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PROPOSAL OF SCANNING PROBE MICROSCOPE WITH MEMS CANTILEVER FOR STUDY OF CONDUCTIVE AND NON-CONDUCTIVE MATERIALS

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Abstract. We have developed a new three-terminal micro-electro-mechanical systems (MEMS) device for scanning probe microscopy. The MEMS-probe comprises a metal cantilever and two electrodes. One electrode is used for adjustment of the gap between the cantilever and another for measuring the tunnelling current. The probe is working in oscillatory regime at resonant frequency. Three feedback mechanisms are used to measure the surface topography. The feedback control is performed fully within the MEMS-probe and the piezo-element is used only for lateral scanning over the surface. In the oscillatory mode the MEMS-probe enables spectroscopic measurements at a high frequency.

In Micro Electro Mechanical Systems (MEMS) technology small moving mechanical structures are often used along with electronic components prepared on the same substrate. The MEMS technology is utilized in accelerometers [1,2], vibration sensors [3], gas and pressure sensors [4,5], optical communications (optical MEMS), adaptive optics [6], microwave switches [7], tunable capacitors [8], *etc*. Despite extensive development of the MEMS for high-tech industry, much fewer applications have been proposed for fundamental research in physics and particularly in nanotechnology. In this paper, we propose a new application of MEMS in scanning probe microscopy.

Since the discovery of scanning tunneling microscopy (STM) in 1981 [9,10] various modifications of the method have been developed. Despite the goals and principles of obtaining the images are different, the surface scanning feedback mechanisms employed in these microscopes rely almost unimously on piezo ceramic elements. Therefore, the accuracy of the measurement and the resolution of the images are limited by properties of the piezo ceramic components. Atomic resolution can be obtained only on a limited number of materials with special preparations, including a high vacuum, very sharp STM tips *etc.* STM can be used for probing conductive surfaces only and AFM cantilevers are relatively large and massive, leading to difficulties in attaining single atom resolution.

The feedback mechanism of the scanning microscope based on the three-terminal MEMS probe consistis of a metal cantilever, a gate electrode and a source electrode. There is a small gap between the cantilever and the substrate of the probe where two control electrodes are fabricated under the cantilever. The natural resonant frequency of the cantilever is given by the equation [11]

$$f_0 = \frac{\lambda^2}{2\pi}\sqrt{\frac{EI}{mL^4}}, \tag{1}$$

where E, I, m and L are the Young's modulus, the area moment of inertia about the neutral axis, mass per unit length, and length of the cantilever, respec-

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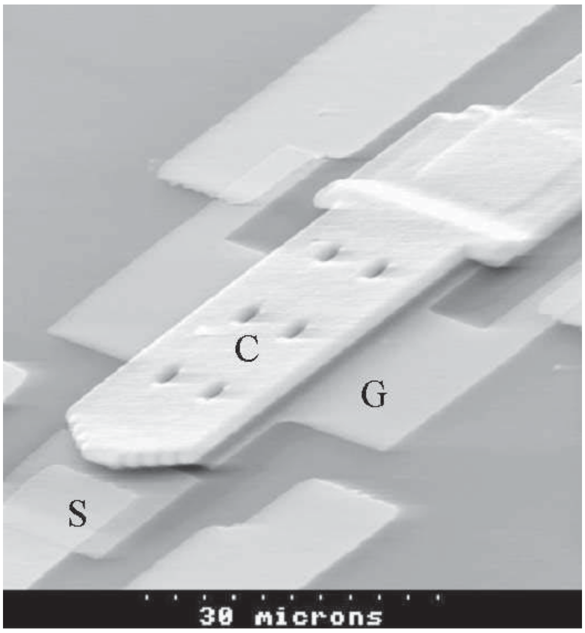

Fig. 1. An electron micrograph image of a three-terminal MEMS-probe consisting of the cantilever (C), the gate (G) and the source (S) electrodes.

tively. The resonant frequency is traditionally measured with a laser Doppler vibrometer [12]. A real resonant frequency might differ from the natural resonant frequency and is correlated with the oscillating quality factor, *Q,* through the equation

$$f = f_0\sqrt{1-\frac{1}{4Q^2}}\,. \qquad (2)$$

The *Q*-factors is determined experimentally using the half-power-point method [13],

$$Q = \frac{f_0}{\Delta f_0}, \qquad (3)$$

where f_0 is the resonant frequency and Δf_0 is the frequency bandwidth at the half-power point.

The working principle of the probe is as follows: the cantilever is oscillating at a resonant frequency when an AC voltage at that frequency is applied on the cantilever, a DC pull-down voltage V_G is applied on the gate electrode for controlling the gap between the cantilever and the substrate of the probe (this substrate is a part of the probe and not the sample) and another DC voltage (or ground) is applied to the source electrode. A relation between V_G and the gap is given by the equation [14,15]

$$V_G = \sqrt{\frac{8K_s g^3}{27\varepsilon_0}}, \qquad (4)$$

where K_s is the spring constant of the mechanical system and *g* is the gap between the cantilever and the gate electrode.

We use resonant switching of the MEMS cantilever onto the source electrode when the control pull-down voltage V_G is much less than the normal switching voltage. The DC tunneling current between the cantilever and the source is used for controlling the feedback mechanism. When the probe approaches the surface of the sample, the oscillating cantilever interacts with atoms on the surface. Interaction forces of different origin influence the properties of the oscillating cantilever making investigations of the surface topography and tunneling spectroscopy possible. Construction of the MEMS-cantilever probe fabricated on silicon is shown in Fig. 1. A cantilever made of platinum has a rectangular shape. The length of the cantilever may vary from a few microns to tens of microns and the resonant frequency from a few hundreds of KHz up to tens of MHz. The gap between the cantilever and the gate and the source electrodes is a fraction of a micron. The gate electrode covers almost the whole surface area under the cantilever for more effective control of the gap. The source electrode is situated near the edge of the beam. The cantilever oscillates at its resonant frequency and therefore the effective gap value is defined only when the tunnelling contact is established. The effective gap is controlled by the voltage applied on the gate electrode.

A schematic diagram of the microscope and the working principle are shown in Fig. 2. There are two measuring loops: the loop 1 is for control of the horizontal *xy* position using a piezo element and the loop 2 is for control of the vertical movement of the cantilever and the feedback mechanism (the piezo element is not connected with the feedback mechanism for vertical control of the cantilever). The piezo *z*-position is constant during measurements. The voltage V_Z applied on the piezo element is adjusted only during initiating of the instrument prior to scanning.

There are several possible feedback mechanisms:

1. Conductive materials. By applying a DC voltage to the sample one can observe the tunneling current between the cantilever and the sample. This current as well as the current between the cantilever and the source or the gate is used in feedback to adjust the DC voltage applied on the gate.

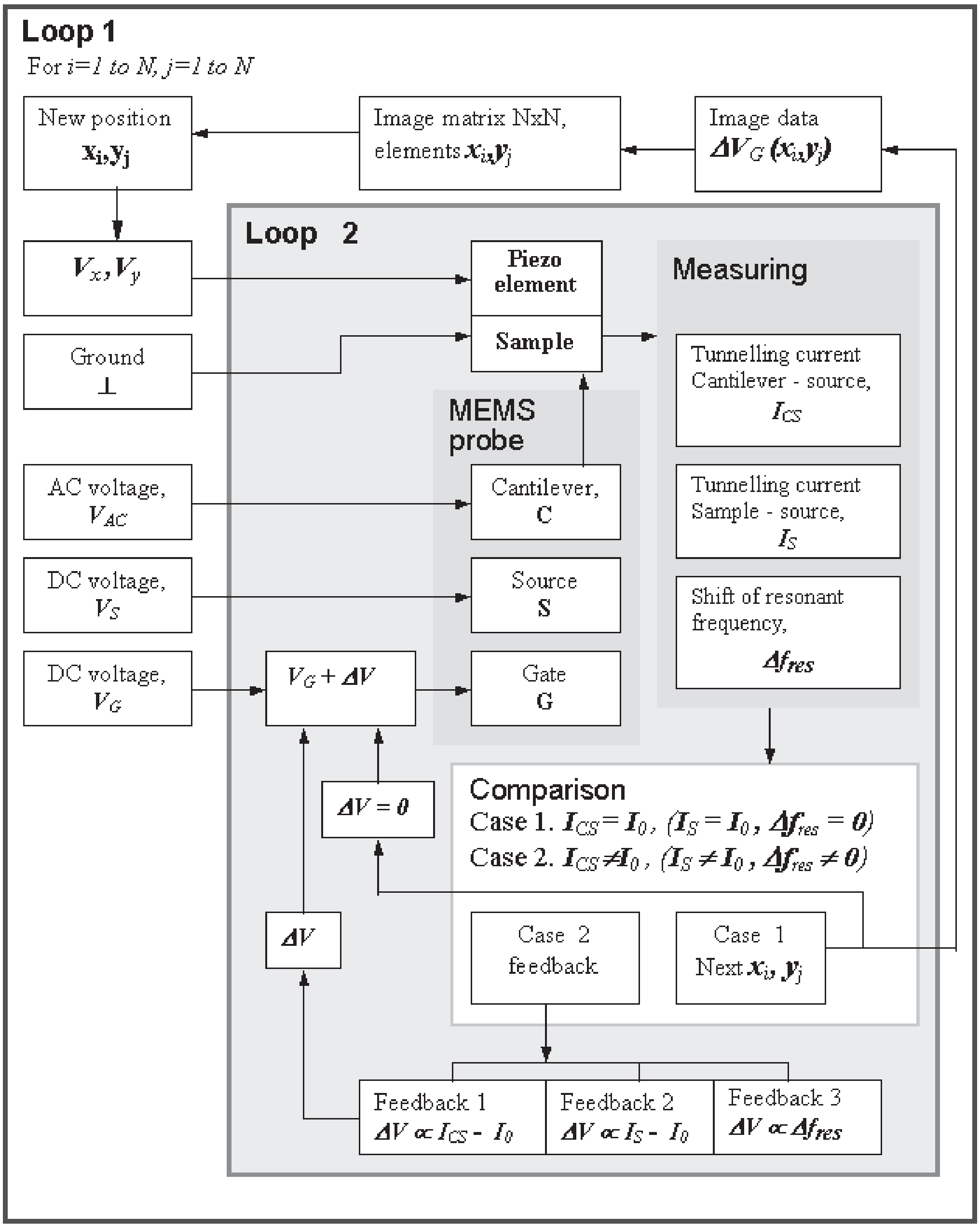

Fig. 2. A schematic set-up of the MEMS-based STM is shown. An image matrix consists of *N* rows and *N* columns of pixels. Each pixel has its coordinates x_i, y_j. Each pair of coordinates has a corresponding pair of voltages V_x, V_y which are applied on piezo element. Positioning of MEMS-probe in the *xy* plane is performed within Loop 1. At a fixed position, the probing and vertical control along *z*-direction is done in Loop 2. Two DC voltages sources and one AC voltage source control the MEMS-probe. The AC voltage V_{AC} is applied on the cantilever (C, Fig. 1) at frequency of mechanical resonance of the cantilever. A special computer program searches the resonant frequency of the cantilever. Therefore, different cantilevers can be used for probing. A small DC voltage V_S within the range 0 to 1 volt is applied on the source electrode (S, Fig. 1) and another DC voltage V_G controls the gap between the oscillating cantilever and the source electrode. The ground is connected to the sample. During probing, the electronic system measures the tunnelling current between the cantilever and the source electrodes I_{CS}, the tunnelling current between the sample and the source I_S and the shift of the resonant frequency Δf_{res}. Each of the measured values can be used in feedback mechanism. For this purpose, the measured values are compared with reference ones. The difference between the measured and the reference parameters is used to adjust the gap by modifying the control gate voltage $V_G + \Delta V$. The feedback procedure is repeated until the measured values are the same as reference ones. In this case, the value $\Delta V(x_i, y_j)$ is added to the Image matrix. The procedure is repeated for all pairs (x_i, y_j) of the image matrix to obtain the surface topography.

By increasing/reducing the gate voltage the gap between the cantilever and the probe substrate decreases/increases and, correspondingly, the gap between the cantilever and the sample surface increases/decreases.

2. Non-conductive materials. The interaction between the cantilever and the surface influences the oscillating cantilever resulting in a change of the amplitude of the oscillation and a change in the gap between the cantilever and the source. The source tunneling current will change accordingly. Again, by adjusting the gate voltage one can modify the gap between the cantilever and the sample in order to control the cantilever-sample interaction.
3. Conductive and non-conductive samples. The interaction between the cantilever and the sample may shift the resonant frequency. This shift can be used for the feedback signal. The gap control is the same as in the previous cases (1) and (2).

The image obtained during scanning over a surface is the function $\Delta V_G\,(x_i, y_j)$. Using the techniques described above we can perform tunnelling spectroscopy of metals, semiconductors and multilayer structures. In this case, the position *(x,y)* of the MEMS-probe is fixed over the sample.

The tunnelling current measured between the source electrode and the oscillating cantilever depends on the amplitude of the oscillation. In the MEMS-probe STM, the cantilever is approached close to the surface of the sample. Basically, the gap between the sample and the cantilever is equal to the gap between the cantilever and the source electrode. During one period of oscillation the cantilever interacts with both, sample and the source electrode. Therefore, the amplitude of oscillation of the cantilever depends on the interaction between the cantilever and the sample. Depending on the properties of the surface of the sample one can use three different feedback mechanisms. Also one can image the same surface using different feedbacks. This may give additional information on the properties of the material of the sample.

An initial position of the MEMS-probe includes *x*,*y* and *z* control of the piezoelement. The control voltage V_Z applied on the piezo is kept constant during measurements and only the *x* and *y* components, V_X and V_Y, applied on the piezo are changed. The value of V_Z is adjusted so that the gap between the sample and the cantilever is small enough to detect the interaction force between the surface and the cantilever. Further control of the *z*-position during measurements is carried out within the MEMS-probe only by controlling the voltage V_G applied on the gate of the MEMS. The loop 2 includes measurement of the tunnelling current within the MEMS-probe. The AC voltage V_{AC} applied on the cantilever and a small DC voltage V_S applied on the source are kept constant during the measurements. The electronic system automatically measures the tunnelling current I_{CS}, I_{SS} and the shift the of resonant frequency Δf_{res}. Depending on the feedback type the electronic system corrects the gate voltage or resonance frequency to keep the tunnelling current or the resonant frequency constant. When the tunnelling current level I_0 or f_{res} is reached then the data are added to the output array. The topography of the surface is obtained from variations of ΔV_G needed to keep the tunneling current constant over the image matrix (x_i, y_j).

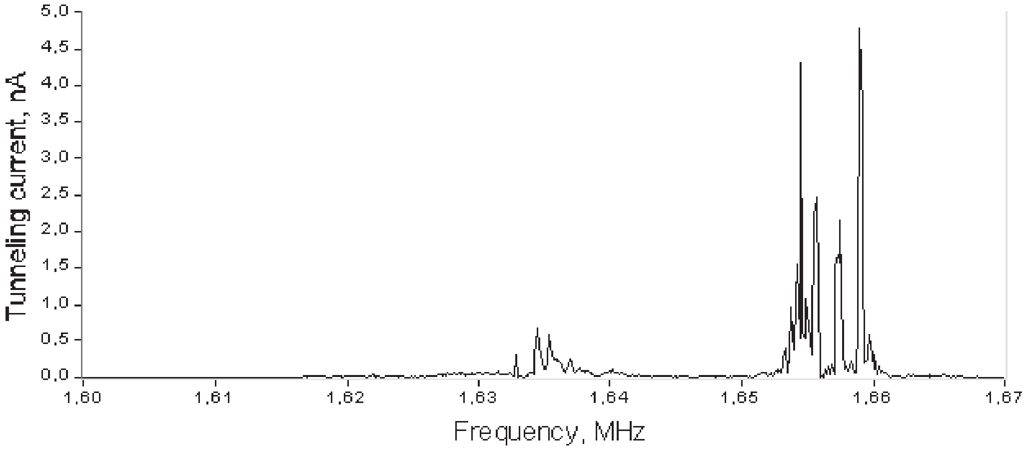

Fig. 3. A dependence of the tunneling current I_{CS} between the cantilever and the source vs. frequency *f* of the AC voltage applied on the cantilever demonstrating the resonance spectrum of the MEMS-cantilever.

The main question of the feasibility of the proposed microscope is related with measurement of the resonant frequency of a vibrating cantilever with high accuracy. For this purpose, a special computer program has been designed. The measurement system automatically searches the resonant frequency of the cantilever by scanning the frequency and measuring the tunnelling current. In our experiments the frequency step was 131 Hz and the amplitude of the ac voltage a few volts. The gate voltage varies in the range of 0 to 10 volts and the source voltage is below 5 volts. These parameters are much lower than 30 to 40 volts needed for usual non-resonant switching of MEMS devices. An example of the oscillation spectrum of the device is shown in Fig. 3, revealing two spectral bands. The first band is relatively weak and the second band has a complex structure of several sharp peaks. The strongest peak is used for probing the surface of the sample.

For investigations of magnetic materials the MEMS-probe can be modified by deposition of a tiny tip of magnetic material on the top-end of the cantilever. The magnetic force acting on the cantilever will change the resonance characteristics and influence the tunnelling current between the cantilever and the source electrode.

In conclusion, we propose a new MEMS-probe scanning tunnelling microscope which will allow high-resolution investigations of surface topography of conductive, non-conductive and magnetic materials. The MEMS-probe works at a resonant frequency of an oscillating cantilever. Resonance switching may be used for investigations of dynamic spectroscopy of surface states.

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