INCREASING THE SENSITIVITY OF THE SCANNING ACOUSTIC MICROSCOPE TO ANISOTROPY

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ABSTRACT

The response of the scanning acoustic microscope to anisotropic materials is theoretically investigated. For this purpose, the reflection coefficient of plane acoustic waves incident on a liquid-anisotropic-solid interface is numerically calculated. The reflection coefficient depends, in general, on polar and azimuthal angles of incidence. For the acoustic microscope case, a mean reflectance function can be defined which depends only on the polar angle, because there is a circular symmetry. With this mean reflectance function it is possible to explore the effects of changing the lens parameters such as the acoustic field at the back side of the lens. It is found that the response of the scanning acoustic microscope can depend heavily on the orientation of the solid material under investigation provided that a suitable lens insonification is utilized. The amplitude of the acoustic microscope signal is influenced by the orientation of the material, because there is an interference between the acoustic waves reflected from the material surface at different azimuthal angles. This interference is revealed as a minimum in the mean reflectance function. It is shown by computer simulation that, sensitivity to orientation can be increased by use of a ring shaped transducer in the near field of the acoustic lens. With such lenses, it may be possible to determine the orientation of crystallites in a material.

I. INTRODUCTION

Scanning acoustic microscope has become a useful instrument in characterizing the properties of materials on a microscopic scale. Its material dependent images are a result of the sound wave reflection at the liquid-solid interface. The reflection coefficient—both amplitude and phase—uniquely characterizes the material under investigation. Crystalline materials such as integrated circuits and thin film structures or the grains of a polycrystalline material are typically acoustically anisotropic. For such materials direction sensitive acoustic lens geometries have been utilized for characterization purposes [1,2,3]. Somekh et al. [4] have studied the reflection coefficient of anisotropic materials at a liquid interface for the purpose of understanding acoustic images obtained by acoustic microscopes. They have numerically calculated the reflection coefficients for some materials and applied the results for interpretation of contrast in acoustic images.

In this paper, the results of a study on the reflection of plane acoustical waves at a liquid-anisotropic-solid interface are applied for the determination of the scanning acoustic microscope response. Ways of improving the sensitivity to anisotropy are discussed.

II. RESPONSE OF SCANNING ACOUSTIC MICROSCOPE TO ANISOTROPIC MATERIALS

For a planar object surface placed perpendicular to the lens axis scanning acoustic microscope output can be expressed as[5,6]

$$V(Z) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} [u^+(x,y)P(x,y)]^2 \mathcal{R}(x/f, y/f)e^{-j4\pi/\lambda Z\sqrt{1-(x/f)^2-(y/f)^2}}dx\,dy \tag{1}$$

where V is the output voltage of the acoustic microscope, u^+ is the acoustic field at the back side of the acoustic lens, $\mathcal{R}$ is the complex reflectance function at the liquid-solid interface as a function of direction cosines in two directions, P is the pupil function of the lens, f is the focal length of the lens and Z is the distance between the focal point and the object position. At $Z = 0$ the microscope output is essentially an integral of the reflection function. Eq. 1 can be written in cylindrical coordinates as

$$V(Z) = \int_0^{2\pi}\int_0^{+\infty} [u^+(r\cos\phi, r\sin\phi)P(r\cos\phi, r\sin\phi)]^2 \mathcal{R}(\frac{r}{f}\cos\phi, \frac{r}{f}\sin\phi)e^{-j\frac{4\pi Z}{\lambda}\sqrt{1-(\frac{r}{f})^2}}r\,dr\,d\phi \tag{2}$$

For circularly symmetric cases, it is possible to reduce the reflection function to a one-dimensional function for for the purposes of calculating the acoustic microscope output [4]. Following the notation of Somekh et al. with $\sin\theta = r/f$ we can define a mean reflectance function and write

$$\mathcal{R}'(\sin\theta) = \int_0^{2\pi} \mathcal{R}(\sin\theta\cos\phi, \sin\theta\sin\phi)d\phi \tag{3}$$

$\mathcal{R}'$ is a function of $\sin\theta$ only. Because the ϕ dependance is removed by an integration in ϕ direction. Due to the complexity of the reflection problem, an analytical solution of $\mathcal{R}$ is not possible [7,8], hence a numerical approach is attempted. A FORTRAN program has been written to compute the reflection function as a function of polar and azimuthal angles. The program can handle materials with arbitrary stiffness matrices of twenty-one constants, so materials with arbitrary orientation can be handled with proper transformation of stiffness matrix by multiplication with Bond-matrices[9]. The program was tested against materials whose reflection coefficients were previosly calculated [4,10]. The integral in Eq. 3 must be carefully evaluated because of the complex nature of the reflectance function. Sufficiently many points must be included in the integral for correct results, especially for large $\sin\theta$ values. We have calculated a number of such curves for SAM response determination. Fig. 1 shows the amplitude and phase plots of $\mathcal{R}'$ for water-silicon interface at principal planes of silicon. Since silicon crystal is of cubic structure, for (001) surface integration is performed for ϕ between 0° and 45°, for (011) surface between 0° and 90° and for (111) surface between 0° and 60°. Figs. 2,3,4 and 5 are similar

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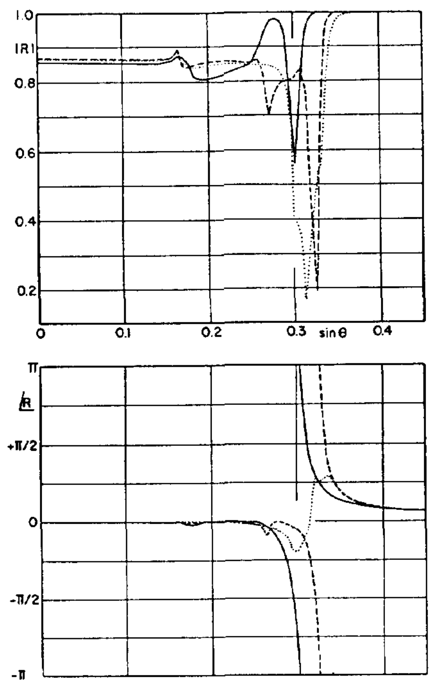

Figure 1: Average reflection function amplitude and phase for water-silicon interface at various orientations, (001) (solid), (011) (dotted) and (111) (dashed) as a function of $\sin\theta$.

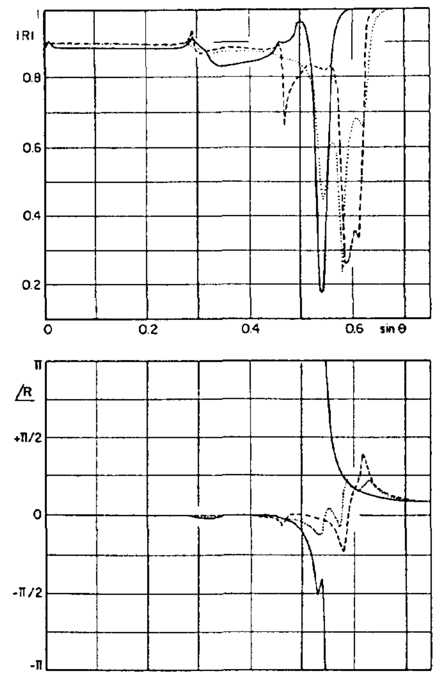

Figure 2: Average reflection function amplitude and phase for water-GaAs interface at various orientations, (001) (solid), (011) (dotted) and (111) (dashed) as a function of $\sin\theta$.

presentations for water-GaAs, -iron, -nickel and -aluminum interfaces. Inspection of the amplitude curves indicate that there is a significant dip in the curves where there is a phase transition. The dip is as a result of interference between reflected rays at different azimuthal angles after the integration operation. The interference is insignificant for isotropic or nearly isotropic materials where the phase transition occurs nearly at the same θ for different ϕ values. But for anisotropic materials the phase transition occurs at different θ values for different ϕ values. When the acoustic rays at these angles are vectorially added, there will be an interference. We must point out that our results for mean reflection function do not fully agree with that of Somekh et al. [4], although plots for $\mathcal{R}$ are in perfect agreement.

We recall that the interference effect, which gives rise to material dependence of V(Z) curves, occurs between the central rays and and the rays near the phase transition angle [11]. For anisotropic materials we observe that the amplitude of the rays near transition angle is considerably reduced because of another interference effect mentioned above. Hence, the nulls and peaks of V(Z) will not be very deep and the sensitivity to material parameters will be less for such materials.

For a circulary symmetric illumination and pupil function Eq. 2 can be simplified. Combining Eq. 3 with Eq. 2 one can arrive at a one-dimensional integral:

$$V(Z) = f^2 \int_0^{\sin\theta_m} \sin\theta [u^+(f\sin\theta)P(f\sin\theta)]^2 \mathcal{R}'(\sin\theta) e^{-j\frac{4\pi Z}{\lambda}\sqrt{1-(\frac{r}{f})^2}}\, d(\sin\theta) \quad (4)$$

This integral is relatively easy to calculate. The functions u^+ and P will be determined from the lens parameters. Typically one uses transducer sizes which will minimize the diffraction loss in the buffer rod. Fig. 6 shows a plot of u^+ for such a case. In Fig. 7 we show the results of calculations for GaAs and nickel crystals at various orientations. Observe that the difference between the curves are appreciable at negative Z values, i.e. when the object surface is brought closer to the lens than the focal distance. It is therefore possible to observe the grain structure of a material under acoustic microscope with a sacrifice in resolution.

III. INCREASING THE SENSITIVITY TO ANISOTROPY

Looking at the Figs. 1-5 it is easy to imagine how one gets an increase in contrast between differently oriented regions of the same material. Comparison of the amplitude curves indicate that the angles around zero degrees do not differ considerably. On the other hand, at higher angle values and especially around the phase transition there is more difference. It may be preferrable to use a pure amplitude response rather than a phase effect.

One should excite only those angles which are more interesting. One needs an annular type excitation. Nikoonahad et al. [12] used an acoustic lens with a suitable transducer to exclude some excitation angles for providing Rayleigh wave suppression. Our proposal here is just the opposite case. The central rays are to be suppressed to increase sensitivity. Note that, providing an annular transducer does not guarantee that excitation u^+ will be annular. Diffraction effects are not at all negligible considering the fact that at typical operating frequencies the wavelength is comparable to the size of the transducer. We have calculated the diffraction loss between two annular transducers as a function of distance between the transducers. The results show that the diffraction loss increases drastically in the Fresnel region of the transducer. One acceptable solution is in the near field of the transducer. This implies that one has to use relatively thin acoustic buffer rods which may be impractical at high frequencies. Nevertheless, it is also possible to find geometries which will give acceptable diffraction loss and generate a reasonably ring shaped illumination at the back side of the acoustic lens. To improve the situation the central portions of the acoustic lens surface may be coated by an absorber material or the antireflection

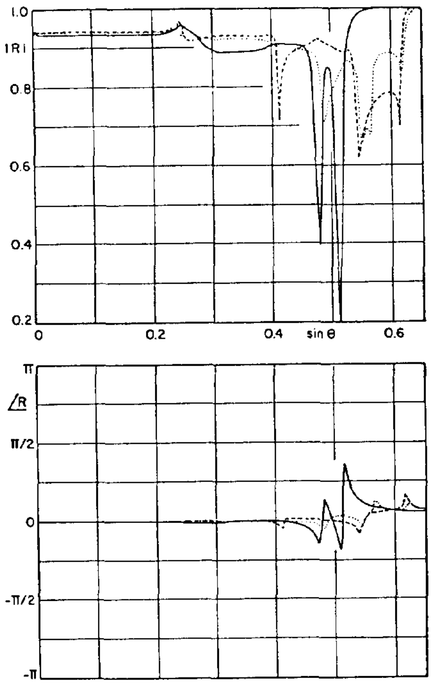

Figure 3: Average reflection function amplitude and phase for water-iron interface at various orientations, (001) (solid), (011) (dotted) and (111) (dashed) as a function of sin θ.

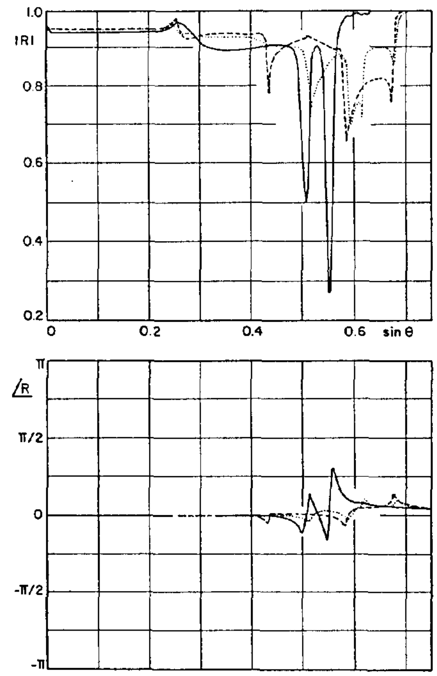

Figure 4: Average reflection function amplitude and phase for water-nickel interface at various orientations, (001) (solid), (011) (dotted) and (111) (dashed) as a function of sin θ.

layer may be etched away in this region.

Once the transducer is illuminated by a ring shaped acoustic field, the response of the microscope for different materials can be calculated. The illumination function u^{+} of Eq. 5 must be appropriately defined for the acoustic field pattern at the back focal plane of the lens. With an illumination function shown in Fig. 6, $V(Z)$ curves for various materials can be compared to see the gain in sensitivity. Fig. 8 depicts calculated $V(Z)$ curves for GaAs and nickel at various orientations with the annular excitation. Comparing this figure with Fig. 7 we note the increase in the difference between the curves. Notice also that the signal level at $Z = 0$ is now significantly different for different orientations. Hence, the grain structure of materials can be observed [13] also at $Z = 0$ without losing resolution. It is possible to increase the sensitivity even further, if a narrower ring excitation can be used. But this is rather difficult because of diffraction effects in the buffer rod.

IV. CONCLUSION

In this paper, the results of numerical calculations on acoustical reflection problem at a liquid-anisotropic-solid interface are presented and the mean reflection coefficient plots of various solids are obtained. It is possible to compute the response of an acoustic microscope for anisotropic materials, once the mean reflection function is determined. Response of the acoustic microscope for various anisotropic crystals at various orientations are presented. We have found that it is possible to increase the sensitivity of the scanning acoustic microscope to anisotropy by using ring shaped transducers. With properly designed lenses, the acoustic image contrast observed between the grains on surfaces of polycrystaline materials will be increased.

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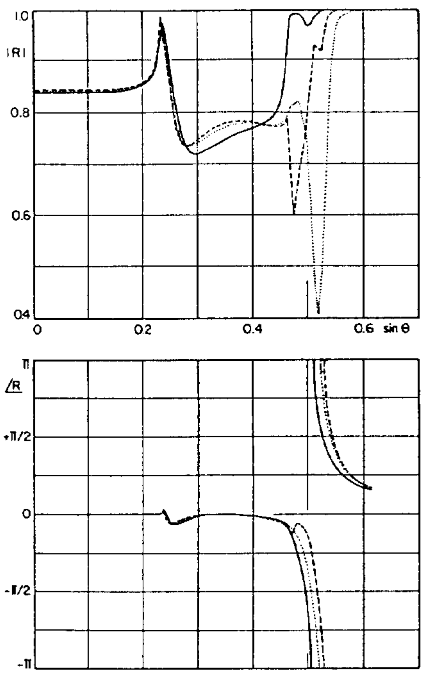

Figure 5: Average reflection function amplitude and phase for water-aluminum interface at various orientations, (001) (solid), (011) (dotted) and (111) (dashed) as a function of $\sin\theta$.

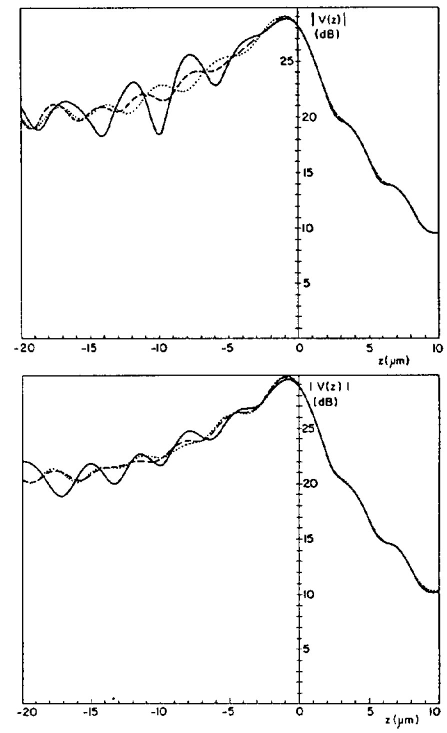

Figure 7: Calculated $V(Z)$ curves for (001)(solid), (011)(dashed) and (111)(dotted) faces of GaAs and nickel.

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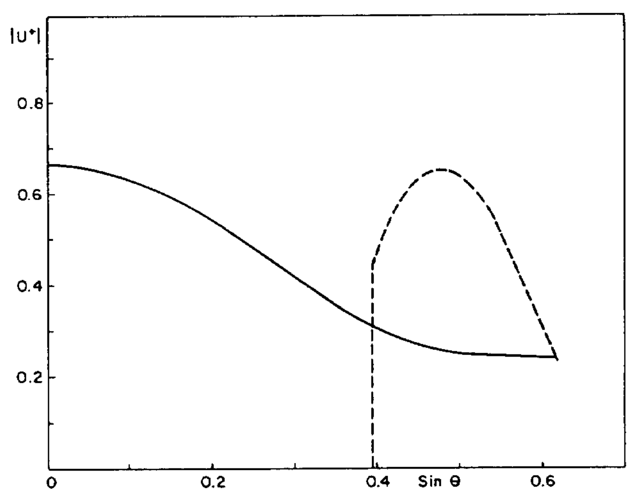

Figure 6: Insonification functions u^+ used in computations for a sapphire acoustic lens with 75μ pupil radius at 1100 MHz: Designed to minimize diffraction loss (solid curve)(105μ transducer radius, 1200μ buffer rod length), designed to improve the sensitivity to anisotropy(dashed line)(55μ transducer inner radius, 75μ transducer outer radius, 500μ buffer rod length, central region blocked).

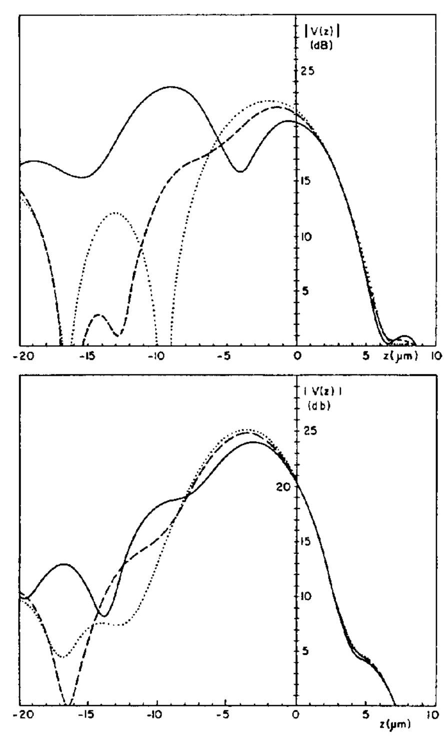

Figure 8: Calculated $V(Z)$ curves for (001)(solid), (011)(dashed) and (111)(dotted) faces of GaAs and nickel with an annular type excitation.