

Distinguishing Manufacturing Defects From Variability Induced Faults in Analog Circuits

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Outline

- 1 Motivation
- 2 Coefficient Based Test
- 3 Fault Classification
- 4 Results

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Fault Classification

Motivation

- 1 Semiconductor processes at advanced nodes are subject to random variability
 - Poly/thin film resistors - line edge roughness ($\sigma \approx 15\% \mu$)
 - Capacitors - Oxide thickness fluctuation & line edge roughness ($\sigma \approx 20\% \mu$)

Fault Classification

Motivation

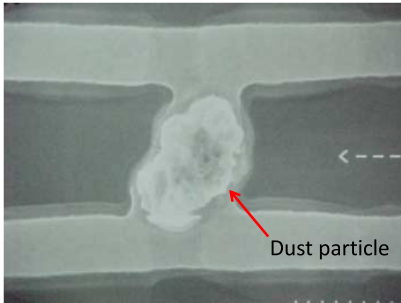
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- 2 Faults due to variability can mask or exacerbate failure from conventional defect mechanisms.
 - Dust contamination, Processing Equipment, Material impurity, Clean room contamination, Operator imperfection, etc., (Fault sizes $\mu_{dev} > 50\%$)

Fault Classification

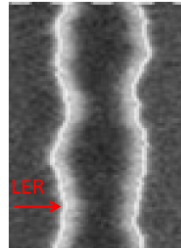
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 - Dust contamination, Processing Equipment, Material impurity, Clean room contamination, Operator imperfection, etc., (Fault sizes $\mu_{dev} > 50\%$)
- 3 Distinguishing failure mechanisms between process variation (PV) and conventional ones can possibly help improve yield.

Types Of Faults



Manufacturing Defect



Random Variation

Ideal Test For An Analog Circuit

Wish list for an analog circuit test scheme

- Suitable for large class of circuits
- Detects sufficiently small parametric faults – high sensitivity
- Low design complexity of the input signal
- Small area overhead – requires little circuit augmentation
- Large number observables – handy in diagnosis

Ideal Test For An Analog Circuit

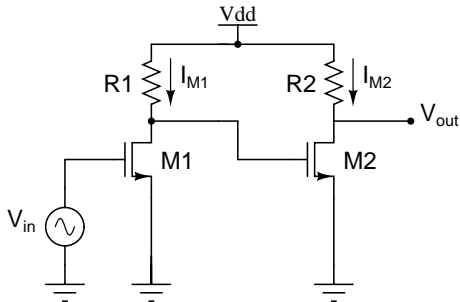
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- Suitable for large class of circuits
- Detects sufficiently small parametric faults – high sensitivity
- Low design complexity of the input signal
- Small area overhead – requires little circuit augmentation
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- **Aids distinction of small defects from process variation (PV) induced faults – need in advanced tech nodes**

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Cascaded Amplifiers – An Example



Two stage amplifier with 4th degree non-linearity in V_{in}

$$V_{out} = c_0 + c_1 V_{in} + c_2 V_{in}^2 + c_3 V_{in}^3 + c_4 V_{in}^4$$

S. Sindia, V. Singh and V. D. Agrawal, "Polynomial Coefficient Based DC Testing of Nonlinear Analog Circuits," pp.69-74, GLSVLSI 2009.

Polynomial Coefficients

$$c_0 = V_{DD} - R_2 K \left(\frac{W}{L}\right)_2 \left[\begin{array}{l} (V_{DD} - V_T)^2 + R_1^2 K^2 \left(\frac{W}{L}\right)_1^2 V_T^4 \\ -2(V_{DD} - V_T)R_1 \left(\frac{W}{L}\right)_1 V_T^2 \end{array} \right]$$

$$c_1 = R_2 K \left(\frac{W}{L}\right)_2 \left[4R_1^2 K^2 \left(\frac{W}{L}\right)_1^2 V_T^3 + 2(V_{DD} - V_T)R_1 K \left(\frac{W}{L}\right)_1 V_T \right]$$

$$c_2 = R_2 K \left(\frac{W}{L}\right)_2 \left[2(V_{DD} - V_T)R_1 K \left(\frac{W}{L}\right)_1 - 6R_1^2 K^2 \left(\frac{W}{L}\right)_1^2 V_T^2 \right]$$

$$c_3 = 4V_T K^3 \left(\frac{W}{L}\right)_1^2 \left(\frac{W}{L}\right)_2^2 R_1^2 R_2$$

$$c_4 = -K^3 \left(\frac{W}{L}\right)_1^2 \left(\frac{W}{L}\right)_2^2 R_1^2 R_2$$

V-Transform

Definition

$$V_{C_i} = e^{\gamma C'_i} \quad \forall 0 \leq i \leq n$$

$$\frac{dC'_i}{dp_j} = \left| \frac{dC_i}{dp_j} \right| \quad \forall 0 \leq i \leq n$$

C_i – i^{th} polynomial coefficient

C'_i – i^{th} modified polynomial coefficient

V_{C_i} – i^{th} V-Transform coefficient

V-Transform Coefficient – Sensitivity Gain

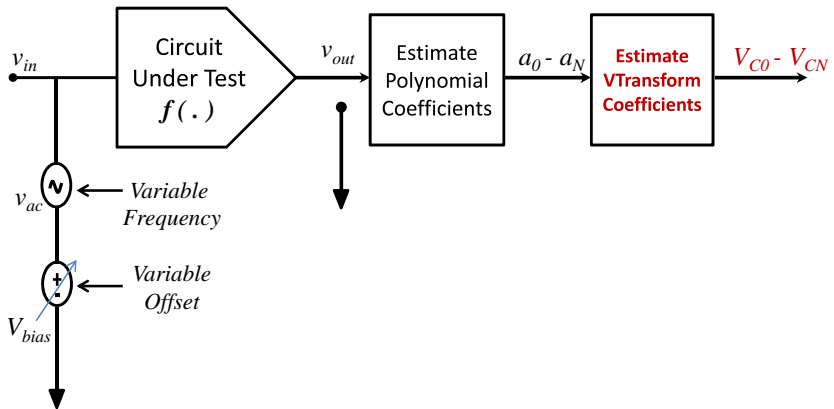
Sensitivity of coefficients

$$\frac{S_{p_i}^{V_{C_i}}}{S_{p_i}^{C_i}} = \frac{\left| \frac{dC_i}{dp_i} \right| \gamma e^{\gamma C_i} \cdot \frac{p_i}{e^{\gamma C_i}}}{\frac{dC_i}{dp_i} \cdot \frac{p_i}{C_i}} = \gamma C_i$$

γC_i – Increased sensitivity over ordinary polynomial coefficients

γ – Sensitivity parameter that can be chosen according to the desired degree of sensitivity

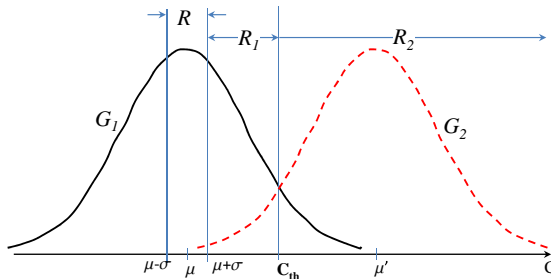
Test Setup



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Fault Classification



$$C \underset{\mathcal{H}_1}{\overset{\mathcal{H}_2}{\leq}} C_{th}$$

\mathcal{H}_1 : Fault likely due to manufacturing defect

\mathcal{H}_2 : Fault likely due to process parameter variation

Fault Classification

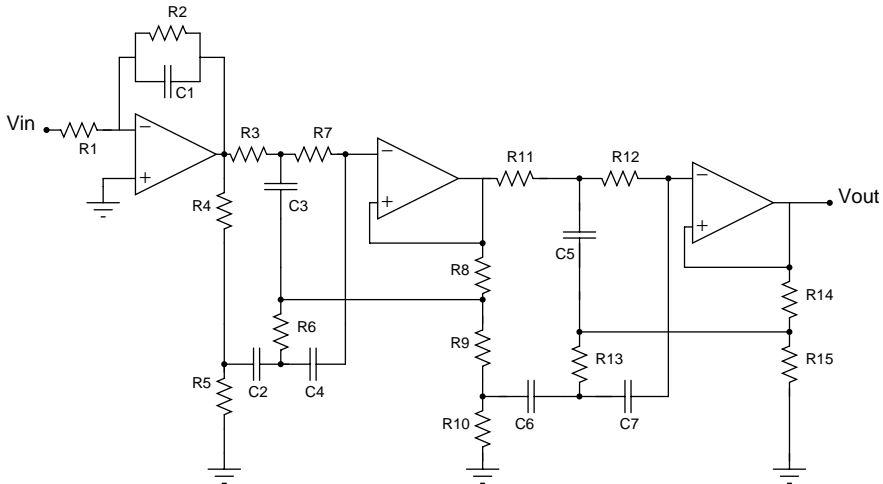
Summary of steps

- Probability density function of the coefficients are computed by Monte Carlo simulations for fault-free
- Probability density function of the coefficients are computed by Monte Carlo simulations for faulty circuits
- Threshold values of coefficients – Boundaries between process variation (PV) and manufacturing defects is estimated for each frequency
- Confidence of classifying a fault as PV or manufacturing defect is improved by observing one or more coefficients at multiple frequencies.

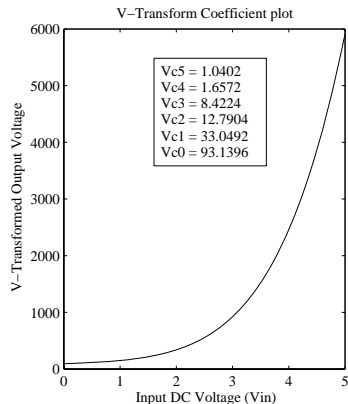
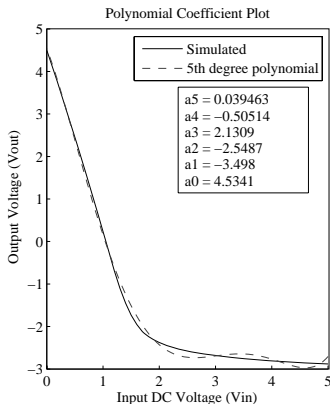
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Results – Benchmark Elliptic Filter



Results - V-Transform Coefficients



$$V_{C_5} = 1.0402 \quad V_{C_4} = 1.6572 \quad V_{C_3} = 8.4224 \quad V_{C_2} = 12.7904 \quad V_{C_1} = 33.0492 \quad V_{C_0} = 93.1396$$

Results at DC - Elliptic Filter

Parameter combinations leading to max values of V-Transform coefficients with $\alpha = 0.05$

Circuit Parameter, (ohm)	V_{C_0}	V_{C_1}	V_{C_2}	V_{C_3}	V_{C_4}	V_{C_5}
$R_1 = 19.6k$	18.6k	20.5k	20.5k	20.5k	18.6k	18.6k
$R_2 = 196k$	186k	205k	186k	186k	186k	205k
$R_3 = 147k$	139k	154k	154k	154k	139k	154k
$R_4 = 1k$	950	1010	1010	1010	1010	1010
$R_5 = 71.5$	70	80	80	70	80	70
$R_6 = 37.4k$	37.4k	37.4k	37.4k	37.4k	37.4k	37.4k
$R_7 = 154k$	161k	161k	146k	161k	146k	146k
$R_{11} = 110k$	115k	115k	104k	115k	104k	104k
$R_{12} = 110k$	104k	115k	104k	104k	104k	104k

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Parameter combinations leading to min values of V-Transform coefficients with $\alpha = 0.05$

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$R_1 = 19.6k$	20.5k	18.6k	18.6k	20.5k	20.5k	20.5k
$R_2 = 196k$	205k	186k	205k	205k	205k	186k
$R_3 = 147k$	150k	139k	139k	146k	154k	139k
$R_4 = 1k$	1010	950	950	950	950	950
$R_5 = 71.5$	80	70	70	80	70	80
$R_6 = 37.4k$	39.2k	39.2k	39.2k	39.2k	35.5k	39.2k
$R_7 = 154k$	146k	146k	161k	146k	161k	161k
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Results at DC - Elliptic Filter

Fault detection for some injected faults

Circuit Parameter	Out of bound polynomial coefficient	Fault detected?	Out of bound V-Transform coefficient	Fault detected?
R ₁ down 25%	c ₃ , c ₄	Yes	V _{c₀} - V _{c₄}	Yes
R ₂ down 30%	c ₂	Yes	V _{c₂} , V _{c₅}	Yes
R ₃ up 25%	c ₃	Yes	V _{c₁} , V _{c₂} , V _{c₃}	Yes
R ₄ down 30%	c ₀	Yes	V _{c₀} - V _{c₄}	Yes
R ₅ up 30%	c ₄	Yes	V _{c₀} , V _{c₄}	Yes
R ₇ up 10%	None	PV (C = 200)	V _{c₁} , V _{c₂}	Yes
R ₁₁ up 15%	None	PV (C = 120)	V _{c₄} , V _{c₅}	Yes
R ₁₂ down 15%	None	PV (C = 90)	V _{c₄} , V _{c₅}	Yes

Conclusion and Future Work

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- Technique for parametric fault detection in analog circuits – faults as small as 25% were uncovered for an elliptic filter example.
- Addressed parametric fault distinction between process variation induced faults.
- Enhanced technique for uncovering parametric faults by increasing sensitivity of polynomial coefficients to circuit parameters.

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Future work

- Technique for optimal choice of frequencies at which CUT ought to be excited
- Optimal order of polynomial expansion as a tradeoff between test time and diagnostic resolution
- Algorithms to predict/map RF & other circuit specifications to polynomial/V-Transform coefficients