phonon peaks becomes higher as the scan curves depart from the zone boundary. All the experimental data have been reported in Fig. 5 (filled circles) within the reduced SBZ. The dispersion of the three lower modes is qualitatively similar to that observed with the same technique on GaAs(110) by Doak and Nguyen,¹ although they did not observe the higher optical branch. This could be due to the fact that this mode would lie at higher energy with respect to InSb (which is softer than GaAs).

In order to interpret these experimental results we have performed first-principles calculations for the structure and dynamics of the InSb(110) surface. All the calculations are based on DFT in the local density approximation (LDA). The electron-gas exchange-correlation energy and potential used to implement LDA are those determined by Ceperley and Alder²³ as interpolated by Perdew and Zunger.²⁴ Our calculations are performed

FIG. 2. Upper panels: four energy converted TOF spectra measured with a He beam energy of 19 meV at four different values of the polar angle θ_{is} : -9.5° , -9.4° , -9.3° , and -9.2° ; raw data are presented on a linear scale. The diffuse elastic peak is put in evidence by a vertical line at zero energy exchange. Markers RW and A2 label the Rayleigh wave and the upper acoustic wave, respectively, where a clear distinction between the two modes is not possible the phonon peak is simply indicated by the label "Acoustic." Lower panel: Scan curves corresponding to the upper phonon spectra (dotted lines). The calculated dispersion curves are superimposed (full lines) and labeled according to the phonon spectra. Filled circles represent the phonons indicated by the arrows in the spectra of the upper panel.

FIG. 3. Upper panels: same as Fig. 2 for θ_{is} : $+2.8^\circ$, $+3^\circ$, and $+3.2^\circ$; raw data are presented on a linear scale together with smoothed data, which are reported with a negative offset. Smoothing has been performed with a box filter of a 5 point kernel. Markers O1 and O2 label the surface resonance and the optical surface wave, respectively. Lower panel: same of Fig. 2 for θ_{is} : $+2.8^\circ$, $+3^\circ$, and $+3.2^\circ$.

FIG. 4. Upper panel: same as the upper panel of Fig. 3, in this case a He beam energy of 30 meV has been used and θ_{is} : $+2^\circ$, $+3^\circ$, and $+4.5^\circ$. Lower panel: same of the lower panel of Fig. 3, with θ_{is} : $+2^\circ$, $+3^\circ$, and $+4.5^\circ$.

FIG. 5. Low-energy part of the phonon spectrum on InSb(110). Filled circles are HAS measurements, full lines and the shaded area correspond to first-principles calculations for the surface modes and the surface projected bulk phonon dispersions, respectively. The dashed line is a guide to the eye for the surface resonance mode.

in the framework of the plane-wave pseudopotential method. Norm-conserving fully separable *ab initio* relativistic pseudopotentials have been used to describe In and Sb.²⁵ We have used a kinetic energy cutoff of 8 Ry and one special $\mathbf{k}$ point in the irreducible wedge of the surface Brillouin zone for reciprocal space integration. The surface has been modeled using supercells consisting of nine atomic planes plus three planes of vacuum in order to avoid interaction between opposite faces of the slab and ensure a bulklike behavior inside the slab. The theoretical lattice parameter $a_0 = 6.297$ Å has been used throughout all the calculations and it is in good agreement with the experimental value of 6.478 Å. The equilibrium atomic geometry of the (110) surface of InSb has been obtained relaxing the ideal atomic positions corresponding to the bulk truncation. Similarly to the other III-V compounds, also in InSb the group-III surface cations (In) move inwards and the group-V anions (Sb) move outward (see lower panel of Fig. 1). The buckling angle is found to be 33.9° in good agreement with the low-energy electron diffraction value of $32 \pm 3^\circ$.^{26,27} In general all the structural parameters, reported in Table I, agree with the experimental findings within 5%. The gain in energy induced by the relaxation is of 0.35 eV/surface

atom, and then stabilizes the relaxed configuration.

Phonon dispersions for the low-energy surface modes along $\bar{\Gamma}\bar{Y}$ have been calculated in the framework of the DFPT,¹⁰ allowing us to determine the phonon dispersions without any empirical or fitting parameter. This method has been recently applied to the calculation of the lattice dynamics of the GaAs(110) surface.¹¹ The calculated dispersion curves were found to be in good agreement with the experimental data obtained by He inelastic scattering along the principal symmetry directions,^{1,2} so that a good reliability is also expected for calculations on the quite similar InSb(110) surface.

HAS measurements and theoretical calculations are shown in Fig. 5 together with the theoretical surface projected bulk phonon dispersions (shaded area) for the $\bar{\Gamma}\bar{Y}$ direction. From DFPT calculations the atomic displacements are determined, so that the vibration polarizations are described in detail. The amplitude and direction of the top layer atom displacements are reported in Fig. 6 for the RW, A2, and O2 modes, as calculated at the half zone and the zone boundary. The spectra show three low acoustic modes with a zone boundary energy of 2.9, 3.4, and 4.2 meV, respectively. The lowest and the highest modes are mainly polarized normal to the In-Sb chains and can be identified with the two acoustic branches experimentally determined. In particular, the upper branch (A2) at the zone boundary corresponds to the top layer vibrating perpendicularly to the surface, while the lower atoms move in the (110) plane perpendicularly to the In-Sb chains. A complementary motion occurs for the lower acoustic branch (the Rayleigh wave). This strong polarization in the surface plane possibly explains why, even when the spectra are scaled by the nearest Bragg peak intensity, the RW phonons close to the zone boundary are very weak and detected only in the third SBZ. In fact, He atoms have a strong coupling with phonons polarized perpendicularly to the surface and longitudinal vibrations are expected to be well observed only at large parallel momentum exchange. Moving away from the zone boundary the perpendicular component in the RW vibration of the top layer increases and at the half zone it is about equal to the parallel component. At the same time the perpendicular polarization of A2 decreases, but at the half zone it is still larger than the parallel one. These variations of the polarization explain the large intensity of the A2 wave at large phonon wave vector (see spectra in Fig. 2). As the zone boundary is approached the Rayleigh phonons become fainter and the A2 phonon intensity increases. In the present case the A2 peak in-

TABLE I. Structural parameters of the ideal clean unrelaxed, and of the clean relaxed InSb(110) surface; symbols are the same as used in the lower panel of Fig. 1. The experimental values obtained by Meyer *et al.*²⁶ and by De Carvalho, Prutton, and Tear (DPT)²⁷ are also reported. Units are in Å unless explicitly indicated.

	a_0	$\Delta_{1,\perp}$	$\Delta_{1,\parallel}$	$\Delta_{2,\perp}$	$d_{12,\perp}$	$d_{12,\parallel}$	ω (deg)
Ideal	6.297	0.000	4.794	0.000	2.260	3.196	0.00
Relaxed	6.297	0.869	5.005	0.330	1.542	3.702	33.9
Meyer <i>et al.</i>	6.478	0.830	5.088	0.240	1.541	3.858	30.9
DPT	6.478	0.810	5.168	0.360	1.500	3.869	32.0

FIG. 6. Calculated atomic displacements (arrows) are shown for the topmost atoms in a side view of the InSb(110) surface structure across the (100) plane. The polarizations of three waves (RW, A2, O2) are reported as calculated at half zone (left panels) and at the zone boundary (right panels). Open and filled circles represent In and Sb atoms, respectively.

tensity is higher than RW intensity (see loss part of the spectra in Fig. 2). On the other hand, the intermediate acoustic branch (A1) is always polarized strictly horizontal with atomic motion parallel to the chains (shear mode) and cannot be observed in our scattering geometry for symmetry reasons.²⁸

The O1 phonons detected at 5 meV close to $\bar{\Gamma}$ are not found to correspond to any calculated surface mode. We note that similar experimental evidence was also found on GaAs(110);¹ this mode was identified with a surface resonance of a bulk vibration by an analysis based on a bond charge model slab calculation,⁷ while, in the successive first-principles analysis, the occurrence of the surface resonance was considered only along the $\bar{\Gamma}\bar{X}$ direction.¹¹ In our case the calculations show a surface resonance almost totally polarized perpendicularly to the surface at $\bar{\Gamma}$; however, the calculated energy is found to be about 1 meV lower than the experimental points. Moreover, the resonance is expected to decay rapidly along $\bar{\Gamma}\bar{Y}$, while He atom scattering has detected this vibration up to almost the half zone (see, for example, the loss part of the spectrum at $\theta_{is} = +3^\circ$ in Fig. 4).

The upper optical mode (O2), observed with HAS, has a true surface character at the zone boundary and decays in the bulk as surface resonance. Measured phonons show that the corresponding branch is almost 0.4 meV

lower in energy at the half zone, possibly indicating a different curvature from that obtained by simple interpolation with a cosine function. This mode corresponds to a phonon mainly localized on the In surface atoms; at the zone boundary the parallel and normal components of the vibration are almost equal, so that the total displacement can be seen as a variation of the buckling angle ω ; moving toward the $\bar{\Gamma}$ point the polarization changes and at the half zone is almost totally perpendicular to the surface. This behavior possibly explains why the O2 phonon peaks are weak close to the zone boundary (see the loss part of the spectra $\theta_{is} = +2^\circ, +3^\circ$ in Fig. 4) and become more intense at half zone, as can be seen in the loss part of the right spectrum $\theta_{is} = +4.5^\circ$ in Fig. 4; in particular the coupling between He and the O2 vibration at half zone is strong enough to produce a small phonon evidence also at the lower beam energy (see spectra $\theta_{is} = +2.8^\circ, +3^\circ$ in Fig. 3).

IV. CONCLUSION

In conclusion, we have shown that calculation of the phonon dispersion within DFPT accounts well for the phonon measurements on InSb(110) along the [001] direction. Both theory and experiments show a close similarity of the vibrational properties of this surface with those of GaAs(110). In our case a surface optical mode has been observed whereas the corresponding vibration was not reported on GaAs, even if predicted by first-principles calculations. A discrepancy is found in the location of the surface resonance close to the $\bar{\Gamma}$ point, which is found to lie 1 meV higher in energy than the calculated value. The calculated polarizations of the phonon waves are in good agreement with the qualitative aspect of the measured phonon spectra. In particular, the predicted changes in the polarization of the two acoustic branches and of the surface optical mode fully agree with the observed intensity variations of the corresponding phonon peaks.

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¹ R.B. Doak and D.B. Nguyen, J. Electron Spectrosc. **44**,

205 (1987).

² U. Harten and J.P. Toennies, Europhys. Lett. **4**, 833 (1987).

³ R. Matz and L.H. Lüth, Phys. Rev. Lett. **46**, 500 (1981).

⁴ M.G. Betti, U. Del Pennino, and C. Mariani, Phys. Rev. B **39**, 5887 (1989).

⁵ Y.R. Wang and C.B. Duke, Surf. Sci. **205**, L755 (1988); C.B. Duke and Y.R. Wang, J. Vac. Sci. Technol. B **7**, 1027 (1989).

⁶ T.J. Godin, J.P. La Femina, and C.B. Duke, J. Vac. Sci.

- Technol. B **9**, 2282 (1991).
- ⁷ P. Santini, L. Miglio, G. Benedek, U. Harten, P. Ruggerone, and J.P. Toennies, Phys. Rev. B **42**, 11 942 (1990).
 - ⁸ P. Santini, L. Miglio, and G. Benedek, Surf. Sci. **241**, 346 (1991).
 - ⁹ R. Di Felice, A.I. Shkrebtii, F. Finocchi, C.M. Bertoni, and G. Onida, J. Electron Spectrosc. Relat. Phenom. **64/65**, 697 (1993).
 - ¹⁰ S. Baroni, P. Giannozzi, and A. Testa, Phys. Rev. Lett. **58**, 1861 (1987); P. Giannozzi, S. de Gironcoli, P. Pavone, and S. Baroni, Phys. Rev. B **43**, 7231 (1991).
 - ¹¹ J. Fritsch, P. Pavone, and U. Schröder, Phys. Rev. Lett. **71**, 4194 (1993).
 - ¹² See, for instance, W.E. Pickett, Comput. Phys. Rep. **9**, 115 (1989).
 - ¹³ J.P. Toennies, in *Dynamics of Gas-Surface Interactions*, edited by G. Benedek and U. Valbusa, Springer Series in Chemical Physics Vol. 21 (Springer, Berlin, 1982), p. 208.
 - ¹⁴ R.B. Doak, in *Helium Atom Scattering from Surfaces*, edited by E. Hulpke, Springer Series in Surf. Sci. Vol. 27 (Springer, Berlin, 1992), p. 5.
 - ¹⁵ V. Bortolani, A. Franchini, and G. Santoro, in *Dynamical Phenomena at Surfaces, Interfaces and Superlattices*, edited by F. Nizzoli, K.-H. Rieder, and R.F. Willis, Springer Series in Surf. Sci. Vol. 3 (Springer, Berlin, 1985), p. 92.
 - ¹⁶ D. Cvetko, A. Lausi, A. Morgante, F. Tommasini, K.C. Prince, and M. Sastry, Meas. Sci. Technol. **3**, 997 (1992).
 - ¹⁷ D. Cvetko, L. Floreano, A. Morgante, M. Peloi, and F. Tommasini, Surf. Sci. **307-309**, 519 (1994).
 - ¹⁸ D. Cvetko, V. De Renzi, L. Floreano, A. Morgante, M. Peloi, F. Tommasini, V. Cháb, and K.C. Prince, Surf. Sci. Lett. **323**, L305 (1995); Phys. Rev. B **51**, 17 957 (1995).
 - ¹⁹ J. Lapujoulade, Surf. Sci. **108**, 526 (1981); in *Helium Atom Scattering from Surfaces* (Ref. 14), p. 95.
 - ²⁰ T.-M. Lu and M.G. Lagally, Surf. Sci. **120**, 47 (1982), and references therein.
 - ²¹ The slight velocity spread of the He beam gives rise to a Bragg diffraction associated to the tails of the He velocity distribution. These additional diffraction peaks, called deceptions, are easy to recognize; however, they can be quite intense obscuring the phonon loss/gain peaks.
 - ²² H. Ibach and T.S. Rahman, in *Chemistry and Physics of Solid Surfaces V*, edited by R. Vanselow and R. Howe (Springer, Berlin, 1984), p. 455.
 - ²³ D.M. Ceperley and B.J. Alder, Phys. Rev. Lett. **45**, 566 (1980).
 - ²⁴ J. Perdew and A. Zunger, Phys. Rev. B **23**, 5048 (1981).
 - ²⁵ R. Stumpf, X. Gonze, and M. Scheffler (unpublished).
 - ²⁶ R.J. Meyer, C.B. Duke, A. Paton, J.L. Yeh, J.C. Tang, A. Kahn, and P. Mark, Phys. Rev. B **21**, 4740 (1980).
 - ²⁷ V.E. De Carvalho, M. Prutton, and S.P. Tear, Surf. Sci. **184**, 198 (1987).
 - ²⁸ V. Bortolani and A.C. Levi, Riv. Nuovo Cimento **9**, 1 (1986).

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