XVI IMEKO World Congress
Measurement - Supports Science - Improves Technology - Protects Environment ... and Provides Employment - Now and in the Future
Vienna, AUSTRIA, 2000, September 25-28

LASER OPTICAL STRAIN SENSOR FOR MATERIAL TESTING

M. Anwander [1], B. Weiss [1], C. Kargel [2], B. Trummer [2]
H. Weiss [2] and B. Zagar [2]
[1] Institute of Materialphysics, University of Vienna, Austria
[2] Institute of Electrical Measurement and Measurement Signal Processing
Graz University of Technology, A-8010 Graz, Austria

Abstract: To increase the reliability of microelectronic components it is frequently required to determine mechanical and thermal properties of the base material in its practical dimensions (e.g. thin foils and films, thin wires, membranes). Due to the known "size effect" these material properties cannot be deduced from macro deformation data. In this investigation a non-contacting laser optical strain sensor is being used to determine deformation data of the so called micromaterials in combination with a specially designed microtensile machine. The strain sensor is based on a laser optical speckle correlation method. The applicability and limitations of this laser sensor is being discussed. Changes of mechanical properties are related to microstructural changes being investigated with special techniques using the electron channeling contrast microscope and a scanning electron microscope.
Keywords: laser optical strain sensor, micromaterials, size-effect, thin foils

1 INTRODUCTION

It is well known that mechanical testing of parts of microelectronic systems being small in all dimensions is a difficult task. Because they require a high degree of accuracy for the measurement of stress and strain and furthermore specimen preparation and handling causes additional experimental efforts. Several different mechanical testing techniques have been developed over the years [1]. The following testing procedures have been frequently used: the nanoindentation method, biaxial bulge testing, bending techniques and the uniaxial tensile testing of free standing foils. A critical evaluation of these methods is presented in [1].

Since the interpretation of the tensile test is simple, various investigators prefer this testing technique, although it is known that specimen loading, handling and alignment requires considerable experimental experience. For the determination of strain non-contact recording systems have to be applied, since strain measurements from crosshead movement is not accurate enough and conventional strain testing devices cannot be applied to specimens with small dimensions.

In this investigation a laser extensometer with high strain resolution is presented. It is based on the digital laser-speckle correlation technique [2,3]. In combination with a specially designed microtensile testing machine the following data are obtained:

Elastic, plastic and fracture properties of metallic foils with varying thicknesses (electro deposited and rolled Cu and Ni) have been used to study size effects. Furthermore using a specially designed testing technique fatigue crack growth properties have been determined to obtain data for the so called "fracture micromechanics" sometimes called fracture electronics (see Michel in [4]). For a better understanding of the deformation damaging processes (e.g. interaction of microstructural features (dislocations, grain boundaries) with the advancing crack tip special SEM techniques in combination with electron channeling contrast imaging (ECCI) [5] are being introduced.

2 SPECKLE-CORRELATION SENSOR

Laser speckle techniques can be used as a non-contacting optical method to determine strain which was originally introduced by [6] and later optimized by [2]. Laser speckles are formed if coherent light is reflected off an optical rough surface. For practical purposes the surfaces of most materials are very rough on the scale of the wavelength of visible light, thus they yield fully developed speckles if illuminated. They are formed by the interference of dephased but coherent wavelets emanating from different microscopic elements.

Constant illumination and observation geometry give a particular subjective speckle pattern which is characteristic for a certain (imaged) surface element and moves in a well defined way when that surface element is displaced. This behaviour permits to determine relative displacement of surface elements of material specimens before and after loading by simply tracking the movement of the speckles associated with it. Usually this tracking is evaluated by different kinds of pattern tracking algorithms. In the present study a digital laser speckle correlation technique (LSC) is used. The resulting displacement vector is derived from the location of the maximum of the digitally calculated two-dimensional cross-correlation estimate [2]. For details see [2, 3]. The optical arrangement to determine strain within a specimen is depicted in Fig. 1. schematically.

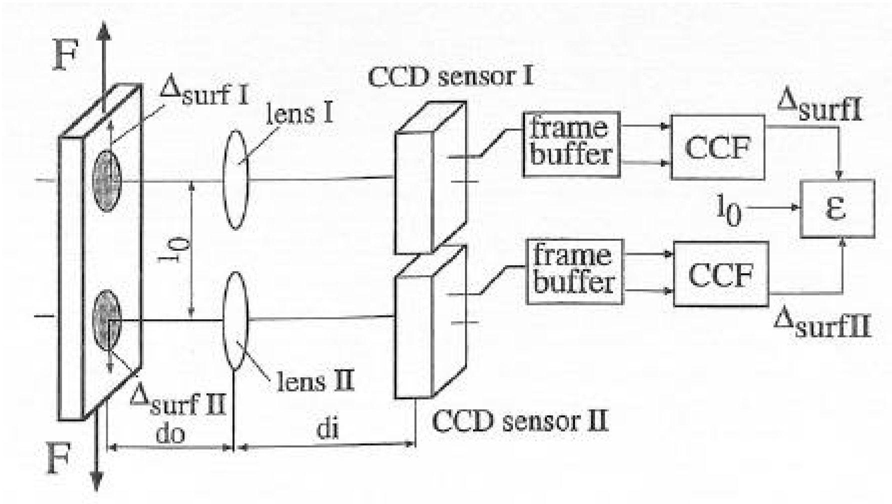

Figure 1. The optical arrangement of the laser speckle correlation system

In order to determine strain ε of the specimen two more or less distant surface elements are tracked. By determining the surface element displacements *Dsurf I* and *Dsurf II*, taking their spatial difference *Dl* and dividing by a selectable baselength l_0 any strain value can be determined as follows:

$$e = \Delta l / l_0 = (\Delta surfI - \Delta surfII) / l_0 \qquad (1)$$

The technical arrangement of the LSC set-up consists of an illuminating system and two displacement recording systems. The illumination is done by two collimated laser diodes with max. power output of 15 mW and a wavelength of 668 nm providing beams of 3 mm in diameter each. The displacement recording is performed by two lenses (separated by the base length l_0) with a selectable focal length and two standard CCD cameras feeding their signals into a PC-based frame grabber, where the signal processing occurs.

For a selected baselength of 20 mm a strain resolution of 2.10^{-5} can be achieved. Since loading of specimens and phase transformation etc. may cause plastic deformation distorsions of the speckle patterns occur resulting in decorrelation. To overcome such effects a repetitive reinitialization of the image acquisition system is performed. Therefore *Dl* is taken as a sum of individual displacement increments. Details are described in [3]. The laser speckle correlation method in combination with a mechanical testing device is suitable to determine the strain of two-dimensional structures such as foils. No surface preparation is required.

3 MATERIAL TESTING APPLICATIONS

As already indicated the LSC method is suitable to determine strain in a non-contacting way of thin elements. Thus to study the influence of the thickness of metallic thin foils on mechanical properties the so called "size effect", the laser speckle correlation technique was applied. As shown in Fig. 2 the testing system consists of a specially designed microtensile testing machine (loading between 10 N – 200 N) in combination with the LSC technique. Special emphasis was placed on on the precise alignment of the foil using a *x-y* die and special designed grips. The very thin foils were glued to the grips. To avoid the effect of detrimental vibrations the entire testing device was mounted on an optical table.

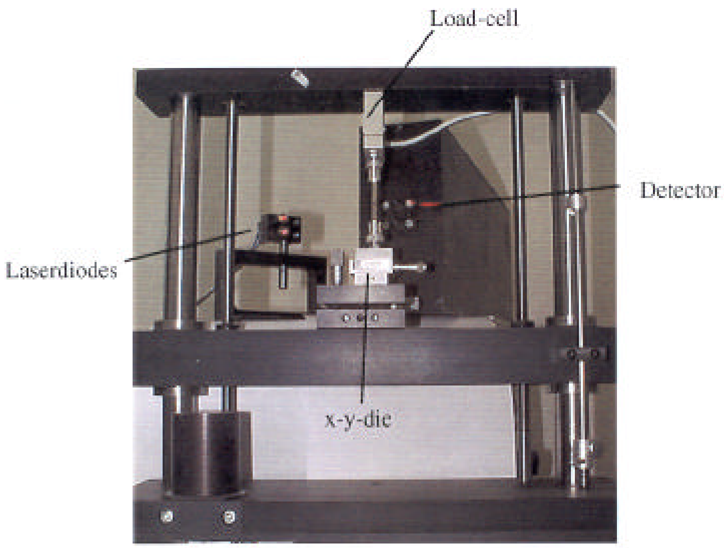

Figure 2. Microtensile testing machine and laser strain sensor

The tensile testing was performed at room temperature with a deformation rate of 2 %/min. The designed data acquisition system allows to obtain stress-strain curves in real time. In this investigation rolled and electrodeposited Cu foils with a nominal purity of 99,95% are presented with thicknesses of 9, 19, 35, 78, 100, 125, 250 µm and 35 µm, 105 µm, respectively. The rolled Cu foils were heat treated in vacuum at a temperature of 973 K for 2 h resulting in grain sizes ranging between 15 µm-35 µm determined from the intercept method (not taking into account twin boundaries). This means a single grain layer for foil thicknesses up to 35 µm, a double grain layer for a thickness of 78 µm and a multiple grain layer exceeding thicknesses of about 100 µm. The electrodeposited Cu foils were tested in the as received condition and exhibited extremely small grain sizes ranging from about 1 µm to 5 µm (see insert in Fig. 5). The size of the tested specimens were 10 mm x 40 mm, the preparation procedure being described in [7]. The rolled Cu specimens exhibit a pronounced cube texture with a twin texture depending on the manufacturing process. For recrystallized rolled Cu foils the stress-strain curves are presented in Fig. 3a and the fracture strain as function of the foil thickness in Fig 3b.
From Fig. 3a a similar hardening behaviour can be observed almost independent of foil thickness. In contrast the fracture strain is strongly dependent on the foil thickness as shown in Fig. 3b, decreasing with decreasing thickness. The fracture strain of a bulk specimen with a thickness of 6 mm indicate a high value of fracture strain of >50%. This size effect may be attributed to the limited number of activated gliding systems in dependence of the ratio of grain size to foil thickness. To support these experimental findings the fracture topography has been investigated as shown in Fig. 4.

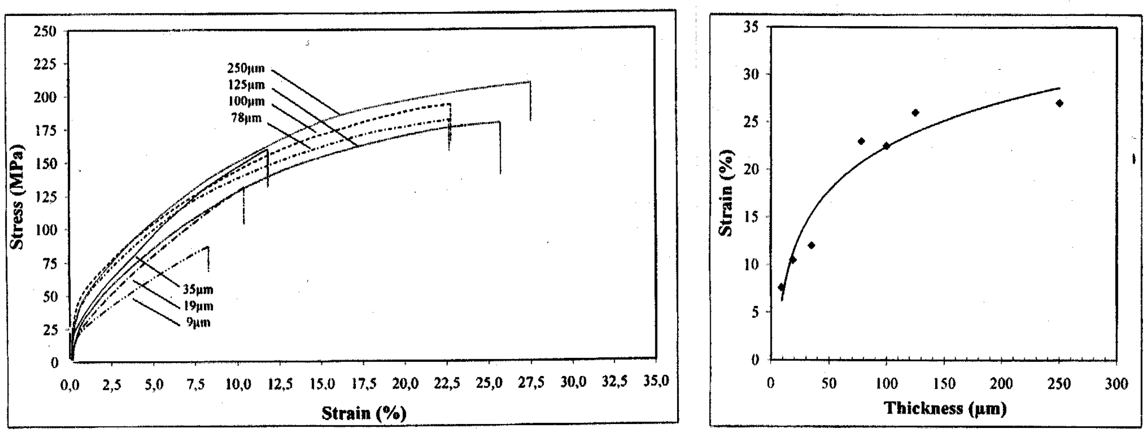

Figure 3. a) Stress-strain curves of Cu foils with varying thicknesses, b) fracture strain in % as function of foil thickness

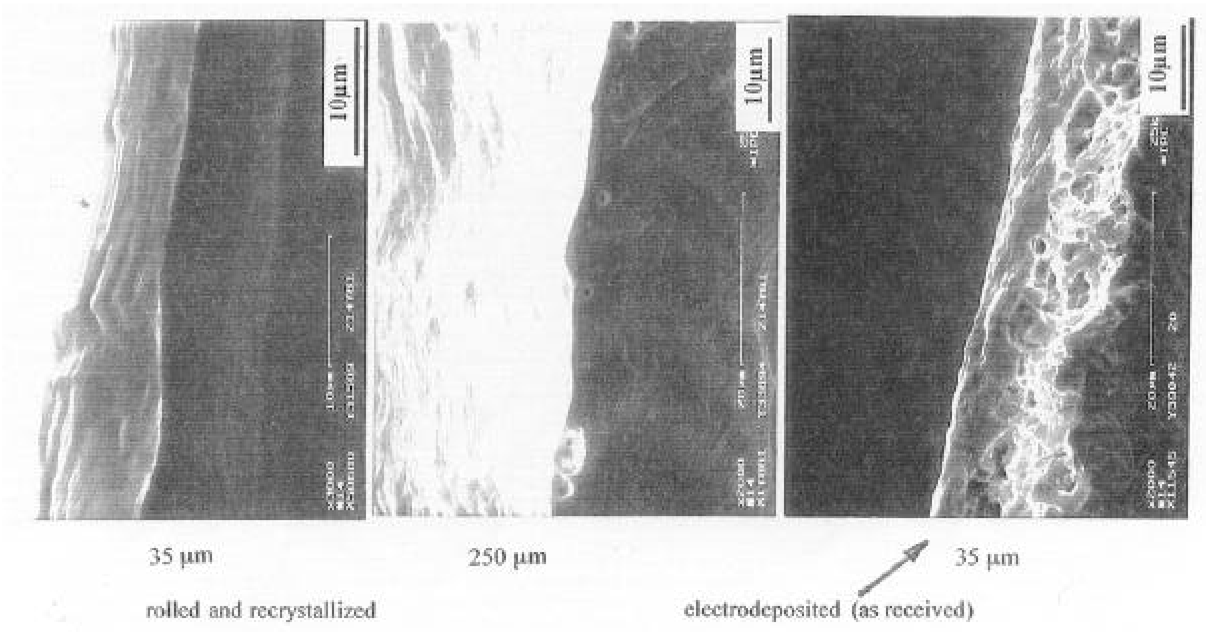

Figure 4. Fracture topography of ruptured Cu foils with various thicknesses; rolled and recrystallized (a, and b) and electrodeposited (c) in the as received condition

For the recrystallized foils two types of fracture topography after rupturing appear. For foils with thicknesses <100 µm ductile failure with typical knife edge rupture without voids and dimples can be observed e.g. as shown for a 35 µm foil in Fig. 4a. With increasing foil thickness dimples and voids can be observed more frequently as shown for the 250 µm foil. These dimples are very small (about 5 µm) (Fig. 4).

Figure 5 exhibits the stress-strain curves for electrodeposited Cu foils indicating a hardening behaviour almost independent of foil thickness possibly due to the high dislocation density being introduced by the special manufacturing process and the extremely fine grain structure (see Fig. 5). The corresponding fracture surfaces show a strong crystallographic appearance as shown in Fig. 4. A detailed explanation of the size effect will be presented in [8].

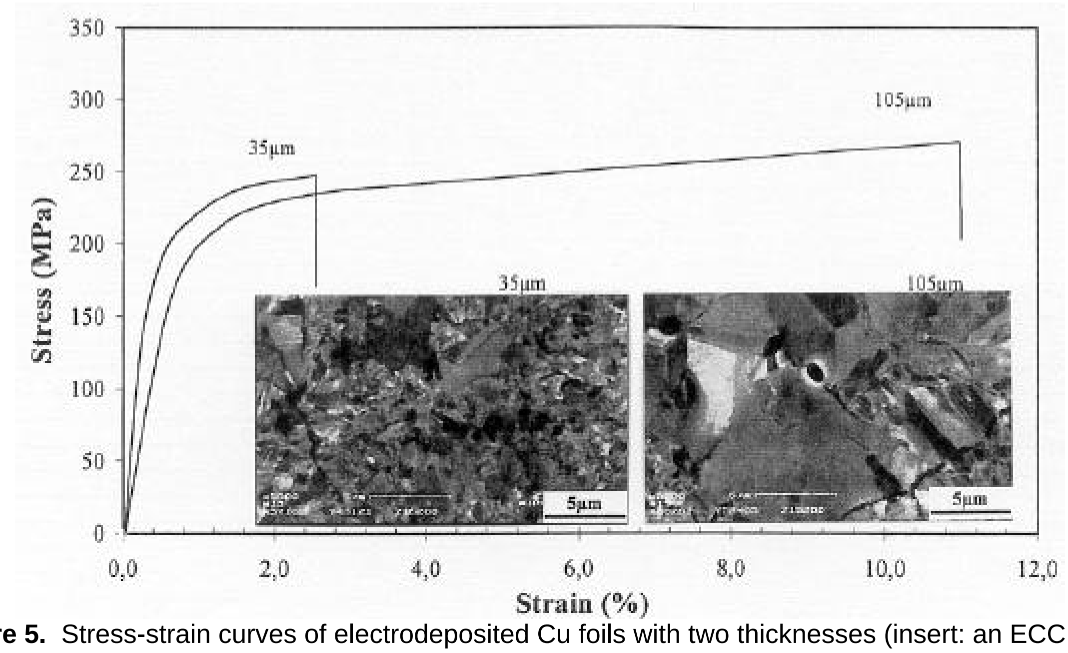

Figure 5. Stress-strain curves of electrodeposited Cu foils with two thicknesses (insert: an ECCI micrograph of electrodeposited Cu foils)

Because of the high strain resolution the laser speckle technique is especially suited for the determination of the Young's E modulus of thin foils, however, great care has to be taken with the alignment and the use of adjustable gripping systems. The values are determined by a loading - unloading technique as shown e.g. for a 35 µm thick electrodeposited foil, see Fig. 6a. A detailed study of the influence of changes in the testing procedure on the value of E is given in [8]. Thus almost parallel lines in a stress-strain diagram can be obtained showing a high degree of strain resolution resulting in Young's modulus values of 98 ± 4 GPa with an error of measurement better than 5 %. From these measurements it may be deduced that the reproducibility is on the order of a few percent. This system was also applied to determine the Young's modulus of a 3,5 µm thick Ni foil (see Fig. 6b). The datapoints resemble repeated tests, the evaluation supports good reproducibility and results in a value of 194 ± 4 GPa.

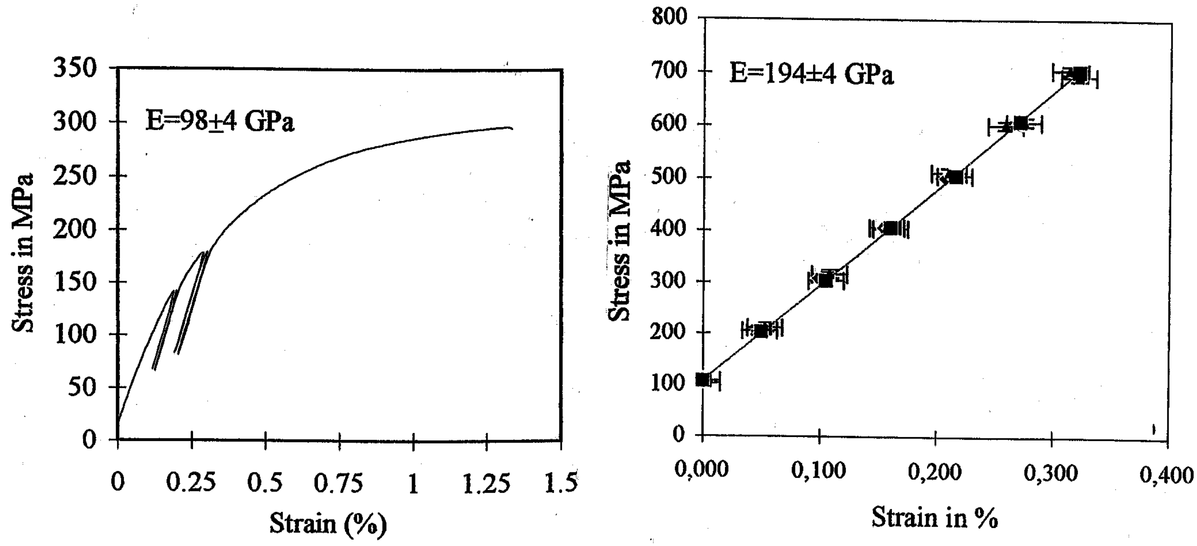

Figure 6. Determination of the Young's modulus E from loading-unloading tests, 6a: stress-strain curve of electrodeposited Cu (t=17 µm), 6b: stress-strain curve of a electrodeposited Ni foil (t=3.5 µm)

4 SUMMARY AND CONCLUSIONS

The laser based non-contacting strain sensor is due to the simple optical arrangement easy adaptable to various testing machines and characterized by high strain resolution on the order of 2.10^{-5}. This system allows to determine the thermal and mechanical response of thin foils and films of most materials, without any special surface preparation. Elastic properties such as Young's modulus - necessary for the characterization of thin foils - have been successfully measured with high accuracy using a special microtensile machine in combination with the LSC-based sensor. Since the base length is at present relatively large, structures with minimum size of at least about 10 mm in one dimension are required. Investigations can be performed over a wide range of testing temperatures corresponding to real test conditions of the microelectronic devices.

A strong size effect could be detected especially concerning the fracture strain of thin metallic foils. This was mainly attributed to the ratio of grain size to foil thickness for values in the order of unity. Similar reasons are responsible for the observed specific fracture behavior. The data obtained from the tension test allows to design microcomponents subjected to complicated stress-strain states.

Using a newly designed test set-up fatigue data of free-standing thin metallic foils under symmetrical loading conditions have been obtained. In comparison to bulk material also a strong size effect was detected, which can be explained with the corresponding stress state.

In addition the ECCI technique is feasible to record the interaction of the microstructure with the crack resulting in a better understanding of material behaviour in order to optimize the properties of the used materials. The fatigue data obtained allow to establish microfracture criteria which are necessary to design reliable microelectronic components This method can also be applied for the study of the fatigue behaviour of multilayered structures.

ACKNOWLEDGEMENT

The authors would like to thank the Austrian Bundesministerium für Wissenschaft und Verkehr (COST-510) and the Austrian Science Foundation (grant P12311-TEC) for their financial support.

REFERENCES

[1] F. Brotzen, *Mechanical testing of thin films*, Int. Materials Rev., 39, pp. 24-45, 1994.
[2] H. Manser, *Laser-Speckle-Korrelationsverfahren zur Verschiebungsmessung bei hohen Probentemperaturen*, Ph.D.-thesis, Graz Univ. of Technology, 1992.
[3] M. Anwander, B. Zagar, B. Weiss, H. Weiss, *Non-contacting strain measurements at high temperatures by digital-laser-speckle technique*, Exp. Mech., in print.
[4] B. Michel, T.Winkler, *Micromat 97*, Conf. Proc. Dt. Verb. für Mat.-forschung, Berlin, 1997.
[5] D. Chen, D. Melisova, B. Weiss, R. Stickler, *The electron channeling contrast technique applied to the characterization of dislocation structures in the vicinity of a fatigue crack*, Fat.and Frac. of Eng. Mat. And Struc, 20, pp. 1551-1561, 1997.
[6] I. Yamaguchi, *A laser speckle strain gauge*, J. Phys.E:Sci.Instr., 14, pp.1270-1273,1981.
[7] C. Dinhobl, M. Klein, M. Anwander, B. Weiss, H.G. Brokmeier, *Die Bestimmung der elastischen und plastischen Eigenschaften dünner Metallfolien mit laseroptischen Methoden*, Band 10, Symp. 13: Werkstoffprüfung, W.J. Muster et al., Wiley-VCH, pp. 247-255, 1999.
[8] A. Hadrboletz, G. Khatibi, B. Weiss*, The size-effect on the fatigue and fracture properties of thin metallic foils*, Proc. EUROMAT, 1999, in print.

AUTHORS: M. ANWANDER, B. WEISS, Institute of Materialphysics, University of Vienna, Austria
C. KARGEL, B. TRUMMER, H. WEISS and B. ZAGAR, Institute of Electrical Measurement and Measurement Signal Processing, Graz University of Technology, A-8010 Graz, Austria