NONDESTRUCTIVE CHARACTERIZATION OF FREESTANDING MEMBRANES AND MICRO-STRUCTURES HAVING SUBMICRON DIMENSIONS

Dieter M. Profunser, Jacqueline Vollmann, Jurg Dual
Center of Mechanics, Swiss Federal Institute of Technology Zürich, CLA H27, 8092 ETH-Zentrum, Switzerland

Abstract

Measuring the high frequency bulk acoustic wave propagation is an interesting measurement method for non-destructive testing as well as for the characterization of material properties especially since the increased use of thin films and micromechanical systems.

A pump-probe short pulse laser acoustic method which is well known for the measurement of thicknesses of thin metallic films on substrates, is adapted and applied to freestanding membranes and three dimensional microstructures.

Results for the measured bulk wave propagation in very thin membranes with total thicknesses in the order of several hundred nanometers are presented. The measured bulk wave propagation in this freestanding aluminium-silicon nitride multi-layer membrane is compared with thermo-elastic models and with measurements of the supported case. For the measurements on microstructures the pump-probe set up has been modified. The pump and probe laser pulses hit the specimen from opposite sides and microscope objectives are used to minimize the laser spot size on the specimen. First results of measurements on aluminium coated silicon cantilevers are presented.

Introduction

Very thin membranes and cantilevers are part of numerous microelectromechanical systems (MEMS), e.g. sensors, actuators or bulk acoustic wave filters. Usually the mechanical properties are important parameters for the correct operation of the MEMS devices. Manufacturing processes and conditions significantly influence the resulting mechanical properties of a microstructure which will be shown for the example of silicon nitride.

After finishing of the manufacturing process of MEMS it is very difficult to measure any material property in a non-destructive way with the conventional methods. The outlined technique based on high frequency ultrasound excited with ultra-short laser pulses is the right approach for providing mechanical properties of thin and brittle MEMS-structures like cantilevers and membranes in a non-contact and non-destructive way.

In the following sections measurements on freestanding membranes and silicon cantilevers in different configurations are presented. The measured velocity of the ultrasonic pulse can be used for estimating the Young’s modulus of the material.

Methodology and Experimental Setup

For measuring the acoustic pulses in thin films and MEMS structures the so called pump-probe technique is used. An overview of the pump-probe technique used for picosecond ultrasound for various film/substrate configurations is given by C. Thomsen et. al. [1], O.B. Wright et. al. [2] and B. Bonello et. al. [3]. Based on the experimental setup presented by J. Vollmann et. al. [4] the pump-probe setup is outlined below.

Ultrashort laser pulses with a wavelength of 800 nm are excited with a titanium sapphire laser system at a repetition rate of 81MHz. The laser pulse duration is in the order 70fs. In accordance with the schematic experimental setup (Fig. 1) the laser pulses are split in pump and probe pulses. With a translation table the arrival time of the pump pulses at the specimen can be adjusted relatively to the arrival time of the probe pulses.

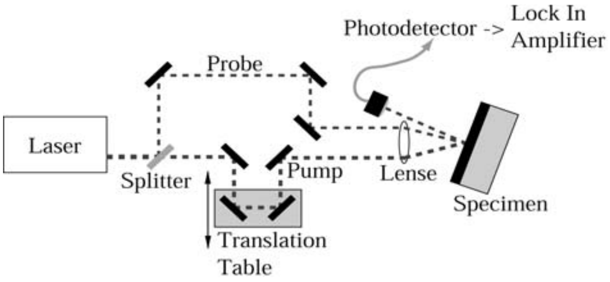

Figure 1: Schematic experimental setup

In the case of an opaque thin film the pump pulses are absorbed and initiates a nearly exponentially decaying temperature distribution in the thickness direction z of the thin film. Caused by the instantaneous heating at the surface of the thin film a acoustic pulse is launched. The mechanical pulse is propagating in the thickness direction of the thin film (z direction, Fig. 1) with the bulk wave velocity (c_1, Eq. 1), which can be calculated with the Lame constants (λ and μ) and the density (ρ) of the film.

$$c_1 = \sqrt{\frac{\lambda + 2\mu}{\rho}} \qquad (1)$$

Reflections of the acoustic pulse or the acoustic pulse itself can be detected by measuring the optical reflectivity with the probe laser pulses. The changes of optical reflectivity caused by the acoustic pulses are very small and contain very high frequencies. Therefore the pump-probe technique is necessary.

Results

Measuring picosecond ultrasound in freestanding membranes having submicron thicknesses

The specimen is a silicon nitride (Si_3N_4) membrane which is coated with aluminium films of different thicknesses. The aluminium films are deposited by electron beam evaporation.

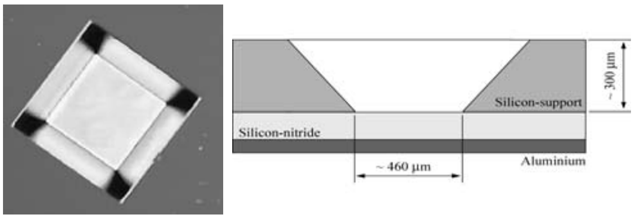

Figure 2: Silicon nitride membrane with surrounding silicon support (left: top view under microscope, right: schematic cross-section)

The thickness of the membrane is in the order of 520 nm. The silicon nitride membrane has an amorphous structure and is grown by an LPCVD process at about 700°C.

Usually the Young’s modulus of aluminium films which are deposited with electron beam evaporation do not vary strongly as a function of the deposition conditions. However, the Young’s modulus of silicon nitride varies in a wide range depending on the conditions of deposition and the used technique. Some literature values of the Young’s modulus are given in the following table

Tabel 1: Young’s modulus of Silicon-nitride

Films grown with LPCVD [5]	290 GPa
Films grown with PECVD [5]	210 GPa
Sputtered films (average) [6]	130 GPa

The presented measurement is carried out on a specimen coated with aluminium film with a thickness in the order of 40nm. The absorbed pump pulse initiates a temperature distribution in the membrane and excites mechanical pulses travelling according to the arrows in Fig. 3. The first reflection which can be observed in Fig. 3 (solid curve) approximately after 13ps is caused by the acoustic pulse reflected at the aluminium/silicon-nitride interface. After 117ps a negative peak of the reflectivity change is observed which corresponds to the reflection of the acoustic pulse at the free surface of the silicon nitride part of the membrane.

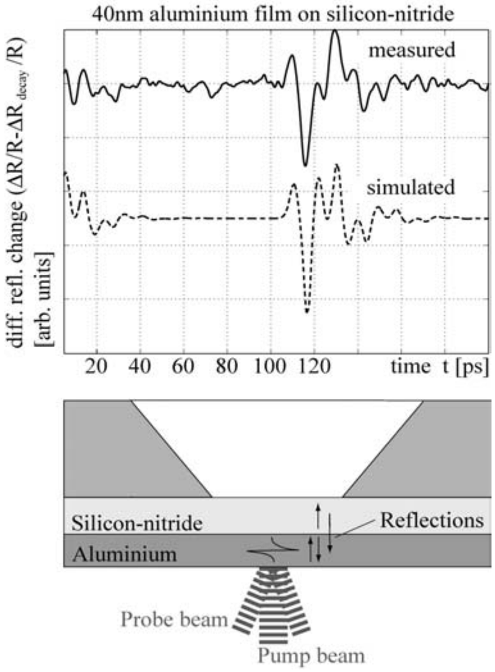

Figure 3: Measurement on a membrane coated with 40nm aluminium without thermal reflectivity change

After again 13ps this wave reaches the free aluminium surface a second time after the reflection at the interface of aluminium and silicon-nitride.

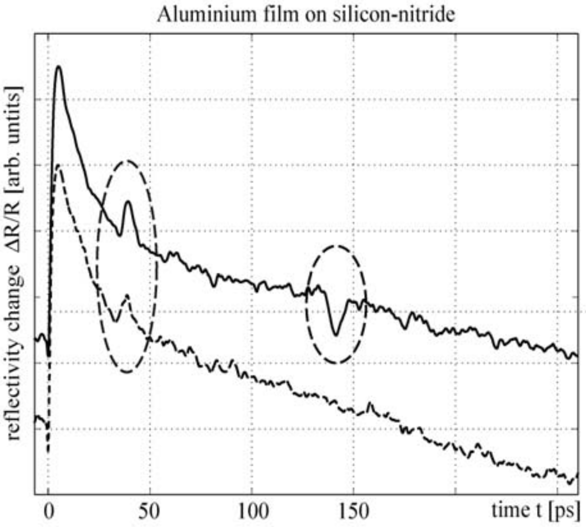

Figure 4: Measurement in membrane coated with 120nm aluminium

The simulations shown in Fig. 3 (dashed curve) are performed with a coupled numerical scheme for the induced temperature in the membrane and the bulk wave propagation according to D.M. Profunser et. al. [7]. The simulations are in good agreement with the measurements. The measurements in Fig. 4 are carried out on a similar specimen but the aluminium coating is 120nm thick. The measurement on the freestanding part of the membrane (solid curve) is compared with the measurement on the silicon supported part. In both measurements the first reflection at 39ps caused by the acoustic pulse reflected at the aluminium/silicon-nitride interface can be observed. However, the negative reflectivity peak after 142ps which corresponds to the reflection of the acoustic pulse at the free surface of the silicon nitride part of the membrane occurs only in the freestanding membrane.The sign change is a result of the stress free boundary at the free surface of the silicon nitride part of the membrane.

To estimate the Young's modulus of the silicon-nitride membrane a density ρ of 3100g/cm^3 (source [6]) and a Poisson's ratio ν of 0.24 is chosen in addition to the measured velocity of the acoustic pulse. The calculated value of the Young's modulus of 263GPa is 10% lower than the modulus given in Table 1 for LPCVD silicon-nitride membranes which can be caused by a slightly increased average temperature in the membrane or an inaccuracy in the poisson ratio.

Measurements on aluminium films in a different configuration

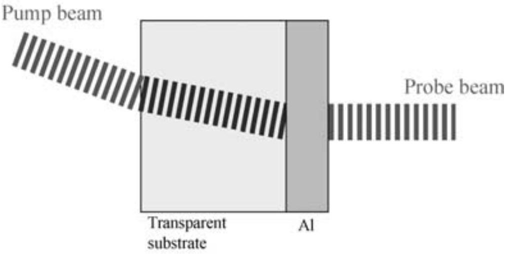

Figure 5: Pump and probe laser pulses hitting the specimen from opposite sides

For the measurements presented below the experimental setup is modified in a way that the probe and the pump laser pulses hit the specimen from opposite sides. Additionally microscope objectives are used to focus both laser pulses towards the specimen. This results in a smaller spot size and a higher signal/noise ratio while working with the same average power. For the measurements presented in Fig. 6 a transparent substrate (borofloat glass) is coated with different aluminium films. The excitation of the acoustic pulses is done through the transparent substrate - the reflectivity is still measured at the free surface of the aluminium film. In the first case the aluminium film has a thickness of 11nm. The incident pump pulse is partly absorbed by the semitransparent 11nm aluminium thin film. The absorption of the pump laser pulse initiates an instantaneous heating of the very thin aluminium coating. The temperature distribution is nearly uniform in the thickness direction. Usually the initiated temperature decrease exponentially with increasing thickness but due to the very small thickness of the aluminium layer which is in the order of the absorption length the temperature distribution can be assumed to be uniform. This is the reason why the sudden increase at a time of approximately 0 ps and the slow decrease of the measured reflectivity change (which is caused by the temperature in the aluminium thin film) can be measured on the opposite side of the excitation. The measured reflectivity change of the 11nm aluminium is nearly similar to that measured in a configuration according to Fig. 1.

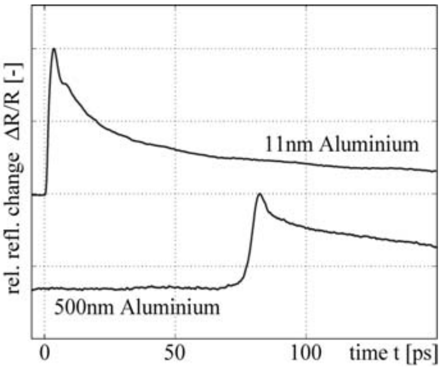

Figure 6: Measurement on aluminium films

On the other hand the measurement in a configuration according to Fig. 5 of a specimen coated with 500nm aluminium looks totally different. The reflectivity change caused by the temperature in the thin film (sudden increase at the beginning and smooth decay) can not be observed. The reason is that the initiated temperature distribution - as described before - decreases exponentially with -z/ζ. ζ denotes the absorption length which is for metal films usually in the order of 10-20nm and z the thickness from the excitation. The heat diffusion is too slow for heat transportation through 500nm aluminium. After approximately 80ps the reflectivity increase suddenly. This is the response of the acoustic pulse reaching the free surface after propagating once through the 500nm aluminium film. After 80ps the reflectivity remains higher than before, which is caused by the different strain pulse shape excited at the interface of film and substrate by the incident pump pulse.

Measurements with cantilevers

The measurement of the bulk wave propagation in cantilevers is performed in the same configuration as the measurements described in the section before. The pump and probe beam hit the cantilever on opposite sides according to Fig. 7. The silicon cantilever is coated on the detector side with an approximately 30nm thick aluminium film. This commercial available cantilevers have typical thicknesses of 2μm and mean widths of 50μm. The cantilever length is in the order of 450μm. The acoustic pulses are excited on the side with the aluminium coating by absorbing the pump laser pulses.

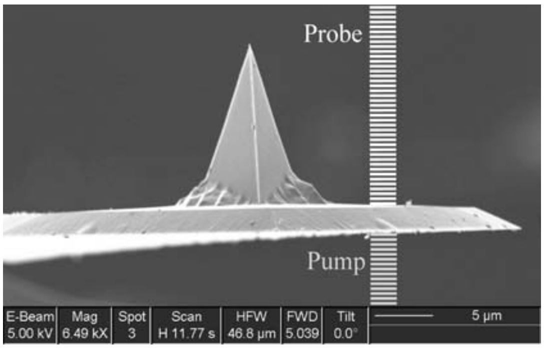

Figure 7: Schematic measurement configuration

After propagating through the cantilever the acoustic pulses are detected by the probe laser pulses. This leads to the peak in the reflectivity at about 240ps in Fig. 8.

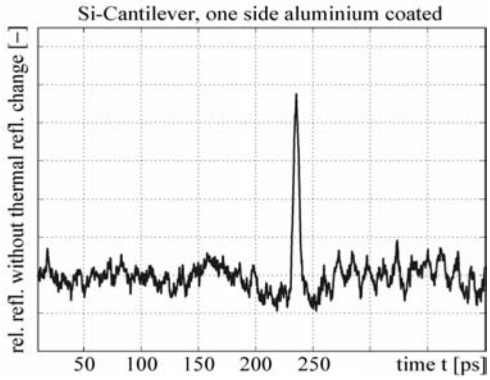

Figure 8: Measured reflectivity of silicon cantilever

For the laser wavelength in the order of 800nm the silicon part of the cantilever is nearly transparent which means that a part of the incident probe pulse is reflected at the surface and the other part is transmitted into the silicon where it is partly reflected by the propagating acoustic pulse. This part of the probe light pulse interferes constructively and destructively depending on the propagating acoustic pulse with the part of the probe laser beam reflected at the surfaces and leads to oscillations in the reflectivity with a measured frequency of 78GHz. According to [8] this leads to a wave speed of ~8500m/s assuming a refractive index n of 3.7 for the laser wavelength of 800nm. The heating of the cantilever by the absorbed part of the incident pump and probe beam and the resulting effects are subject of further research.

Conclusions

The presented laser based picosecond ultrasound technique has shown to be a good approach for the non-destructive determination of material properties of microstructures (MEMS). The non-contact and non-destructive manner of the presented method is especially important for very thin and brittle structures like freestanding membranes and cantilevers for example.

With the picosecond ultrasonic measurements on aluminium coated freestanding silicon-nitride membranes a Young’s modulus of 263GPa can be estimated. The results of the measurements with silicon cantilevers leads to a bulk wave velocity of ~8500m/s.

References

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