Atomic force probe for sidewall scanning of nano- and microstructures

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An atomic force microscope (AFM) probe applicable for sidewall scanning has been developed. In its configuration, a horizontal AFM cantilever is microassembled with a vertical AFM cantilever. An AFM tip located at the free end of the vertical cantilever and extending horizontally is capable of probing in a direction perpendicular to sidewalls. The bending, torsion, or deformation of the horizontal cantilever is detected when the tip is brought into contact, intermittent contact, or noncontact with sidewalls. Measurement results taken at the sidewalls of microtrenches, microgears, and line edge roughness samples are presented. © *2006 American Institute of Physics*.
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Nanoscale surface measurements at sidewalls are urgently required. Roughness and waviness of sidewalls as well as the relative position of the sidewalls with respect to the top/bottom planes are important parameters impacting the functionality of microsystems, for instance, microgears and microinjection nozzles. Line edge roughness of pattern features needs to be well characterized in the semiconductor industry. However, measurement instruments available today, such as atomic force microscopes (AFMs), scanning electron microscopes (SEMs), stylus/optical profilometers, and coordinate measuring machines (CMMs), encounter unavoidable problems at sidewall profiling. For instance, the radiation beams of optical or scanning electron microscopes are very poorly reflected by sidewalls back to detectors, the tips of AFMs and stylus profilometers never come in close proximity to sidewalls, no matter how sharp and thin the tips are, and the diameters of smallest conventional CMM probes reach tenth of millimeters. Some special micro-CMM probes may have a diameter down to tens of micrometers;[1–4] however, they are not suitable for roughness measurements of sidewalls.

Several true three-dimensional (3D) AFM scanning techniques have been developed in the last 15 years based upon modified AFM tips comprising protrusions or reentrant structures at their tip region,[5,6] for example, a kind of boot-shaped tip used by Martin and Wickramasinghe[6] It allows the detection of surface slope by vibrating the tip in the z (vertical) and x (horizontal) directions. However, the technique still has two disadvantages: (i) the tip has a flared shape leading to a poor lateral resolution[7,8] (ii) the tip height is limited to a few micrometers due to the fabrication technique. Consequently this method can hardly satisfy the demands of sidewall measurements for microstructures.

In this letter, an AFM probe applicable for sidewall scanning of both micro- and nanoscale structures is presented. This probe, named as "assembled cantilever probe" (ACP), consists of a horizontal AFM cantilever (L1) onto which one or more vertical AFM cantilevers (L2) are glued. An ACP is shown in Fig. 1 as an example. Its cantilevers L1 and L2 are directly taken from conventional AFM probes commercially available (e.g., NanoWorld AG, types ZEILR and NCH), leading to low fabrication costs. For surface sensing a probe tip is located at the free end of L2, extending in the horizontal direction. When this probe tip is brought into contact, intermittent contact or noncontact with sidewalls, the static deformation, or the dynamic behavior of the cantilever L1 will change and can be applied for feedback, i.e., measurements. For exactly gluing the cantilever L2 onto the L1 at the desired position and orientation, a microassembling system based on a motorized hexapod micromanipulator (Physik Instrumente GmbH, F206) is developed. The cantilever L2 to be assembled can be adjusted in full six degrees of freedom with respect to the L1 under the observations of two charge-coupled device (CCD) cameras located along the x and z axes, respectively. Optical adhesive (NOA 63, Norland Products Inc.) is employed for fixing the parts to be assembled.

This design provides two important advantages over conventional AFM probes for sidewall scanning. First, the

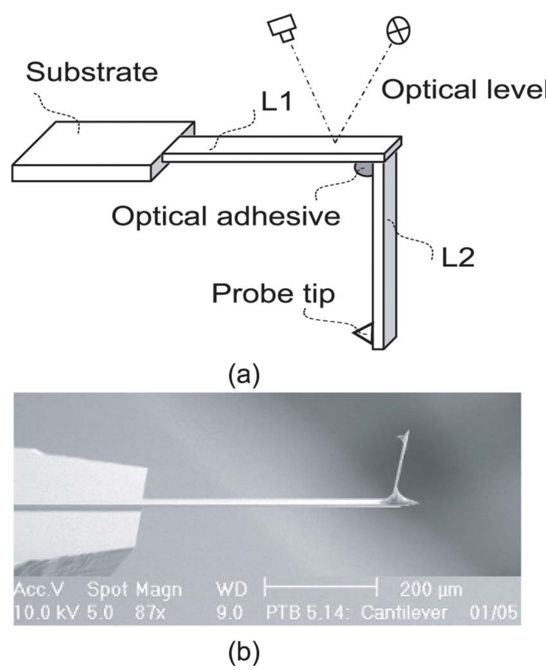

FIG. 1. (Color online) Schematic diagram showing the construction of an "assembled cantilever probe" (ACP) (a) and a SEM image taken on a realized ACP (b).

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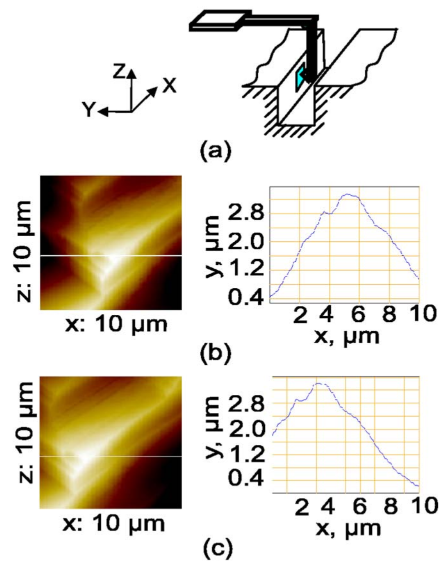

FIG. 2. (Color online) Measurements of a microtrench with a height of 50 μm (a); (b) and (c) show two images taken consecutively at the sidewall using scanning mode. The color scale ranges from 0 nm (dark brown) to 3.2 μm (white). The scan position in (c) is shifted by 2 μm along the x axis with respect to that in (b).

probe tip extends substantially in the horizontal direction. Consequently it can probe sidewalls in their normal directions, assuring a high measurement sensitivity and repeatability. Second, the probe tip is connected to the cantilever L1 via a kind of extension (here, the cantilever L2), providing a large spacing between the tip and the cantilever L1. Therefore, the tip may probe sidewalls with a depth of up to hundreds of micrometers without being hindered by the cantilever L1. In contrast, conventional AFM can only scan structures with limited heights of a few micrometers.

Compared to conventional CMM and micro-CMM probes,[1–3] the tip radius of the ACP is much smaller and may be only a few nanometers in diameter, allowing a very high lateral resolution at sidewall measurements. AFM tips fabricated using advanced techniques, such as carbon nanotube AFM tips or SuperSharpSilicon™ tips (NanoWorld AG), can also easily be adopted in ACP for measuring structures with high aspect ratio. Furthermore, the probing force of the ACP is low; even in contact mode it reaches only a few

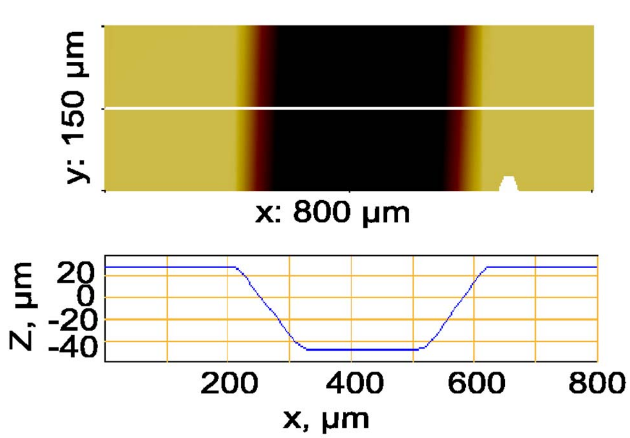

FIG. 3. (Color online) Top: image of a microgroove structure with a depth of 75 μm using the touch-trigger mode; bottom: a cross-sectional profile at the marked position.

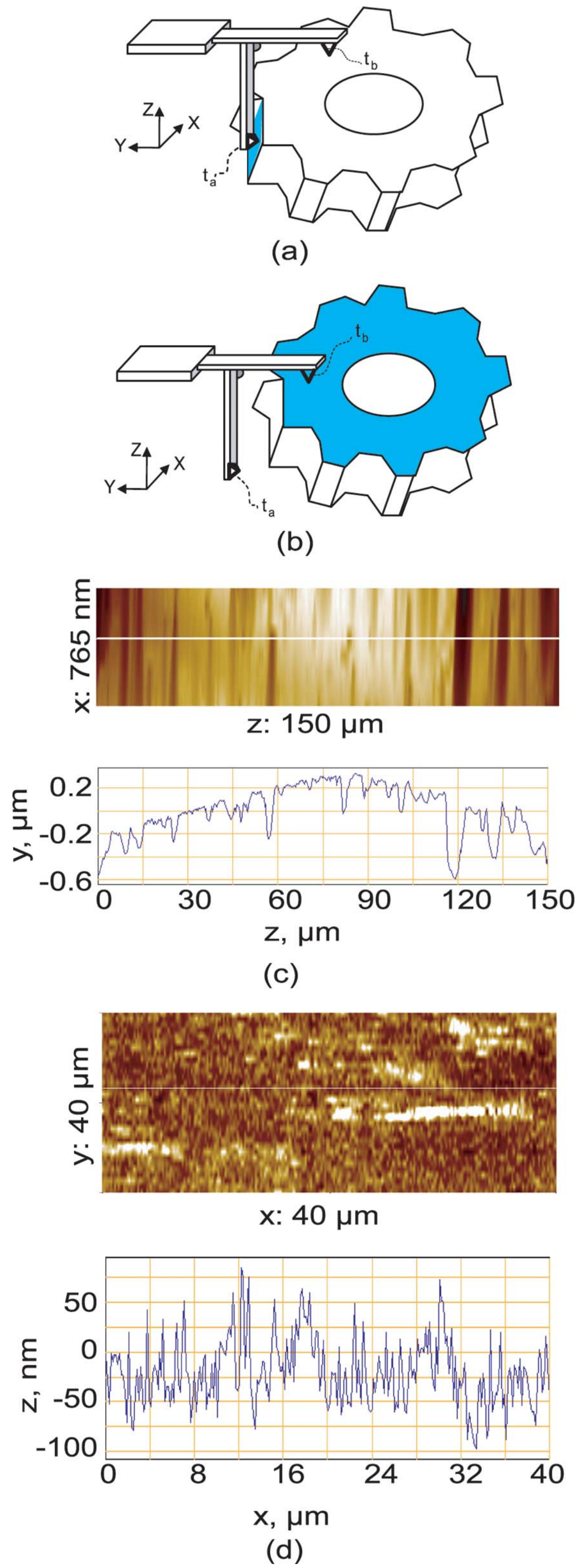

FIG. 4. (Color online) ACP applied for measurements of microgears. The tip t_a which extends horizontally is used for measuring the sidewall of the gear teeth, as shown in (a), while the tip t_b which extends vertically is applied for measuring the upper surface of the gear, as shown in (b). Images and profiles obtained at the sidewall and top surface are given in (c) and (d), respectively.

nanonewtons and is therefore feasible for nondestructive measurements.

The ACP can be used either in scanning mode [functioning as a scanning probe microscope (SPM) probe] or in a touch-trigger mode (functioning as a conventional CMM

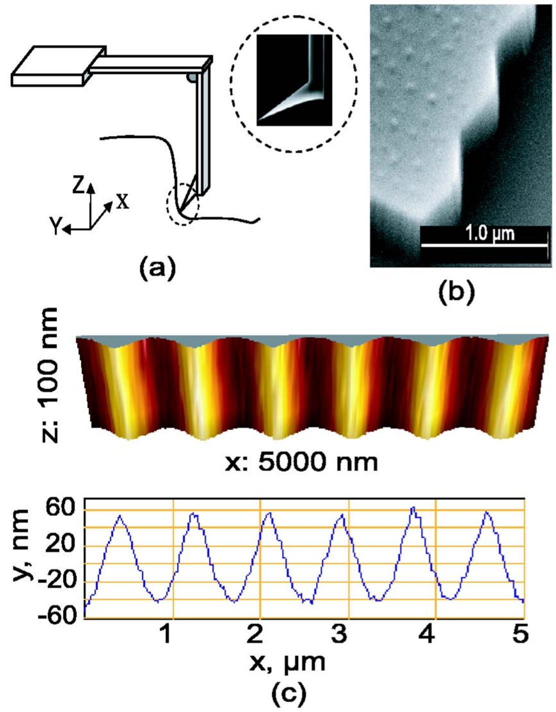

FIG. 5. (Color online) The design of an ACP using advanced TEC™ silicon tip applicable for line edge roughness (LER) measurement is shown in (a). A SEM view and a measured image using the ACP probe of a line edge roughness standard are shown in (b) and (c).

probe). In scanning mode, the tip is scanned along the z or x direction while the feedback is performed in the y direction with respect to surfaces. However, the feedback axis can be easily software switched to the x axis for scanning the other sidewall or to the z axis for measuring top/bottom planes. In the touch-trigger mode, the ACP gets into contact with the surface instantaneously at each measurement point. Once touching the surface, the ACP evokes a trigger signal for latching the measurement data. The ACP tip is then retracted and moved to the next measurement point. As an example, Fig. 2 shows images taken at the sidewall of a microtrench using the scanning mode, and Fig. 3 was taken at the top and bottom plane of a microgroove structure using the touch-trigger mode.

Based upon the proposed idea, versatile designs can be adopted for ACP to fulfil different measurement tasks. Figure 4 shows an ACP applicable for measuring microgears. In this realization, both cantilevers L1 and L2 comprise a probe tip. The tip t_a which extends horizontally is used for measuring the sidewalls of the gear teeth, as shown in Fig. 4(a); while the tip t_b which extends vertically is applied for measuring the top surface of the gear as shown in Fig. 4(b). In Figs. 4(c) and 4(d), images measured at the sidewall and top surface of the microgear, respectively, are demonstrated. The proposed method has the other advantage that both the sidewall and top surface are measured in the same coordinate system. Consequently, the relative dimension, e.g., the orthogonality of the sidewall with respect to the top surface, can be accurately determined.

Figure 5 illustrates an ACP suitable for line edge roughness (LER) measurements of pattern features of integrated circuits. In this configuration, the probe tip fabricated on the cantilever L2 is located at the very end of the cantilever,

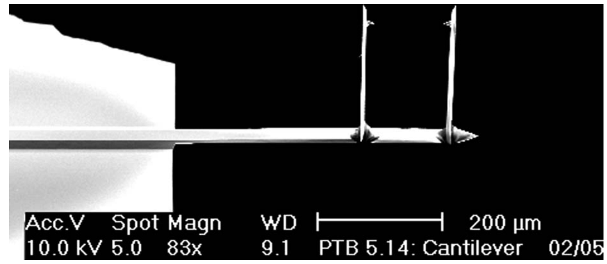

FIG. 6. SEM image of an ACP where two vertical cantilevers are microassembled on a horizontal cantilever as a caliper.

known as the advanced TEC™ silicon tip (NanoWorld AG). With such a design, the ACP is capable of measuring the sidewall near to the etch ground, as shown in Fig. 5(a). In the measurements, the x and z directions are selected as the fast and slow scan axes, respectively, while the y axis is set to be the feedback axis. In such a way, long profiles at the sidewall can be scanned directly. As an example, a LER sample as measured by a SEM and the proposed ACP method is presented in Figs. 5(b) and 5(c). The results obtained by the ACP method agree well with the design specifications of the sample. The advantage of this method over the boot-shaped tip in LER measurements[7,8] is its very high lateral resolution, down to a few nanometers.

Figure 6 demonstrates an ACP where two vertical cantilevers are microassembled on a horizontal cantilever, forming a caliper. After calibrating the spacing between the pair of tips using a suitable standard artifact, this probe can be used for measuring the outer diameters of microstructures. Using a similar construction with the tips pointing outwards, inner diameters of microstructures can also be measured.

A kind of atomic force probe realized by assembling various arrangements of cantilevers has been reported, and first results show its potential for direct and nondestructive sidewall measurements of nano- and microstructures. Although the presented ACP is designed and fabricated on the basis of commercially available AFM cantilevers, it is not limited to such parts. Other microstructures and probes can also be microassembled onto a cantilever for measurement purposes, providing the possibility of developing new kinds of true 3D coordinate measuring probes and advancing AFMs to "micro-nano-CMMs."

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[1]W. O. Pril, Ph.D. thesis, Technische Universiteit Eindhoven, 2002.
[2]U. Brand, T. Kleine-Besten, and H. Schwenke, *Proceedings of the ASPE 15th Annual Meeting, Scottsdale, AZ, 22–27 October 2000* (ASPE, Raleigh, NC, 2000).
[3]UMAP103, Mitutoyo Corporation, www.mitutoyo.co.jp
[4]G. Ji, H. Schwenke, and E. Trapet, Proc. SPIE **3538**, 348 (1998).
[5]D. Nyyssonen, L. Landstein, and E. Coombs, J. Vac. Sci. Technol. B **9**, 3612 (1991).
[6]Y. Martin and H. K. Wickramasinghe, Appl. Phys. Lett. **64**, 2498 (1994).
[7]C. Nelson, S. C. Palmateer, A. R. Forte, and T. M. Lyszczarz, J. Vac. Sci. Technol. B **17**, 2488 (1999).
[8]N. Orji, T. V. Vorburger, J. Fu, R. G. Dixson, V. N. Nguyen, and J. Raja, Meas. Sci. Technol. **16**, 2147 (2005).