

Nanoscale evaluation of thin oxide film homogeneity with combined shear force emission microscope

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Very fast development of large scale integrated circuits causes downsizing of the structures. Due to this fact, the thickness of oxide layer in the gate area decreases as well. In order to perform test of dielectric layer with nanometer resolution in a lateral plane, one can use AFM with a conductive tip. Biased tips can be used to measure current flow to the surface of the sample in order estimate its electrical properties. In the paper a modular shear force emission microscope has been presented. A metallic scanning microtip is used as a nano e-beam and it allows one to measure the local surface emission and investigate the quality of dielectric layers in semiconductor chips.

Key words: *AFM; field emission; shear force microscopy; gate oxide tests*

1. Introduction

The progress of downscaling of the integrated circuits continues as a result of increasing the performance and reducing the power consumption. More than four decades ago this progress was predicted by Moore [1] although it was expected to last about ten years. Today one can still observe new achievements of semiconductor's technology when new generations of integrated circuits are released. It should be emphasized, that once this level was reached – the engineers must face specific issues and in order to solve problems, they need very sophisticated tools.

One of the important components of the MOS transistor is the dielectric layer, which isolates the gate and the channel. Its thickness obtained level of few nanometers or even 1.2 nm [2] in experimental chips. Theoretically it can be reduced down to 0.8 nm [3]. Silicon dioxide layers are fabricated by oxidation the silicon surface. This process is known and developed very well. It is however very difficult to obtain such thin layer and avoiding presence of defects which could make the structure useless. The fabrication process if not adjusted properly can lead to appearance of undesired

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objects like pinholes or even larger conductive spots. Thereby one must very carefully investigate the quality of oxide layer in order to optimize the production process and perform the tests of developed structures during mass production.

The oxide quality and reliability is essential when the lifetime of the integrated circuit is considered. Thereby this issue was investigated [4] as well as the methods of diagnosing the ultrathin oxide layers [5, 6]. One of the tools which allows investigation of the surface with nanometer resolution is atomic force microscopy (AFM). This method was developed by Binnig et al. [7]. The idea of AFM methods has been developed, and several scanning methods are now available in order to investigate various parameters of the surface. By using conductive tip and biasing the sample, one can measure the topography and current flow between the tip and sample. This allows to investigate electrical properties of the surface [8–14]. Such methods unlike in macroscopic measurement techniques can deliver much more valuable information about the oxide layer homogeneity and continuity. The application of the AFM scanning tip to diagnose the oxide layer was already successfully attended [15, 16]. Although generally very small force is applied to the tip in order to observe tip-sample interaction, sharp tip can damage very thin layer during the scanning process. Thereby non-contact methods can reduce significantly the risk of damaging the surface. Moreover, the wear of the tip changes the electrical field around the tip and the measurement conditions can become unstable.

2. Experimental setup

The experiments were performed with a home-built setup. Its simplified scheme is shown in Fig. 1. As a scanning tip, the tungsten wire with diameter 120 μm was used. After electrochemical etching the obtained curvature radius of the tip was about 30 nm.

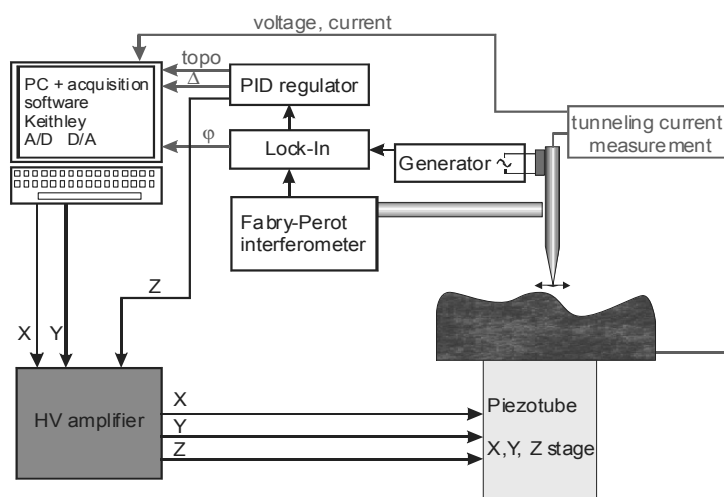


Fig. 1. A simplified diagram of the combined shear force emission microscope setup

In a shear force microscope, the tip oscillates laterally to the surface near one of its mechanical resonant frequencies. At a distance of a few nanometers from the surface in question, oscillations become damped out by shear forces (Fig. 2). This is used for tip-sample distance regulation as a basis for high resolution topographic imaging. In order to measure the microtip oscillation, a fibre Fabry–Perot interferometer is used. An advantage of this system is that quantitative measurements of tip vibration amplitude are easily performed.

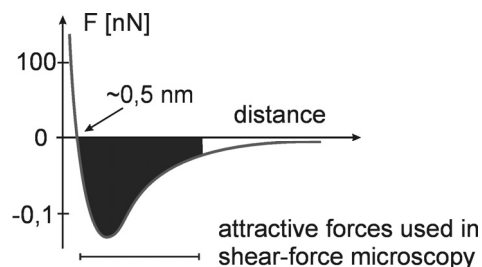


Fig. 2. Tip-sample force distribution curve. The vertical scale is distorted in order to show both attractive and repulsive forces

Moreover, the optical detection system allows one to apply voltage to the conductive microtip. In this case, the microtip can be used as an electron beam (e-beam), as a collector of field emission current flowing between the tip and surface. The small amount of force acting between the tip and a sample increases the lifetime of the tip and reduces the risk of the tip and sample damaging.

At the wire length varying from 5 to 7 mm, and when the spring constant is in the range from 1 N/m up to 3 N/m, the resonance frequency is about 12 kHz and a typical Q factor of the resonance is 100–200. Tungsten tips are commonly used in STMs due to convenient etching technology and well known work function.

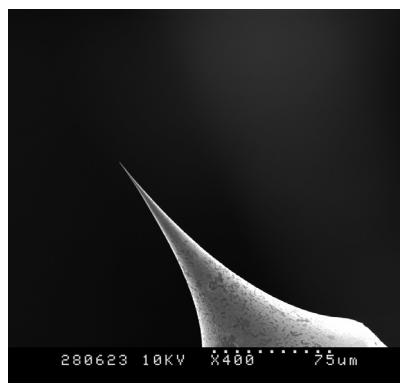


Fig. 3. The SEM photograph of electrochemically etched tungsten scanning tip used in the setup. The diameter of tungsten wire is 120 μm

The tip oscillation amplitude was measured with a single mode fibre Fabry–Perot interferometer. The face of the fibre was placed in the distance of several hundreds of micrometers from the tip, which reflected light beam back to the fibre. The main part of the interferometer was placed outside the measurement chamber and therefore stable environmental conditions for the laser and detector were provided. The interfer-

ometric signal detected by a lock-in voltmeter allowed the measurement of the tip oscillation amplitude and to use it as the tip–sample distance indicator. As the tip approaches the surface, the oscillation amplitude decreases and a phase shift appears.

During the experiments, the setpoint value was about 90% of the free oscillation amplitude, which correlates with the tip–sample distance of about 10 nm. The detailed description of the interferometric detection setup has been published elsewhere [17, 18]. This solution allowed one to obtain a quantitative measurement with very high sensitivity.

When the biasing tip–sample voltage is applied, the setup allows taking measurements in two modes: simultaneous surface topography and emission current (Fig. 4), and the voltage–current curve measured in a specific spot over the surface.

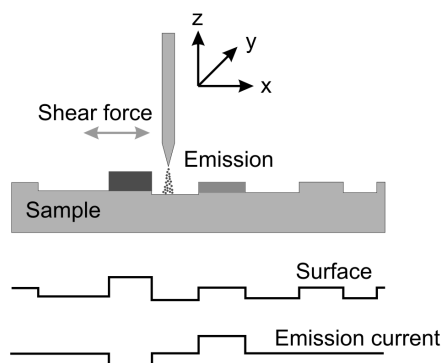


Fig. 4. The idea of simultaneous investigation of the topography and properties of the electrical surface with the combined shear force emission microscope setup

The field emission appears when electrical field causes deformation of potential barrier and electrons can leave the surface due to their high energy. This phenomena is also called the Fowler–Nordheim tunnelling [18], and can be described as follows:

$$I \approx A \frac{CE^2}{\phi \cdot t^2(y)} \exp \left\{ -\frac{B\phi^{3/2}v(y)}{E} \right\} \quad (1)$$

where A is the emitter surface area, E is the applied electric field, ϕ is the work function of the metal, B and C are constants, $v(y)$ as well as $t(y)$ are functions which arise due to the inclusion of image charge effects. The emission current depends on work function of the surface when other parameters are constant.

The energy necessary to obtain field emission phenomena is achieved as the result of a very small tip–sample distance. By the typical distance between 10 and 15 nm and the applied tip–sample voltage just about few volts – the electric field can reach level of tens of MV/m. It is must be mentioned that the real distance between the tip and conducting bulk can be bigger than the approach curve could indicate, due to presence of water film on the surface and thin oxide layer (oxidation process can appear naturally, when the clean metallic surface is exposed to the humidity, and as result the surface is covered by thin oxide layer). Thereby a real electric field can be smaller

than the estimated one, nevertheless it is still sufficient to obtain emission current from the surface which was confirmed experimentally.

According to the presented equation, when the all factors are constant, the value of current will vary, when the tip moves over the areas made of different materials (different values of work function).

3. Results

In order to demonstrate the efficiency of the method, some tests were performed. Presented examples were obtained by simultaneous measurement of the surface topography and the emission current. The first example shows a two metal sample: alumina structures deposited on chromium substrate by magnetron sputtering. The topography is shown in Fig. 5. The edge of the structure is visible clearly as well as relatively rough surfaces of chromium and alumina. Also, the side of the structure is visible due to sample tilt. It allows one to recognize the structure and the substrate very clearly.

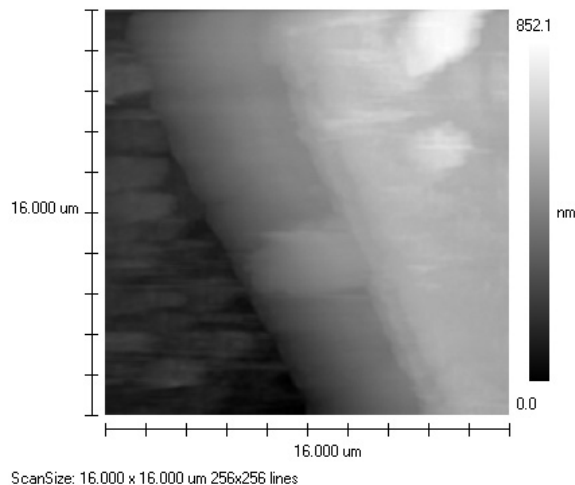


Fig. 5. The surface picture recorded on alumina deposited on chromium substrate

On the emission picture (Fig. 6), one can see the emission area which is correlated to the chromium surface but no emission was recorded over the alumina surface. The result is connected probably to the relatively thick native alumina oxide layer which makes the emission very weak in this measurement conditions. Increase of the voltage could allow one to obtain the emission current through the alumina oxide but the risk of overload the current–voltage converter during the chromium area emission measurement should be taken into account. This problem can be solved by applying logarithmic current–voltage converter instead of the linear one. It can allow one to meas-

ure the current up to eight orders of magnitude which should be a satisfying solution in this case.

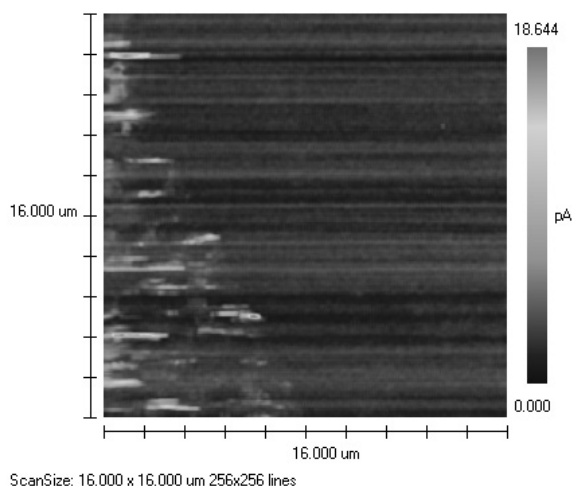


Fig. 6. The emission picture recorded on alumina deposited on chromium (tip-sample voltage – 11 V)

Next example shows a silicon sample covered with a native oxide layer (Fig. 7). Such layers are usually ca. 1 nm thick. This surface is very flat, without major features or structures. At a closer look, one can note few black points which can be easily overlooked, but even noticed, can be ignored as insignificant artefacts connected to the noise presence during the measurement.

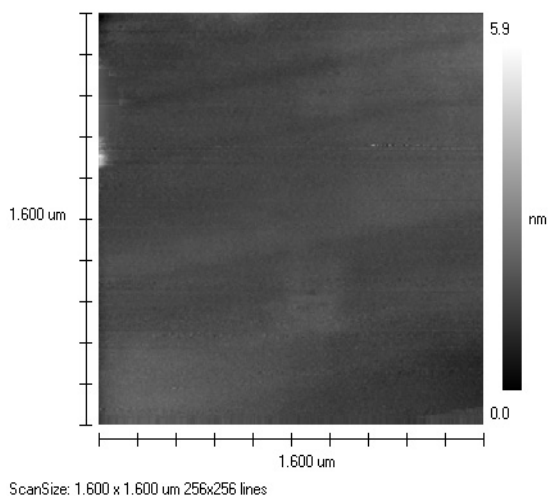


Fig. 7. The surface picture recorded on a silicon sample

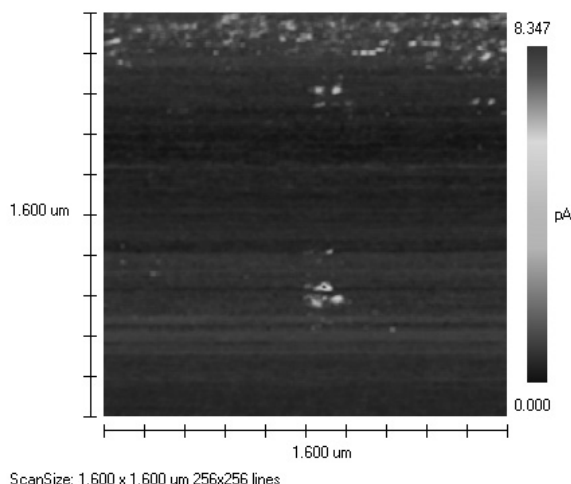


Fig. 8. The emission picture recorded on a silicon sample (tip-sample voltage -5 V)

The current emission map shows the correlation between black spots on the topography picture and significantly increased emission areas (Fig. 8). This picture shows weak points of the oxide layer, where the potential barrier is smaller than the other places and current flows easier. An additional measurement of the topography in those areas should be performed in order to investigate more closely the conductive spots.

4. Summary

The modular shear force emission microscope has been presented. It can be used for diagnostics of thin dielectric layers. Such layers are used not only in semiconductor industry but they are utilized generally in wide spectra of industrial production. In this case, however, the quality and continuity of the dielectric layer in submicrometer scale is crucial. Thereby this method can be applied in other research issues as well.

One should be aware of possible difficulties. Some surfaces can be covered relatively quickly by native oxide when left in ambient conditions. This issue must be taken into account when the measurement is planned. This problem can be solved by performing the measurements in vacuum, but that causes major increase of costs. Moreover some processes cannot be performed in vacuum and another solution must be developed in such cases.

The main advantage of presented method is a non-contact measurement which allows providing the long life of the tips. Moreover, electrochemically etched tungsten tips are much cheaper than silicon cantilevers with metal covered tips and very good known work function of the tungsten is always valid. Thereby one can always measure

with confidence. In silicon cantilevers, the metal coating can be removed from the tip due to wear and the results can be no longer reliable.

Presented results proved efficiency of the method, however further research and tests are necessary in order to develop the method and the setup as well. In addition, the measurement conditions, sample preparation procedure, and its impact on the result should be carefully investigated.

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