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◆ 특집 ◆ 차세대 기능성 유연필름 제조기술

인쇄 패턴의 기하학적 특성 측정 및 인쇄성 평가

Measurement of Geometric Properties of Printed Patterns and Evaluation of their Printability

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Printed electronics devices are made of several sets of printed patterns. The quality or printability of the printed patterns determines the electrical performance of such devices. Moreover, control of the printability determines the reliability of such devices. Despite its importance, few studies have been reported for the measurement of the printed patterns to evaluate their printability. In this study, a measurement method is proposed for printed patterns, including the definition of the properties to be measured, and the related software is described. The proposed method measures the width, pinholes, and edge waviness and evaluates the printability of the patterns quantitatively. The proposed measurement method could be an efficient tool to evaluate and enhance the printability of printed patterns in printed electronics.

Key Words: Printed electronics (인쇄전자), Printability (인쇄성), Printed pattern (인쇄패턴), Measurement (측정), Digital Image Processing (디지털 화상 처리)

Nomenclature

$A_{pinholes}$ = area of the pinholes
$A_{pattern}$ = area of the pattern
E_i = position of the i-th edge
$E_{0,i}$ = mean value of Ei
E_w = edge waviness
$f_E(y)$ = position difference between two edges
n = number of data points
y = coordinate of the pattern in the length direction
w_0 = average width
w_L = largest width
w_S = smallest width
w_0 = peak-to-peak to mean width

1. Introduction

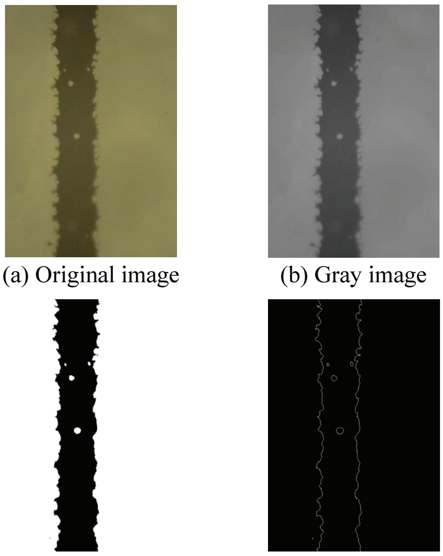
Nowadays, printed electronics have become a well-known technology for manufacturing flexible electronics such as flexible displays, flexible solar cells, flexible PCBs, and flexible touchscreen panels by printing methods.[1,2] Such printed electronics devices are considered promising for applications to wearable devices and the Internet of things (IoT) owing to their flexibility and cost-efficiency. These devices consist of sets of printed patterns made on flexible films using functional inks by several types of printing methods. Therefore, the quality and reliability of printed electronics devices are limited by the printed patterns that constitute them, because these patterns show quality variations in their geometries owing to variations in the ink transfer, ink spreading, and printing conditions. The performance and reliability of printed electronics devices depends on how the quality of printed patterns is controlled and maintained within a certain level.[3-5] For example, the edge waviness of printed patterns, a frequently observed degradation of quality in printed patterns, could affect the resonant frequency of radio frequency identification (RFID) tag antennas[3]. Although the printability or quality of printed patterns is the key factor that affects the quality and determines the reliability of printed electronics devices, methods and standards for measuring printed patterns have not yet been established. The patterns made by the printing method could inherently show waviness in their edges or non-uniformities; therefore, the line width could differ depending on the measurement standard. For example, the line width of a typical printed pattern could be measured differently as 51.7μm or 35.4μm depending on the measurement standard. The line width and channel length of lines in thin-film transistors (TFTs) are the significant factors that determine the TFT performance; however, if these properties are not controlled and measured properly based on suitable measurement methods, it is difficult to expect uniform and reliable performances of TFTs. The properties of printed patterns, such as pattern width, pinholes, and edge waviness, have not been defined, and no measurement standard is available for these properties.

Fig. 1 Example of different measurement of pattern width

Although proper measurements including the definition of the properties of printed patterns are very important for the quality control of printed electronics devices, few studies have focused on the measurement of printed patterns.[6] Fortunately, an international standard for the measurement of printed patterns to evaluate printability has been proposed and is under development in IEC/TC119 (Printed Electronics).[7] In this study, measurement methods, including the definition of the properties of printed patterns for pattern width, pinhole, and edge waviness, are proposed based on the international standard in IEC[7]. Free software for the measurement of printed patterns is developed, and its algorithm and characteristics are described in detail. As an application example of the measurement of printed patterns, the evaluation and classification of pattern qualities are proposed based on the proposed measurement method.

2. Development of pattern measurement software

The pattern measurement software was developed by graphical user interface development environment of MATLAB. Through pattern measurement program based on graphical display, the properties of printed patterns can be measured easily. This software measures the geometric properties of printed patterns, such as pattern width, pinholes, and edge waviness. The measurement of these geometric properties requires digital image processing techniques. In this software, image scale conversion, edge detection, and cropping methods are used as image processing techniques, as shown in Fig. 2. First, the true color image is converted to the grayscale image, which is the matrix of data showing gray shapes. The grayscale image is converted to a binary image having pixels of 0 or 1. Second, the boundary information between the pattern and the film is obtained by an edge detection method. The edges are detected by the first and second derivatives of the trace composed of a pattern and film. We use three types of conventional edge detection


(a) Original image (b) Gray image

(c) Binary image (d) Edge detected image

Fig. 2 Steps of image process

methods: Sobel, Canny, and Laplacian of Gaussian (LoG).[8-10] Furthermore, cropping, in which a user uses a mouse to select the region of interest (ROI), is also employed.

3. Measurement of geometric properties of printed patterns

The geometric properties of printed patterns can be obtained from the matrix of the image having information on the positions of edges as well as pinholes. For example, the data of the image shown in Fig. 2 is converted to a matrix where its row corresponds to the position of the pattern in the length direction and its column, to the position of the pattern in the width direction. As shown in Fig. 3, we can calculate the pattern width or pinhole width in terms of the pixel number at a given position of the pattern in the direction of pattern length using the coordinates of the positions of edges and pinholes. For example, if the first edge of the eleventh line has a coordinate of [11, 24] and the second edge of the eleventh line, a coordinate of [11, 108], the pattern width from one edge to the other edge is 108 - 24 = 84 pixels. From information about the matrix of pattern width and pinhole width, we can define the pattern area $A_{pattern}$, and pinhole area $A_{pinholes}$.

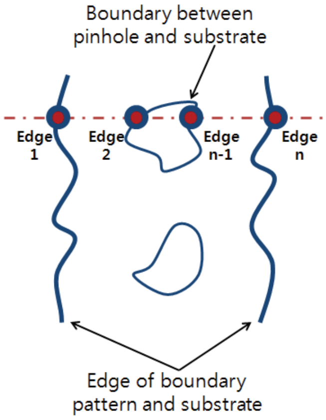
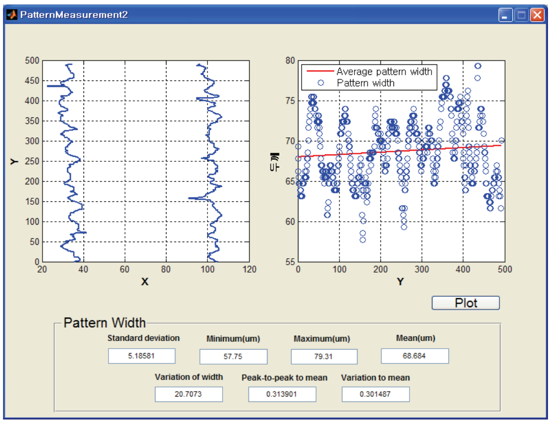


Fig. 3 Measurement of positions of edges and pinholes



Pattern Width

Standard deviation: 5.18581
Minimum(um): 57.75
Maximum(um): 79.31
Mean(um): 68.684
Variation of width: 20.7073
Peak-to-peak to mean: 0.313901
Variation to mean: 0.301487

Fig. 4 Capture image of software to measure the geometric properties of patterns

The pattern area is calculated by

$$A_{pattern} = \sum_{i=1}^{n} A_{pattern,i}, \tag{1}$$

and the pinhole area is calculated by

$$A_{pattern} = \sum_{i=1}^{n} A_{pinhole,i}, \tag{2}$$

where $A_{pattern,i}$ and $A_{pinhole,i}$ are i-th pattern area and i-th pinhole area, respectively.

If we have information on the pixel size, we can obtain the width value as the number of pixels multiplied by the pixel size. We can obtain the same information on pinholes as well. When we obtain information on whole length of the patterns, we can obtain information on the width variation as a function of length, as shown in Fig. 3, and obtain information on the positions and sizes of pinholes. In Fig. 4, which shows a capture image of the developed software, the graph of the left-hand side window captures edges of the patterns, and the right-hand side window shows a plot of the width variation or position difference between two edges as a function of length: $f_E(y)$, where y is the coordinate of the pattern in the length direction. Note that the width variation is the difference between two edges and differs from the variations of edges, which are variations of each edge and consequently defined at each edge.

From information about the width variation, we can define the largest width w_L (maximum value of $f_E(y)$), smallest width w_s (minimum value of $f_E(y)$), and average width w_0 (average of $f_E(y)$). We can calculate the degrees of width variation in terms of the peak-to-peak to mean value as

$$w_{pp} = (w_L - w_S)/w_0 \,. \tag{3}$$

We can also determine edge variations by calculating the standard deviation of each edge. The property of pinholes is calculated by

$$A_p = A_{pinholes} / A_{pattern} \,, \tag{4}$$

where $A_{pinholes}$ is the area of the pinholes and $A_{pattern}$ is the area of the pattern in the ROI.

The edge waviness is calculated as

$$E_w = \sqrt{\left[\sum E_i(y) - E_{0,i}\right]^2 / (n-1)}, \tag{5}$$

where E_i is the position of the i-th edge; $E_{0,i}$ is the mean value of E_i; and n is the number of data points.

We can obtain information to evaluate the printability of the printed patterns using Eqs.(3)–(5) given above.

4. Evaluation of printability of printed patterns

The actual printed patterns are used to measure the geometric properties and evaluate the printability from the measured results. The printed patterns are obtained by the direct gravure method using silver conductive ink with viscosity of 30,000 cps. The target pattern is a single line pattern with 50μm width. The image is obtained by an optical microscope and image-processed and measured using the developed software. Based on Eqs.(3)-(5), the peak-to-peak to mean , pinhole ratio , and edge waviness are calculated for 57 different patterns, and their distributions are plotted in Figs. 5, 6, and 7. In each figure, three different types of patterns with different values of properties are also shown as examples.

As shown in these figures, even these 57 samples show different qualities or printability of the printed patterns. The measurement method and software used to measure the geometric properties of the printed patterns and calculate the printability can clarify the printability of the printed pattern quantitatively. For example, the pattern images shown in Fig. 5 have peak-to-peak to mean values of 0.3, 0.58, and 0.87, respectively, and we

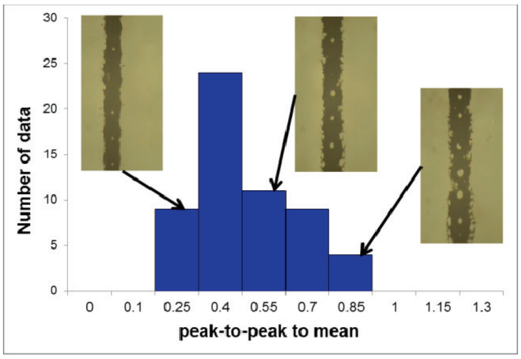


Fig. 5 Distribution of measured data of samples: peak-to-peak to mean

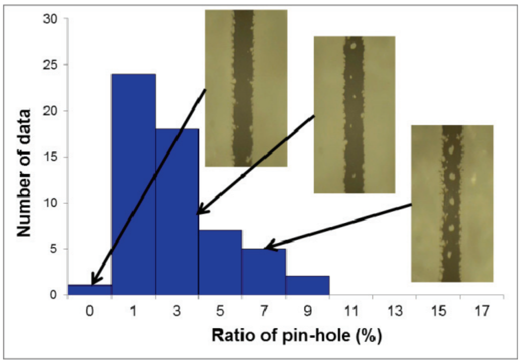


Fig. 6 Distribution of measured data of samples: pinhole area to pattern area

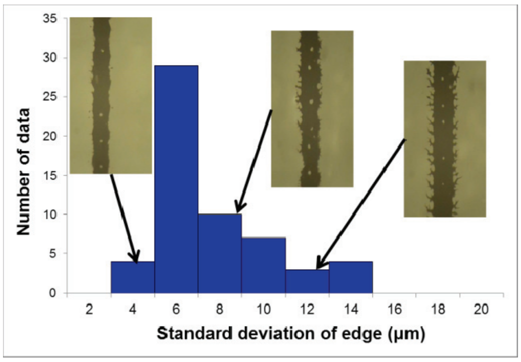


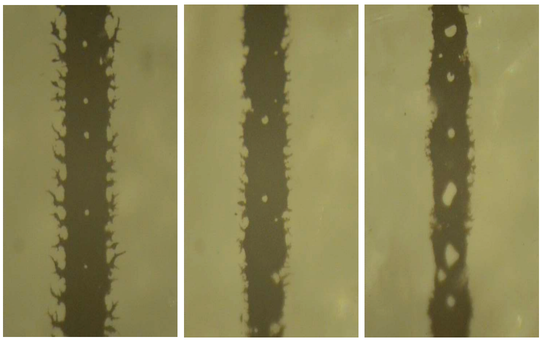
Fig. 7 Distribution of measured data of samples: standard deviation of edge

Table 1 Grade of printability of patterns

Grade	Width	Pinhole	Edge
	Peak-to-peak to mean (w_{pp})	Pinhole ratio (A_p, %)	Edge waviness (E_w)
1	<0.1	<1	<2
2	<0.2	<2	<4
3	<0.3	<3	<6
4	<0.4	<4	<8
5	<0.5	<5	<10
6	<0.6	<6	<12
7	<0.7	<7	<14
8	<0.8	<8	<16
9	<0.9	<9	<18
10	0.9≤	9≤	18≤

can relate the peak-to-peak to mean values with the quality or printability of patterns from the viewpoint of width uniformity.

We can assign a grade or classify the printability of printed patterns based on the measurement results shown in Figs. 5-7. Table 1 shows the grade of the patterns as classified by the width (peak-to-peak to mean), pinhole (ratio of pinhole area), and edge (edge waviness: standard deviation). This classification of the printability of printed patterns is one example that is proposed in this study. The 1st grade is the finest level, and the increase in the grade number implies the degradation of printability. Fig. 8 shows examples of printed patterns with different grades of width, pinhole, and edge, in reference to Table 1. Before assigning grades for the patterns, we can say that the pattern in Fig. 8(b) is better than others and that in Fig. 8(c) is better than that in Fig. 8(a). However, we cannot say how much better one pattern is than the others. The classification of patterns based on Table 1 can clarify the differences among patterns quantitatively. The pattern in Fig. 8(a) has grades of 6, 1, and 7 for the width, pinhole, and edge, respectively. On the other hand, the pattern in Fig. 8(b) has grades of 3, 1, and 3 for the width, pinhole, and edge, respectively. The two patterns have the same grade for pinhole, but different grades for width and edge. The pattern in Fig. 8(c) has grades of 5, 9, and 4 for the width, pinhole, and edge, respectively, and its grades for width and edge are superior to those of Fig. 8(a); however, its grade for pinhole is much lower than that of Fig. 8(a), with a difference of 8.



(a) 6, 1, 7 (b) 3, 1, 3 (c) 5, 9, 4

Fig. 8 Grades of patterns for width, pinhole, edge

5. Conclusion

In this paper, the measurement method of the geometric properties of the printed patterns as well as related software is proposed to evaluate the printability of printed patterns. The measurement method gives criteria for the evaluation of the printability in terms of width, pinhole, and edge. Based on the evaluation criteria, the pattern could be classified into different grades, with which we could classify the printed patterns into bad or good ones quantitatively. As examples, the geometric properties of the total 57 sample patterns are measured using developed software and the printability for each pattern is calculated. The printed patterns could have different printability for width, pinhole, and edge. The comparison of printed patterns having different grades shows that we can distinguish the patterns with low printability from the patterns with high printability quantitatively.

We should have the printed patterns of high grades in the printability to have printed electronics devices with high performance as well as maintain the high grades to obtain reliable and uniform qualities of printed electronics devices. The proposed measurement method could be an efficient tool to evaluate the printability in the printed electronics.

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