

Design of Soft and Fast Nanocantilever for High-Speed Atomic Force Microscopy

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Summary:

The key to enhance the imaging rate without damaging delicate biological samples in life science applications is to design a cantilever probe with low spring constant but high resonance frequency. Achieving these two key mechanical characteristics is challenging due to their direct proportional relationship. Here, we report a silicon dioxide-based cantilever design that enabled low spring constant while ensuring high resonance frequency. In comparison to the existing cantilevers for HS-AFM for life science applications, this cantilever demonstrated the lowest spring constant with the highest resonance frequency to spring constant ratio and addressed the challenge.

Keywords: Low spring constant, HS-AFM, Tapered HS-AFM, High resonance frequency, tapered beam, grey-scale lithography

Motivation and Objective

Due to the high demands in life science applications, designing a cantilever with a low spring constant is essential for ensuring safe scanning of soft samples. On the other hand, to capture their dynamic behavior, a high resonance frequency cantilever is needed for enabling fast imaging rate [1]. To this end, various cantilever designs for such applications have been reported. Nanoworld produces a $7 \mu\text{m} \times 2 \mu\text{m} \times 0.08 \mu\text{m}$ ultrashort cantilever for life science applications [2]. This cantilever exhibits a resonance frequency of 1.2 MHz and a spring constant of 0.15 N/m and has been used to study the effect of host defense peptides on cell wall synthesis at 0.5 – 2 frames per second (fps), facilitating the development of superior drug discovery [2]. Fantner et al. were able to measure the kinetics of pre-death activity of antimicrobial peptides using silicon nitride-based cantilevers that has a low spring constant of 0.3 – 1 N/m. Although the cantilever exhibits one of the lowest spring constants available amongst the cantilevers, the resonance frequency (355 kHz in air) of the cantilever was so low that it was not possible to detect biological reactions that occur at sub-second time scale or even faster [3]. Most commercially available HS-AFM cantilevers exhibit a spring constant of 0.15 – 0.7 N/m and resonance frequency of 0.2 – 1.3 MHz, making them unsuitable for imaging dynamic interactions in nanoscale and soft biological samples simultaneously. Most of the reported cantilevers are silicon nitride-based due to its large Young's Modulus

suitable for high resonance frequency applications. However, it has the disadvantage of yielding stiff cantilevers. In this work, the design of the lowest spring constant cantilever that also exhibit high resonance frequency comparable to previously reported cantilever probes for HS-AFM application is reported.

Methodology

The unique design features of the soft and fast cantilever design are: (a) linear tapering in the xz plane as illustrated in Fig. 1(a). The linear profile is defined by $Q_0 = (u_0, w_0) = (0, w_0)$ and $Q_1 = (u_1, w_1) = (L, w_1)$ and described by Eq. (1); (b) Bézier parabolic tapering in the xy plane as illustrated in Fig. 1(b). The tapering is defined by three points $P_0 = (0, 0)$, $P_1 = (0, y_1)$ and $P_2 = (L, y_2)$ and described by Eq. (2); (c) made from a silicon dioxide, SiO_2 thin film as opposed to silicon or silicon nitride, SiN in previous reports.

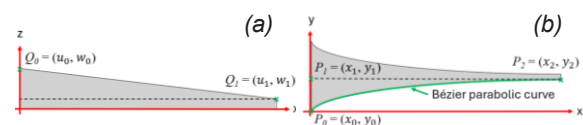


Fig. 1. (a) Vertically linear tapered profile in the xz plane; (b) Bézier parabolic tapering profile in the xy plane

$$H(x) = \frac{w_1 - w_0}{u_1 - u_0} x + w_0 = \frac{w_1 - w_0}{L} x + w_0 \quad (1)$$

$$f(x) = (y_2 - 2y_1) \left(\frac{\sqrt{4x_2(x)}}{2x_2} \right)^2 \pm 2y_1 \left(\frac{\sqrt{4x_2(x)}}{2x_2} \right) \quad (2)$$

Results and Discussions

The methodology is applied to a typical rectangular cantilever with $7 \mu\text{m} \times 0.7 \mu\text{m} \times 0.27 \mu\text{m}$ overall dimension. The cantilever has 5 MHz resonance frequency and 0.7 N/m spring constant - resulting in a figure of merit (FoM), which is the ratio of resonance frequency to spring constant, of 7.14 (MHz.m/N). When the Bézier parabolic profile is introduced to the rectangular cantilever, its resonance frequency increases by 80 % to 8.5 MHz and its spring constant is reduced by 57.14 % to 0.5 N/m as seen from Fig. 2. The resonance frequency further increases by 9 MHz and the spring constant reduces to 0.3 N/m by 40 % as the control point P_1 moves away along the y axis from P_0 . The effect of introducing the linear vertical tapering on the resonance frequency and spring constant is studied as function of thickness at the free end and compared to the rectangular cantilever in Fig. 3. The resonance frequency is increased by as much as 2 MHz to 7 MHz and the spring constant is reduced significantly to 0.15 N/m. When both the linear tapering and the Bézier parabolic tapering profile are introduced, the resonance frequency is more than doubled to 10.5 MHz while the spring constant is reduced by a factor of 70 to 0.01 N/m as shown in Fig. 4(a). In comparison to the typical SiN cantilevers, significant reduction in spring constant while yielding similar resonance frequency has been demonstrated by the proposed SiO₂ based cantilever design, leading to the softest cantilever with and the highest FoM of 300 to our knowledge as can be seen from Fig. 4(b).

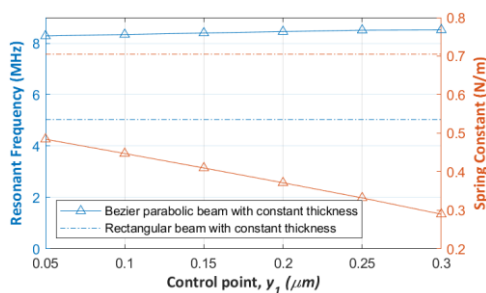


Fig. 2. Effect of Bézier parabolic profile on the resonance frequency and spring constant of SiO₂ beam

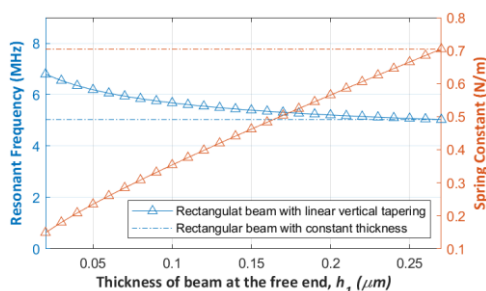


Fig. 3. Effect of vertically linear tapering on the resonance frequency and spring constant of SiO₂ beam

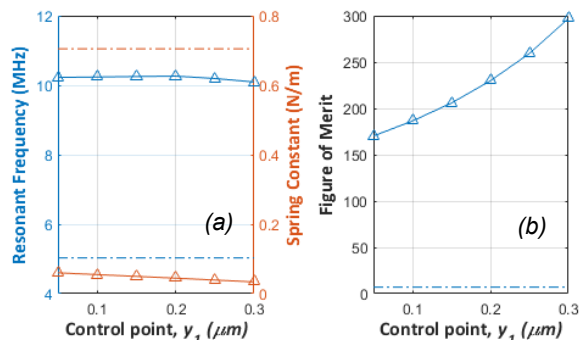


Fig. 4. (a) Effect of double-axis tapering on the resonance frequency and spring constant of SiO₂ beam; (b) Effect of double-axis tapering on the figure of merit

The designed cantilever has been fabricated and characterized, substantiating the design approach. The SEM image of fabricated cantilever is shown in Fig. 5.

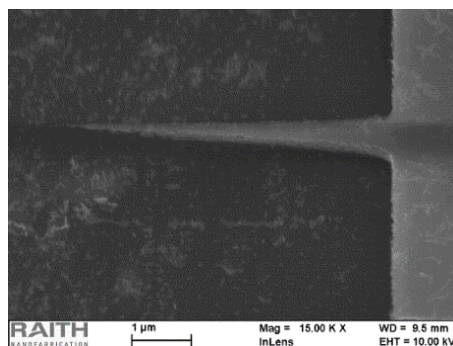


Fig. 5. SEM image of released cantilever

References

- [1] T. Ando, High speed atomic force microscopy coming of age, *Nanotechnology*, 23 (2012); doi: 10.1088/0957-4484/23/6/062001
- [2] USC-F1.2-K0.15 - NanoWorld® (2025) NanoWorld. Available at: <https://www.nanoworld.com/Ultra-Short-Cantilevers-USC-F1.2-K0.15> (Accessed: 25 April 2025)
- [3] S. Jekhmane, M. G. Derks, S. Maity, C. J. Slingerland, K. H. Tehrani, J. Medeiros-Silva, V. Charitou, D. Ammerlaan, C. Fetz, N. A. Consoli, et al., Host defence peptide plectasin targets bacterial cell wall precursor lipid ii by a calcium-sensitive supramolecular mechanism, *Nature microbiology*, 9(7):1778–1791; doi: 10.1038/s41564-024-01696-9
- [4] G. E. Fantner, R. J. Barbero, D. S. Gray, and A. M. Belcher, Kinetics of antimicrobial peptide activity measured on individual bacterial cells using high-speed atomic force microscopy, *Nature nanotechnology* 5, 280–285 (2010); doi: 10.1038/nnano.2010.29