A System for Electro-Mechanical Reliability Testing of MEMS Devices

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Abstract

This paper reports on a setup and a method that enables automated analysis of mechanical stress impact on microelectromechanical systems (MEMS). In this setup both electrical and optical inspection are available. Reliability testing is possible on a single chip as well as on the wafer level. Mechanical stress is applied to the tested structure with programmable static forces up to 3.6 N and dynamic loads at frequencies up to 20 Hz. The applications of the presented system include the postmanufacturing test, characterization and stress screens as well as reliability studies. We report preliminary results of long-term reliability testing obtained for a CMOS-based stress sensor.

Introduction

Microelectromechanical systems are employed in safety-critical fields such as automotive, aerospace and medical applications. Therefore, their reliability is receiving growing attention. This includes both ensuring the correct functioning of a MEMS just after it has been fabricated, i.e. the manufacturing test and studying the possible deterioration of the device in its application. The latter issue is of special importance, as MEMS applications often intrinsically involve mechanical stress which could damage or destroy microstructures [1].

The manufacturing test focuses on deciding whether a device is ‘good’, i.e. can be shipped to the customer, or ‘bad’. In high-volume manufacturing, electrical testing methods are more attractive than optical or chemical techniques, as the former result in high throughput and consequently low costs. Moreover, available automatic test equipment for integrated circuits (ICs) can be leveraged [2]. The characterization of a device serves the purpose of obtaining a better understanding of its physical behavior. Available techniques range from structural methods (optical, micro-Raman, scanning electron and transmission electron microscopy) to chemical analysis (X-ray, Auger and secondary ion mass spectroscopy) and special electrical approaches (thermally-induced voltage alteration, resistive contrast imaging) [3]. Although these methods provide detailed information on the behavior of both fault-free and faulty devices, they are associated with significant cost and are not applicable to volume manufacturing. The reliability studies examine the device’s ability to retain the desired functionality in possibly harsh environments.

In this paper, we propose a system for the fully automated wafer-level testing of mechanical stress impact on the functionality of MEMS. The mechanical stress is induced by an impact object that exerts a force on the surface of the device under test (DUT). The applied force level, force duration, frequency of dynamic force loads and the location at which the force is applied are user-defined and can be precisely controlled. The system can step over a 6-inch wafer without operator interaction and hence is well suited for long-term stress test runs. The electrical and optical inspection of device behavior before, during, and after the application of mechanical stress to the DUT is available.
Experimental Setup

The mechanical part of the measurement system is schematically shown in Figure 1. It consists of a positioning stage used for wafer stepping, a frame and a mechanical impact control unit attached to the frame (see Figure 2). The positioning stage consists of two linear stages (OWIS LIMES 120) for moving the wafer in the $x$ and $y$ directions, a linear stage (OWIS HVM 60) for positioning in the $z$ (vertical) direction, and a rotation stage (PI M-036) for further alignment. A vacuum chuck to fix the wafers is mounted to the rotation stage. The mechanical impact control unit shown in Figure 3 comprises (i) a fixture for the impact object controlled by a closed-loop $xyz$ nanopositioning system (PI P-611.3S NanoCube), (ii) a force sensor (ME-Messsysteme KD40S5N) for surface detection and calibration, and (iii) a manual $xyz$ stage for coarse positioning of the NanoCube and the impact object with respect to a probecard. This probecard (HTT GmbH, Dresden) is used to electrically contact the DUT and is integrated into the mechanical impact control unit. Note that for the application of mechanical stress, the impact object, e.g., a needle-like probe, is moved by the NanoCube, whereas the probecard position is fixed relative to the mounting frame. This is achieved by a hole in the probecard through which the impact object is translated towards the DUT, as shown in the inset of Figure 1. A microscope can be attached to the system for optical inspection.

In the mechanical stress experiment, the impact object is repeatedly pressed by the NanoCube against predefined positions on the wafer, which is fixed on the vacuum chuck. The stepping of the wafer underneath the probecard is performed by the positioning stage. The mechanical impact control unit is not moved in the $xy$ plane during the experiments. A micrograph taken during an experiment is
forces up to 5 mN; however it can be easily replaced by a different sensor

The NanoCube in combination with the force sensor can apply in case higher force values or better accuracy are necessary.

The NanoCube and the force sensor are controlled via a RS232 serial interface.

The parameter analyzer and the position stage are controlled over the GPIB bus using a LabVIEW program developed for this purpose. The DUT is connected to the parameter analyzer using a probecard. An experiment is preceded by the following initialization steps: (i) the position stage is calibrated by moving the linear stages and the rotation stage to their zero position, (ii) the wafer is moved in the $xy$ plane such that the first DUT is underneath the impact object, (iii) the NanoCube is manually positioned close to the wafer surface, and (iv) the automatic surface detection procedure runs for fine calibration of the NanoCube in the $z$ direction. The automatic surface detection procedure moves the impact object in 1 $\mu$m steps towards the wafer surface until the force measured by the force sensor increases significantly, i.e. the impact object touches the wafer. The movement of the impact object is continued until the predefined force level is achieved. The respective vertical positions of the contact point and for the desired force value are memorized.

During the experiment, the wafer is placed on the vacuum chuck, which is part of the position stage. The linear stage for the $z$ direction brings the chuck into two positions: up and down. In the upper position, the DUT on the wafer is contacted by the needles of the probecard and electrical measurements can be performed. In the lower position, the wafer can be moved in the $xy$ plane by the position stage without damaging the DUT or other structures on the wafer by the probecard contacts. Mechanical stress is only applied to the DUT in the upper position.

The mechanical stress experiment itself is performed by moving the vacuum chuck to the upper position, applying the mechanical stress and simultaneously performing electrical and/or optical inspection. Duration, frequency and absolute level of mechanical stress can be chosen freely, limited only by the parameters of the NanoCube and the force sensor used in the automatic surface detection procedure. The employed force sensor has a range of up to 5 N with a resolution of 5 mN; however it can be easily replaced by a different sensor in case higher force values or better accuracy are necessary. The NanoCube in combination with the force sensor can apply forces up to $F_{\text{max,eff}} = (3.61 \pm 0.02) \text{ N}$ at a frequency of up to 20 Hz. In principle, forces up to 30 N would be accessible by the NanoCube. However, due the low stiffness of the force sensor and a maximum travel range of the NanoCube of $\Delta L_0 = 100 \mu$m this value is reduced by almost one order of magnitude. As the stiffness of the other sub-assemblies is higher than that of the force sensor, their effect on the maximum force value can be neglected. The options for electrical measurements are determined by the capabilities of the parameter analyzer, but it is also possible to use any gauges for electrical measurement, which fits the needs of the actual investigation of the DUT.

Once the measurement is finished for one DUT, the chuck is moved to the lower position and the position stage places the wafer so that the next die lies underneath the probecard. Next, the electrical measurement is repeated for this DUT, and so on. The system makes possible for the full wafer characterization of 6-inch wafers. The positioning stages LIMES 120 have an accuracy of 2 $\mu$m and a travel path length of 200 mm. Consequently, no re-positioning in $xy$ plane is required during the experiment. However, a recalibration in the $z$ direction is done by repeating the wafer surface detection procedure. Also the parameter analyzer is automatically recalibrated after a certain time interval. Nevertheless, none of the recalibration procedures involve any manual activity, so that the experiment, once started, is fully automatic. The whole experiment is controlled by a program developed using LabVIEW, an integrated development environment by National Instruments. All parts of the experimental setup, i.e. the parameter analyzer, the NanoCube, the linear stages, and the force sensor, are remotely controlled over GPIB and RS232 buses. The schematic view of the software control is shown in Figure 5.

**Dynamic Force Application**

The complete measurement setup has a complex mechanical behavior. If the NanoCube applies a force to the DUT some components of the setup will be squeezed while others will be stretched. This takes time till all components have reached a static deformation. The overall behavior can be approximately described by the differential equation

$$Tx_a + x_a = K_p (x_c + T_c x_e),$$

where $K_p$ is the force feedback control gain, $x_a$ is the actual displacement of the force sensor, $x_c$ is the commanded displacement, $T_c$ is the current time, and $x_e$ is the environmental disturbance.
where \( T, K_p, x_e, \) and \( T_v \) denote the time constant of the exponential decay of the output force function \( x_o \), a proportionality factor, the input force function, and a second time constant. The ratio between \( T \) and \( T_v \) describe to height of overshoot at the beginning of the output force function if a \( x_e \) is a jump function. Figure 6 shows a respective response measured at a force jump of \( 1 \text{ N} \) at \( t = 0 \text{ s} \).

This behavior of the measurement system is unproblematic during static measurements. An adjustment control can be used to control the applied force in such a way that \( 0.2 \text{ s} \) after a force step the measured force is the targeted force within the accuracy of the force sensor. The adjustment control works as follows. First the NanoCube is programmed to move to a position \( p \). Second the force sensor delivers the actual force applied to the DUT and sends this value to the computer that calculates the deviation between the target force and the applied force and sends a corrected position \( p' \) to the NanoCube.

For dynamic measurements it was not possible to implement the adjustment control due to the slow communication speed between the three invoked components of the measurement setup: (i) NanoCube, (ii) force sensor, and (iii) computer. One cycle has a duration of \( 20 \text{ ms} \). To get around this drawback, a control system was implemented which learns the positions of the NanoCube that are needed to apply the desired force function to the DUT within the accuracy of the force sensor. The algorithm works as follows. First the computer sends an array of predicted positions to the NanoCube. The NanoCube moves in a given time step width to each given position in the array. During the movement of the NanoCube the force sensor measures the applied forces and sends an array with the force evaluation to computer. These measured forces are then used to determine a corrected position array. The new position array then is sent to the NanoCube that uses the new positions. This procedure is iterated until a convergence to the desired force function is achieved. The performed measurements show that after five learning cycles the applied force function differs from the desired force function by less than the accuracy of the force sensor. Figure 7 shows the deviation between the desired square function with jumps from \( 0 \text{ N} \) to \( 1 \text{ N} \) at \( 0 \text{ s} \) and back to \( 0 \text{ N} \) at \( 5 \text{ s} \). After five learning cycles the deviation is given by the accuracy of the force sensor, i.e. \( 5 \text{ mN} \). The deviation at the jump positions is larger than the force sensor accuracy, due to the rise and fall time constant of the NanoCube.

### Experimental Results

#### Device Under Test

The device tested in this study is a CMOS-based stress sensor similar to those presented in [4, 5]. It was fabricated using the 0.6 \( \mu \text{m} \) triple metal, double poly CMOS process CX by X-FAB AG (Erfurt, Germany). The stress sensitivity of the sensor is based on the shear piezoresistance effect, also termed the pseudo-Hall effect in silicon. The sensor has four terminals, two of which serve as inputs and two serve as outputs as shown in Figure 8. The sensor is biased with an input current \( I_{in} \). Upon application of a mechanical shear stress \( \sigma_{xy} \) the stress sensitive the pseudo-Hall voltage \( V_{pH} \) is measured. It is defined as

\[
V_{pH} = \pi_{44} \sigma_{xy} V_{in} \tag{4}
\]

where \( \pi_{44}, \sigma_{xy}, \) and \( V_{in} \) are the piezoresistance sensitivity coefficient, the shear stress, and the biasing voltage, respectively. Figure 8 illustrates the direction of \( I_{in}, V_{pH} \) and \( \sigma_{xy} \) in case of a square stress sensor with four point contacts. The size of the active area of the sensor is approximately \( 13 \mu\text{m} \times 13 \mu\text{m} \). The sensor is a n-channel field effect transistor. Its sides are aligned along the \( <110> \) crystal direction parallel to the flat of the wafer flat.

#### Measurements

We applied a series of 600 stress cycles to a DUT. Each stress cycle was composed of a period of \( 2 \text{ s} \) in which a force of \( 1.3 \text{ N} \) was applied to a location \( 250 \mu \text{m} \) away from the sensor. This was followed by another \( 1.7 \text{ s} \) in with zero force. A spring contact probe (Feinmetall F58510S063L130) with head and sleeve fixed using solder in order to eliminate any suspension effects was used as the impact object. The electrical response \( V_{pH} \) of the device to mechanical stress
during one stress cycle, is shown in Figure 9. The force is applied between 1.0 s and 3.0 s. It can be seen that the sensor responds to mechanical stress by a change of $V_{pH}$ of around 0.8 mV. We define $\Delta V_{pH}$ as the difference between $V_{pH}$ at 0 s and its value at 2.0 s.

In order to characterize the degradation of the sensor due to cyclic stress, $\Delta V_{pH}$ was measured for the first 600 stress cycles. The results are shown in Figure 10. The values remain roughly at the same level, suggesting that there is no deterioration in the first 600 cycles. This is likely due to the short overall duration of this measurement run of approximately 40 minutes. Further experiments are currently being conducted, using different forces, frequencies, application positions and impact object materials and shapes. The measurement setup also has proven its capability by other measurements. As an example, the measurement setup was used to determine the force versus $V_{pH}$ characteristic of the stress sensor for a given position of the force application [6].

The measurement makes use of the accurate force measurement of the system. The measurement system was used also to determine mechanical parameters of a 3D silicon force sensor [7]. In particular, the system was used to examine the long term reliability of the 3D force sensor. In these measurements the sensor was exposed 50,000 load cycles with a target force of 500 mN [8]. The average applied force was 503.52 mN with a standard deviation of 0.32 mN.

Conclusions

We implemented a modular test system for wafer-level electrical inspection of MEMS under mechanical stress. Test parameters such as force level, frequency and location are programmable, and the impact object can easily be changed. Wafers up to 6 inches in diameter can be stepped through the system automatically. Consequently, the system is suited for characterization and accelerated stress screens for different types of MEMS. Although our preliminary data collected for a CMOS-based stress sensor indicates no deterioration during 600 stress cycles, we are gathering more data using different mechanical stress parameters and other impact objects.

While studying and improving the reliability of the device under test is an important application of the equipment, our long-term goal is to enhance our understanding of defect mechanisms in MEMS. Of particular interest is the applicability of structural test methods based on fault models to MEMS testing as suggested in [9]. A further field of investigations is the quantitative analysis of the influence of built-in self test and self repair structures on MEMS reliability [10].

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References


