SCANNED IMAGING TECHNIQUES FOR SURFACE NDE

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ABSTRACT

A phase sensitive laser probe in which the focused spot is small, as compared with the acoustic wavelength, is capable of measuring the complex distributions of a SAW field along prescribed scan lines. Using the probe, it is possible, on a defect free sample, to measure the SAW velocity surface with an accuracy of a few parts in 10^5. Such accuracy suggests that the technique is sufficiently sensitive to detect small changes in surface characteristics; the presence of a defect is revealed by perturbations in the relationship between various scans. The scattered radiation patterns from a surface crack irradiated by acoustic surface waves can be utilised to determine the defect size and location with improved accuracy. Results on deliberate and real cracks are presented.

Acoustic microscopy has proved to be a valuable tool for the NDE of complex IC devices. With the advent of VLSI there is a clear need for an acoustic microscope showing sub-optical resolution. We report on the design of a high pressure gas acoustic microscope operating at room temperature which should provide a resolution below 100nm.

Finally, following the demonstration of a photoacoustic microscope at Stanford University, there has been a great deal of interest in the subject of photoacoustic microscopy. We describe the work at University College London which is based on the use of a conventional gas photoacoustic cell together with pulsed laser excitation. A finite difference approach has been used in order to study the effect of an inclusion buried under the surface on the photoacoustic signal. In the case where the thermal properties of the inclusion are known a priori, our one dimensional model indicates that it should be possible to obtain not only the depth of the inclusion beneath the surface but also its thickness.

INTRODUCTION

Detection of surface opening cracks is now quite wide-spread and several techniques capable of estimating the size of such cracks have been reported in the literature (1-6). We have been working on a scheme which is based on the use of a laser probe to record the scattered surface waves from the defect. The scattered field not only provides valuable information about the size and orientation of a surface crack but also enables one accurately to determine its position. Recent results will be presented in the following section.

Acoustic microscopy has proved to be a valuable tool for the NDE of complex IC devices (7). Currently, acoustic microscopes operating at room temperature (using water as the coupling medium) are limited to a resolution which is comparable to that of high quality optical instruments. This limitation stems from the lack of a suitable liquid coupling medium which can offer a performance superior to that in water. We have been investigating an alternative class of fluid which is superior to water, viz gases at elevated pressure. Section 3 will be devoted to discussing the design of a gas acoustic microscope which should provide sub-optical resolution working at rather modest pressures.

Photoacoustic microscopy has attracted considerable interest over the past few years, perhaps mainly as it represents a complementary technique for surface NDE. In section 4 we shall present our initial work in this area.

Finally, section 5 will contain a brief summary of the main points in this paper.

DETECTION AND SIZING OF SURFACE DEFECTS

The technique for obtaining the scattered SAW field from a defect was described in detail at the 1979 DARPA/AFML meeting (8). The heart of the system is a computer controlled laser probe which is capable of recording the complex SAW field with a sensitivity down to 10^-4 Â in a bandwidth of 1 MHz. Since this system has been considerably modified over the past year, we shall begin with a brief description of the probe.

The basic optical and electronic systems are illustrated in Figs. 1 and 2 respectively. The laser probe is an a.c. interferometer. Coherent light, from a 5mW HeNe laser is directed onto a 25 MHz water Bragg cell which provides a 50 MHz optical carrier.

The use of an optically generated carrier renders the system insensitive to phase variations caused by microphonics in the optical system, as they appear both in the signal as the reference channel. The detected SAW field is finally converted into the in-phase and quadrature components, r and i, using a lock-in-analyser which has an adjustable bandwidth. The three outputs of the detection system, r, i and c are read by the computer, r and i being divided by c in order to eliminate variations due to surface reflectivity.
The scanning and data logging operations are computerised. The scan positions are programmed and the stepping motors control the positioning with an accuracy of \(1 \mu m\). The measured phase accuracy is about \(\pm 3^o\). Thus, a velocity accuracy of a few parts in \(10^5\) is readily achieved over \(1 \text{ cm}\) distance at an operating frequency of \(60 \text{ MHz}\) (9). Such accuracies achieved in velocity measurements encourage the use of the device for the evaluation of scattered spectra from measurements on perturbed SAW fields.

We are able to illuminate a surface with a wide SAW beam and then investigate the amplitude of the SAW signal detected along a transverse scan line. In the case of a defect being present, harmonics will be generated in both the transmitted and reflected waves due to the opening and closing of the gap (10). This approach can therefore establish the presence of any defect. This technique has not yet been fully implemented due to the bandwidth limitation imposed by the front end of the detection system.

The other technique for detecting and locating defects is to record the complex field distribution along several scan lines and then use this information to deduce the scattered field. This technique was explained in detail at the previous meeting (8). Very briefly, the SAW field is represented as the sum of an incident (I), reflected (R) and scattered (S) component. By recording the complex fields along three separate scan lines, it is then possible to relate their FT's and thereby obtain I, R and S, (see Fig. 3).

Several experiments were carried out on real and deliberate cracks. As a test on the information obtained from the processed scattered field, a set of results were obtained for reflection off the edge of a LiNbO₃ substrate. The SAW source was an apodizing transducer operating at a synchronous frequency of \(44 \text{ MHz}\). The edge was produced deliberately, it was not a cleaved edge. It was at an angle to the incident power flow direction. The reflected spectrum off the edge is shown in Fig. 4a. The reflected spectrum was then repeated by absorbing the incident beam at the edge, Fig. 4b.
The most recent results obtained, are a set of measurements achieved on cracks generated on a crystalline quartz substrate. The cracks are generated by rapid cooling of the sample from an elevated temperature. The crack is illuminated by a 100A aperture uniform interdigital transducer. Fig. 5 represents the results of the incident and reflected spectra evaluated for a multi-cross shape tight crack. Fig. 6 shows the calculated incident and reflected spectra for a triangular crack with irregular sides. In each case, the width of the main lobe relates to the physical dimensions of the crack. However, as shown in Figs. 5 and 6, the recovery of the reflected spectrum is not perfect. The imperfections are attributed to the fact that the subtraction was carried out using a slowness curve which was derived from book values of elastic constants rather than a measured slowness curve for the particular substrate under test. In principle, the reflected spectrum can be used to reconstruct (and hence locate) the defect by backward propagation (11). We have not attempted to do this for this particular data set.

Acoustic microscopy has proved to be a valuable tool for the NDE of complex IC devices (7). By stretching the existing technology to its limits, the reflection SAM has been operated in water at 3 GHz, with a corresponding wavelength of 520 nm (12). With the advent of VLSI, there is a clear need to extend the resolution beyond this point. The major difficulty encountered in improving the resolution of a SAM is the high value of the absorption of sound in water. To obtain a wavelength below 520 nm, one must find a fluid which has a lower velocity, a lower absorption, or, preferably both. One possibility is to use cryogenic liquids such as Argon and Helium (13, 14). However, the use of such liquids involves several instrumental complexities and strict limits on the type of sample which can be studied. For example, the low temperatures involved immediately exclude the study of living biological systems - an application which is ideally suited to acoustic microscopy. It is for this reason that we have begun to investigate an alternative class of fluids - gases at high pressure. It is well known that the velocity of sound in gases is 5 - 10 times lower than that in most liquids. The acoustic absorption on the other hand is typically 100 - 1000 times higher. We have shown that the acoustic absorption - at least in the case of monoatomic gases such as Argon and Xenon - varies inversely with pressure so that it should, in principle, be possible to approach the value in water at elevated pressures (15). The results of our initial work in this area, where we demonstrated a reflection SAM operating in Argon at 30 bar and 45 MHz, with a resolution of 7 μm, appeared in a recent publication (16). This resolution is five times better than what can be achieved in water at the same frequency.

Since the configuration of a gas acoustic microscope is substantially different to a conventional acoustic microscope, we shall briefly describe it here. Fig. 7 shows its basic construction. It consists of a small-volume pressure cell connected to a regulated gas supply. The object is supported on a piezoelectric bimorph, which, when driven at resonance, provides a fast scan out of the plane of the diagram. Both the scanner and acoustic lens are mounted on movable pistons. These pistons are supported by hydraulically reduced micrometer heads.
such that the slow scan and focusing can be performed externally. A typical result from this apparatus working in Argon at 45 MHz and 30 bar, is shown in Fig. 8.

![Gas Acoustic Microscope Configuration](image)

**Fig. 7** Configuration of the Gas Acoustic Microscope.

![Reflection Acoustic Micrograph of SEM Finder Grid at 45 MHz](image)

**Fig. 8** Reflection Acoustic Micrograph of SEM Finder Grid at 45 MHz.

We can define a new coefficient of merit for a coupling fluid by calculating the minimum wavelength that can be achieved for a fixed loss and transit time within the fluid and relating it to the corresponding value in water.

$$M = \frac{(a/f^2)^{1/2}}{(a/f^2)^{1/2}} \left(\frac{C_w}{C}\right)^{3/2}$$

where $C$ is the velocity of sound in the fluid, $a/f^2$ is its attenuation coefficient normalised with respect of the square of the frequency and the subscript $w$ refers to corresponding quantities in water.

The table below lists the coefficient of merit for several liquids and gases.

<table>
<thead>
<tr>
<th>Liquid</th>
<th>$T$(°C)</th>
<th>$C$(Km/s)</th>
<th>$a/f^2 \times 10^{17}$($S/m$)</th>
<th>$M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>25°C</td>
<td>1.495</td>
<td>25.0</td>
<td>1.00</td>
</tr>
<tr>
<td>Water</td>
<td>35°C</td>
<td>1.523</td>
<td>17.7</td>
<td>1.09</td>
</tr>
<tr>
<td>Water</td>
<td>60°C</td>
<td>1.55</td>
<td>10.2</td>
<td>1.29</td>
</tr>
<tr>
<td>Carbon disulfide</td>
<td>25°C</td>
<td>1.31</td>
<td>10.1</td>
<td>1.61</td>
</tr>
<tr>
<td>Mercury</td>
<td>23.8°C</td>
<td>1.45</td>
<td>5.8</td>
<td>2.04</td>
</tr>
<tr>
<td>Argon(40bar)</td>
<td>20°C</td>
<td>0.323</td>
<td>81</td>
<td>2.00</td>
</tr>
<tr>
<td>Argon(250bar)</td>
<td>20°C</td>
<td>0.323</td>
<td>83</td>
<td>5.00</td>
</tr>
<tr>
<td>Xenon(40bar)</td>
<td>20°C</td>
<td>0.178</td>
<td>953</td>
<td>4.00</td>
</tr>
</tbody>
</table>

From this table, it is clear that gases such as Argon and Xenon under pressure can provide substantial improvements in resolution over water. Specifically, Argon at 40 bar will provide a factor of 2 improvement in resolution over water, while Xenon will provide a factor of 4. The figure of merit varies as $P^2$, so that, at 250 bar, the value in Argon is 5.

We are currently working on a system which will use Argon at 40 bar as the coupling medium and a 10 μm radius lens as the imaging element. We expect to obtain a resolution of 220nm at 1 GHz. Alternatively, one could use Xenon a 40 bar and obtain a resolution of 170nm at 740 MHz. (17). Although we plan to work with both gases, our initial experiments will be exclusively in Argon, as it is significantly cheaper than Xenon.

One major difficulty encountered with this system is that of matching the acoustic waves into the gas. There is an impedance ratio of $1:10^{-3}$ going from Sapphire to Argon (at 40 bar) so that there will be a two-way loss of 54 dB at this interface. At low frequencies (below 740 MHz) one can use a quarter-wave matching layer of polystyrene to bring this loss down to 7 dB as shown in Fig. 9. At higher frequencies, the losses in polystyrene become too high for it to act as an efficient quarter-wave transformer. In this situation, one could resort to a double matching layer. Fig. 10 shows the computed insertion loss curve for the case of a Fused Quartz lens followed by a quarter wave layer of Tungsten and then a quarter-wave layer of glass transmitting Argon at 100 bar. As we can see, it is possible to achieve an extremely small insertion loss while at the same time preserving enough bandwidth to transmit a 30ns pulse.

Finally, we are in the process of constructing an instrument that would operate at much higher pressures (around 250 bar) with the aim of attaining resolutions well below 100nm.
PHOTOACOUSTIC MICROSCOPY

Since the first photoacoustic micrograph was published, (18), there has been considerable interest in the subject of photoacoustic microscopy (19,20,21). As the technique can provide information about the thermal properties of the sample being investigated, it represents new tool for surface NDE. For example the presence of a flaw (such as a void) underneath the surface should result in a large change in photoacoustic signal. Indeed recent results on the detection of sub-surface structure are encouraging (20,21,22,23, 24).

The system we are working on is similar in many respects to a system described in the literature (19). A schematic diagram is shown in Fig. 11. It consists of a conventional photoacoustic cell which is mechanically scanned in a raster pattern. Lateral resolution is provided by focussing the laser beam onto the object using a microscope objective. The laser beam is tunable, so that it is possible in principle to record photoacoustic spectra on a microscopic scale.

Our initial experiments were conducted by modulating the incident laser beam at a few KHz and using a microphone in a phase-locked configuration to detect the photoacoustic signal (19,24). With this system, we have found that the average power level required in order to record images in seconds rather than minutes is around 250 mW and can often result in sample damage. We have therefore resorted to a pulsed system in which we use high peak power, low energy pulses, thereby increasing the signal strength while at the same time limiting the average laser power. Many experiments have not been conducted with this new system, but initial results are encouraging. Fig. 12 shows a photoacoustic signal from an EH grid structure taken using the pulsed system. The average optical power was 100 mW and the pulse width was 10 ms.

A finite difference approach has been used to study the effect of pulsing the laser on the photoacoustic signal. We have defined an effective thermal diffusion length for the pulsed case as being the depth below the surface of the material being heated at which the temperature is 1/e of the value at the surface (at the end of the duration of
the pulse). In fact, with this definition, the thermal diffusion length works out to be exactly the same value that would be obtained for the periodic heating case, if the period was taken to be equal to double the pulse width.

We have attempted to model the effect of an inclusion having known thermal properties on the photoacoustic signal (25). Although we have only worked on a one dimensional model (which would apply in practice when the focussed spot is large in comparison to the thermal diffusion length) the results show that it should be possible to obtain both the size (thickness in a one dimensional model) of the inclusion and its depth below the surface. The situation we have modelled is illustrated in Fig. 13. The substrate material is aluminium and there is a nickel inclusion 3 microns thick. Optical absorption takes place in a 1 micron region at the air/aluminium interface. The depth of the nickel inclusion can be varied from 2 µm to 6 µm. We can control the effective diffusion length by varying the pulse width; this can have any value between 0 and 200 ns. Fig. 13 also illustrates the temperature evolution with time. The temperature rises rapidly when the pulse is applied, reaching a maximum at the end of the duration of the pulse, after which the sample cools down slowly to an equilibrium value.

![Fig. 13 Configuration Used for Finite Difference Model of Photoacoustic Effect.](image)

With the inclusion at a fixed depth below the surface, we have calculated the maximum surface temperature (Km² Watt⁻¹) as a function of pulse duration. We have then repeated these results after changing the depth of the inclusion below the surface. Thus we would have one curve of temperature vs pulse width (or temperature vs effective diffusion length in the host material) for each value of the depth of inclusion below the surface. Fig. 14 shows a plot of the maximum surface temperature (normalised with respect to the value obtained with no inclusion) versus the depth below the surface (normalised with respect to the diffusion length in the host material). This plot, in fact, represents many sets of data points obtained for different values of inclusion depth. It is immediately apparent that all these sets in fact lie on one single curve; i.e. the curve is unique for a given thickness of inclusion material. If the inclusion thickness is reduced to 1 µm we obtain a different curve as shown in Fig. 14. In particular, the value corresponding to zero depth below the surface is smaller, and the decay rate with depth below the surface is different. This suggests a technique for getting both the depth below the surface and the thickness of the inclusion. One would simply record the normalised temperature as a function of pulse duration. The next step would be to plot the normalised temperature as a function of (depth/diffusion length), where X is a constant. One could then vary X until a fit is obtained with one of the curves in the set shown in Fig. 14. The value of X then corresponds to the depth below the surface while the thickness can be deduced by knowing with which curve the best fit was obtained. Although all this is based on a one dimensional model, the results are encouraging, and we are in the process of verifying this technique experimentally.

![Fig. 14 Plot of Normalised Temperature vs Normalised Depth for Different Inclusion Thicknesses.](image)

**SUMMARY**

A phase sensitive laser probe has been used to record the complex surface wave field with a sensitivity down to 10⁻⁶ A. By recording the complex SAW field along three scan lines, it has been possible to deduce the scattered spectra from real and deliberate cracks. By reconstructing the scattered field, it is possible to locate the defect with an accuracy which is only limited by diffraction.

Recent work on gas acoustic microscopy has been described, and we have indicated that it should be possible to achieve a resolution below 200 nm using gases such as Argon and Xenon at 40 bar. By going to higher pressures (around 250 bar) it should be possible to achieve resolutions well below 100 nm.

Finally we have presented our initial work on photoacoustic microscopy. The system used is a scanned gas photoacoustic cell, together with pulsed laser excitation. A finite difference approach has been used in order to study the effect of an inclusion buried under the surface on the photoacoustic signal. In the case where the thermal properties of the inclusion are known apriori, our one dimensional model indicates that it should be possible to obtain not only the depth...
of the inclusion beneath the surface but also its thickness.

REFERENCES


Gordon Kino, Chairman (Stanford University): Time for one or two questions.

Unidentified Speaker: What's your sensitivity for your inclusions? How small an inclusion?

Kumar Wickramasinghe (University College London): A sensitivity of (inaudible).

Christian Burger (Iowa State University): Do I understand your thermal analysis right? You're hitting the specimen with the laser and then you were measuring the maximum temperature at the spot where you hit it?

Kumar Wickramasinghe: Yes

Christian Burger: How did you measure that?

Kumar Wickramasinghe: The maximum temperature phototransducer signal proportion, not temperature.

Christian Burger: To the maximum temperature.

Gordon Kino, Chairman: If there are no more questions, thank you.