Inkjet Geometric Design & Compensation Rules Generation and Characterization

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Abstract

Geometric design and compensation rules aim to guarantee that layout representations match final printed patterns within a valid tolerance for a desired process yield. The more conservative the rules are, the better is the yield. So, for a given process and after an experimental extraction of the required process parameters, it is possible to derive minimum design rules that characterize the technology process to a point where design engineers can address physical design to develop devices and systems without a deep knowledge of process and materials.

A methodology to extract and characterize inkjet geometric design and compensation rules is proposed in this work as a first step to separate design from fabrication in a similar way as in silicon technology.

Introduction

Inkjet printing is a challenging technique that will lead to a new paradigm in electronics fabrication through the construction of electronic devices and circuits drop by drop.

Designing devices and circuits requires a wide knowledge of process aspects and a complex interaction among concepts, tools and processes coming from different science and engineering disciplines.

In the late 1970`s, the Mead-Conway design rules concept [1] revolutionized IC design. Their idea was to abstract physics to a point where design engineers could address physical design with sufficient certainty.

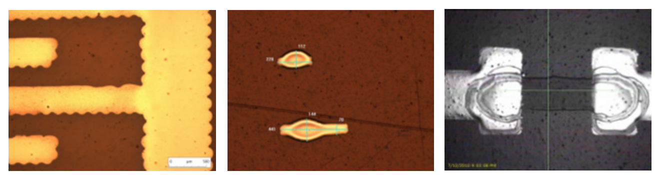
Our work is based on the experience of the microelectronic silicon foundry model, and the concept of the process design kit (PDK) as the nexus between design and technology [2]. A PDK is a set of files related to specific device models, which are used to accurately describe manufacturing process details to designers and integrated in EDA tools containing geometrical and electrical design rules, device technology parameters and simulation models. However, although the main idea can be adopted, and tools and knowledge recycled, a new approach has to be considered.

Geometric design rules aim to guarantee that layout representations match final printed patterns within a valid tolerance for a desired process. So, for a given process and after an experimental extraction using specific tests patterns and a compensation methodology to increase the achievable resolution and pattern transfer fidelity, we will be able to find out the minimum intra- and inter-layer design rules for our process.

Inkjet printed considerations

In printed electronics, the various roles of active materials lead to different constraints on device technology. The various aspects of ink-substrate interactions must be revisited for printed electronics. Different works [3][4] demonstrated the need for improved control of the behavior of inkjet-printed lines and shapes. By characterizing the conditions that lead to different printed morphologies, electronic devices can be improved.

Some representative effects of inkjet-printed features are reviewed in Figure 1 as an example of printing behavior. The discrete drop nature of inkjet-printed shapes can create waviness line behaviors as shown in Figure 1.a. Also, the balance between drop size, drop spacing and substrate interaction can create a bulging effect as shown in Figure 1.b.



a) b) c)

***Figure 1**. a) to c) Different printing behaviors*

Printing layer-by-layer directly affects device performance because printing functional materials on prior deposited layers modifies expected morphologies as shown in Figure 1.c.

Technology Characterization

For PDK generation we need a concise description of process characteristics. This is done through technology characterization of geometries and morphologies of printed patterns. The quantitative relation between designed patterns and printed dimensions is the key factor, as discrete inkjet printing resolution and inkjet spot-based patterning restricts pattern generation.

As the spot diameter can be measured, a first approach to printed dimensions can be done using the following equation [5]:

$$\text{Width} = (n - 1) \times DS + D \tag{1}$$

Where n is the number of deposited dots, DS is the drop spacing and D is the spot diameter. However, this equation can only be considered as a first approach to estimate dimensions for printed patterns. The nature of printed lines is complex and differences arise due to a number of process factors (e.g. ink-substrate interaction, drop spacing, jetting frequency, ink composition).

Some works reporting one-dimensional [3][4] and two-dimensional [6] models for printed line dimensions can be found in the literature. Another option is its extraction for defined shapes by using an empirical method through test patterns printing and characterization. This is a costly method but, useful for the generation of controlled pattern libraries for target applications.

Pattern characterization Methodology

We develop a methodology to optimize the morphology of the printed lines. We propose and define some parameters in order to find out the optimal printing feature and prevent line instabilities.

It is known in the literature that one can tune the relative distribution of material across the printed line by controlling the substrate temperature [7]. Our work will extend the research by means of tuning both the temperature substrate and drop lattice [8]. We will focus on the percentage of droplets of the line providing a useful pattern characterization structure for the improvement of film homogeneity.

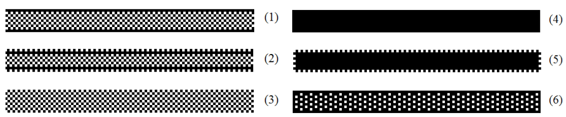


***Figure 2**. Different drop lattice evaluated*

The pattern characterization structure was divided into a set of lines with different pixel lattices as detailed in Figure 2. Pattern structures were printed using a drop spacing of 20µm and ranging the substrate temperatures from 20ºC up to 60ºC.

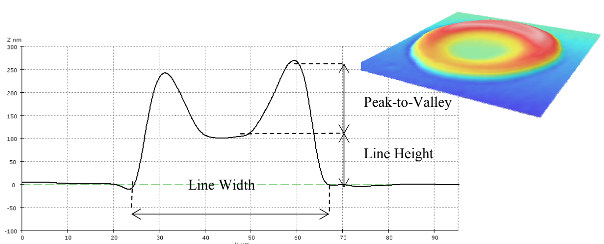


***Figure 3**. 3D and sectional image of a drop and bead parameters defined.*

The device characterization methodology defines some qualitative analyses labeled (1) line width, (2) line height, (3) peak-to-valley coffee ring verse height ratio and (4) line uniformity. The strategy is based on comparing and seeking the optimal parameters of each cross-section that leads to a squared profile.

Experimental results

Inkjet printing was carried out using a Dimatix DMP2831 printer. The ink used was a 20 wt% silver nanoparticle content (Sunchemical Suntronic EMD5603) and the characterization structures were printed on a flexible PEN substrate (DuPont Teijin Teonex® Q65FA). The measured diameter of the drop was around 42µm as shown in Figure 3.

The purpose of the printing experiments was to measure the named parameters for different patterns, substrate temperature and printing directions taking cross-sections near the ends and several at the center for each line by means of confocal and interferometric microscopy techniques (Leica DCM 3D).

Figure 4 shows the dependency of line width for each pattern on the temperature substrate and orientation. The expected line width was 200µm, as predicted using Equation 1.

The patterns (4) and (5) fit fairly to the desired width. Obviously an increase in line width is observed when the pattern becomes denser, resulting more material deposited. However, the wider line appears for pattern (6) instead (4). In the same way, as the orientation influences on the width, the horizontal lines present larger widths than vertical ones. Nevertheless pattern (4) shows a closer width in both orientations at 40 ºC.

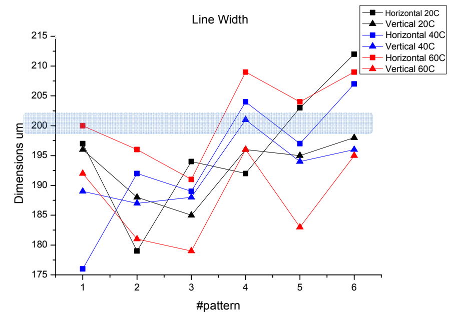


***Figure 4**. Measured line width*

As depicted in Figure 5, and in the same tendency as line width, a further increase of height is got owing to merging of the beads deposited. Consequently, the height is maximized for the 100% solid line pattern (4) in both orientations at 60ºC.

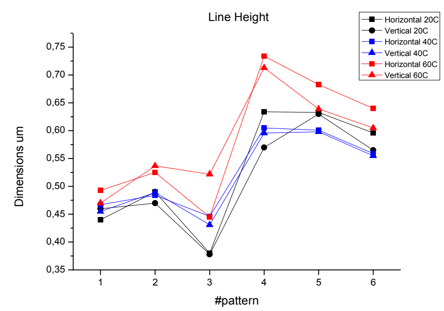


***Figure 5**. Measured line height*

The coffee ring effect is a well-known phenomenon, and arises from the fluid flow from the center of droplet toward the edge to compensate for evaporation losses [9]. The morphology of the coffee ring on the patterns is assessed considering temperature substrate and orientation shown in Figure 6. Illustrated as blue box, the value of zero means square profile without coffee ring. Positive values mean a convex profile and negative means concave profile in the line.

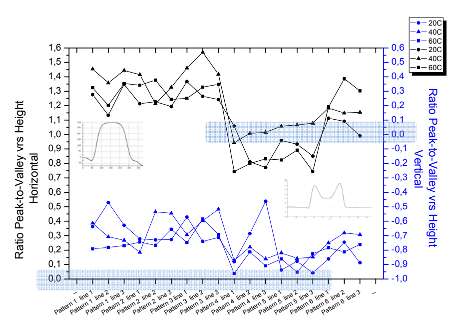


***Figure 6.** Measured ratio peak-to-valley vs height*

Respectively, for higher and lower values the influence of the effect compared with height is enhanced. Strikingly as the substrate temperature increases, the coffee ring effect is not enhanced. Besides, the coffee ring arises in dense patterns such as (4), (5) and (6) occurring exclusively to horizontal lines. Therefore there exists a strong dependence on the orientation. The horizontal patterns (4) and (5) at 40ºC have squared profiles.

The line uniformity was investigated by means of ridge width [9], Figure 7. The ridge width of scalloped pattern is defined as variation distance of individual rounded contact lines [7].

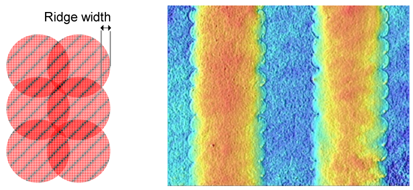


***Figure 7**. Ridge width effect of scalloped lines*

The following table shows the ridge width depending on the pattern, orientation and substrate temperature. Data listed is an average of measurements. The value 0 means straight line without ridge.

Ridge width (μm) measurement

	20ºC		40ºC		60ºC	
	Vert.	Horiz.	Vert.	Horiz.	Vert.	Horiz.
Pattern#1	2,5	0,0	0,0	0,0	2,9	0,0
Pattern#2	7,6	5,9	9,2	1,5	11,0	7,4
Pattern#3	8,0	7,1	12,1	4,1	11,2	7,2
Pattern#4	0,0	5,9	0,0	2,9	2,8	0,0
Pattern#5	4,0	5,0	0,0	4,3	8,6	5,2
Pattern#6	2,0	2,0	0,0	0,0	3,3	0,0

The experimental results show that the influence of phenomenon scalloped is stronger for vertical lines than horizontal lines. Besides as the temperature substrate increase, the instability is slightly enhanced for patterns (2) and (3) as these patterns have 50% solid external line. The patterns (1) and (6) formed at 40ºC no ridge occurs. Taking a glance of the results, at 40ºC the ridge effect is not rather pronounced.

Finally, considering (1) line width, (2) line height, (3) ratio peak-to-valley *vs.* height and (4) line uniformity for different patterns ranging substrate temperature one can conclude that the best condition printing is the pattern (4) at 40ºC in horizontal direction.

Geometric Design Rules

Although Geometric design rules can comprise a very large set of restrictions, they are based on two considerations: (1) the geometrical patterns that can be reproduced by the process and (2) the interaction between different layers.

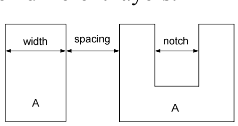


***Figure 8**. Definition of Basic Geometric Design Rules*

In the field of Printed Electronics is important to control feature fidelity of the patterning to reproduce exactly the layout of the circuit. By defining the optimal patterning we can find out about the design rules such as minimum width, spacing, notch and so on up to get the minimum feature size manufacturable allowed by the technology as shown in Figure 8.

Design Rules characterization Structure

By carefully characterizing and understanding the conditions that lead to different printed line morphologies by means of pattern test structures we will be able to find out the design rules of a particular ink. In this work, we present a set of pattern test structure useful for obtaining the physical limits resolution of the manufacturing process.

Minimum width

The structure consists of a set of lines which line width progressively increases, whereas the spacing among them remains constant as shown in the following figure.

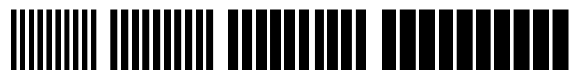


***Figure 9**. Characterization pattern for minimum width rule extraction*

By means of this pattern one can find out the minimum rule width values such that the line is sufficiently straight, smooth and without stacked coins, scalloped or bulging behaviors.

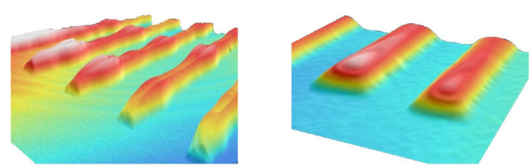


***Figure 10.** Non-homogeneous (left) and homogeneous (right) line behavior*

Minimum spacing

The structure consists of a set of lines which spacing progressively increases, whereas its width remains constant.

***Figure 11**. Characterization pattern for minimum spacing rule extraction*

By means of this pattern one can find out the minimum spacing rule such that the lines are sufficiently separated avoiding merging with neighbor lines. Figure 12.b shows a displacement error that might lead to short circuit as shown in Figure 12.c.

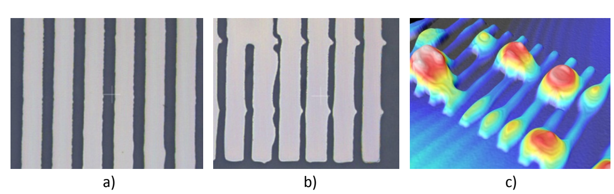


***Figure 12**. a) Correct spacing, b) Printer misalignment, c) Electrical shorts*

Minimum notch

The concept of minimum notch rule concerns to the structure of U-shaped open loop, shown in Figure 13. The goal of this rule is to avoid merging at the inner corners of bended lines.

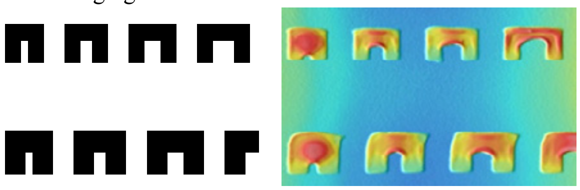


Figure 13*. Test pattern and 3D image for minimum notch rule extraction*

Corner structures

Integrated circuits require the patterning of corners. Convex corners occur at the junction of lines for instance. Furthermore, an abrupt change of direction of a line has resolution limits owing to corner rounding among others non-desired effects.

The proposal of this pattern is to assess the convex corners by means of the common corner structure as shown in Figure 14.

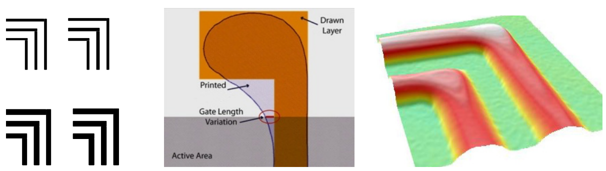


Figure 14*. Designed, printed and 3D image of corner patterns*

By means of this test structure one can find out the optimal line width and spacing such that the ink was confined in right angle line junction as shown in the previous figure.

Compensation Rules Methodology

For inkjet printed technology, the deposited pattern is deteriorated markedly due to fluidic causes leading to the compensation techniques. These techniques consist on modifying the shape pattern in order to avoid instabilities during the printing. The goal of the compensation techniques is to redistribute the local density of ink in order to reduce the ink accumulation/lack in some positions of the structure transferring properly the desired pattern.

The Pattern Shape Correction (PSC) is a compensation technique [2] based on Resolution Enhancement Techniques (RETs), especially on Optical Proximity effect Correction (OPC) from photolithography process in silicon technology.

Basically, the efforts are being focused on the junction of perpendicular lines as main critical point.

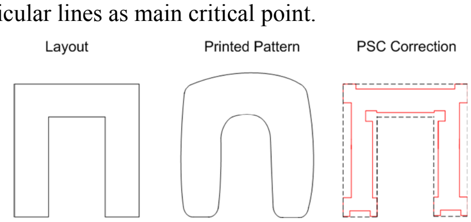


Figure 15*. Layout, Printed Pattern and PSC Correction for U-shaped structure*

Complementary serif corners compensation methodology is applied to both inner and outer corners to heighten the sharp-edged. Moreover, several drops at the inner corners were taken out to avoid round corners shown in Figure 15 and 16 left.

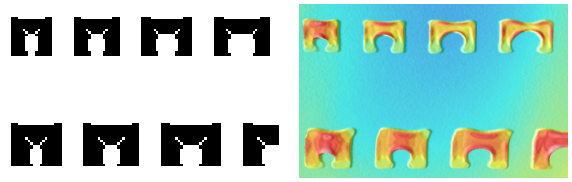


Figure 16*. Test pattern and 3D image for compensated notch rule*

Regarding Figure 13 and 16, an outstanding improvement of the width notch was obtained by applying PSC compensation getting a further resolution and optimizing minimum notch rule.

Summary

We have discussed the benefit of building a characterization methodology to extract geometric design rules and apply compensation rules for manufacturing reliable and precise designs based on the knowledge inherited from silicon VLSI technology.

We focused on technology characterization concerning geometric issues. This leads to the proposal of the use of design rules and their extraction from fabricated patterns to produce highly precise devices, and the application of compensation techniques to get higher resolutions.

Acknowledgements

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Author Biography

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