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EFFECTIVENESS OF WAVELET DENOISING ON SECONDARY ION MASS SPECTROMETRY SIGNALS[†]

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Our objective is "Use of Digital Signal Processing to cross Physical and Instrumental Limits in the field of Microelectronics". We interest of SIMS (Secondary Ions Mass Spectrometry) signals, denoising the secondary signal, which is altered by the measurement, is considered that an essential step prior to applying another signal processing technique, that aims enhance the SIMS signals, such as deconvolution (which is a technique for restoration the original signal). Wavelet theory has already achieved huge success. The most efficient and widely used wavelet denoising method is based on wavelet coefficient thresholding. Indeed, we choose the wavelet transform to denoise the SIMS signals. In this paper, we aim to achieve a better result for the denoised signal. To achieve this, we manipulate the parameters of the DWT (Discrete Wavelet Transform) such as the decomposition level and the type of wavelet. The choice of wavelet type and the level of resolution can have a significant influence; it is important to note that the choice of resolution level depends on the type of signal we are dealing with, the nature of the present noise, and our specific goals for the denoised signal. It is generally recommended to test different resolution levels and evaluate their impact on the quality of the denoised signal before making a final decision. Moreover, the results obtained in wavelet denoising can be significantly influenced by the selection of wavelet types. The chosen wavelet type plays a crucial role in the extraction of signal details. Indeed, the effectiveness of denoising the MD6 sample has been demonstrated by the results obtained with sym4, db8, Haar and coif5 wavelets. These wavelets have effectively reduced noise while preserving crucial signal information, leading to an enhancement in the quality of the denoised signal.
Keywords: *SIMS Analysis; Discrete Wavelet Transform; Multiresolution Decomposition; Wavelet shrinckage; Denoising; Noise Reduction*
PACS: 25.40.Ep, 25.40.Lw, 43.30.Re

1. INTRODUCTION

Secondary Ions Mass Spectrometry (SIMS) is an analytical technique used to analyze the elemental and molecular composition of solid surfaces. SIMS analysis has a wide range of applications in materials science semiconductor manufacturing, geology, and biology, among others. It is particularly valuable for its high sensitivity and the ability to provide detailed information about the elemental and molecular composition of surfaces at high special resolution [1-3]. Any measurement, regardless of its nature or the object being measured, is susceptible to being affected by various unwanted signals commonly referred to as noise. In other words, when conducting a measurement, it is common for disruptive or parasitic elements to mix with the desired signal, which can impact the quality or precision of the obtained measurement. Noise can originate from various sources, such as electromagnetic interference, environmental variations, instrumental errors, or even inherent limitations of the measurement method used. It is important to consider these parasitic signals during result analysis and implement appropriate techniques to attenuate or eliminate them in order to achieve the most accurate and reliable measurement possible. Wavelet denoising techniques provide a high quality and flexible solution for mitigating noise in signals and images. The wavelet transforms (WT), a powerful tool in signal and image processing, has been successfully applied in various scientific domains, including signal processing, image processing computer graphics, and pattern recognition [4-6]. The denoising of the secondary signal in SIMS is widely recognized as an effective pre-treatment technique for enhancing the signal quality and even depth resolution. In particular, deconvolution, a signal restoration technique, plays a crucial role as an important tool in improving depth resolution.

2. EXPERIMENTAL

2.1. Data and acquiring techniques

In this work, we will use two types of signals, one is a simulated profile, and the other is a real profile that was measured using the Cameca Ims-6f at oblique incidence. The simulated profile is obtained by convolving a square wave signal with the DRF (Depth Resolution Function), which is the impulse response of the SIMS system. The addition of noise with a signal-to-ratio ultimately leads to a signal heavily distributed by noise. The experimental profile (real

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profile) is obtained by analysis of the delta of boron doped silicon in a silicon matrix, analyzed using Cameca Imf-6f at oblique incidence. MD4 is a profile that contains four multi-Delta-layer. Utilizing a threshold technique and discrete wavelet transform (DWT), the SIMS signals were denoised and implemented using the MATLAB wavelet toolbox.

2.2. Noise Removal
Wavelet denoising with thresholding

The most efficient and widely used wavelet denoising is based on thresholding wavelet coefficients. This process follows three important steps: (i) Wavelet decomposition*:* the input signals are decomposed into wavelet coefficients; (ii) Thresholding*:* the wavelet coefficients are modified according to a threshold; and (iii) Reconstruction*:* modified coefficients are used in inverse transform to obtain the noise-free signal (Fig. 1). Several researchers have used thresholding wavelet denoising techniques [6-10].

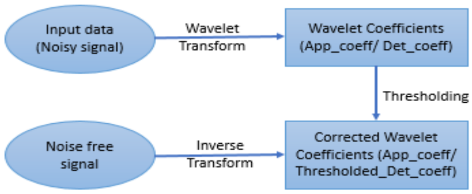


Figure 1. Basic flow chart of wavelet-based signal denoising.

3. RESULTS AND DISCUSSION
3.1. Denoising of simulated and experimental profiles. Influence of decomposition level

In this section, we discuss the influence of the decomposition level of the wavelet used for denoising. In this case, we use a simulated signal. The result is shown in Figure 2 (all the figures are illustrated on a logarithmic scale). A real profile is also used, and figure3 displays the result.

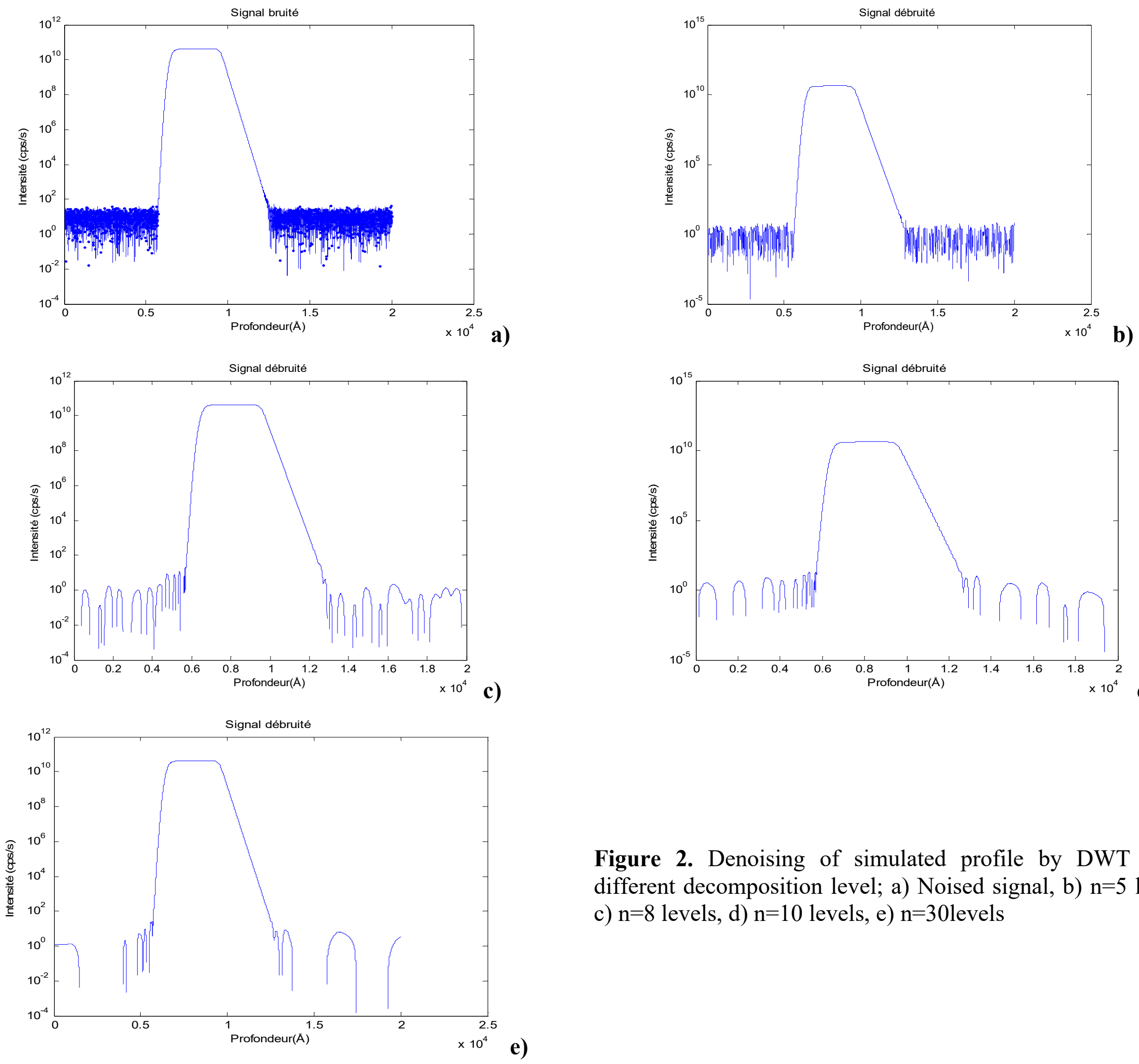
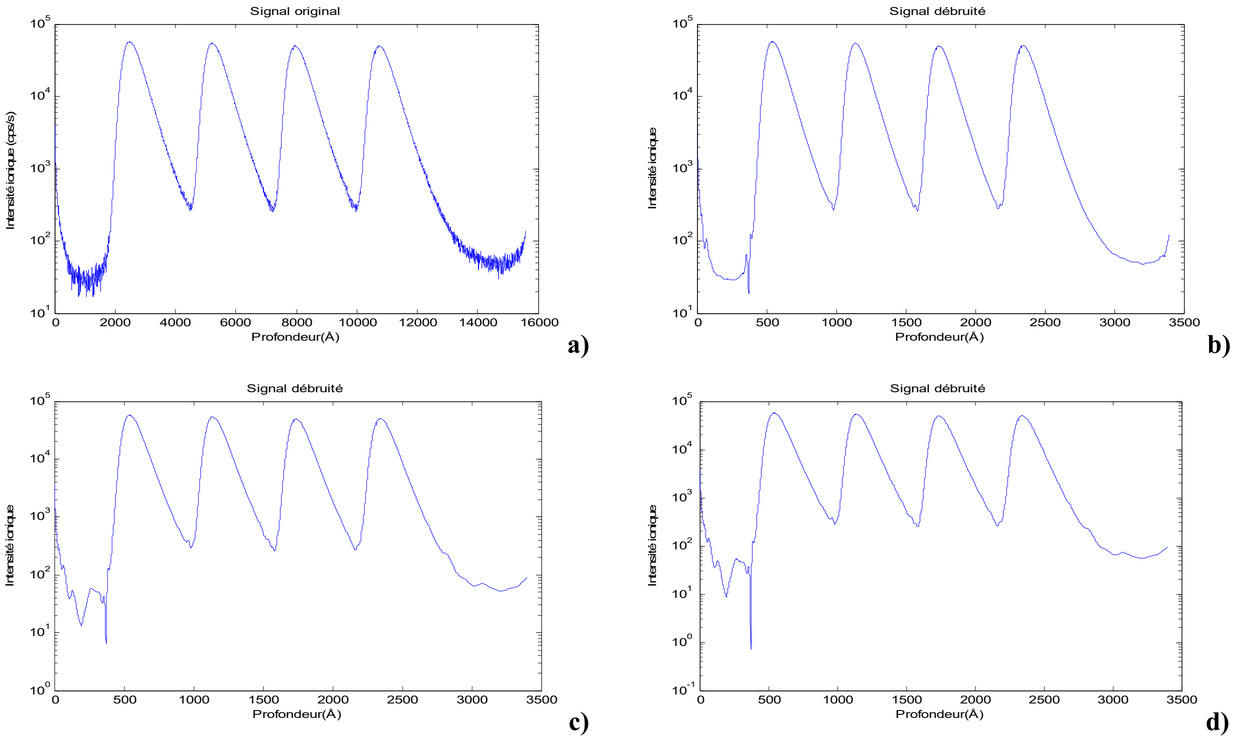


Figure 2. Denoising of simulated profile by DWT using different decomposition level; a) Noised signal, b) n=5 levels, c) n=8 levels, d) n=10 levels, e) n=30levels

During wavelet denoising of a signal, the level of decomposition is directly related to the level of resolution. In general, a higher number of decomposition levels allows for a finer resolution, while a lower number of decomposition levels leads to a coarser resolution.

If we choose a higher resolution level, it means that we will retain more fine details of the signal, but there is also a higher chance of preserving some of the noise. This can be useful if we want to analyze subtle details of the signal, but it can also make the final signal noisier.
On other hand, if we opt for a lower resolution level, we will achieve better noise suppression because higher-frequency components (which are often associated with noise) will be removed. However, this can result in a loss of important signal details, which may be undesirable in certain applications.



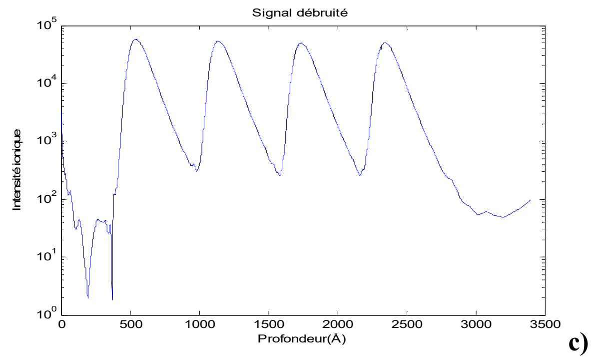


Figure 3. Denoising of experimental profile (MD4 sample) by DWT using different decomposition level; a) Noised signal, b) n=5 levels, c) n=8 levels, d) n=10 levels, e) n=30 levels

In summary, the influence of resolution level when using wavelet techniques to denoise the signal varies depending on the specific preferences and requirements of each application. It is essential to experiment with different resolution levels to find the right balance between noise suppression and preservation of signal details.

3.2. Denoising of sample MD6. Influence of wavelet types

In this section, we address the denoising of the MD6 sample (experimental profile which contains six Multi-Delta layers) using wavelet transform, with a focus on the influence of different types of wavelets used. The choice of wavelet type can have a significant impact on the denoising results (see Fig.4).

For signal decomposition, it is important to make a good choice of the mother wavelet or analysis wavelet. This wavelet must possess the following properties: symmetry, orthogonality, and suitability for discrete wavelet transform (DWT), [11-14]. A group of mother wavelets has been tested, including the Haar wavelet, Daubechies wavelet, Symlet wavelet, and Coiflet wavelet. The results obtained with the sym4, db8, Haar, and coif5 wavelets have demonstrated their effectiveness in denoising of the MD6 sample. These wavelets have successfully reduced noise while preserving important signal information, resulting in an improvement in the quality of the denoised signal.

In conclusion, the choice of wavelet type significantly influences the denoising process of the MD6 sample using wavelet transform. A thoughtful selection of the appropriate wavelet can result in a noticeable enhancement of signal quality by effectively eliminating noise while preserving essential information.

Regarding the SNR (signal-to-noise ratio), it is an evaluation criterion (quantitative criterion) that we use in this work. The result improves as the SNR increases, but with caution. Additionally, we use visually inspect the denoised signals, which serves as a qualitative evaluation criterion.

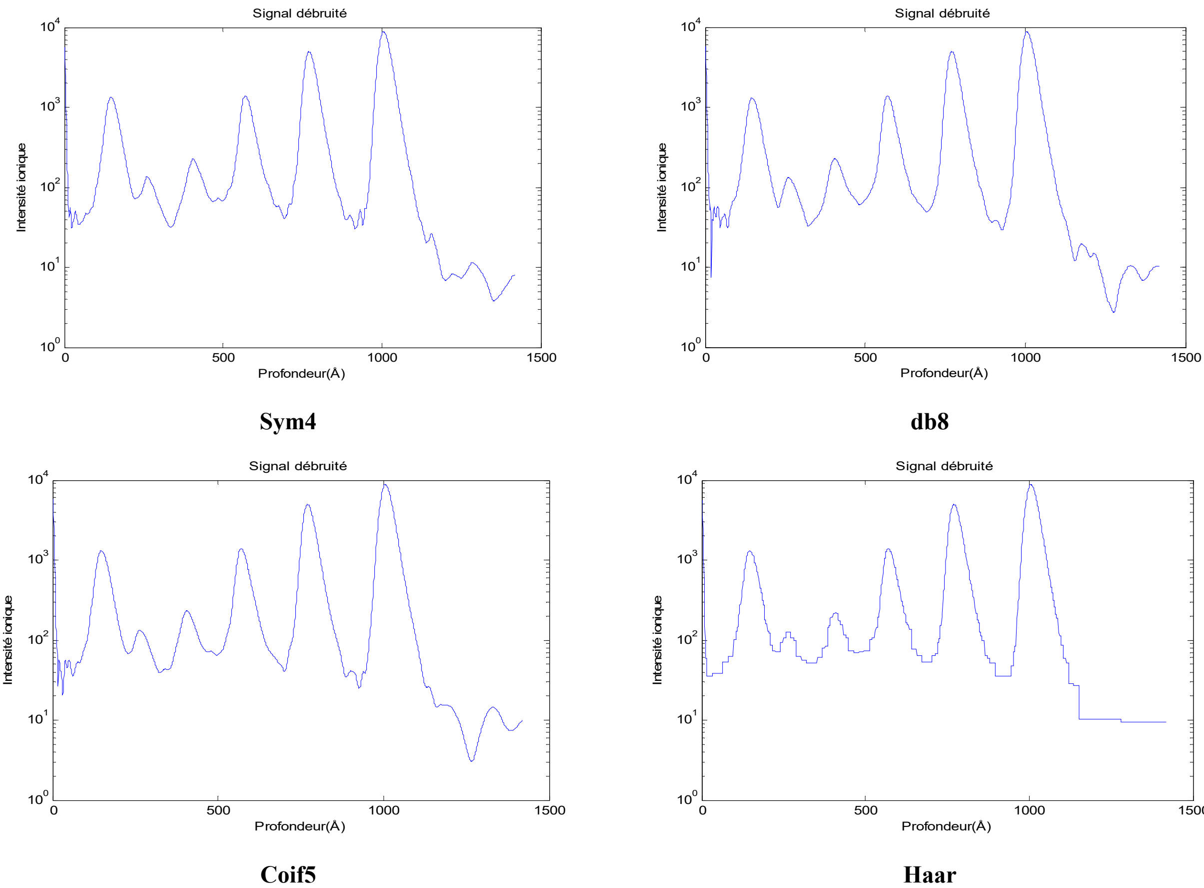


Figure 4. Denoising of experimental profile (MD6 sample) by DWT using different wavelet types (sym4, db8, Haar and coif5)

3.3. Evaluation by SNR

In the context of wavelet denoising, evaluation using Signal-to-Noise Ratio (SNR) is often employed to measure the effectiveness of noise reduction methods. However, it is important to note that SNR alone does not provide a comprehensive assessment of signal quality. Other factors such as preservation of signal details, introduced distortion, and subjective perception should also be considered for a more comprehensive evaluation. There is no strict rule to determine the exact number of appropriate decomposition levels in wavelet denoising procedures. The choice of the number of decomposition levels generally depends on the nature of signal and the level of noise present.

In some cases, using a larger number of decomposition levels may be preferable to capture finer details of the signal. However, this can also lead to the amplification of unwanted noise. On the other hand, using too few decomposition levels may not sufficiently represent the signal details and reduce the effectiveness of denoising.

Table 1. Signal-to-noise-ratio of SIMS signal after denoising using various levels of decomposition

Signals Levels	Simulated Profile	Experimental profile	
		MD 4	**MD 6**
5	171.8791	58.2853	46.9578
8	180.5946	64.5308	58.0944
10	185.6339	64.6143	65.3376
30	207.4209	114.2810	123.6753

Different wavelet types have distinct properties in terms of temporal resolution, frequency resolution, and filtering characteristics. The selected wavelet type can affect the ability to effectiveness extract signal details and suppress unwanted noise. Certain wavelet types, like the Haar wavelet transform, are well-suited for detecting abrupt discontinuities in a signal but may not be as effective in preserving continuous signals. On the other hand, other wavelet types, such as the Daubechies wavelets, can provide better frequency resolution and are often employed for processing smoother signals.

Table 2. Signal-to-noise-ratio of SIMS signal after denoising using various wavelet types

SignalsWavelet	Simulated Profile	Experimental profile	
		MD 4	**MD 6**
Sym 4	171.8879	58.2853	46.9578
db 8	172.3121	56.9330	44.9978
Coif 5	172.3118	57.1596	44.5535
Haar	77.3432	53.7140	42.3112

4. CONCLUSION

Wavelet theory has already a powerful tool in the field of signal processing. For SIMS signals, denoising the secondary signal, which is altered by the measurement, is considered that an essential step prior to applying such a signal processing technique that aims enhance the SIMS signals.

In the fields of signal processing and image processing, there are many types of criteria to evaluate such work. In our case, we choosea quantitative criterion, such as the signal-to-noise ratio (SNR), which does not require comparison with SNR values calculated prior to applying the DWT. Instead, the SNRs of the denoised signals are compared among themselves. And the other hand, we choose a qualitative criterion, which is based on the direct visualization of the denoised signals.

In this work, the choice of wavelet type and the level of resolution can have a significant influence; in practice, it is common to experiment with different numbers of decomposition levels and evaluate the results obtained. Criteria such as noise reduction, preservation of important signal features, and overall improvement in signal quality can be used to guide the selection of the appropriate number of decomposition levels.

In addition, it is a common practice to conduct experiments using various wavelet types and choose the one that delivers optimal outcomes in terms of noise reduction while preserving crucial signals features.

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ЕФЕКТИВНІСТЬ ВЕЙВЛЕТ-ПРИДУШЕННЯ ШУМУ В СИГНАЛАХ ВТОРИННОЇ ІОННОЇ МАСС-СПЕКТРОМЕТРІЇ

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Нашою метою є «Використання цифрової обробки сигналів для перетину фізичних та інструментальних обмежень у галузі мікроелектроніки». Нас цікавлять сигнали SIMS (мас-спектрометрія вторинних іонів), придушення шуму вторинного сигналу, який змінюється в результаті вимірювання, вважається важливим кроком перед застосуванням іншої техніки обробки сигналів, яка спрямована на посилення сигналів SIMS, наприклад деконволюція (яка є технікою відновлення вихідного сигналу). Теорія вейвлетів вже досягла величезного успіху. Найефективніший і широко використовуваний метод вейвлет-знищення шуму базується на пороговому визначенні вейвлет-коефіцієнта. Дійсно, ми вибираємо вейвлет-перетворення для придушення сигналів SIMS. У цій статті ми прагнемо досягти кращого результату для сигналу з шумом. Щоб досягти цього, ми керуємо параметрами DWT (дискретне вейвлет-перетворення), такими як рівень розкладання та тип вейвлета. Вибір типу вейвлета та рівня роздільної здатності може мати значний вплив; Важливо відзначити, що вибір рівня роздільної здатності залежить від типу сигналу, з яким ми маємо справу, характеру поточного шуму та наших конкретних цілей щодо знешумленого сигналу. Зазвичай рекомендується протестувати різні рівні роздільної здатності та оцінити їхній вплив на якість знешумленого сигналу перед прийняттям остаточного рішення. Крім того, вибір типів вейвлетів може суттєво вплинути на результати, отримані при вейвлет-знищенні. Вибраний тип вейвлета відіграє вирішальну роль у вилученні деталей сигналу. Дійсно, результати, отримані з вейвлетами sym4, db8, Haar і coif5, продемонстрували ефективність усунення шумів у зразку MD6. Ці вейвлети ефективно зменшили шум, зберігаючи важливу інформацію про сигнал, що призвело до покращення якості знешумленого сигналу.

Ключові слова: *аналіз SIMS; дискретне вейвлет-перетворення; декомпозиція з різною роздільною здатністю; вейвлет-обрізання; знешумлення; зменшення шуму*