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Brillouin scattering by pseudosurface acoustic modes on $(1\bar{1}1)$ GaAs

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Abstract. We have studied the propagation of pseudosurface acoustic modes on the $(1\bar{1}1)$ plane of GaAs. From a calculation of the surface density of phonon states, two resonances are found in the continuum of modes, corresponding to the pseudosurface acoustic modes, called PSM and HFPSM. Experimental evidence for these modes is given by Brillouin spectra taken for different directions on the $(1\bar{1}1)$ plane of a GaAs crystal. We found a good agreement between the experimental spectra and the theoretical cross sections, calculated taking into account both the ripple and the elasto-optic contributions to the scattering process.

1. Introduction

It is well known that the phonon states of a solid medium are affected by the presence of a boundary surface. One finds that the lack of translational invariance allows inhomogeneous acoustic modes, consisting of bulk-like and evanescent partial waves, to be present. In particular, both an acoustic surface mode, the Rayleigh wave (RW), and two different types of radiating modes, called the pseudosurface mode (PSM) and the high frequency pseudosurface mode (HFPSM), can exist. The RW is the only true surface mode since its Poynting vector lies parallel to the free surface and its particle displacement field decays exponentially within the medium. The pseudosurface modes [1], unlike the RW, radiate energy into the bulk of the medium, thus undergoing attenuation. They can be considered as surface phonons with a finite lifetime, decaying into bulk phonons.

Lim and Farnell [2], have shown that a PSM can propagate along some specific directions on the surface of anisotropic media with phase velocity lying between the velocities of the two quasi-transverse bulk waves. This mode cannot exist in elastically isotropic media on account of the collapse of the phase velocity of the two transverse waves. Glass and Maradudin [3] have shown, however, that in isotropic media another kind of pseudosurface mode, called the HFPSM, can exist, the phase velocity of which lies between the velocities of the transverse and of the longitudinal wave. Camley and Nizzoli [4] have discussed the analogies and the differences between the PSM and the HFPSM on isotropic and anisotropic solids. They have related the properties of these modes to the

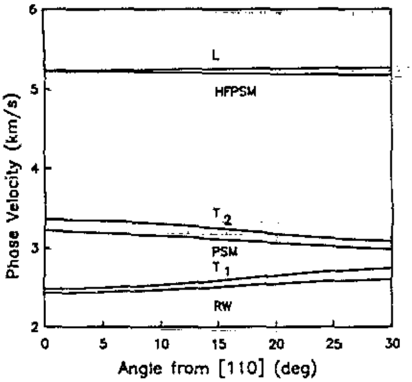

Figure 1. Phase velocity of the bulk waves L, T_1 and T_2, of the Rayleigh wave and of the pseudosurface modes PSM and HFPSM on the $(1\bar{1}1)$ plane of GaAs. These velocities are plotted as a function of the angle between the acoustic wavevector and the [110] direction.

anisotropy factor of the medium and shown that the HFPSM corresponds to a maximum in the reflection coefficient for mode conversion from bulk shear to a bulk longitudinal wave at the free surface. In addition, the calculated surface power spectrum of the longitudinal modes exhibits a sharp peak at the frequency of the HFPSM [4, 5].

Measurements performed on the (110) surface of GaAs [6] and of polycrystalline gold [7] have given evidence of a resonance in the Brillouin spectra occurring at a frequency close to that of the longitudinal wave. This resonance can be recognized as the HFPSM.

In the present paper we present the results of an investigation of surface and pseudosurface acoustic modes on the $(1\bar{1}1)$ face of GaAs. This face is of particular interest since both a PSM and an HFPSM are present, thus allowing a direct comparison between these two modes to be made. Acoustic propagation is analysed and the surface density of phonon states calculated for different propagation directions on the $(1\bar{1}1)$ plane. Results of Brillouin scattering measurements are presented and compared with the theoretical light scattering cross-section.

2. Power spectra of acoustic phonon states on the $(1\bar{1}1)$ plane of GaAs

Our analysis is concerned with long wavelength surface acoustic phonons propagating on the $(1\bar{1}1)$ plane of a GaAs single crystal. The phase velocities of the three bulk modes propagating along directions parallel to this plane are plotted in figure 1 together with those of the Rayleigh mode and of the pseudosurface modes. The elastic data used in these and the other calculations presented in this paper are given in table 1, together with the optical data which enter the Brillouin cross-sections of the next section.

The branches L, T_1 and T_2 correspond to the quasi-longitudinal and to the two quasi-transverse bulk acoustic waves, respectively. The acoustic displacement field of each wave consists of components both parallel to and perpendicular to the surface, except for propagation along [110] and [121]. Along [110] the L wave is pure longitudinal, while T_1 and T_2 are shear waves with the particle displacement vector at an angle with respect to the surface. Along [121] L and T_1 are polarized in the sagittal plane, while T_2 becomes pure transverse with particle displacement parallel to the surface (SH wave).

The RW is a surface wave of the generalized type [1] with an elliptical particle displacement out of the sagittal plane; it becomes a pure sagittal wave for propagation

Table 1. Values of all material parameters entering the calculations. n and k are the real and imaginary part of the refractive index, respectively.

Elastic constants [1] (10^{11} N m^{-2})			Elastooptic constants [8]			Refractive index [9]		Mass density [1] (kg m^{-3})
c_{11}	c_{12}	c_{44}	k_{11}	k_{12}	k_{44}	n	k	ρ
1.188	0.538	0.585	42.5	51.0	25.5	17.64	3.19	5230.0

along [121]. Pseudosurface modes correspond to resonances in the phonon power spectrum [10] occurring at frequencies higher than that of the RW. Both the PSM and the HFPSM are seen in figures 2(a) and 2(b) where the power spectra of the surface displacement components u_1, u_2 and u_3 are plotted against the frequency for the [110] and [121] directions. We refer here to a coordinate system (x_1, x_2, x_3) with the x_1 axis parallel to the acoustic wavevector and x_3 orthogonal to the surface.

The PSM, whose phase velocity lies between the branches T_1 and T_2, consists of three partial waves; two of them are confined at the surface, while the third one is a bulk wave

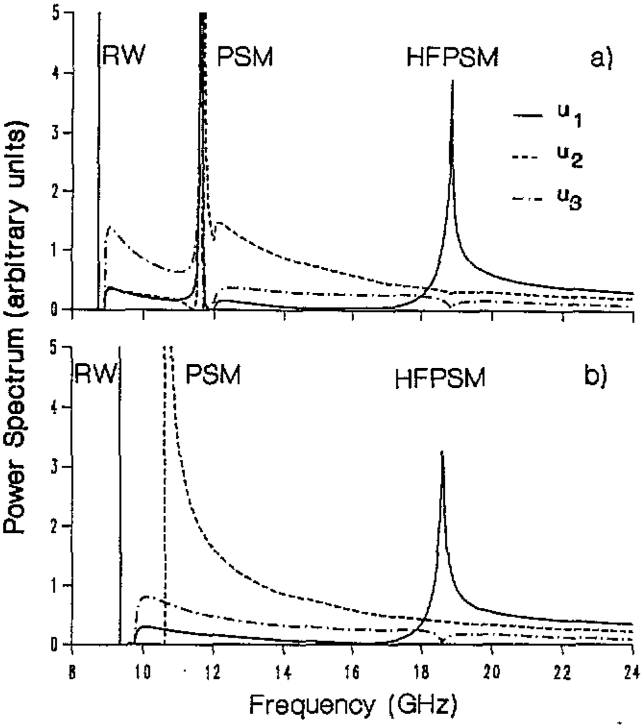

Figure 2. Power spectra of surface displacement components on the (1$\bar{1}$1) plane of GaAs for an acoustic wavevector component parallel to the surface $Q = 22.6\,\mu\text{m}^{-1}$. The acoustic wavevector is (a) along [110] and (b) along the [121] direction.

propagating into the medium. Energy is thus radiated away from the surface and the PSM undergoes attenuation. Its displacement field has components both parallel (u_1, u_3) and orthogonal (u_2) to the sagittal plane and depends on the propagation direction. When this direction approaches the [121] axis, the PSM is dominated by its u_2 component until it degenerates into a bulk shear horizontal wave with the wave vector tilted by 10.2° with respect to the surface. Its acoustic Poynting vector is contained in the sagittal plane and is parallel to the surface.

The second pseudosurface acoustic mode, the HFPSM, has a phase velocity slightly lower than that of the quasi-longitudinal bulk wave propagating parallel to the free surface. It has a pure longitudinal polarization for any propagation direction on the $(1\bar{1}1)$ plane and consists of three partial waves. Unlike the PSM, only one partial wave is confined at the surface, while the other two are bulk waves radiating energy into the medium. The HFPSM is thus much more strongly attenuated than the PSM.

3. Experimental results and discussion

Brillouin spectra were taken on a (111) GaAs single crystal with a tandem triple pass Fabry Perot interferometer [11], using a single mode of the 514.5 nm line of an Ar^+ ion laser. Measurements were taken at room temperature in the backscattering geometry with both the incident and the detected light beams polarized in the plane of incidence (p–p scattering). The backscattering geometry is illustrated in several papers in the literature: the reader is referred to figure 6.2 of the review paper of J R Sandercock [11].

Experimental spectra obtained for three different directions on the $(1\bar{1}1)$ plane of the sample are shown in figure 3 together with the theoretical cross sections. These were

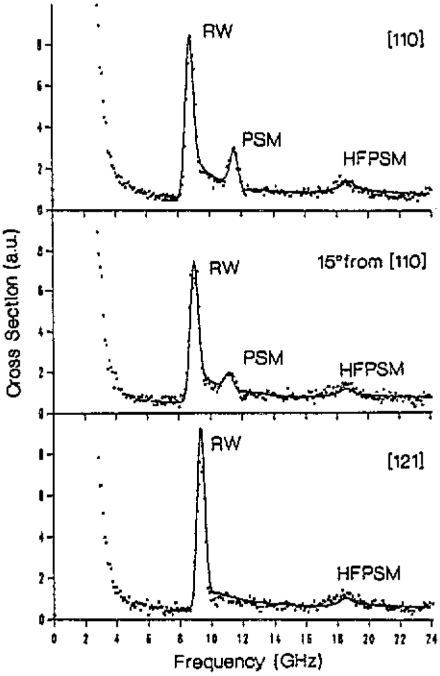

Figure 3. Experimental spectra and theoretical cross sections (full curve) for three different directions on the $(1\bar{1}1)$ plane of GaAs. The backscattering angle is 67.5°.

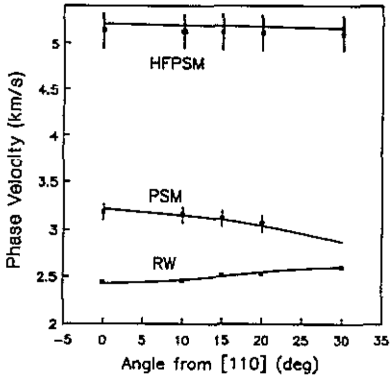

Figure 4. Phase velocity of the Rayleigh wave and of the two pseudosurface modes on the (1$\bar{1}$1) plane of GaAs for different directions of the acoustic wavevector. Full curves are the calculated values.

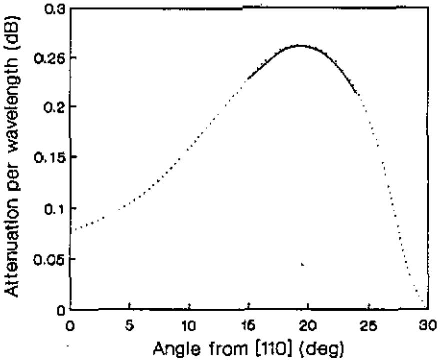

Figure 5. Attenuation of the pseudosurface mode PSM for different directions of its acoustic wavevector on the (1$\bar{1}$1) plane of GaAs. The full curve is evaluated from the linewidth of the theoretical cross section, while the dotted curve is obtained assuming PSM as a leaky mode with a complex wavevector (see [2]).

calculated by taking into account both ripple and elasto-optic contributions, according to the theoretical approach of Marvin *et al* [8, 12], and convoluted with a Gaussian curve in order to reproduce the instrumental broadening. The values of the photoelastic and optical constants of GaAs, taken from [8, 9] are given in table 1. The agreement between experimental spectra and theoretical cross sections looks fairly good.

The spectra exhibit three peak structures at about 9, 11 and 19 GHz, corresponding to the Rayleigh wave, to the PSM and to the HFPSM, respectively. From the position of the Brillouin peaks we have determined the phase velocities of the RW and of the two pseudosurface modes. They are in good agreement with the values obtained from the theoretical cross section, as seen in figure 4.

The Rayleigh wave produces a sharp and pronounced peak for any propagation direction since both ripple and elasto-optic contributions to the scattering process are rather strong.

The peak corresponding to the PSM shows an amplitude which depends strongly on the propagation direction; along [110] it is rather large since the vertical component u_3 of the acoustic displacement gives a strong contribution to the scattering cross section via the ripple mechanism. As the direction of propagation is rotated away from [110], the peak decreases until it vanishes along [121]. This happens, as already pointed out, because the PSM degenerates into an SH wave which gives no contribution to the p–p scattering process. The width of this peak depends on the instrumental resolution and, to some extent, on the linewidth of the resonance, which accounts for the finite lifetime of phonons. In our experiments, however, the instrumental resolution was not sufficient to allow the intrinsic attenuation of this mode to be measured. Attenuation was then evaluated from the linewidth of the calculated cross-sections of the mode before convolution with the instrumental transfer function. This procedure can be rigorously applied when the peak is fitted by a Lorentzian curve. In our case this occurs in a limited range of directions, as shown in figure 5 (full curve). The values obtained are consistent with those calculated according to the procedure given by Lim and Farnell [2], which considers the PSM as a leaky mode with a complex wavevector propagating along the surface (dotted curve in figure 5). Attentuation was then evaluated for all directions in the $(1\bar{1}1)$ plane. It can be seen that it increases as the propagation direction is rotated away from [110] up to a maximum of 0.27 dB per wavelength attained at an angle of about 20° and then decreases until it vanishes along [121]. Actually, along this direction the PSM degenerates into a SH bulk wave with the Poynting vector parallel to the surface, as already pointed out.

The peak corresponding to the HFPSM is rather weak for any propagation direction since this mode has a longitudinal displacement only, so that there is no ripple contribution to the scattering process. In addition, the peak is rather broad on account of the strong attenuation of the HFPSM. Its intrinsic attenuation could not be determined from the width of the peak, however, since the shape of the resonance is far from being a Lorentzian, as can be inferred from inspection of the surface density of phonon states in figure 2. It can be noticed that the HFPSM, although weak, is always present in the spectra of the $(1\bar{1}1)$ surface, while it can be observed only rarely on the (100) and (110) surfaces.

In conclusion, we have studied the propagation of the pseudosurface acoustic modes PSM and HFPSM on the $(1\bar{1}1)$ surface of GaAs, giving experimental evidence of both modes by Brillouin scattering measurements. We found the experimental spectra to be in good agreement with the cross-sections calculated according to the theory of Marvin *et al* [8, 12]. No adjustable parameter has been used in the calculations which are based on the values of photoelastic and dielectric constants derived independently for the (100) and (110) surfaces of GaAs. The phase velocities of both pseudosurface modes, measured from the peak position in the spectra, fit the calculated values fairly well. Finally, the attenuation of the PSM has been evaluated theoretically in the two alternative approaches of considering this mode either as a surface mode with a complex wavevector or as a resonance in the surface density of phonon states.

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