Array detector for the atomic force microscope

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We present a method for measuring the deflection of the optical beam in an atomic force microscope (AFM) that yields an increased signal-to-noise ratio, compared to the conventional two-segment detection. This increase is achieved by distributing the optical power from the beam across an array of photodetector segments and splitting it into multiple channels. Each channel has an adjustable gain factor that is set dynamically to weigh the contribution from each channel. We find a mathematical condition for the gain factors that allows detection of cantilever deflections with maximum signal-to-noise ratio and demonstrate this for the case of a 12-μm-long cantilever in an AFM for small cantilevers. © *2000 American Institute of Physics.* [S0003-6951(00)05024-5]

The atomic force microscope[1] (AFM) has become an important tool in nanoscale science. Its applications include the measurement of sample surface properties such as topography, elasticity, and adhesion.[2] These measurements rely on the detection of AFM cantilever deflections with subangstrom accuracy. Optical beam deflection[3,4] has become the prevalent detection method due to its simplicity, but also optical interferometry[5] and piezoresistivity[6] have been used. Recently, a number of single-molecule techniques using the AFM have emerged, which measure mechanical and chemical properties of individual molecules.[7–9] These advanced techniques set increasing requirements on the force resolution of the AFM. Small cantilevers were introduced recently that exhibit reduced thermal motion that often limits force resolution.[10–12] But, as intrinsic cantilever noise is reduced, improved detection becomes more and more critical.[13]

For optical beam deflection detection, an incident laser beam is focused and reflected off the cantilever. Deflections of the cantilever cause translations of the reflected beam on a position-sensitive detector. Conventionally, a two-segment photodiode is used and the cantilever deflection signal is generated by a differential measurement of the light power incident on the two segments. This works well for reflected light beams that are of approximately Gaussian shape. Frequently, however, reflected beams are of less-than-ideal shape,[14] especially those that arise in AFMs for operation in liquid and in AFMs for small cantilevers. Multiple optical interfaces and prototype cantilevers often cause the reflected beam to look scattered and spotted. In this case, centering the beam on the two-segment detector does not necessarily position the part of the beam with the highest intensity between the segments, a condition that is required for high detection sensitivity.[13,15,16] Moreover, if there are multiple intensity maxima, they cannot be centered all at the same time.

Here, we present a method that optimizes detection sensitivity by dissecting the shape of the reflected beam. The reflected beam is expanded by a diverging lens and is distributed across a one-dimensional array of photodetector segments. The cantilever deflection signal at the detector output is generated by first converting the fraction of the total light power that is incident on each of the n detector segments P_i into an electrical signal (Fig. 1). These n electrical signals are then individually amplified by their respective gain factors g_i that can be set dynamically and independent of each other. Finally, the sum of these n amplified, and therefore weighted, signals is formed, making the cantilever deflection signal. When the cantilever is deflected by a small amount, the position and/or the shape of the reflected beam on the detector changes and the fraction of the light power incident on each segment changes by ΔP_i (we assume $\Delta P_i \ll P_i$). The cantilever deflection signal S becomes

$$S=\sum_{i=1}^{n} g_i \Delta P_i , \tag{1}$$

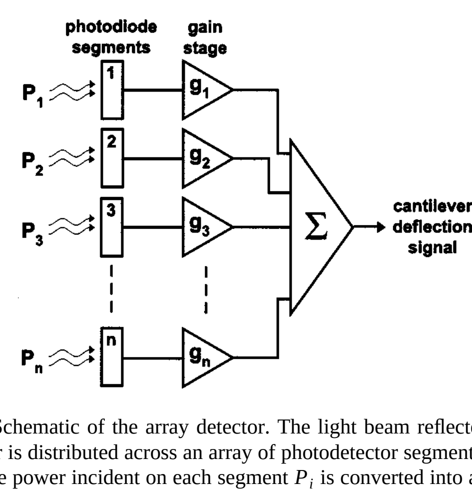

FIG. 1. Schematic of the array detector. The light beam reflected from the cantilever is distributed across an array of photodetector segments. The fraction of the power incident on each segment P_i is converted into an electrical signal and amplified by an individual gain factor g_i. These gain factors can be set dynamically and independently of each other. The individual signals are added to form the cantilever deflection signal. This procedure allows weighing the contribution from each segment to the cantilever deflection signal.

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where perfect responsivity of the photodiode segments was assumed and a constant dc offset $\Sigma_{i=1}^{n} g_i P_i$, originating from the undeflected cantilever, was subtracted.

A physically fundamental limiting noise source in the cantilever deflection signal is the photonic shot noise. This results in root-mean-square (rms) light power fluctuations on each segment with magnitude $(2\hbar\omega\Delta f P_i)^{1/2}$, where $\hbar\omega$ is the energy of one photon and Δf is the detection bandwidth. These light power fluctuations are weighted by their respective gain factors g_i. Since the resulting individual contributions $g_i(2\hbar\omega\Delta f P_i)^{1/2}$ are uncorrelated with respect to each other, they are added in quadrature to obtain the rms noise

$$N = \left(2\hbar\omega\Delta f \sum_{i=1}^{n} g_i^2 P_i \right)^{1/2}. \tag{2}$$

We now would like to choose the gain factors g_i such that the signal-to-noise ratio $(\mathrm{SNR}=S/N)$ of the cantilever deflection signal is maximized. From Eqs. (1) and (2) it can be seen that the SNR is invariant with respect to a common positive multiplicative scaling of the gain factors. We will show, however, that the freedom to choose each gain factor individually can be used to improve the SNR of the cantilever deflection signal. Maximization of the SNR follows by simultaneously solving the n equations

$$\frac{\partial(S/N)}{\partial g_i} = 0, \quad i = 1,2,\ldots,n. \tag{3}$$

This results in the conditions for the n gain factors

$$g_i = \beta \frac{\Delta P_i}{P_i}, \tag{4}$$

where β is an arbitrary positive scalar. In practice, we choose β such that the gain factors g_i are distributed anywhere in between ± 1. No assumptions about the particular arrangement and shape of the detector segments were made in this derivation. In particular, Eq. (4) works for both one- and two-dimensional arrays and is suitable for interferometric detection schemes as well, since it makes optimum use of the knowledge of the P_i and the ΔP_i, regardless of their origin. Furthermore, previously necessary adjustment procedures such as centering the optical beam on the detector are obsolete for an array detector with optimized gain factors.

We demonstrate the increased sensitivity of an array detector with 16 segments for the case of a particular prototype small cantilever that was 12 μm in length and 5 μm in width. It was made of silicon nitride and had a gold pad, 5 μm $\times$5 μm in size, at its tip to enhance light reflectivity.[12] The cantilever was mounted in an AFM for small cantilevers that produces a small focused spot size, similar in design to one described before.[17] The intensity profile of the beam reflected from this cantilever is displayed in Fig. 2(a) (solid bars). The shape of this profile differs from those that are frequently obtained with a conventional AFM setup and that are of approximately Gaussian shape [Fig. 2(a), dashed line]. The reason for this difference might be due to a rough or warped surface of the gold pad, for example, but can also be caused by a nonperfect setup of the beam optics in the AFM for small cantilevers. In the case of a perfectly Gaussian reflected beam profile, the detection SNR can be calculated, using the above formulas, to be 25% higher with an array detector than with a two-segment detector. But, we will demonstrate in the following that a significantly higher improvement can be achieved in other cases.

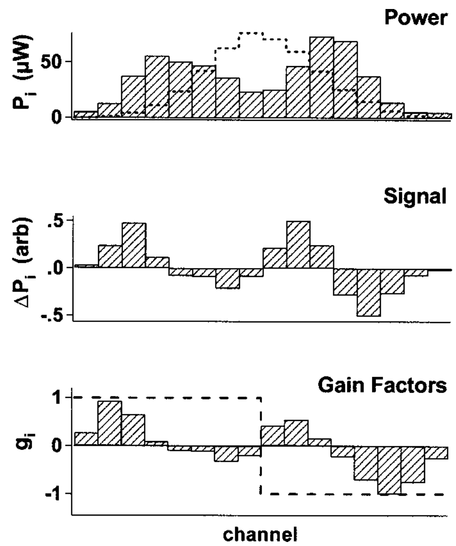

FIG. 2. Measurable quantities and parameter of the array detector in the case of a particular 12-μm-long cantilever in an AFM designed for small cantilevers. (a) Power distribution of the light beam reflected from the undeflected cantilever on the array detector. For conventional AFMs and cantilevers, this distribution frequently has an approximately Gaussian shape (dashed line). For prototype AFMs, operation in liquid or prototype cantilevers, the power distribution often significantly varies from a Gaussian shape. In the case of this particular cantilever, the power distribution exhibits a double peak (solid bars). (b) Change in light power on each segment when the cantilever is deflected by a small amount. Some segments show a larger change in power than others, indicating that they are affected by the cantilever deflection more strongly than other segments. (c) Calculated optimum gain factors of the array detector for the measured quantities from (a) and (b) (solid bars). These gain factors optimize the signal-to-noise ratio of measurements of cantilever deflections in the case of shot noise, compared to a conventional two-segment detector (dashed line).

To set up the array detector for measurements with maximized sensitivity, a simple, one-time calibration measurement needs to be performed, thereby correlating cantilever deflections with translations of the reflected beam on the detector. First, the fraction of the total light power that is incident on each segment P_i was recorded separately at zero-cantilever deflection [Fig. 2(a)] by setting the respective gain factor g_i to 1 and all others to zero and repeating this procedure for all segments. Then, a small deflection of the cantilever was produced to measure the change of the incident power on each segment ΔP_i in the same way [Fig. 2(b)]. In our case, we vibrated the cantilever off-surface with the help of a piezoelectric actuator, but the exact mechanism for producing this cantilever deflection is not important. It can also, for example, consist of lightly pushing the tip of the cantilever into a sample surface. Finally, the optimum gain factors are calculated using Eq. (4) [Fig. 2(c), solid bars].

To demonstrate the improvement of the SNR of cantilever deflection measurements with such a setup, we first operated the array detector as a two-segment detector by setting half of the gain factors to $+1$ and the other half to -1 [Fig. 2(c), dashed line], and measured the spectrum of cantilever deflections due to Brownian motion (Fig. 3, upper trace). Only a portion at the tip of the cantilever's thermal resonance peak protrudes above the background noise level. We then transferred the optimum gain factors from Fig. 2(c) to

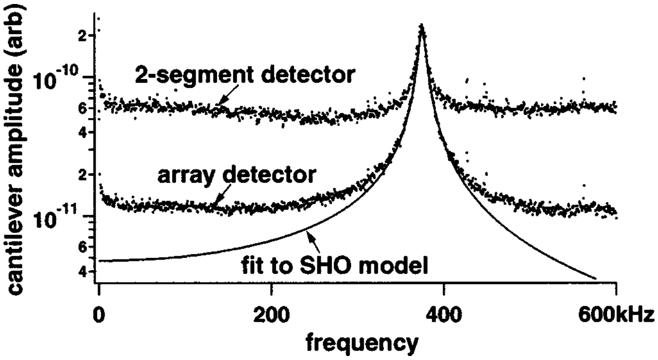

FIG. 3. Deflection spectral densities due to thermal motion of the 12 μm cantilever in an AFM for small cantilevers. In the case of detection with a conventional two-segment detector (simulated with the array detector by setting half of its gain factors to $+1$ and the other half to -1, upper trace), only the tip of the thermal resonance peak protrudes above the background noise level. Applying the optimized array detector gain factors that were calculated in Fig. 2(c) increases the SNR of the cantilever's thermal resonance peak by a factor of 5 in this particular case (middle trace). This increase in SNR reveals more of the true thermal cantilever motion that is displayed as a fit of the thermal resonance peak to a simple-harmonic-oscillator function (bottom trace).

the array detector and measured the thermal spectrum again (Fig. 3, middle trace). The SNR of the thermal resonance peak increased by a factor of 5. A fit of a simple-harmonic-oscillator function to this resonance peak reveals the underlying thermal cantilever motion (Fig. 3, bottom trace).

In summary, we have demonstrated that it is possible to increase the SNR of the cantilever deflection signal with the use of an array detector. This array detector has several independent channels, each of which has a dynamically adjustable gain factor that amplifies, and consequently, weighs the information in its channel. We provide a general formula for the optimum gain factors for a given experimental condition. In the case of a particular 12-μm-long cantilever, the SNR of cantilever deflection measurements was higher for an array detector than for a two-segment detector by a factor of 5.

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[1] G. Binnig, C. F. Quate, and C. Gerber, Phys. Rev. Lett. **56**, 930 (1986).
[2] H. G. Hansma and L. Pietrasanta, Curr. Opin. Chem. Biol. **2**, 579 (1998).
[3] G. Meyer and N. M. Amer, Appl. Phys. Lett. **53**, 1045 (1988).
[4] S. Alexander, L. Hellemans, O. Marti, J. Schneir, V. Elings, P. K. Hansma, M. Longmire, and J. Gurley, J. Appl. Phys. **65**, 164 (1989).
[5] D. Rugar, H. J. Mamin, and P. Guethner, Appl. Phys. Lett. **55**, 2588 (1989).
[6] M. Tortonese, H. Yamada, R. C. Barret, and C. F. Quate, in *The Proceedings of Transducers '91* (IEEE, New York, 1991), p. 448.
[7] S. Kasas, N. H. Thomson, B. L. Smith, H. G. Hansma, X. S. Zhu, M. Guthold, C. Bustamante, E. T. Kool, M. Kashlev, and P. K. Hansma, Biochemistry **36**, 461 (1997).
[8] K. Kitamura, M. Tokunaga, A. H. Iwane, and T. Yanagida, Nature (London) **397**, 129 (1999).
[9] M. Rief, M. Gautel, F. Oesterhelt, J. M. Fernandez, and H. E. Gaub, Science **276**, 1109 (1997).
[10] D. A. Walters, J. P. Cleveland, N. H. Thomson, P. K. Hansma, M. A. Wendman, G. Gurley, and V. Elings, Rev. Sci. Instrum. **67**, 3583 (1996).
[11] T. E. Schäffer, J. P. Cleveland, F. Ohnesorge, D. A. Walters, and P. K. Hansma, J. Appl. Phys. **80**, 3622 (1996).
[12] M. B. Viani, T. E. Schäffer, A. Chand, M. Rief, H. E. Gaub, and P. K. Hansma, J. Appl. Phys. **86**, 2258 (1999).
[13] T. E. Schäffer and P. K. Hansma, J. Appl. Phys. **84**, 4661 (1998).
[14] M. Pierce, J. Stuart, A. Pungor, P. Dryden, and V. Hlady, Langmuir **10**, 3217 (1994).
[15] C. A. J. Putman, B. G. De Grooth, N. F. Van Hulst, and J. Greve, J. Appl. Phys. **72**, 6 (1992).
[16] M. G. L. Gustafsson and J. Clarke, J. Appl. Phys. **76**, 172 (1994).
[17] T. E. Schäffer, M. Viani, D. A. Walters, B. Drake, E. K. Runge, J. P. Cleveland, M. A. Wendman, and P. K. Hansma, Proc. SPIE **3009**, 48 (1997).