A layout defect-sensitivity extractor

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A LAYOUT DEFECT-SENSITIVITY EXTRACTOR

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ABSTRACT

A new method based on a deterministic geometrical construction of critical areas is presented to determine the sensitivity of layouts to spot defects. The models for fatal faults considered are bridges and cuts related to patterns in one layer. Our approach, based on the new concept of "susceptible sites", has a complexity $O(N \log N)$, where N is the number of line segments. Moreover, only two scans are necessary to extract all "susceptible sites" which then are used to compute the "critical areas" for a whole set of points in a domain of defect sizes.

1. INTRODUCTION.

For a long time layout verification has been confined mainly to validate the design rules imposed by the technological process. However, as the processes tend to mature and to advance to smaller resolution features other forms of layout verification become imperative. In the past, external contaminants that could lead to defective layouts were not relevant and in most of the cases were not taken into account. Nowadays their significance is crucial to the successful manufacturing of the chip even though there is a precise control of the line features. One such form of layout verification is to foresee the robustness of the artwork in real manufacturing environments. We propose the identification of "critical areas" [1-3] in layouts as a suitable means to analyse the robustness of the artwork against defects.

Existing tools for yield simulation and fault analysis [4,5] implicitly make use of some concept of critical areas, yet these tools neither extract nor compute the critical areas accurately on the basis of a thorough theoretical model.

Due to the complexity of the layouts, several authors prefer to derive a "layout image" to avoid the real extraction and computation of the critical areas. This is the case with the concept of "virtual layouts" introduced in [7] and the one with "equivalent layouts" in [8]. These layout images are composed of parallel lines which represent statistically the width, length, and spacing of all the patterns of the actual layout. The approach cannot point out the critical regions in the real layout, and moreover the area computed is only an approximation of the exact value. Other authors [13,6] find some set of patterns that is likely to fail due to a predefined defect size, however the area of those patterns, or the area contained in the space between them is not the correct critical area. Usually the results are pessimistic estimates of the exact critical area.

Suggested approaches [2],[14] to extract the critical areas in

complex layouts are based on a statistical Monte Carlo simulation, and analytical methods [8] are restricted only to simple and regular layouts. We present a layout verifier capable of identifying the critical areas in complex layouts. Unlike the Monte Carlo approaches our method is deterministic. The implementation is based on a simple scan line algorithm. Given a defect type the algorithm performs only one layout extraction for any span of defect sizes.

2. FINDING THE CRITICAL AREAS IN LAYOUTS.

In this paper we restrict ourselves to catastrophic faults related to patterns in one layer, namely, the *bridge* (joining patterns unintendedly), and the *cut* (breaking patterns unintendedly)

It is difficult to model the exact shape of defects since in reality they are rough-edged splotches. However, we propose to model defects as square shaped objects. We stipulate that this approximation is sufficiently correct. It can be shown that it implies very simple and fast algorithms.

It has been shown [11] that the critical areas can be found geometrically. Under this approach the critical areas for bridges are found by expanding each pattern by an amount equal to half of the defect size, and then by checking if the expansions intersect. If so, then the amount of intersection corresponds to the critical area between the patterns. In the case of critical areas for cuts every pattern is shrunk by half of the defect size, and a critical area is established only when on shrinking parallel edges pass over each other. This solution has a quadratic complexity, in the case of bridges, because pairs of patterns have to be investigated, and thus it is computationally prohibitive for very large layouts. Also, the expansion of the patterns implies that a layout extraction has to be executed for each defect size. For the areas sensitive to cuts the problem is simpler since only individual patterns have to be considered.

3. MATHEMATICAL FOUNDATION.

A point set A_i is a connected open set of points in a mask plane. The boundary of A_i is a closed contour of cartesian straight lines called edges. The point set A_i divides the layout mask in two disjoint regions, the *interior* and the *exterior* that are separated by the contour of A_i . The point sets A_i may be the set of opaque zones of a mask.

We say that the horizontal line segments s_1 and s_2 are *comparable* at abscissa x if there exists a vertical line that intersects them. The

relation *above at x* is defined as: s_1 is above s_2 at x if s_1 and s_2 are comparable at x and the intersection of s_1 with the vertical line lies above the intersection of s_2 with that line [10]. The relationships *to the left of y* and *to the right of y* are defined correspondingly by rotating the configuration by 90 degrees.

Our algorithm is based on the geometrical approach explained in section 2. However, instead of proceeding directly to establish the critical areas we determine first those regions where a defect of any size may potentially cause a fault. These regions are parts of the empty spaces between patterns, for the case of bridges, and the patterns themselves, for the case of cuts. Therefore only a single layout extraction is needed for any span of defect sizes, and thus the problem is reduced to determining the shape of subsets constituting the critical area from these regions for any given defect size.

Definition 1 Let $(y(u); l(u), r(u))$ denote the coordinates of a horizontal line segment u with ordinate y having l and r ($l < r$) as its left and right abscissae respectively. Assume three line segments α , β , and γ , such that $l(\alpha) > r(\gamma) \wedge y(\alpha) > y(\gamma)$ and that $y(\alpha) > y(\beta) \wedge l(\alpha) < r(\beta) \wedge r(\alpha) > l(\beta)$. We say that α and γ are "diagonally neighbouring" if in the open rectangle $S_{diagonal}$ with cornerpoints (d_1, d_2) there exist no points of any other point set of the same mask, where $d_1 = (r(\gamma), y(\gamma))$ and $d_2 = (l(\alpha), y(\alpha))$. We call $S_{diagonal}$ a *left corner susceptible site for bridging faults relative to α* . We also say that α and β are "vertically neighbouring" if in the open rectangle $S_{lateral}$ with cornerpoints (s_1, s_2) there exist no points of any other point set of the same mask, where $s_1 = (\max(l(\alpha), l(\beta)), y(\beta))$ and $s_2 = (\min(r(\alpha), r(\beta)), y(\alpha))$. We call $S_{lateral}$ a *vertical susceptible site for bridging faults*. Horizontal susceptible sites are defined analogously.

We omit the formal definition of *susceptible sites for cutting faults*.

Definition 2 Assume that we have a defect of size δ , a lateral susceptible site S_l , and a corner susceptible site S_c . Referring to our previous notation assume that $y(\alpha) < y(\beta) + \delta$ and that $(l(\alpha) < r(\gamma) + \delta) \wedge (y(\alpha) < y(\gamma) + \delta)$. Then the rectangular open point set $R_l(\delta)$ with cornerpoints (r_1, r_2) given as $r_1 = (\max(l(\alpha), l(\beta)) - \frac{1}{2}\delta, y(\alpha) - \frac{1}{2}\delta)$ and $r_2 = (\min(r(\alpha), r(\beta)) + \frac{1}{2}\delta, y(\beta) + \frac{1}{2}\delta)$, and the rectangular open point set $R_c(\delta)$ with cornerpoints (q_1, q_2) given as $q_1 = (l(\alpha) - \frac{1}{2}\delta, y(\alpha) - \frac{1}{2}\delta)$ and $q_2 = (r(\gamma) + \frac{1}{2}\delta, y(\gamma) + \frac{1}{2}\delta)$ are called *critical regions*. The area enclosed in a critical region is called the *critical area*.

We now give two theorems which reduce the time complexity of the computation of critical areas. The idea behind these theorems is that some critical regions for bridges are contained in others and thus need not be considered.

Theorem 1 Let S_1 and S_2 be two *corner susceptible sites*, and $R_1(\delta)$ and $R_2(\delta)$ their corresponding critical regions for a defect size δ , respectively. If $S_1 \subset S_2$ then $R_2(\delta) \subset R_1(\delta)$.

Proof: Assume three line segments α , β , and γ , such that α and β , and α and γ are diagonally neighboring in the following order $r(\alpha) < l(\beta) < r(\gamma) < l(\gamma) < r(\alpha)$, and $y(\alpha) > y(\beta) \geq y(\gamma)$. Let S_1 and S_2 , $S_1 \subset S_2$, be the corresponding corner susceptible sites given by the corner points (q_1, q_2) and (r_1, r_2) , respectively, expressed as: $q_1 = (r(\alpha), y(\beta))$, $q_2 = (l(\beta), y(\alpha))$, $r_1 = (r(\alpha), y(\gamma))$, $r_2 = (l(\gamma), y(\alpha))$. If a defect of size $\delta \geq \max(|l(\gamma) - r(\alpha)|, |y(\alpha) - y(\gamma)|)$ is placed in such a form that it affects the three open connected point sets simultaneously, then the critical regions $R_1(\delta)$ with corner points (u_1, u_2) , and $R_2(\delta)$ with corner points (v_1, v_2) , that are obtained from S_1 and S_2 ,

respectively, are given by $u_1 = (l(\beta) - \frac{1}{2}\delta, y(\alpha) - \frac{1}{2}\delta)$, $u_2 = (r(\alpha) + \frac{1}{2}\delta, y(\beta) + \frac{1}{2}\delta)$, $v_1 = (l(\gamma) - \frac{1}{2}\delta, y(\alpha) - \frac{1}{2}\delta)$, $v_2 = (r(\alpha) + \frac{1}{2}\delta, y(\gamma) + \frac{1}{2}\delta)$. It can be seen that the abscissa of u_1 is smaller than the one of v_1 and also that the coordinates of $u_2 \geq v_2$, from which it follows that $R_2(\delta) \subset R_1(\delta)$.

Theorem 2 Let A , B and C be three open connected point sets, such that A and B , as well as B and C , are vertical neighbours. Let S_{AB} , S_{BC} , and S_{AC} be the susceptible sites between A and B , B and C , and A and C , respectively. Let also $S'_{AB} \subset S_{AB}$, $S'_{BC} \subset S_{BC}$, and $S'_{AC} \subset S_{AC}$ be the largest three rectangular open point sets with the property that they share the same left and right coordinates. Assume that a defect of size δ is placed. Let R_{AB} , R_{BC} , and R_{AC} be the corresponding subsets of critical regions of S'_{AB} , S'_{BC} , and S'_{AC} , respectively, obtained in the same manner as indicated in definition 2. Then, $R_{AC} \subset (R_{AB} \cup R_{BC})$.

Proof: Let α , β , β' , and γ be four maximal horizontal line segments of the open connected point sets A , B , and C , respectively, such that the interior of A is below α , the interior of B is above β and below β' , and the interior of C is above γ . Suppose also that the four line segments are comparable at a closed interval $[a, b]$ of the domain of points of the abscissae. Assume that the following order is imposed $y(\alpha) < y(\beta) < y(\beta') < y(\gamma)$. Let (q_1, q_2) , (r_1, r_2) , and (s_1, s_2) be the corner points of the lateral susceptible sites S'_{AB} , S'_{BC} , and S'_{AC} , respectively, expressed as $q_1 = (a, y(\alpha))$, $q_2 = (b, y(\beta))$, $r_1 = (a, y(\beta'))$, $r_2 = (b, y(\gamma))$, $s_1 = (a, y(\alpha))$, $s_2 = (b, y(\gamma))$. Assume that a defect of size $\delta \geq |y(\gamma) - y(\alpha)|$ is placed in such a form that it affects the three open connected point sets simultaneously, then the critical regions R_{AB} with corner points (u_1, u_2) , R_{BC} with corner points (v_1, v_2) , and R_{AC} with corner points (w_1, w_2) , obtained from the susceptible sites S'_{AB} , S'_{BC} , S'_{AC} , respectively, are given by $u_1 = (a - \frac{1}{2}\delta, y(\beta) - \frac{1}{2}\delta)$, $u_2 = (b + \frac{1}{2}\delta, y(\alpha) + \frac{1}{2}\delta)$, $v_1 = (a - \frac{1}{2}\delta, y(\gamma) - \frac{1}{2}\delta)$, $v_2 = (b + \frac{1}{2}\delta, y(\beta') + \frac{1}{2}\delta)$, $w_1 = (a - \frac{1}{2}\delta, y(\gamma) - \frac{1}{2}\delta)$, $w_2 = (b + \frac{1}{2}\delta, y(\alpha) + \frac{1}{2}\delta)$. We can notice that $w_1 = v_1$ and $w_2 = u_2$; since the bottom coordinates of u_1 and u_2 are smaller than v_1 and v_2 , respectively, it follows that $R_{AC} \subset (R_{AB} \cup R_{BC})$. This property of the critical regions is known as the "proximity effect" [2].

We outline now the steps involved in the computation of critical areas.

Step 0. For some mask assign unique identification numbers to the open connected sets. Decompose them into line connected segments.

Step 1. Sweep the layout horizontally and vertically to extract, from the pre-processed mask, all the susceptible sites for bridges and cuts. Store them in two different data structures, one for bridges and one for cuts. We denote these data structures as "susceptibility structures".

Step 2. For every defect size defined in the range of sizes traverse the "susceptibility structure". The coordinates of areas sensitive to bridges, or cuts, are obtained by shrinking the abscissae (for horizontal sites), or the ordinates (for vertical sites), or both abscissae and ordinates (for corner sites) of the related susceptible sites. See Fig. 1.

Step 3. For every defect size compute the total critical area enclosed in the set of coordinates found above. The total critical area per defect size is the area of the union of the individual critical regions found in step 2.

Sections 4 and 5 give details of the algorithms.

Figure 1. The critical regions for both bridges and cuts are found by shrinking the susceptibles sites

4. EXTRACTION OF SUSCEPTIBLE SITES.

We classify all line segments as belonging to two types. The horizontal (vertical) line segments are of type BEGIN when the interior of their open connected point set is above (to the right) of the line segment. Similarly, the line segments are of type END when the interior of the open connected point set is below or to the left of the line segment. Each vertical line segment is specified by its x-coordinate and the y-values of the lower and upper endpoints. Each horizontal line segment is similarly specified by its y-coordinate and the x-values of its left and right endpoints. We store the horizontal and vertical line segments in two different data structures.

The extraction of susceptible sites is based on the principle of the scanline algorithm [10]. We perform two orthogonal layout sweeps: a bottom-up and a left-right sweep that cover all the susceptible sites parallel to the scanline. The bottom-up sweep, or VERTICAL sweep, scans the data structure with the horizontal line segments. The left-right sweep, or HORIZONTAL sweep, scans the one with the vertical segments. As the algorithms for finding susceptible sites for bridges and cuts are very similar the explanation to follow is restricted to bridges.

Suppose now that the vertical sweep is carried on. Let $P = \{p_1, \dots, p_n\}$ be the set of line segments in ascending y-order. M a set of line segments sorted in ascending x-order, and S a set to store the susceptible sites found. The main loop of the algorithm sweeps a scanline through the set P . Every END line segment swept is stored in the set M ordered by its left coordinate. Initially M is empty. Whenever a BEGIN line segment is encountered we check for intersections with the (horizontal line) segments of M . For every intersection a new susceptible site is made and stored in the set S only if the identification numbers of the BEGIN and END line segments are different. Based on theorem 1, we also look, in M , for the nearest line segments to the left (predecessor) and to the right (successor) of the endpoints of the BEGIN line segment. If these lines exist the corresponding left and right corner susceptible sites are created too.

Lateral susceptible sites are labeled as VERTICAL, or HORIZONTAL, depending on the sweep in which they were found. Corner susceptible sites are always labeled as CORNER. The justification of labeling the susceptible sites is because in step 2 we need to know what coordinates to shrink, either the abscissae or the ordinates before we can deduce if a critical region is established.

The set M is updated in such a form that only the intersected sections of the intersected line segments are deleted. Theorem 2 guarantees that these sections are no longer necessary to create critical regions with other line segments ahead of the scanline position.

The extraction of susceptible sites for cuts is essentially the same

except that in the algorithm the BEGIN line segments are the ones that are stored in the set M , and only the BEGIN and END line segments with the same identification number are processed. In some situations the algorithm will apparently find the same susceptible site for both vertical and horizontal sweeps. This is because we assumed that the "current cross edges" of the open connected point sets can be either vertical or horizontal. Since we are dealing with independent masks there is no way to know the signal flow (left to right, top to bottom ?) in order to determine if the pattern was broken in two nonequipotential regions. See Fig. 2 for an illustration of this case.

5. CREATION OF CRITICAL REGIONS.

The critical regions related to bridges and cuts are found by traversing their corresponding susceptibility data structures.

Figure 2. Two different critical regions for the same open connected point set. (a) For vertical current cross edges. (b) For horizontal current cross edges

Let $S = \{s_1, \dots, s_n\}$ be the set of the susceptible sites in ascending y-order. The main loop of the algorithm traverses the set S . For each susceptible site we check its label and then see if the critical region, for a given defect size, is established by shrinking the appropriate edges. If a critical region is formed we saved it in the set C indexed by the defect size. This procedure is repeated until the range of defect sizes is exhausted. Worth noticing is that each defect size has its unique critical regions in the layout, and that in fact the critical regions compose a "critical mask" specifically for the defect size in turn.

6. COMPUTATION OF CRITICAL AREAS.

The algorithm to compute the areas is an adaption of the algorithm presented in [10]. The implementation runs a scanline from left to right in the critical mask. We denote the left side of a critical region as BEGIN and the right side as END. Let $C = \{c_1, \dots, c_n\}$ be the set of vertical BEGIN and END line segments of the critical regions in ascending x-order, and also let $(key; bottom, top)_{c_i}$ represent an edge c_i situated at abscissa key having $bottom$ and top ($bottom < top$) as the ordinates of its endpoints. At any instance of c_i the total area is updated by evaluating the area of the union of the rectangle's sections that lie in the plane strip $key(c_i)$ and $key(c_{i-1})$. A segment tree M is used to determine the length of the intercept of the scanline in the strip with the union of the rectangle's sections.

7. COMPLEXITY ANALYSIS.

Table 1 presents the time complexity analysis of each of the steps of our method. The nomenclature used is N for the number of line segments of the preprocessed layout, and k for the number of susceptible sites. The number of susceptible sites is dependent on the style of the IC artwork, in the worst case $k \rightarrow N$. Let $\#d$ be the number of defect sizes, then the total time complexity to find the

critical areas for a range of defect sizes, assuming worst case, is $O(N^2 + \#d(N(1+\log N)))$. The quadratic complexity of step 1 is because our current implementation uses a linear list data structure. However, if the data structure is changed to a balanced tree the complexity of this step would be $O(k + N \log N)$ [9].

TABLE 1. Time complexity analysis of the proposed method

Step	Operation	complexity
1)	Susceptible sites	N^2
2)	Critical regions	k
3)	Critical areas	$k \log(k)$

No results of similar tools [14] have been presented in the literature as to make comparisons. We will assume a hypothetical case in which the critical areas are found according to: 1)growing the patterns, 2)finding overlaps of the grown patterns, and 3)computing the areas. Table 2 shows the ideal time complexity analysis. In this case $u(\delta)$ represents the number of overlaps, as a function of the defect size δ , that were created in the "pattern expansion" process of step 1. Notice that as the defect size increases $u(\delta) \rightarrow N^2$ since most patterns will be intersecting each other. For this algorithm, the total time complexity to find the critical areas for a range of defect sizes, assuming also a worst case, is $O(\#d(N(1+\log N) + N^2(1+\log(N^2))))$.

TABLE 2. Time complexity analysis of the hypothetical case.

Step	Operation	complexity
1)	Pattern expansion	N
2)	Overlap search	$N \log(N) + u(\delta)$
3)	Critical areas	$u(\delta) \log(u(\delta))$

Comparing both complexity analyses we can see that our method is $N \log N$ and depends only on the geometry of the layout. The hypothetical case is dependent on both the defect size and the layout geometry. For very large defect sizes, our method is superior. The $O(N \log N)$ complexity and defect size independency of our method provides an approach for interactive applications.

8. EXPERIMENTAL RESULTS.

The previous algorithms were implemented in a system aimed at layout yield prediction [12]. Fig. 3 shows the critical regions for bridges of a layout mask. The minimum resolution features are 6μ . The defect size is 20μ .

Fig. 4 shows the corresponding critical areas for bridges and cuts in the form of "sensitivity curves" (defined as the ratio of the total critical area to the layout area).

Figure 3. Critical regions are highlighted in black. Critical regions for bridges for a defect size of 20μ .

Figure 4. Mask Sensitivity.

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