Sensors and Actuators A 267 (2017) 164–176

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

3D piezoresistive silicon microprobes with stacked suspensions for tailored mechanical anisotropies

D. Metz*, N. Ferreira, A. Dietzel

Technische Universität Braunschweig, Institute of Microtechnology, Braunschweig, Germany

ARTICLE INFO

Article history:
Received 24 April 2017
Received in revised form
16 September 2017
Accepted 20 September 2017
Available online 6 October 2017

Keywords:
3D micro probing system
Piezo-resistive effect
Tactile coordinate measurement
Laser structuring
Wafer-level bonding and tailored mechanical anisotropy

ABSTRACT

Different kinds of piezoresistive microprobes based on silicon have been developed to enable measurement with high accuracies. However, the typical mechanical anisotropy of such systems leads to the slip of the tip, when probing inclined surfaces. Here, a novel microprobe design is presented, which can be tailored to provide a range of anisotropy or even a perfect isotropy. In the first approach, the microprobe is composed of two stacked silicon membranes. In the second approach, a stainless steel suspension in the form of a laser structured foil is stacked on a silicon membrane. Geometrical parameter studies were carried out by mechanical FEM simulations to determine their influence on the stiffnesses in all spatial directions and to predict anisotropies. Microsystems with selected geometries were fabricated and stacking was obtained through selective adhesive transfer and bonding on a wafer level. Prototypes with anisotropies between 3 and 0.4 were characterized confirming the simulations.

1. Introduction

The needs and challenges of measuring complex microstructures are growing. Two fundamentally different types of sensors for measuring microstructures are widely employed in coordinate measurement machines (CMMs). On one hand, optical sensors are used, which enable a fast probing of structures with many measuring points. On the other hand, tactile sensors enable an accurate measurement with the possibility of probing structures which are hidden and optically not accessible. Microprobes are typically still integrated into specific, accurate and expensive μCMMs. However, measuring small structures with a high accuracy on more widely available conventional CMMs through microprobes that can be integrated is an advantageous alternative [1,2]. A tactile microprobe is typically a sensing device with an attached stylus. The tip of the stylus comes in contact with the measured surface, and the sensing device registers the displacement of the tip. Tactile micro probing systems on the base of different physical principles have been developed and optimized [3,4]. Next to sensing properties and small tip diameters, the mechanical construction of the suspension carrying the stylus is also important. These miniaturized suspensions typically entail anisotropic mechanic stiffnesses, which can lead to slipping of the tip when probing inclined surfaces. This increases measurement uncertainty.

A vibrating "non-contact" silicon 3D-microprobe has been developed where the stylus is suspended with three silicon springs. During probing, the oscillation drift can be accurately measured [5]. In this case, the mechanical anisotropy is essential in getting different resonance frequencies in each direction. A combined optical/tactile microprobe was developed where a fiberglass with a melted tip is used as a stylus, of which the position is captured through the reflection of laser light from the tip [6]. Through an optimized leaf spring, an anisotropy of 1.4:1 could be achieved [7]. This microprobe is only available on the CMM from Werth company [8]. Further, a precision machined micro probing system has been fabricated from an aluminium cube, which is composed of a three parallelogram mechanism with elastic hinges. This allowed a perfect isotropic mechanical stiffness of 20 mN $\times$ mm^{-1} to be achieved [9]. However, the inertial mass of this microprobe combined with its low stiffness prohibits its integration in a conventional CMM because the low resonance frequency renders movements of the probing system impossible. Previous works include a probing system with a variable stiffness [10], which is able to achieve close to isotropic mechanical behavior (1.3) by using a special suspension structure and applying piezo-electric compressive loads. Furthermore, three-legged suspension structures for low-probing forces have been also investigated [11]. These flexures were made from 50 μm thin beryllium–copper sheets. The stiffness of these suspen-

* Corresponding author.
E-mail address: d.metz@tu-braunschweig.de (D. Metz).

https://doi.org/10.1016/j.sna.2017.09.039
0924-4247/

sions containing three capacitance transducers is isotropic in the main probe directions X–Y with tolerances of about 10%. These suspensions joined with a stylus having a probe sphere of about 70 μm in diameter are commercially available (IBS Precision Engineering) for specific CMMs [12]. A microprobe suspended using three silicon slender rods, each with metallic piezo resistive strain gauges in a Wheatstone bridge configuration was developed, thus enabling accurate measurements [13]. An optimization by rods of different stiffnesses revealed systems isotropic in X-Y but still anisotropic (6:1) with respect to z-direction [14].

In previous works [1], a silicon membrane based microprobe (Fig. 1) was developed. In the middle of the membrane, a boss structure is located, on which a tungsten carbide stylus with probe ball diameters between 50 μm and 300 μm is mounted (Fig. 1a). Strain sensors are provided by piezoresistive paths realized by local diffusion doping of the membrane (Fig. 1b). Such microprobes have already been integrated into a commercial CMM (gear measuring machine P40, Klingelnberg) and a micro gear artifact has been measured for test purposes [2,15]. However, it was noticed that the stiffness of these systems in the z-direction (about $20\,\mathrm{N\cdot mm^{-1}}$) is 20–40 times higher than in x-, y-directions (about $1\,\mathrm{N\cdot mm^{-1}}$), which leads to recognizable slipping effects. When probing a sphere with a diameter of 2 mm, a slip up to 30 μm is observed at a nominal deflection of 20 μm in the sphere radius direction.

Two stacked membranes (silicon-silicon) have already been proposed earlier to reduce the anisotropy [16], but with the compromise that the stiffnesses in all directions strongly increase. Here we present new microprobes with reduced anisotropy and even with almost perfect isotropy which allow lower x-, y-stiffness. Two stacked membrane designs (silicon-silicon and metal-silicon) will be described and the choice of design parameters will be supported by simulations. In a second part, the manufacturing and assembly process of both designs will be explained in detail. Finally, the mechanical and electrical characterization of the manufactured prototypes will be discussed in the light of the simulations.

2. Microprobes with stacked suspensions

Two new microprobe designs based on a silicon single-cross-membrane suspension (in following: single Si suspension) with piezo-resistors as sensing elements stacked with an additional mechanical suspension have been investigated. This stacked additional suspension has only a minor influence on the stiffness in the z-direction but strongly influences the stiffness in the x- and y-directions, thus reducing anisotropy. In one design, a femtosecond-laser structured stainless steel foil is mounted on top of a single Si suspension (in following: steel/Si suspension) (Fig. 2a). In the second design, a second silicon cross-membrane is mounted on top of the first one (in following: double Si suspension) (Fig. 2b). The fabrication and stacking process of both substrates will be discussed later.

Laser machining of the metal foil allows a free definition of the geometry of this part of the suspension. In Fig. 3, three different exemplary designs of steel foil suspensions are presented. The stiffnesses in the x-y plane obtained from FEM-simulations of steel/Si suspension reveal that only the four-rod design with double axes symmetry is isotropic in the x-y directions (Fig. 3d). For this reason, only this design of foil has been considered in the following.

In order to get systems with tailored 3D anisotropies, geometry parameters of both the Si-membrane and the stainless steel foil can be adapted while keeping an external dimension of $6.5 \times 6.5\,\mathrm{mm^2}$ for the silicon chip. This is identical to previous designs and allows the use of the established concept of integration into the CMM.

Table 1
Stiffness for different stylus dimensions.

No.	d_{tip} [mm]	d_{shaft} [mm]	S_a [$\mathrm{N\cdot mm^{-1}}$]	S_r [$\mathrm{N\cdot mm^{-1}}$]
1	0.05	0.035	1.43×10^3	2.63
2	0.1	0.07	3.75×10^3	11.28
3	0.2	0.12	7.58×10^3	27.72
4	0.3	0.18	12.06×10^3	45.51

3. Simulations

3.1. Simulation methods

Static mechanical simulations (using ANSYS workbench) of both new stacked microprobe designs were undertaken, allowing comparison even with previous non-stacked designs. Material properties (Young's moduli E and Poisson ratios ν) were assumed as E = 193 GPa [17,p. 360] and ν = 0.28 [18,p. 913] for stainless steel (metal foil material, X5CrNi18-10 or AISI 304), and E = 620 GPa and ν = 0.18 for tungsten carbide (stylus material) [19,p. 114]. The anisotropic mechanical behavior of (100) silicon can be described by the following stiffness matrix [20,21], where the x-, y- and z-axis of the FEM model are aligned to the $\langle 011\rangle$, $\langle 0\bar{1}1\rangle$, $\langle 100\rangle$ directions of the silicon wafer respectively:

$$\begin{pmatrix} 194.45 & & & & & \\ 35.25 & 194.45 & & & & \\ 63.9 & 63.9 & 165.8 & & & \\ 0 & 0 & 0 & 79.6 & & \\ 0 & 0 & 0 & 0 & 79.6 & \\ 0 & 0 & 0 & 0 & 0 & 51 \end{pmatrix}_{\mathrm{GPa}}$$

In all simulations, the frame contour of the silicon membrane is fixed, and an external $F = (F_X,\ F_Y,\ F_Z)$ acts on the center of the tip sphere (Fig. 4). Simulations reveal the resulting displacement vectors of the tip $\left(d_x,\ d_y,\ d_z\right)$and the stiffness of the microprobe $\left(S_x,\ S_y,\ S_z\right)$ can be determined as $S_i = \frac{F_i}{d_i}$. The model has been meshed with the help of the proximity size function, which optimizes the size of tetraeder-elements in dependence of geometric structure width (the following settings are used: Relevance "100", Relevance Center "Coarse", Initial Size Seed "Active Assembly", Smoothing "medium", Transition "Fast", Span Angle Center "Coarse" and Num. Cell Across Gap "2"). For more than two cells over the gap the FEM results did not change. For a minimum of two cells the thinnest geometries were modeled with a finer mesh. Fig. 4 also illustrates the fine mesh over Si-beams and the thin metal rods.

3.2. Parameter study

The geometry of the design was parameterized so that a number of variations could be automatically simulated through a variation-matrix. For each variation, the stiffness components S_x and S_z were determined for a force of 50 mN as well as the mechanical anisotropy $A = \frac{S_z}{S_x}$ for futher analysis. The stiffnesses S_x and S_y are equal as a result of the symmetry of the system. For the suspension part made from the stainless steel foil, three geometry parameters were varied: the diameter of the suspension d_{foil}, the width of the rods w_{foil} and the thickness of the foil t_{foil} (Fig. 5a). Concerning the silicon cross-membrane, the thickness of the membrane t_{mem}, the width of the membrane w_{mem} and the width of the cross beams w_{cross} (Fig. 5b) were varied. Finally, different styli have been investigated by reducing the tip diameter d_{tip} and shaft diameter d_{shaft} (Fig. 5c). The length of the stylus was fixed to 5 mm.

3.2.1. Stiffness of the stylus

Four different styli have been considered according to Table 1. The radial stiffness S_r and axial stiffness S_a of them were determined for a stylus without any suspension. The stylus can be acknowl-