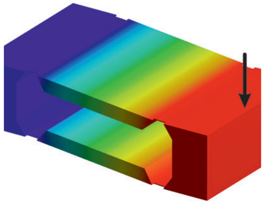

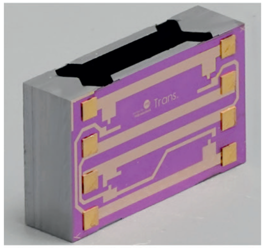

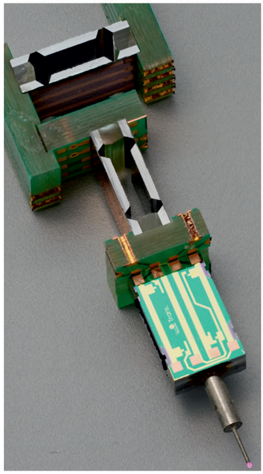

3D microprobe with isotropic serial kinematics for coordinate metrology

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Institut für Mikrotechnik

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Preface and acknowledgment

The present PhD thesis is based on the results I achieved during my work as a research assistant at the Institute for Microtechnology (IMT) of the Technische Universität Braunschweig and in the Department 5.3 “Coordinate Metrology” of the Physikalisch-Technische Bundesanstalt (PTB) in the period from November 2013 to October 2019. Funding was provided by the German Research Foundation (DFG) within the framework of the transfer project "Dreiachsiger Mikrotaster mit isotropen mechanischen Eigenschaften zum Transfer in die industrielle Mikro-Koordinatenmesstechnik." The main results obtained during this project have been reported in peer review papers [1–4], at national and international conferences [5–9] and in patents [10, 11].

I would like to thank all people with whom I collaborated during this project. My special thanks go above all to my doctoral supervisor, Prof. Dr. rer. nat. Andreas Dietzel director of the IMT, who enabled me to work independently and under excellent technical conditions. Through his trustworthy care and support made a significant contribution to the success of this work.

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David Metz Braunschweig, Mai 2020

Abstract

The remarkable developments in the field of micro- and nanofabrication in recent decades have been complemented by adapted new dimensional measurement techniques. Thus, the high demand for quality control of miniaturized components with high functional integration is met.

Tactile coordinate metrology has become a key technology to inspect 3D geometries in ranges from sub-micrometers up to meter sizes with high accuracy. With this purpose, workpiece surfaces are probed point by point in a coordinate measuring machine (CMM) using a probing system or probe. Micro-measurements are performed in special micro-CMMs with microprobes to allow the use of smaller probing elements, resulting in critical interactions with the workpiece. However, such devices are still only accessible to a few users.

Based on earlier investigations on membrane-based microprobes, a novel 3D microprobe design was developed to allow micro-measurements in conventional CMMs. Composed of three micro-fabricated measuring cells forming an isotropic serial kinematics, this microprobe offers a compact solution with an outer dimension of Ø 11 mm. The parallelogram structure made of thin silicon hinges of the measuring cell allows large deflections of up to 600 µm in all three directions and low probing forces < 30 mN for 100 µm deflections. These miniaturized load cells use piezoresistive sensors diffused into the silicon hinges to measure the deflection with sub-micrometer accuracy and resolution.

In this work, the novel and patented 3D microprobe design, its micro-fabrication, and a complete mechanical analysis are presented and discussed. Extensive characterization experiments confirmed the predictions of the theoretical analysis and provide design rules for also reaching future targeted properties of this novel class of microprobes. Finally, the successful integration and evaluation of the microprobe based on measurements of a gear standard in a CMM are reported, thereby opening up new possibilities for micro-probing in conventional CMMs.

Keywords: microprobe, silicon, piezoresistivity, micro-fabrication, isotropy, serial kinematics, coordinate metrology.

Kurzfassung

Die Entwicklungen in der Mikro- und Nanofabrikation in den letzten Jahrzehnten wurden durch geeignete neue dimensionale Messverfahren ergänzt. So kann den hohen Anforderungen der Qualitätsprüfung von Miniaturbauteilen mit hoher Funktionsintegration nachgekommen werden.

Die taktile Koordinatenmesstechnik hat sich zu einer Schlüsseltechnologie entwickelt. 3D-Geometrien mit Submikrometern können so bis hin zu Metergrößen mit hoher Genauigkeit geprüft werden. Dabei erfolgt die punktweise Abtastung von Werkstückoberflächen in einem Koordinatenmessgerät (KMG) über ein Tastsystem. Mikromessungen werden in speziellen Mikro-KMGs mit Mikrotastern durchgeführt, um die Verwendung kleinerer Antastelemente zu ermöglichen. Jedoch sind solche Geräte nach wie vor nur wenigen Nutzern zugänglich.

Anhand vorheriger Arbeiten an membranbasierten Mikrotastern wurde ein neuartiger 3D-Mikrotaster für Mikromessungen in konventionellen KMGs entwickelt. Dieser besteht aus drei mikrogefertigten Messzellen, die eine isotrope serielle Kinematik bilden. Er bietet eine kompakte Lösung mit einem Außendurchmesser von 11 mm. Die Parallelogrammstruktur der Messzelle, die aus dünnen Silizium-Festkörpergelenken besteht, erlaubt große Auslenkungen von bis zu 600 µm in allen drei Richtungen und geringe Antastkräfte < 30 mN bei 100 µm Auslenkung. Diese Miniaturkraftmesszellen verwenden in Siliziumgelenken eindiffundierte Piezowiderstände. So kann die die Auslenkung mit einer Genauigkeit und Auflösung im Submikrometerbereich ermittelt werden.

In dieser Arbeit werden der neuartige und patentierte 3D-Mikrotaster, dessen Mikrofertigung sowie eine vollständige mechanische Analyse vorgestellt und diskutiert. Umfangreiche Charakterisierungsexperimente bestätigten die theoretischen Vorhersagen und liefern Konstruktionsregeln, um in Zukunft gezielte Eigenschaften dieses neuartigen Mikrotasters zu erreichen. Schließlich wird über die erfolgreiche Integration und Evaluierung des Mikrotasters anhand von Messungen eines Verzahnungsnormals in einem KMG berichtet. Hierbei wird deutlich, dass sich neue Möglichkeiten für die Mikromessung in konventionellen KMGs eröffnen.

Stichwörter: Mikrotaster, Silizium, Piezoresistivität, Mikrofabrikation, Isotropie, serielle Kinematik, Koordinatenmesstechnik.

Contents

List of symbols and abbreviations

Symbol (latin)	Unit	Explanation
a	Å	Lattice specific length
a	mm	Oscillations amplitude
a_{CMM}	$m \cdot s^{-2}$	Acceleration
A	-	Anisotropy
A	Mm^2	Area
CM	$mm \cdot V^{-1}$	Conversion matrix
$c_{ij,kl}, c_{ij}$	Pa or $N \cdot m^{-2}$	Elastic constants
C, C_{ij}	$mm \cdot N^{-1}$	Compliance
d	mm	Deflection
d_{t}	mm	Tip diameter
d_i^Y, d_i^Z	mm	Microprobe dimension
E_{n}	-	Proficiency test score
E_F	$V \cdot V^{-1} \cdot N^{-1}$	Force sensitivity
E_u	$V \cdot V^{-1} \cdot mm^{-1}$	Deflection sensitivity
E	Pa or $N \cdot m^{-2}$	Young's modulus
$E_{0,MPE}$	m	maximum permissible error
$f_{\mathrm{H}\alpha}, f_{\mathrm{f}\alpha}, F_{\alpha}$	m	Profile slope, form and total deviation
$f_{\mathrm{H}\beta}, f_{\mathrm{f}\beta}, F_{\beta}$	m	Helix slope, form and total deviation
f, f_0	Hz	Frequency, eigenfrequency
F	N	Forces
G	Pa or $N \cdot m^{-2}$	Shear modulus
G_i	-	Transformation matrix of change of basis
h	mm	Height or thickness
I	A	Current
I_y, I_z	mm^4	Second moments of inertia
J	mm^4	Torsional moments of inertia
J_{ui}	-	Transformation matrix of deflections
J_{Li}	-	Transformation matrix of loads
k	-	Coverage factor
K, K_{ij}	$N \cdot m^{-1}$	Stiffness
K	-	K-Factor of piezoresistive materials
l, L	mm	Length
L	-	Loads vector
l_i, m_i, n_i	-	Direction cosines
m	kg	Mass
M	$N \cdot m$	Torsional and Bending, moment

N	cm^{-3}	Dopant concentration
p	Pa or $N \cdot m^{-2}$	Contact pressure
P	-	Probability
P	-	Piezoresistive correcting factor
r	m	Radius
R	Ω	Resistance
R_i	-	Rotation matrix of change of basis
R	-	Resonance function
$s_{ij,kl}, s_{ij}$	Pa^{-1} or $m \cdot N^{-2}$	Elastic coefficients
s	-	Experimental standard deviation
T	°C or K	Temperature
T_E	-	Euler’s rotation matrix
u	m	Deflection
u	-	Measurement uncertainty
U	-	Extended measurement uncertainty
U	N·m or J	Energy of strain
U_e	V	Wheatstone bridge excitation voltage
U_{si}	V	Sensors output signals
v, v_i, v_{ij}	-	Poisson’s ratio
v	$m \cdot s^{-1}$	Speed
V_i		Verification/correction matrix
w	m	Body width

Symbol (greek)	**Unit**	**Explanation**
α, β, γ	rad	Euler’s angles
δ	m	Deformation depth
δ_{ovt}	m	Over-travel
ε	m	Parasitic displacement error
$\varepsilon, \varepsilon_{ij}$	%	Mechanical strain
ε_{lin}	%	Linearity error
θ	rad	Azimuthal angles
μ_s	-	Friction coefficient
π_{rq}, Π	Pa^{-1} or $m \cdot N^{-2}$	Piezoresistive coefficient, -matrix
ρ	Ω·m	Resistivity
σ, σ_{ij}	Pa or $N \cdot m^{-2}$	Mechanical stress
$\sigma_{0.2}$	Pa or $N \cdot m^{-2}$	Yield strength
σ_F	Pa or $N \cdot m^{-2}$	Facture stress
φ	rad	Oscillations phase
φ	rad	Elevation angles

Abbreviation	Explanation
CBA	Compliance based analysis
CMM	Coordinate measuring machine
EMC, EMI	Electromagnetic compatibility, interference
FEA, FEM	Finite element analysis, method
IMT	Institute of microtechnology, TU Braunschweig
ISO	International Organization for Standardization
IP	Interposers parts
KOH	Potassium hydroxide
MEMS	Microelectromechanical systems
METAS	Swiss Federal Institute of Metrology (Switzerland)
NMI	National measurement institute
NPL	National physical laboratory (United Kingdoms)
PCB	Printed circuit board
PDMS	Polydimethylsiloxane
PI	Polyimide
PTB	Physikalisch-Technische Bundesanstalt (Germany)
RIE, DRIE	Reactive-ion etching, Deep reactive-ion etching
SOI	Silicon on isolator