INVESTIGATIONS OF ANOMALOUS BEHAVIOR OF POSITIVE SAW VELOCITY DISPERSION CURVES FOR WATER/LAYERS/SILICON SYSTEMS

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Abstract

Velocity dispersion curves of surface acoustic waves for layered systems (water/layer/substrate) when the phase velocity in the layer is faster than that in the substrate are investigated, in this work. Thus, several thin films (SiC, AlN, Si_3N_4 and Al_2O_3) deposited on silicon substrates were considered. It was found that (i) the behavior of the dispersion curves has an anomalous character characterized by a decrease for small thickness, $h/\lambda_{TC} < 0.1$ followed by a normal dependence and (ii) this anomaly is dependent on elastic properties (densities, ρ and velocities, V_R) of both the layer (ρ_l and V_{Rl}) and the substrate (ρ_s and V_{Rs}). Hence, to quantify this behavior, we introduce a new parameter defined as: $\xi = (\rho_F/\rho_s)/(V_{RF}/V_{Rs})$. For $\xi > 1$, the anomalous decrease is observed which becomes more enhanced as ξ becomes higher; this behavior is thus, unexpectedly, due to the loading effect which seems to dominate in this region.

Introduction

Nowadays, acoustic microscopy has been greatly used in nondestructive investigations of materials via the study of surface acoustic wave, SAW, propagation in thin- and thick films solids [1 - 4].The film/substrate combinations, which play important roles in many technological, industrial and scientific fields, have received a great deal of interest by many research groups. Such structures are characterized by what is known dispersion effect, i.e. the dependence of the SAW velocity on the film thickness. Most reported investigations were carried out in the case of *slow on fast* combination (or mass loading effect) [5, 6], but little on *fast on slow* structures (or stiffness effect) [7, 8]. The terms *slow* and *fast* refer to SAW velocity values in film/substrate structures.

In this context, we investigate dispersion curves when the phase velocity in the layer is faster than that in the substrate for several thin films (SiC, AlN, Si_3N_4 and Al_2O_3) deposited on silicon substrates. Thus, we concentrated on the variation of leaky Rayleigh velocity for the structure water/thin film/silicon for different film thickness.

Anomaly Observation

Theoretical simulations were carried out in the case of a scanning acoustic microscope at an operating frequency of 142 MHz, a half opening angle of 50° and water whose density, ρ = 1000 kg/m^3 and longitudinal velocity V_L = 1500 m/s. The Si substrate is characterized by a density, ρ_S = 2300 kg/m^3 and a Rayleigh velocity V_{RS} = 4712 m/s, whereas each deposited film is characterized by its typical density ρ_F and Rayleigh velocity, V_{RF}. These characteristics are summarized in table 1 in terms of relative velocities and densities between films and Si substrate.

Table 1 : Relative elastic properties of structures used in this investigation where Mx_1 and Mx_2 are fictitious materials and $\xi = (\rho_F/\rho_S) / (V_{RF}/V_{RS})$.

Structure	Al_2O_3/Si	Si_3N_4/Si	AlN/Si	SiC/Si	Mx_1/Si	Mx_2/Si
V_{RF}/V_{RS}	1.19	1.21	1.36	1.45	1.21	1.45
ρ_F/ρ_S	1.73	1.38	1.42	1.40	1.73	3.13
ξ	1.45	1.14	1.04	0.96	1.43	2.16

In the present calculation we considered the slowest mode that corresponds to that of Rayleigh. Thus, the obtained velocity values for many materials deposited on Si substrates are displayed in figure 1 against normalized film thickness, h/λ_{TF}. It should be noted that, in general, for positive dispersion curves ($V_{RF} > V_{RS}$), the phase velocity increases initially from that of the substrate V_{RS} then saturates when it approaches a value that corresponds to the Rayleigh velocity of the film, V_{RF}. However, we can clearly see in fig.1 that for the structures SiC/Si, AlN/Si, Si_3N_4/Si and Al_2O_3/Si the curves can be divided into three regions.

- Region I: ($0.0 < h/\lambda_{TF} < 0.2$) is characterized by an anomalous behavior consisting of peaks and/or valleys as a result of decreases and/or increases of the initial curves.
- Region II: ($0.2 \leq h/\lambda_{TF} \leq 1.0$) the velocity increases to approach V_{RF}.

- Region III: ($1.0 \leq h/\lambda_{TF} \leq 2.0$) the curves tend asymptotically to Rayleigh velocity values corresponding to bulk materials of each thin film.

The anomalies observed in region I differ from one structure to the other in both their form as well as their amplitude; this phenomenon is better illustrated in figure 1b. which is an enlargement of region I of fig. 1a. It is clear that, e.g. the curve of AlN/Si is lower than that of Si_3N_4/Si, despite the fact $(V_{RF}/V_{RS})_{AlN} > (V_{RF}/V_{RS})_{Si3N4}$. This suggests the existence of another parameter, in addition to SAW velocities, responsible for the anomalous behavior, as will be discussed below.

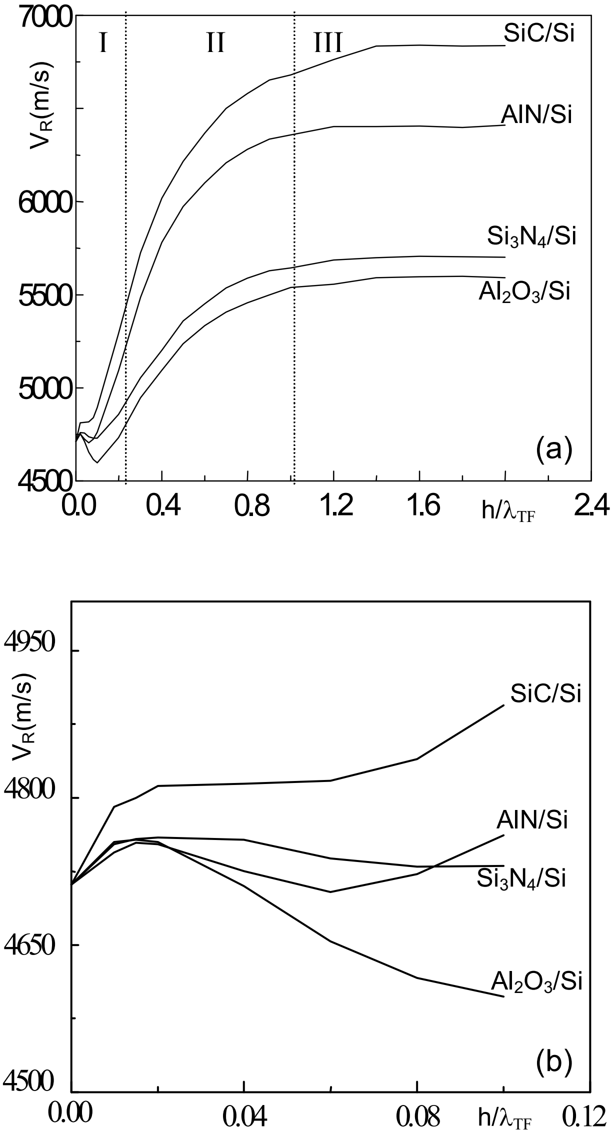

Figure 1. Velocity dispersion curves for different structures over the whole range (a) and in region I (b).

Anomalous Behavior Origin

In order to explain the appearance of peaks phenomena in dispersion curves, let us consider the structures Si_3N_4/Si and Al_2O_3/Si as well as a fictitious material Mx_1 whose longitudinal and transverse velocities are similar to those of Si_3N_4 whereas its density is equal to that of Al_2O_3 (Table 1). The results of the calculated velocity dispersion curves for these three structures are illustrated in figure 2 for the whole investigated range (a) and, for clarity, the initial variations are enlarged (b). It can be seen that the initial curve variation, $h/\lambda_{TF} < 0.2$, of Mx_1/Si structure is completely superimposed on that of Al_2O_3, whereas for large normalized thickness, $h/\lambda_{TF} > 1$, the curves joins quite well that of Si_3N_4. A close analysis of region I (fig. 2b) shows that for very small thickness,

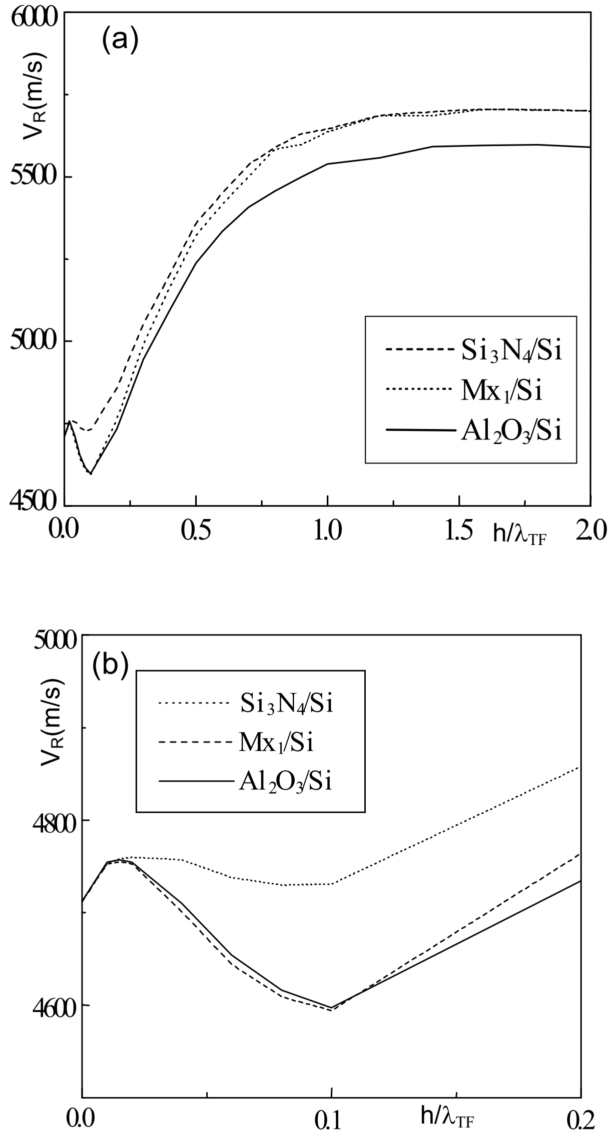

Figure 2. Velocity dispersion curves for different structures over the whole range (a) and in region I (b).

$h/\lambda_{TF} < 0.02$, all the curves are superimposed with the same type and magnitude of velocity increase. This is indicative of the predominance of the velocity effect as well as the mechanical properties of the Si substrate with respect to those of thin films. In the range $0.02 < h/\lambda_{TF} < 0.1$, all three curves decrease. This decrease agree quite well between the structures Al_2O_3/Si and Mx_1/Si characterized by the same densities. Whereas, the gradient is different between the structures Si_3N_4/Si and Mx_1/Si despite the fact that they are characterized by the same velocities. Thus, these observations suggest that the loading effect (densities) is responsible, in this range, for this anomalous behavior. In the range $h/\lambda_{TF} > 0.1$ the velocity effect takes over causing the usual increase up to the saturation region that coincide with that of Si_3N_4/Si which is equal to that of the fictitious material Mx_1.

Quantification and Discussion

A close analysis of Fig. 1b and Table 1 shows that as the ratio ρ_F/ρ_S takes a relatively a high value the wave velocity decreases further, except for the SiC/Si structure which does not show apparent decrease as compared to Si_3N_4. To better understand this behavior we consider another fictitious material Mx_2 characterized by SAW velocities similar to those of SiC and a very high density equal to that of chromium ($\rho_{Mx2} = \rho_{Cr} >> \rho_{SiC}$) to eliminate such effect and to enhance loading effect. Figure 3 the dispersion curves of SiC/Si and Mx_2/Si. It can be seen that the decrease of the fictitious material is more pronounced than that of SiC. The anomaly representation for Mx_2/Si combination, in figure 3b, shows the existence of an initial increase up to $h/\lambda_{TF} = 0.02$, followed by an important decrease in the range $0.02 < h/\lambda_{TF} < 0.08$ and finally the curve regains its normal increase.

For discussion simplicity, we define a parameter, ξ, which quantifies the effects of loading with respect to velocities, such that :

$$\xi = (\rho_F/\rho_S) / (V_{RF}/V_{RS}).$$

The calculated ξ values are listed in Table 1 for all investigated structures. The first conclusion that one may draw is the appearance of anomaly effects when ever ξ differs from unity. The trend of the curves depends on whether ξ is greater or smaller than unity. When $\xi< 1$, as in the SiC/Si case, the velocity effects is greater than the loading effect. Hence, dominating the anomaly behavior leading to the reduction and/or elimination of the decrease that should be observed, as in the SiC/Si case. Thus, as ξ increases from 0.96 (for SiC/Si) to 2.16 (for Mx_2/Si) the anomalous behavior becomes more pronounced leading to a faster decrease in velocity curves in the range of thickness concerned. Therefore, it is safe to conclude that the loading effect dominates for higher density materials and is consequently the most important origin of anomalous behavior appearance, in the range of small normalized thickness where the velocity decreases.

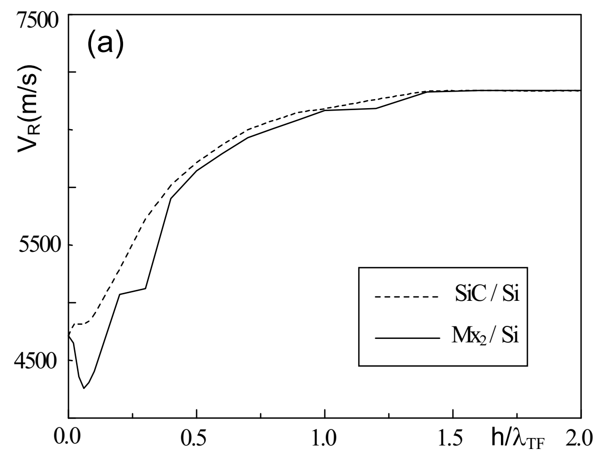

Figure 3. Velocity dispersion curves for different structures over the whole range (a) and in region I (b).

Conclusion

The analysis of positive dispersion curves of several thin/silicon substrate combinations (SiC/Si, AlN/Si, Si_3N_4/Si and Al_2O_3/Si) characterized by stiffness effect showed the appearance of anomalous behavior in a range of small normalized thickness. Thus, the evolution of the curves are not only influenced by velocity but also by densities (loading effects). The latter effect is shown to play an important role, at small normalized thickness, for higher values of ξ that was defined to quantify the effect of each parameter or both of them.

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