Non-contact biaxial nanoprobe utilized for surface measurements of MEMS

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ABSTRACT

In this work an oscillating biaxial nanoprobe is presented that measures the surface profile of macroscopic objects with 100 nm accuracy. The biaxial nanoprobe oscillates in two directions to realize scanning measurements and to overcome the challenges of sticking. Two electrostatic actuators drive the nanoprobe, and two electrostatic sensors measure the position of the probe. If the touching element of the biaxial nanoprobe reaches the vicinity of the measurement object (≤ 1 µm) the oscillations are damped due to squeeze film damping between the measurement object and the spherical touching element. A contact model for the oscillating nanoprobe is presented. Therewith, the influences of the measurement environment on the behaviour of the nanoprobe will be discussed.

Keywords: biaxial nanoprobe, non-contact, electrostatic actuator, silicon micromachining, oscillating

1 INTROCUCTION

Surface measurement of MEMS is a crucial task to evaluate their fabrication process and functionality. Despite some limiting drawbacks atomic force microscopy (AFM) [1] and optical sensors [2] are utilized to precisely scan a topography. AFM enables high accuracy measurements but is not suitable for high aspect ratios and large measurement areas because of the slow measurement speed. In contrast, optical focus sensors enable high measurement speeds of low 3D measurement accuracies. Hence, a measurement system is demanded which enables high speed measurements at higher 3D measurement accuracy than focus sensors.

In this work an oscillating biaxial nanoprobe (Figure 1) is presented which measures the surface of a measurement object. Plugged in the nanopositioning and nanomeasurement machine [3] the nanoprobe enables high speed measurements with nanometre accuracy.

The innovative properties of the biaxial nanoprobe in comparison with other vibrating tactile probing systems [4-6] are the fully-integrated design based on a single silicon-on-insulator substrate (no glued connection between stylus and passive suspension), the independent resonant oscillation in two perpendicular axes to avoid sticking and the negligible contact forces caused by non-contact measurement regime.

The biaxial nanoprobe is actuated in two directions to realize non-contact scanning measurements which reliably avoid sticking [7-8]. Sticking is caused by thin water films on the surfaces of the measurement object and the tip ball which entail capillary forces in case of a hard contact. The capillary force between ball plane interfaces generally increase with a decreasing diameter of the touching element [7-8]. If the diameter and the spring stiffness are small ($d < 200$ µm, $c < 50$ N/m), false triggering and snap back occurs. This leads to measurement faults and slow measurement speeds because the system oscillates after release from the measurement object [9].

The aim of this work is the presentation of a contact model for the oscillating nanoprobe and its validation by measurements.

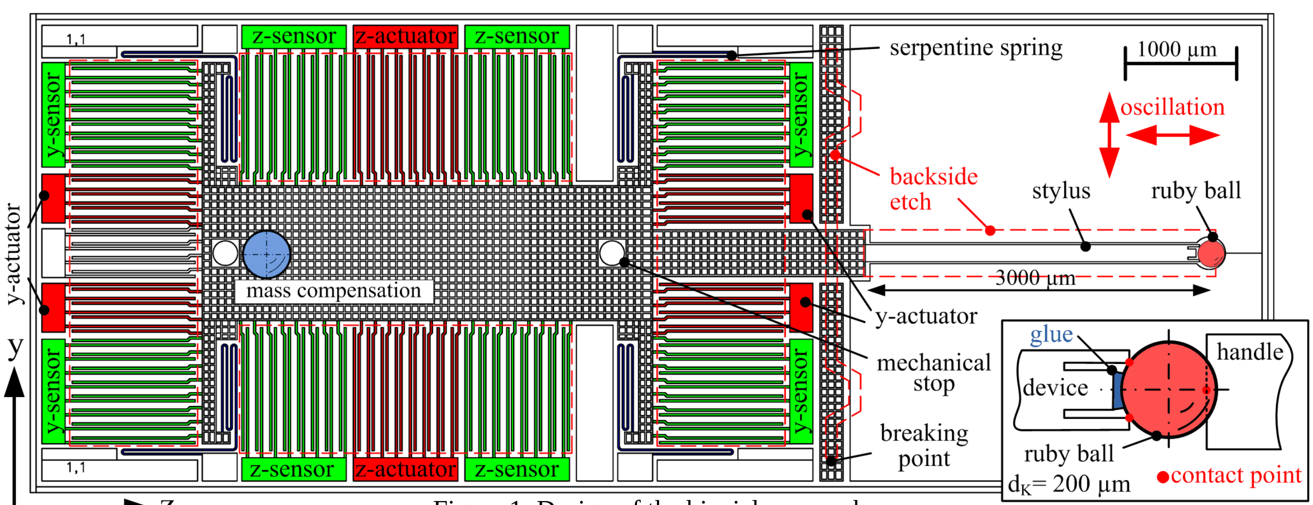

Figure 1: Design of the biaxial nanoprobe

2 DESIGN OF THE BIAXIAL NANO-PROBE

The biaxial nanoprobe comprises the typical elements of a probing system: stylus, tip ball, sensors and passive suspension (cf. Figure 1). The perpendicularly arranged electrostatic sensors measure the z- and y-position of the tip ball. Differential sensors increase the output voltage and enable the independent evaluation of the ball position (cf. Figure 2).

Electrostatic actuators for each direction are additionally integrated into the SOI-substrate. These actuators allow driving the nanoprobe in resonant motion and to measure in a non-contact or semi-contact mode. Serpentine springs are utilized to ensure a passive suspension with a low material volume and varying stiffness in z- and y-direction, respectively. The latter is important to obtain different resonance frequencies and independent motion.

More design characteristics are briefly described afterwards:

- the backside of the electrodes is released to minimize squeeze film damping,
- the centre of gravity of the nanoprobe is moved to the geometrical midpoint by the compensation mass,
- the step in the electrode design enables a nearly independent motion of the z- and y-actuator,
- the stylus is released by defined breaking points,
- a ruby ball is attached utilizing an epoxy glue.

Important fabrication steps are the evaporation and structuring of aluminium and the dry etching process (DRIE) on the top and the bottom of the substrate, respectively. [10]

3 TOUCHING REGIME

The biaxial nanoprobe is operated at semi-contact or non-contact mode utilizing two oscillations in z- and y-direction. If the nanoprobe oscillates near a measurement object the oscillation in z-direction is damped or the probe rotates around the rotation point D (cf. Figure 2). [10]

The contact behaviour between the probe tip and the specimen depends on the contact conditions and the spring stiffness in the relevant direction (z- or φ-direction). Hence, two effects can be considered to describe the contact behaviour: The contact damping and the contact stiffness.

If the contact stiffness is the main effect the probe is operated at a semi-contact mode and touches the surface of the measurement object. Nevertheless, the contact time is very short and the contact force low [4]. Mathematically, the contact stiffness is described by Equation 1 [11].

$$c_{\text{contact}} = \frac{3}{2}(16/9\ R_{\text{tip-ball}}\ E^{*2}\ F_{\text{contact}})^{\frac{1}{3}} \tag{1}$$

The second relevant effect for the contact behaviour is contact damping. Here the probe tip does not touch the measurement surface because of sufficiently large squeeze film damping between probe tip and surfaces. Low suspension stiffness, smooth surface and low actuation force are the crucial requirements for a non-contact measurement regime. Equations to calculate the damping force are given in [12].

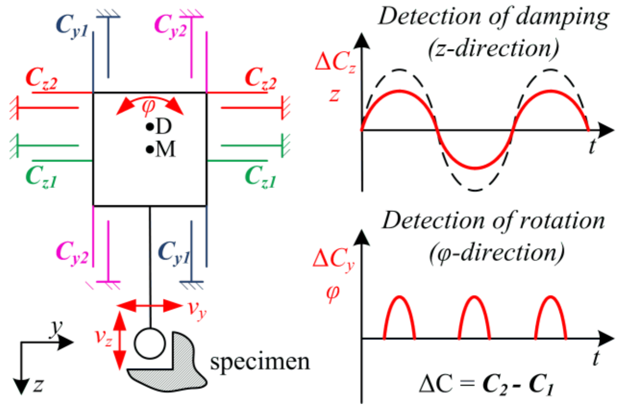

Figure 2: Touching regime of the biaxial nanoprobe and evaluation principle of the sensor capacities

4 PARAMETERS OF THE BIAXIAL NANOPROBE

The dimensioning of the biaxial nanoprobe is described in [10]. Important parameters are listed in Table 1. Assumed ambient conditions are air at normal pressure of 1013 hPa and a temperature of 20°C.

Table 1: Parameters of the biaxial nanoprobe

	z-direction	**y-direction**	**φ-direction**
capacitance *C*	0,603 pF	0,603 pF	0,603 pF
damping factor *k*	$2{,}3\cdot10^{-5}$ kg·m	$2{,}4\cdot10^{-5}$ kg·m	-
mass *m*, inertia *J*	$1{,}21\cdot10^{-6}$ kg	$1{,}21\cdot10^{-6}$ kg	$1{,}45\cdot10^{-12}$ Nm
stiffness *c*	33,76 N/m	41,11 N/m	2,2 N·mm/rad
actuator voltage U_0	15 V	15 V	-
frequency f_R	821 Hz	906 Hz	1310 Hz
offset x_0	86 nm	71 nm	-
amplitude x	4,81 µm	4,35 µm	-

The spring stiffness in z- and y-direction has to be different to realize different resonance frequencies and thus an independent motion. Besides the z- and y-direction the rotation φ has to be considered because the resonance frequency of the rotation is also important for the probe behaviour. Preferably, $f_{R\varphi}$ is higher than f_{Ry} so that the tip ball can follow the impact of the measurement object in y-direction.

The calculated damping factors consider the squeeze film damping between the electrodes and the slide film damping between the handle and device layer. These are the dominating damping forces for the biaxial nanoprobe [10].

The actuators of the biaxial nanoprobe are driven with a voltage $U_1 = U_0 + U_0 \sin(\omega t)$. A reduced bandwidth and a smaller offset x_0 are the advantages of a driving voltage with predefined offset. The second resonance peak is the price to pay for this voltage supply. [10]

5 CHARACTERIZATION OF THE BIAXIAL NANOPROBE

The characterization of the biaxial nanoprobe is carried out with an electronics which charges and discharges the sensor capacities and evaluates the difference between the sensor voltages, [13]. Besides the evaluation board a characterization utilizing the high speed camera VW-9000 (*Keyence GmbH)* was performed. Therewith, a comparison between the movement analysis of the camera software and the output voltage of the evaluation board is possible.

The piezo actuators which simulate the contact and the biaxial nanoprobe are shown in Figure 3. For first measurements the ruby ball is replaced by a silicon cylinder.

5.1 Frequency-amplitude characteristic

The measured frequency-amplitude characteristics of the biaxial nanoprobe are shown in Figure 4. The driving voltage was $U_\mathrm{i} = 15\mathrm{V} + 15\mathrm{V}\sin(2\pi f_i\, t)$. The measured resonance frequencies and oscillation amplitudes agree with the calculated ones and sufficiently differ from each other so that an independent motion of the two axes is realized. The lower maximum amplitude in y–direction is caused by the higher spring stiffness (cf. Figure 4).

Both resonance curves exhibit a resonance peak at half of the resonance frequency which is caused by a second overtone within the spectrum of the chosen driving voltage. Nevertheless, the primary peaks do not influence the nanoprobe behaviour because the quality factors of the oscillations are high.

5.2 Dynamic impact in z-direction

The interaction between a measurement object and the tip ball is simulated with the closed-loop piezo actuator P-641.B (*Physic Instruments*) which moves into the nanoprobe oscillation. The actuator is driven at a sine oscillation at 400 mHz and an amplitude of 18 µm.

The output signal $U_{z\,out}$ of the sensors during an impact of the piezo actuator into the z-oscillation is shown in Figure 5. During the impact the probe was also driven in y-direction, but a significant change in the voltage $U_{y\,out}$ was not observed. Thus, the motions in y- and z-direction are independent from each other.

For conclusions referring to the contact behaviour or the measurement accuracy the minima of the nanoprobe oscillation and the phase shift were investigated (Figure 6).

The overlay of the piezo signal to the unfiltererd output voltage of the nanoprobe shows that the oscillation minima map the impact of the piezo actuator very well. The comparison of the minima and the piezo movement results in a coincidence of 200 nm. However, a filtered signal will improve the measurement accuracy with the drawback of a slower dynamic.

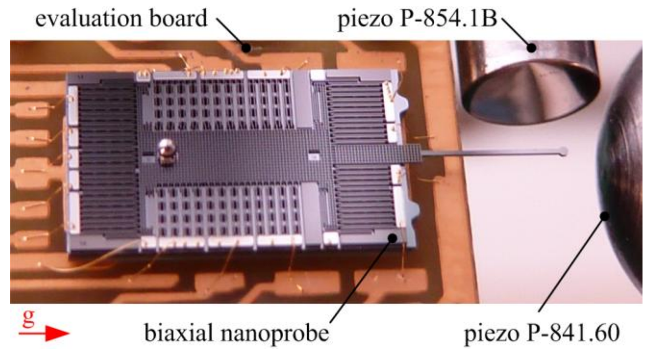

Figure 3: Biaxial nanoprobe with silicon probe tip and test equipment (g – direction of gravity)

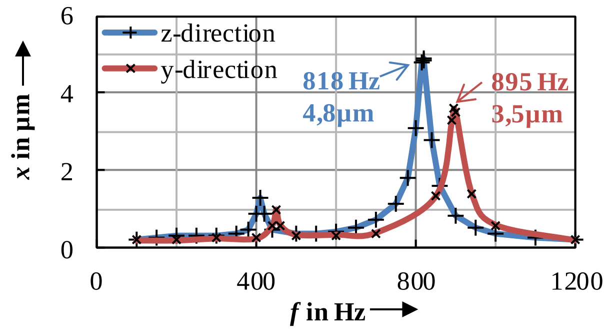

Figure 4: Frequency-amplitude characteristics of the biaxial nanoprobe

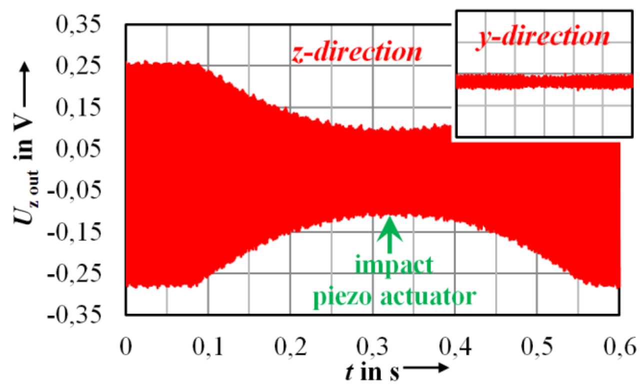

Figure 5: Impact into the nanoprobe oscillation in z-direction ($f_z = 818$ Hz, $x_z = 4{,}8$ µm, unfiltered signal)

The contact behaviour in z-direction is dominated by the contact stiffness [11]. This assumption is confirmed by the phase shift characteristic during the impact.

Figure 6 shows that the phase shift decreases during the impact. This behaviour is explained by a higher stiffness and thus an increasing resonance frequency during the contact which leads to a lower oscillation amplitude and a lower phase shift [11]. Thus, the biaxial nanoprobe operates at semi-contact mode in z-direction. However, the contact forces are very low (< 5 µN, simulated value) so that plastic deformations of the measurement object are avoided.

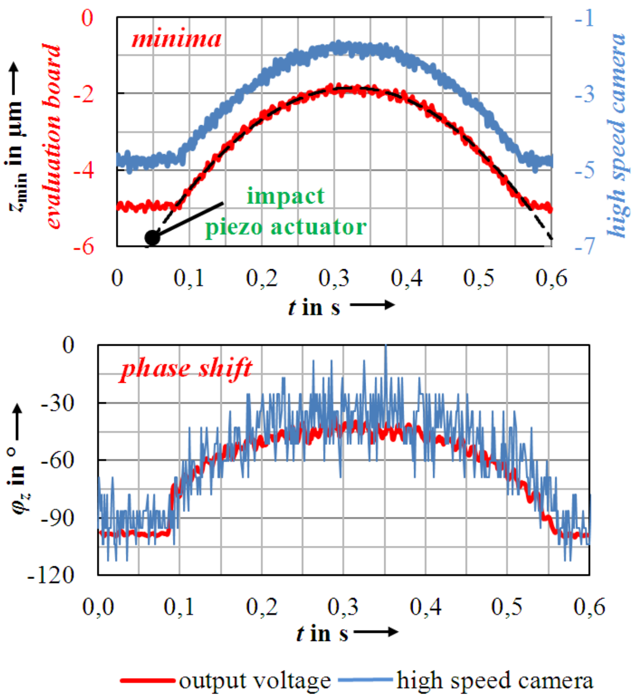

Figure 6: Minima envelope and phase shift of the nanoprobe oscillation during the z-impact of the piezo

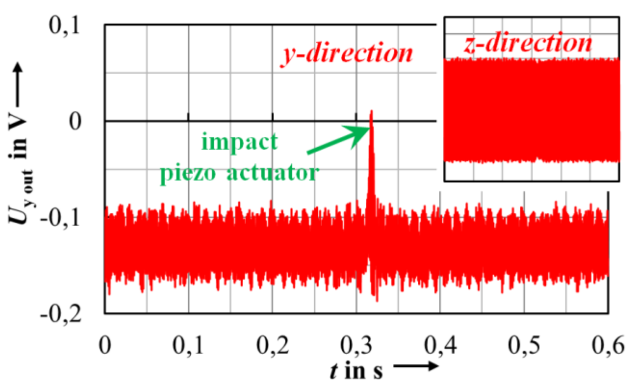

Figure 7: Impact into the nanoprobe oscillation in y-direction (f_y = 895 Hz, x_y = 3,5 µm, unfiltered signal)

5.3 Dynamic impact in y-direction

The contact behaviour of the biaxial nanoprobe in the y-direction differs from that one in z-direction. The interaction between the tip ball and the measurement object results in a rotation around the rotation point D (Figure 2). Thus, the sensor capacities are evaluated in a cross arrangement whereby the output voltage is not proportional to the y-oscillation.

The output signal during a contact between the tip ball and the measurement object is shown in Figure 7. The impact of the piezo actuator was approximately 25 nm. The peak of the output signal indicates that contact damping is the dominating effect in y-direction. A small impact generates a high output voltage because the oscillation provokes a high compression of air during the contact and deflects the probe tip.

The output voltage of the y-direction features a binary evaluation of the interaction between the measurement object and the probe tip, only (0 – non contact, 1 – contact). Nevertheless, sticking is safely avoided and the accuracy of the y-contact is lower than 25 nm.

6 CONCLUSIONS

We presented a biaxial nanoprobe which oscillates in two directions for sticking prevention. Measurements showed that the contact regime differs in z- and y-direction. The z-contact is dominated by the contact stiffness [11]. Thus, the nanoprobe operates in semi-contact mode with small contact times and low contact forces. In y-direction the damping behaviour depends on the contact damping force. Hence, the probe tip does not touch the measurement object and the system measures in non-contact mode.

Advantages of the biaxial nanoprobe are the fully integrated design based on a silicon-on-insulator substrate, the independent resonant motion in two directions and the very low contact forces achieved by semi-contact and non-contact measurement modes.

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REFERENCES

[1] Vorbringer-Dorozhovets, N.; In: IOP Publishing - Meas. Sci. Technol. 22, Nr. 9, 2011
[2] Mastylo, R. et al.; In: Optical measurement systems for industrial inspection IV, p. 238–244, 2005
[3] Manske, E. et al.; In: IOP Publishing - Meas. Sci. Technol. 18, Nr. 2, 2007
[4] Claverley, J. D.; Leach, R. K; In: Springer Publ. - Microsystem Technologies 16, p. 1507–1512, 2009
[5] Mitutoyo Europe GmbH: Umap Vision System. http://www2.mitutoyo.de/, 2012
[6] Woody, S. C.; Smith, S. T.; Elsevier: Prec. Eng. 27, p. 221-233, 2003
[7] Bhushan, B.; In: J. Vac. Sci. Technol. B 21, Nr. 6, p. 2262–2296, 2003
[8] Fearing, R. S.; Proc. Int. Conf. Intelligent Robots and Systems, Nr. 2, 1995
[9] Weckenmann, A. et al: Probing Systems In Dimensional Metrology. In: Ann. CIRP 54, 2004
[10] Goj, B.; Hoffmann, M.; In: Proc. 23rd MME Workshop, Verl. ISLE, 2012 ISBN 978–3–938843–71–0
[11] Shi, X.; Polycarpou, A.; ASME: J. of Vibration and Acustics, Vol. 127, p. 52-60, 2005
[12] Bao, M. H.: Micro Mechanical Transducers - Handbook Of Sensors & Actuators, 8, Amsterdam: Elsevier B. V., 2002
[13] Goj, B.; Hoffmann, M.; Proc. Actuator 2012, Nr. 7, P. 726-729, 2012