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Cut-off characteristics of leaky Sezawa and pseudo-Sezawa wave modes for thin-film characterization

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A new method of determining the elastic constants, density, and thickness of thin-film materials with the line-focus-beam acoustic microscope is developed using propagation characteristics of leaky Sezawa and pseudo-Sezawa waves in the neighborhood of the cut-off region. It is demonstrated for a sample of gold film on fused quartz that the values of the stiffness constant, C_{44}, and density are, respectively, about 11% and 5.5% less than those for polycrystalline bulk gold, and the thickness is determined as 6370 Å.

Applications of line-focus-beam (LFB) acoustic microscopy to quantitative material characterization have been developed extensively through the $V(z)$ curve analysis.[1-10] One of the most important applications, which cannot be performed by any other conventional analytical means, is elastic characterization of as-grown films and implanted or diffused layers.[11] These include such research problems as determination of the acoustic properties and film thickness or effective depth, evaluation of adhesion, contamination, disbonding at the interface, and residual stresses. Much effort has been successfully paid to establish a basis of the application. Even isotropic thin-film materials have four independent variables to be determined, viz. the stiffness constants, C_{11} and C_{44}, density, ρ, and thickness, H. The possibilities for success have been clearly shown from the comparison of experimental and theoretical results with several simpler sample configurations.[1] For example, it was demonstrated recently for gold films on fused quartz[5] and on silicon substrates[6] that measurements of the film thickness by utilizing the velocity dispersion curves could be made. It was also verified, for polycrystalline ZnO films on fused quartz and for epitaxial ZnO films on Z-cut sapphire substrates, that the acoustic properties of polycrystalline films are quite different from those of epitaxial films and of the single crystals.[12] The measurement of velocity and attenuation of relevant leaky waves, for any kind of layered structures, has become easier and more accurate.[4,13] Thus, it can be expected that a method of complete characterization, including film thickness determination, will be developed.

In this letter, we propose a new method for such determinations using propagation characteristics of leaky Sezawa and pseudo-Sezawa waves, as well as those of leaky Rayleigh waves. For this purpose, it is shown theoretically and experimentally, using a sample of gold film on fused quartz, that the cut-off region of leaky Sezawa and pseudo-Sezawa waves plays an important role for the determination.

We first carried out exact numerical calculations of the propagation characteristics of both modes of leaky Sezawa and pseudo-Sezawa waves in the neighborhood of the cut-off region with the bulk constants of polycrystalline gold[14] and fused quartz,[15] as shown in Fig. 1. In the figure, the two modes are distinguished at the point of $fH = 128.2$ Hz m, where f is the acoustic frequency, and with the phase velocity corresponding to the shear wave velocity V_s of fused quartz. The leaky Sezawa waves radiate acoustic energy only into water due to the water loading effect on the sample surface, and exist in a velocity region between the velocities of V_s and V_w, where V_w is the longitudinal velocity of water. On the other hand, the leaky pseudo-Sezawa waves radiate acoustic energy into both water and substrate, and exist in a velocity region between V_s and the velocity of $V_{\mathrm{lsscw}} = 5980$ m/s for a leaky surface skimming compressional wave on water-loaded fused quartz. It should be noted that the attenuation, normalized by the wave number, varies greatly around cut-off, while the velocites of both modes are almost continuous through the point. In comparison, the dotted line in Fig. 1 shows the calculated results of the attenuation of the pseudo-Sezawa wave mode for the case of no water loading. The attenuation is only due to the energy leakage into the substrate. As the fH reaches the cut-off frequency, the attenuation approaches zero. In the case of water loading, leaky pseudo-Sezawa waves might be considered to be at the same leaky level into the substrate, so that the large difference between the attenuations of leaky Sezawa and pseudo-Sezawa modes around cut-off is affected strongly by the water loading.

Experiments were performed to confirm these propagation characteristics. A gold film of about 6000 Å in thickness was fabricated on a fused quartz substrate

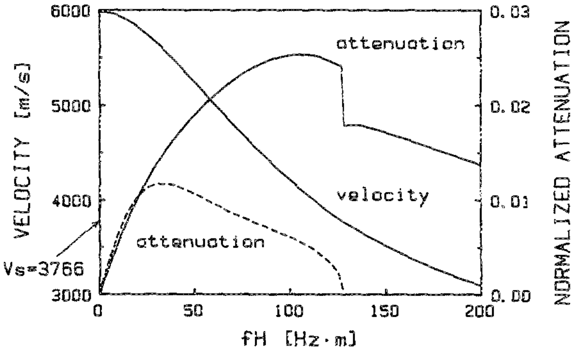

FIG. 1. Calculated propagation characteristics for leaky Sezawa and pseudo-Sezawa wave modes for specimen of gold film on fused quartz substrate. The dotted line is for the attenuation of the pseudo-Sezawa wave mode with no water loading.

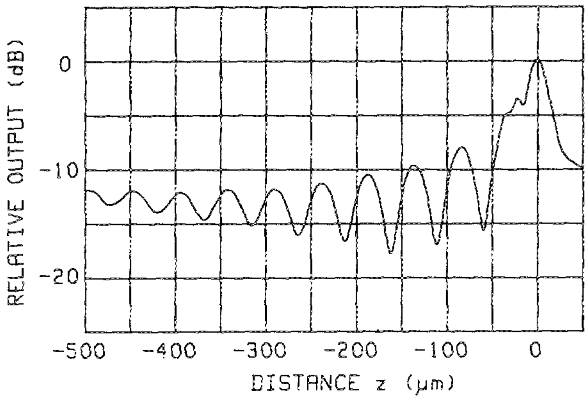

FIG. 2. Typical $V(z)$ curve measured for gold film on fused quartz substrate at 190 MHz.

($30\times 50\times 2$ mm^3) by vacuum evaporation. The sample has a moderate thickness distribution suitable for investigation. Velocities and attenuation values were measured at a position of the sample using an LFB system by varying the frequency in 5 MHz increments from 150 to 260 MHz. Figure 2 shows the typical $V(z)$ curve at the frequency of 190 MHz containing two modes of leaky Rayleigh and pseudo-Sezawa waves. The leaky pseudo-Sezawa wave is well recorded for the measurement and the leaky Rayleigh wave mode attenuates rapidly in the $V(z)$ curve. The velocity and normalized attenuation were determined to be $V_{\rm lpsw} = 3898$ m/s and $\alpha_{\rm lpsw} = 2.66\times 10^{-2}$, respectively. The measured frequency dependences of velocity and attenuation are shown in Fig. 3.

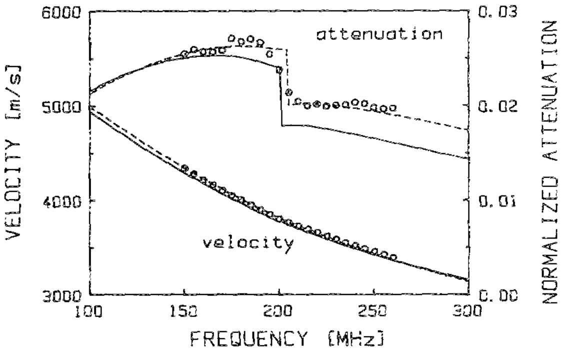

FIG. 3. Frequency dependence of measured and calculated propagation characteristics of leaky Sezawa and pseudo-Sezawa wave modes for gold film on fused quartz substrate. The solid lines are calculated with the bulk constants of gold, while the dotted lines are computer fitted.

TABLE I. Determined material constants of gold film.

	$C_{44}(\times 10^{10}$ N/m$^2)$	$\rho(\times 10^4$ kg/m$^3)$	H(Å)
film	2.611 (− 11%)	1.824 (− 5.5%)	6370
bulk	2.99	1.93	· · ·

Next, we evaluate the material constants of the gold film by computer fitting the propagation characteristics. In Fig. 3, the solid lines show the calculated results with the bulk constants, using the film thickness of 6370 Å determined from the relation of $fH = 128$ Hz m. There is good agreement between the measured and calculated velocity values, while for attenuation some interesting features and differences are found. The measured attenuation values around 150 MHz coincide well with those calculated. As the frequency increases and approaches the cut-off frequency, the difference between the measured and calculated values increases, especially in the region of $f > 205$ MHz, where the measured values are much greater than those calculated. In fitting the calculations, the stiffness constant C_{11} can be assumed to be equal to the bulk value because in the frequency region the value of C_{11} of the gold film does not have a significant influence on the propagation characteristics of these Sezawa modes, although the frequency dependence of the propagation characteristics are very sensitive to the values of C_{44} and ρ.[16] So, we can determine them by the computer fitting. The dotted lines in Fig. 3 show the fitted curves with the reduced values of 11% for C_{44} and 5.5% for ρ, respectively, compared with the bulk values. The determined material constants are summarized in Table I.

In addition to the two modes around the cut-off frequency, a leaky Rayleigh wave mode can be used to complete a novel method of determination of all the material constants, viz., C_{11}, C_{44}, ρ, and H of as-grown thin films. In the case of the sample configuration used here, it might not be so easy to determine the propagation characteristics of leaky Rayleigh waves with sufficient accuracy as seen from Fig. 2. It is suggested that further measurements should be made with another LFB device operating at lower frequencies for the same sample, as previously described.[5]

In conclusion, a new method for determining material constants of as-grown films has been developed taking notice of the remarkable fH dependence of the propagation characteristics of the leaky Sezawa and pseudo-Sezawa wave modes around the cut-off region. It has been successfully demonstrated for a sample of as-evaporated gold film on fused quartz substrate. For practical use, ultrasonic attenuation of gold film should be taken into consideration because relatively higher frequencies are employed in the characterization. In this method, determination is made through the theoretical calculations of the propagation characteristics, so that the material constants of substrates must be known. The LFB system is also useful for determination of the bulk constants of substrates.[7] The detailed procedure of the method will be reported elsewhere.

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