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Modeling of 3-Dimensional Defects in Integrated Circuits
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Abstract
Although the majority of defects found in manufacturing lines have predominantly 2-Dimensional effects, there are many situations in which 2D defect models do not suffice, e.g. tall layer bulks disrupting the continuity of subsequent layers, abrupt surface topologies, extraneous materials embedded in the IC, etc. In this paper, a procedure to capture the catastrophic effect of 3-Dimensional defects is presented. This approach is based on the geometrical properties that result from the interaction between IC and defect size in two coordinate spaces: x-y and z. Our approach is a natural extension to the concept of critical areas, namely, the extraction of critical volumes. Through the course of this work hints to the origins of 3D defects will be given, conditions to capture critical volumes will be developed, and it will be shown that the net effect of 3D defects is accumulated from layer to layer.

1 Introduction
During the manufacturing of integrated circuits various types of defects arise out of which a few could be benevolent and the remaining catastrophic [8]. Benevolent defects are harmless while catastrophic defects impair the circuit performance of the IC. As it has been shown in literature these defects induce faults such as stuck at lines, stuck at transistors, floating lines, etc. [6].

There are many reasons for yield loss, however, it has been acknowledged that the main impediment in the successful manufacture of IC’s are spot defects. Spot defects are undesired portions of missing or extra material in some layer and conceptualized as circles, squares, octagons, etc. to approximate its splotch nature [5].

Effects of 2D defects have been captured by means of the concept of critical areas [2-5]. A 2D defect arises from projecting the image of a contaminant onto the surface of the IC; the contaminant can be a particle of dust, a rupture in the glass of lithographic masks, etc. Notice, that there are single and multi layer 2D defects. For instance, a 2D single layer defect is the one that introduces bridges and cuts to patterns in its same layer of origin. On the other hand, a 2D multi layer defect is the one that affects patterns in its layer of origin and some other layers, e.g. a spot defect of Polysilicon on top of an Active Area region.

A limitation in the theory of 2D defects is that it does not take into account defects which could be caused due to the presence of a 3D object embedded in the IC. The object would cause defects which are more detrimental to the IC and relatively harder to perceive than the 2D defects. Hence, a 3D defect is a defect which is caused due to an undesired contaminant embedded in the IC. As an example, consider a small speck of dust landing on the surface of some layer and then a second layer deposited on top of the first layer and disrupted by the height of the contaminant. See Fig. 1 for an illustration of 2D and 3D defects.
2 Properties and Consequences of 3D Defects

As it was previously mentioned, a 3D defect arises from the existence of a contaminant in the integrated circuit [1]. The contaminant could be a mound of dust or an unwanted material in a layer, for example a dust particle in a Poly layer, a spot of Poly in a Metal layer etc. Thus, the cause of these 3D defects is, as in the case of 2D defects, process instabilities and random disturbances [5]. For instance, wafer profiles show that some parts of the wafer are more oxidized than others. Among various reasons, this is because a temperature gradient exists in the furnace which causes an uneven heating for different regions of the wafer [7]. As a result, the topology of the oxide grown is not uniform and could even have abrupt peaks on its surface, which could be detrimental to the layers deposited on top of it. Naturally, there could be many instances where similar phenomena takes place. Random disturbances such as specks of dust are another important source of defects [8]. If such one speck is present on the wafer, a bulk is formed for the next layer above it at the intersection of the dust particle and the layer. The bulk may have its peak so tall that either a poor step coverage or a partial lithographic defocus may occur for the next layer [5, 9, 10].

Depending on their electrical properties such defects are broadly classified as conducting and insulating. In general, we have:

1. Breaks in insulating layers due to 3D conducting defects.
2. Breaks in conducting layers due to 3D insulating defects.
3. Shorts due to 3D conducting defects in insulating layers separating conducting layers.
4. Breaks in conducting layers due to 3D insulating defects in insulating layers underneath.
5. Shorts among conducting layers due to 3D conducting defects in insulating layers underneath.
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Figure 2: Bridges with Z and Y dimensions.

In general, if the defect is of a conducting type it can cause a break in an insulating layer, say, $L_j$ and consequently a short between any conducting layers insulated by $L_j$. If the defect is of an insulating type it could cause a break in insulating and conducting layers, yet its effect may not be noticeable in the insulating layer. Notice that failure primitives 4 and 5 are typical for 3D defects, i.e. the effects of defects are accumulated from layer to layer.

3 Modeling of Critical Volumes

A critical volume is defined as a volume where the centroid of the defect must lie in order to cause a fault. The sufficient condition to have a critical volume for cuts is that the defect’s height, $\delta$, should be greater than the pattern’s height, $h$. In a similar way, a critical volume for bridges arises when the defect’s height breaks the insulating layer between any two conducting layers. In this paper, 3D defect modeling is done by considering the defect as a 4 sided right rectangular prism, orthogonal to the IC surface.

3.1 Critical Volumes for Bridges

3D bridges cause faults only when nonequipotential regions are joined together. Consider that a conducting 3D defect of dimensions $\delta_x$, $\delta_y$, and $\delta_z$ exists between two conducting patterns in a stack of layers, such that a short circuit between them is caused. In a stack of layers, $\delta_z$ is the dimension which determines whether a short circuit would occur between the two conducting patterns. Additionally, there are also occurrences when a 3D defect could cause a short in $\delta_x$ and $\delta_y$ or $\delta_x$ dimensions as shown in Fig. 2.

An insulating bridge between two conducting patterns, and a conducting bridge in two insulating patterns are electrically meaningless.

3.1.1 Bridges for 2 Patterns: Consider two distinct conducting patterns $L_1$ and $L_3$, of length $l$ and of height $h_1$ and $h_3$, respectively, separated by the insulating pattern $L_2$ of height $h_2$. Let $c_i$ represent some constant value for a layer $L_i, i \in \{1,2,\ldots,n\}$, where $n$ is the number of layers in the stack. For additive processes $c_i$ represents the maximum allowed stretching of the deposited layer $L_i$. A defect and pattern set-up is shown in Fig. 3.

Assume that a 3D defect originates in layer $L_1$ and that its height is $\delta_z > h_1 + h_2 + c_1 + c_2$. Assume now that the defect is embedded through the three layers, as
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Figure 3: Defect and pattern set up

Figure 4: Critical volume for a bridge (a) Geometrical situation. (b) Critical volume - lateral view (c) Critical Volume - Top view

shown in Fig. 4. As this is a conducting defect, the result is a bridge between layers $L_1$ and $L_2$.

Then, the critical volume for this situation is obtained as:

$$V_{2Y} = [\delta_x - (h_2 + h_1 + c_1)]_{\text{height}} [\delta_x + 2\delta_z - c_2 + w]_{\text{width}} [l + 2\delta_z]_{\text{length}}$$

which reduces to

$$V_{2Y} = [\delta_x - (h_2 + h_1 + c_1)]_{\text{height}} [\delta_x + w]_{\text{width}} [l + \delta_z]_{\text{length}}$$

In this case the defect’s effect begins in $L_2$ because a conducting defect in a conducting layer is meaningless - the same concept applies to insulating defects originating in insulating layers. The term $[\delta_x - (h_2 + h_1 + c_1)]$ corresponds to the critical region in $Z$ direction. The remaining terms correspond to the critical region in $X$ and $Y$ directions. The short is present even when the defect’s center is located half the defect size away from the patterns contour. Thus, in Eq. (1), the end effects, which are extensions of half the defect size on both sides of the pattern, are taken care in $X$ and $Y$ directions.

3.1.2 Generalization of $n$ Patterns for Bridges: Consider a stack of $n$ patterns that have the same width and length. Assume that the insulating and conducting patterns are alternating. If there is a short between the $k^{th}$ and $n^{th}$ conducting pattern, caused by a conducting defect originating in the layer $L_k$ we
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Figure 5: Critical volume for a Cut(a) 3D geometrical view (b) lateral view (c) top view

have a critical volume:

\[ V_{ZY} = V_{ZX} = [\delta_z - (\sum_{i=1}^{n-1} h_i + c_i)]_{\text{height}} [\delta_x + w]_{\text{width}} [l + \delta_y]_{\text{length}} \]  

(3)

We get the summation starting from the \( k \)th pattern, to the \( (n-1) \)th pattern because even though the effect of the conducting defect in the conducting patterns corresponding to indices \( k \) and \( n \) is electrically meaningless, we have to include \( k \) in the equation, as the defect originates from layer \( L_k \). For bridges, we get the same volume in \( ZY \) and \( ZX \) directions as a result of the symmetry of the terms in the Eq. (3).

3.2 Critical Volumes for Cuts

A pattern is said to have been cut by a 3D defect when either two of the three dimensions of the defect are greater than the corresponding dimensions of the pattern. For instance, a break is said to have occurred if either of the two following conditions is satisfied:

1. \( \delta_x > h, \delta_z > w \)
2. \( \delta_x > h, \delta_x > l \)

where \( \delta_i \) is the defect size in \( X, Y \) or \( Z \) directions and \( l, w \) and \( h \) are the length, width and height of the pattern, respectively. Cuts in conducting patterns due to conducting defects, and those in insulating patterns due to insulating defects are electrically meaningless.

3.2.1 Cut for a Single Pattern: Consider a cut in a conducting pattern due to a right rectangular prism shaped contaminant embedded in the pattern. Let us assume that \( \delta_x > h \) and \( \delta_z > w \). Then the critical volume for this case, shown in Fig. 5, is given by:

\[ V_{ZX} = [\delta_x - (h + c)]_{\text{height}} [\delta_z - w]_{\text{width}} [l + \frac{\delta_x}{2}]_{\text{length}} \]  

(4)
which reduces to

$$V_{ZX} = [\delta_1 - (h + c)]_{\text{height}} \cdot [\delta_x - w]_{\text{width}} \cdot [l + \delta_y]_{\text{length}}$$

The terms $(\delta_1 - (h + c))$ and $(\delta_x - w)$ in Eq. (4) bound the critical regions in $Z$ and $X$ directions, respectively. For any defect size, if the center of the defect lies in these regions then it is catastrophic to the pattern. The term $(2L + w)$ in Eq. (4) confirms that the cut is present even when the defect's center is located half the defect size away from the patterns edges. Thus, in Eq. (4) the end effects are taken care of in the $Y$ direction.

Now let $\delta_1 > h$ and $\delta_y > l$. In that case critical volume is given by:

$$V_{ZY} = [\delta_1 - (h + c)]_{\text{height}} \cdot [\delta_y - l]_{\text{length}} \cdot [w + \delta_x]_{\text{width}}$$

which is the symmetric case for a cut in the $Y$ direction.

3.2.2 Generalization of $n$ Patterns for Cuts: For a cut in the $n^{th}$ conducting pattern, assuming that all the patterns have the same width and that the insulating defect originates in the $L^{th}$ conducting pattern, then the critical volume for a cut between the $I^{th}$ and $n^{th}$ conducting pattern is obtained as:

$$V_{ZY} = [\delta_1 - \left( \sum_{i=k}^{n} h_i + c \right)]_{\text{height}} \cdot [\delta_y - l]_{\text{length}} \cdot [w + \delta_x]_{\text{width}}$$

As the effect of the insulating defect is from the $k^{th}$ to the $n^{th}$ pattern, the index in Eq. (7) runs from $k$ to $n$. In Fig. 6, a stack of three patterns is considered with the insulating pattern present between the two conducting patterns. Assume a conducting defect originating in the conducting pattern and causing a cut in the insulating pattern. The critical volume for a cut in the insulating pattern is as shown in Fig. 6.

4 Defect Sensitivity

Layout Defect Sensitivity is defined as the ratio of the total critical region to the total region of the layout [3]. This region could be an area or a volume.
4.1 Sensitivity for Cuts

Consider a pattern of length $l$, width $w$ and height $h$, cut in ZX direction. Let for this case the dimensions of the defect be $\delta_l > h$ and $\delta_l > w$. Now if the defect size increases in $Z$ and $X$ directions, the sensitivity starts increasing till it reaches unity. By the definition of defect sensitivity, and by using Eq. (5) we get,

$$S_{ZX} = \frac{V_{ZX}}{V} = \frac{(\delta_l - h) \cdot (\delta_l - w) \cdot (\delta_l + l)}{l \cdot h \cdot w}$$

(8)

for $l >> \delta_l$, the above equation reduces to,

$$S_{ZX} \approx \frac{(\delta_l - h) \cdot (\delta_l - w)}{h \cdot w}$$

(9)

In Fig. 7 the sensitivity $S_{ZX}$ is plotted with respect to $\delta_l$ and $\delta_l$, using Eq. (9). In this setup a pattern of unit height and width is considered. A cut occurs, when the defect's height and width are greater than the height and width of the pattern respectively. As shown in the figure, sensitivity starts increasing with the increase in defect size and reaches its maximum value of 1.

4.2 Sensitivity for Bridges

Bridges are assumed to be sensitive in ZX direction. Consider three patterns in a stack. Let each one of them have length $l$, height $h$, width $w$. Let the middle pattern be insulating and the other two be conducting. Let us assume that there is a short between the two conducting layers. The critical volumes are shown for such condition in Eq. (2). Again, by the definition of defect sensitivity and by Eq. (3) we get,

$$S_{ZX} = \frac{V_{ZX}}{V} = \frac{(\delta_l - (h_1 + h_2)) \cdot (\delta_l - w) \cdot (\delta_l + l)}{l \cdot (h_1 + h_2) \cdot w}$$

(10)

For $l >> \delta_l$ then the above equation reduces to,

$$S_{ZX} \approx \frac{(\delta_l - (h_1 + h_2)) \cdot (\delta_l + w)}{(h_1 + h_2) \cdot w}$$

(11)
Figure 8: Sensitivity for Bridges for a stack of 3 patterns

Figure 9: Sensitivity for Cuts with overlapping volumes.

The sensitivity $S_{ZX}$ is plotted with respect to $\delta_x$ and $\delta_z$, using Eq. (11) in Fig. 8. Let $h_1 = h_2 = w$. Assuming that a bridge of growing dimensions exists in between the two conducting patterns, it is noted from the plot that the sensitivity increases with defect size.

4.3 Sensitivity for Cuts for Patterns with Overlapping Critical Volumes

Consider three stacked patterns of length $l$ and width $w$. Let the middle pattern, of height $h_2$, be insulating and the other two, of height $(h_1 = h_3 = h)$, be conducting.

Let us assume that there is a cut between the two conducting patterns and that the size of the defect is $\delta$ in $X$, $Y$ and $Z$ directions. The sensitivity $S_{ZX}$ is determined by the following equations:

$$S = \begin{cases} 0 & \text{if } 0 < \delta_x < h, 0 < \delta_z < w \ldots \ldots (i) \\ 2(\delta_x - h)(\delta_z - w)/(2h + h_2) \cdot w & \text{if } h < \delta_x < 2h + h_2, \delta_z > w \ldots \ldots (ii) \\ (\delta_x + h_2)(\delta_z - w)/(2h + h_2) \cdot w & \text{if } 2h + h_2 < \delta_x, \delta_z > w \ldots \ldots (iii) \end{cases}$$

The critical volume for each conducting pattern grows independently till these volumes meet halfway between the patterns. (ii) represents the conditions for cuts in the two patterns independent of each other. (iii) is based on the proximity effect [4]. The merging of the critical volumes occurs when the defect size is equal to twice the height of the conducting pattern plus the distance separating them. For the plot of Fig. 9, drawn using (ii) and (iii), it is assumed $h = w = 1$ unit and $h_2 = 2 \cdot h$. 

\[
\text{Sensitivity} \\
0.5 \\
0 \\
1.5 \\
1 \\
2 \\
0.5 \\
1 \\
1.5 \\
2 \\
\text{Defect in Z direction} \\
\text{Defect in X direction} \\
\text{Sensitivity} \\
0.5 \\
0 \\
1.5 \\
1 \\
2 \\
0.5 \\
1 \\
1.5 \\
2 \\
\text{Defect in Z direction} \\
\text{Defect in X direction}
\]
A distinct change of slope is observed when $\delta_z > 2$ units, because of the proximity effect.

5 An Example

A simple inverter [11] will be used to study the effect of 3D effects. The sensitivity for cuts of Metal and Poly layers will be studied in particular. The 3D layout of the inverter and its top view are shown in Fig. 10. The thickness of the Poly layer is about 0.6$\lambda$, and that of the Metal layer is about 3$\lambda$. The critical regions of Metal are shown for a defect size of 4$\lambda$, and that of Poly for a defect size of 3$\lambda$. The plot of sensitivity $S_{ZX}$ vs $\delta_z$ and $\delta_x$, using Eq. (12) is shown in Fig. 11.

$$S_{ZX} = \frac{\sum_{i=1}^{n} (\delta_z - h_i)(\delta_x - w)}{W \cdot H}$$

where $W$ and $H$ are the total width and height of the layout, respectively, and $n$ is the number of patterns. The equation holds for sensitivity of breaks in $ZX$ directions. It is observed in Fig. 11, that as the defect size increases, sensitivity of Poly reaches to 1 much faster than that of Metal, as it is a comparatively thinner layer.
6 Conclusion

A definition for 3D defects is given first to avoid confusing their effects with multi-layer 2D defects. The effects of 3D defects is captured by using the concept of critical volumes which is an extension to the well known concept of critical areas. Expressions to derive critical volumes are presented and it is shown how the effect of 3D defects is cumulative from layer to layer. 3D defect modeling is a precise way of modeling as in real life situations the defects are a 3D structure. Such true to size modeling will offer an improved fault modeling accuracy and set up the platform for exploring new yield models with a better fidelity.

7 References