ATOMIC FORCE MICROSCOPE FOR GENERATING A SMALL INCIDENT BEAM SPOT

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BACKGROUND OF THE INVENTION

Optical detection in atomic force microscopy (AFM), such as with an optical lever or with an interferometric system, is a means of measuring the deflection of a cantilever caused by forces acting on it. Conventionally, cantilevers of 100–200 μm length with spring constants of 0.01–100 N/m are used to measure the surface properties of a sample. However, physical laws put lower limits on the achievable resolution and scan speed of these cantilevers. To get the best resolution measurements, one wants the cantilever tip to exert only a low force on the sample. In biology, for example, one often deals with samples that are so soft that forces above 10 pN can modify or damage the sample. This also holds true for high resolution measurements on 'hard' samples such as inorganic crystals, since higher forces have the effect of pushing the tip into the sample, increasing the interaction area and thus lowering the resolution. For a given deflection of the cantilever the force increases with the spring constant, k, of the cantilever. For general operation in fluid, small spring constants (<~1 N/m) are desirable. For operation in fluid on soft samples, practice has shown that spring constants <~0.1 N/m are desirable. For tapping mode in air, spring constants below 30 N/m are desirable.

A high resonant frequency, f_R, of the cantilever is required for rapid scanning and for low noise operation. The time it takes for a cantilever to respond after passing over a feature is of order $1/f_R$ for contact mode and Q/f_r for tapping mode where Q is a quality factor for the cantilever. This sets a fundamental limit on scanning speed. The thermal noise of a cantilever involves fixed noise energy (of order kT) spread over a frequency range up to approximately the resonant frequency f_R where k is the Boltzmann constant and T is the temperature in Kelvin Thus, the higher f_R, the lower the noise per unit band width below f_R. Higher resonant frequencies with low spring constants can be achieved by having smaller and thinner cantilevers. However, there are difficulties with using current AFMs with cantilevers significantly smaller than conventional ones. For optimal optical lever detection, the spot should substantially fill the cantilever. Underfilling results in a loss of optical lever detection efficiency because the reflected beam diverges more than necessary. Overfilling the lever means losing light and producing unwanted interference fringes due to light reflected off the sample. However, different operating requirements may be best met by different spot geometries even for the same cantilever. For example, for very low noise measurements of protein motion one may want to overfill the cantilever to achieve the best low noise operation, assuming one is not shot-noise limited, i.e., there is sufficient light intensity for the detector signal error to be within acceptable limits. For large-scale measurements on reflective samples one may want to underfill the cantilever to minimize interference effects from light reflected by the sample.

It is desirable to be able to use the AFM with its cantilever immersed in a fluid such as water; see for example U.S. Patent No. Re. 34,489: "Atomic Force Microscope With Optional Replaceable Fluid Cell," by Hansma et al wherein the cantilever probe is mounted to a module, which facilitates the formation of an annular seal to form a fluid cell around the cantilever probe. A plurality of cantilever tips can be on the same chip. Each of the cantilevers should be accessible to the optics of the system without undue manipulation to re-focus the system when shifting from one cantilever to another.

SUMMARY OF THE INVENTION

The present invention provides an AFM that meets the foregoing needs by generating a small incident beam spot. The AFM is provided with an optical system including a light source for producing a focused incident beam and means for directing the focused beam onto a cantilever to reflect therefrom to a detector. The system has a numerical aperture (NA) sufficient with the wavelength of the light from the light source whereby the focused beam forms a spot diameter, Wo, of 8 μm or less in at least one dimension. The spot diameter, W_o in μm, is commonly defined as $2\times\lambda/(\pi\times NA)$ where λ=the wavelength in μm and NA is defined by $n\times\sin\theta$ where θ is ½ the angle of the far-field light cone (at the $1/e^2$ point) and n is the index of refraction (equal to 1 in air). For red light at λ=670 nm, NA should be greater than 0.05. For blue light at λ=400 nm, NA should be greater than 0.03. For ultraviolet light the minimum NA would be lower.

For red light, or even blue light, large numerical apertures of the focusing optics required by this invention results in a shallow depth of focus. The depth of focus of the incident beam spot can be defined as the range in which the beam spreads by 10% of the spot size. For example, if one requires a spot diameter of 2 μm and operates with light of 670 nm wavelength, the depth of focus is of the order of about 5 μm. As a result, with a plurality of adjacent cantilevers, one would have to check and possibly refocus the incident beam on each cantilever. Refocusing also may be necessary when replacing the chip on which the cantilevers are mounted. In accordance with the present invention, a confocal viewing system is implemented that has its focal plane at the same position as the focal plane of the incident light beam. By bringing the cantilever in focus in the viewing system, the incident light beam is automatically focused in the plane of the cantilever. By adjusting until the line of focus on the sample is normal to the cantilever, one can assure that the cantilever chip is parallel to the sample, thereby preventing interference of the chip with the sample. The AFM of this invention can utilize a plurality of adjacent cantilevers on the same chip; the focus of the incident beam is shifted from one cantilever to another while remaining substantially in focus with each cantilever. Chips with parallel cantilevers are commercially available.

In addition to causing a shallow depth of focus, optical access problems arise from the large opening angle of the incident beam used to achieve a high numerical aperture. To avoid complex lens systems or an accumulation of lenses in close proximity to the cantilever, the incident and reflected light beams may be arranged so that they overlap and are taken through the same lens system. The incident and reflected light beams are separated by polarization using a beamsplitter in conjunction with a quarterwave plate, a concept well-known in interferometry; e.g., see D. Rugar et al., *Review of Scientific Instruments,* 59, 2337–2340 (1988). Because the lens system of this invention is compact, it may be mounted directly on the cantilever module. In addition, piezoelectric elements can be located in the cantilever module support for tapping mode AFM operation.