



Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/mr

Fast and trusted intrinsic stress measurement to facilitate improved reliability assessments

D. Vogel ^{*}, E. Auerswald, Gh. Gadhiya, S. Rzepka

Micro Materials Center, Fraunhofer ENAS, Technologie-Campus 3, D-09125 Chemnitz, Germany

ARTICLE INFO

Article history:

Received 5 July 2016

Accepted 11 July 2016

Available online xxxx

Keywords:

Residual stress

Focused ion beam

Digital image correlation

Reliability

ABSTRACT

A new measurement method for mechanical stresses with microscopic and sub-microscopic spatial resolution is presented. It bases on classical stress relief techniques in experimental mechanics, as for example the familiar hole drilling method. Applicability of the classic method for micro and nano size objects was achieved, using very local stress relief caused by ion milling inside commercial FIB equipment and image correlation algorithms for the determination of corresponding relaxation strains. Approximately 10 years ago, first publications demonstrated the principal feasibility of the approach. Now, this work gives a more detailed view on different measurement variations, their capabilities and limitations. The paper reports on the effort made for qualifying the new method for use under real industrial conditions, which includes validation of techniques, best practice based choice of tools and sufficient automation of the measurement process. Finally an application example from 3D integration in electronics demonstrates practical benefit obtained by the method.

© 2016 Elsevier Ltd. All rights reserved.

1. Introduction

Intrinsic stresses in semiconductor and MEMS devices significantly affect functional behaviour and reliability [1]. Trusted knowledge on stress amount and sign is a basic need developing new products. Electronics and MEMS devices often demand an extremely high spatial resolution of stress states. Only a few methods, like X-ray [2–4]/electron diffraction [5] and micro-Raman spectroscopy [6,7] have been established as indirect stress measurement tools. Even finite element simulation reaches its limits to predict reliably mechanical stresses, if systems are rather complex and material laws are insufficiently known. Stress measurement by means of FIB based ion milling and subsequent quantification of stress relief deformation is a new approach, published first, approximately 10 years ago [8–10]. In the meanwhile the method has been utilized and strengthened by several research labs [11–13]. Currently an extensive European program is realized to qualify this method for commercialization and to apply it under industrial conditions [14]. This contribution gives an overview of the measurement method, the current state-of-art for the method qualification, the measurement capabilities and limits considering needs for electronics and MEMS applications. A typical research lab application of 3D integration components like TSVs is demonstrated as well.

2. The FIB-DIC method

2.1. Basics of the stress relief method

Mechanical stresses cannot be measured in a direct way. Either measurable physical properties affected by stress (like e.g. quantised phonon energy in Raman spectra) are used as a sensing vehicle or object deformations are determined and transferred into stresses. Several diffraction-type methods [3–5,15] detecting lattice distortions of crystalline materials have been well established and are being used routinely over decades. Lattice strains can be converted into stresses by using the constitutive material law, in most cases the generalized Hooke's law. Unfortunately, these applications are limited to sufficiently crystalline materials. Moreover computation of stresses becomes rather sophisticated, if the probed diffraction volume comprises stress gradients. Micro and sub-micro scale spatial resolution of stress fields can be expensive and time-consuming. The new method reported in this paper overcomes the obstacle of a required material lattice for strain/stress evaluation.

Another generic stress measurement approach bases on the generation of relaxation strains caused by a local modification of an object with stresses. Removing material, strain-stress distributions are re-arranged. Measured deformations can be transformed into stress, if an appropriate mechanical model of the material relaxation process is implemented, e.g. the well-known Kirsch's solution for the hole-drilling method [16]. At the same time primarily determined relaxation strains can be captured by quite different approaches. In the past, e.g., purely mechanical drilling and strain gage or optical strain measurements have been

^{*} Corresponding author.

E-mail address: dietmar.vogel@enas.fraunhofer.de (D. Vogel).

used. Development of nano science material treatment and characterization initiated a rigorous miniaturization of stress relaxation experiments, first documented in 2003 [8]. Ion milling replaced mechanical milling, Digital Image Correlation (DIC) replaced strain gages. The new approach often is named FIB-DIC method.

Ion milling in standard Focused Ion Beam (FIB) equipment is used to release stresses very locally. Utilizing Digital Image Correlation (DIC) algorithms on high resolution Scanning Electron Microscopy (SEM) micrographs captured before and after milling, the relief deformation field around the milling pattern is computed. Stresses prior to ion milling are found assuming linear elastic material relaxation. Various ion milling patterns have been deployed in the past, in dependence on the strived for stress tensor components, the suitability for measurement automation and the spatial measurement resolution. Two typical and often favoured ion milling features are shown in Fig. 1 with overlaid relaxation displacements. They correspond to the trench method where the relaxation attenuates with increasing distance from the trench line, and to the ring-core geometry which rather results in a homogeneous relaxation strain over the pillar surface. The first approach, e.g., shows advantage if very thin stressed layers are tested, because of the higher relaxation sensitivity at the very trench rim. The second approach exhibits better and simpler automation potentials as it does not demand in general a detailed numerical derivation for the strain-stress relaxation of a particular measurement process.

In the simplest case of mechanically isotropic material with equibiaxial stress, the normal, in-plane stress tensor components σ_{ii} can be determined from the measured relaxation strain $\Delta\epsilon_{ii}$ in a **ring-core or rectangle pillar arrangement** by [17]

$$\sigma_{ii} = -\Delta\epsilon_{ii} \frac{E}{(1-\nu)} = -\Delta\epsilon_{ii} E' (1+\nu) \quad (1)$$

where ν is the Poisson ratio, E and E' are the Young's and the plane-strain moduli, respectively. The plane-strain modulus is derived straightforward, e.g., from nanoindentation. Formula (1) relies on the fact, that strain relief at the pillar surface is complete. This condition is achieved, if the free-standing pillar height approximately is equal or larger than the pillar diameter. In many cases this condition is accessible.

Furthermore, the ring-core method is also easy to use if no complete strain relief can be achieved, e.g. in the case of thin layers where the diameter of the pillar cannot be reduced further. Fig. 2 gives a plot of the normalized strain relief at the pillar surface vs. the normalized milling depth. The normalized milling depth is the aspect ratio of the pillar, i.e. the milling depth divided by the pillar diameter. The normalized strain relief is a property proportional to the DIC measured strain relief and is given in MPa units. For aspect ratios beyond the complete strain relief, the normalized strain relief equals to the original normal in-plane stress prior to ion milling.

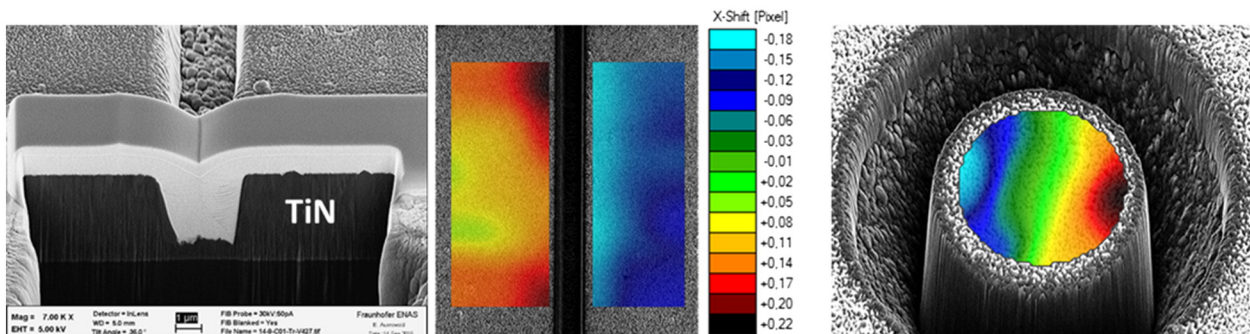


Fig. 1. Ion trench (left/middle) and pillar milling (right) used to cause stress relief. Relaxation displacements (colored isoline plots) are used to compute stresses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

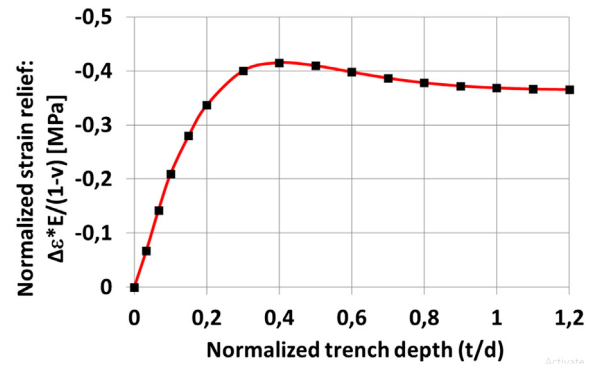


Fig. 2. Computation of strain relief in dependence on the milling depth. t – milling depth, d – pillar diameter, E – Young's modulus, ν – Poisson ratio, $\Delta\epsilon$ – measured strain relief. Assumed residual stress in the graph: 366 MPa.

If no complete strain relief is reached (flat pillars), the curve in Fig. 2 can be used as a master curve for stress calculation from the measured strain relief knowing the aspect ratio of the pillar size. It can be shown, that this curve is independent of the Young's modulus and the Poisson ratio of the investigated material. A strain relief value comparable to complete relief is reached already for relatively flat pillars, e.g. for an aspect ratio of 0.2, as can be seen from the figure.

The **trench milling approach** is more elaborate in comparison to the ring-core method. However, it exhibits several advantages for stress measurement on thin layers below 200 nm thickness. The strain relief reveals a distinctive gradient on both sides of the trench, which depends on elastic material properties and trench cross section geometry. For that reason, no master curve as for the ring-core geometry can be used. For every measurement a Finite Element (FE) simulation for the linear elastic stress relief is carried out in parallel to the DIC treatment. DIC and FE displacement fields are fitted to each other to extract stress values. Fig. 3 illustrates this procedure. The spreading of the DIC data points in Fig. 3 originates from the limited sub-pixel accuracy of DIC analyses.

2.2. Validation approaches of the FIB-DIC method

Different approaches are imaginable to verify the new stress measurement method. Comparison of stress results obtained by independent measurement methods have been utilized as well as evidence from stress states known from defined sample load conditions. The mentioned cross validation to other methods was applied with respect to X-ray diffraction, Raman spectroscopy and classic bow measurements. On the other hand, a well-defined sample loading can be applied by 4-point bending of a homogeneous bar. Stress over the specimen cross section behaves linearly, with zero stress in the neutral mid-plane of the specimen. 4-point bending displacement or loading force

Download English Version:

<https://daneshyari.com/en/article/4971848>

Download Persian Version:

<https://daneshyari.com/article/4971848>

[Daneshyari.com](https://daneshyari.com)