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A feasibility study

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GHz half wavelength contact acoustic microscopy (HaWaCAM): a feasibility study

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ABSTRACT

The semiconductor industry needs to fit ever more devices per unit area to improve their performance; hence a trend towards increasingly complex structures by varying material combinations and 3D geometries with increasing aspect ratios. The new materials used may be optically opaque, posing problems for traditional optical metrology methods. One solution is to use acoustical waves, which present the double advantage of not being hampered by optically opaque layers and allowing for penetration depths of 10's of µm at sub-µm wavelengths; which is considerably larger than most traditional optical methods (O(100 nm's - µm's)).

Here, we present a novel acoustic metrology method using GHz ultrasound waves to measure deeply buried subsurface features (>5 µm). The concept consisted of a GHz acoustic transducer integrated above the tip of a custom designed probe, which is then scanned across a sample. The method uses non-damaging solid-solid contact without the need for liquid coupling layers – in contrast to conventional acoustical microscopy. This allows for the use of much higher acoustic frequencies, hence higher on-axis resolutions. The transducer is used in pulse-echo mode and a stage controller is used to move the probe for scanning. An experimental setup was built with a 4 GHz transducer and tested successfully on 1.5-2 µm size features buried below a 5 µm PMMA or 10 µm SiO_2 layer, respectively. A good match was further obtained between the measurements and the model predictions. These results demonstrated the feasibility of the new method, opening new opportunities for metrology and inspection applications.

Keywords: GHz acoustic metrology; acoustic metrology; solid contact; half wavelength contact area; half-wavelength contact acoustic microscopy; HaWaCAM

1. INTRODUCTION

The semiconductor industry needs to fit ever more devices per unit area to improve their performance; hence a trend towards increasingly complex structures by varying material combinations and 3D geometries with increasing aspect ratios and multiple layers. Traditional metrology methods such as Scanning Electron Microscopy (SEM) or Atomic Force Microscopy (AFM) are limited to surface sample topography, others such as Transmission Electron Microscopy (TEM) can retrieve subsurface information but are limited to thin (100 nm) layers. Cross-sections of samples can be taken using a combination of Focused Ion Beam (FIB) and SEM, however these techniques are destructive. Other methods are being investigated, such as Critical Dimension Small Angle X-ray scattering (CD-SAX) or hybrid metrology combining different techniques[1], but their penetration depth is limited (O(100 nm's - µm's))[2]. The new materials used, metals or amorphous carbon layers for instance, may further be opaque for electrons or photons[1]. There exists, to the author's knowledge, no solution for non-destructive imaging of deeply buried features below optically opaque layers.

One possible way to circumvent these challenges, is to use acoustical waves, which present the double advantage of not being hampered by optically opaque layers and allowing for penetration depths of 10's of µm at sub-µm wavelengths.

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2. METHODS

2.1 HaWaCAM Concept

The half wavelength contact acoustic microscopy (HaWaCAM) instrument consisted of a GHz acoustic piezoelectric transducer integrated above the tip of a custom designed probe. The tip of the probe was blunt and the contact diameter was O(half wavelength). The tip was in direct solid-solid contact with a sample, without the need for a coupling layer. The probe was further subjected to a fixed static force such as to maintain the desired contact diameter and to prevent any tip or sample damage. The probe was moved in 2D along the sample surface in order to create 3D subsurface datasets. The instrument operated in pulse-echo mode: the GHz piezoelectric transducer emitted a GHz acoustic wave that traveled linearly through the probe, the tip-sample interface and the sample. The acoustic wave was scattered by subsurface features and traveled back linearly via the same route to the GHz transducer, where it was converted to electrical signals, see Figure 1.

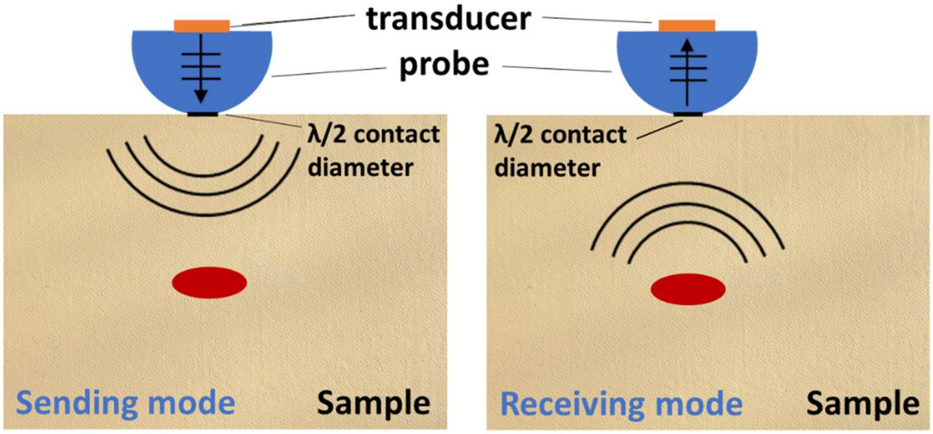

Figure 1. Schematic image showing the half wavelength contact acoustic microscopy (HaWaCAM) inspection concept. Sending (left) and receiving (right) modes during pulse-echo measurements.

2.2 Prototype device and measurement setup

Custom probes were designed and developed. A 4 GHz disk piezoelectric transducer was integrated on top of said probes together with the associated electrical connections. The piezoelectric element was based on AlN. The probe was of a custom design with a blunt tip (tip radius > 10 µm). See Figure 2 for SEM pictures of a probe with an integrated transducer. Said transducer was excited using linear chirps centered around the transducer design frequency (4 GHz) and with a -6dB bandwidth of 4 GHz, duration 5ns. Said pulse was then sent to a high speed switch (custom printed circuit board) allowing a switching time of 15ns between sending and reception mode. The received acoustic echoes where then amplified and displayed on an oscilloscope. The displayed traces were then recorded via a computer after 400 traces were averaged per point. The probe static force and X-Y positioning control was ensured via an atomic force microscope. See Figure 3 for a schematic of the experimental setup layout.

Traces were recorded either on single positions, or scanning the surface in 1D or 2D. The time traces were then processed using several steps, including: time delay/jitter compensation, time windowing, pulse compression, filtering, attenuation and diffraction compensation, imaging[3].

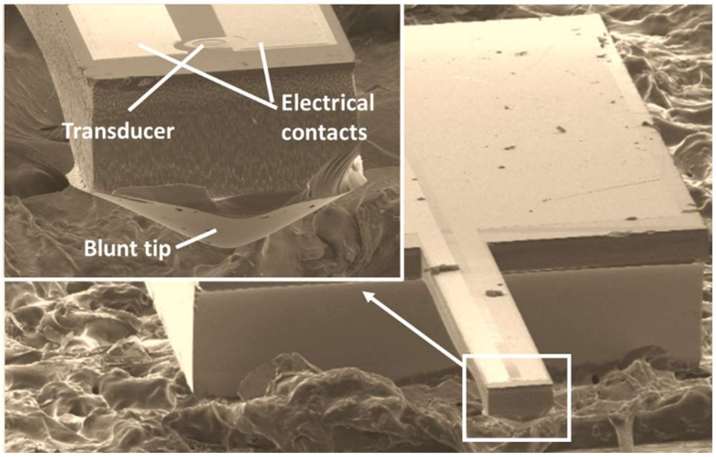

Figure 2. SEM image of the custom probe including (zoom): GHz piezoelectric transducer with electrode electrical contacts on top of blunt probe tip.

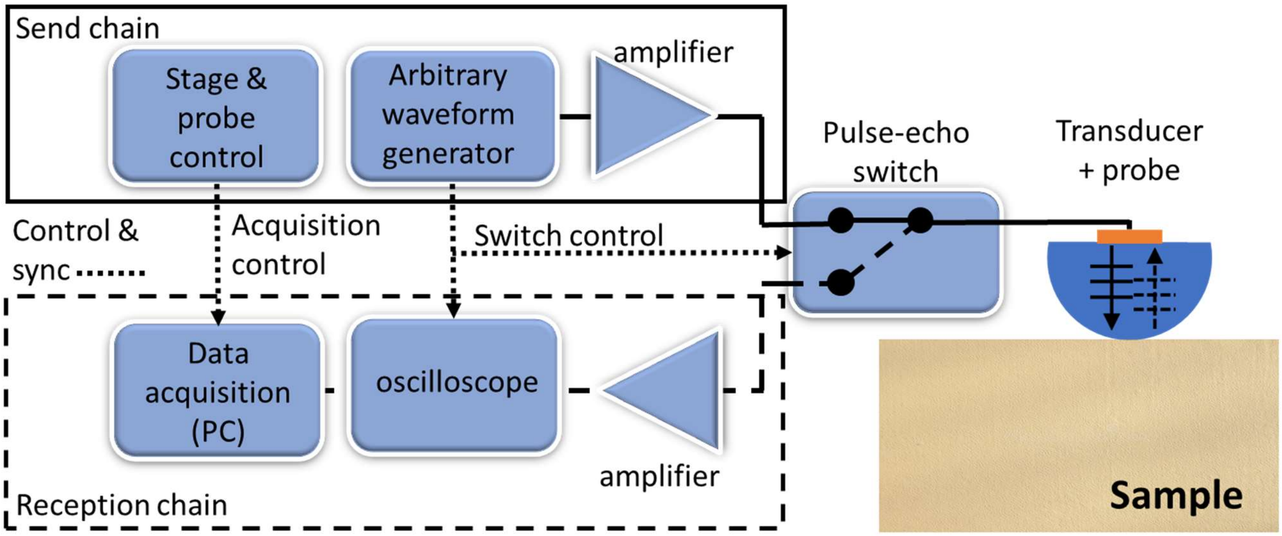

Figure 3. Schematic of the experimental setup.

2.3 Sample description

Two samples were used to test the measurement method. Both samples consist of a silicon substrate and features. On the first sample, the features consisted of 0.8 – 1.5 µm wide lines of height 100nm with a pitch of twice the lines width. The features were buried under 9.7 µm of SiO_2 deposited on the Si substrate. On the second sample, the features consisted of a 15x15 matrix of 2 µm wide square features of height 300 nm with a pitch of twice the features width. The features were buried under 5 µm of PMMA deposited on the Si substrate.

3. EXPERIMENTAL RESULTS

3.1 Sample measurements: parallel lines under 9.7 µm of SiO_2

In this section, the results obtained on the first sample are presented and discussed. The silicon linear features were 1.5 µm wide, 300 nm high and with a pitch of 3.0 µm buried under 9.7 µm of SiO_2. In Figure 4 (left hand side), time traces after signal processing are presented. The time axis is scaled so that the tip echo and expected SiO_2/Si interface echo are visible. The SiO_2/Si interface echo is expected at around 3.3ns, which corresponds to a sound speed of about 5900 m/s in SiO_2. Measurements are compared under different conditions: probe in air, 10's of µm away from the sample surface (black line), probe in contact with the sample surface and off-feature (blue dotted line) or in contact and on-feature (red fine dotted line). An echo is visible (black vertical dotted lines) at about 3.3 ns when the probe is in contact, which corresponds to the expected traveling time in SiO_2. The tip echo amplitude is further higher when the probe is not in contact, as expected, it corresponds to the coupling of acoustical energy in the sample. In Figure 4 (right hand side), a zoom around the SiO2/Si interface echo (orange dotted box in left hand side figure) confirm these observations. In particular, no subsurface echo is visible when the probe is not in contact. The two black vertical lines correspond to the theoretical SiO_2/Si interface (large dots) and subsurface feature height (fine dots) arrival time. The 24 ps time delay between the on- and off-feature SiO2/Si interface corresponds well with the geometry and the material properties (100 nm feature height and a sound speed of 9600 m/s in Si).

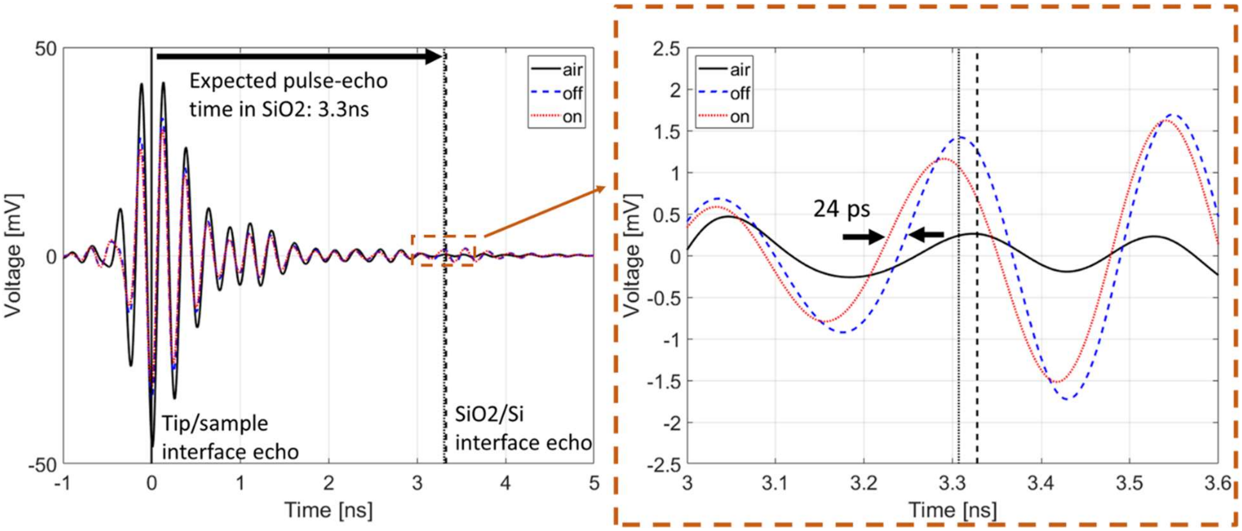

Figure 4. left: Time signals for measurement where the probe tip is in air (black line), off-feature (blue line), and on-feature (red line). The time axis is fixed around the expected arrival time of the probe tip echo and the subsurface feature echo. Right: Further zoom around the subsurface feature echo. The two vertical black lines correspond to the theoretical time of flight for the SiO_2/Si interface (large dots) and the feature echo (fine dots).

3.2 Sample measurements: square matrix under 5 µm of PMMA

In this section, the results obtained on the second sample are presented and discussed. The silicon square features were 2 µm wide, 100 nm high and with a pitch of 4 µm buried under 5 µm of PMMA. Data were acquired in 2D on a surface of 12x70 $µm^2$ with 250 nm steps in both directions. The acquired time traces were processed and a migration algorithm allowed to reconstruct the subsurface in 3D, as described in section 2.2. The data corresponding to t = 3.32 ns is presented in Figure 6 (top) where the color represents the signal level in mV. In this figure, 4 lines of 15 subsurface features are clearly visible, slightly tilted with respect to the scan directions. The number of features per line, the features sizes and pitch are in good agreement with the sample description.

A cross-correlation operation was further applied, using an arbitrary trace as reference. This allowed to assess visually the on-off feature time difference. Figure 6 (bottom) shows the relative arrival time differences of the features subsurface echoes, with the color scale indicating the time differences in ps. The on-off feature relative time difference is about 140 ps, which is in agreement with the time difference expected between an off-feature position and an on-feature corner reflection.

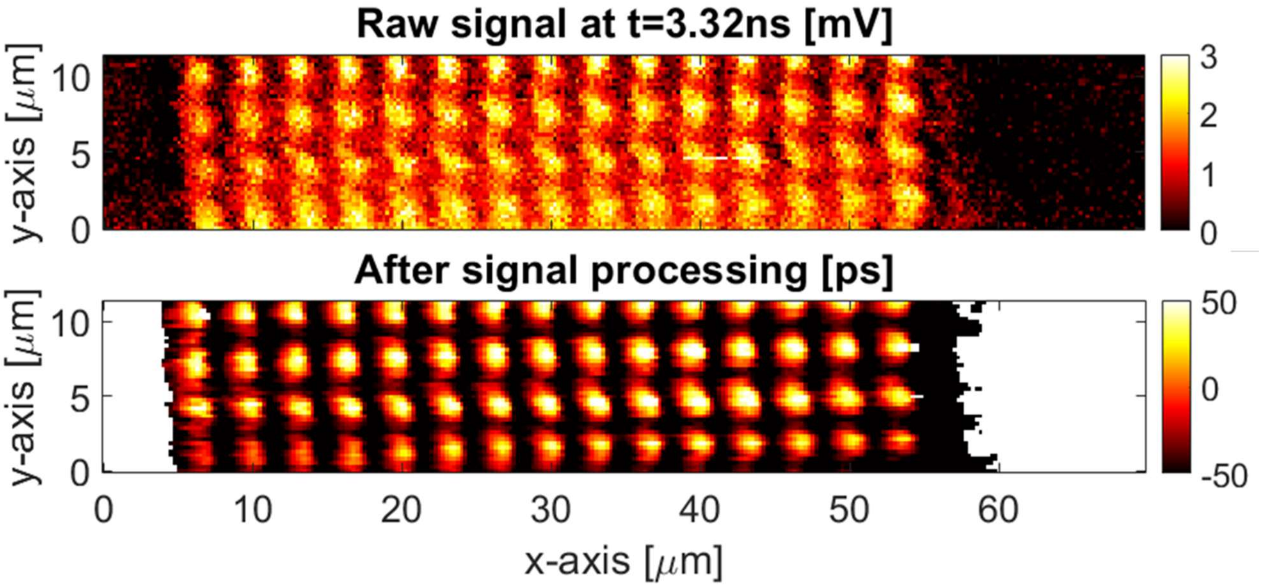

Figure 5. Sample of silicon with matrix arrays of features (width 2 µm, pitch 2x width, height 300 nm) buried below a 5 µm PMMA top layer. 4 lines x 15 columns of subsurface features scanned here. Top: Signal level as measured 3.32 ns after the tip-sample echo, color scale in mV. Bottom: arrival time difference of the subsurface grating echoes relative to a reference data trace, after post-processing, color scale in ps. The white pixels on the left and right sides of the subsurface gratings correspond to pixels with a low correlation coefficient (noise).

4. DISCUSSION

The experimental results obtained on the SiO2 and PMMA samples show that deeply buried features can be imaged using the HaWaCAM concept, even in highly attenuative materials such as PMMA (the attenuation in PMMA is about 0.24 dB/µm @4GHz where attenuation in SiO_2 is 2.4 mdB/µm @4GHz). For more realistic samples, multi-layered samples with sub-wavelength layers are foreseen to be handled as a mixed attenuation. Larger layers in the stack could lead to strong reflections, limiting the acoustic energy going through but we foresee , nonetheless, that measurements on 3D-NAND stacks with 100s of layers should be feasible, which is not possible with the current metrology techniques. Furthermore, the HaWaCAM concept allows a 3D reconstruction of the subsurface layers, which is useful for imaging of features or localization of defects for instance. An additional advantage, in terms of integration, is that the technique is non-damaging, as was observed on a soft (PMMA) and harder (SiO_2) sample.

SUMMARY AND CONCLUSION

In this work, HaWaCAM, a novel method for GHz acoustic metrology of deeply buried structures in solid samples was presented. The technique was based on non-damaging solid contact between the metrology device and sample. The technique features a penetration depth of O(10s of µm), is non-destructive/non-damaging and is not hampered by optically opaque layers (as it is acoustics based). The method was successfully tested on linear and matrix grating structures with feature size ~2 µm buried below 5 – 10 µm of PMMA or SiO2, respectively. We foresee potential applications in e.g. metrology on or through 100+ layer 3D-NAND stacks.

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