Parallel plate approximation in electrostatic force microscopy

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The parallel plate approximation for a tip-sample capacitor is the easiest way for modeling electrostatic force detection in atomic force microscopy, and it enables quantitative capacitance analysis [1]. However, the dependence of the electrostatic force on the tip-sample distance is different between the actual AFM and the parallel plates model [2,3] because the electrostatic force is affected by the tip shape and consequent broadening of the electric field in complex ways. Only for a small distance change in nanometer-scale, to the contrary, the measured frequency shift, caused by the electrostatic force, as a function of the tip-sample distance was well fitted using the parallel plate approximation [1], implying that this approximation is valid for small deviations in the plate gap. To validate this approximation, in this study, we have examined its accuracy and applicable conditions for an actual electrostatic force microscopy (EFM).

Figure 1 shows the schematic of parallel plate approximation. In this approximation, ξ is a distance between the tip apex and sample surface where the approximation is applied, and an area $S(\xi)$ of the parallel plates and a distance offset $\Delta(\xi)$ are parameters modeling the complex tip shape. For amplitude modulation EFM, electrostatic force under the parallel plate approximation and the parameters can be expressed in eqs (1), (2), and (3), respectively. Figure 2 shows a comparison between the electrostatic force for the hemisphere tip and that for the parallel plate approximation, and they show good agreement for small distance change. We will also discuss how the approximation should be modified for a tip with conical shape and for frequency modulation EFM.

This work was partially supported by JST ACT-X JPMJAX24DI and JSPS KAKENHI JP17H02783.

Reference

[1] R. Fukuzawa et al., *Jpn. J. Appl. Phys.*, **61**, SL1005 (2022). [2] S. Hudret et al, *Eur. Phys. J. B*, **2**, 5 (1998). [3] J. Colchero et al., *Phys. Rev. B*, **64**, 245403 (2001).

$$F_{\mathrm{pp}}(z,\xi) = \frac{1}{2}\epsilon_0 V^2 \frac{S(\xi)}{(z+\Delta(\xi))^2}, \quad (1)$$

$$\Delta(\xi) + \xi = -2\frac{F_{\mathrm{actual}}(\xi)}{F'_{\mathrm{actual}}(\xi)}, \quad (2)$$

$$S(\xi) = \frac{4}{\epsilon_0 V^2}\frac{(F_{\mathrm{actual}}(\xi))^3}{(F'_{\mathrm{actual}}(\xi))^2}. \quad (3)$$

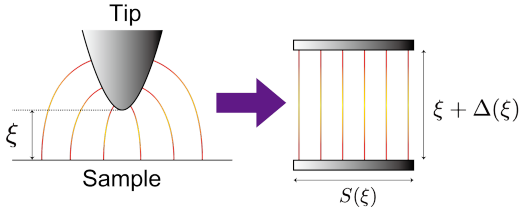

Figure 1. Parallel plate approximation.

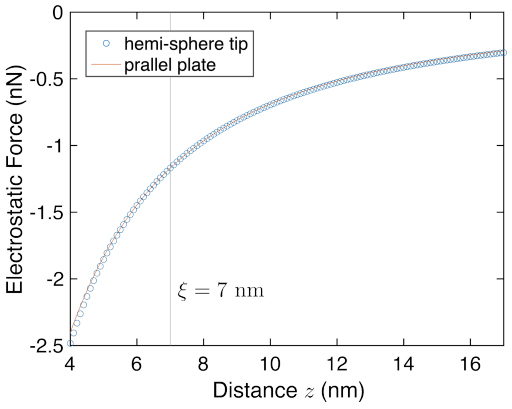

Figure 2. Comparison between the electrostatic force for the hemisphere tip and that for the parallel plate.