Towards Manufacturability Closure: Process Variations and Layout Design

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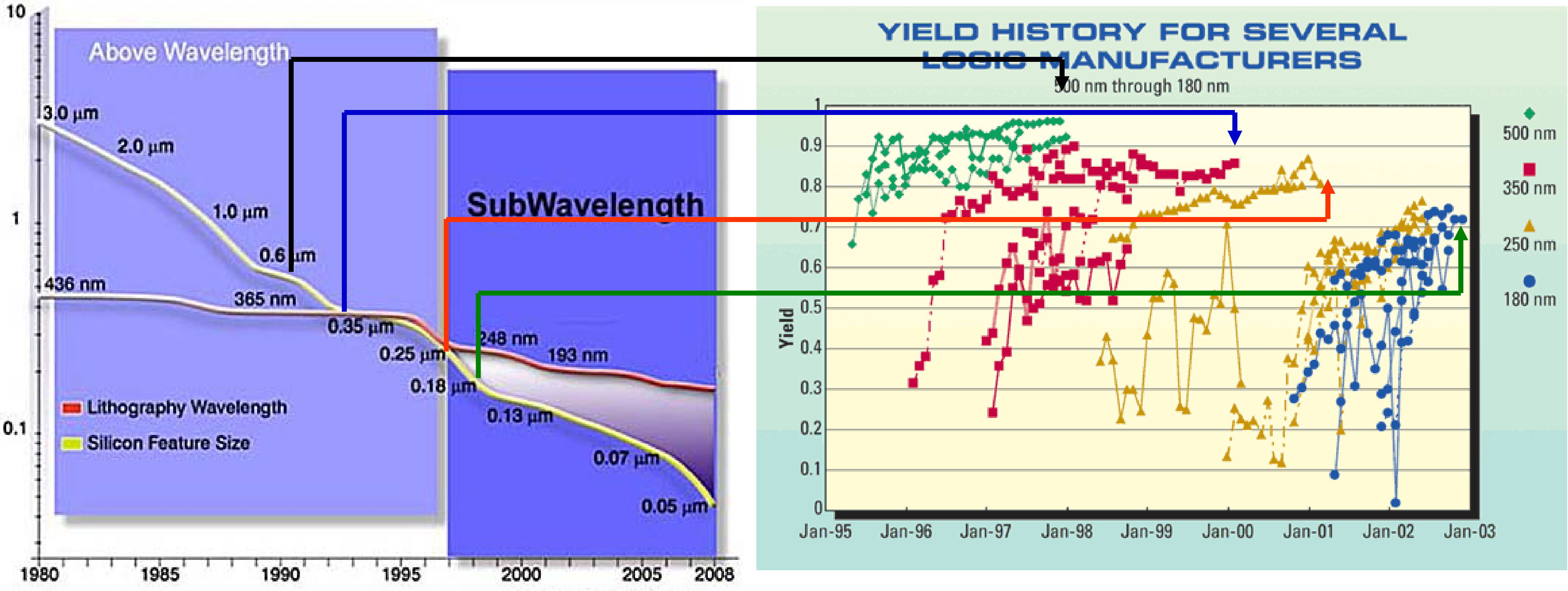
Outline

- Problem definition
- Pattern-centric DFM framework review,
  - Objects, Operators, Guidelines
- Manufacturability Closure for a 130nm library cell
- Electrical response of traditional and optimized cell
- Conclusions and future work

Sub-Wavelength Gap?



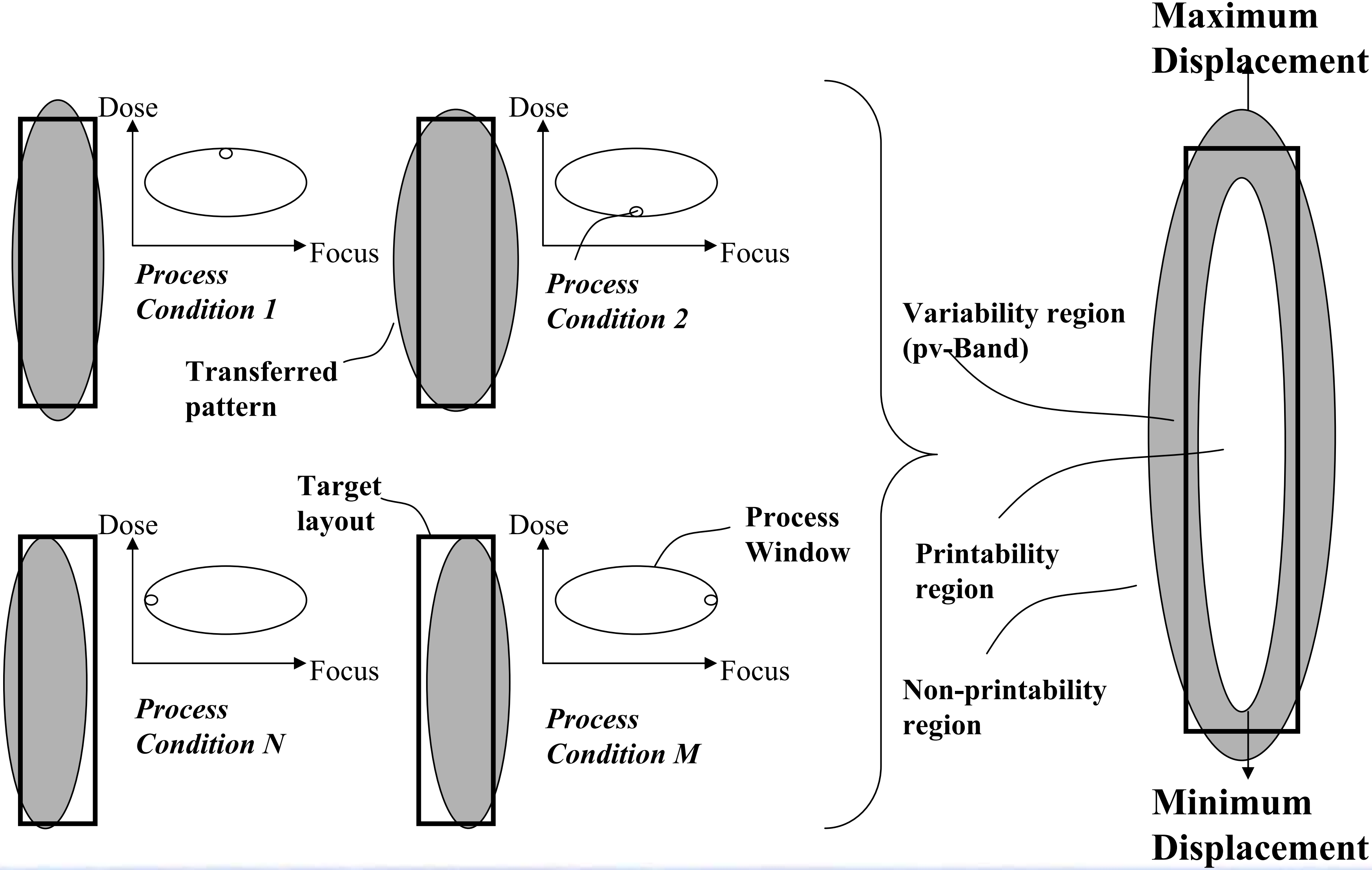
Source: Berglund , Northwest Technology Group. and PDF Solutions

- **While there are more effects that drive pattern transfer imperfections. Lithography is believed to be one of the main contributors.**

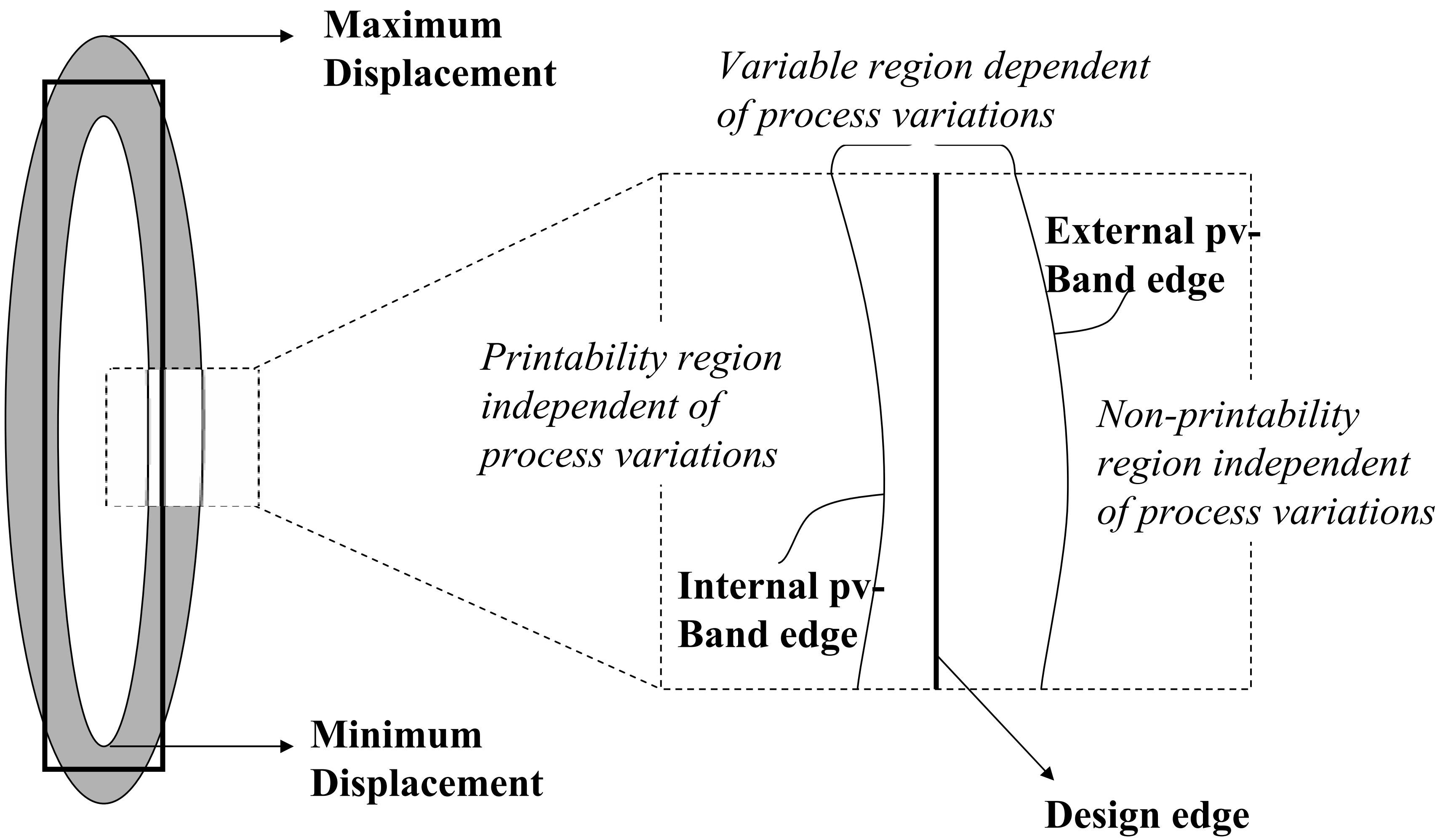
Pattern Centric DFM framework

- Composed by:
  - Objects: Layout and pv-Bands
  - Operators: Booleans and distance checks
  - Guidelines: Process Based Design rules and Manufacturability Indices.

Object: pv-Band



pv-Band definition



Maximum Displacement

Variable region dependent of process variations

External pv-Band edge

Printability region independent of process variations

Non-printability region independent of process variations

Internal pv-Band edge

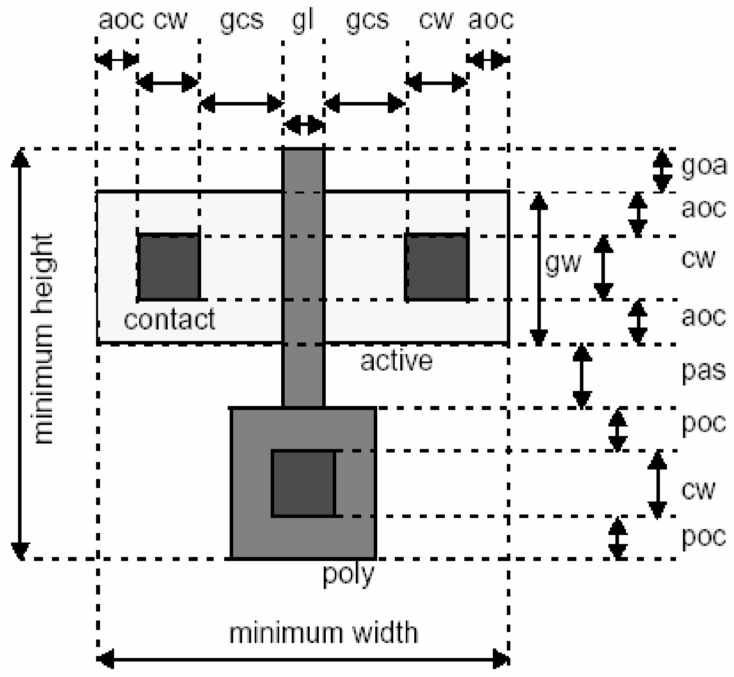
Minimum Displacement

Design edge

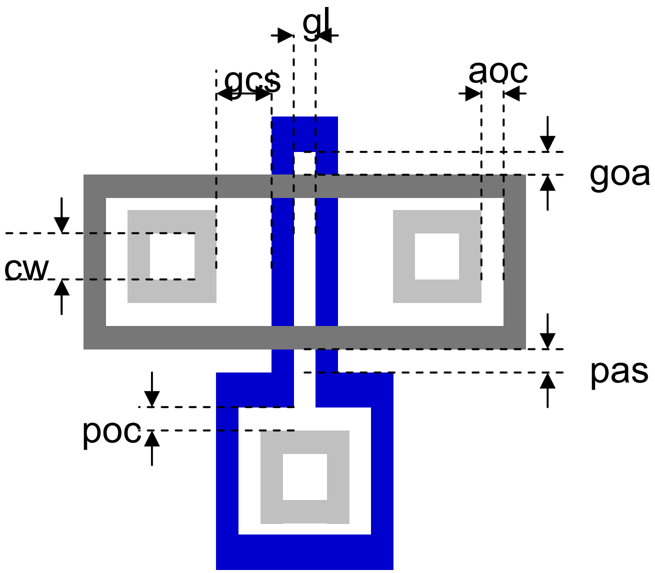
Operators

Operator	**Description**
PVBAND(*Layer*)	Calculates the process variability band of *Layer*, and creates a *pvBand* object.
E2I($pvBand_i$, $pvBand_j$)	Measures the distance between the external $pvBand_i$ edge and the internal $pvBand_j$ edge and creates a marker layer that completely encloses the selected region.
E2E($pvBand_i$, $pvBand_j$)	Measures the distance between the external $pvBand_i$ edge and the external $pvBand_j$ edge and creates a marker layer that completely encloses the selected region.
I2I($pvBand_i$, $pvBand_j$)	Measures the distance between the internal $pvBand_i$ edge and the internal $pvBand_j$ edge and creates a marker layer that completely encloses the selected region.
OR($Object_i$…$Object_j$)	Boolean operation that adds all the contents of $Object_i$ through $Object_j$ creating a derived layer. *Object* can be an original or derived *Layer* or *pvBand*.
AND($Object_i$…$Object_j$)	Boolean operation that adds the common contents of $Object_i$ through $Object_j$ creating a derived layer. *Object* can be an original or derived *Layer* or *pvBand*.
NOT($Object_i$, $Object_j$)	Boolean operation that discounts the common contents of $Object_i$ and $Object_j$ from $Object_i$ creating a derived layer. *Object* can be an original or derived *Layer* or *pvBand*.
AREA(*Object*)	Calculates the area of the *Object*. *Object* can be an original or derived *Layer* or *pvBand*.

Guidelines: Design rules



Symbol	Design rule
aoc	Active overlap of contact
cw	Contact width
gcs	Gate to contact spacing
gl	Gate length
goa	Gate overlap of active
gw	Gate width
pas	Poly to active spacing
poc	Poly overlap of contact



Pseudo-expressions for design rules

$$aoc_{Violation} = OR\begin{pmatrix} AND((pvBand(contact), pvBand(active))), \\ E2I(pvBand(contact), pvBand(active)) \le aoc_{\min} \end{pmatrix}$$

$$cw_{Violation} = OR\begin{pmatrix} AND(pvBand(contact)), \\ I2I(pvBand(contact)) \le cw_{\min} \end{pmatrix}$$

$$gcs_{Violation} = OR\begin{pmatrix} AND((pvBand(poly), pvBand(contact))), \\ E2E(pvBand(poly), pvBand(contact)) \le gcs_{\min} \end{pmatrix}$$

$$goa_{Violation} = OR\begin{pmatrix} AND((pvBand(poly), pvBand(contact)), endCap), \\ E2I(pvBand(active), pvBand(poly)) \le goa_{\min} \end{pmatrix}$$

$$gw_{Violation} = OR\begin{pmatrix} AND(pvBand(poly)), \\ I2I(pvBand(poly)) \le gw_{\min} \end{pmatrix}$$

$$pas_{Violation} = OR\begin{pmatrix} AND((pvBand(active), pvBand(poly))), \\ E2E(pvBand(active), pvBand(poly)) \le pas_{\min} \end{pmatrix}$$

$$poc_{Violation} = OR\begin{pmatrix} AND((pvBand(contact), pvBand(poly))), \\ E2I(pvBand(contact), pvBand(poly)) \le poc_{\min} \end{pmatrix}$$

Guidelines: Manufacturability Indices

Process Manufacturability Index:

- **Best used by Fab: Helps determine best process conditions.**

$$PMI = \sum_{layer} \frac{AREA(pvBand(layer))}{AREA(layer)} + \sum_{layer_i, layer_j} \frac{AREA(AND(pvBand(layer_i), pvBand(layer_j)))}{AREA(AND(layer_i, layer_j))}$$

Design Manufacturability Index:

- **Best used by design teams. Helps to identify sensitive topologies.**

$$DMI = \sum \frac{AREA(DesignRuleViolations)}{AREA(SupportLayer)}$$

Manufacturability Closure

- **Pattern-transfer manufacturability can be measured. Therefore, manufacturability targets can be set.**

Regime I. Desirable: The process is stable and the design is manufacturable $PMI \to PMI_{\min}$ $DMI = 0$	Regime III. Process limited: The process is unstable but the design is manufacturable $PMI >> PMI_{\min}$ $DMI = 0$
Regime II. Design limited: The process is stable and the design is not manufacturable $PMI \to PMI_{\min}$ $DMI > 0$	Regime IV. Undesirable: The process is unstable and the design is not manufacturable $PMI >> PMI_{\min}$ $DMI > 0$

130nm Example

For this 90nm example only a subset of single layer violations are considered

$$pinch_{Violation} = OR\begin{pmatrix} AND\left(pvBand\left(layer\right)\right), \\ I2I\left(pvBand\left(layer\right)\right) \leq pinch_{\min} \end{pmatrix}$$

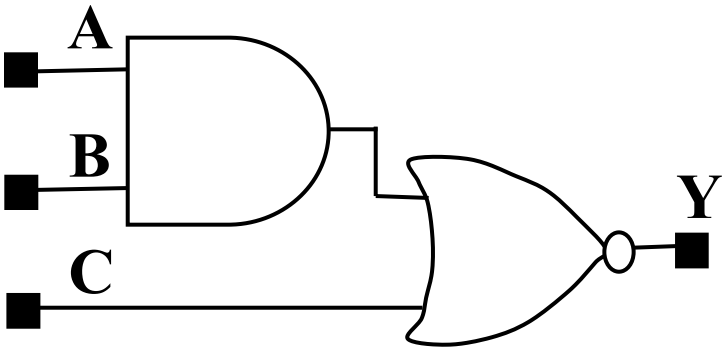
$$bridge_{Violation} = OR\begin{pmatrix} AND\left(pvBand\left(layer\right)\right), \\ E2E\left(pvBand\left(layer\right)\right) \leq bridge_{\min} \end{pmatrix}$$

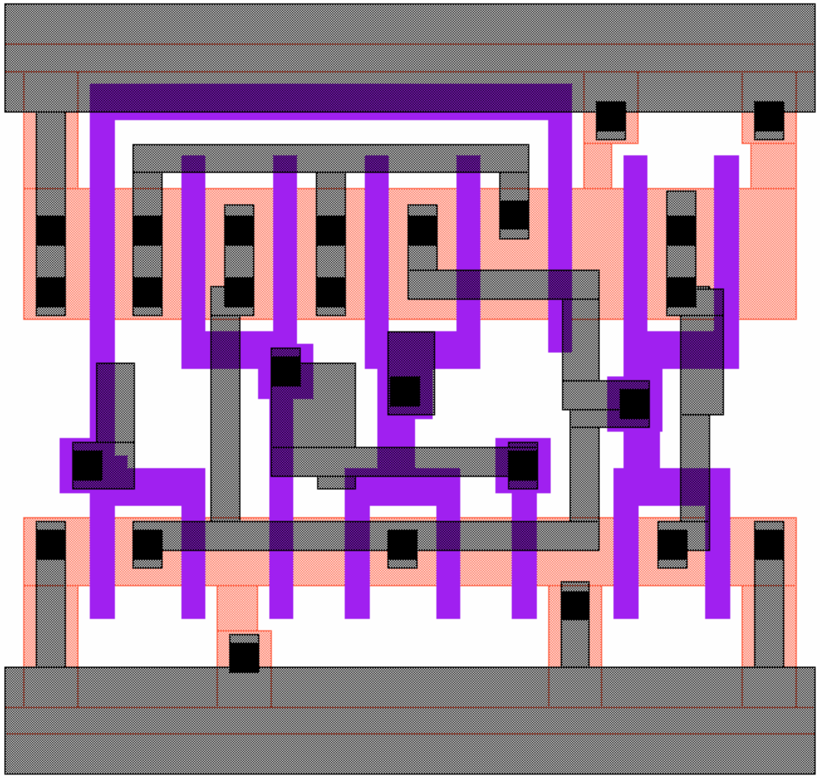
Where,

$pinch_{min}$ = 45nm, $bridge_{min}$ = 45nm

The support region needed to calculate DMI was the layer itself. The process variations are limited to dose and defocus lithographic effects. The dose margins were varied from +/- 5% to +/- 20%, while the defocus variations were modified from +/-50nm to +/-150nm.

Synthesis





Initial cell using current layout synthesis methods.

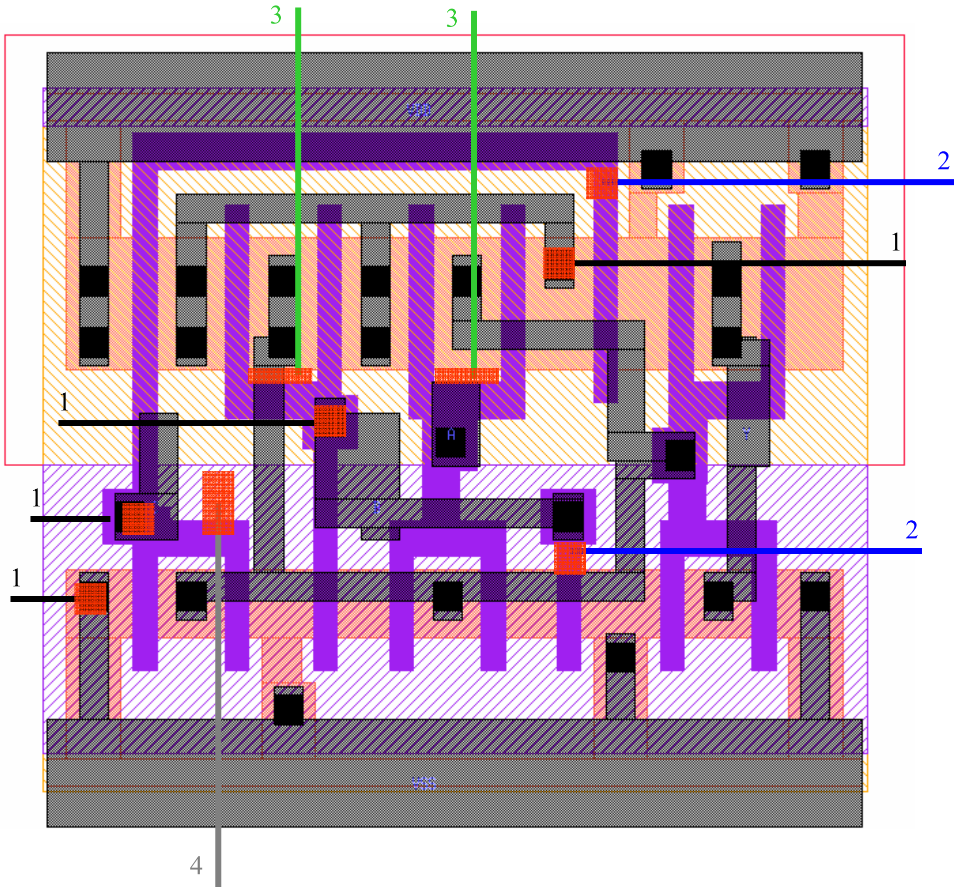
Initial Error and Index Calculation

Critical Errors

1. **Non resolving contacts**
2. Poly silicon pinching
3. Poly to active spacing
4. Printing assist feature in metal

Layer	PMI	DMI
POLY	0.384	0.008
CONTACT	0.879	0.294
METAL1	0.230	0.004

@ DOF = 400nm, EL = 40%, Simple OPC.



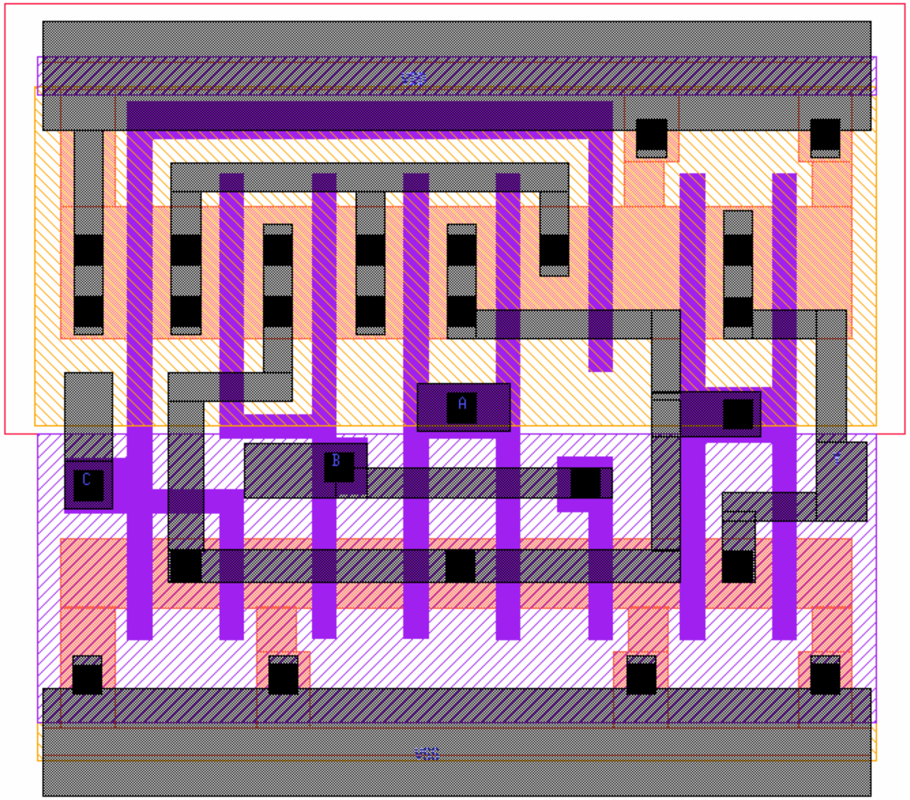
Increase Metal width and remove large poly blocks

Critical Errors: None

Layer	PMI	DMI
POLY	0.384	0.008
CONTACT	0.879	0.294
METAL1	0.230	0.004

Layer	PMI	DMI
POLY	0.374	0.007
CONTACT	0.856	0.000
METAL1	0.246	0.004

@ DOF = 400nm, EL = 40%, Simple OPC.



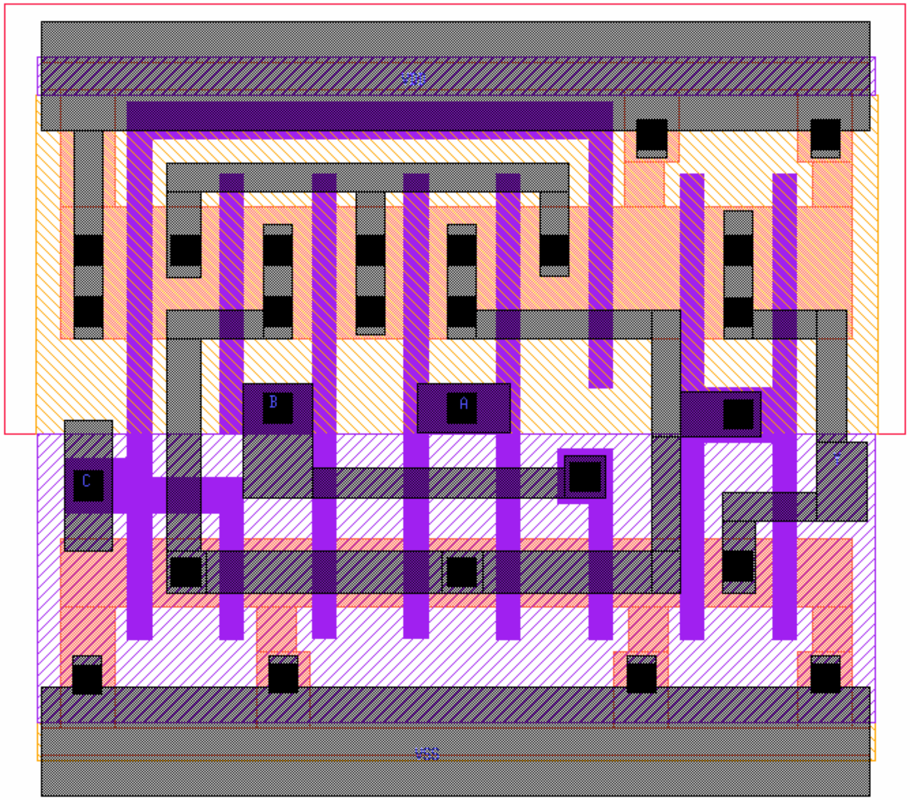
Evaluate: Widen Metal, Contact Enclosure & Line-end extension

Critical Errors: None

Layer	PMI	DMI
POLY	0.384	0.008
CONTACT	0.879	0.294
METAL1	0.230	0.004

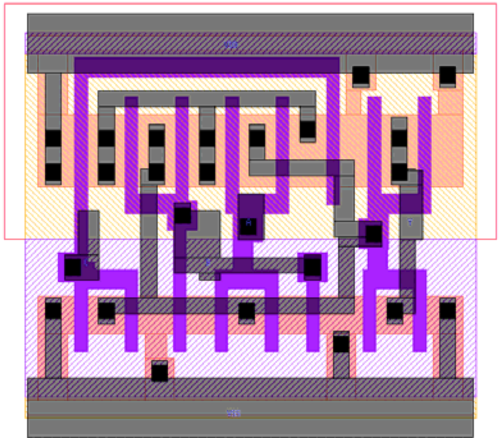
Layer	PMI	DMI
POLY	**0.379**	**0.007**
CONTACT	**0.862**	**0.000**
METAL1	**0.221**	**0.004**

@ DOF = 400nm, EL = 40%, Simple OPC.

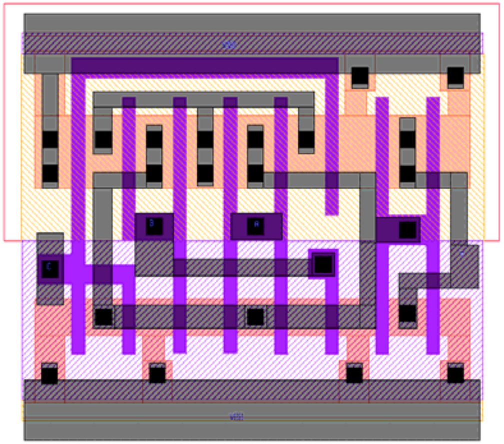


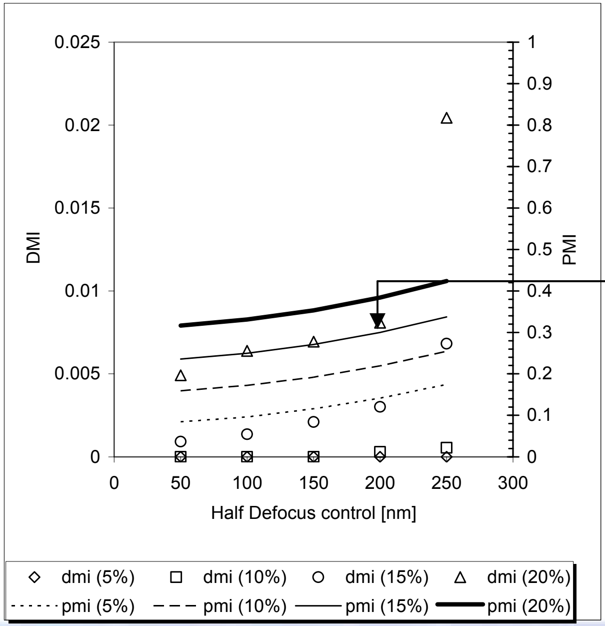
Multiple arrangements can be evaluated. Such as evaluating recommended design rules.

Quantifying the final results: Poly

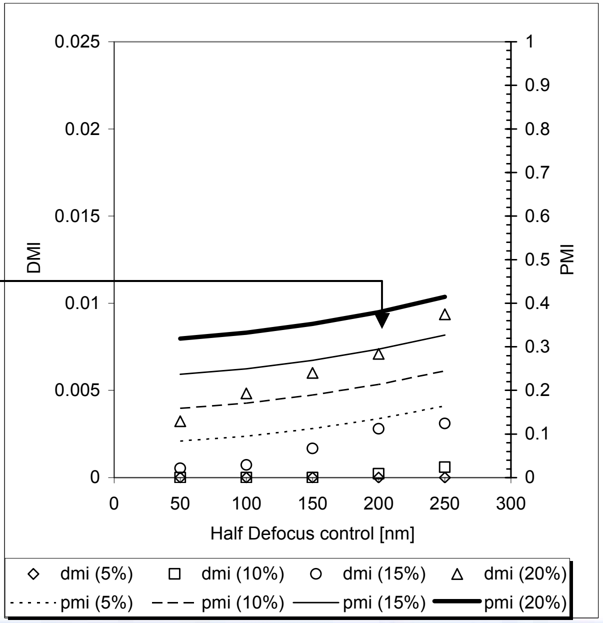


Poly silicon layers by the nature of their topology have a smoother index behavior. Not all features fail at the same rate.

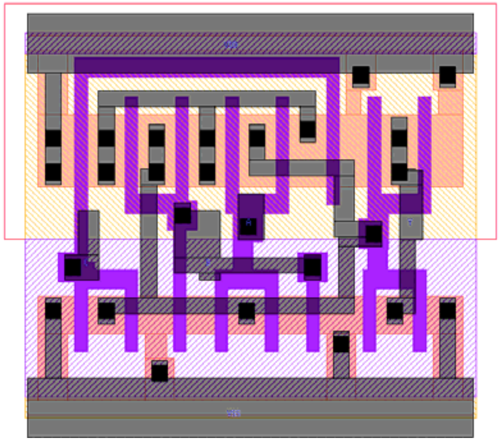




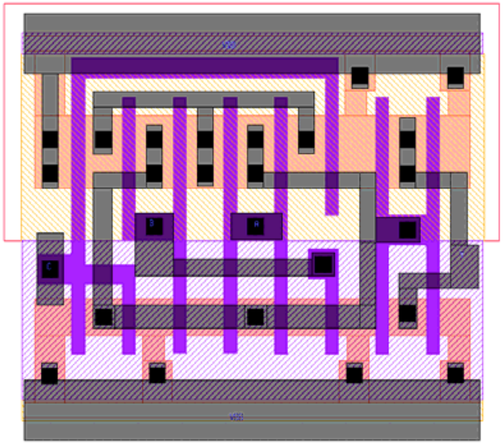
Critical failure region extended

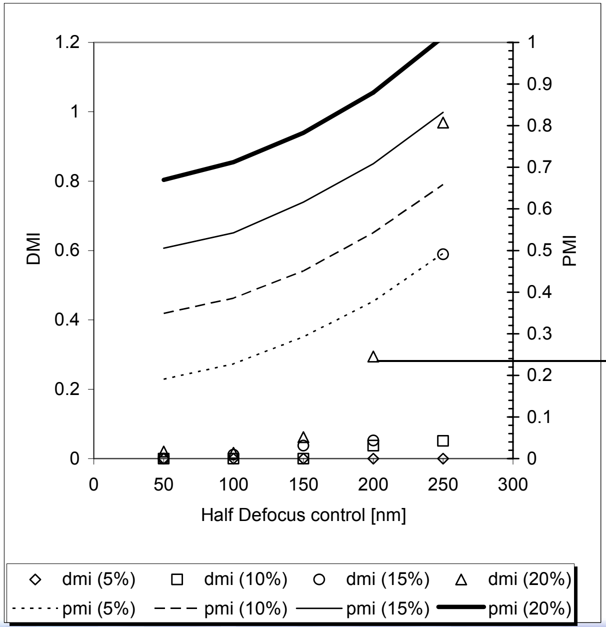


Quantifying the final results: Contacts

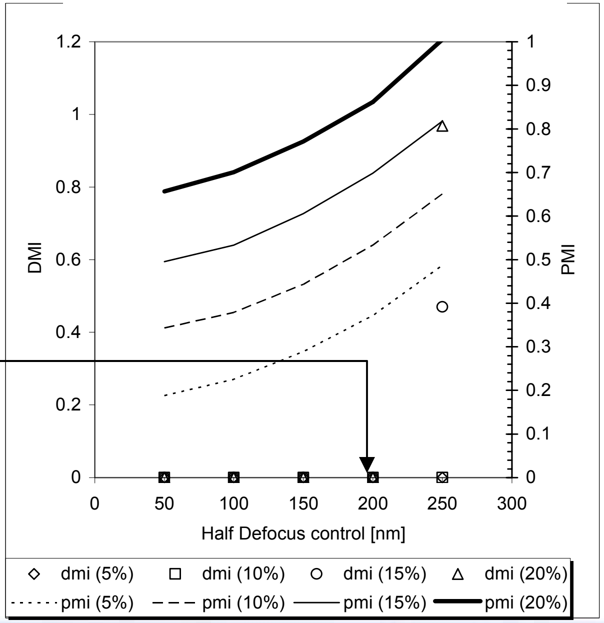


Contact layers have a more abrupt behavior since a contact is either closed or open with little room in between. For that reason the sudden jump in the index.

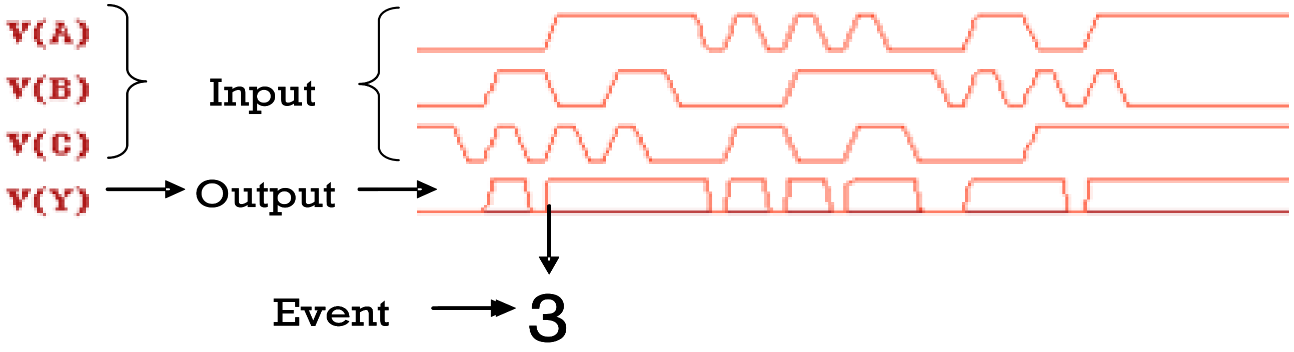




Critical failure region extended



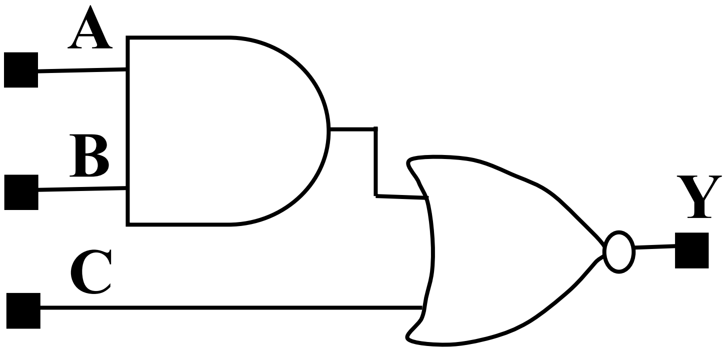
Electrical Impact: Test Vector



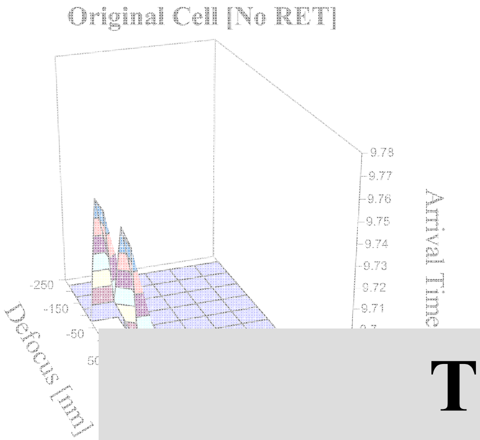
Transition.

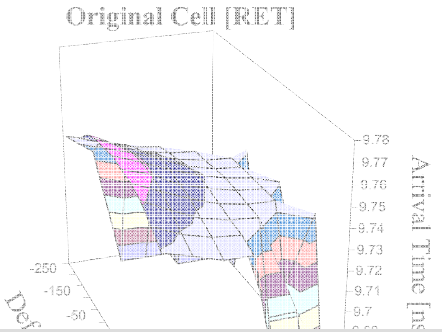
From: A=0, B=1, C=0

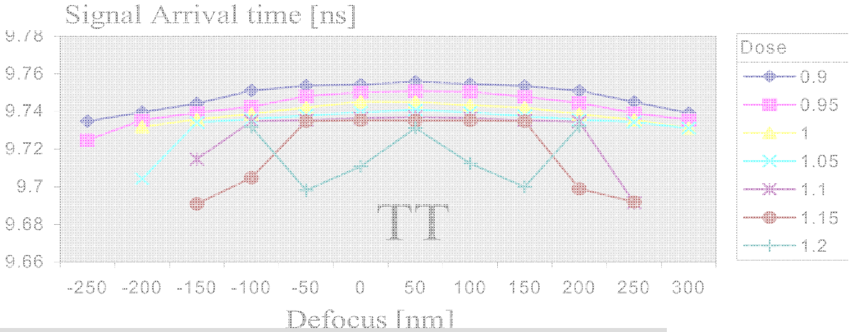
To: A=1, B=0, C=1



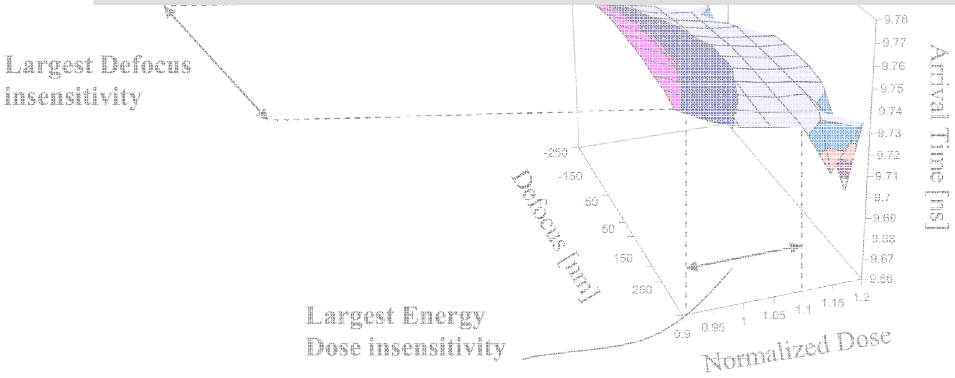
Parametric benefit


Original Cell [No RET]

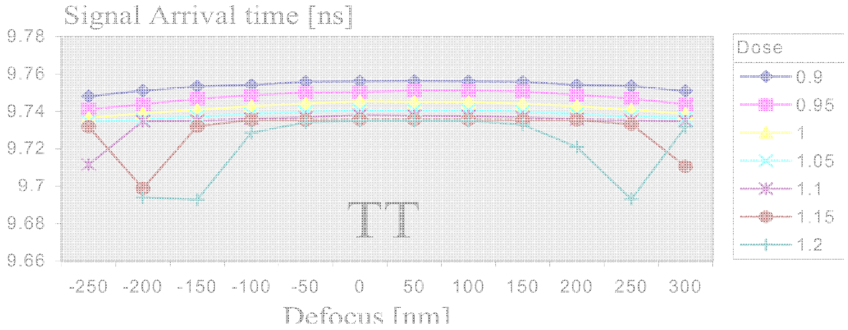

Original Cell [RET]


Signal Arrival time [ns]

The Final Layout pattern is
more robust to Process Window variations
Which translates to better Parametric Behavior


Largest Defocus insensitivity

Largest Energy Dose insensitivity


Signal Arrival time [ns]

Conclusions and Future Work

- Defining manufacturability based on process variability response allows the definition of a real number which could drive manufacturability closure requirements.

- RET's are implicitly accounted for since their effect is observed. Thus allowing the present method to be used in conjunction with any RET.

- A full IC-DFM framework should address parametric and random process components, and it remains to be fully defined.

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