Typical NMOS Modeling Using a Skewing Method

- An NMOS Modeling Method for RF Analog Circuit Design Centering -

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Outline

- Research Background
- Typical Target Skewing Flow
- Calculations of Theoretical Target Specifications
- Target Device Selection and Its Modeling
- Model Parameter Skew to Typical E-Test Parameters
- Verifications of RF Circuit Simulations
- Conclusions

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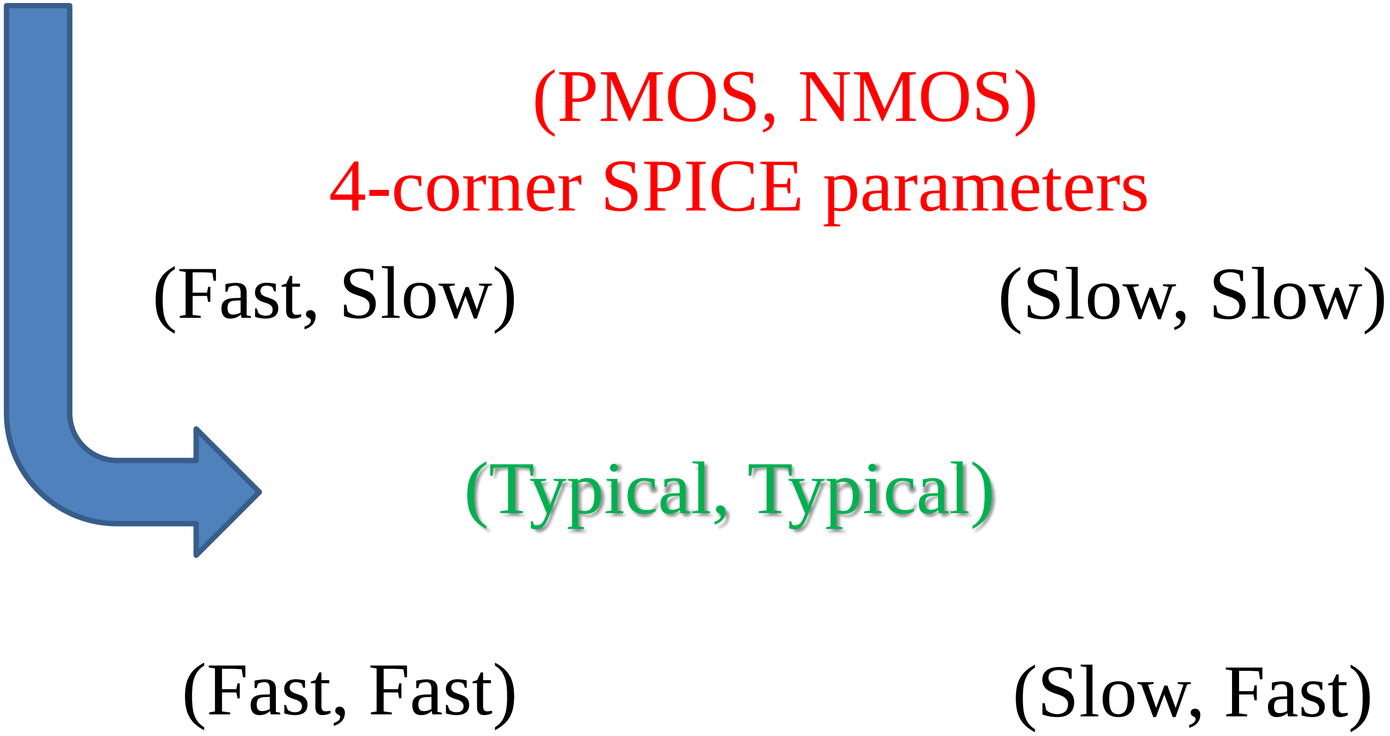
Research Background

- For better integrated circuit design,

design centering is one of the important issues !



(PMOS, NMOS)
4-corner SPICE parameters

(Fast, Slow) (Slow, Slow)

(Typical, Typical)

(Fast, Fast) (Slow, Fast)

Initial design: Typical models are used.
Next design step: Worst/best models are used.

Conventional Method and Problem

- Most semiconductor manufacturers do NOT pay enough attention to extract "Real Typical Models".

- Conventional methods to define typical target specification are
  - based only on process specifications and conditions
  - without using test results of fabricated devices.

⇩

Not very accurate typical model

Research Objective

Development of novel skewing method

for “typical model”

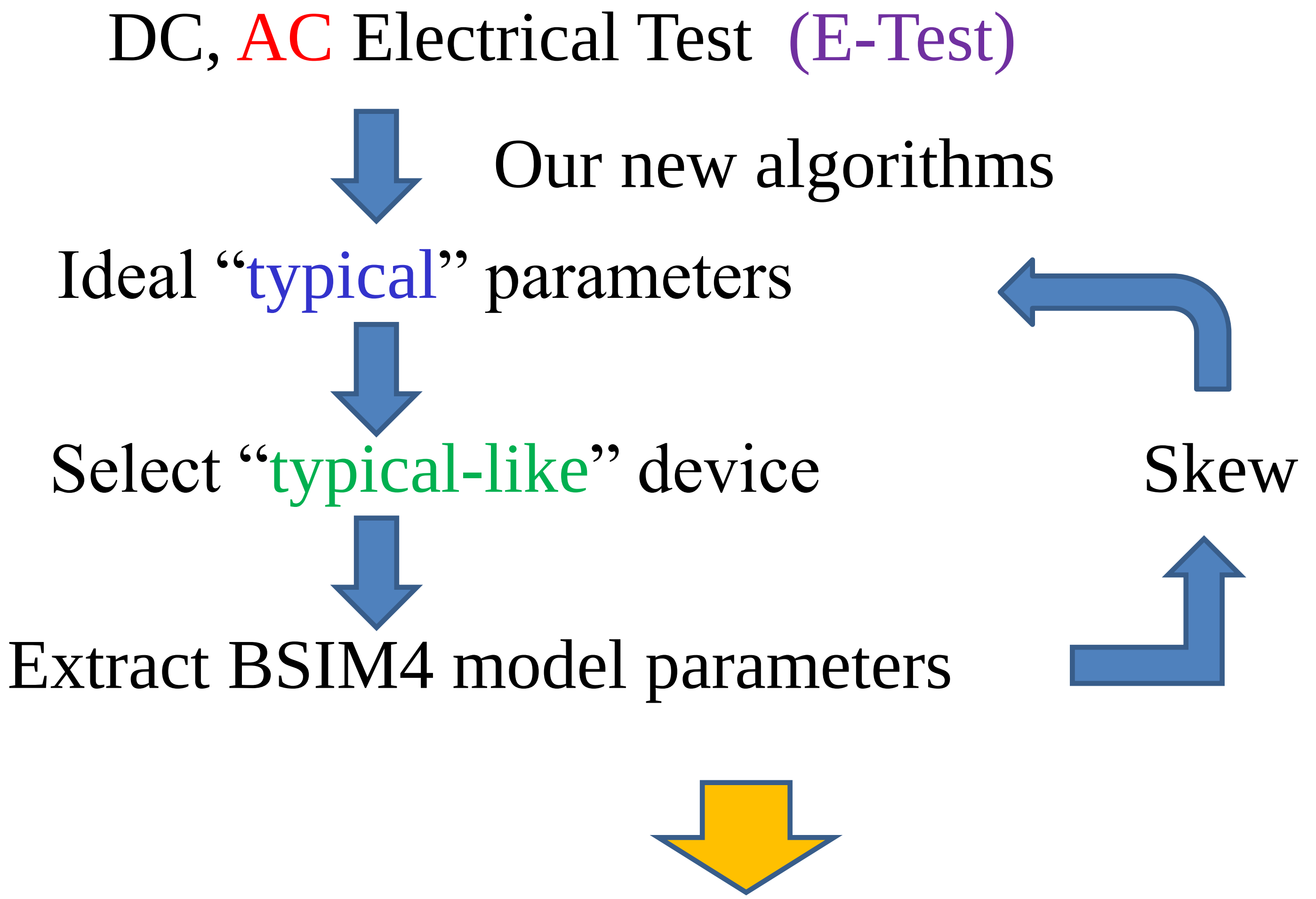
- based on process wafer test (E-Test)

- considers analog and RF circuit design (both DC, AC characteristics)

↓

Obtain accurate typical model

Our Work



DC, AC Electrical Test (E-Test)

Our new algorithms

Ideal “typical” parameters

Select “typical-like” device

Skew

Extract BSIM4 model parameters

Obtain DC, AC “typical” BSIM4 model parameters

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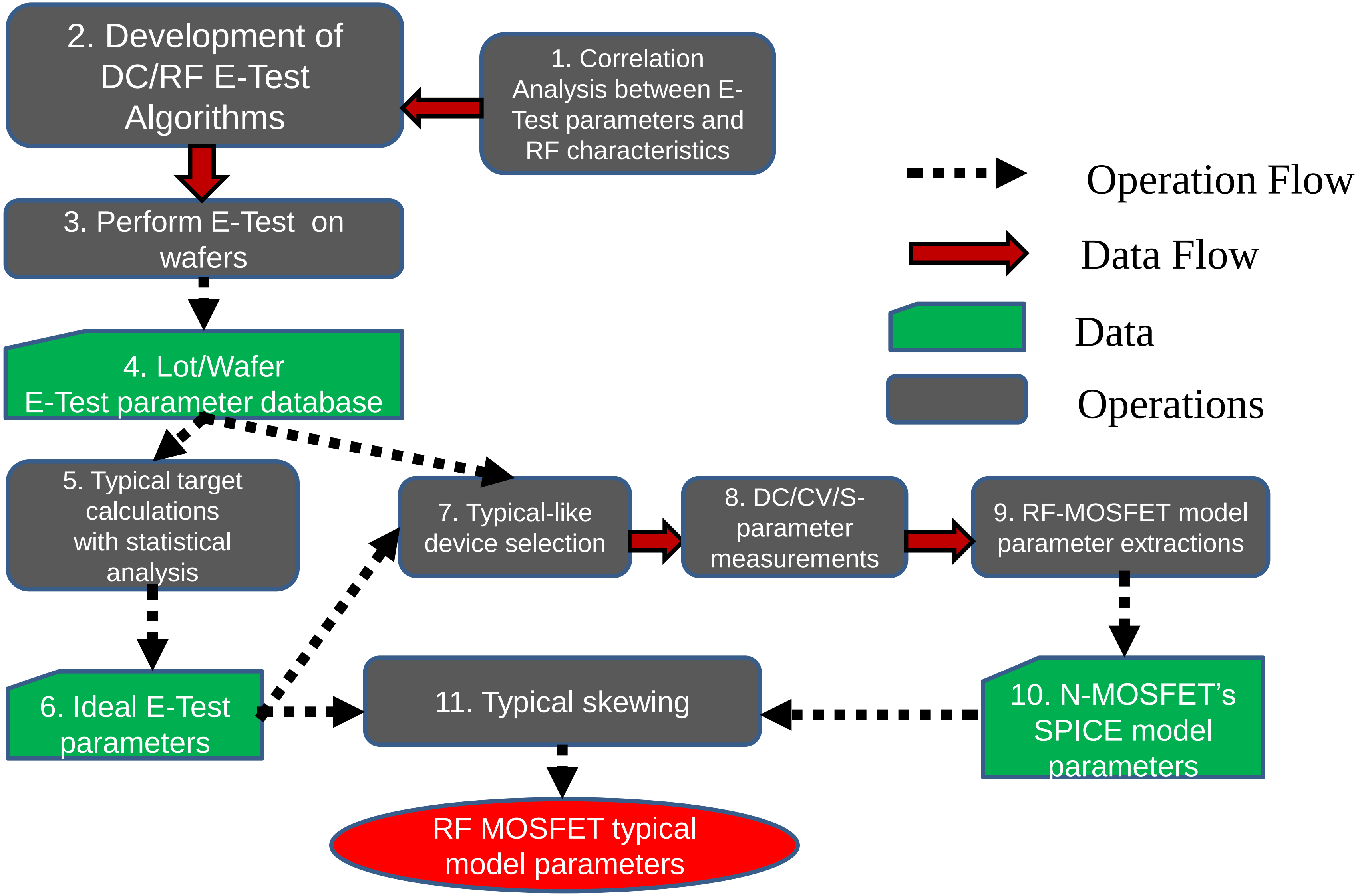
Typical Target Skewing Flow



2. Development of DC/RF E-Test Algorithms

1. Correlation Analysis between E-Test parameters and RF characteristics

3. Perform E-Test on wafers

4. Lot/Wafer E-Test parameter database

5. Typical target calculations with statistical analysis

6. Ideal E-Test parameters

7. Typical-like device selection

8. DC/CV/S-parameter measurements

9. RF-MOSFET model parameter extractions

10. N-MOSFET's SPICE model parameters

11. Typical skewing

RF MOSFET typical model parameters

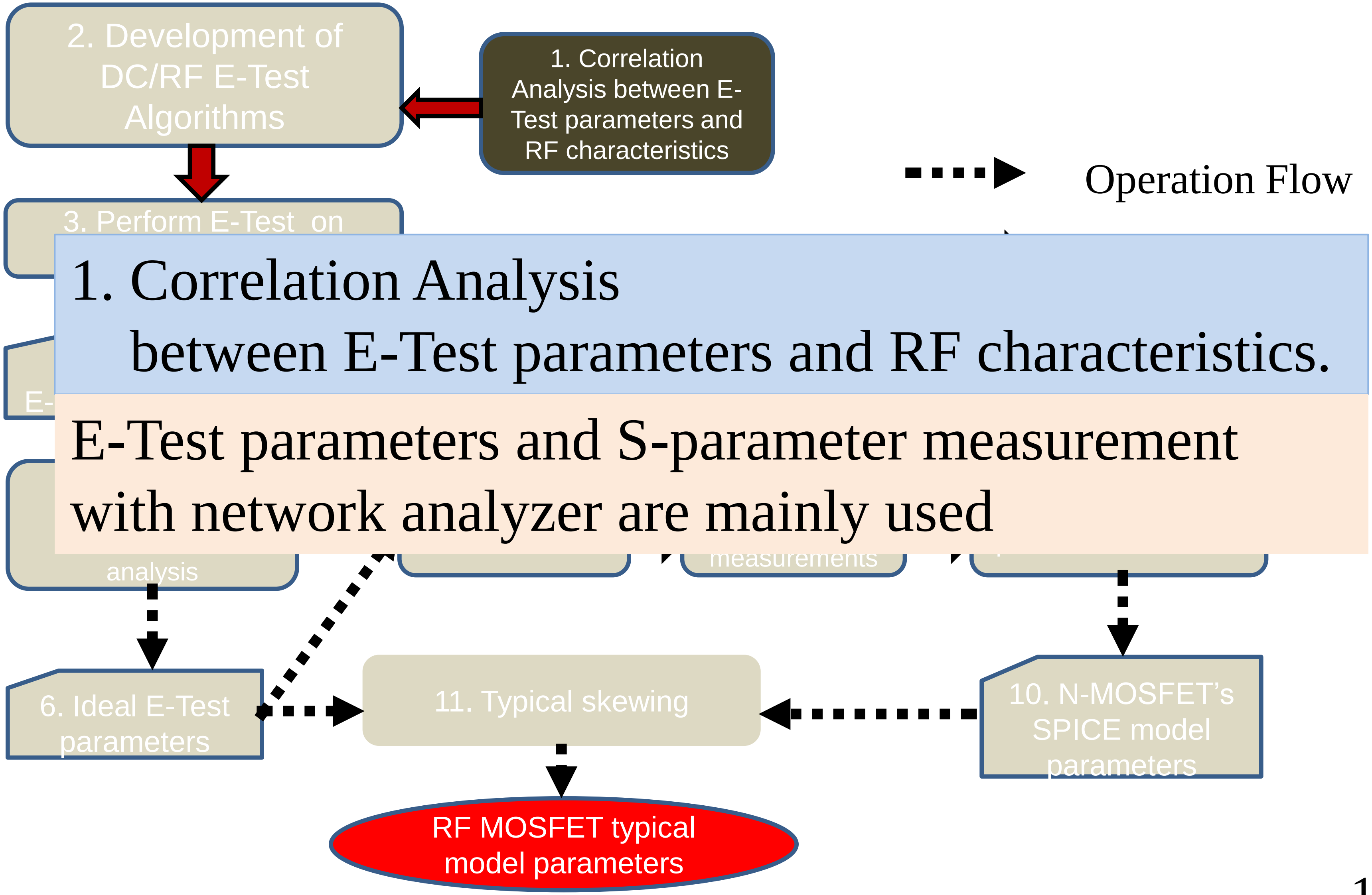
Operation Flow

Data Flow

Data

Operations

Typical Target Skewing Flow (1)



2. Development of DC/RF E-Test Algorithms

1. Correlation Analysis between E-Test parameters and RF characteristics

Operation Flow

3. Perform E-Test on

E-

analysis

measurements

6. Ideal E-Test parameters

11. Typical skewing

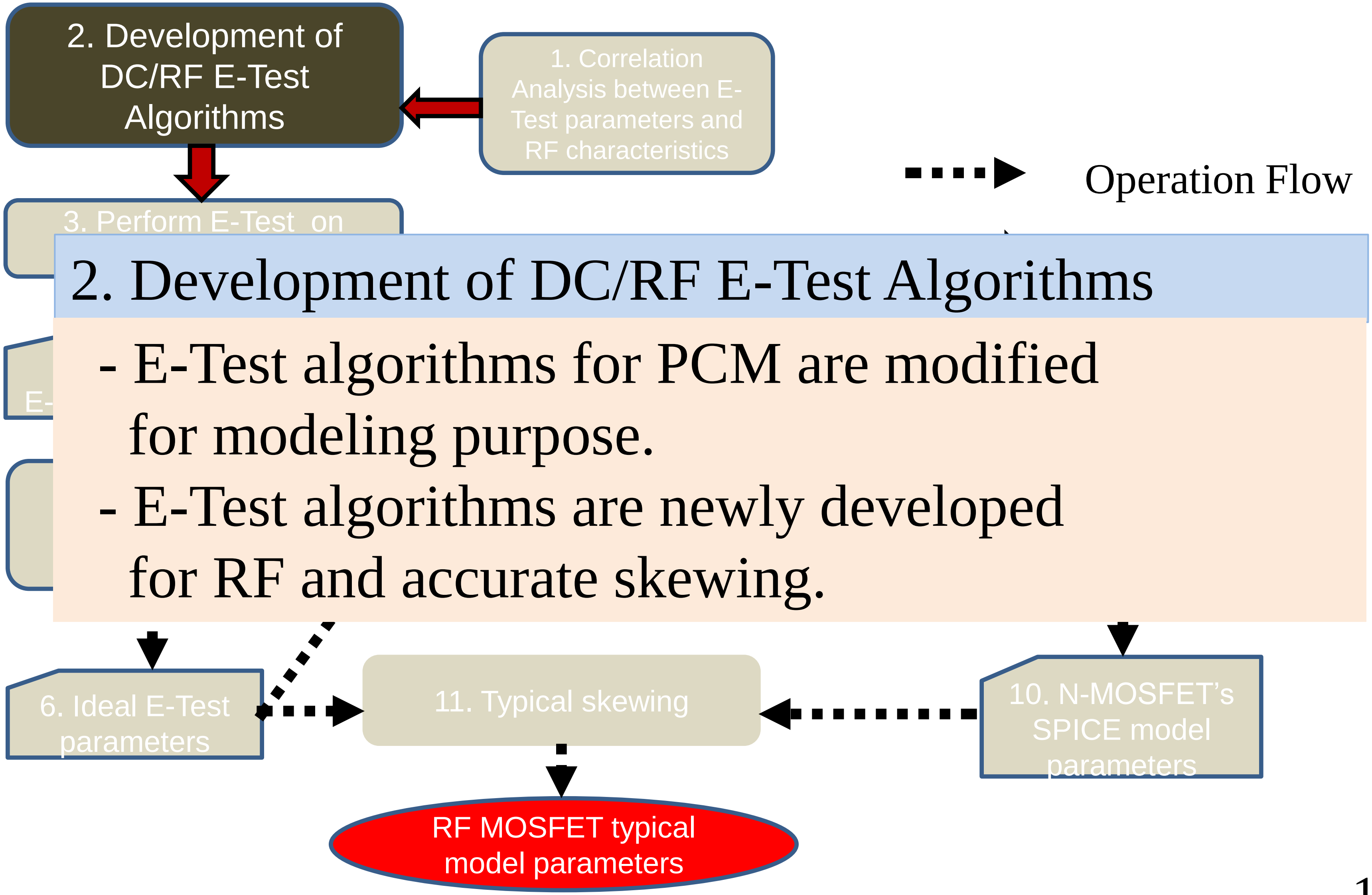
10. N-MOSFET’s SPICE model parameters

RF MOSFET typical model parameters

1. Correlation Analysis
between E-Test parameters and RF characteristics.

E-Test parameters and S-parameter measurement with network analyzer are mainly used

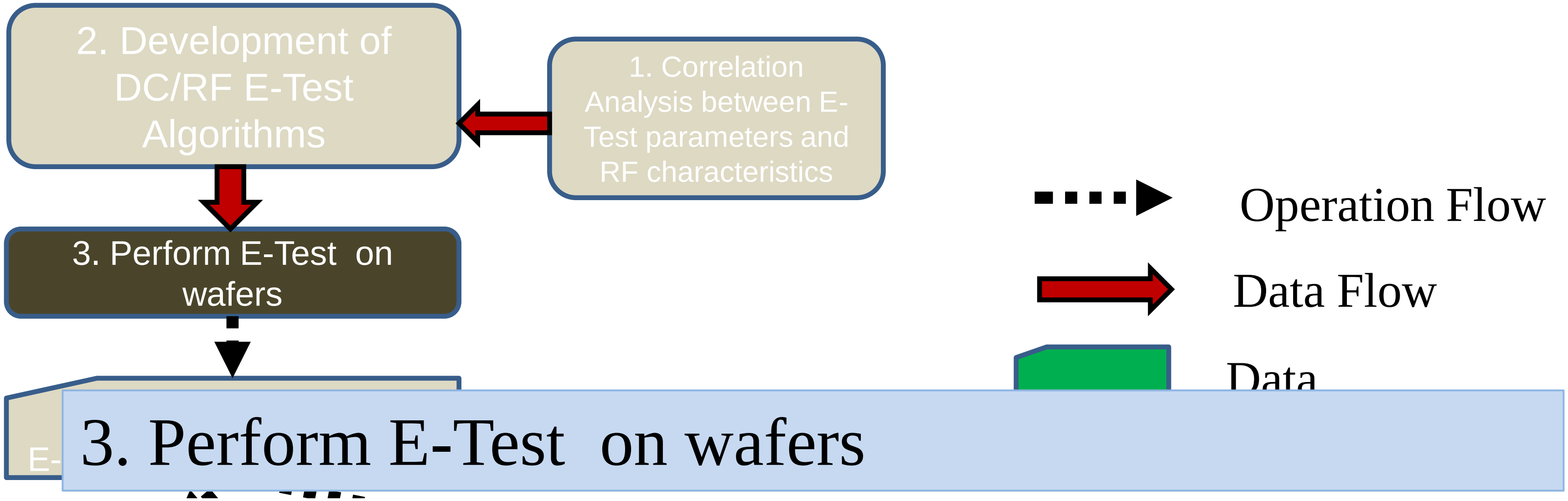
Typical Target Skewing Flow (2)



2. Development of DC/RF E-Test Algorithms

- E-Test algorithms for PCM are modified for modeling purpose.
- E-Test algorithms are newly developed for RF and accurate skewing.

Typical Target Skewing Flow (3)



2. Development of DC/RF E-Test Algorithms

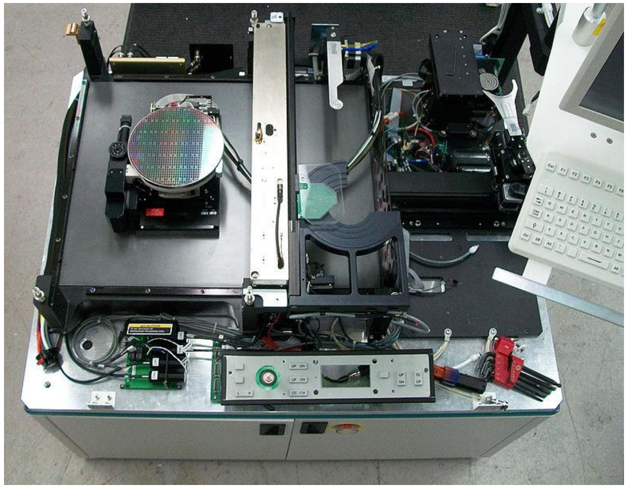
1. Correlation Analysis between E-Test parameters and RF characteristics

3. Perform E-Test on wafers

E-

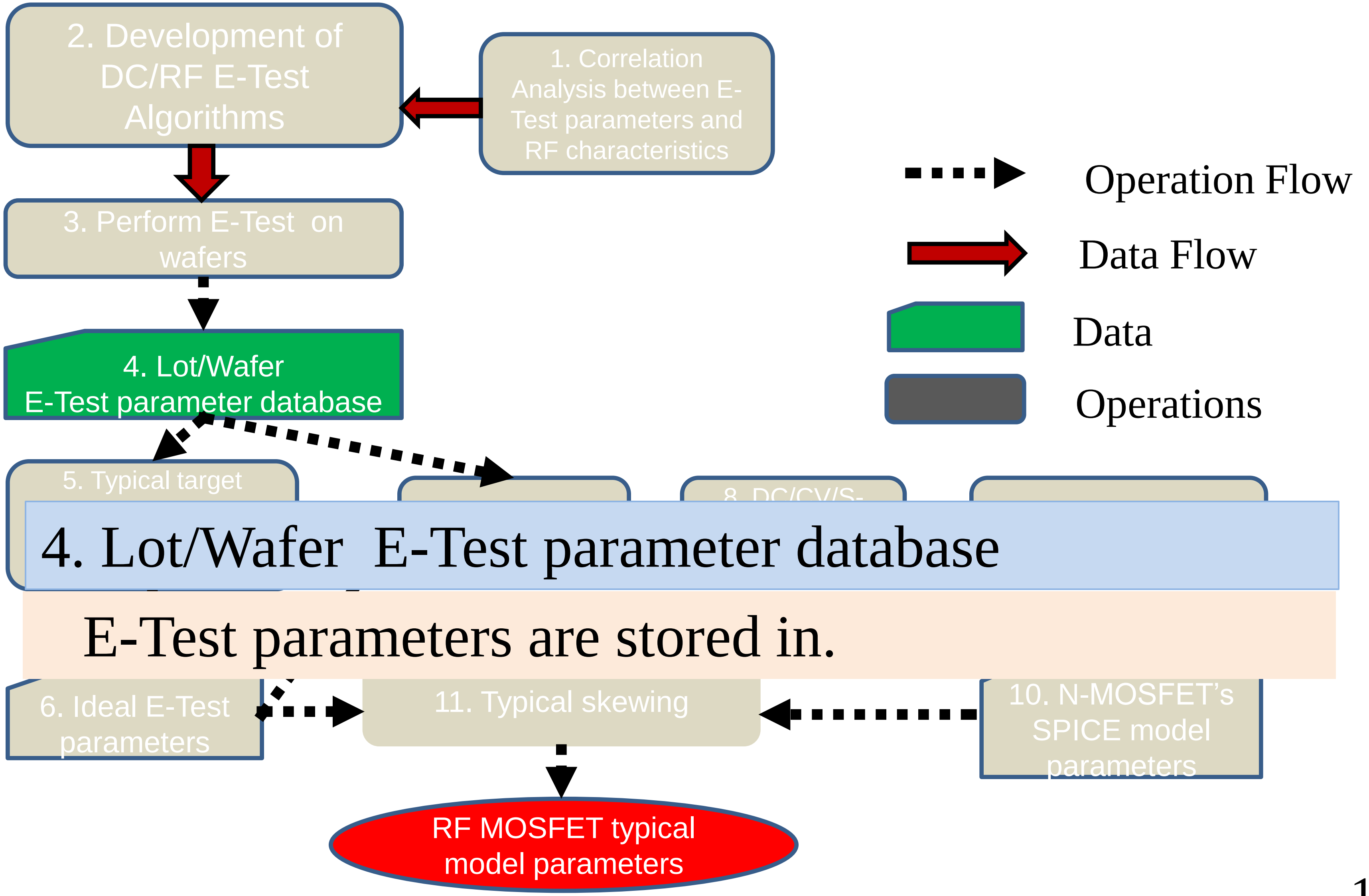
- ■ ■ ■ ■▶ Operation Flow
- 🟥➡ Data Flow
- 🟩 Data

3. Perform E-Test on wafers



Wafer test

Typical Target Skewing Flow (4)



2. Development of DC/RF E-Test Algorithms

1. Correlation Analysis between E-Test parameters and RF characteristics

3. Perform E-Test on wafers

4. Lot/Wafer
E-Test parameter database

5. Typical target

8. DC/CV/S-

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10. N-MOSFET's SPICE model parameters

RF MOSFET typical model parameters

Operation Flow

Data Flow

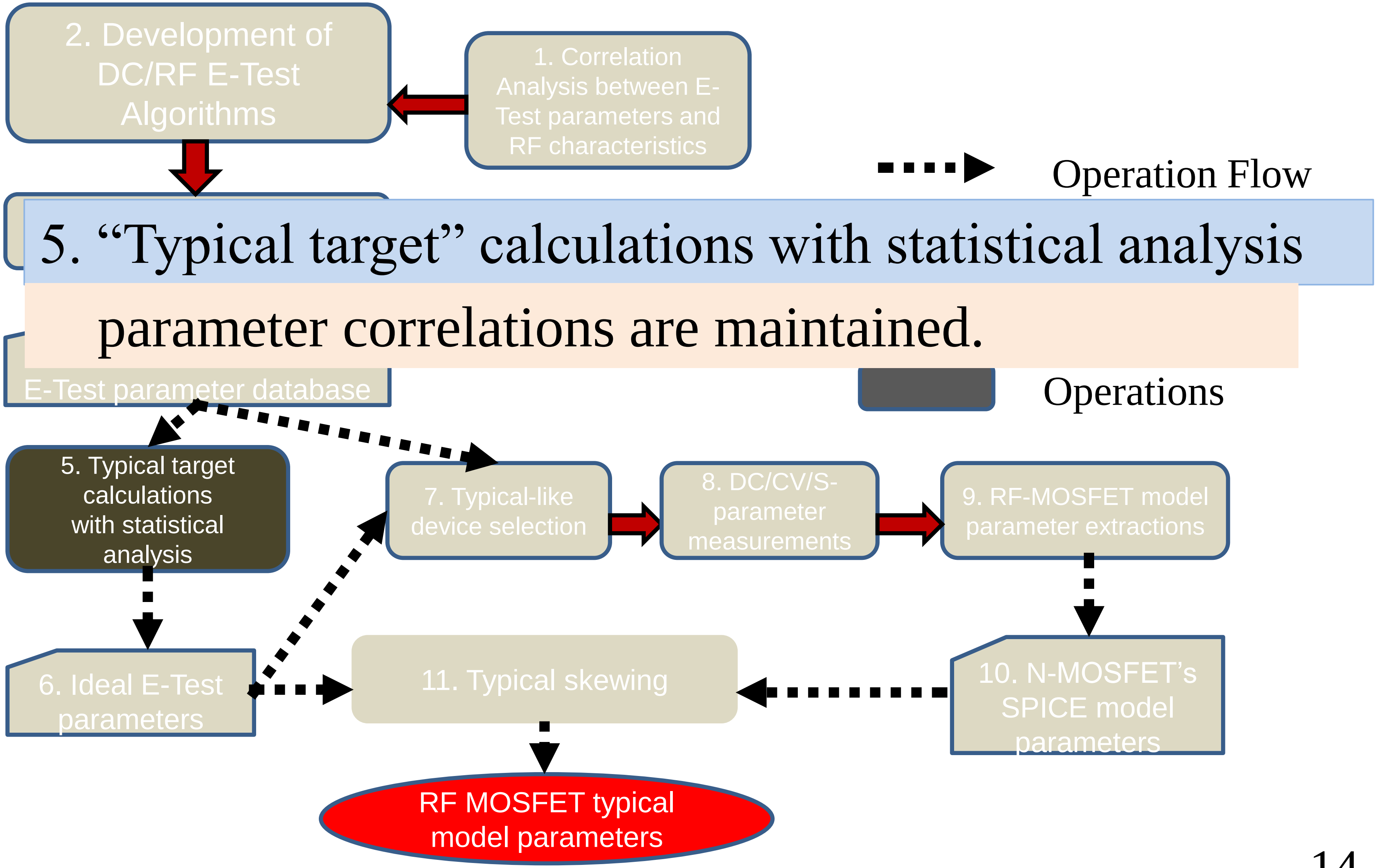
Data

Operations

4. Lot/Wafer E-Test parameter database

E-Test parameters are stored in.

Typical Target Skewing Flow (5)



2. Development of DC/RF E-Test Algorithms

1. Correlation Analysis between E-Test parameters and RF characteristics

Operation Flow

5. “Typical target” calculations with statistical analysis parameter correlations are maintained.

E-Test parameter database

Operations

5. Typical target calculations with statistical analysis

7. Typical-like device selection

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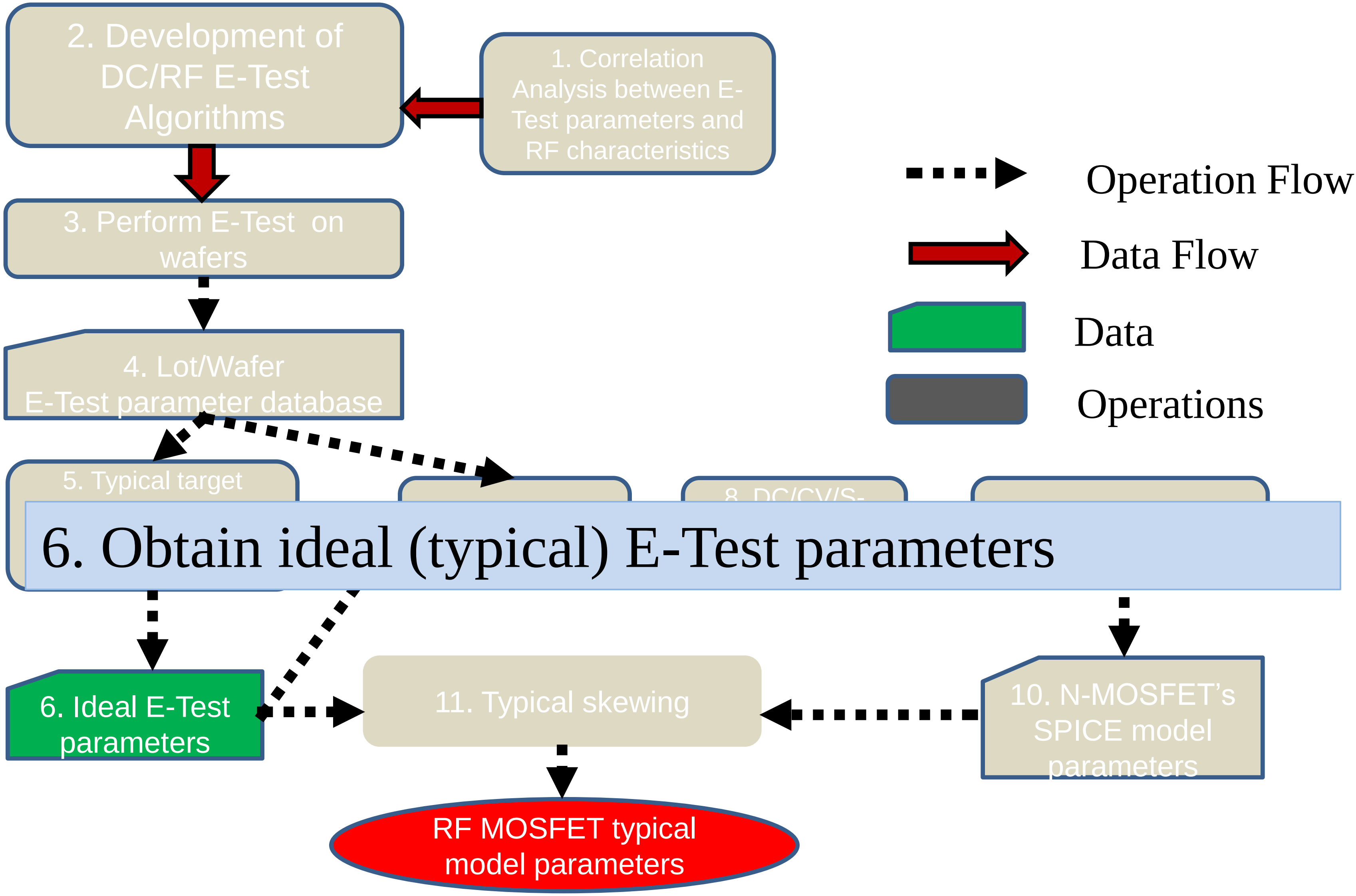
RF MOSFET typical model parameters

Typical Target Skewing Flow (6)



2. Development of DC/RF E-Test Algorithms

1. Correlation Analysis between E-Test parameters and RF characteristics

3. Perform E-Test on wafers

4. Lot/Wafer E-Test parameter database

5. Typical target

8. DC/CV/S-

6. Obtain ideal (typical) E-Test parameters

6. Ideal E-Test parameters

11. Typical skewing

10. N-MOSFET's SPICE model parameters

RF MOSFET typical model parameters

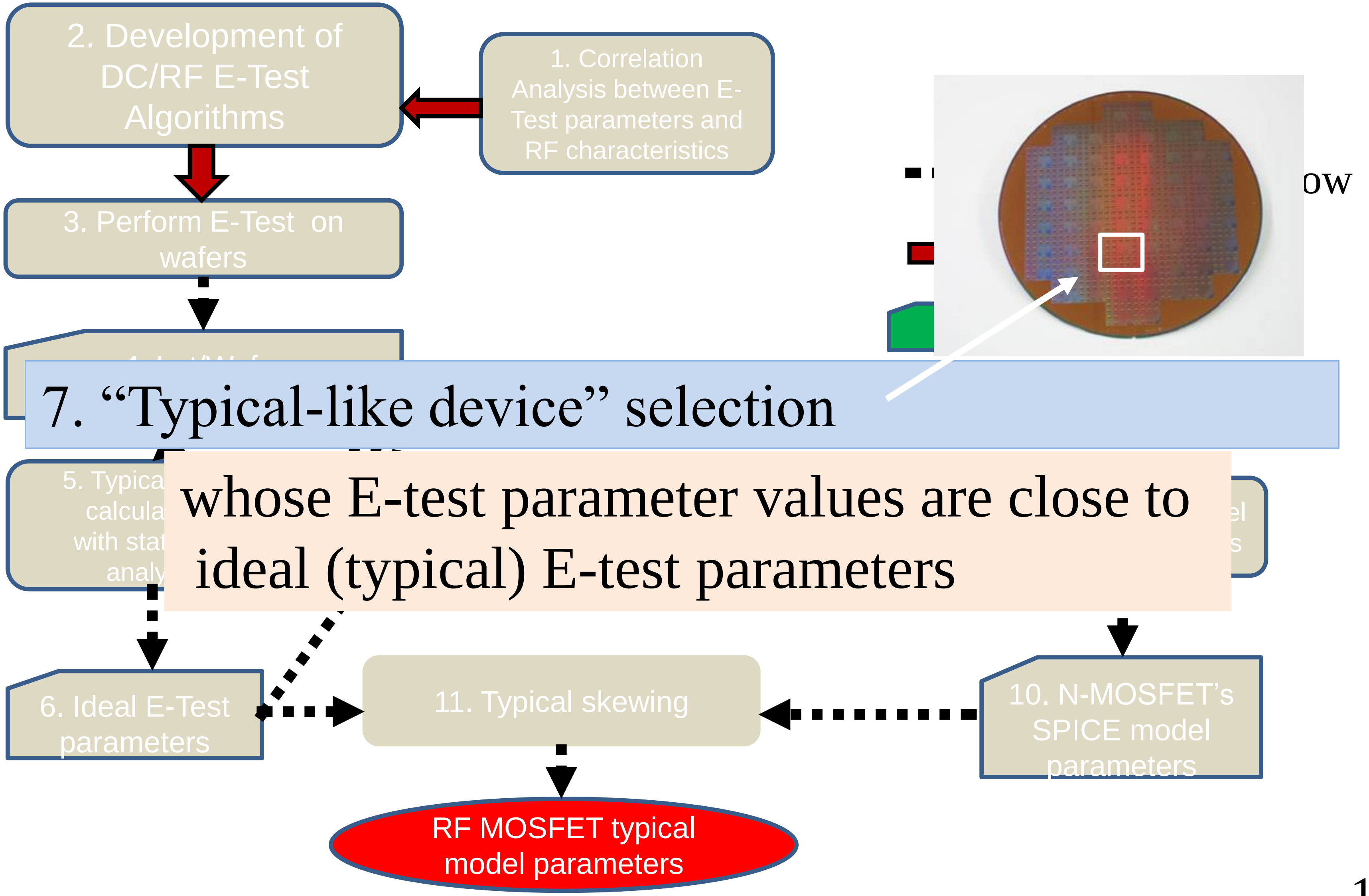
⇢ Operation Flow

→ Data Flow

🟩 Data

■ Operations

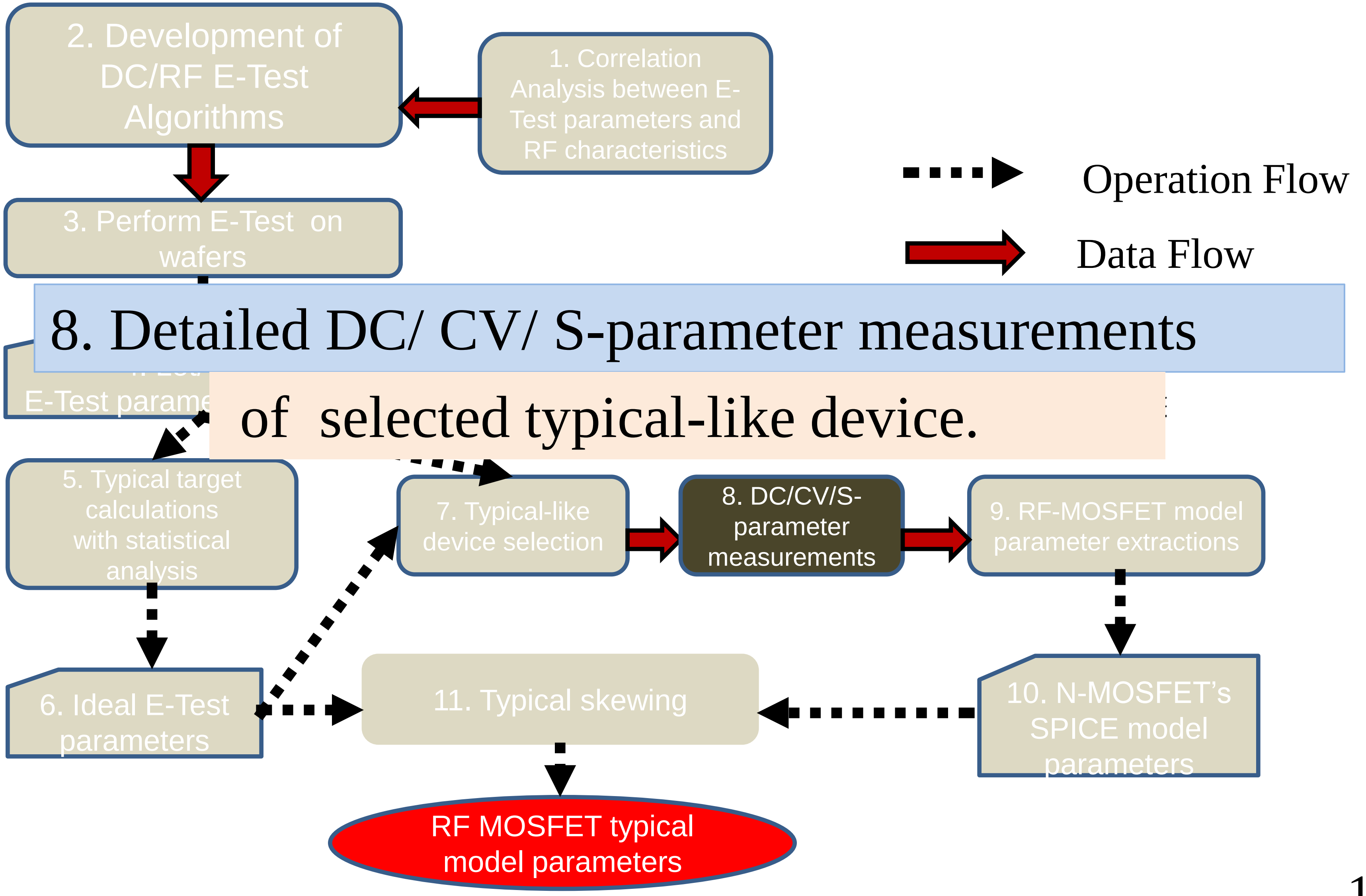
Typical Target Skewing Flow (7)



7. “Typical-like device” selection

whose E-test parameter values are close to ideal (typical) E-test parameters

Typical Target Skewing Flow (8)



2. Development of DC/RF E-Test Algorithms

1. Correlation Analysis between E-Test parameters and RF characteristics

3. Perform E-Test on wafers

E-Test parame

5. Typical target calculations with statistical analysis

6. Ideal E-Test parameters

7. Typical-like device selection

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RF MOSFET typical model parameters

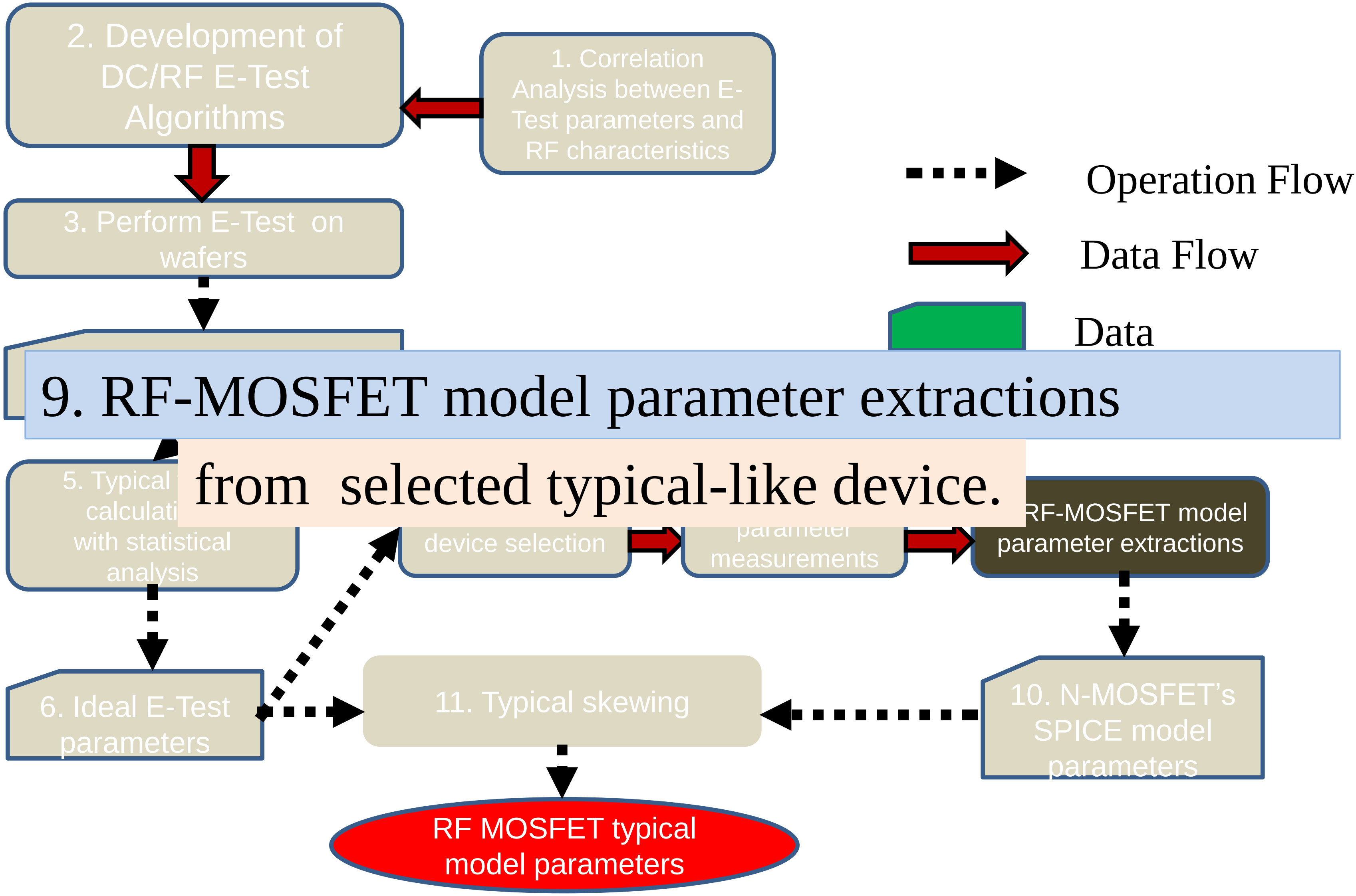
Operation Flow

Data Flow

8. Detailed DC/ CV/ S-parameter measurements

of selected typical-like device.

Typical Target Skewing Flow (9)



2. Development of DC/RF E-Test Algorithms

1. Correlation Analysis between E-Test parameters and RF characteristics

3. Perform E-Test on wafers

5. Typical calculati with statistical analysis

device selection

parameter measurements

RF-MOSFET model parameter extractions

6. Ideal E-Test parameters

11. Typical skewing

10. N-MOSFET's SPICE model parameters

RF MOSFET typical model parameters

Operation Flow

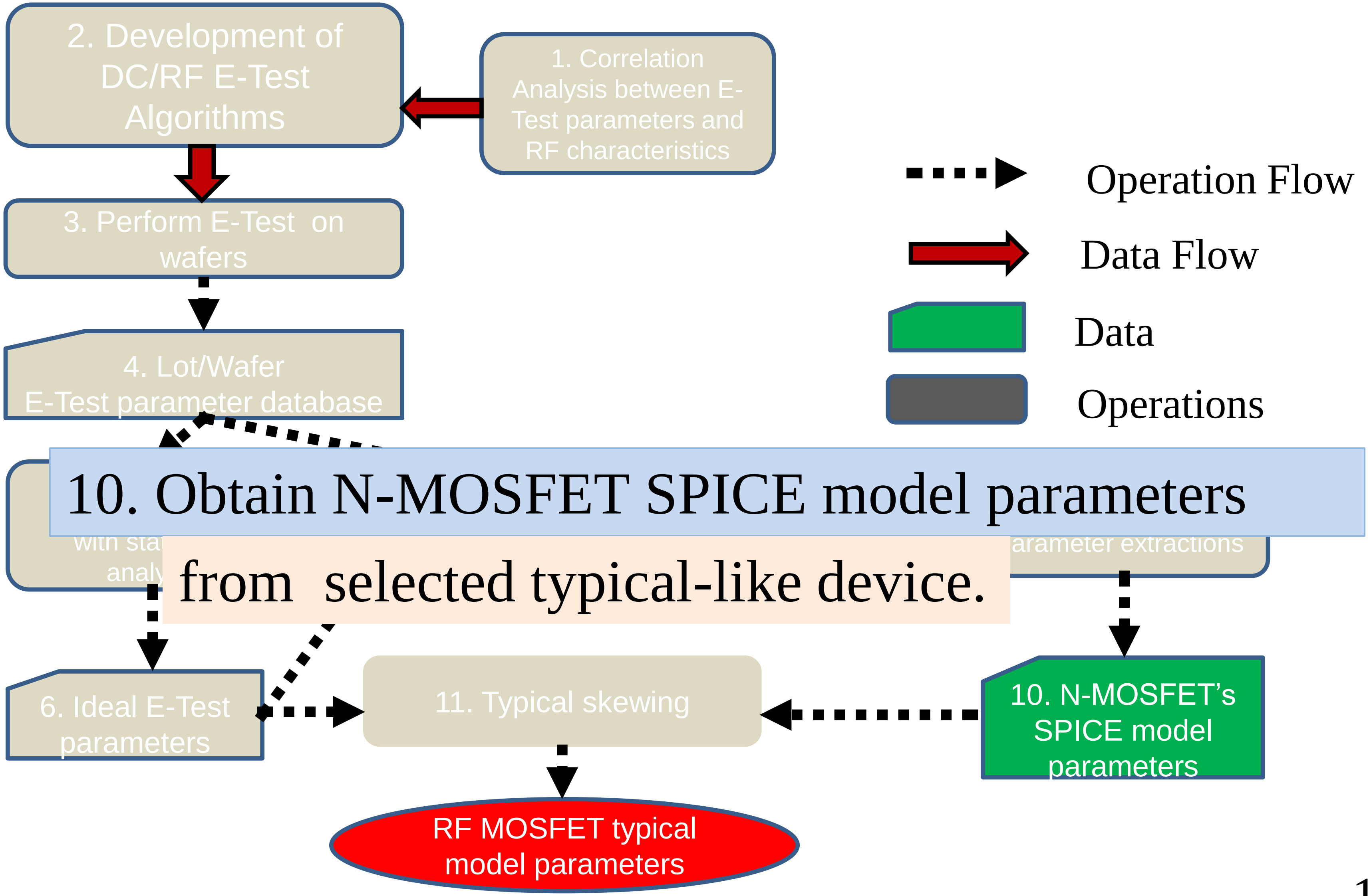
Data Flow

Data

9. RF-MOSFET model parameter extractions

from selected typical-like device.

Typical Target Skewing Flow (10)



2. Development of DC/RF E-Test Algorithms

1. Correlation Analysis between E-Test parameters and RF characteristics

3. Perform E-Test on wafers

4. Lot/Wafer E-Test parameter database

with sta

analy

arameter extractions

6. Ideal E-Test parameters

11. Typical skewing

10. N-MOSFET's SPICE model parameters

RF MOSFET typical model parameters

Operation Flow

Data Flow

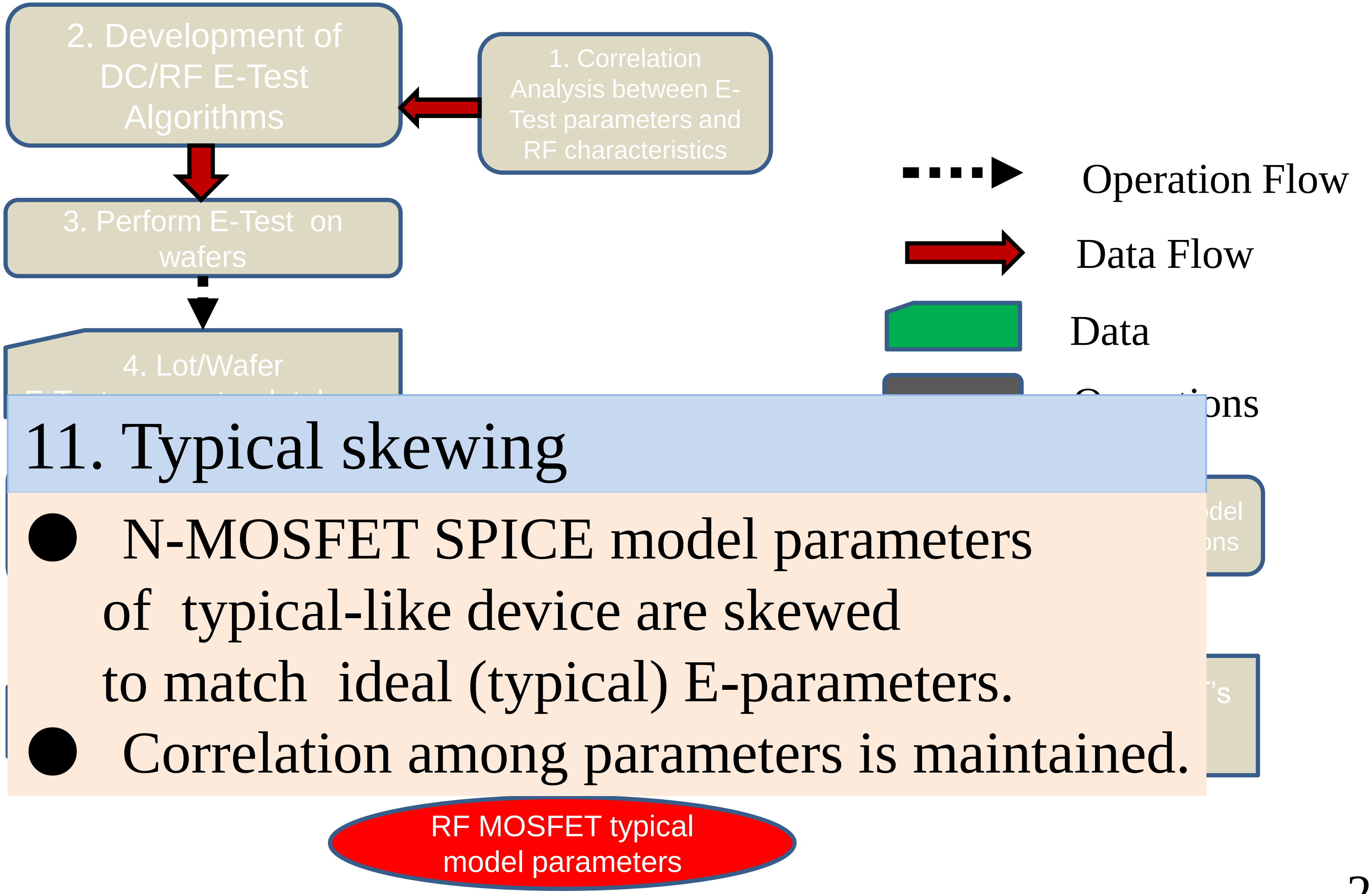
🟩 Data

⬛ Operations

10. Obtain N-MOSFET SPICE model parameters

from selected typical-like device.

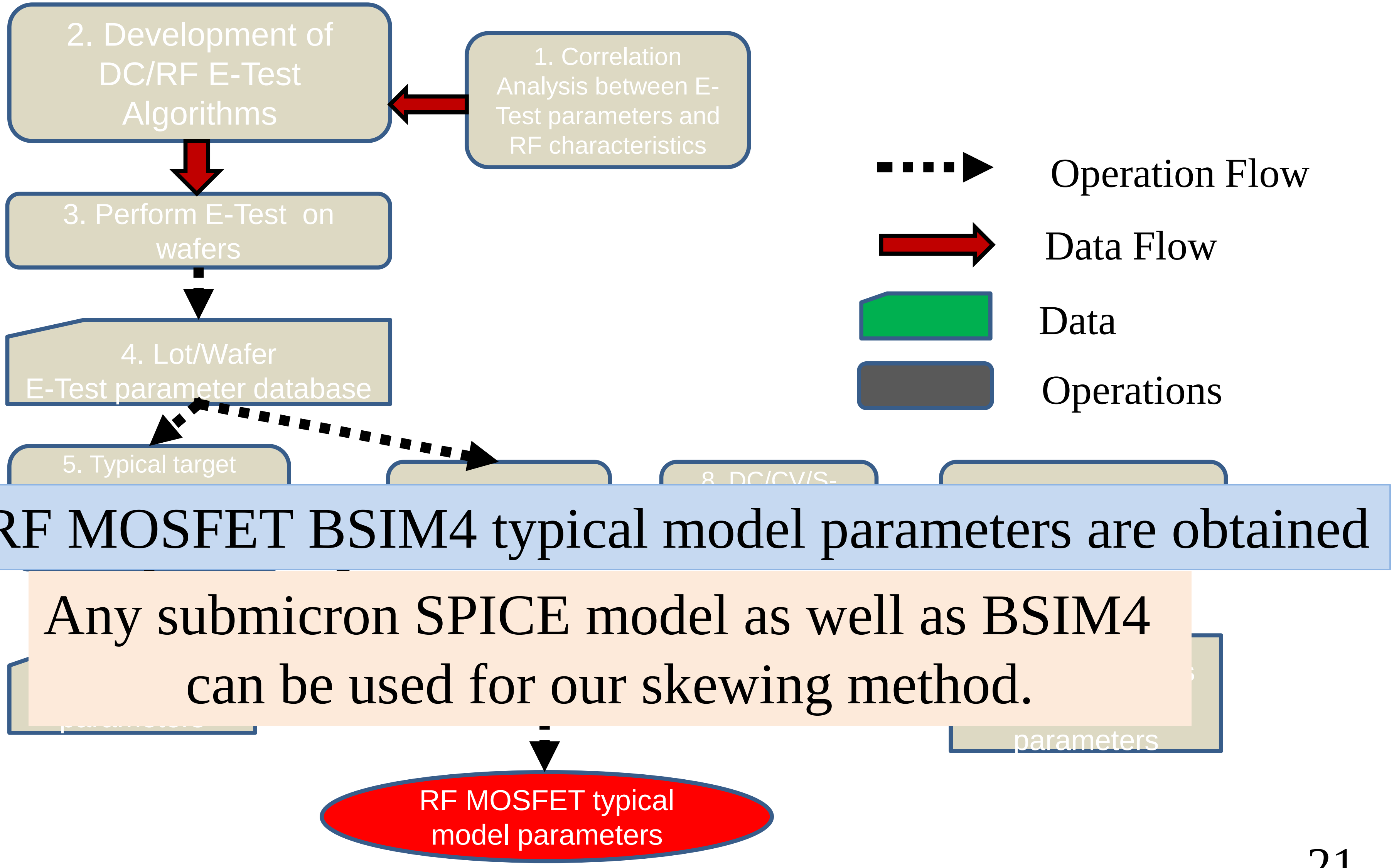
Typical Target Skewing Flow (11)



11. Typical skewing

- N-MOSFET SPICE model parameters of typical-like device are skewed to match ideal (typical) E-parameters.
- Correlation among parameters is maintained.

Typical Target Skewing Flow (Final)



2. Development of DC/RF E-Test Algorithms

1. Correlation Analysis between E-Test parameters and RF characteristics

3. Perform E-Test on wafers

4. Lot/Wafer E-Test parameter database

5. Typical target

8. DC/CV/S-

parameters

parameters

RF MOSFET typical model parameters

Operation Flow

Data Flow

🟩 Data

Operations

RF MOSFET BSIM4 typical model parameters are obtained

Any submicron SPICE model as well as BSIM4 can be used for our skewing method.

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Calculations of Theoretical Target Specifications

- Development of E-Test parameters
  - Modifications, additions of test specifications, algorithms from PCM (Process Control Monitor)
  - RF model definitions
  - RF E-Test parameter inclusions

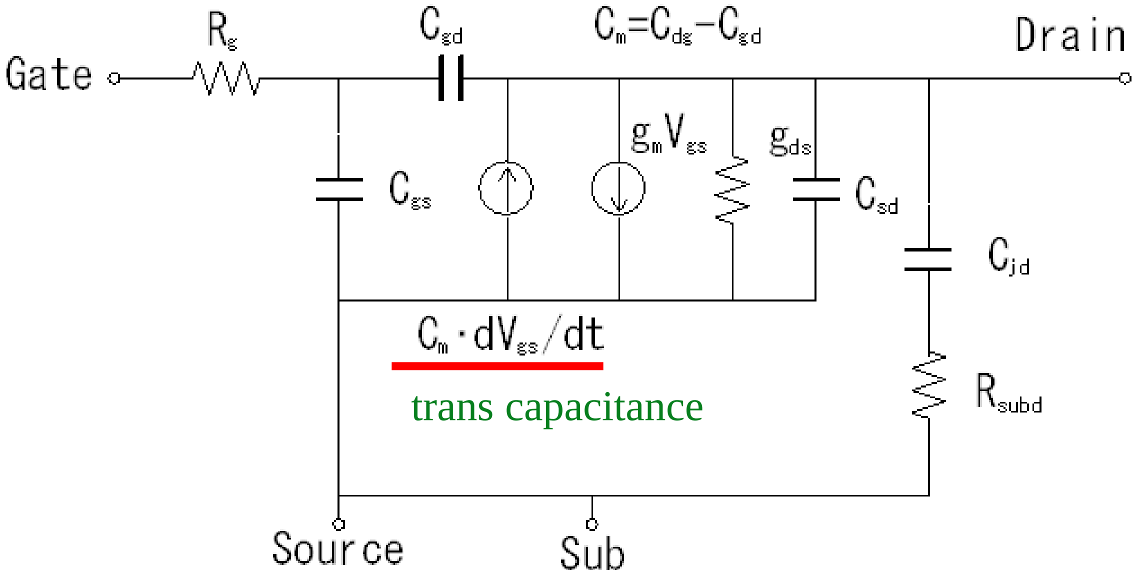
- Statistical analysis for typical parameter calculations
  - E-Test executions, E-Test parameter screening with statistical functions
  - Correlation analysis to maintain the relationships between E-Test parameters

RF NMOS Model Definition and Parameters

- KAIST small signal equivalent circuit [1]
- S-parameters

↓ easy to convert

Y-parameters



trans capacitance

$$Y_{11}=\frac{j\omega\left(\underline{C_{gs}}+\underline{C_{gd}}\right)}{1+j\omega\left(\underline{C_{gs}}+\underline{C_{gd}}\right)R_g}\qquad Y_{12}=-\frac{-j\omega\underline{C_{gd}}}{1+j\omega\left(\underline{C_{gs}}+\underline{C_{gd}}\right)R_g}\qquad Y_{21}=\frac{\underline{g_m}-j\omega\underline{C_m}-j\omega\underline{C_{gd}}}{1+j\omega\left(\underline{C_{gs}}+\underline{C_{gd}}\right)R_g}$$

$$Y_{22}=\underline{g_{ds}}+\frac{j\omega\underline{C_{jd}}}{1+j\omega\underline{C_{jd}}R_{subd}}+j\omega C_{sd}+j\omega\underline{C_{gd}}+\frac{\omega^2\underline{C_{gd}}R_g\left(\underline{C_{gd}}+\underline{C_m}\right)+j\omega\underline{g_m}\underline{C_{gd}}R_g}{1+j\omega\left(\underline{C_{gs}}+\underline{C_{gd}}\right)R_g}$$

[1] I. Kwon, et.al., “A New Small Signal Modeling of RF MOSFETs including Charge Conservation Capacitances,” ESSCIRC (Jul. 2000).

E-Test Parameters
Used for Typical Device Targeting

E-Test Parameter	Meanings
TOX	Oxide thickness
LD	Diffusion length
WD	Diffusion width
Idsat	Saturation current
Gmmax	Maximum conductance
Beta	Slope of Ids-Vgs Plot
Rcon	Contact resistance
Rdiff	Diffusion resistance
VTO	Threshold voltage
COV	Overlap capacitance
CJ	Area Junction capacitance
CJW	Perimeter Junction capacitance

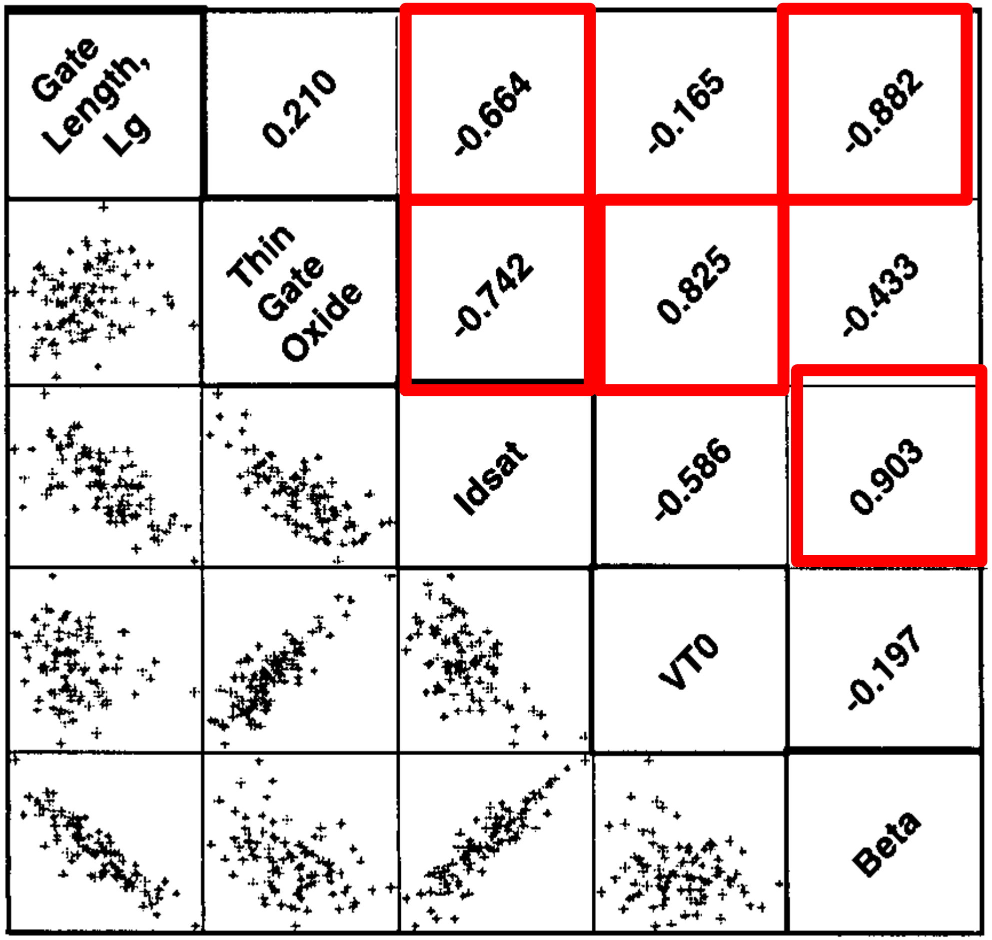
New algorithm for calculation (TOX through VTO)

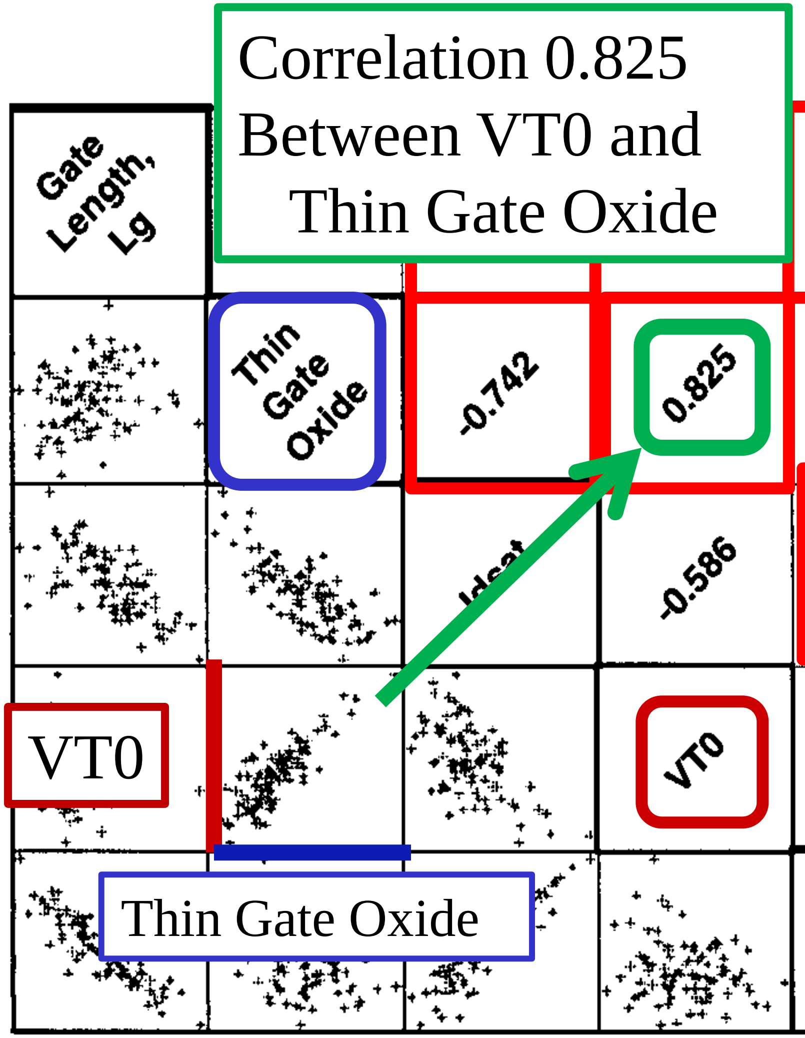
New parameters as E-Test (COV, CJ, CJW)

Conventional E-test parameters were only for DC.

Correlation Analysis of E-Test Parameters

Correlation Matrix





Correlation 0.825 Between VT0 and Thin Gate Oxide

VT0

Thin Gate Oxide

- Their correlation represents device process.
- Correlation > 0.6 should be maintained for statistical modeling.

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Target Device Selection and Its Modeling

Calculated ideal (typical) E-Test parameters

Typical Target Parameters.

VT0.Short = 4.545e-001
BETA.Short = 1.369e+004
Idsat.Short = 6.109e-003
VT0.Large = 2.423e-001
BETA.Large = 2.833e+002
GMMAX.Large = 9.312-006
Idsat.Large = 2.612e-004
VT0.Narrow = 1.484e-001
BETA.Narrow = 5.766e+000
Idsat.Narrow = 6.127e-006
TOX = 2.751e-009
Rcon = 6.211e+000
Rdiff = 2.122e+000
DL = 7.6433e-008
DW = 8.7021e-008
COV = 2.453e-012
CJ = 3.812e-012
CJW = 5.146e-012

Extracted BSIM4 parameters of selected "typical-like device"

Typical-like Device

Device (No:12) --- wafer_no.: 5
shot_no.: 1 x: 7 y: 4

VT0.Short: 0.465
VT0.Short Error: 2.306211 %
BETA.Short: 13500
BETA.Short Error: 1.382729 %
Idsat.Short: 0.00599
Idsat.Short Error: 1.943933 %
VT0.Large: 0.242
VT0.Large Error: 0.125286 %
BETA.Large: 283
BETA.Large Error: 0.088261 %
GMMAX.Large: 9.300-006
GMMAX.Large Error: 0.092261 %
Idsat.Large: 0.000261
Idsat.Large Error: 0.075203 %
VT0.Narrow: 0.147
VT0.Narrow Error: 0.974377 %
BETA.Narrow: 5.79
BETA.Narrow Error: 0.408770 %
Idsat.Narrow: 6.2e-006
Idsat.Narrow Error: 1.192038 %

TOX: 2.711e-009
TOX Error: 1.450000 %
Rcon: 6.2e-006
Rcon Error: 1.192038 %
Rdiff: 6.2e-006
Rdiff Error: 1.192038 %
DL: 7.5233e-008
DL Error: 1.570000 %
DW: 8.7661e-008
DW Error: 0.007400 %
COV: 2.491e-012
COV Error: 1.549112 %
CJ: 3.805e-012
CJ Error: 0.183612 %
CJW: 5.124e-012
CJW Error: 0.427532 %
****
Average Error: 1.126090 %

There are discrepancies and skewing is needed.

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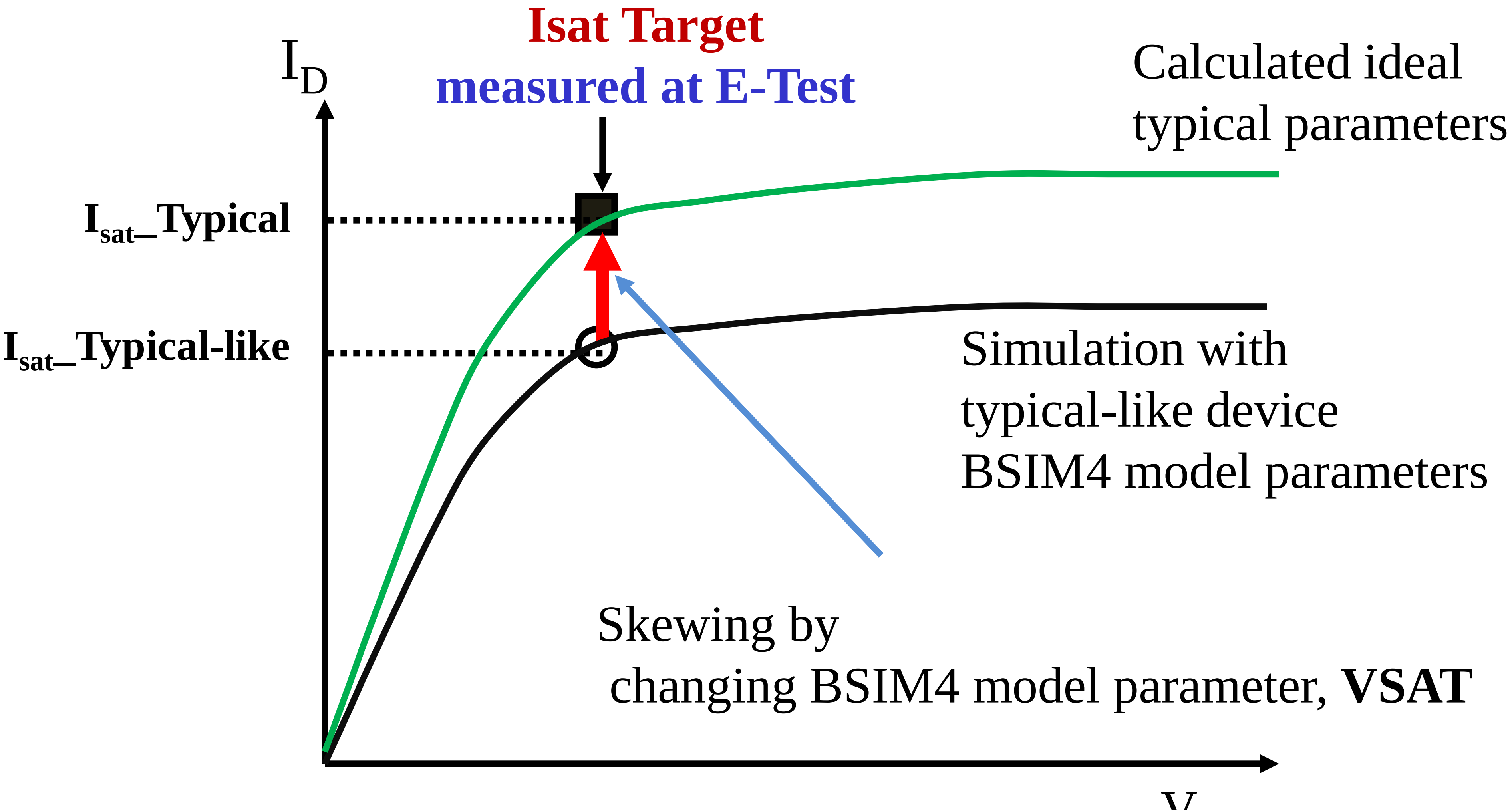
BSIM4 Model Parameter Skew to Typical E-Test Parameters

Skewing Conditions

- Model parameters should be
  - physical
  - process oriented.
- Slope of *IV* or *CV* should NOT be
  - changed drastically by skewing model parameters

Skewing Concept with VSAT



Isat Target
measured at E-Test

Calculated ideal typical parameters

Simulation with typical-like device BSIM4 model parameters

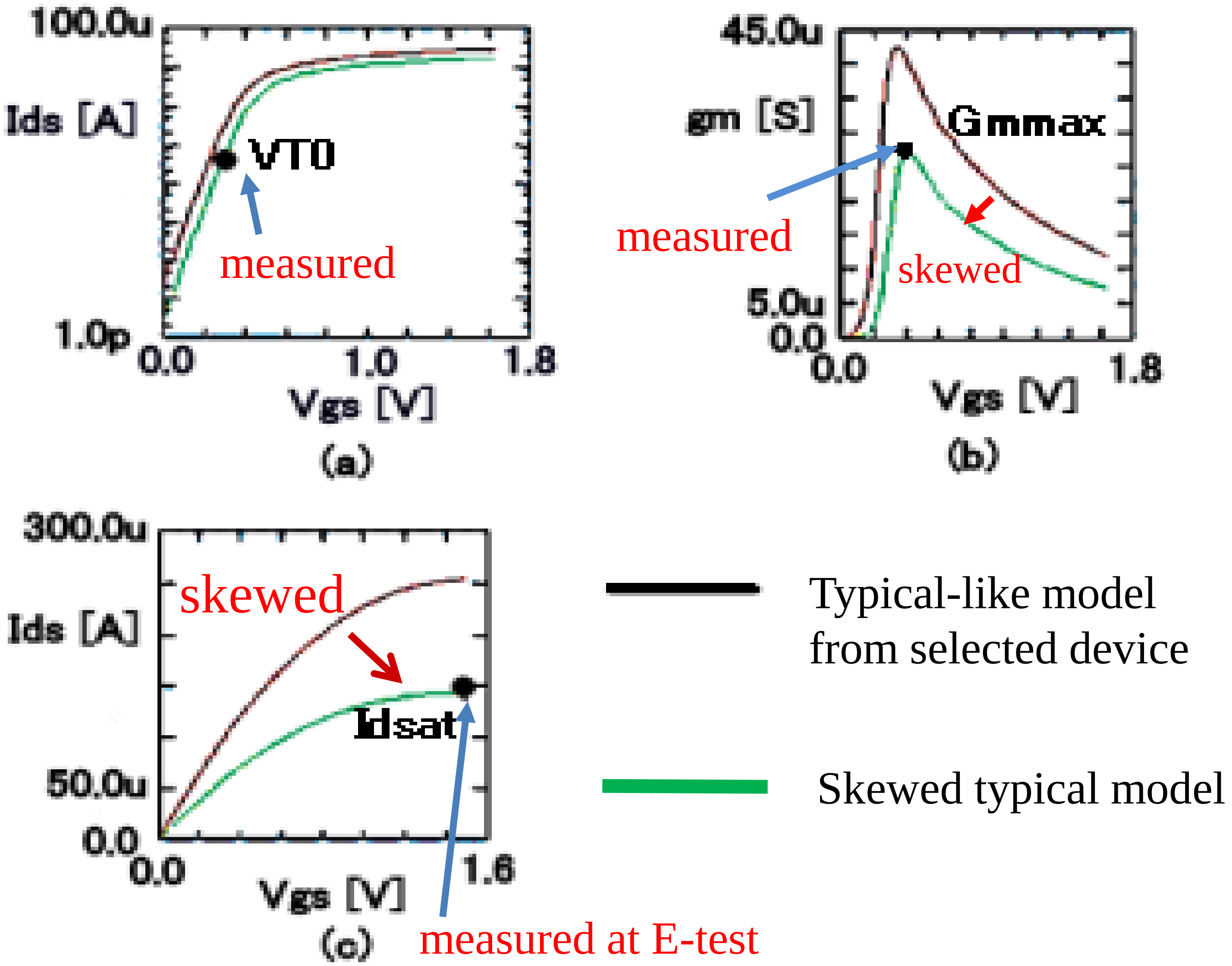
Skewing by changing BSIM4 model parameter, **VSAT**

Isat : E-Test parameter
VSAT: BSIM4 parameter

E-Test Parameters for Target and BSIM4 Model Parameters for Skew

Type of the simulation	E-Test parameter as targets	BSIM4 Model parameters for skewing
I_{DS} vs. V_{GS}	VT0.Large	VTH0
g_m vs. V_{GS}	GMMAX.Large, BETA.Large	UA
I_{DS} vs. V_{GS}	VT0.Narrow	K3, WINT, DVT0W
I_{DS} vs. V_{GS}	VT0.Short	DVT0
I_{DS} vs. V_{DS}	Idsat.Large	U0
I_{DS} vs. V_{DS}	Idsat.Narrow	WINT
I_{DS} vs. V_{DS}	Idsat.Short	VSAT, LVSAT
C_{GC} vs. V_{GC}	COV	CGS0 (=CGD0), CGSL (=CGDL)
C_J vs. V_J	CJ.area	CJ0
C_J vs. V_J	CJ.perim	CJSW

Examples of *DC* Parameters Skew



measured

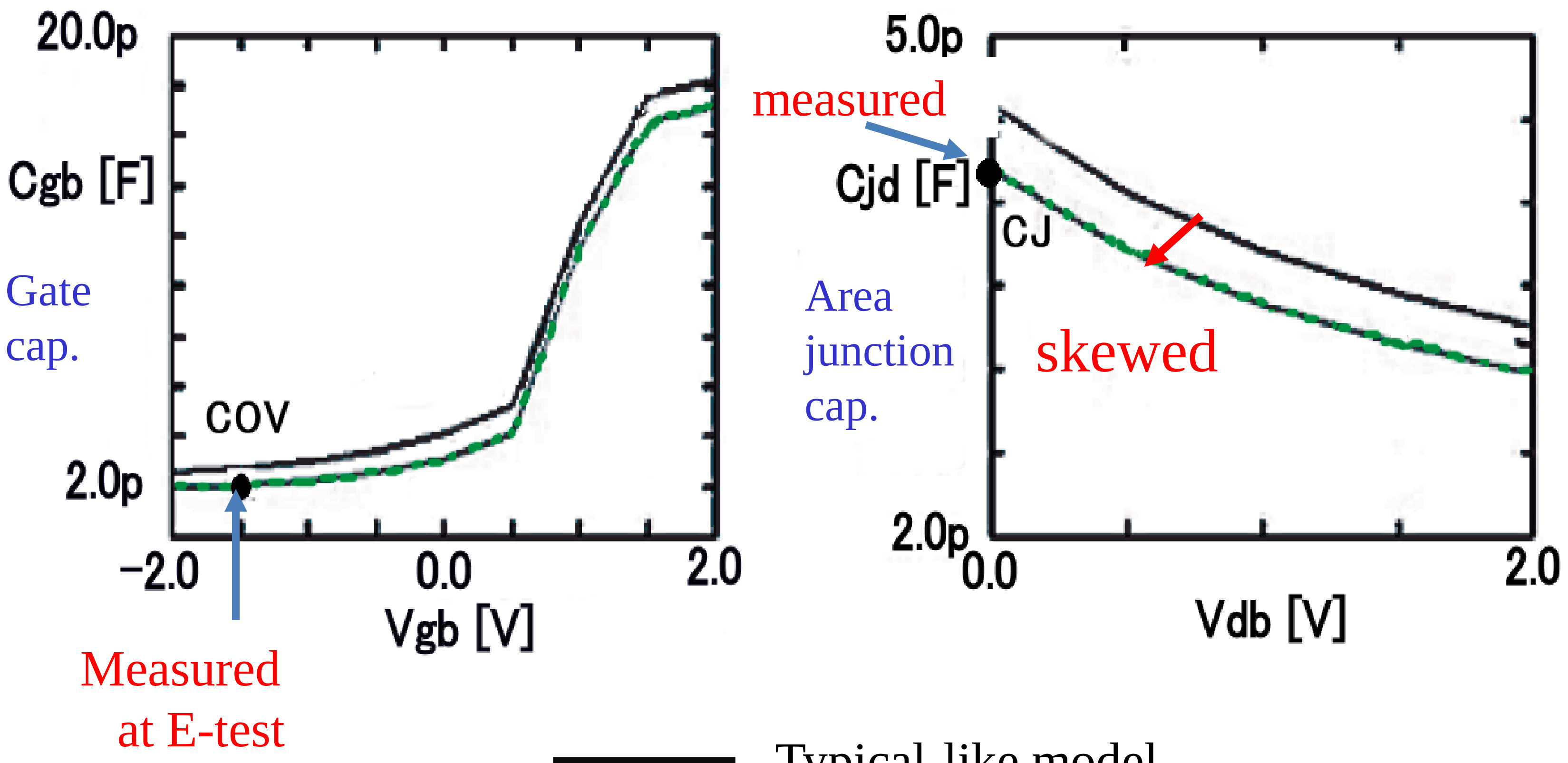
measured

skewed

skewed

measured at E-test

Examples of *CV* Parameters Skew



Gate cap.

Measured at E-test

measured

Area junction cap.

skewed

▬ Typical-like model from selected device

🟩 Skewed typical model

Useful for RF design

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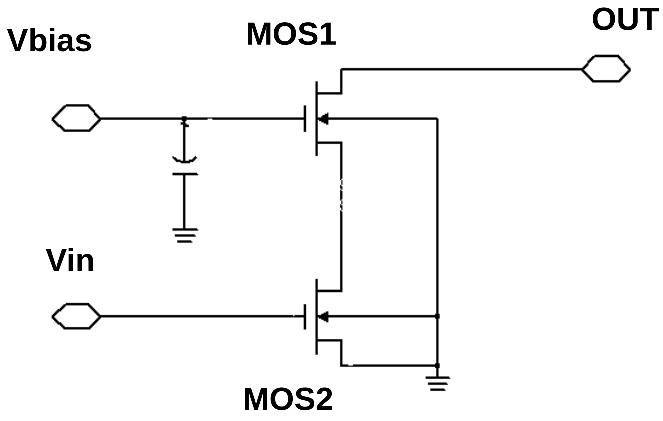
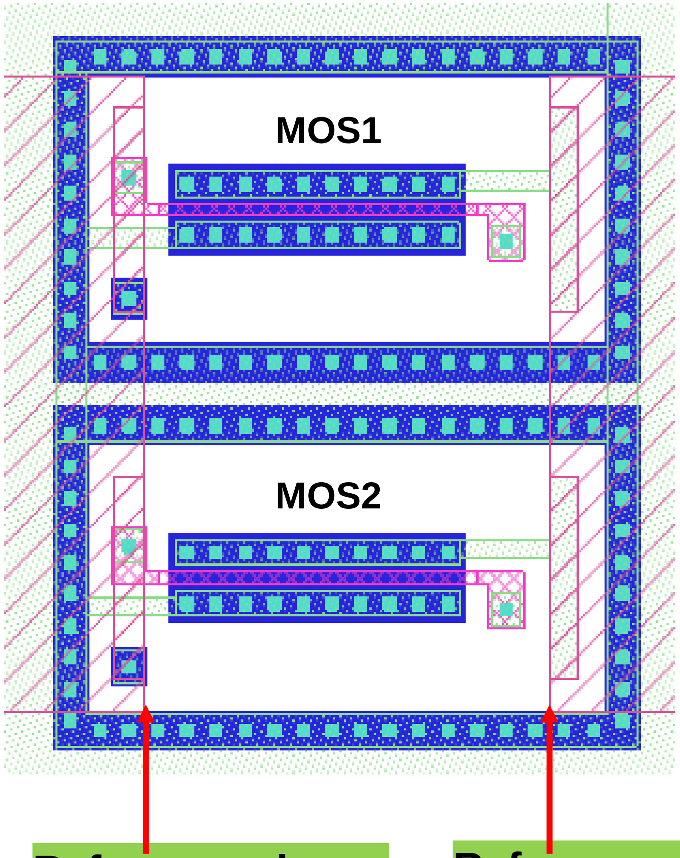
Verifications of RF Circuit Simulations

A cascode amplifier for verification

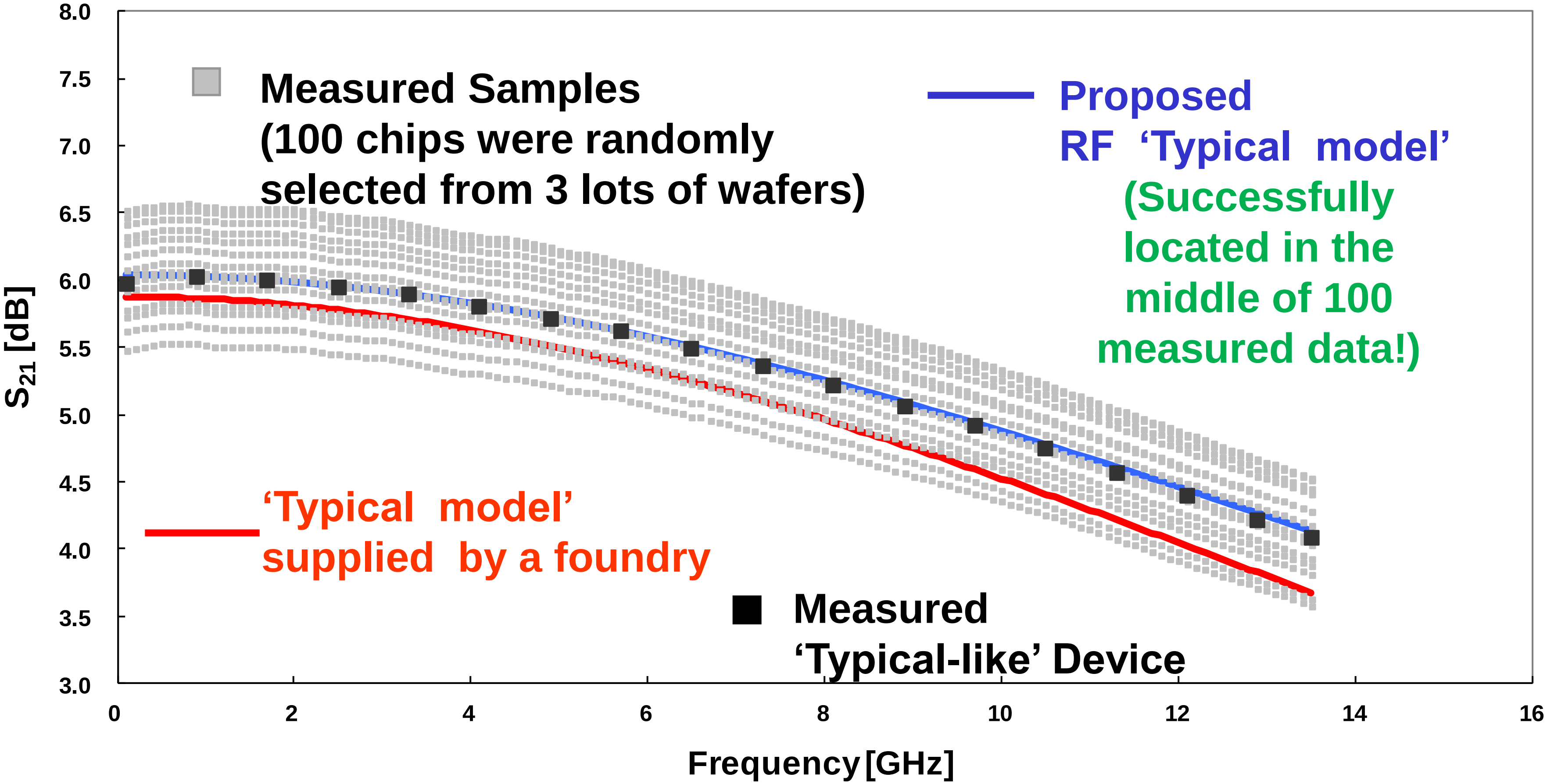




Reference plane of Port1

Reference plane of Port2

Measurement and Simulation Results of S_{21} Dependencies on Frequency of Cascode Amplifier



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➢Conclusions

Conclusions

- A new procedure of NMOS typical target and a skewing method for RF analog applications were demonstrated.
- RF NMOS typical targeting results were examined with a simple cascode amplifier designed and fabricated in our TEG.

↓

- Skewed results were located in the middle of randomly measured 100 S_{21} data.

This typical model generation method

→ practical, useful for CMOS circuit designer.