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Rapid Communication

Scanning Near-Field Acoustic Microscopy

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Abstract. Scanning near-field acoustic microscopy (SNAM) is a new method for imaging the topography of nonconducting surfaces at a potential lateral resolution in the sub-micron range. The basic element of this method is a distance sensor consisting of a sharply pointed vibrating tip, which is part of a high-Q quartz resonator driven at its resonance frequency. The decrease of the resonance frequency or of the amplitude of vibration when an object comes into the proximity of the tip serves as the important signal. The dependence of this signal on pressure and composition of the coupling gas shows that the hydrodynamic forces in the gas are responsible for the coupling between object and tip. The sensor is incorporated into a scanning device. Well-resolved line scans of a grating of 8 μm periodicity, a lateral resolution of 3 μm and a vertical resolution of 5 nm have been achieved in our first experiments.

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Microscopy of electrically conducting surfaces in the submicron range is presently almost exclusively the domain of electron microscopy. Recently, however, new types of microscopes for imaging non-conducting surfaces have been developed, for example, the atomic force microscope (AFM) [1] and the scanning near-field optical microscope (NFOS) [2], inspired mainly by the invention of scanning tunneling microscopy. The AFM makes use of the van der Waals interaction between a tip and an object for measuring the distance and for imaging the surface. New experiments with the AFM [3,4] use a cantilever oscillating close to its resonance frequency in order to improve the resolution of the force measurement. The possible influence of the coupling gas on the force between tip and substrate has been neglected so far, although some AFM's are operated under atmospheric conditions.

Here we demonstrate a new concept of scanning near-field acoustic microscopy, which also makes use of a vibrating tip as a distance sensor. The tip is part of a high-Q quartz oscillator, which is driven at resonance, but, in contrast to the previous AFM, the interaction of the tip with the surface of the object occurs via hydrodynamic forces in the acoustic near-field region around the tip and leads - when approaching an object - to a decrease of both the resonance frequency and the vibration amplitude which are used as an input signal for the image formation.

1. Experimental Observations During the Approach

A 32.7 kHz tuning fork quartz is used as a resonator [5]. It has a quality factor Q = 14000 in air and an elastic compliance c_q = 3200 N/m. One arm of the tuning fork has a length of 2.52 mm, a width of 0.265 mm and a thickness of 0.125 mm.

In a first set of experiments, a flat part of the tuning fork was made to approach a metal ball as indicated in Fig. 1. Considering that the wavelength at 32 kHz in air is about 1 cm, we

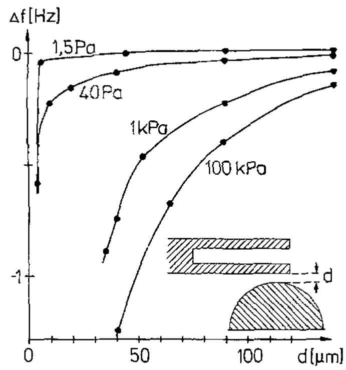

Fig.1. The interaction between the vibrating quartz and the metal-surface. For simplicity the surface of a ball with a small curvature is used as a sample surface. The frequency-shift as a function of the relative distance d is plotted for different air pressures (100kPa = 1atm). The choice of d = 0 is arbitrary

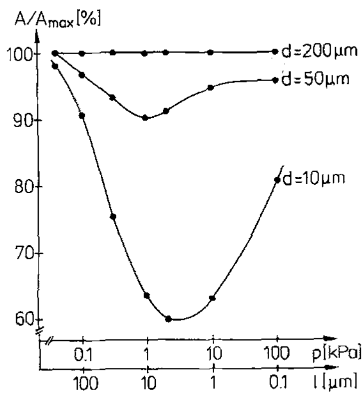

Fig.2. Vibration amplitude as a function of the air pressure at the three fixed distances for the experimental arrangement of Fig.1. The pressure dependence of the amplitude is different depending on whether the mean free path l is larger or smaller than the gap distance d

anticipate that near-field phenomena can be demonstrated for gap distances d well below 1 mm. The tuning fork oscillator shown in Fig.1 is excited at its resonance frequency by a feedback circuit. It is mounted in such a way that the endface of one arm of the tuning fork vibrates perpendicularly to the reference surface. The relative distance d between this endface and the reference surface can be changed and adjusted by means of a differential screw to an accuracy of 0.1 μm. The absolute value of the distance, however, cannot be determined in this way. If the tuning fork is "touching the surface", the oscillation stops. This point is an approximate measure for zero distance. As shown in Fig.1, the decrease of the resonance frequency already starts at a distance of 200 μm and reaches larger values of a few Hz upon further approach. For smaller distances the oscillation stops.

The vibration amplitude also depends on distance [6]. At large distances (200μm) the amplitude decreases by a few percent. At small distances the decrease becomes larger reaching 50%, and soon after the oscillation stops.

These characteristic changes of frequency and amplitude versus distance strongly depend on the pressure of the coupling gas. As is well known, the frequency of a freely oscillating tuning fork also depends on the pressure [5], but here we are only concerned with the changes induced by varying the distance to the reference surface. On decreasing the pressure these frequency shifts are diminished.

Interestingly, the amplitude-versus-pressure curves at constant distance (Fig.2) show two different pressure ranges with a minimum in between. The amplitude has a minimum in the range of 1 to 10 kPa. At high pressure the mean free path l is much smaller than the distance d; for low pressure it is much larger. The resolution of such a distance sensor is best if the pressure is about 2 kPa, but it works also at atmospheric conditions (100 kPa).

In a further experiment the tuning fork was adjusted to move parallel to the reference surface. In this case, too, a decrease in frequency is observed over a range of about 100 μm [6].

If, instead of a plane reference surface, a tip with a radius of curvature of only a few μm is used, the range of interaction is reduced from ~100 μm to 0.2 μm and changes of the distance by only 5 nm can be detected. Furthermore, a strong dependence on the gas pressure is also observed in this case [6].

2. Theoretical Interpretation of the Results

As a simple model of the quartz resonator used in our experiments we take a harmonic oscillator having a resonance frequency ω_{res}, a vibration amplitude a, an elastic compliance k, an effective mass m, a damping constant δ, an amplitude of the driving force F_0, a frequency of driving force ω, and an additional elastic compliance F' due to the interaction with the surroundings:

$$\frac{d^2z}{dt^2} + 2\delta \frac{dz}{dt} + \frac{k + F'}{m} z = \frac{F_0}{m} e^{i\omega t} , \qquad (1)$$

$$\omega_{res} = \sqrt{\omega_0^2 - 2\delta^2} , \qquad (2)$$

$$\omega_0^2 = \frac{k + F'}{m} ,$$

$$a = \frac{F_0}{m} \frac{1}{2\delta\omega_0} . \qquad (3)$$

From the simple description it can be seen that, for the condition specified below, a change in amplitude can only be understood if the damping constant depends on the distance. Therefore we split the damping constant into two parts, only the second of which depends on distance.

$$\delta = \frac{1}{2\sqrt{3}} \frac{\omega_0}{Q} + \delta_2(d) . \qquad (4)$$

The pressure dependence of the frequency-shift Δf and of the vibrating amplitude shown in Fig.1 and Fig.2, respectively, can be explained - in the high pressure region - by assuming that the distance-dependent part of the damping constant $\delta_2(d)$ is independent of pressure, and that the Q-value of the free oscillator decreases with increasing pressure [5].

Thus above 2 kPa one expects:

$$\Delta f(d,p) = - \frac{1}{\sqrt{3}\pi Q(p)} \delta_2(d) , \qquad (5)$$

$$\frac{a}{a_{max}} (d,p) = \left[1 + \frac{\sqrt{3}}{\pi} \frac{Q(p)}{f_0} \delta_2(d) \right]^{-1} . \qquad (6)$$

For pressures above 2 kPa, we consider air - in volumes which are small compared to the acoustic wavelength and large compared to the mean free path ℓ ($\ell \sim 0.1$ μm at 100 kPa = 1 atm) - to be a viscous, incompressible fluid having a pressure independent viscosity η [7]. Only at very low pressures does the friction decrease, because then $d \leq \ell$ and only few gas molecules are trapped in the gap between the vibrating quartz and reference surface. This we believe is the cause of the decrease of the amplitude change observed at pressures below 1 kPa (Fig.2).

To calculate the hydrodynamic friction between the vibrating quartz and the reference surface, we will adopt a simple model: A cylindrical stamp having a flat endface oscillates in a viscous liquid in front of a planar substrate as shown in Fig.3. The liquid is pressed out and sucked in again periodically. This fluid streaming

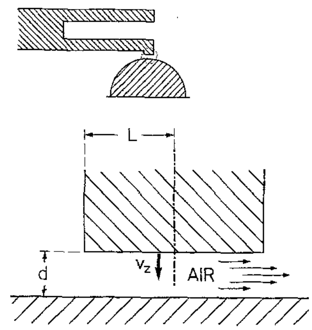

Fig.3. Simplified model for the theoretical interpretation of our results

in and out leads to the observed viscous forces, which are responsible for the damping of the oscillation.

For this geometry and for $d >> \ell$ the frictional force F is

$$F = - \frac{3\pi\eta v_z L^4}{2d^3} . \qquad (7)$$

The symbols are explained in Fig.3. From this equation we get the damping constant δ_2, which depends on the distance d betweeen quartz and surface:

$$\delta_2 = \frac{3\pi\eta L^4}{4m} \frac{1}{d^3} . \qquad (8)$$

For a quantitative estimate we use $\eta = 1.5 \cdot 10^{-5}$ kg/ms, L = 0.3 mm, m = 10μg and Q = 14000. With (8) and (6) we get for a distance d = 10 μm a frequency shift $\Delta f \sim 0.4$ Hz, which is in good agreement with our observation.

A further strong indication of the hydrodynamic nature of the coupling between the vibrating quartz and substrate is inferred from the experiment with the vibration parallel to the reference surface [6]. Certainly only hydrodynamic forces are acting in this case.

All observed phenomena described here are near-field phenomena, in the sense that the range of interaction is much smaller than the acoustic wavelength. Therefore the interaction is quasistatic and scales with the geometry of the interacting bodies.

3. Linear Scan Images of a Line grating

Further experiments were performed in order to test whether the distance sensor is also suitable as a near-field sensor of a scanning microscope. For

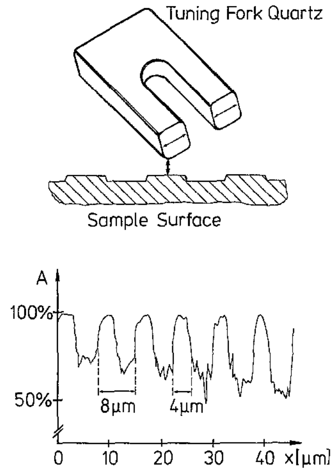

Fig.4. For the line-scan experiments we adjusted the tuning fork, such that one edge can be used as distance probe. Here a line-scan image of an evaporated chromium grating of only 30nm thickness is shown

this purpose the tuning fork was mounted on a scanning device. For our first experiments we used the scanner of a commercial scanning acoustic microsocpe [8] and the tuning fork was inclined at an angle of about 45° relative to the sample surface, such that one edge of the tuning fork faces the sample surface (Fig.4).

As a test sample for microscopy we used an evaporated chromium grating of only 30 nm thickness and of 8 μm periodicity. For a line scan, the edge of the resonator was approached to the grating until a first change in the amplitude was observed. The distance was further decreased until the vibration amplitude decreased to about half of its maximal value. Linear scans were subsequently performed without further adjustment of the distance and the amplitude of vibration was simply recorded as a function of the lateral position. The result of such a scan is shown in Fig.4. The periodicity of 8 μm is clearly resolved. Repetitive scans were well reproducible. We estimate the vertical resolution to be about 5 nm and the lateral resolution to about 3 μm, which is consistent with a radius of curvature of the edges of our tuning forks as observed in a light microscope.

4. Conclusion

A new distance sensor has been described which makes use of the hydrodynamic coupling between a vibrating tip and a surface which is mediated by the gas within the gap. The tip is part of a high-Q quartz oscillator. In first experiments it is demonstrated that a scanning near-field acoustic microscope can be built using such a sensor. In order to increase the resolution and improve the performance of such an instrument we are planning to use quartz resonators with sharply pointed tips as a probes and to perform microscopy with a feedback loop similar to the operation in a STM. The signal used to control the vertical distance is the vibrational amplitude of the quartz resonator. It could be kept constant during the scan and the feedback signal would be used for the image formation. It is further desirable to increase the scanning speed, which is presently limited by the relatively long response time of the high-Q resonator. This may be achieved by using resonators of higher frequency or lower Q. Such a microscope can also be used to obtain new information about the local properties of the surface or adsorbed liquid films on the surface.

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References

1. G.Binnig, C.F. Quate, Ch. Gerber: Phys. Rev. Lett. **56**, 930 (1986)
2. U.Ch. Fischer, U.T. Dürig, D.W. Pohl: Appl. Phys. Lett. **52**, 249 (1988)
3. Y. Martin, C.C. Williams, H.K. Wickramasinghe: J. Appl. Phys. **61**, 4723 (1987)
4. U. Dürig, J.K. Gimzewski, D.W. Pohl: Phys. Rev. Lett. **57**, 2403 (1986)
5. M. Christen: Sensors and Actuators **4**, 555-564 (1983)
6. P. Güthner, U.Ch. Fischer, K. Dransfeld: Beitr. elektronenmikroskop. Direktabb. Oberfl. **21**, 27 (1988)
7. L.D. Landau, E.M. Lifschitz: *Lehrbuch der theoretischen Physik*, Bd. 6 (Hydrodynamik) (1966)
8. Leitz ELSAM acoustic microscope, prospectus of the Ernst Leitz Wetzlar GmbH