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OBTAINING THE POROSITY OF POROUS SILICON FROM SEM IMAGES BASED ON THE IMAGE PROCESSING METHOD

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ABSTRACT

This project presents a new method to characterize porous silicon (PS) from the scanning electron microscope (SEM) image. Conventionally, the porosity from the PS film is able to be determined by using gravimetric or quasi-gravimetric method. However, the gravimetric method requires various stages of processing to obtain the porosity of PS where using the gravimetric method, the mass of the silicon sample is measured despite the fact that the final result would suggest that the porous film would be destructed. This is due to the usage of an alkaline solution that dissolves the sample. In addition, the problem of this method is that it will provide low accuracy of the porosity characterization. In this paper, the new method of characterization which uses the image processing technique is proposed. It uses segmentation via a clustering algorithm called the AFKM. The objective is to determine the porosity of PS with a non-destructive manner which will not harm the sample. The implementation of the AFKM technique as image segmentation is to segment the image into two significant regions i.e. the holes (black region) and the background (white region) of the image so that it can easily be identified. Next, the area for the black region is calculated in order to obtain the porosity of the PS. The porosity is calculated by calculating the ratio of the black area to the total area of SEM images. From the porosity calculation, their stability can be identified. Furthermore, this method provides a more accurate determination of the total area of the pore sizes and most importantly, it will not destruct the sample.

Keywords: porous silicon; porosity; image processing; image segmentation; clustering.

1. INTRODUCTION

Porous silicon (PS) is a material based on silicon that is composed of pores with diameters ranging from several micrometers to several nanometers. From the past two decades, there are many interesting discoveries about the usefulness of the PS material. Most of the researchers are interested in the characteristics of the PS. The characteristics that they are looking for include the ratio of the surface area to define the volume (Barillaro, Diligenti, Marola, &

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Strambini, 2005), the chemical reaction at room temperature (Islam & Saha, 2006), the cost application (Behzad, Yunus, Talib, Zakaria, & Bahrami, 2012), the PS potential in the silicon integration technology (Baratto et al., 2001), and the use of the PS in the fabrication of the silicon wafer. The PS material also has many potential applications in various different areas such as in the biological sensor, chemical sensor in liquid or gas, waveguides and ID photonic crystals (Suhaimi, Rusop, & Abdullah, 2013).

Typically, the technique to form the PS is by using the iodization technique. Iodization technique is the technique based on the formation of PS which occurs during electrochemical dissolution, where the silicon is soaked in hydrofluoric acid (HF). The silicon wafer acts as the anode while the cathode serves as a HF-resistant material. Since the silicon wafer is the anode, the PS will form on any wafer surface which is in contact with the HF solution.

The iodization technique can affect the physical properties, optical and electrical properties (Kumar, Lemmens, Ghosh, Ludwig, & Schilling, 2009). The physical properties of the PS are mainly dependent on the porosity. The special significance of the PS is that, it is able to form corrosion on the silicon surface at room temperature (Nakahara, 1979) and produce high sensitivity (Suhaimi, et al., 2013), hence influencing the electrical behaviour (Lehmann, 2002). The large surface area of the PS absorbs more interface with the environment (Angelescu & Kleps, 1995). Therefore, the surface structure of the PS constitutes one of the major concerns in sensor applications such as in gas (Boarino et al., 2000) and humidity (Kim, Park, Lee, & Yi, 2000).

The porosity value can be calculated by evaluating the structure of pores on the PS surface. The conventional method that is used to determine the porosity is by using the gravimetric or quasi-gravimetric method. The gravimetric method requires various stages of processing to obtain the porous silicon. By using this method, the mass of the silicon sample will be measured. The problem occurs when the final result destructs the porous film and it will dissolve in the alkaline solution. In addition, this method is also difficult to obtain accurate values of the etched area on the wafer surface (Ahmed et al., 2012).

In the advance of the computer technology, another method for determining the porosity is by using image processing. Image processing is a method that serves to enhance the image and it has large memory. The most common application of image processing is used in the military, medical imaging, film industry and remote sensor. Image processing can be divided into two methods, which are analogue and digital images (Rosenfeld & Kak, 2014; Smith, 2013). Currently, most of the customer electronic products use the digital image processing to determine the image. Digital image processing converts the image to the digital form using number of bits and it groups a set of objects into similar characteristics called the clustering algorithm method. The special significance of the digital image processing is flexibility, repeatability and conservation of the original data. Image processing has different branches such as image enhancement, image restoration, image reconstruction and image analysis (Rosenfeld & Kak, 2014; Smith, 2013).

The knowledge of the computer technology is explored by a few researchers to simplify the process of determining the porosity. One work that has been done is by Ahmed et al. (2012) which applied the binary image technique and implemented the algorithm in the MATLAB software to calculate the porosity. This method provides a more accurate result but consists of

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several steps and procedures. It proposes the first step which is to initialize each image as pixels. Then it converts the final image into a binary image where it consists of value 1 (white) and 0 (black) pixels. Subsequently, the threshold value is determined to execute the specific level which is either 1 or 0 value. This technique also requires a filter to reduce the noise variance. The disadvantage of this method is that it is difficult to determine the threshold value, the pre-processing time consumption and variance noise (Ahmed et al., 2012).

Consequently, the new improvement technology has been proposed which is non-destructive to the sample of porous film- it is an image segmentation based on the clustering process. This method is capable to segment and classify the region of interest. Besides, it also can provide a more accurate clustering, determine the total area of the pore size quickly and calculate the porosity of the PS.

2. THE AFKM SEGMENTATION TECHNIQUE

In this paper, a new method of determining the porosity of the PS by using the image segmentation method i.e. the Adaptive Fuzzy K-Mean (AFKM) (Sulaiman & Mat-Isa, 2010) clustering algorithm is proposed. This section will explain in detail the AFKM clustering algorithm. The AFKM clustering algorithm is the combination of two conventional methods of calculating the distance from each data i.e. the K-Means (KM) and the Moving K-Means (MKM) clustering algorithm and the Fuzzy concept i.e. the Fuzzy C-Means (FCM). The KM method is to determine which data belong accurately to the cluster and that they are not included in another cluster. The weakness of this method is it ignores small clusters and only considers their local converge (Sulaiman & Mat-Isa, 2010). The FCM method has allowed all data to belong to two or more clusters at different degrees of memberships but the disadvantage is that the significant boundary is not clear (Sulaiman & Mat-Isa, 2010). Another method introduced to overcome the clustering problem is the MKM clustering. The disadvantage of MKM is that it is sensitive to noise (Mat-Isa, Salamah, & Ngah, 2009). The latest version to solve the clustering problem is the AFKM where it implements the fuzzy concept (Sulaiman & Mat-Isa, 2010) and always updates the distance between the membership and centres.

The implementation of the AFKM segmentation technique will be described in this section. Consider an image with $X \times Y$ pixels. X pixel is the number of columns, Y pixel the number of rows. Consider $p(x,y)$ as pixel and c_k as the k-th centre. Let V_t be the t-th data and calculate the new position centre using (Sulaiman & Mat-Isa, 2010):

$$c_k = \frac{\sum_{t=1}^{N} (M_{kt}^{m}) V_t}{\sum_{t=1}^{N} (M_{kt}^{m})'} \quad (1)$$

Where (M_{kt}^{m}) refer to the membership while $(M_{kt}^{m})'$ is the updated membership. The fuzzy concept is applied to this AFKM method where it allows more than one class to be able to be assigned and at the same time it allows different degrees of membership. The AFKM membership function does not receive influence from any outsider member. The distance between each data will affect the clustering result. The closer distance is the priority to

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identify the new position of the centre. To produce better clustering results, each data need to have a specific value of belongings. Then, we need to identify which member has a stronger relationship between the centres. Stronger relations between them produce higher degree of belongings and perform a better clustering result. The degree of belonging, B_k is determined using (Sulaiman & Mat-Isa, 2010):

$$B_k = \frac{c_k}{M_{kt}^m} \tag{2}$$

Besides, to improve the clustering, we always have to update the degree of membership and minimize the distance between the memberships. The iteration can be updated using (Sulaiman & Mat-Isa, 2010):

$$(M_{kt}^m)' = M_{kt}^m + \Delta M_{kt}^m \tag{3}$$

$$\Delta M_{kt}^m = \alpha(c_k)(e_k) \tag{4}$$

$$e_k = B_k - \hat{B} \tag{5}$$

Where, $(M_{kt}^m)'$ refers to new membership and e_k is an error of belongings. The value of α is the constant between 0 and 1 and normally it is set to 0.1. Consequently, the new optimized membership is calculated using (Sulaiman & Mat-Isa, 2010):

$$J = \sum_{k=1}^{n_c} \sum_{t=1}^{N} (M_{kt}^m) \|V_t - C_k\|^2 \tag{6}$$

3. METHODOLOGY

The objectives of this project are to segment the image into two significant regions which are the holes (black region) and the background (white region) and to determine the black area of the image in order to calculate the porosity of the PS, hence evaluating the stability of the porosity. Therefore, to achieve the objectives of this project, the AFKM method is proposed. It can be proven by most of the consumer electronic products which use the digital image segmentation to provide some feature images such as the classification of the size, shape and position of the image by using segmentation clustering.

In this section, six original PS images from the SEM image obtained from the Nano-Optoelectronics Research and Technology Laboratory (NOR Lab) USM are chosen to analyse the characteristics of porosity. The original images are shown in Figures 1 (a) to (f) namely SEM_1, SEM_2, SEM_3, SEM_4, SEM_5 and SEM_6, respectively. Next, it will present the performance of the AFKM technique in order to prove the ability and suitability of this technique in characterizing the porosity.

The implementation of the AFKM segmentation technique on the PS can be seen in Figure 2. Firstly, all centres are initialized to a certain value that represents two regions. Then the image will be segmented into two significant regions i.e. where, specifically the holes are (the black region) and the background is (the white region) of the image. Afterwards, each pixel is

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assigned to the nearest clustering centre. Members that have a strong relationship between the clustering centresneed to be identified. It will produce a higher degree of belongings and perform better data clustering. Besides, the membership is updated according to the cluster centre and also the cluster centreupdated according to the membership. Next, all values of the centre are to be identified, where it no longer moves before the percentage of porosity can be calculated.

The procedure of this experiment consists of four important steps. The first step is to implement the AFKM image segmentation to segment the image into two significant regions. The second step is to analyse the image and enhancing the region of interest (black area). The third step is to calculate the porosity by taking the ratio of the black area to the total area of the SEM images. The last step is to identify the stability of the PS. The procedures are depicted in Figure 3 below.

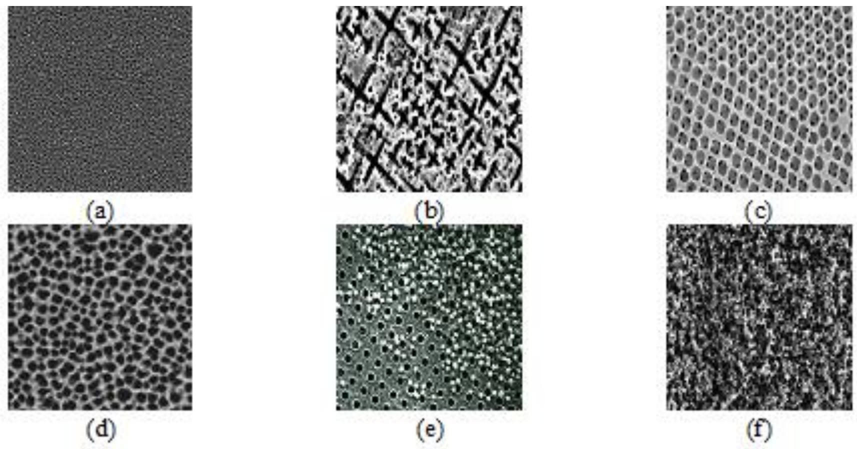

Figure 1: SEM image of porous silicon with different physical properties. The original image of (a) Image Porous Silicon 1, SEM_1 (b) Image Porous Silicon 2, SEM_2 (c) Image Porous Silicon 3, SEM_3 (d) Image Porous Silicon 4, SEM_4 (e) Image Porous Silicon 5, SEM_5 (f) Image Porous Silicon 6, SEM_6.

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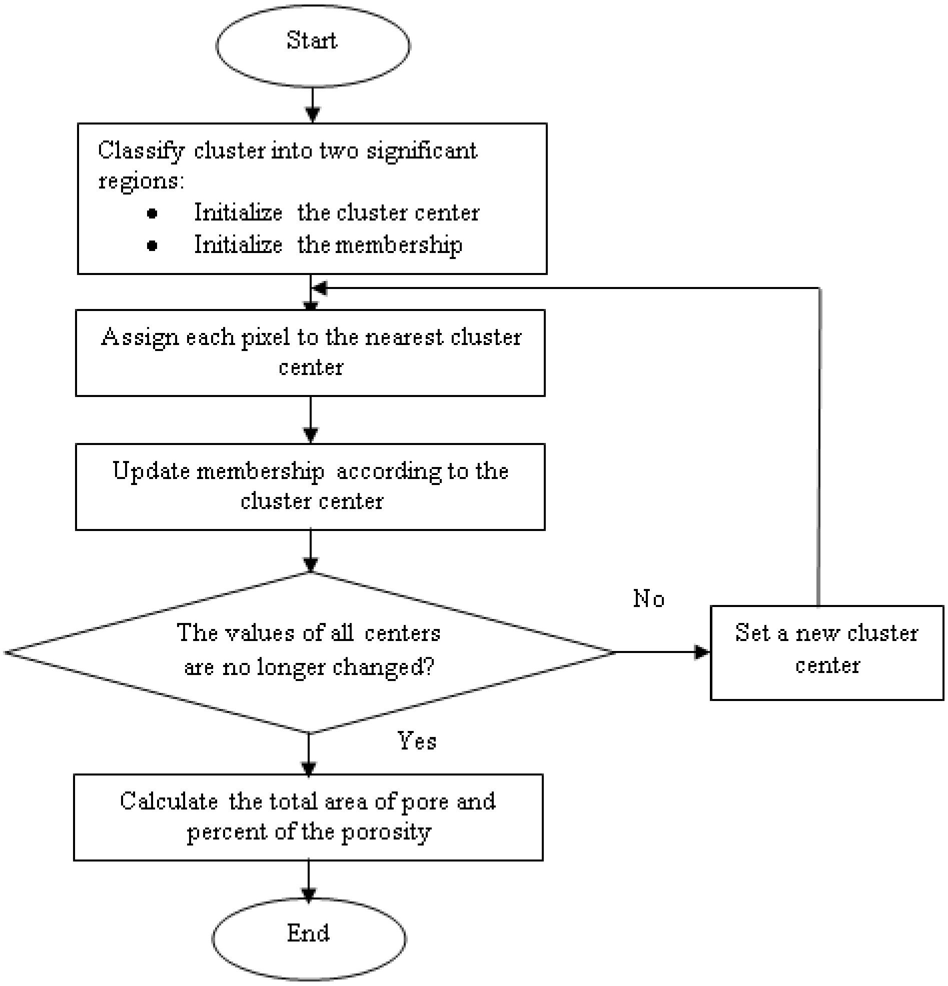

Figure 2: Flowchart programming of the AFKM method used to calculate the area pore and porosity.

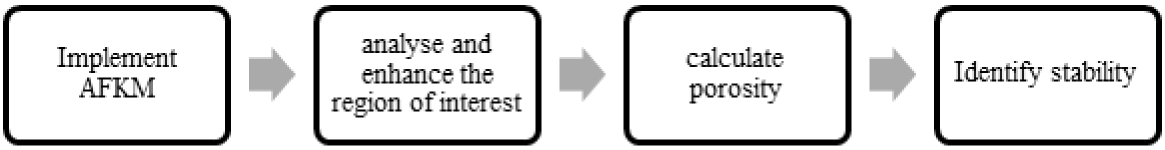

Figure 3: The experimental procedure.

4. RESULT AND DISCUSSION

This section shows in detail the image tested by using the AFKM methods to prove that the capability of the AFKM method can be applied in the electronic field. Also, the purpose of this project is to propose a simple method to calculate the porosity without requiring the sample PS. The porosity can be calculated by taking the ratio of the black area to the total area of the SEM images. To find the correct value of the black area, the segmentation image is proposed to segment the image correctly. The improvement in segmentation will perform better image segmentation performance. It can be proven from the observation where the images of the PS become clearer and sharper.

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This project uses various surface structures of PS to evaluate the performance of the AFKM method. Figure 4 shows the resultant image after being processed with the AFKM (refer to the third column). For the first SEM_1 (refer to Figure 4 on the first row), the image illustrates smaller pores. It is not an easy task for human eyes to compare the region between the pore and silicon surface. Thus, the AFKM method is proposed to help humans evaluate the image and obtain information from the image. The second image is SEM_2 (refer to Figure 4, the second row), whereby from the top view, the original PS image shows different patents of pores. The pattern is not uniform in the circle shape but sometimes it can be a random pattern as shown in SEM_2 and SEM_6. Consequently, it can be visualized that by using the AFKM clustering algorithm the pores are clearly highlighted and distinguished from the background. Thus, it proves that the AFKM method can be used to process various patterns of pore shape. The third image is SEM_3 (referring to Figure 4, the third row), the image shows the pore size in a blurry image. After using the AFKM method, the pore size of the image becomes clearer. The next image is SEM_4 (refer to Figure 4, the fourth row), where the original image is not clear and has a shadow. Therefore the image analysis becomes difficult to perform. However, the AFKM method can be applied to analyse the area pore to become more accurate.

Another image tested is image SEM_5 (refer to Figure 4, the fifth row), where the pores are not uniform. At the top of an image, they have many pores and below it, the pore size becomes larger. The pore size is not uniform and it is difficult to analyse. Nevertheless, the AFKM method can solve the problem on the image. Then, the result presents a more accurate boundary between the pore area and the silicon surface. Lastly, there is the image SEM_6 (refer to Figure 4, the sixth row), where it shows that the surface of the image is not smooth and provides shadow. Therefore, it is difficult to analyse the image. However, the AFKM method can be used to analyse non-uniform images. The result shows the better performance image and the image has become sharper. Based on the observation, most of the original SEM images are not clear and sharp. Therefore, this AFKM method has been proposed to improve the evaluation of the image performance and to get some information from the image, such as the total area of the pore.

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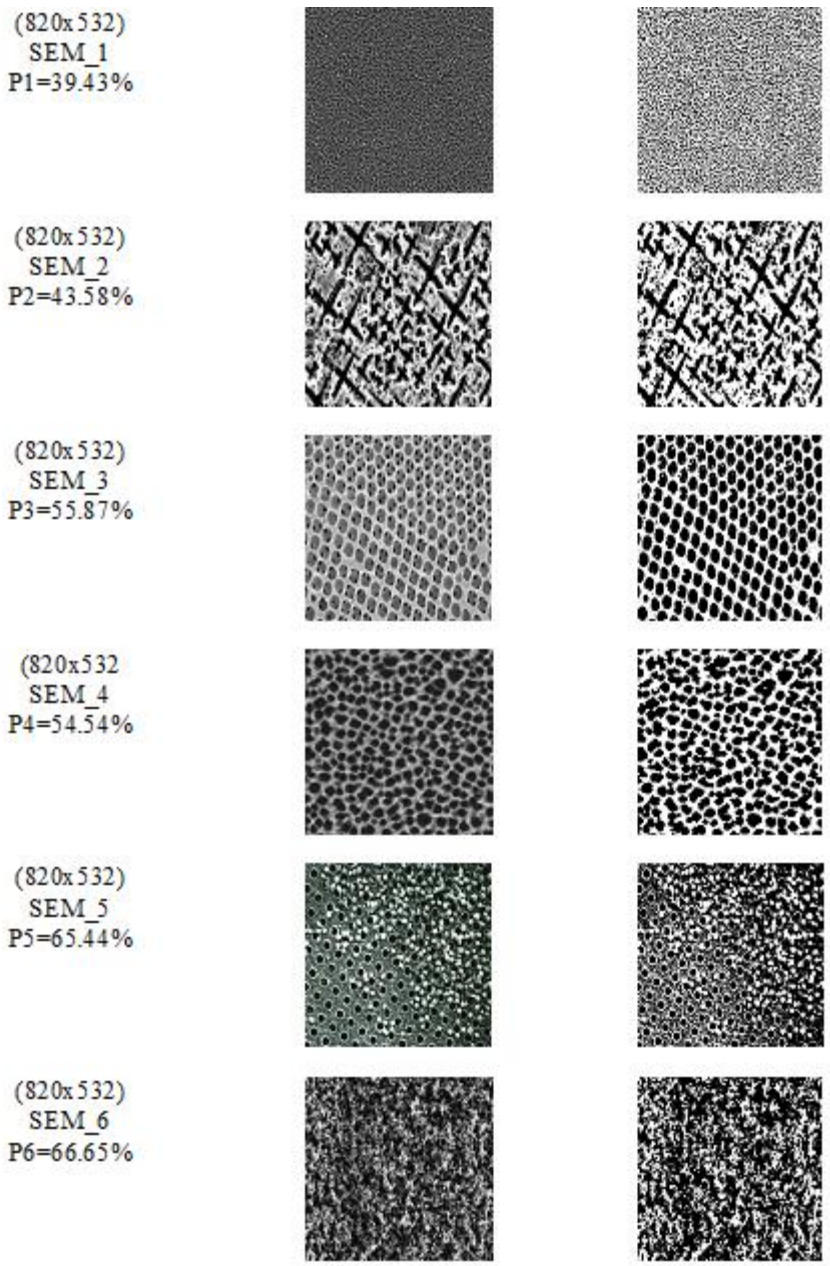

Figure 4: Result of the image segmentation was present based on two cluster regions using the AFKM method. The first column is the pixel number and the percentage of porosity. The second column is the original image. The third column is the processing image.

The proposed AFKM is used to obtain accurate total of the pore size, hence calculating the porosity. Besides that, it also discusses the stability of porosity which is suitable to be used in the sensor field. Table 1 shows the resultant percentage porosity in different sample images of PS but with a constant value of the total area image. The higher the percentage of porosity, the more uniform and accurate the structure that will be provided. It is because the higher porosity value of PS can affect the pore size. It can prove that the higher value of the total pore area will increase the percentage of the porosity (refer to Table 1). The higher total area pores will lead to the photoluminescence spectrum shifting to blue. It can be concluded that the blue spectrum tends to be a visible light and it can be used for the detector sensor (Naderi,

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Hashim, & Amran, 2012). Typically, accepted values of porosity are P>60% showing a stable surface and that it is suitably used for sensor applications. It is because high porosity produces a higher sensitivity. If the value of porosity P<60% the surface of the PS is not stable and it may be affecting the device performance (Angelescu & Kleps, 1995).

Table 1: A detailed value of porosity is analysed by different samples of the PS SEM image.

No of Picture	Total Pore Area	Total Area Image	P = Total Number of Pore/ Total Area Image
P1	171997	820x532	39.43%
P2	190103	820x532	43.58%
P3	243714	820x532	55.87%
P4	237931	820x532	54.54%
P5	285492	820x532	65.44%
P6	290766	820x532	66.7%

From the evaluation, the AFKM proposed is suitable to analyse the porosity which uses the clustering segmentation. However, the processing technique has a limitation. This project also proposes two numbers of clusters because there are only two regions of interests namely black and white regions. Essentially, this project is one of the new developed areas for the research concerned with exploring into the image processing in this field. Overall, the result has successfully proven that the AFKM method can be applied to characterize the PS and determine the porosity.

The second test for the AFKM method is to compare other original SEM images in different number of pixels. This comparison is used to prove that the AFKM method can be used in characterizing the total pore area of PS with various image sizes. The results are presented in Figure 5. From Figure 5, it can be clearly seen that the resultant images i.e. the image after processing with the AFKM clustering algorithm becomes sharp, clear and distinguishable from its background.

Table 2 represents the value of porosity with different values of a total area image. From the result it can be proven that the AFKM method is able to process different surface structures of the PS image but it also can process different total area images. Different area images of PS can affect the percentage of porosity. It is because the percentage of the porosity of PS depends on the pore area size and area image.

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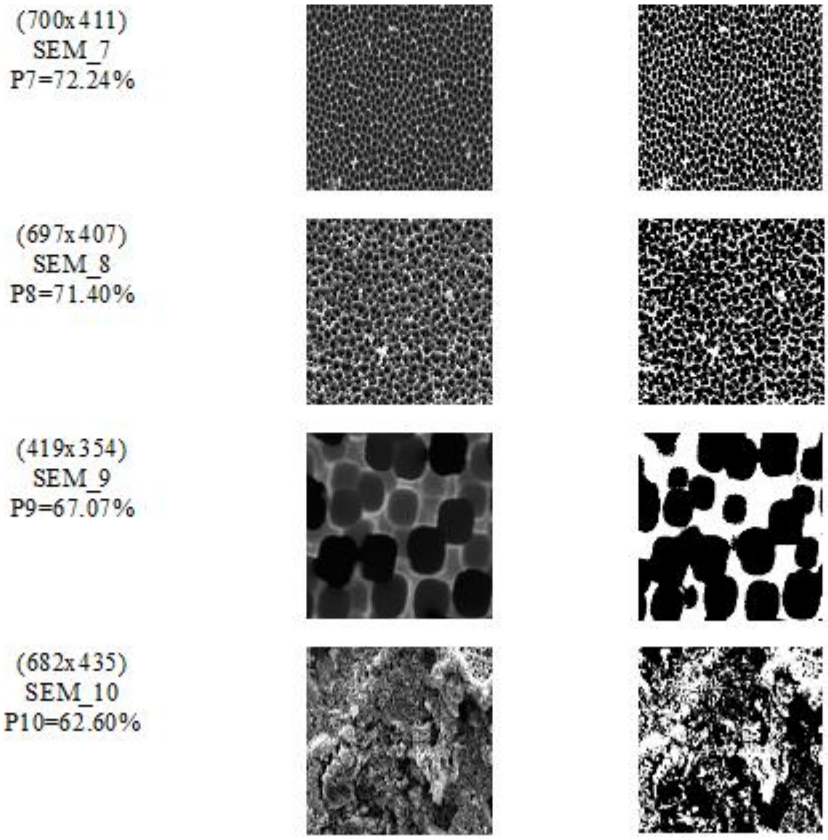

Figure 5: Result image segmentation was present based on different pixel number using the AFKM method. The first column is the pixel number and percentage of porosity. The second column is the original image. The third column is the processing image.

Table 2: A detailed value of porosity is analysed by different samples of the PS SEM image.

No of Picture	Total Pore Area	Total Area Image	P= Total Number of Pore/ Total Area Image
P7	207834	700x411	72.24%
P8	202558	697x407	71.40%
P9	98337	419x354	66.30%
P10	185724	682x435	62.60%

The additional test for the AFKM method is to compare the conventional gravimetric method and AFKM method. As mentioned, the gravimetric method calculates the porosity by using the mass before starting the etching process and after the porous layer is removed in alkaline solution. Therefore, the gravimetric method does not require any image size information. However, the most important information that is used to calculate the porosity by using the AFKM method is based on the image size. Thus, the comparative result of Table 3 shows the different values of porosity. This is because typically, the original image captured from the SEM image is a small section of the porous film. Therefore, the comparison between the gravimetric and AFKM methods is not suitable to be analysed.

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Table 3: The comparison between the gravimetric and the AFKM methods to calculate the porosity of PS for the same image structure.

Comparison	**Porosity (%)**
Calculate porosity by using the gravimetric method	71
Calculate porosity by using the AFKM method	43.58

Based on Naderi, et. al. (2012) they used the gravimetric method to calculate the porosity based on the sample in Figure 6. The problem occurs when the information of the image size that the SEM image has captured is not included. Thus, the recommendation for the next developer is to add another parameter to continue the analysis i.e. the correlation test.

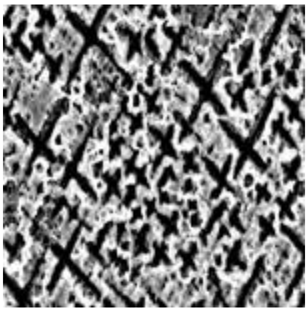

Figure 6: The PS sample from the SEM image used for comparison between the gravimetric and AFKM methods.

5. CONCLUSION

This paper proposes a new clustering process called the AFKM method to present a better clustering segmentation. The method combines the fuzzy application and minimizes the distance between the membership and centre. This project also achieves the objective to determine the porosity of the PS without destructing the sample. Besides, this project has focused on the analysis image between original images compared to processing images. From the view, it can be concluded that the AFKM method can make the comparison to the original image more accurately and clearly. Then, from the image, we can identify the total area of the pore and calculate the porosity. Moreover, this method is practically simple and efficient. The recommendation for the next developer to achieve good result is to add the current density and correlation test. It is because the formation of pores is dependent on the current density.

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REFERENCES

Ahmed, N. M., Ramizy, A., Hassan, Z., Amer, A., Omar, K., Al-Douri, Y., & Alattas, O. S. (2012). Nano and micro porous GaN characterization using image processing method. *Optik-International Journal for Light and Electron Optics, 123*(12), 1074-1078.

Angelescu, A., & Kleps, I. (1995). *Electrical characterization of porous silicon.* Paper presented at the Semiconductor Conference, 1995. CAS'95 Proceedings. 1995 International.

Baratto, C., Faglia, G., Sberveglieri, G., Boarino, L., Rossi, A., & Amato, G. (2001). Front-side micromachined porous silicon nitrogen dioxide gas sensor. *Thin Solid Films, 391*(2), 261-264.

Barillaro, G., Diligenti, A., Marola, G., & Strambini, L. (2005). A silicon crystalline resistor with an adsorbing porous layer as gas sensor. *Sensors and Actuators B: Chemical, 105*(2), 278-282.

Behzad, K., Yunus, W. M. M., Talib, Z. A., Zakaria, A., & Bahrami, A. (2012). Effect of preparation parameters on physical, thermal and optical properties of n-type porous silicon. *Int. J. Electrochem. Sci, 7*, 8266-8275.

Boarino, L., Baratto, C., Geobaldo, F., Amato, G., Comini, E., Rossi, A. M., ... Sberveglieri, G. (2000). NO2 monitoring at room temperature by a porous silicon gas sensor. *Materials Science and Engineering: B, 69*, 210-214.

Islam, T., & Saha, H. (2006). Hysteresis compensation of a porous silicon relative humidity sensor using ANN technique. *Sensors and Actuators B: Chemical, 114*(1), 334-343.

Kim, S.-J., Park, J.-Y., Lee, S.-H., & Yi, S.-H. (2000). Humidity sensors using porous silicon layer with mesa structure. *Journal of Physics D: Applied Physics, 33*(15), 1781.

Kumar, P., Lemmens, P., Ghosh, M., Ludwig, F., & Schilling, M. (2009). Effect of HF concentration on physical and electronic properties of electrochemically formed nanoporous silicon. *Journal of Nanomaterials, 2009*, 18.

Lehmann, V. (2002). Electrochemistry of Silicon: Instrumentation. *Science, Materials and Applications (Wiley-VCH 2002).*

Mat-Isa, N. A., Salamah, S. A., & Ngah, U. K. (2009). Adaptive fuzzy moving K-means clustering algorithm for image segmentation. *IEEE Transactions on Consumer Electronics, 55*(4), 2145-2153.

Naderi, N., Hashim, M., & Amran, T. (2012). Enhanced physical properties of porous silicon for improved hydrogen gas sensing. *Superlattices and Microstructures, 51*(5), 626-634.

Nakahara, S. (1979). Microporosity in thin films. *Thin Solid Films, 64*(1), 149-161.

Rosenfeld, A., & Kak, A. C. (2014). *Digital picture processing* (Vol. 1). London: Academic Press, Inc.

p-ISSN 1675-7939; e-ISSN 2289-4934

Smith, S. (2013). *Digital signal processing: A practical guide for engineers and scientists*. Burlington: Newnes.

Suhaimi, M., Rusop, M., & Abdullah, S. (2013). Porosity and thickness effect of porous silicon layer on photoluminescence spectra. *Proceedings of International Conference on Technology, Informatics, Management, Engineering, and Environment (TIME-E)* (pp.115,118). Bandung: IEEE.

Sulaiman, S. N., & Mat-Isa, N. A. (2010). Adaptive fuzzy-K-means clustering algorithm for image segmentation. *IEEE Transactions on Consumer Electronics, 56*(4), 2661-2668.

p-ISSN 1675-7939; e-ISSN 2289-4934