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Stress imaging in structural challenging MEMS with high sensitivity using micro-Raman spectroscopy

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ABSTRACT

The development cycle of microelectromechanical systems (MEMS) includes several numerical simulation and optimization iterations. To verify and calibrate the models with experimental data, the non-destructive measurement and imaging of stress distribution in structural challenging regions with high sensitivity is of great importance. This is possible to achieve using micro-Raman spectroscopy. Due to limitations of commercially available software regarding flexibility and sensitivity, the authors developed an alternative approach which ensures that the quality of spectra is taken into account in the evaluating calculations. In this way a remarkable stress resolution below 20 MPa becomes possible even on structural challenging MEMS devices.

1. Motivation

Topical package developments harboring System-in-a-Package (SiP) concepts have been increasingly successful on the market as they allow a combined optimization of key parameters as functionality, performance and universality at smallest size in 3D and low cost: Different components of different technology can be combined into one package, including *e.g.* Si-based ASICs together with microelectromechanical systems (MEMS), RF, power and passives, starting to pervade a variety of key applications sectors such as automotive, mobile, consumer, medical as well as avionics [1,2]. Still, their employment requires special attention to potential thermo-mechanical reliability concerns brought about by their multi-material, multi-interface and multi-process nature and the absence of widely accepted standards. This calls for upfront design for reliability as a top priority to assure mature products upon market introduction [3]. The need for this has already been widely recognized and is implemented in large companies' design and workflows, including modeling and characterization strategies based on physics-of-failure principles, *i.e.* paradigms putting the failure mechanisms at the center of their R & D and application efforts. Taking into account the trends in complexity (SiP) and miniaturization, the involved modeling and failure analytical techniques need to feature necessarily high spatial resolution as well as accuracy to be able to validate numerical models and to account for variations, decalibration, aging or failure due to processing flaws, material variations, thermo-mechanical loads during processing, testing and field operation. This is especially necessary when MEMS are concerned, as the complex chip-package interaction may severely impact the functionality and reliability of the sensor or actuator in question due to the delicate mechanical structures and possible parasitic effects emerging from thermo-mechanical stress and strain. Before this background it is vital to be able to assess these effects on the MEMS device by a precise and preferably easy-to-use analytical technique during different stages of the packaging process and application. This is exemplified in the following by a high-precision piezoresistive force sensor (MEMS-device) by Raman-spectroscopy as a non-destructive, highly local and accurate experimental method to characterize stresses which may come about during processing or operation.

2. Introduction

The development of microelectromechanical systems requires reliable testing methods giving access to the stress distribution with high sensitivity, which can be applied to a working device. While stress measurements are possible by a variety of techniques such as Fourier transform infrared spectroscopy (FTIR), low energy electron diffraction (LEED), X-ray diffraction, and Raman spectroscopy [4,5], only the latter requires virtually no sample preparation, is applicable to any optically

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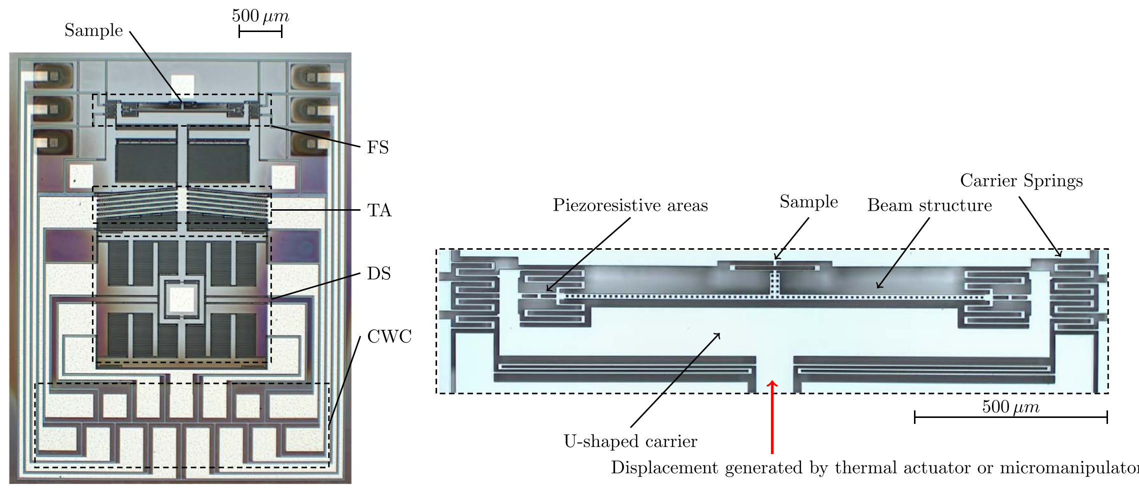

Fig. 1. Left: MEMS tensile testing platform with piezoresistive force sensor (FS), thermal actuator (TA), capacitive displacement sensor (DS), and the contact areas for a multi-contact wedge card (CWC). Right: The piezoresistive MEMS force sensor in an overview depicting the layout of the main components [images by optical microscope].

accessible sample and a variety of materials [6–12], and offers micro-scale spatial resolution [13,14].

When applied to silicon-based MEMS, one would convert stress-induced Raman peak shifts $\Delta\omega$ to stress σ_b by multiplying it by a proportionality coefficient. In the special case of uniaxial stress the stress is given by

$$\sigma_b\,[\text{MPa}] = -434\cdot\Delta\omega\,[\text{cm}^{-1}]. \tag{1}$$

The scaling factor -434 is an empirical value. In addition to the value selected, -518 was published as well [6,8,15]. We are going to use Eq. (1) for the stress calculation as suggested by previous works such as ref. [16]. Thus, for silicon-based MEMS, Raman spectroscopy with a highly sensitive instrument allows the detection of peak shifts down to 0.02 cm^{-1}, which corresponds to a stress level of 10 MPa mentioned in refs. [17,18]. Therefore, the mentioned limit is a limitation dependent on the state-of-the-art instrumentation of Raman spectroscopy.

However, when aiming to obtain information about the spatial distribution of stress in a working MEMS device, several other considerations become important:

- A MEMS is a spatially inhomogeneous structure, where obtaining a proper stress-free reference requires an excellent spatial correlation between the reference and the loaded structures.
- Obtaining a high spatial resolution requires the acquisition of multiple spectra at different locations, limiting the achievable signal to noise ratio due to long acquisition times and thermal drifts, and thus affecting strain sensitivity.
- Finally, the Raman characterization of a MEMS implies the use of laser illumination, which tends to heat up the sample, resulting in shifted Raman peaks. This shift is different depending on the size of the investigated structure since it depends on the heat dissipation.

Therefore, compromises between spatial resolution and strain sensitivity must be made which limit the application of Raman hyperspectral imaging in the investigation of microdevices. In order to tackle this limitation, here we propose an approach for the spatially-resolved Raman characterization of stress distribution of a working microstructure achieving a stress sensitivity of 18.5–19.2 MPa close to the limit mentioned in ref. [17] using a force sensor of a MEMS tensile testing device as a model system. This system is studied in two distinct states, labeled as loaded and unloaded state. The latter one is acting as reference state. Therefore we are only studying the influence of the applied load on the sensor.

Our method is based on the batch analysis of thousands of individual Raman spectra with a refined algorithm that selects only those spectra that fulfill certain quality criteria. The results of this method are benchmarked against numerical simulations showing a remarkably good agreement and high accuracy for the method developed in this work.

In contrast to earlier published results and applications of micro-Raman spectroscopy to MEMS as refs. [17,19-23], to name only some, the method described here allows for a batch analysis of spectra, therefore mitigates the need of the manual selection of regions of interest, and automatically drops spectra with low quality, originating *e.g.* from holes in the structure, which otherwise might falsify the results.

3. Characteristics of the MEMS model system

The MEMS testing platform analyzed here consists of a thermal actuator (TA [24]), a capacitive displacement sensor (DS), and a piezoresistive force sensor (FS), fabricated using Bonding and Deep Reactive Ion Etching (BDRIE, [25]) processed multilayer SOI wafers. The loading stage with all of its components, labeled building blocks, is depicted on Fig. 1 (left). Each reticle holds four testing platforms with different sample types and additionally each building block by its own. This allows for the characterization of the building blocks without influences by other components.

All experiments were performed on the piezoresistive force sensor. The MEMS force sensor is layouted as a bending beam with piezoresistive areas embedded to it. The beam itself is mounted inside a U-shaped carrier structure, as depicted in Fig. 1 (right). A number of springs are used to connect the carrier to the surrounding providing support and electrical contact as well. The size of the MEMS force sensor is given by $1672 \times 280\ \mu\text{m}^2$, while each of the piezoresistive areas only measures $106 \times 5\ \mu\text{m}^2$.

The functional principle can be describes as follows: As in the case of a macroscopic testing device, the force sensor is mounted between sample and actuator. While active, the actuator in addition with the resistance of the sample generates stress inside the piezoresistive areas as the bending beam structure is bent. All four piezoresistive elements are used to form a Wheatstone bridge circuit [26,27] to translate the stress into an electrical signal. Typically the displacement is generated by the thermal actuator of the MEMS testing platform. For testing reasons and to ensure longtime stability and reproducibility, external mechanical stimulation can be used on the single MEMS force sensor as well. In such a case a micromanipulator can displace the sensor.

The piezoresistive force sensor is the result of a numerical modeling and optimization process. Therefore, the experimental results provide calibration and verification data not only of the sensor but of the