TILTED SAMPLE ACOUSTIC MICROSCOPY FOR ANISOTROPY MEASUREMENT

F. L. Degertekin, B.V. Honein and B.T. Khuri-Yakub

E.L. Ginzton Laboratory Stanford University, Stanford CA 94305

ABSTRACT

The conventional acoustic microscope with the spherical lens insonifies the samples with circularly symmetric fields. In case of anisotropic samples, this field distributions result in an anisotropy insensitive V(Z) curve, since the material properties are averaged over all azimuthal directions. The circularly symmetric excitation and detection should be avoided to improve the sensitivity to anisotropy of the sample. We present a method in which the sample is simply tilted to improve anisotropy sensitivity of the acoustic microscope with high spatial resolution. No change in the conventional lens and transducer structure is required. A theoretical model based on angular spectrum approach is developed to calculate the V(Z) curves for the tilted sample acoustic microscope. The directivity and resolution of the tilted sample acoustic microscope is evaluated as a function of lens and material parameters and the tilt angle using the developed approach. Validity of calculations is tested by comparing measured and calculated V(Z) curves for (100) silicon and excellent agreement is observed. The anisotropy of surface waves in (100) gallium arsenide is also observed by a tilted sample acoustic microscope in agreement with calculations.

INTRODUCTION

In many applications of the acoustic microscope, the sample materials under investigation are anisotropic [1]. The semiconductor crystals such as silicon and gallium arsenide with some layered structure are common materials that have elastic anisotropy [2]. The conventional acoustic microscope with the circular transducer and spherical lens is not suitable for direction dependent characterization, because of the circular symmetry averaging the directional information [3]. One extreme approach avoiding the circular symmetry to obtain anisotropy sensitivity is the line focus beam microscope [1]. The drawback for this approach is the complete loss of resolution in one of the lateral directions. Other methods that compromise resolution for directional information are also proposed by various researchers. Many of these methods either require one or more lenses or specially built transducers. Using a shear wave transducer or blocking the center part of the lens are also proposed as means for improving anisotropy sensitivity using the conventional lens structure.

Another way of obtaining anisotropy information without changing the conventional lens and transducer structure was proposed earlier [4]. In this method, the planar sample is simply tilted as depicted in Fig. 1 with respect to the lens axis, resulting a non circularly symmetric field distribution on the sample. In this paper, the response of the tilted sample acoustic microscope configuration is analyzed using the angular spectrum approach [5]. The V(z) curves are calculated and compared with the experimental data to verify and test the anisotropy sensitivity of the method.

RESPONSE OF THE TILTED SAMPLE ACOUSTIC MICROSCOPE

The angular spectrum of acoustic plane waves is commonly used to calculate the V(z) curves for conventional acoustic microscope. The general expression relating the angular spectrum of a longitudinal wave transducer and the output voltage in presence of a scatterer is obtained using the generalized reciprocity relations [6]. Using that formulation, the output voltage ,V, of the transducer can be written as

$$V = K\int_{-\infty}^{+\infty}\int U^{+}(-k_x,-k_y)U^{-}(k_x,k_y)k_z dk_x dk_y \qquad (1)$$

where, $U^{+}(k_x,k_y)$ and $U^{-}(k_x,k_y)$ are the incident spectrum excited by the transducer traveling in the +z direction and the resulting scattered angular spectra traveling in the -z direction, respectively. The formula does not assume the paraxial approximation and the only restriction is that the angular spectra should be evaluated at the same plane. For the tilted sample acoustic microscope shown in Fig. 1, the plane of integration is chosen as the focal plane f.

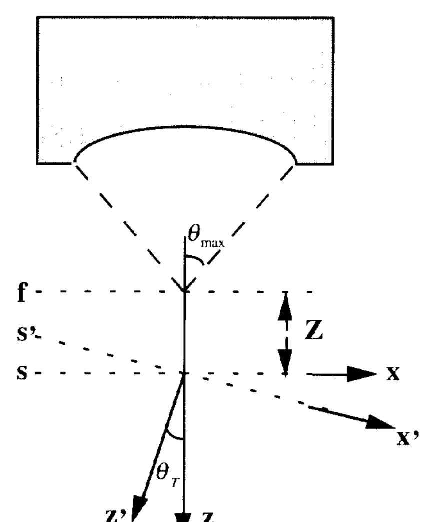

Figure 1. Geometry and coordinate system used for the angular spectrum analysis.

The sample is located at the origin and lies on the s' plane coinciding with the x'-y' plane, where the primed coordinates are obtained by tilting the x-y plane around y-axis by an angle θ_T

without loss of generality. The incident angular spectrum at focal plane is denoted by $U_f^-(k_x,k_y)$ and it is directly related to the field distribution at the back focal plane of the lens by the Fourier transform. To find the scattered spectrum, $U_f^-(k_x,k_y)$ at the focal plane, we first propagate the field to the plane s, than find the angular spectrum on the sample s', using primed coordinates as

$$U_{s'}^+(k_x',k_y') = \begin{cases} U_s^+(k_x,k_y)\dfrac{k_z'}{k_z} & for\ k_z' > 0 \\ 0 & else \end{cases} \quad (2)$$

where

$$U_s^+(k_x,k_y) = U_f^+(k_x,k_y)\exp(jk_z z) \quad \text{and}$$
$$k_x' = k_x\cos(\theta_T) + k_z\sin(\theta_T)$$
$$k_y' = k_y \quad (3)$$
$$k_z' = k_z\cos(\theta_T) - k_x\sin(\theta_T)$$

The condition $k_z' > 0$, should be satisfied to have waves incident on the sample. The factor $\frac{k_z'}{k_z}$ results from the Jacobian operation [7]. The reflection at the liquid sample interface is included by multiplication of the spectrum components with corresponding plane wave reflection coefficient leading the equation

$$U_{s'}^-(k_x',k_y') = U_{s'}^+(k_x',k_y')R(k_x',k_y') \quad (4)$$

After rotating the spectrum back to plane s and propagating the field back to the focal plane, we obtain

$$U_f^-(k_x'',k_y'') = U_s^-(k_x',k_y')\ \exp(jk_z Z)\ \frac{k_z''}{k_z'} \quad (5)$$

to see the relation between the spectra $U_f^-(k_x,k_y)$ and $U_f^+(k_x,k_y)$, equation (5) can be explicitly written as,

$$U_f^-(k_x\cos(2\theta_T)+k_z\sin(2\theta_T),k_y) = U_f^+(k_x,k_y)\ *\exp(jZ(k_z+k_z''))\frac{k_z''}{k_z}$$
$$*R(k_x\cos(\theta_T)+k_z\sin(\theta_T),k_y)$$

$$\text{with } k_z'' = \sqrt{k_0^2 - k_x''^2 - k_y''^2} \quad (6)$$

Equation (6) can be interpreted as follows: The reflected spectrum is a shifted and distorted version of the incident spectrum scaled by a shifted reflector, diffraction due to propagation and the Jacobian factor. Using this equation, the integral in (1) can be evaluated to get the V(Z) curves for the tilted sample acoustic microscope. For a circularly symmetric transducer and spherical lens, $U_f^+(k_x,k_y)$ will be circularly symmetric including the effect of the pupil function, but because of the shifting in k-space after reflection, the integrand will not have the symmetry yielding direction dependent output voltage at the transducer. The V(Z) curves for anisotropic samples are evaluated using uniform circular or measured pupil function for the lens as $U_f^+(k_x,k_y)$, and the reflected field is interpolated using a fine grid in k-space.

RESOLUTION AND DIRECTIVITY OF TILTED SAMPLE ACOUSTIC MICROSCOPE

To investigate the effect of tilting the sample on resolution and directivity of the acoustic microscope, the factors affecting the output signal through the integral formula should be examined closely in k-space. As mentioned in the V(Z) theory section, the main and information conveying components conributing to the output voltage are the pupil function, which shapes the incident spectrum $U_f^+(k_x,k_y)$, the shifted reflectance function $R(k_x\cos(\theta_T)+k_z\sin(\theta_T),k_y)$ around the Rayleigh critical angle and the shifted reflected field $U_f^-(k_x\cos(2\theta_T)+k_z\sin(2\theta_{max}),k_y)$. Assume an ideal circular pupil function with a radius $k_{max}=k_0\sin(\theta_{max})$ in k_x-k_y plane incident on the Z=0 plane as shown in Fig. 3. With small tilt angle approximation, the reflected spectrum will approximately be a circular region with a shifted center at $k_x=k_0\cdot 2\theta_T$ and the reflectance function involved will also be approximately a circular region centered at $k_x=k_0\cdot\theta_T$. The region where the Rayleigh angle is excited is depicted as the strip-like section for an anisotropic material, which is part of the reflectance function. When there is no tilting of the sample, all three regions are circular with their center at origin. With the tilt, the incident spectrum does not shift, but the reflected spectrum and the reflectance function shift on k_x axis to different locations. The output voltage is determined by integrating the intersection of these regions as shown by cross hatched area. The lateral resolution will be proportional to the Fourier transform of the cross hatched region and the directivity will increase mainly with decreasing containment of the strip in the integration. Three different cases of tilt angles are depicted in Fig. 2. For the θ_T=0 case as depicted in part a), we have the conventional microscope averaging the directional information. For $\theta_{max}-\theta_T>\theta_{C\max}$, where $\theta_{C\max}$ is the Rayleigh critical angle in the slowest direction, the directional contributions are still averaged and there is no clear directivity as shown in part b). The resolution in x-direction decreases due to lower bandwidth in k_x direction.

In case of $\theta_{max}-\theta_T<\theta_{C\max}$, as depicted in part c), the Rayleigh wave is not excited in some azimuthal directions, leading to a possibility of directivity. The lateral resolution is degraded further through the Fourier transform relationship. Using the exact reflectance function, the acceptance angle θ_{max} and tilt angle θ_T can be chosen according to the sample properties to determine the directivity and resolution. Finally, the V(Z) curve should be calculated to test the assumptions, since the leaky wave contributions from the limited azimuthal angles can still cancel each other. If the acceptance angle of the lens is slightly larger than $\theta_{C\max}$, as in most cases where the surface wave excitation efficiency is maximized, it is possible to have a high directivity with a small tilt angle without compromising the resolution [8]. However, for materials with higher surface wave velocities, this means a smaller θ_{max} and a lower resolution even the sample is not tilted.

As an example, we consider the case of (100) silicon sample and a lens with a uniform pupil function with θ_{max}=22°. The V(Z) curve for θ_T=10° is plotted in Fig. 3, with the tilted x -axis aligned with the <100> and <110> directions of the crystal. $\theta_{C\max}$ is around 17° for this sample, so with θ_T=10°, some direction dependent information can be expected. The anisotropy of surface wave velocity results in a different

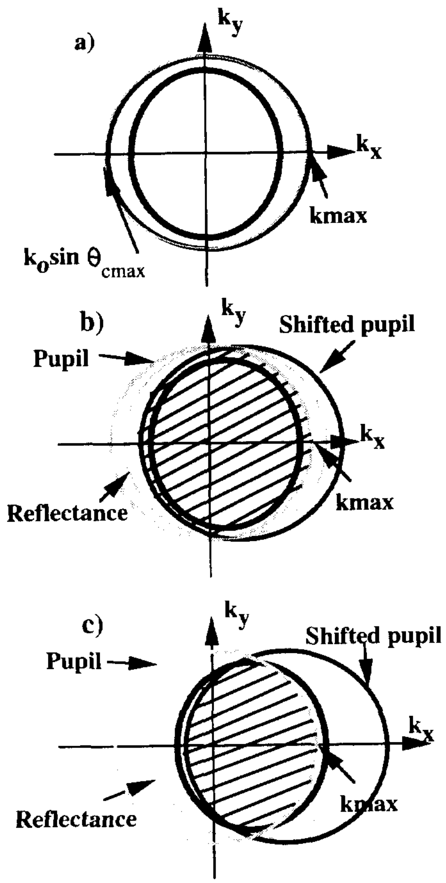

Figure 2 The coordinates and related regions for resolution and directivity analysis.

periodicity in V(Z) curve. From the periodicity one can calculate the surface wave velocities as 5062 m/sec when the tilt is in <110> direction and 4943 m/sec in the <100> tilt direction. case. The results show that for the given parameter combination, the directivity can be estimated to be better than +/- 10° around the direction perpendicular to tilt axis.

EXPERIMENTAL RESULTS

To obtain V(Z) curves for the tilted sample acoustic microscope and compare with the theoretical results, an existing acoustic microscope system is modified to have tilt capability. The particular lens used in experiments operates at 48 MHz with an F-number of 0.85 and acceptance angle θ_{max} of 36.8°. However, the pupil function of the lens measured and used in calculations has higher spatial frequency content due to diffraction in the buffer rod and the lens aperture. To compare with the calculated V(Z) curves with tilted anisotropic solids as samples, a (100) silicon sample is used.

In Fig. 4, the calculated and measured V(Z) curves are plotted with θ_T =5°. The overall agreement is good and the discrepancies can be attributed to the errors in the pupil function measurement, which was done using a teflon sample. The maximum critical angle for the surface waves on (100) silicon is around 17°, and the resulting period in V(Z) curve is around 0.35 mm, as expected. Because of the tilted sample, the periodicity is scaled by the factor $1/\cos(\theta_T)$ and this factor should be taken into account while calculating the leaky wave velocity. It should be noted that since the surface wave critical angle is much smaller than θ_{max}, no anisotropy sensitivity is observed by changing the tilt direction.

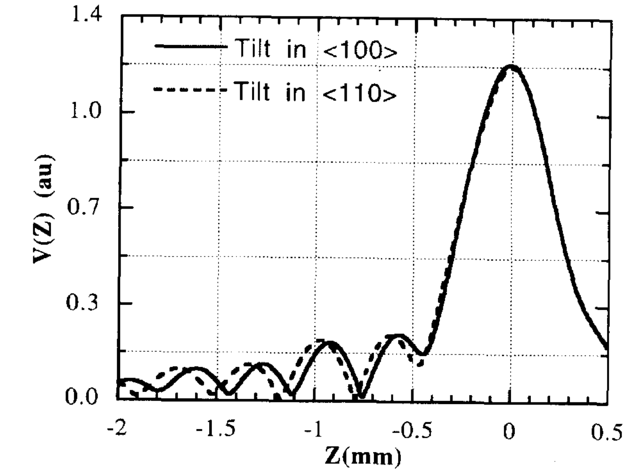

Figure 3. Calculated V(Z) curves for (100) silicon for two different tilt directions. Frequency is 48 MHz.

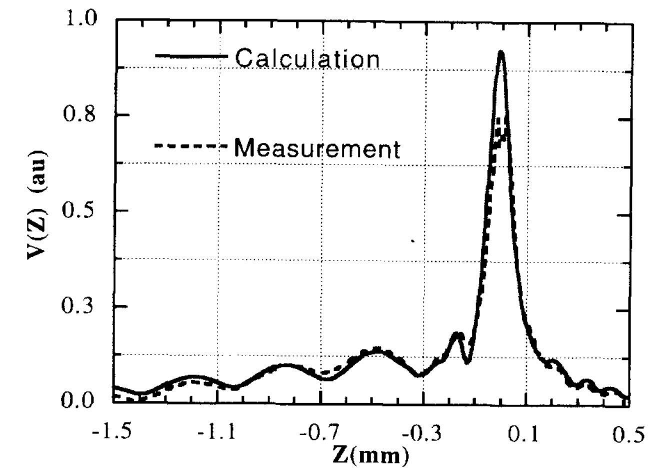

Figure 4. Calculated and measured V(Z) curves for (100) silicon sample with θ_T=5° in <100> direction.

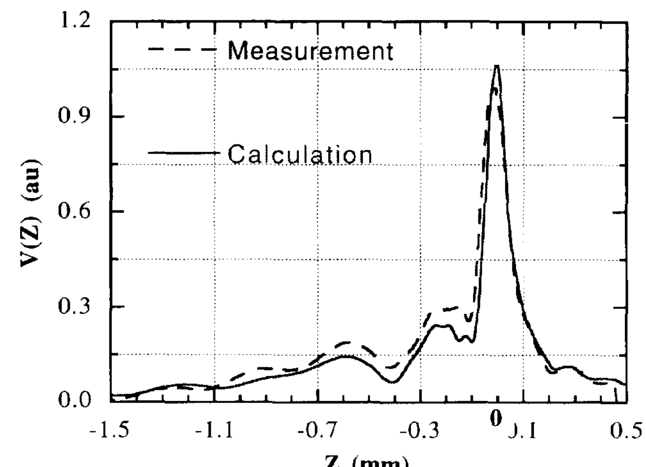

Figure 5. Calculated and measured V(Z) curves for (100) silicon sample with θ_T=10° in <100>direction.

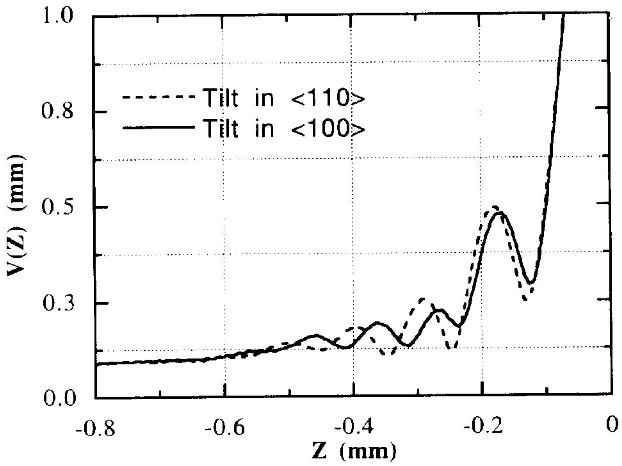

Figure 6. Measured tilted sample acoustic microscope V(Z) curves for (100) gallium arsenide sample with θ_T=15° in <100> and <110> directions.

Fig. 5 shows the V(Z) curves for θ_T=10°. Again agreement with calculation is good and no significant directivity is observed to get quantitative information by rotating the sample. A (100) gallium arsenide sample is used to test the directivity of the tilted sample acoustic microscope. Since $\theta_{C_{max}} \approx 32°$ which is close to the acceptance angle, some directivity is expected in the V(Z) curves. Fig. 6 shows the measured V(Z) curve with θ_T=15°, in <100> and <110> as tilt directions. The V(Z) curve is different for two directions showing that the directivity is high enough so that the anisotropy effect is not washed out, as predicted by the considerations in the previous section.

CONCLUSION

The anisotropy sensitivity of conventional scanning acoustic microscope is enhanced by tilting the sample under investigation without an important loss of resolution. The improvement in anisotropy sensitivity occurs when the lens or the sample is tilted so that the leaky surface waves can not be received by the lens aperture at some azimuthal angle. The direction and directivity of sensitivity depends on the tilt angle, acceptance angle of the lens and the elastic properties of the sample. This information can be obtained by examining the angular spectrum of the lens aperture and the reflectance function of the sample. The good agreement between the theoretical model developed using the angular spectrum approach and the measured V(Z) curves can be used to measure anisotropy of solid materials with high lateral resolution. Also, acoustic imaging using a tilted lens is possible revealing direction dependent spatial properties of sample materials.

ACKNOWLEDGMENTS

The authors would like to thank Anoop Sinha for his help in software and hardware development for this study. This work is supported by SRC and Sematech under the contract no: 94-YC-704.

REFERENCES

[1] J. Kushibiki and N. Chubachi, "Material characterization by line-focus-beam acoustic microscope", *IEEE Trans Sonics Ultrason.*, vol. 32, pp 189-212 1981.
[2] B.A. Auld, *Acoustic fields and waves in solids,* New York: John Wiley & Sons Inc., Vol. 1&2, 1973.
[3] A. Atalar, "Improvement of anisotropy sensitivity in the scanning acoustic microscope", *IEEE Trans. Ultrason. Ferroelec. Freq. Contr.*, Vol. 36, pp 264-273, 1989.
[4] T. Hoshimiya and B. T. Khuri-Yakub, "V(z) calculation for a focused beam incident on an inclined plane", in *Proceedings of IEEE Ultrasonics Symposium,* Nov. 1993.
[5] T. Tommasi,"V(z) equation for tilted planar specimens in acoustic microscopy", *IEEE Trans. Ultrason. Ferroelec. Freq. Contr.*, Vol. 41, pp 412-415, 1994.
[6] A. Atalar, "A backscattering formula for acoustic transducers", *J. Appl. Phys.*, vol. 51, pp. 3093-3098, 1980.
[7] Y. Tsukahara, N. Nakaso and K. Ohira, "Angular spectral approach to reflection of focused beams with oblique incidence in spherical-planar-pair lenses", *IEEE Trans. Ultrason. Ferroelec. Freq. Contr.*, Vol. 38, pp 468-480, 1991.
[8] C. Chou, B.T. Khuri-Yakub and G. Kino, "Lens design for acoustic microscopy", *IEEE Trans. Ultrason. Ferroelec. Freq. Contr.*, Vol. 35, pp 464-468, 1988.