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OPTOACOUSTIC AND PHOTOTHERMAL MATERIAL INSPECTION

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Introduction

Though both the optoacoustic effect /1/ and the thermal wave concept /2,3/ are known since a century, only less than a decade ago it has been found that the theoretical description of the optoacoustic effect is possible in terms of thermal waves /4-6/.

If the temperature at the surface of a solid is modulated

$$(1) \quad \Delta T(x=0) = \Delta T_o \cdot \sin \omega t$$

then the temperature modulation propagates like a damped wave. With increasing depth x there is an exponential decrease in magnitude and a linear phase shift:

$$(2) \quad \Delta T(x) = \Delta T_o \cdot \exp(-x/\mu) \cdot \sin(\omega t - x/\mu)$$

where μ is the thermal diffusion length

$$(3) \quad \mu = (\ 2k/(\omega \rho c))^{1/2}$$

(k= heat conductivity, ω= modulation frequency, ρ= density, c= specific heat).
For aluminium at 20 Hz modulation frequency the thermal diffusion length is μ = 1.2 mm, wavelength is 7.5 mm, and phase velocity of the thermal wave is $\omega \cdot \mu$ = 15 cm/s.

There are different ways to generate these waves and to detect the correlated temperature modulation ΔT, and unfortunately different names are in use depending on the method of detection:" opto (also called "photo) - acoustic" detection is based on modulated thermal expansion of the sample or of the gas layer next to it /5,7,8/, while with "photothermal" detection one observes the modulation of infrared thermal emission /9/, hence this method allows for real remote thermal wave observation.
Imaging with thermal waves means that the locally obtained signal is mapped as a function of the sample coordinates, therefore wave generation or detection must be confined to a spot which is scanned across the sample surface while the signal (magnitude or phase) is recorded.
In optoacoustic detection the observed signal is the integrated sample response, so wave generation has to be localised (e. g. by focusing the beam of an intensity modulated light source). The "mirage effect"/10/ is based on the deflection of a sensing light beam near the sample surface. Here the observed signal is proportionalto the integral of the thermal wave along the optical path projected on the sample/11/. However, photothermal detection allows for local resolution. To give an example, Fig.1 shows the thermal wave magnitude at the rear surface of a razor blade. A chopped laser beam (40 Hz) is focused on the front surface to make

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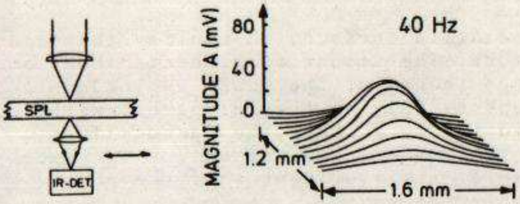


Fig. 1: Thermal wave behind a razor blade/12/.

a point source (50 μm diameter) for the thermal waves. To avoid confusion it should be mentioned that thermal wave imaging is different from thermal imaging which is basically a DC-method monitoring the emitted infrared radiation, while thermal wave imaging is a dynamical method based on the AC-component ΔT which is a complex quantity characterised by magnitude A and phase φ. The usefulness of phase angle imaging will be shown later.

<u>Photothermal transmission imaging</u>

In the following experiments the infrared detector is not moved, it stays opposite to the laser focus and observes a sample spot of about 0.3 mm diameter at the maximum of the thermal wave in Fig. 1. The sample is then scanned across the laser beam.
When the sample is a wedged piece of aluminium provided with subsurface holes, the result shown in Fig. 2 is obtained for the phase angle (the logarithm of the magnitude of ΔT gives the same result).

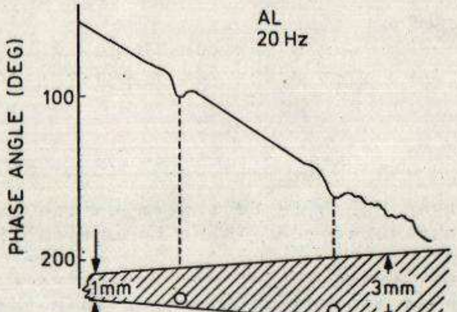


Fig. 2: Photothermal transmission probing /12/.

The linear dependence agrees well with what one would expect in a one dimensional arrangement and variable depth x under a semi-infinite sample as given by equ. 1-3 /13/. So the phase angle indicates directly the local thermal thickness of the sample. Because ofthe linear relation, the signal change due to the holes can be estimated in a simple way if one assumes thermal wave propagation along the circumference of the holes, thus increasing the thermal path length. Therefore the two equal holes in sample regions of different thickness give rise to the same signal change. When the sample was rotated to bring the holes to the upper surface, the result was the same. Obviously, in photothermal transmission one detects subsurface structure within or beyond the thermal diffusion length, but one cannot decide in which depth the structure is.

Not all samples have a clean metallic surface, in reality there may be some optical surface structure. The amount of generated heat and the signal magnitude will change then, but the phase angle does not because it is a delay which depends only on thermal path length. This difference is demonstrated in Fig.3 where the dashed lines indicate subsurface holes and the black areas the optical surface structure of the aluminium sample. It is evident that the phase

Fig. 3:

Magnitude (b) and phase (c) image of an aluminium sample provided with holes and surface absorption.

angle image gives information only on non-optical structure/14/.

An application to a more realistic sample is shown in Fig.4 where stainless steel of 0.5 mm thickness was welded. The diagonal in the

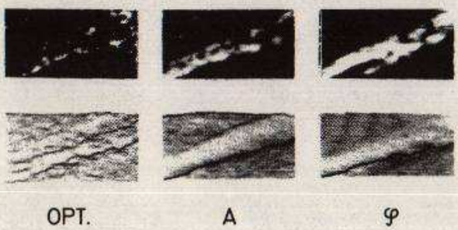


Fig.4:

Optical (left) and photothermal transmission inspection of welded steel.
A= magnitude image
φ= phase angle image /12/.

5x11 mm^2 field of view is the seam which is best seen on the phase angle image (φ). The simultaneously recorded image of optical reflexion barely reveals the seam.
First experiments on photothermal transmission microscopy were performed /14/, but interpretation is more difficult than in metal imaging because the sample (an integrated circuit) was not completely opaque for the generated infrared radiation.

<u>Optoacoustic imaging</u>

In this arrangement the thermal wave is monitored at the front surface of the sample. Therefore one does not observe the transmitted wave, but the resulting complex vector of all thermal waves from different depths of the sample. Waves coming back from deep in the sample contribute much less to the sum than those the origin of which is close to the surface, because they are heavily damped. A more careful treatment /5/ shows that the signal as a function of sample thickness is non-linear, and that depth range (the maximum sample thickness which can be derived from the signal) is about the thermal diffusion length μ for magnitude imaging and twice that for phase angle imaging/15/ (see Fig. 5). This is still much smaller

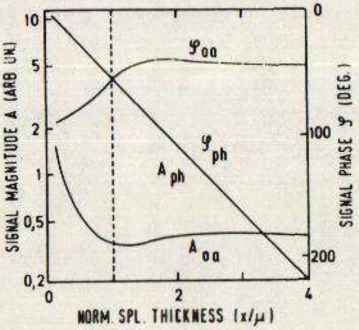


Fig. 5:

Signal as function of sample thickness for optoacoustic (oa) and photothermal detection (ph) /15/.

than the thickness one can inspect with thermal wave transmission /13/, but on the other hand there is the possibility of depth profiling /15/: structures are shown only within a depth which can be changed via modulation frequency. An example for depth analysis is shown in Fig. 6 where at the lower frequency both holes are within

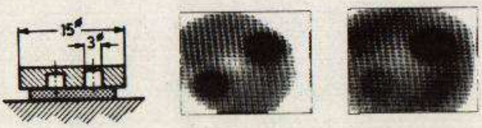


Fig. 6:

Optoacoustic magnitude imaging of subsurface holes (middle: 18Hz, right:180Hz)

range while at 180 Hz one finds only the hole ending near the surface /16/.
As sample regions within depth range distance from the laser focus contribute to the front surface signal, lateral resolution is about twice that value and hence depends on modulation frequency. Microscopy of thermal structures therefore requires modulation frequenciesof 10^5 - 10^6 Hz. An example for optoacoustic microscopy at 180 KHz is shown in Fig.7. Evidently phase and magnitude of the signal

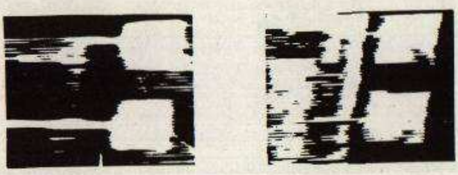


Fig. 7:

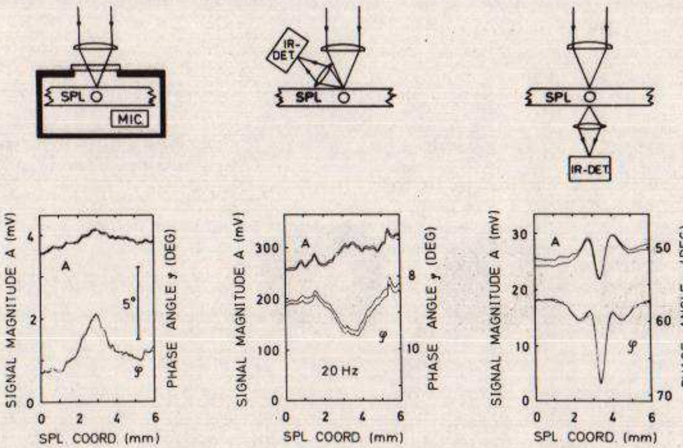
Optoacoustic microscopy of an integrated circuit (left: magnitude, right: phase)

Discussion

Photothermal transmission imaging does not require physical contact with the sample. A simple equation describes in a good approximation how the observed signal depends on sample geometry. As all parts of the sample contribute equally to the signal, depth resolved analysis is not possible with the simple arrangement described above.

In front surface imaging using optoacoustic or photothermal detection mostly near-surface regions contribute to the signal, thermal diffusion length limits both resolution and depth range thus allowing for depth profiling. This advantage has to be compared to the loss of depth range and of resolution, as is shown in Fig.8 where an aluminium sample with a hole was scanned using three different

Fig. 8:
/12/



methods at the same modulation frequency (20 Hz). Though photothermal front surface imaging (middle) is also remote detection with local resolution, the halfwidths observed demonstrate that it is very similar to optoacoustic imaging (left).

The different methods of thermal wave imaging allow for nondestructive material inspection. Optical background structure is eliminated in phase angle images. Though at this state of development any prediction is difficult it seems that photothermal imaging (front or rear surface) will find applications because it is remote inspection which does not limit sample size. Therefore it should be a good alternative to conventional methods based on x-rays or ultrasonics.

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