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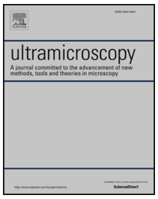

Wavelet transform-based electron tomography measurement of buried interface roughness

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ABSTRACT

Interface roughness is a critical parameter determining the performance of semiconductor devices. We show that a continuous wavelet transform is useful to describe not only the magnitude of the interface roughness, but also the spatial frequencies that describe the interface. We propose a simple presentation of the results that makes it convenient to compare between interfaces. In particular, an average and maximum value wavelet profile that is obtained from a series of one dimensional wavelet transforms provides a traceable and quick survey of the results. We demonstrate the wavelet transform method using both computer simulations and by applying it to experimental data obtained by electron tomography of a test sample and to a molecular layer interface. Wavelet descriptions of the interface roughness suffers less from the presence of shot noise in the experimental data than the traditional root mean square error description of interface roughness. An increase in lateral dimensions of an interface that has large features increases the content of low spatial frequencies in wavelet transforms. In comparison, the value of root mean square error increases in an untraceable manner with the same increase in lateral dimensions on the same interface. Morse wavelets with $\gamma = 9$ and $\beta = 3$ appear to be a suitable choice for applications in interface roughness measurement.

1. Wavelet transform is an alternative to root mean square interface roughness

The interface roughness (*IR*) of buried interfaces between layers of semiconductor devices or surface roughness of a deposited thin film is usually described by a root mean square (*RMS*) distance from a plane fitted to the interface. The *RMS* result is favorable in that it can estimate the magnitude of an interface's roughness, but it communicates no information about spatial variations of the interface. In many applications it is both the magnitude and the lateral spatial frequencies of the interface that affect the end application. For example, surface irregularities with small lateral scale have limited effect on light transmission but roughness at length scale comparable to the wavelength of the incident radiation can have a significant effect even if the amplitude of the irregularities is small. Similarly, roughness at a long scale has a limited effect on electron transport in electronic devices, while roughness at a few nanometer lateral scale leads to poor electron transport in devices [1]. Small spike defects in insulating layers of semiconductor devices are hardly seen as a change in *RMS* roughness, but have a profound effect on a device's performance.

Here we report the utility of the continuous wavelet transform (*WT*) as a tool for the description of nanoscale *IR*. The *WT* description enables users to evaluate not only the magnitude of the interface roughness, as the *RMS* does, but also to differentiate the spatial frequencies of the interface of a device. The method is first evaluated using computer generated interfaces, and is then demonstrated on buried interfaces measured by electron tomography (*ET*) data collected without a missing wedge [2].

The *WT* as an analysis method is popular in a wide range of fields. An excellent summary of wavelet transform theory and techniques is given by Addison [3]. Many examples of *WT* applications for analysis are available, including ocean movements [4], atmospheric turbulence [5], surface roughness of roads [6], and fluid turbulence [7]. *WT* are used to measure traffic patterns from a sequence of CCTV images [8], concrete floor flatness from laser scanner measurements [9], and terrestrial patterns in satellite landscape images [10]. There are other reports on small-scale surface flatness measurements, including the use of discrete *WT* on atomic force and scanning electron micrograph images [11], studying amorphous metals under load using scanning tunneling microscopy [12] and analyzing the roughness of metallic surfaces measured with an optical microscope [13].

The paper starts with a short summary of the *RMS* error method in

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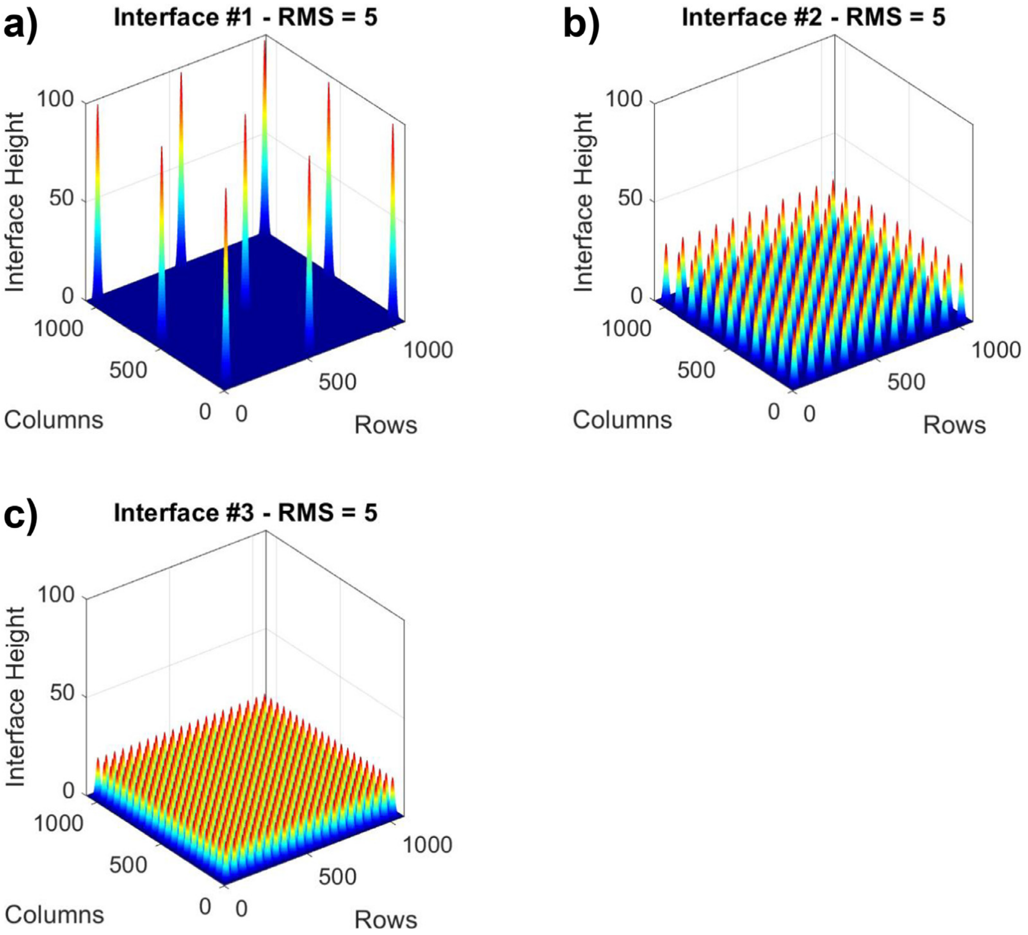

Fig. 1. Examples of interfaces with different appearance that have RMS = 5.
a) Interface with Gaussian spikes with 500 pixel period. b) Interface with Gaussian spikes with 100 pixel period and c) an interface with Gaussian spikes with 50 pixel period.

Section 2, including its benefits and drawbacks. Following this is an introduction to continuous *WT*s and their application to *IR* in Section 3. The results of *WT* analysis on computer simulation surfaces is presented in Section 4. Section 5 discusses two experimental applications analyzing buried interfaces measured with *ET* in a transmission electron microscope (*TEM*). A summary is presented in Section 6.

2. Root-mean squared error oversimplifies roughness description

A standard method to compute *RMS* values is:

$$RMS = \sqrt{\frac{1}{N}\sum (y_{exp} - y_{fit})^2} \tag{1}$$

here N is the number of sample points on the interface;
y_{exp} is the position of the measured interface as a vector;
y_{fit} is the position of the least-squares fitted plane for the interface as a vector.

Therefore, the *RMS IR* is the magnitude of the difference between the interface and a least-squares fitted plane to the interface. The method is applicable to data in one and two dimensions (1D and 2D). The *RMS* approach to determining the roughness of an interface is simple and straightforward, and it produces a single number as a result. This approach's result is straightforward to compare to other interfaces to quantitatively determine roughness.

One of the drawbacks of the *RMS* method is demonstrated in Fig. 1, which shows an example of computer generated interfaces composed of 3^2, 11^2 and 21^2 grid patterns of Gaussian peaks. The amplitude of the Gaussian peaks in the interfaces are scaled such that the calculated *RMS IR* of all three interfaces are the same, *RMS* = 5. From a visual inspection of the interfaces in Fig. 1 it is clear that interfaces with the same *RMS* values appear different and could have different properties.

Fig. 2(a) displays two example interface profiles, taken as sin(x) + 1 and sin(2x) + 1, that are expected to have the same *RMS IR* equal to $1/\sqrt{2}$, but instead have different *RMS* values at 0.69 and 0.66 respectively. Furthermore, the fitted lines for the interfaces has slopes with a value not equal to zero and intercepts not equal to 1, as is normally expected for $\sin(x) + 1$ and $\sin(2x) + 1$ interfaces. This discrepancy arises from the fact that the interfaces are analyzed over an interval that is not an integer multiple of π. Additionally only a small number of periods of the signals are present within the examined interval, as is often seen in a TEM experiment. The resulting slope of the fitted line and the resulting *RMS IR* make the results difficult to interpret. This proves that size and location of the studied region can have an effect on the *RMS* value.

Fig. 2(b) imitates a situation encountered in thin film growth of device layers, where the z = 0 plane is a substrate onto which a film is grown with surface height variations arising from various processes controlling the growing film morphology [14]. The *RMS IR* approach