Effects of speckle in Makyoh topography for the studies of extended defects

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Abstract. The effects of the speckle phenomenon on Makyoh-topography imaging is analysed. The speckle manifests itself as a quasiperiodic pattern in the Makyoh image which is easily mistaken for an image of a periodic surface morphology. The characteristic signature of speckles in Makyoh images is determined, thus allowing for its recognition. The effects of speckle on the Makyoh imaging is analysed as a function of surface roughness, illumination coherency and wavelength, light source size and instrumental parameters. It is shown that speckle effects are present even for incoherent illumination because of the coherency enhancement due to the limited source size. The findings are illustrated with experimental images of various semiconductor samples.

1. Introduction
Makyoh (or magic-mirror) topography (MT) is a simple but powerful optical method for the study of macroscopic surface defects in semiconductor wafers and structures [1-3]. The principle of the method is the following: any topographical irregularity of the sample surface acts as a (local) convex or concave mirror therefore a parallel or spherical light beam impinging on the surface produces an image on a screen at certain distance that reflects the sample morphology because of the light/bright contrast due to focusing or defocusing effects (figure 1). Practically realised set-ups usually contain additional optics and a CCD camera as an imaging tool. The advantages of the technique, as compared to other methods, are the following: simple, inexpensive, robust set-up, relative immunity to vibrations, real-time operation and high dynamic range.

MT emerged as a tool applied mainly for the qualitative assessment of the polishing quality of semiconductor wafers: saw and lapping marks, dimples and other defects are clearly visualised by MT [1-2]. However, it has been demonstrated that the method is sensitive enough to detect the surface fingerprints of extended defects as well, such as stresses of grain boundaries in GaSb crystals [4], swirl defects in p-Si [5] and bunches of dislocation slip lines in GaAs wafers [6]. Figure 2 shows an example of a concentric rippled morphology of a p-Si wafer associated with a swirl defect [5].

Makyoh is usually considered a geometrical optical technique. Coherency effects are observed only as diffraction fringes at sample edges and around isolated surface defects. However, another coherency effect, the speckle phenomenon, has been overlooked by researchers dealing with MT. The speckle pattern is caused by self-interference of a reflected beam because of the sample’s surface roughness. In this paper, the effect of the speckle phenomenon on MT imaging is analysed. First, the background on Makyoh topography and the speckle phenomenon is summarised, then, the relevance
to Makyoh topography is analysed. The findings are illustrated with experimental data with emphasis on problems related to the imaging of surface fingerprints of (point-like and periodic) extended defects. Since Makyoh topography is a chiefly qualitative technique, we restrict ourselves to a semi-quantitative analysis stressing the basic characteristics.

2. Background on Makyoh topography

A geometrical optical model of image formation has been presented in [7]. The two basic imaging equations are:

\[ f(r) = r - 2L \text{grad} h(r) \]  \hspace{1cm} (1)

and

\[ I(f) = \left| (1 - 2LC_{\text{max}})(1 - 2LC_{\text{max}}) \right|^{1/4}. \]  \hspace{1cm} (2)

Equation (1) gives the position \( f(r) \) of the image of a sample point \( r \), while equation (2) gives the image point’s intensity \( I(f) \) normalised to that of a flat surface, for a given surface height profile \( h(r) \).
We assume unity surface reflectivity. The key parameter of Makyoh imaging is \( L \) the screen-to-sample distance. \( C_{\text{min}} \) and \( C_{\text{max}} \) are the two principal curvatures at point \( r \), that is, the minimum and maximum of the second derivatives of \( h(r) \). Increasing \( L \) results in increasing contrast, thus higher sensitivity, but also the distortion of the imaging topology.

3. Basics of speckle phenomena
If a fully or partially coherent light beam is reflected from a rough surface, a speckle pattern is formed on a distant screen or sensor by the self-interference of the reflected beam [8-9] (this is the so-called objective speckle). The speckle is a quasi-periodic pattern with two main characteristic parameters: the speckle size and the contrast. The average speckle size \( s \) is given by

\[
s \approx \frac{\lambda L}{d},
\]

where \( d \) is the diameter of the area from which the reflected rays can interfere at a given screen point, and \( \lambda \) is the illumination wavelength [8]. The intensity distribution follows an exponential decay. The associated speckle contrast \( C_S \) is defined as the rms intensity distribution divided by the average intensity. The speckle contrast is determined by the roughness [9]. Its exact nature depends on the actual surface statistics in a complex way even for the simplest models. Generally, the contrast monotonically increases with roughness and saturates at unity at the rms roughness of about \( \lambda/4 \). Note that the contrast does not depend on \( L \) for a given surface and wavelength.

4. Implications for Makyoh topography
The Makyoh arrangement is naturally prone to the speckle phenomenon. The lasers and LEDs used for illumination have coherence lengths of several meters and \( \sim 10 \mu m \), respectively. As a result speckle effects are expected to occur. Although the coherence lengths of incandescent lamps (often used in Makyoh set-ups) is a few microns at most, an increase of the spatial coherency occurs because of the small source size [9], giving rise to speckle. This effect will be discussed later.

To account for the observed speckle contrast, we have to consider the surface roughness. Today’s high-quality Si wafers have rms roughness in the sub-nm range, compound semiconductors have that in nm’s, giving contrast of a few percent at most which is just noticeable. However, chemically etched semiconductor surfaces and deposited metal layers may have higher roughness values up to tens of nm, yielding \( C_S \) of maximum \( \sim 20\% \).

Since speckle is a quasiperiodic pattern, it can be easily mistaken for the Makyoh image of a periodic surface relief. However, two features make them distinguishable: (1) the speckle size linearly increases with \( L \), while the feature size of a Makyoh image is independent of \( L \) (for a closely flat sample), and (2) the Makyoh contrast increases with increasing \( L \), while the speckle contrast has no \( L \) dependence. Varying \( L \) thus facilitates recognizing the speckle. Independent knowledge on the surface roughness may also help in separating the speckle and the Makyoh contrasts.

How does an existing speckle pattern influence the “readibility” of the relief-related (Makyoh) contrast is a complex question. For surfaces that are subjects of MT studies, a dominant specular reflection exists and the speckle will only modulate the reflected beam’s intensity. Consequently, the image contrast is still determined chiefly by the surface curvature variations. Speckle will pose a limit to the observation of the image only if the speckle pattern and the Makyoh patterns are matched in shape and periodicity. To quantify this effect, we consider the Makyoh contrast. It has been shown in [10] that the Makyoh contrast \( C_M \) of a sine-like surface having a peak-to-peak amplitude \( A \) and periodicity \( k \) is

\[
C_M = 8\pi^2 ALk^2,
\]

where \( \rho \) is the dimensionality of the surface (one for a surface of translational symmetry and two for a general surface). The contrast in equation (4) is defined in the same way as for the speckle, however, the intensity distribution of the Makyoh image is not exponential. Nevertheless, as a crude limiting approximation, it can be stated that the speckle contrast \( C_S \) sets an ultimate limit on the Makyoh
sensitivity, that is, $C_M > C_S$ must be fulfilled to observe the Makyoh image. In the more probable case, where the Makyoh image has a characteristic spatial pattern different from the speckle pattern (isolated point or line defects, parallel lines etc.), the statistically uniform spotty speckle appears as a noise on the Makyoh image, usually degrading visibility, but still allowing recognition. This problem leads to the complex field of pattern recognition in gray-level images [11]. For a clearer observation of the Makyoh pattern, small speckle sizes are preferred.

5. Experimental results and discussion

Experiments were carried out using a home-made Makyoh-topography set-up [12] that employs a pigtailed LED for illumination ($\lambda = 670$ nm, estimated coherency length is about 10 $\mu$m, source diameter $d_S \approx 50$ $\mu$m). Our set-up uses a converging lens placed close to the sample for collimating the illumination and providing a “magnifyer” for the CCD camera used for imaging (focal length $f = 500$ mm). The set-up is optically equivalent to the original “parallel-beam and screen” arrangement [7]. Negative $L$ values are also possible with this kind of set-up.

Figure 3 shows some examples of Makyoh images exhibiting speckles: part (a) shows the image of the half-polished backside of a Si wafer, exhibiting a textbook example of a fully developed speckle, and (b) shows a Si wafer having two regions with different amounts of speckle contrast. The images have been corrected for the magnification of the optical system. The effect of changing $L$ is clearly visible as a change of the speckle size. The results with samples having various degree of roughness indicated that equation (3) approximately holds but the resulting $d$ is significantly lower than the sample size: we found roughly $s \approx |L|/1000$, leading to $d \approx 1.5$ mm. This confirms the reduction of the surface’s coherency area due to finite source size. A semi-quantitative account of this effect can be outlined as follows. Since the speckle is formed by interference of the rays reflected by the sample surface, we have to consider the transverse coherence area at the sample plane (similarly to the Young double-slit experiment). The theoretical size (diameter) $d_C$ of the coherency area is given by [9]

$$d_C = \frac{\lambda}{\omega}, \tag{5}$$

where $\omega$ is the angle subtended by the light source at a surface point. In our case,

$$\omega = \frac{d_S}{f}. \tag{6}$$

(For an arrangement without collimator lens, the source-to-sample distance replaces $f$.) For our set-up, we get $d_C = 6.7$ mm. Simple considerations dictate that $d_C$ should be equal to $d$; our evaluation of $d \approx 1.5$ mm is contradictory. However, this discrepancy may be due to the simplified formulae used and to the fact that the actual intensity distribution was not taken into account.

Assuming that $d_C$ equals $d$, combining equations (3), (5) and (6), we obtain for the speckle size
that is, the speckle size is independent of the wavelength. The factor $L/f$ is an instrumental geometrical parameter depending only on the actual arrangement of the set-up which usually takes a value on the order of unity.

Finally, figure 4 illustrates the effect of the speckle pattern on real Makyoh images. The sample is a semiconductor wafer showing saw marks, a global deformation and some surface defects. The images taken at different $L$ settings show the dominant presence of a fully developed speckle pattern, but the Makyoh contrast is also well visible.

![Figure 4](image_url)

Figure 4. Makyoh images of a semiconductor wafer showing both speckle and Makyoh contrast. $L$ values from left to right: $\approx 10$ mm, $55$ mm and $110$ mm.

6. Conclusions
Coherency effects, including speckle, are present in Makyoh topography even for incoherent illumination because of the small light source size. Speckle effects as quasiperiodic patterns are encountered with contrast determined by the surface roughness and average size on the order of light source size. The speckle phenomenon appears as a disturbing effect on Makyoh topography.

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