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Elastic properties of GaAs/AlAs superlattices

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Elastic properties of GaAs/AlAs superlattices have been investigated with use of Brillouin scattering. No evidence of anomalous elastic behavior, such as that reported in many metallic superlattices, is observed. The absence of an anomaly in GaAs/AlAs is consistent with a number of different theories that have been proposed to explain the effects in metallic systems. We also present experimentally determined elastic constants of pure AlAs [$C_{11}=(12.1\pm0.2)\times10^{11}$ dyn/cm^2 and $C_{44}=(4.74\pm0.08)\times10^{11}$ dyn/cm^2] and compare them with previous estimates.

Since the first report of huge anomalies in the elastic properties of Au/Ni and Cu/Pd superlattices,[1] there have been many reports in which other metallic superlattices were also found to exhibit anomalous elastic behavior.[2] In spite of the fact that over the past ten years there has been a considerable effort invested in studying these systems, the origin of the effect is still controversial. Original ideas of dislocation pinning[3] have now been largely dropped, while an explanation based on the folding of the electronic bands[4] has been available for some time. Very recently, three new alternative explanations have been proposed: one based on structural disorder at the interfaces,[5] another based on electron transfer,[6] and a third on "surface tension" at the interfaces.[7] An explanation based on coherency strains[8,9] has also been proposed, but appears to be in contradiction with a specific calculation for Cu/Ni superlattices.[10] The difficulty encountered in distinguishing between the theoretical models is due primarily to the lack of detailed experimentally verifiable quantitative predictions in the various models. For example, the disappearance of the elastic anomaly in Ag/Co superlattices on irradiation with C ions[11] (without destroying the layers) can be explained at least qualitatively in the context of all models.

An investigation of GaAs/AlAs superlattices appeared to be a good candidate to constrain the number of possible explanations: being nonmetallic, anomalous behavior is not expected from the mechanisms described in Refs. 4 and 6; furthermore, since these superlattices can be grown as "perfect" crystals, the mechanism of Ref. 5 would also predict no anomaly. A previous investigation of GaAs/Al$_x$Ga$_{1-x}$As superlattices[12] showed small deviations from expected behavior, which indicate that only the surface-tension explanation is viable.[7] The absence of anomalous behavior, however, would not contradict any of the above-mentioned models. Because of this, we have performed detailed elastic measurements in order to ascertain the presence or absence of an anomaly in pure GaAs/AlAs superlattices.

In the previous Brillouin-scattering study of GaAs/Al$_x$Ga$_{1-x}$As superlattices,[12] only surface waves were investigated and samples with varying composition (x), modulation wavelength (Λ) and ratio of layer thicknesses were used. The present study is aimed specifically at determining the existence or absence of anomalous behavior, and we therefore have reduced the number of variables by choosing $x=1$ (i.e., GaAs/AlAs) and keeping the ratio of the GaAs and AlAs layer thicknesses equal to 1. The only remaining parameter is Λ. Our study includes bulk longitudinal and transverse waves as well as surface waves.

Samples, of total thickness $\sim 1\ \mu$m, were prepared by molecular-beam epitaxy and characterized using x rays as described earlier.[13] The normal to the surface is a $\langle 001 \rangle$ direction and the earlier structural study showed that these superlattices exhibit a cumulative roughness of one atomic plane. The Brillouin-scattering technique is described in the literature[14] and we review here only the necessary concepts and equations. If incident and scattered light, of wave vector $\mathbf{k}$, subtend the same angle (θ) with the surface normal, the wave vector (q) of the phonon probed is given by, (i) for surface phonons,

$$q=2k\sin\theta\ , \tag{1}$$

and (ii) for bulk phonons,

$$q=2nk\ , \tag{2}$$

where n is the refractive index of the medium.

In our experiments the wave vector of the surface phonons on the (001) plane was chosen to be along the [100] direction; for bulk phonons q is in the (010) plane, subtending an angle

$$\alpha = \sin^{-1}(\sin\theta / n) \quad (3)$$

with the surface normal. Our experiments were carried out using 514-nm radiation from a single-mode Ar laser. In the data analysis we have used $\rho_{GaAs} = 5.317$ g/cm^3 and $\rho_{AlAs} = 3.70$ g/cm^3. The refractive indices for each material at 514 nm are 4.202 and 3.28, respectively.[15]

We first discuss our results on pure GaAs and AlAs. Figure 1 shows the velocities of longitudinal (v_L, solid symbols) and transverse (v_T, open symbols) waves in GaAs and AlAs as a function of the propagation angle away from [001]. We note that when $\alpha = 0$ the transverse modes should not be observed in Brillouin spectra obtained in the backscattering geometry. The fact that they are observed in AlAs is attributed to the finite-collection aperture. For $\alpha = 0$ the velocities correspond to $v_L = \sqrt{C_{11}/\rho}$ and $v_T = \sqrt{C_{44}/\rho}$. In GaAs for propagation along [001] the measured values yield $v_L = 4.74 \pm 0.05$ and $v_T = 3.31 \pm 0.04$ km/sec in good agreement with the values obtained using the literature values of the elastic constants[16] ($C_{11} = 11.9 \times 10^{11}$ dyn/cm^2, $C_{44} = 5.95 \times 10^{11}$ dyn/cm^2, and $C_{12} = 5.38 \times 10^{11}$ dyn/cm^2), which yield $v_L = 4.71$ km/sec and $v_T = 3.35$ km/sec.

The AlAs sample (1 μm thick) was grown on a GaAs substrate with a 500-Å GaAs capping layer to avoid deterioration of the AlAs. Along the [001] direction our values yield $v_L = 5.71 \pm 0.06$ km/sec and $v_T = 3.58 \pm 0.04$ km/sec, which, in turn, yield $C_{11} = (12.1 \pm 0.2) \times 10^{11}$ dyn/cm^2 and $C_{44} = (4.74 \pm 0.08) \times 10^{11}$ dyn/cm^2. To our knowledge, there is only one other experimental determination of an elastic property of AlAs,[17] which yielded $v_L(100) = 6.44 \pm 0.32$ km/sec ($C_{11} = 15.1 \times 10^{11}$ dyn/cm^2). The elastic constants of AlAs are usually taken from an interpolation of other III-V compounds: the values commonly accepted are[16] $C_{11} = 12.02 \times 10^{11}$ dyn/cm^2, $C_{44} = 5.89 \times 10^{11}$ dyn/cm^2, and $C_{12} = 5.70 \times 10^{11}$ dyn/cm^2. It is clear that although the estimated value of C_{11} is reasonably good, C_{44} was overestimated by $\sim 20\%$.

In order to calculate the effective elastic constants of the superlattice[18] we have had to assume C_{12} of AlAs to be given by the above-mentioned estimated value. With this assumption we obtain[18] $C_{11} = C_{22} = 12.0 \times 10^{11}$ dyn/cm^2, $C_{12} = 5.36 \times 10^{11}$ dyn/cm^2, $C_{33} = 11.9 \times 10^{11}$ dyn/cm^2, $C_{13} = C_{23} = 5.36 \times 10^{11}$ dyn/cm^2, $C_{44} = C_{55} = 5.28 \times 10^{11}$ dyn/cm^2, and $C_{66} = 5.35 \times 10^{11}$dyn/cm^2. In interpreting the data from superlattices, we have used the refractive index $n = 3.77$ derived from the indices of the constituents.[19] Figure 2 shows the longitudinal (dots) and transverse (triangles) sound velocities measured in equal-layer-thickness GaAs/AlAs superlattices as a function of modulation wavelength for $\theta = 50°$. The dashed lines are the expected velocities calculated using the effective elastic constants given above for a propagation direction at $\sim 12°$ from the [001] direction, viz., $v_L = 5.23$ km/sec and $v_T = 3.42$ km/sec. It is clear from Fig. 2 that within our experimental error there is no elastic anomaly in GaAs/AlAs superlattices. The small differences between the calculated and measured velocities can be ac-

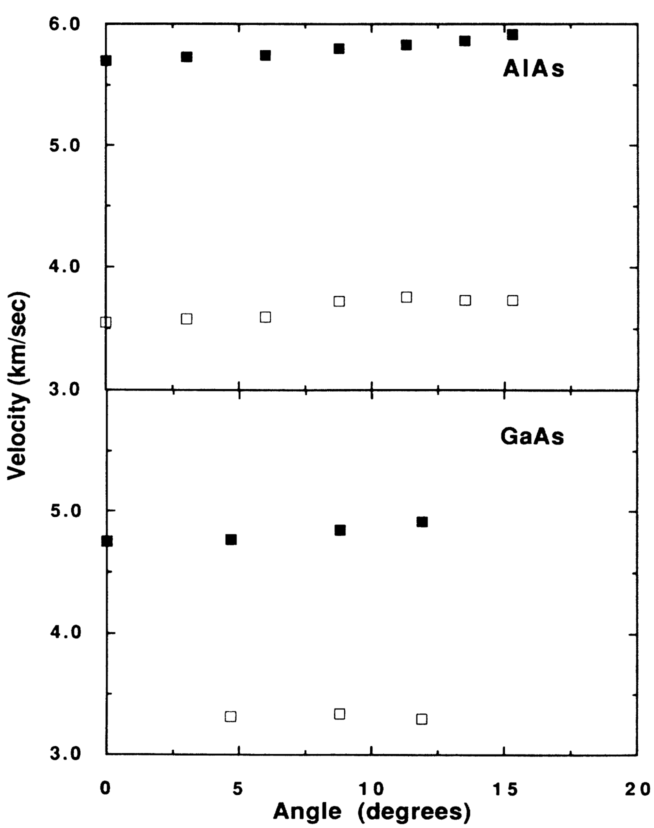

FIG. 1. Velocity of longitudinal (solid symbols) and transverse (open symbols) waves in AlAs and GaAs as a function of propagation direction along (cosα, sinα, 0).

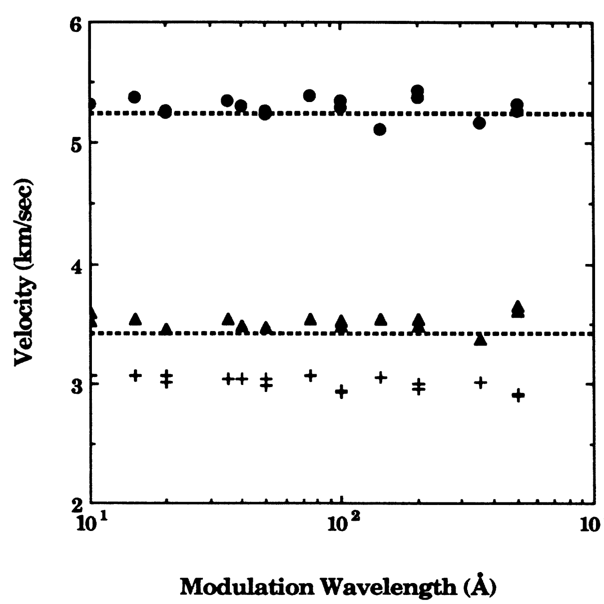

FIG. 2. Sound velocities in GaAs/AlAs superlattices as a function of modulation wavelength. The dots, triangles, and crosses correspond to longitudinal, transverse, and surface waves, respectively. The dashed lines are longitudinal and transverse sound velocities determined from the calculated elastic constants of the superlattices.

counted for by errors in propagation direction and refractive indices and by the uncertainties in the C_{ij} (especially C_{12} of AlAs).

Since anomalous behavior in metallic superlattices[2] has often been found in the velocity of surface-acoustic waves, we have also measured them on GaAs/AlAs superlattices (Fig. 2, crosses). As expected from the theory of surface waves,[20] they are about 5% slower than bulk shear modes and show no change as a function of Λ.

The absence of anomalous behavior in GaAs/AlAs superlattices is not in contradiction with any of the proposed explanations for the supermodulus effect. It does, however, have the following implications for the proposed explanations: it is consistent with "electron"-based theories[4,6] which predict no anomaly in nonmetallic systems; since the roughness of our GaAs/AlAs superlattices is ~ 1 atomic layer, the grain-boundary-based explanation[5] requires a roughness which is larger to produce a measurable effect; a microscopic picture, which includes roughness, of the interfacial-tension model[7] is needed before any conclusions can be made about it. We also note that the absence of an anomaly is consistent with explanations based on coherency strains,[8,9] which are very small in this case.

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