

# Makyoh topography: a simple and powerful method for the flatness characterisation of semiconductor wafers

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The paper presents our research in the field of Makyoh topography, a method based on an ancient principle. The method's application is the qualitative and quantitative study of semiconductor wafers and other mirror-like surfaces.

## 1. Introduction

Semiconductor technology requires perfectly flat and defect-free single crystal wafers as starting material. Any deviation from the ideal flatness can hinder processing steps or degrade process quality. Therefore, a high interest exists both from wafer manufacturers and users towards contactless, highly accurate, clean and fast characterisation tools which can be used to screen or characterise the wafers with regard to geometrical or topographical defects.

Numerous methods exist for flatness characterisation. The surface topography can be measured with high accuracy using surface stylus methods, but they are slow, require mechanical movement and the stylus can scratch the surface. The requirements of non-contact operation are fulfilled by the optical methods [1], such as laser scanning or other, mainly interferometric, techniques. However, the realisation of these methods for large-size samples is difficult.

As an adaptation of the ancient Japanese magic mirror [2], a new alternative tool, *Makyoh topography* appeared in the late 1970s [3,4] (*Makyoh* means 'magic mirror' in Japanese). The principle of the method is the following: the surface under study is illuminated by a homogeneous, collimated light beam, and the reflected beam is intersected by a screen placed some distance away. Because of the surface's microdeformations, a non-uniform intensity distribution characteristic to the surface topography appears on the screen (*Fig. 1*).

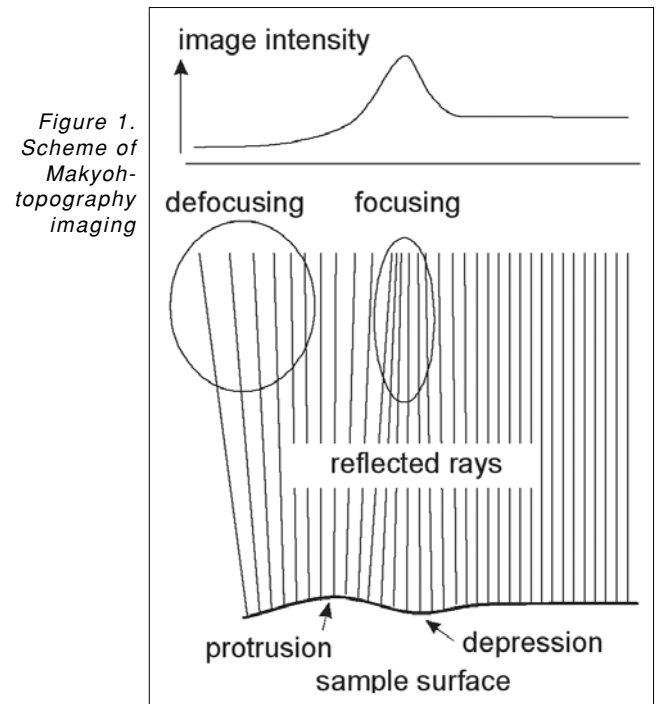
In practice, optical set-ups containing a CCD camera and other optical elements, equivalent to the original one, are used. A number of researchers and manufacturers were inspired to apply the technique by its exceptional simplicity. The method has been applied more widely from the '90s mainly for wafer screening and the assessment of lapping-polishing technology [4-6]. The construction of the set-up is simple, the scaling for large-area studies is straightforward, and the method is able to detect surface defects in real time and with high sensitivity.

However, a drawback of the technique in its original form was its inability to perform quantitative studies.

The aim of the present paper is a short, concise description of the basic and applied research in the field of Makyoh topography conducted at MFKI (Műszaki Fizikai Kutatóintézet) and at the legal successor MFA.

## 2. Initial steps

Research on the method commenced at MFKI in the beginning of the 1990s. *Fig. 2* shows the scheme of the first set-up constructed at MFKI [7]. The light source is a pigtailed LED (wavelength, 820 nm) providing a 50- $\mu$ m-diameter light spot. A 500-mm focal length lens, positioned above the sample, serves as a collimator for the light source and as a 'magnifier' for the camera. The



maximum sample diameter is limited to 75 mm by the lens aperture. The images obtained by the camera were recorded and stored on a video tape recorder.

The research and manufacturing of GaAs devices at the Department of Microwave Devices of MFKI as well as our international contacts provided a large number of samples for characterisation [8,9]. These studies – in accordance with the state of the art at the time – remained within the framework of qualitative interpretation. Some characteristic examples are shown in Fig. 3. The pattern of closely parallel arcs indicates saw marks, the periodic, dark spots indicate a rough surface morphology, while large-size features with the slowly varying contrast are due to large-scale wafer deformation.

### 3. Fundamentals of image formation

As measurements providing numerical results are basic requirement of modern technology assessment, our further research aimed at the understanding of the image formation of Makyoh topography. Since for Makyoh topography set-ups an optically equivalent system can be found, which, disregarding a magnification factor, consists only of a collimated illumination and a distant screen, the imaging can be characterised by a single parameter, the equivalent screen-sample distance ( $L$ ) [10,11].

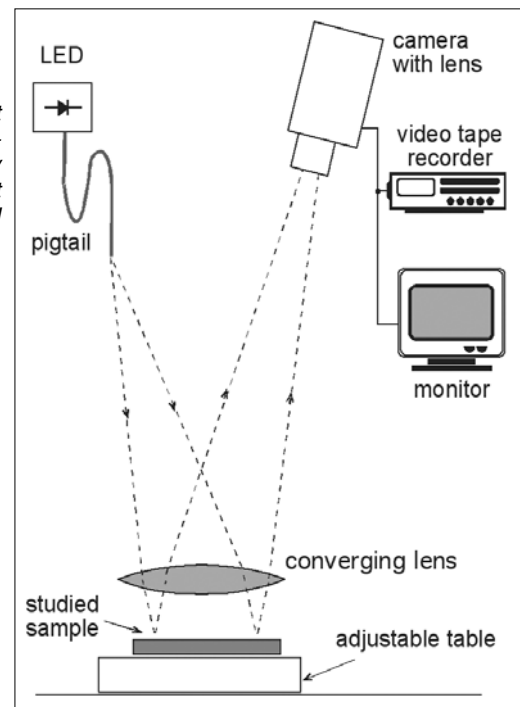
The geometrical optics model of Makyoh imaging was described in Ref. [12] in detail. Here we present only the final result. The screen position  $\mathbf{f}(\mathbf{r})$  of a light beam reflected from a given  $\mathbf{r}$  point of the surface is given by the following formula (for small incidence angles, that is, for a relatively smooth surface):

$$\mathbf{f}(\mathbf{r}) = \mathbf{r} - 2L \text{grad } h(\mathbf{r}). \quad (1)$$

This equation follows trivially from the law of reflection: the shift of the reflected beam's position relative to a flat sample surface is proportional to the surface gradient at the given point. The  $I(\mathbf{f})$  intensity of the  $\mathbf{f}(\mathbf{r})$  point (relative to that of a flat surface with unity reflectivity) is described by the following formula:

$$I(\mathbf{f}) = \frac{\rho(\mathbf{r})}{|(1 - 2LC_{\min})(1 - 2LC_{\max})|}, \quad (2)$$

Figure 2. The first Makyoh-topography set-up built at MFKI

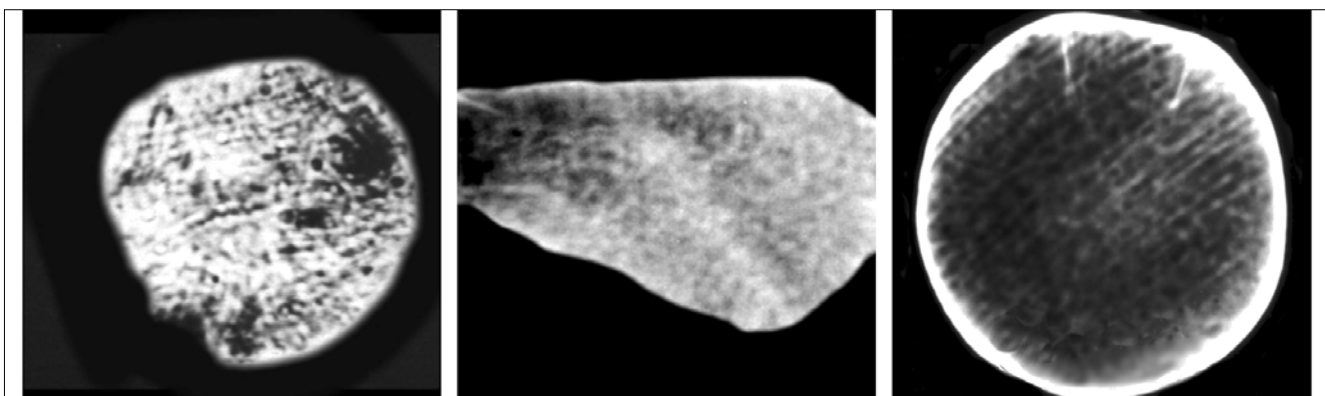


where  $\rho(\mathbf{r})$  is the local reflectivity of the surface, and  $C_{\min}$  and  $C_{\max}$  are the local maximum and minimum curvatures of the surface. That is, the intensity of the reflected beam is determined by the second-order properties of the surface.

It follows from the above equation, that at small  $|L|$  values, a given surface point and its image are close to each other (assuming the sample and screen are effectively in the same plane), and the main component of the image contrast is resulted from the inhomogeneities of the surface reflectivity. Increasing  $|L|$  increases the contrast and the distance between the point and its image, suppressing the component due to reflectivity variations. The optimum setting is therefore in that medium region of  $|L|$  which gives high enough contrast for the safe observation of the image while retaining the integrity of the surface topology in the image.

Although the geometrical optics description is approximate, it gives satisfactory description for most cases. Significant diffraction effects are encountered only if the sample has sharp surface topography features, e.g. at

Figure 3. Typical Makyoh images of semiconductor wafers



the edges of openings. The geometrical optics approach may also not be sufficiently accurate if many beams meet at a certain point in the image. In practice however, the wafers studied using the technique have a uniform reflectivity, their surface topography is mainly smooth and varies slowly, and the optimum imaging regime is just when focussing effects are not encountered.

#### 4. Quantitative Makyoh topography

Although the imaging laws of Makyoh topography are simple, the equations describing the imaging are not invertible, thus the analytic determination of the surface topography from the Makyoh image is not possible in the general case [13]. However, if the homogeneous illumination is structured by some mask, certain points of the surface are 'labelled'. Thus, based on Equation (1), the surface gradient can be determined at the labelled points if the positions pertaining to the ideal flat surface are known. Equation (2) thus becomes superfluous. The most expedient way of structuring is a square grid. The  $h(x, y)$  height topography in the grid points can then be approximated by the following sum [13]:

$$h(x, y) = \frac{1}{2L} \sum_i [\Delta x(x_i - f_{xi}) + \Delta y(y_i - f_{yi})] \quad (3)$$

Here  $\Delta x$  and  $\Delta y$  are the grid cell sizes, and  $(f_x, f_y)$  are the co-ordinates of the  $(x, y)$  grid point;  $(x_i, y_i)$  denotes the co-ordinates pertaining to the ideal flat surface, which can be determined by the measurement of a flat reference mirror. The summing starts at a point whose height can be chosen arbitrarily. In principle, the summation path can be chosen arbitrarily since all paths with the same starting and end points should give the same sum. In practice, however, because of the finite resolution of the grid, the error of the integral sum depends on the path and its value is not predictable. The accuracy of the method can significantly be increased if the sums of all paths (or, more precisely, the paths contained in a rectangle spanned by the starting and end points) are calculated and averaged. This procedure, however, can take a long time even for a small grid. We therefore developed a recursive algorithm which gives the same result but is much faster [14,15].

We have also developed an algorithm for the location of the grid points. The algorithm runs a cross-like weight function over the Makyoh image and their correlation is determined. By finding the local maxima of the correlation function, the coordinates of the grid points can be determined with subpixel accuracy.

The described method can easily be automated, it allows simple and fast (quasi real time for a 50x50 grid) quantitative studies. It is important to note that, provided that the grid lines are significantly thinner than the grid pitch, the Makyoh image remains visible showing the contrast caused by small-size surface defects. This property corresponds to the requirements of the semiconductor industry, since the topography of the wafers,

in general, is a result of the superposition of a slowly varying deformation (curvature, warp) and localised defects (polishing, lapping marks etc.). It is advantageous if the image of the grid is nearly focussed. This can be achieved by the arrangement described in Section 2.

The path-dependent error component of the integral sum can be eliminated by an iterative (so called relaxation) procedure [15,16]. This method is more accurate than the direct integration, but it is slower, rendering it unsuitable for real-time measurements.

### 5. Applications

#### 5.1. Studies of deformations induced by wafer reclaim

Large-diameter semiconductor wafers are expensive, and wafers that were rejected by one the technology line may still be suitable for certain other purposes. Wafer reclaim is therefore a dynamically growing branch of semiconductor industry. The same considerations apply for the novel, costly compound semiconductor materials, such as SiC. Wafer reclaim includes the removal of the device layers and subsequent polishing of the wafer. A model experiment was carried out in our institute [17] with an aim to study the deformations induced by the wafer reclaim steps and to explore their possible causes. In the course of this experiment, the deformations of two-inch-diameter processed Si wafers were examined after each layer removal.

We have shown that the removal of the functional layers (oxide or metallisation) induces a uniform change of the wafer curvature, while the final polishing step causes a non-uniform deformation, which depends on the amount of the original deformation and the parameters of the polishing process. Comparing the samples after final polishing, we established that the originally flat or uniformly curved wafers remained flat or uniformly curved upon polishing. Our interpretation is that upon polishing, the attachment of an originally curved wafer to the supporting plate makes it flat, and, upon releasing it after polishing, it re-acquires its original shape. In contrast, the topography of the wafers having irregular topography before polishing changed upon polishing showing no obvious correlation with the original shape. These deformations are presumably related to imperfections of the polishing process.

#### 5.2. Studies of the deformation of MEMS elements

Although the chief application of Makyoh topography is the study of the large-area surfaces, and the strongly structured MEMS samples cause strong diffraction patterns, in simple cases, the method can still be used efficiently. We studied the deformation of 4-10 mm side length Si/SiN<sub>x</sub> square membranes [18]. We compared the measured deflection of the centre point of the prepared membranes with the deflection values obtained by finite element thermo-mechanical simulations in order to determine the thermal expansion coefficient of SiN<sub>x</sub>. We obtained good agreement if we set 2.62x

$10^{-6}\text{K}^{-1}$  for the thermal expansion coefficient of  $\text{SiN}_x$ . We emphasize that the height of the membranes' centre points were below  $0.1\ \mu\text{m}$ , which shows the high sensitivity of the method.

Fig. 4. shows a Makyoh image and the corresponding calculated height map as well as a characteristic simulation result. According to the measured Makyoh topogram, a shallow ( $\approx 0.01\ \mu\text{m}$  deep) depression is situated in the centre of the otherwise convex membrane, well reproduced also by the simulations. The deformation of the substrate around the membrane area is visible on the Makyoh topogram as well as on the simulated topography.

## 6. Novel experimental set-ups: a mirror-based arrangement and the Digital Micromirror Device

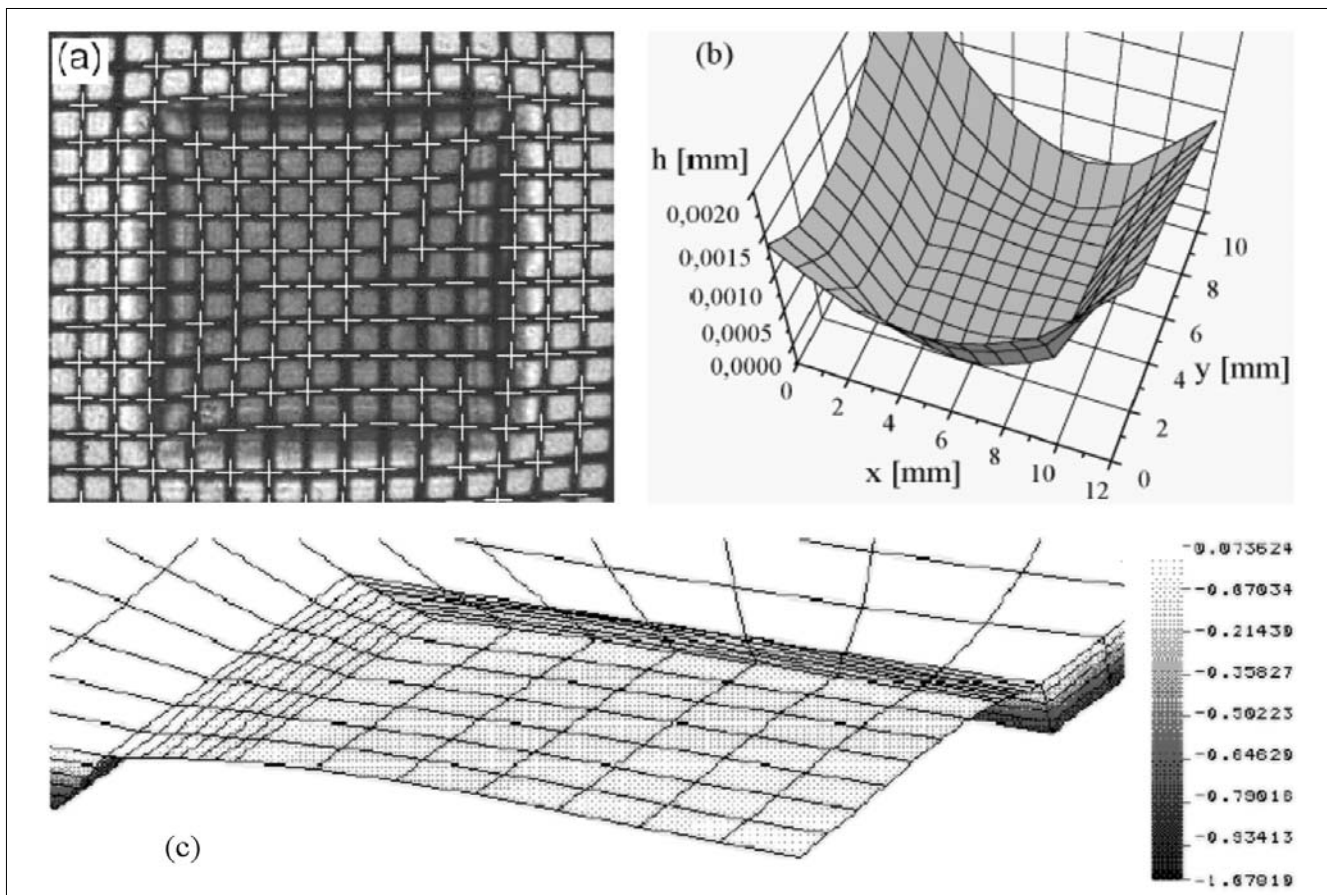
The greatest disadvantage of the arrangement described in Section 2 is the inability of studying large-diameter samples, because a large-diameter collimator/magnifier lens without significant aberrations it is extremely costly. To circumvent this problem, we constructed a mirror-based system (Fig. 5) [19-22]. The parabolic mirror applied in off-axis arrangement eliminates spherical aberration, and the beam splitter makes the imaging free

of parallax errors. The diameter of the parabolic mirror is 300 mm, its focal length is 1524 mm. The value of  $L$  can be varied between approx. 0 and 5500 mm by changing the distance setting of the camera lens. With this equipment we have a modern, sensitive, high dynamic range, widely applicable tool. The greatest advantage of the device is its scalability: off-axis parabolic mirrors of 450 mm diameter and  $\lambda/20$  surface quality are available on the market. As an alternative arrangement, a set-up employing separate spherical mirrors in the illuminating and detecting paths was built and its operation was demonstrated [20]. The advantage of this arrangement over the one based on the parabolic mirror is its smaller cost.

The greatest disadvantage of the grid version is the bad lateral resolution: a grid must be sparse enough in order to allow the safe detection of the grid points. The lateral resolution can be increased by applying a shifted grid and sequential image recording; the grid is shifted by a fraction of the grid period between each exposure, thus we obtain a "supergrid" with a period equalling the shift distance. Real-time measurements cannot be realised. The most expedient way of the realisation of this concept is a programmable mirror matrix (Digital Micromirror Device, DMD). The DMD consists of a matrix array of individually addressable micromirrors that can be tilted around their diagonal. (Such devices are used e.g. in DLP projectors.)

Figure 4.

The Makyoh image of a  $10\times 10\ \text{mm}$   $\text{SiN}_x$  membrane (a) with the localised grid points, (b) the calculated height profile and (c) the profile as simulated by the finite element method (height data are in  $\mu\text{m}$ )



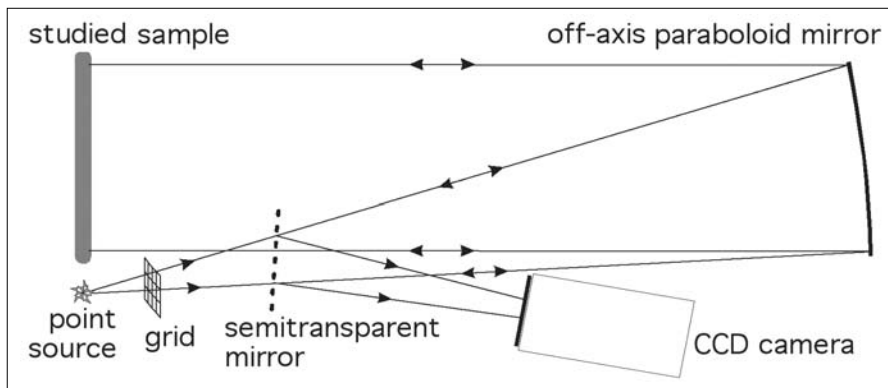


Figure 5.  
The scheme of a mirror-based  
Makyoh-topography set-up

Because the pattern is finer than that of the traditional fixed grid, it is more important to ensure that the image of the mask be sharp on the Makyoh image. Because it is more difficult to achieve this with the mirror-based system, we positioned the DMD in a telescopic system consisting of two converging lens. The first (lens-based) version of the set-up has been built in the University of Oxford [16]; 0.7 mm lateral resolution was achieved, and a maximum 10% difference projected to the total height span of 7  $\mu\text{m}$  was demonstrated comparing the results to interferometry.

The application of DMDs opens new perspectives in Makyoh topography [21]. In addition to the described shifted-grid set-up, a grid with any period (or even any arbitrary pattern) can be realised, thus the trade-off between measurement speed and lateral resolution can be optimised.

## 7. Summary

The research we described contributed to the basic understanding of an already known research tool: the “magic” phenomenon became an understood, widely applicable method that knocks on the door of industrial applications. Regarding further applications and other aspects we kindly refer the reader to the literature [23-25] and to the home page of the research:

<http://www.mfa.kfki.hu/~riesz/makyoh/>

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