Detection of subsurface structures by use of the atomic force acoustic microscopy technique

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Introduction

The influence of small defects, such as voids, inclusions and delaminations, on the performance of the active elements in micro- and nano-electronics becomes more critical as their size decreases. In addition, the diagnostic of defects with size less than several micrometers becomes challenging, especially if the defects are buried under the structure surface. To image such small structures one needs a technique with spatial resolution and the ability of subsurface imaging. In this study we propose the use of atomic force acoustic microscopy (AFAM) technique [1] for detection of subsurface defects. AFAM technique is a dynamic enhancement of atomic force microscopy (AFM) method that is able to detect local changes in the sample elastic properties. Depending on the mode of operation one can acquire qualitative images containing information about changes in the effective elastic properties of the sample. The values for the local elastic modulus can be obtained quantitatively from single position measurements [2] or from quantitative maps of the elastic modulus [3]. It was shown that AFAM technique is sensitive to small differences in sample elastic properties due to e.g. elastic anisotropy or presence of ferroelectric domains [2]. This technique was also used to determine elastic properties of nickel films thinner than 1 µm [4]. There, it was shown that the volume probed in the AFAM measurement can be controlled by parameters such as applied static loads and tip radius. In the study reported here, it will be shown that AFAM technique is capable of detecting air-filled defects placed 30-300 nm deep under the sample surface.

Investigated samples

Several reference samples with well defined buried structures were prepared in order to test the lateral and depth limits of AFAM technique. The first studied structure was a 30 nm thick membrane of silicon nitride deposited on silicon wafer. The silicon was chemically etched in area of 500 µm² till the chemical agent was stopped by the membrane. An optical image of the membrane was obtained after it was placed on the surface of a coupling medium. One can see in the figure the presence of air bubbles trapped in the membrane corners.

In order to test the depth-detecting ability of AFAM technique, two additional samples were prepared. In Fig. 1b one can see an SEM image of nine square membranes with edge length of 3.7 µm. The thickness of the membranes increased step wise from 30 nm to 270 nm in eight 30 nm large steps. Fig. 1c presents an SEM image of a trench structure 1.6 µm wide with thickness increasing linearly from 0 to 2.7 µm over 50 µm length. The membranes and the trench structures were prepared with ion-beam etching.

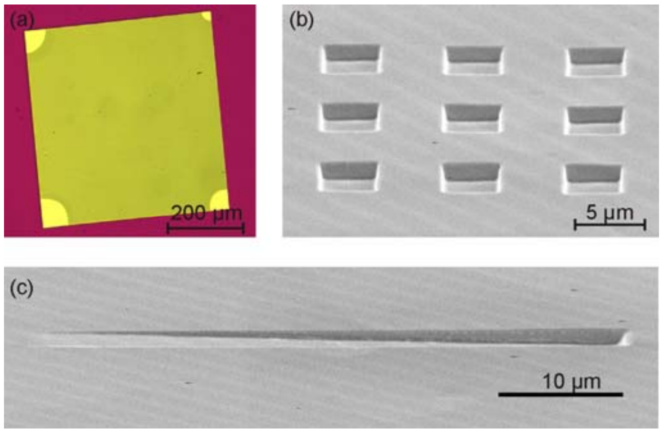

Fig 1: (a) Optical image of 30 nm thick membrane of silicon nitride,) SEM images (b) of silicon membranes, and (c) trench structures**.**

Experimental method

The AFAM technique is based on contact mode of the AFM technique. The scheme of the experimental AFAM set-up is presented in Fig. 2. The sample is placed on top of an ultrasonic transducer that emits longitudinal waves at ultrasonic frequencies into the sample and causes out-of-plane surface vibrations of small amplitudes. The movement of the surface is translated into continuous movement of an AFM cantilever via the contacting sensor-tip. The amplitude of the cantilever vibrations is detected by a laser beam that is reflected from the cantilever surface to a photodiode detector. The signal from the photodiode is the send to a lock-in amplifier where it is analyzed at the excitation frequency. The details concerning quantitative AFAM can be found elsewhere [5]. Only the qualitative AFAM imaging-mode will be described shortly in this section.

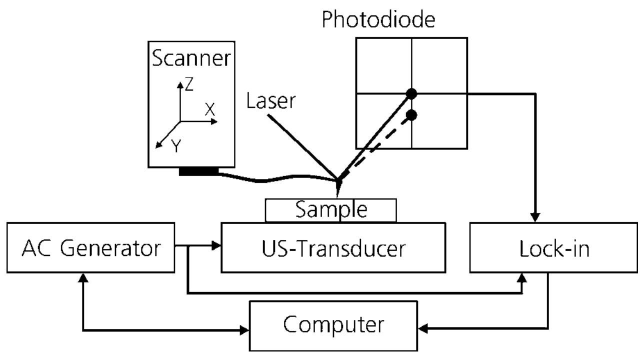

Fig. 2: Schematic of AFAM experimental set-up.

In AFAM amplitude imaging mode, changes in amplitude of the cantilever vibrations excited at a fixed frequency are analyzed and used as an imaging quantity. In order to obtain AFAM amplitude image a frequency range where the contact resonance frequency occurs must be known. Then a fixed frequency from within this range is applied to the sample while the AFM cantilever scans the sample surface. For example, if the applied excitation frequency is near to a contact resonance frequency for one of the samples components, then the cantilever will vibrate at higher amplitude while in contact with this particular phase, than with other components. Changes in the excitation frequency cause changes in the vibration amplitude of the cantilever contacting different phases of the tested samples. Contrast of AFAM amplitude images is excitation frequency dependent.

Results and discussion

The 30 nm thick membrane of silicon nitride was the first structure tested in these experiments. In order to avoid the damage of the membranes, a cantilever with relatively low spring constant k_c of about 3 N/m was used for imaging. The first free resonance frequency was 76 kHz. Figure 3 presents the (a) topography and (b) AFAM images obtained parallel at static load of about 40 nN and excitation frequency of 400 kHz. The imaged area was 100 µm x 100 µm and contained one of the corners of the membranes with the trapped air bubble. These features cannot be distinguished in the topography image, while the AFAM image shows clearly the corner of the membrane. In addition, one can see the presence of the air bubble.

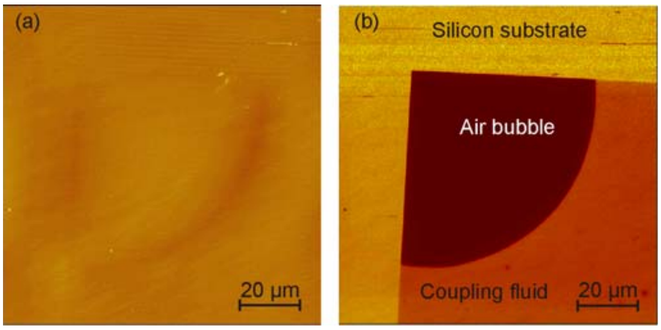

Fig. 3: (a) Topography and (b) AFAM amplitude image obtained for the 30 nm thick membrane of silicon nitride. The height scale of the topography image was 300 nm.

AFAM images obtained for the set of silicon membranes and the silicon trench structure are presented in Figs. 4 (a) and (b), respectively. The cantilever used in these measurements, had a diamond coated tip and a spring constant of about 60 N/m. Both images were obtained at the same static load and excitation frequency of 600 nN and 767 kHz, respectively. It can be seen in Fig. 4a that it was possible to detect the all the nine membranes including the thickest one of 270 nm. Analysis of the AFAM image presented in Fig. 4b revealed that it was possible to detect the differences in the effective stiffness for the trench thickness of about 320 nm.

The thumb rule of contact mechanics says that the volume probed during an indentation measurement extends about three times the contact radius into the sample [6]. However, presence of a subsurface defect changes the effective elastic properties. Contact resonance spectra obtained for the 30 nm thick silicon nitride membrane allowed estimating that effective contact stiffness measured for membrane-silicon substrate area was about 7 times greater than that measured for the membrane-air region. This fact allowed us to not only to distinguish between the region of membrane and bulk silicon but also to distinguish the areas of air bubbles trapped in the coupling fluid under the membrane. The depth at which the defects can be hidden and still detected with AFAM method will depend on the differences in the acoustic impedance and elastic properties of the surface and the defect, the contact radius, the geometry of the tip, and the size of the defect.

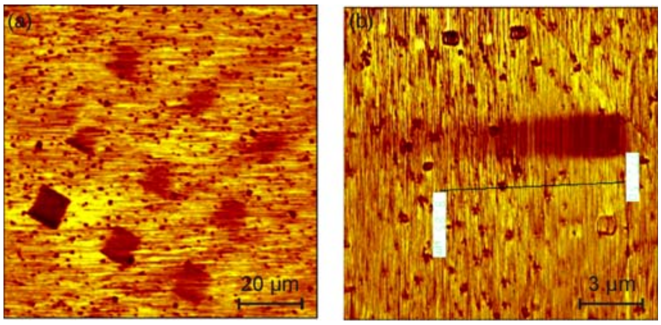

Fig. 4: AFAM images obtained for the (a) set of nine membranes and (b) trench structure with varying thickness.

Literatur

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