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Acoustic Microscopy for Materials Characterization

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Abstract
An acoustic microscope with mechanical scanning and piezoelectric film transducers for the input and output has been developed for the microscopic examination of materials.1 In the reflection mode it is possible to work with an acoustic wavelength of 0.5 micrometers and a resolution that compares to that of the optical microscope. The elastic images of material surfaces as recorded with this instrument display interesting features which provide information which complements the optical microscope. In particular we find that different phases show up with good contrast and in alloy material the texture of the grains can be recorded since the grain orientation influences the acoustic reflectivity.

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ACOUSTIC MICROSCOPY FOR MATERIALS CHARACTERIZATION

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ABSTRACT

An acoustic microscope with mechanical scanning and piezoelectric film transducers for the input and output has been developed for the microscopic examination of materials.[1] In the reflection mode it is possible to work with an acoustic wavelength of 0.5 micrometers and a resolution that compares to that of the optical microscope. The elastic images of material surfaces as recorded with this instrument display interesting features which provide information which complements the optical microscope. In particular we find that different phases show up with good contrast and in alloy material the texture of the grains can be recorded since the grain orientation influences the acoustic reflectivity.

THE SCANNING PRINCIPLE

With conventional microscopes it is common to view the entire field of view with one setting of the controls. The image appears either on the retina of the observer, on photographic film or on a fluorescent screen. With acoustic radiation there is no available method for recording the entire field of view in this manner. Other means must be found. We want to use piezoelectric films for they are efficient, highly sensitive and they operate over the entire range of interest. With this choice one could in principle build up an array of detectors to form an acoustic retina. In such an array careful attention must be given to both the phase and amplitude of the signal from each element. The degree of complexity in this system was such that we found that we were working on arrays whereas it was the microscope that held our interest. A single detector and a mechanically scanned object is the alternative. In an imaging system based on scanning the beam is tightly focused and the image field is constructed point by point as the object is moved in a raster pattern through the focus of the beam.

At first we turned to this system as an expedient but as we gained experience we found that a scanned system has advantages not found in conventional systems.

In electron microscopy the scanning principle is widely used in both SEM and STEM. They have found it advantageous to use single detectors where the response can be optimized to highlight selected parameters in the scattered radiation.

The primary drawback for the mechanical system required for acoustic scanning is the speed. It is slow. Several seconds are required to build up a single frame as compared to television rates of 30 frames/second. This will be overcome in time for we have built mechanical systems that operate at ten frames a second but the work to be reported here will be limited to the systems which use slow scans.

The advantages inherent to scanning systems with focusing were not obvious in the beginning. It is now becoming evident that scanning systems which record a single point at a time exhibit properties that are different from those that display the entire field of view. In the scanned system there is no problem with coherent radiation. Since the energy at the focus is confined to a diameter that is less than one wavelength in dimension there are no interference fringes of the type that are common with optical microscopes that use coherent laser radiation. These fringes arise from the scattered radiation from two points on the object that are separated by many wavelengths.

We have been operating a reflection microscope[2,3,4] for some time now at a frequency of 1100 MHz (λ = 1.4 μm). We have also carried out some preliminary work at 3000 MHz (λ = 0.5 μm). With this instrument we have learned that it has some interesting and perhaps unique properties when used to study the microscope features of materials and integrated circuits.

THE INSTRUMENT

The transmission instrument which has been developed at Stanford[5] consists of two confocal lenses, one to focus the acoustic radiation down to the smallest possible diameter, the "waist", the other to collimate the radiation transmitted through, or scattered by, the object which is placed in the focal plane and which is mechanically moved television-like in two orthogonal directions, in the focal plane. Figure 1 is a sketch of the geometry of the microscope which is almost as simple in reality as in the sketch. Water fills the space between the lenses and the object, held in place by capillary attraction.

The lenses are simple spherical surfaces ground into sapphire blocks. They are almost aberration-free because (1) they are small (typically 100 micron radius of curvature) and (2) the effective refractive index between water and sapphire is 7.45. The large change in velocity reduces spherical aberration to a negligible quantity.

The "field of view" for such a lens is small but this can be tolerated with a mechanically scanned microscope since good imaging quality is only required on the axis. The resolution of these lenses has been measured; it corresponds closely to the "Rayleigh-criterion" of a single lens, which states that the distance d between two object points which can be resolved is given by $d = (0.66\lambda/N.A.)$ where λ is the wavelength in the medium and N.A. is the numerical aperture (the sine of the half-angle of convergence). In our imaging system we use <u>two</u> lenses as shown in Fig. 1 and the spatial frequency response of this combination is almost twice that of a single lens.

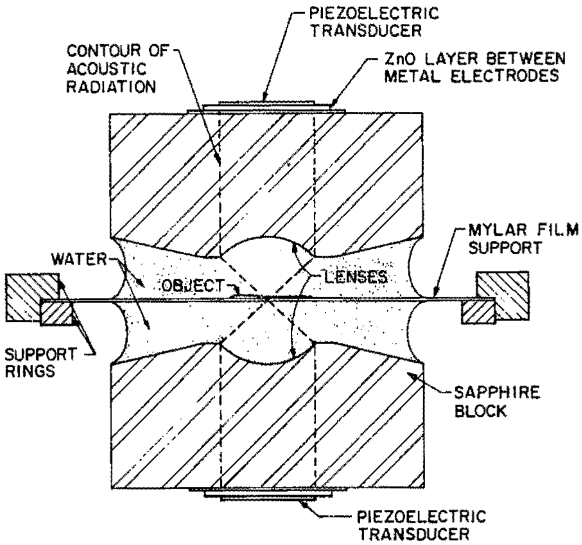


Fig. 1 --Sketch of microscope geometry.

In operation, a fraction of a watt of microwave power is converted into a plane acoustic wave in the sapphire block by one of the transducers. The spherical lens converts this into a spherically converging wave in the water. After it is modified or scattered by the object which is mechanically moved across the waist of the acoustic beam it is collimated, or made plane, by the second lens so that the radiation impinges everywhere in phase on the second transducer. The electrical signal from this transducer is amplified, rectified and used to modulate the display which may be a cathode-ray tube scanned in synchronism with the motion of the object. The magnification is simply the ratio of the deflection of the cathode-ray tube spot to the displacement of the object. Figure 2 shows the microscope with its mechanical scanning system.

So far the mechanical scanning we have used is sinusoidal at a frequency near 60 Hz in one, say, the x-direction and uniform motion in the y-direction, so that it takes several seconds to obtain a complete picture, recorded with a camera attached to the cathode-ray tube screen. The scan amplitude and hence the field of view is but a fraction of a millimeter; if a larger object is to be examined the picture has to be pieced together from adjoining pictures in the form of a mosaic.

The usual picture shows detail by way of an intensity modulation; the more radiation reaches the detedtor the brighter the image. It is an inherent feature of any scanning type of microscope that the contrast in the picture is under the control of the operator of the instrument. If the signal-to-noise ratio is adequate, a variation in the radiation transmitted through, or reflected by, the object of, say 1%, can easily be amplified to appear as a 100% modulation in the final picture. In the acoustic microscope, at microwave frequencies, we find that the contrast exhibited by most objects is large enough so that contrast amplification is not needed and it is possible to record a signal which is directly proportional to the amplitude of the radiation received by the second lens. Thus the instrument can be made quantitative in a very simple and direct manner.

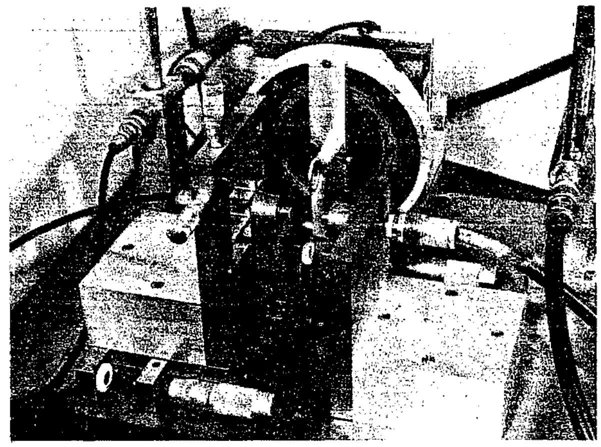


Fig. 2 --Photograph of the acoustic microscope's mechanical components.

Much of our work has been done with a reflection mode. The essential parts of this form of the acoustic imaging system is shown in Fig. 3. The transducer which is piezoelectric generates the acoustic wave. It serves to convert the rf voltage across the piezoelectric film into a plane acoustic wave propagating normal to the surface. The acoustic lens is merely a spherical cavity on the opposing side of the crystal. It serves to focus the plane wave into a narrow waist at the focal point. A liquid, such as water, fills the gap between the object and the lens in order to provide a path for sound propagation. The reflected sound wave returns through the lens to the transducer which is now acting to convert the acoustic signal into the electrical signal. It is important to note that the transducer is sensitive to the phase of the returning wave and that the rf voltage at the output is obtained by integrating the acoustic field over the area of the transducer. A microwave circulator separates the reflected and incident signals. Normally the object is near the focus point and it is mechanically scanned in a raster pattern normal to the axis of the beam. The amplitude of the returning signal is used to control the intensity of a synchronously scanned electron beam in a CRT. In this way the image is displayed on the CRT and it is recorded by photographing the face.

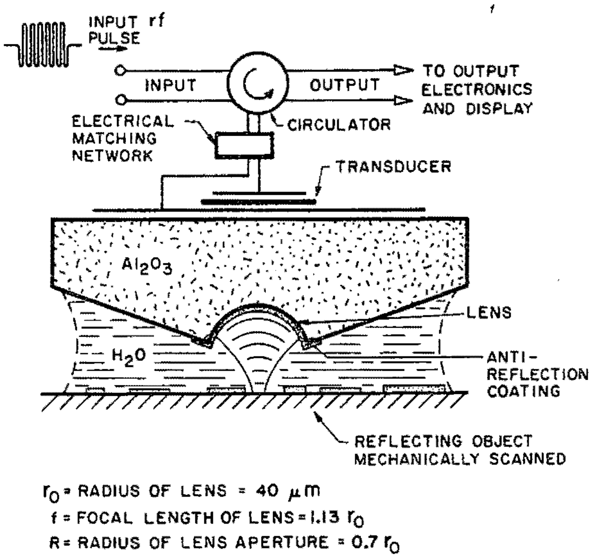


Fig. 3 -The configuration of the scanning acoustic microscope as used in the reflection mode.

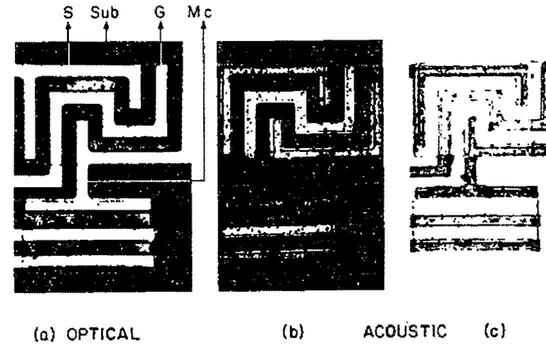


Fig. 5 -Optical (a) and Acoustic (b), (c) images of H-MOS transistors on an SOS chip. Acoustic images are recorded at different Z positions. Source (S), gate (G), metal connection (MC) and substrate (Sub) regions are indicated.

ACOUSTIC MICROGRAPHS FOR INTEGRATED CIRCUITS AND MATERIALS

The product of any investigation with a microscope is the final image and in this section we will include acoustic micrographs as selected to illustrate the present state of acoustic imaging at microwave frequencies.

In the first micrograph of Fig. 4 we show the cross section and optical image of an integrated circuit fabricated with silicon-sapphire. The acoustic images of this structure are shown in Fig. 5. There we see the change in contrast as we change the spacing between the lens and the sample.

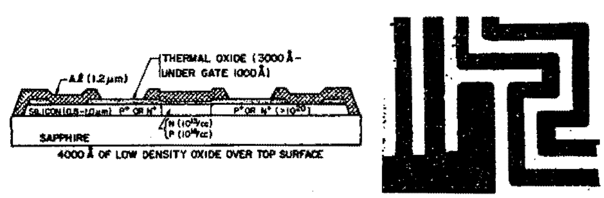


Fig. 4 -The cross section and optical image of the SOS device of Fig. 5.

This feature of altering the lens-sample spacing is further illustrated in Fig. 6. There we display the magnitude of the reflected signals as a function of the lens-sample spacing. In this case there is no transverse scanning as is common for imaging. We see that the maximum return occurs when the sample is at the focal point of the acoustic beam and it diminishes on either side of this point. The important point is that the shape of this curve is dependent on the elastic properties of the reflecting surface. We have carried out the analysis which tells us that this curve is a sensitive function of the shear wave velocity in material under examination. Still more on this topic can be seen in the micrographs of Fig. 7. There we show the response for pure silicon, for silicon with a 1 μm layer of aluminum and for silicon with 2 μm of silicon. The shape of the curve varies because of the acoustic energy that is confined to the aluminum layers. It suggests that one can exploit this effect to monitor changes in the thickness of metallization layers such as this.

Another application of this idea is shown in Fig. 8. At the top we have an optical image of an SOS circuit — the dark region is the sapphire substrate, the grey regions are silicon and the bright stripes are aluminum (7 μm in width). On top of the silicon layer and beneath the aluminum there is a 300 Å layer of oxide. This allows the aluminum to "crossover" the silicon without interference. At these points where they want the voltage on the aluminum stripe to control the silicon current (or gate) the oxide thickness is reduced from 3000 Å to 1000 Å. The two squares in the acoustic image indicate the regions where the oxide is reduced. In Fig. 9 we show the optical and acoustic images of a silicon IC circuit. The greater contrast in the acoustic image results from the variations in the layering. In some ways this contrast improves the quality of the image in that it allows the viewer to more easily see the composition of the layering.

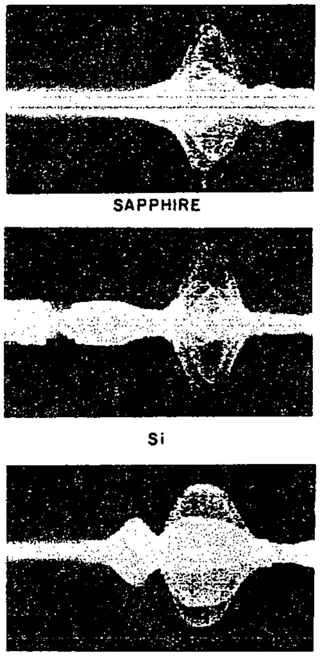


Fig. 6 --The V(Z) curves for single crystals.

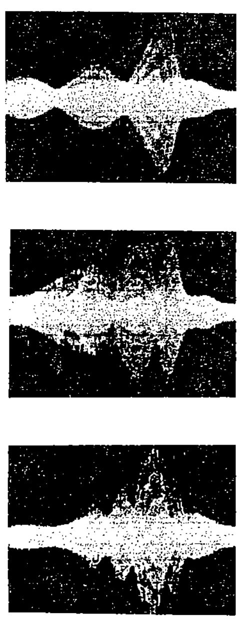


Fig. 7 -The V(Z) curves for silicon with layering.

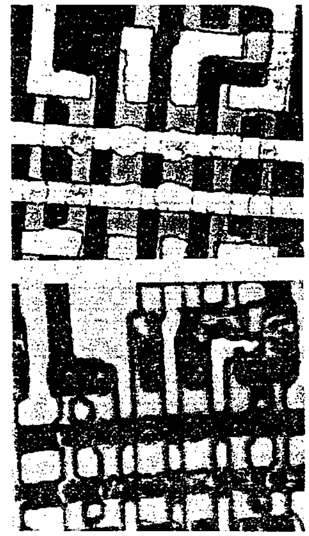


Fig. 8 -Optical and acoustic comparison of SOS silicon devices.

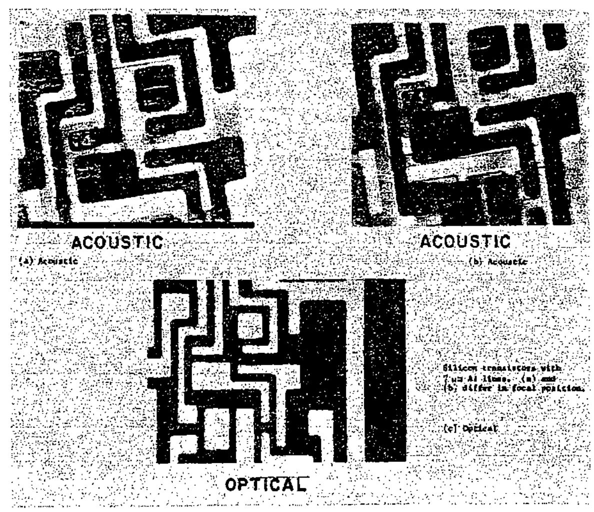
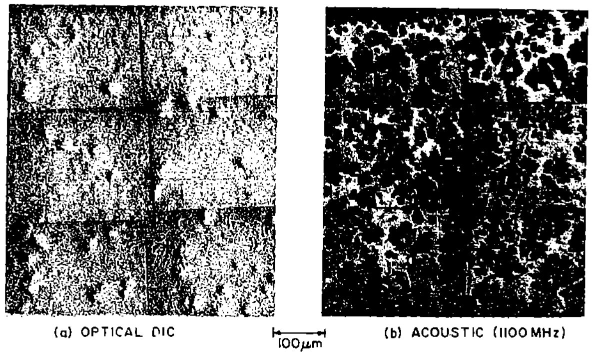


Fig. 9

And finally in Fig. 10 we compare the optical and acoustic image for the polished surface of an alloy of Cobalt-Titanium. The hillocks in the optical image represents surface contours. The dark region in the acoustic image represent regions where the phase of the material has changed. There are four possible phases in the Co-Ti alloy and each of these phases have a different reflection coefficient for acoustic waves since the elastic constants vary from phase to phase. This shows up in the acoustic micrograph as four different shades of grey.



Co-Ti ALLOY SHOWING 4 PHASES. OVERALL COMPOSITION, 59% Co 41% Ti

Fig. 10

ACKNOWLEDGEMENTS

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