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Non-standard techniques of surface characterization in scanning electron microscope

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In this paper the specific techniques considerably extending the capabilities of a standard scanning electron microscopy (SEM) for quantitative topographic and voltage contrasts, supplemented by those concerning the low energy and the high pressure microscopy, are discussed. The techniques involve special detector systems combined with proper signal processing units. They have been designed mainly for investigations of semiconductor materials and devices, however they may be also useful in other fields of technology.

1. Introduction

Scanning electron microscopy (SEM) is a basic tool of surface characterization in many fields of science and technology. Such a high position of SEM among scientific instruments results from the fact that it can deliver a very wide spectrum of information about a sample without complex preparations. However, the type of an obtainable piece of information depends on the kind of signal, and the manner of its detection. Apart from many signals that are generated from the sample under the electron beam bombardment, secondary electrons are usually detected in a standard SEM. It portraits the surface with a combination of lights and shadows, that express, in a qualitative way, mixed information about surface topography and material composition. Other kinds of information or specific forms of their presentation need special systems of the signal detection and processing [1]. Some of the systems are offered in a form of specialized microscopes as, for instance, electron beam testers that apply many kinds of voltage contrast for searching electrical malfunctions of integrated circuits.

Authors developed a series of systems for acquisition of special types of contrast, which were designed as a kind of equipment that can be installed in the standard SEM without any disarrangement of its original structure.

2. Quantitative characterization of surface topography

There is a possibility to separate different kinds of information by a proper processing of the signals obtained from a multi-detector system with directional properties [2], [3]. In this case, a method called “the shape from signal distribution” has been applied.

The current collected by one of the detectors shown in Fig. 1 can be written in the simple form

$$I_A = \int_{\Omega_A} i_0 \cos\gamma \sec\varphi_p \, d\Omega \tag{1}$$

where i_0 is the maximum angle density of the secondary electron current with the Lambert angular distribution.

After proper evaluation the expression for the detector A current takes the form

$$I_A = i_0 [\mathrm{d} \tan\varphi_0 \cos(\Theta_A - \Theta_p) + \mathrm{c}]. \tag{2}$$

In turn, the relative difference of signals of the detectors A and B obeys the equation

$$a_x = \frac{I_A - I_B}{I_A + I_B} = \frac{\mathrm{d}z}{\mathrm{d}x}, \quad \text{for } \Theta_A = 0. \tag{3}$$

Finally, an integral of the expression represents the surface profile along x axis, *i.e.*,

$$z(x, y_i) = a_x \int_{x_0}^{x_i} \left[\frac{I_A - I_B}{I_A + I_B}\right]_{y = y_i} \mathrm{d}x + C_i \tag{4}$$

where: x_0, x_k — coordinates of the beginning and the end of the scan line i, C_i — the integral constant, *i.e.*, the height at the beginning of the scan line.

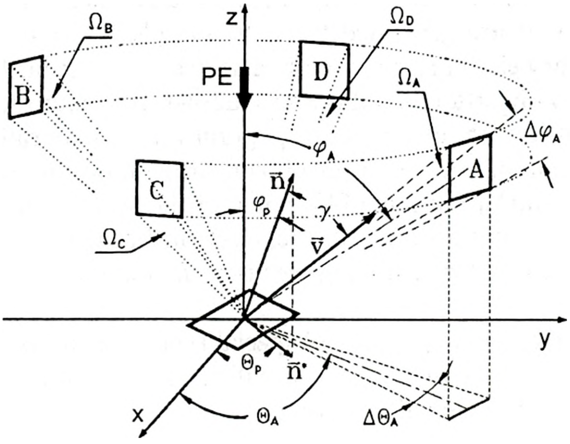


Fig. 1. Characteristic angles in a simplified detector system: A, B, C, D — detectors, PE — primary electron beam, $\vec{n}$ — vector normal to the sample surface φ_p — surface slope angle, γ — electron emission angle, $\vec{v}$ — initial velocity vector, $\Omega_{A,B,C,D}$ — electron detection solid angles, φ_A, Θ_A — detector position angles.

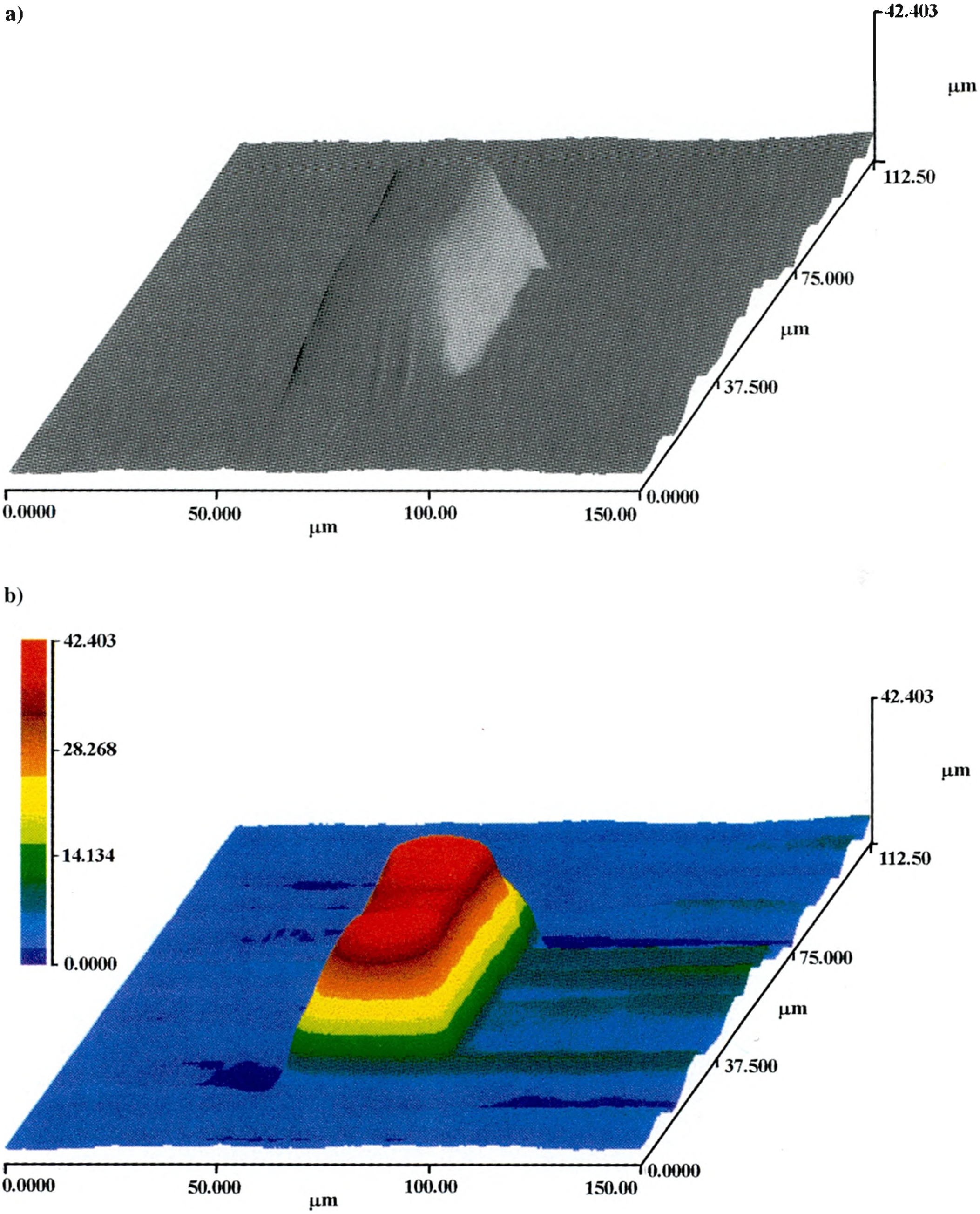


Fig. 2. Three-dimensional images of the etching in a silicon wafer: **a** – object shaded with the differential signal, **b** – object height coded with colours.

A fully three-dimensional image can be obtained when the second pair of the detectors (C, D) is used to provide information about surface slopes in the yz plane. Then, the final expression defining the surface topography along the successive scan lines takes the following shape:

$$z(x,y_i) = a_x \int_{x_0}^{x_k} \left(\frac{I_A - I_B}{I_A + I_B}\right)_{y=y_i} \mathrm{d}x + a_y \int_{y_{i=1}}^{y_i} \left(\frac{I_C - I_D}{I_C + I_D}\right)_{x=x_0} \mathrm{d}y + C_0. \tag{5}$$

The second integral reconstructs the surface profile in the y direction along the starting points of all lines ($x = x_0$), beginning with the initial altitude C_0.

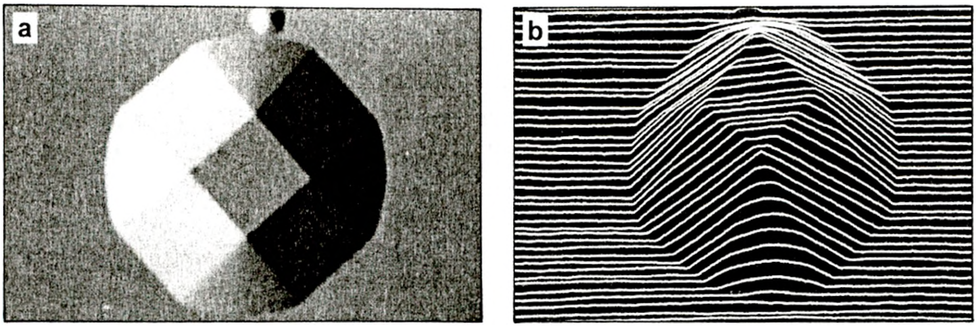


Fig. 3. Images of etchings in a silicon plate at the final beam energy $E_r = 1.5$ keV, horizontal field width 100 μm: **a** – "topo S" mode, **b** – "profile" mode.

The formulas for signal processing, (4) and (5), can be realised both in analogue and computer systems. A fully three-dimensional visualisation of the surface implies some kind of axonometric imaging (Fig. 2), easily accessible on the computer. Analogue systems seem more suitable for imaging the surface topography in a shape of profiles (Fig. 3), which is a form of two-dimensional representation and can be displayed on the analogue monitor in a "real time".

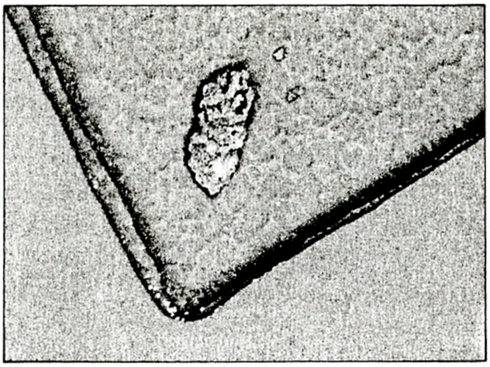
3. Modification of low energy microscopy (LESEM)

Shortcomings of the standard SEM are charging effects and radiation damages caused by a high energy electron beam, which limit examining insulators and semiconductor devices. To avoid these limitations the multiple detector gauge equipped with a retarding electron lens was elaborated [4]. The lens can reduce the final electron beam energy up to ten times. The electron irradiation of so low energy cannot be harmful to semiconductor devices and thus the image contrast for light materials may be essentially improved. When the energy is optimally chosen, a necessary balance between the electron beam current and the secondary emission is obtainable, which eliminates charging effects on dielectric surfaces. The multi -detector gauge still allows to obtain three-dimensional images using the earlier mentioned system.

Images of the etchings in a silicon plate shown in Fig. 3 may serve as examples of the system functioning. Signals processed according to the formula (3) express only local surface inclinations along the x-axis, so the image synthesized with the signal (Fig. 3**a**) shows the "pure topographic contrast" displayed in the qualitative way of lights and shadows. The shape can be estimated in quantitative terms (the height and side slopes) in Fig. 3**b** where the surface profiles have been reconstructed according to the formula (4).

4. Modification of high pressure microscopy (HPSEM)

SEM are designed to operate in high vacuum and primarily for electrically conducting specimens. This eliminates the insulator specimens or those with high vapour constituents, for instance biological materials. The disadvantages of conventional SEMs lead to the development of the high pressure scanning electron microscopy (HPSEM) [5]. In these microscopes, an acceptable value of the working pressure in the specimen chamber is higher than 609 Pa (pressure of saturated water vapour at 0 °C).



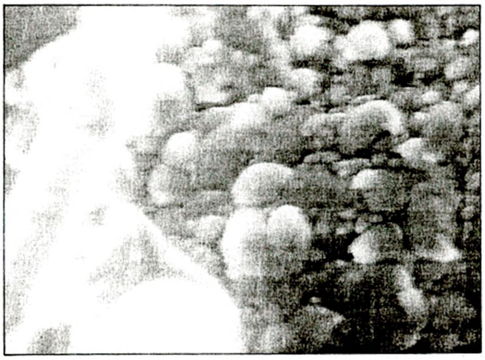


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Fig. 4. Fragment of IC with a dust (horizontal field width 120 μm, Robinson detector, $E_a = 20$ keV, $p = 5$ hPa).

Fig. 5. Frost on a leaf surface with a protruding hair (horizontal field width 300 μm, ionisation detector, $E_a = 20$ keV, $p = 5$ hPa).

A unit necessary for adaptation of a standard SEM to HPSEM technique has been designed [6]. The main part of the unit is an intermediate vacuum and detection chamber, designed in the form of a compact head that may be inserted into the sample chamber through a proper window at its side. The head is connected with a rotary pump and equipped with two vacuum meter gauges and a gas dosing system. The detector part of the head consists of a "gaseous secondary electron detector" and the Robinson detector for backscattered electrons. A cooled sample stage may also supplement the set of equipment to extend its range of applications.

The unit allows gas pressures over 20 mbar in the sample chamber. It is high enough for examining not only dielectric samples, as those shown in Fig. 4, but also a range of water- and other liquid-containing specimens (Fig. 5).

5. Voltage contrast

As the size of electronic devices has shrunk below the micrometer scale, the fact that SEM can combine high resolution with imaging of the surface potential distribution and the ability to measure voltages, makes it in many cases a very handy tool of characterization, diagnostics and failure analysis [7]. Thus, the voltage contrast detection unit has been designed for the above-mentioned purposes [8]. The most important part of the unit is a retarding field electron energy analyzer of a novel design. A standard SEM equipped with the unit can work in a few regimes listed below:

- imaging of the surface potential distribution including low-frequency alternating voltages,
- direct measurements of constant voltages on conducting paths,
- wave form observations for alternating voltages on conducting paths.

An example of the potential distribution imaging obtained with the unit is shown in Fig. 6.

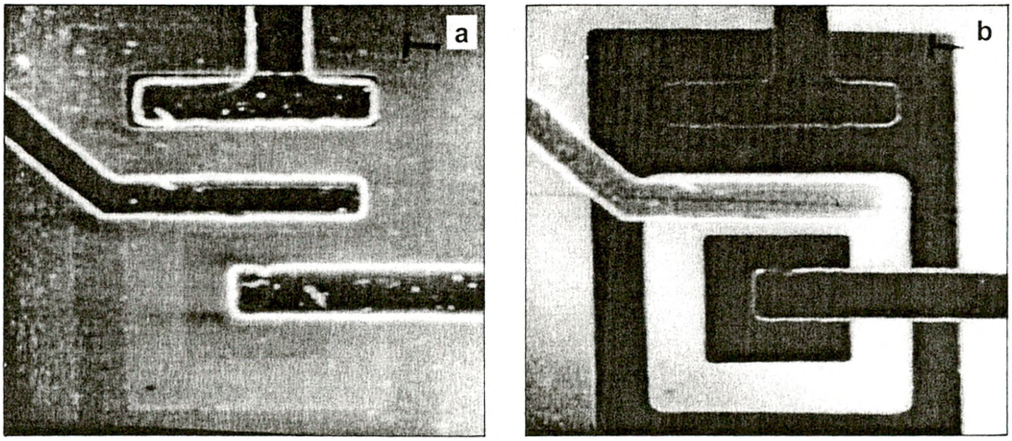

Fig. 6. Surface voltage distribution on the part of IC MAA501 (horizontal field width 400 μm): a — unbiased, b — biased with constant voltage 5 V.

6. Conclusions

A few examples of the equipment discussed above has shown that capabilities of a standard SEM may be considerably extended at a relatively low cost. A special kind of contrast involves specialized detector systems combined with proper signal processing units which may be easily mounted in SEM or disassembled. The types of equipment discussed were designed mainly to investigate semiconductor devices and materials, however they may be also useful in other fields of technology.

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