euspen's 22nd International Conference & Exhibition, Geneva, CH, May/June 2022
www.euspen.eu

Active load cell with positive, negative and zero stiffness operating modes for micronewton range contact force monitoring in electrical probing

Michal Smreczak[1], Hubert Schneegans[1], Charles Baur[1] and Simon Henein[1]

[1]*Instant-Lab – IGM – STI – EPFL (Ecole Polytechnique Fédérale de Lausanne)*

michal.smreczak@epfl.ch

Abstract
This article describes a novel method for applying a contact force in the range of 1 to 100 µN with pointed probe on a microscale sample in order to perform ohmic electrical measurements. The solution is based on the new TIVOT active load cell combining the functions of a force sensor and an actuator. Probe movement is performed by a piezo actuator which allows the probe tip to be moved over a 5.64 mm range with submicrometric precision. Force measurement is enabled by measuring the elastic deformation of a compliant structure with adjustable stiffness. Strategies are presented to remotely adjust the sensitivity of the mechanism leading to resolutions from 12 µN to 10 nN for forces ranges from 0-60 mN to 0-1 mN respectively. The piezo-actuated stiffness adjustment enables the mechanism to operate in a bistable mode with a tunable maximal threshold force, thus protecting the probe and sample from overloads. Zero offset tuning, in combination with the non-linear characteristic of the mechanism, allows reaching a quasi-constant force characteristic after landing the probe which helps maintaining a stable electrical contact during measurement. Experimental results show that this approach secures and improves probe to sample contact force leading to more efficient measurements than with the traditional methods.

Force sensor, Compliant mechanism, Bistable mechanism, Microprobing, Probe landing, Contact force

1. Introduction

Measuring basic electrical parameters such as current and voltage on devices whose scale is visible to an unaided eye is relatively simple. However, such measurements become a challenge for integrated circuits (IC) fabricated at the micro- and nanoscale. The terms micro- and nanoprobing refer to the technique of analyzing electrical samples under a microscope (optical or electron) which is based on making a point contact with a sample to measure its electrical parameters [1].
Nowadays, micro- and nanoprobing are typically performed by a skilled human operator without any assistance of automation, thus increasing costs and a risk of failure. While solutions to the automated probe positioning using micromanipulators are known (e.g., [2]), one of the remaining challenges is to detect and maintain a stable contact between probe and sample at micro- and nanoscale as shown in Fig. 1.
Control of contact force is a critical factor in automated probe landing: excessive force may damage the probe or the sample, while insufficient force may lead to high electrical resistance or even contact loss due to thermal drift or mechanical vibrations.

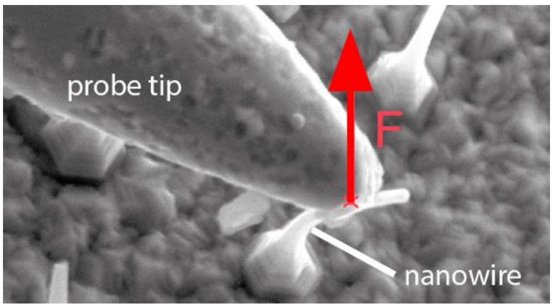

Fig. 1 Contact force in electrical micro- and nanoprobing (a view from electron microscope).

The optimal range of forces is difficult to determine and depends, among other factors, on the size and type of samples. For example, a sample of 100 nm-diameter vertical GaAs nanowires requires forces ranging from 0.1 µN to 10 µN, while a sample of 100 µm-side rectangular pads, slightly oxidized, may require contact forces above 1 mN [3].
There are few solutions allowing for the force measurement in such a wide range and these are mainly MEMS (e.g. [4]) which are characterized by high fragility and in general do not allow the replacement of a damaged or worn probe tip. Moreover, the typical force sensors do not provide functionality protecting against the exertion of excessive contact force and do not help to maintain a constant contact force for the duration of the electrical probing. All these drawbacks limit the contribution of existing force sensing technologies to automated micro- and nanoprobing. Our device, being an improved version of the solution presented in [5], solves these issues. It provides sufficient force measurement range, allows the use of interchangeable commercial probes, and enables the use of control strategies dedicated to micro- and nanoprobing which protect the probe and the sample, and facilitate the probe landing.

2. Load cell with adjustable stiffness and offset

2.1 General concept

The concept of the load cell investigated in this article is based on a lever whose pivoting motion with respect to the fixed frame is guided by flexures. As the suspension of the lever is made of three flexible blades arranged in a 'T' shape, this mechanism is referred to as TIVOT [6]. As depicted in Fig. 2, when an input force F is applied to the tip of the probe (1), the lever deflects by an angle α. Since the movement of the lever extremity is small in relation to the length of the lever, it is possible to approximate its circular displacement by a linear one (*x*), which leads to force-displacement characteristic *F(x)*.

2.2 Stiffness adjustment

The stiffness of the load cell mechanism links the input force *F* with the output displacement *x*. We use the tangent stiffness definition (eq. 1) to describe the load cell.

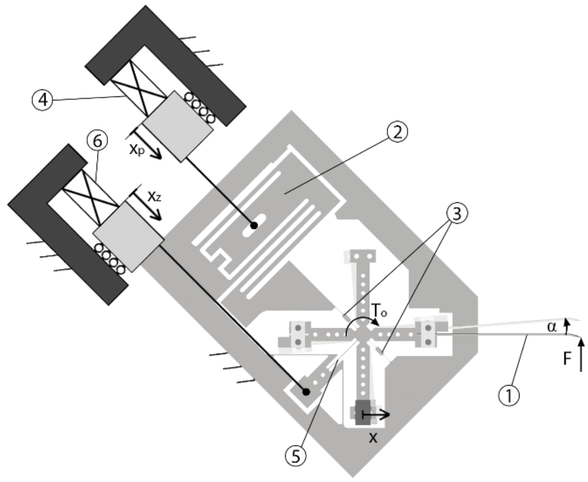

Fig. 2 Schematic of the novel load cell

$$k_t(x) = dF/dx \qquad (eq.1)$$

The lower the stiffness $k_t(x)$, the greater the sensitivity of the load cell. The stiffness $k_t(x)$ is regulated by the preload mechanism (2) that exerts a compressive force on the two longitudinal blades (3). The bending stiffness of flexible blades can be adjusted according to the applied compressive or tensile load [6]. The preload is adjusted by means of a piezoelectric actuator (4) generating displacement x_p, and allows the stiffness $k_t(0)$ to be selected over of a range from 25 N/m to -29 N/m with the resolution of ±0.01 N/m.

2.3 Offset adjustment

The offset F_o is the force measured by the load cell when no external load is applied to the probe tip (i.e., *F = 0*). The offset adjustment allows compensating for differences in the operation of the device, e.g. resulting from limited manufacturing precision or gravity effects on the lever. In some cases, it is preferable to set an offset value to a non-zero value. e.g. to extend the measuring range or change the probe tip position, which is presented in more detail in section 3.

The working principle of the offset mechanism is generating a fixed torque T_o around the rotational axis of the lever, by adjusting the deformation of the transversal blade (5). The torque corresponds to the force F_o multiplied by the length of the lever. The adjustment is made by a piezoelectric actuator (6) generating displacement x_z, and allowing the offset F_o to be selected over a range from -6 mN to 4 mN with the precision of ±0.8 µN.

2.4. Analytical model by polynomial fit

Several examples of force-displacement characteristics obtained experimentally for different stiffnesses $k_t(x)$ and $F_o=0$ are shown in Fig. 3. Based on them, we applied a 5th order polynomial fit to build the analytical model (eq. 2).

$$F = \sum_{n=1}^{5} A_n(k_t(0))x^n + Fo \qquad (eq.2)$$

It should be noted that the characteristics are non-linear which is favorable for the control strategies described in section 3. Note that this model does not consider gravity effects as for the tested configuration a constant mass of the lever was assumed, whose center of gravity coincides with its rotation axis.

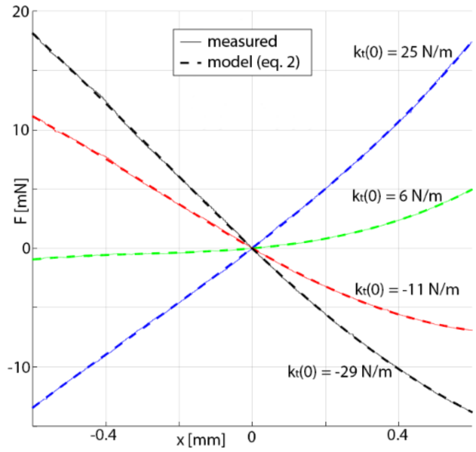

Fig. 3 Force-displacement characteristics of the load cell

2.5 Self-calibration

The model (eq. 2) can be used to determine one of the adjustable parameters - stiffness or offset - with the knowledge of the other one, and when no force is applied to the probe tip (i.e., *F = 0*). Such a measurement, referred to as self-calibration, allows increasing the precision of stiffness and offset adjustments, and even allows them to be regulated without a need of an additional displacement sensor.

3. Measuring modes

The device offers several operating modalities thanks to its wide-range of force-displacement characteristic adjustment: Four operating modes are proposed: positive stiffness, negative stiffness (bi-stability), constant-force, and force-sweep.

3.1 Positive stiffness operating mode

When operating with positive stiffness, there is only one stable position for the lever. If offset is zero, and the probe tip is not in contact with the sample, the lever's nominal position is *x = 0*. Coming into contact with the sample causes the lever to rotate (x>0), by an angle depending on the magnitude of the contact force F. The stiffness adjustment allows for the simultaneous change of sensitivity and the range of the force measurement, while the offset adjustment in this mode allows changing the nominal probe position, thanks to which it is possible to extend the measurement range without affecting the sensitivity. In this mode, the lever remains stationary until it comes into contact with the sample, therefore probe landing requires the sample to be lifted towards the probe tip. The operation of the sensor in the positive stiffness mode was tested on a sample of

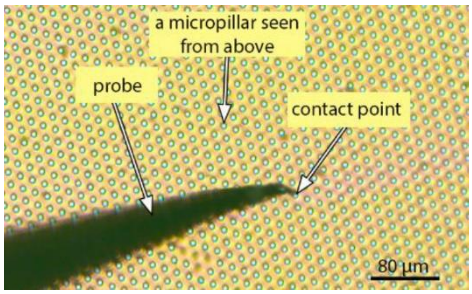

Fig. 4 Probe landing on micropillars (optical microscope view)

10 µm-diameter silicon micropillars (see Fig. 4). Figure 5 presents the force measurement by the load cell prototype during probe landing compared to the measurement by the reference force sensor FUTEK FSH03395 placed under the sample. The precision of the reference force sensor was ±5 µN which is worse than the precision of the prototype, which was 0.4 µN at stiffness $k_t(0)$ = 0.02 N/m. The contact force of 7.5 µN was maintained for over 500 seconds, which is sufficient to carry out typical electrical measurements.

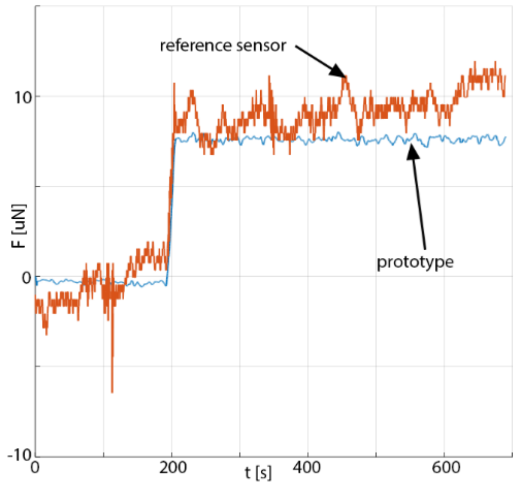

Fig. 5 Force measurement in the positive stiffness mode

3.2 Negative stiffness operating mode (bi-stable)

In the negative stiffness mode, the force-displacement characteristic has a negative slope. This means that the lever operates in a bi-stable mode, typically with stable positions at both extremes of the movement range, when the lever rests on mechanical stops (1A in Fig. 6). The lever remains at rest against its mechanical end-stop until the contact force exerted by the probe tip on the sample reaches the threshold force (2A in Fig. 6). Then, further movement of the sample towards the probe causes the lever to deflect while reducing the contact force. After crossing an unstable equilibrium at the nominal position, the lever suddenly snaps to the second stable position (3A in Fig. 6).

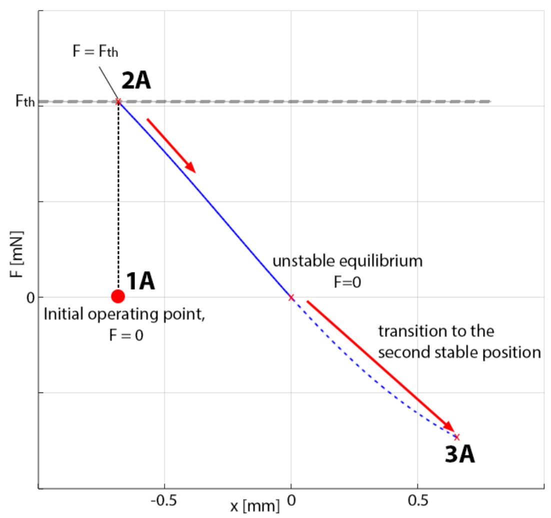

Fig. 6 Working principle of the negative-stiffness mode, qualitative graph

Experimental validation of the negative stiffness mode when landing on microwires is shown in Fig. 7. The maximum contact force F_{th} was 75 µN. Then the contact force was decreasing until it was lost at *t=160* seconds.

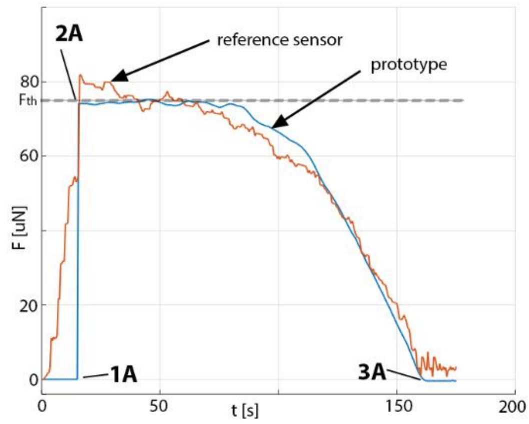

Fig. 7 Force measurement in the negative stiffness mode

3.3 Constant-force operating mode

Constant-force mode requires the stiffness to be adjusted so that the derivative of the force-displacement characteristic at a given operating point x is close to zero ($k_t(x) \approx 0$). This means that the contact force remains stable regardless of small changes in the position of the lever, e.g., caused by vibrations or an overshoot in positioning when landing the probe (see Fig. 8). Offset adjustment can be used to shift the characteristic, thus setting the level of the constant-force.

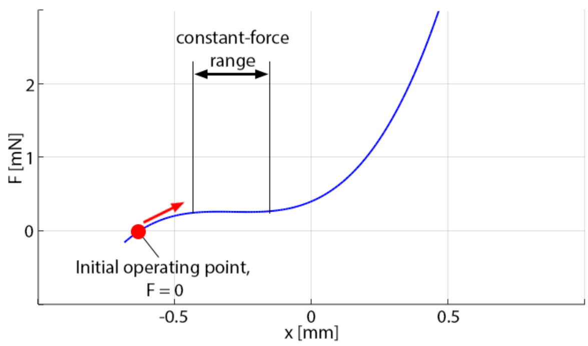

Fig. 8 Working principle in the constant force mode, $k_t(0)$=1.65 N/m, F_o=0.38 mN

Fig. 9 Force measurement in the constant-force mode

Experimental results of probe landing on micropillars in the constant-force mode is shown in Fig. 9. The sample was moved towards the probe tip until contact within the constant-force range was established at *t=80* seconds. Then the sample was moved alternately up and down with an amplitude of 10 µm to test the stability of the contact force. The contact force measured with a precision of ± 0.01 µN was stable between 63.07 to 63.16 µN.

3.4 Force-sweep operating mode

The force-sweep is the only mode in which the probe tip is moved instead of the sample. The lever can be precisely rotated by the offset adjustment mechanism. The stiffness of the mechanism must be positive and its value affects the speed and range of the tip's movement. For example, the highest resolution of the probe tip motion achieved experimentally for $k_t(0)$ = 25 N/m is 12.8 nm, with a travel range of 0.836 mm. With a stiffness of $k_t(0)$=4.5 N/m, the largest travel range of 5.64 mm was achieved, with a resoltion of 70.9 nm.

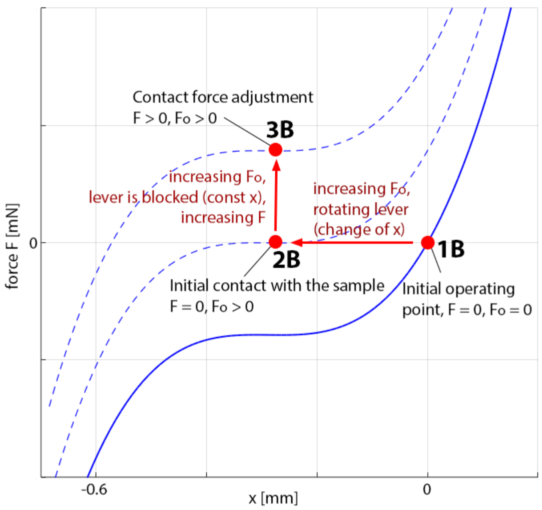

Fig. 10 Working principle of the force-sweep sensing mode, qualitative graph

Beginning at the nominal position (1B in Fig. 10), the offset is incremented causing the probe tip to move towards the sample. When the initial contact with the sample is established (2B in Fig. 10), it can be detected as a discrepancy in the position of the lever in relation to the model (eq. 2). When the probe tip is landed on the sample, the lever rotation is blocked, therefore further adjustment of the offset controls the magnitude of the contact force (3B in Fig. 10). Experimental validation of this operating mode performed on a sample of microwires is shown in Fig. 11.

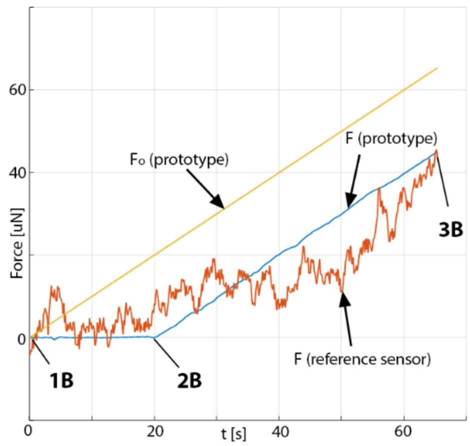

Fig. 11 Force measurement in the force-sweep operating mode

3.5 Summary

The advantages and disadvantages of all operating modes are summarized in Table 1

Table 1 Comparison of the four operating modes

Mode	Advantages	Disadvantages
3.1 Positive stiffness	• best sensitivity for small forces (i.e., *F ≈ 0*) • possible stiffness self-calibration • advantageous when optimal contact force is unknown	• the lever is prone to oscillations around the nominal position
3.2 Negative stiffness	• overload protection • the lever is not prone to oscillations as it rests on the mechanical stop • advantageous when passive force control is required	• insensitive to contact until the threshold force is reached
3.3 Constant-force	• best stability of the contact force • most precise measurement • advantageous when optimal contact force is fixed and known a priori	• limited force range • limited precision outside the constant-force range
3.4 Force-sweep	• possible probe tip actuation • advantageous for multiprobe applications where each probe lands independently on the sample	• the lever is prone to oscillations • limited precision by the offset adjustment

4. Conclusion

Thanks to its stiffness adjustments and offset adjustments features the novel TIVOT load cell allows controlling the sensitivity and the range of the measured forces within four, distinct operating modes dedicated to various types of electrical micro- and nanoprobing. Novel properties include non-linear characteristic for an increased dynamic range, bi-stable mode for protection against excessive forces and probe tip vibration suppression, zero stiffness for improved stability of the contact force. Theses modes were experimentally tested on microwires, demonstrating the possibility of achieving stable contact forces in the range of 0 to 100 µN. Further research includes characterizations of the load cell dynamics.

References

[1] Z. Ma and D.G. Seiler, 2016, Metrology and diagnostic techniques for nanoelectronics. chapter 24. Pan Stanford Publishing.
[2] Shi, C., Luu, D. K., Yang, Q., Liu, J., Chen, J., Ru, C., ... Sun, Y, 2016, Recent advances in nanorobotic manipulation inside scanning electron microscopes. Microsystems & Nanoengineering.
[3] Paul G. Slade, 2014 Electrical Contacts Principles and Applications, Second Edition.
[4] Chao Zhe Ma, Jin Song Du, Yi Yang Liu, and Yun Kai Chu, 2014, Overview of micro-force sensing methods. Applied Mechanics and Materials, 462-463:25–31.
[5] M. Smreczak, C. Baur, L. Rubbert. 2020. Design of a compliant load cell with adjustable stiffness, Precision Engineering.
[6] Loic Tissot-Daguette, Michal Smreczak, Charles Baur, and Simon Henein, 2021, Load cell with adjustable stiffness based on a preloaded t-shaped flexure pivot. Euspen 2021