

EE 330

Lecture 21

- Bipolar Process

Exam Schedule

Exam 1	Friday Sept 24
Exam 2	Friday Oct 22
Exam 3	Friday Nov 19
Final	Tues Dec 14 12:00 p.m.

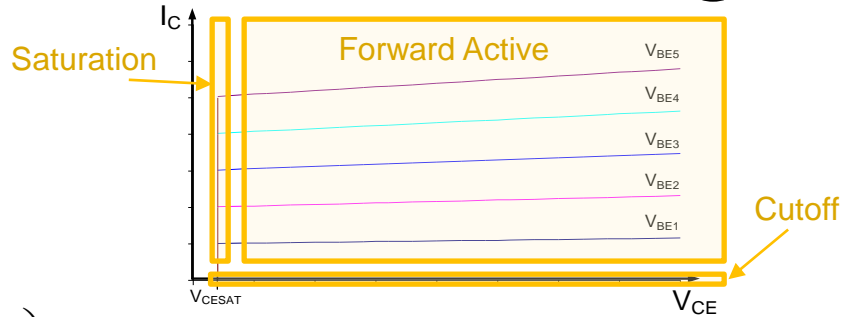
Photo courtesy of the director of the National Institute of Health (NIH)



As a courtesy to fellow classmates, TAs, and the instructor

Wearing of masks during lectures and in the laboratories for this course would be appreciated irrespective of vaccination status

Simplified Multi-Region Model



$$I_C = J_S A_E e^{\frac{V_{BE}}{V_t}} \left(1 + \frac{V_{CE}}{V_{AF}} \right)$$

$$I_B = \frac{J_S A_E}{\beta} e^{\frac{V_{BE}}{V_t}}$$

$$V_t = \frac{kT}{q}$$

Forward Active

$$V_{BE} = 0.7V$$

$$V_{CE} = 0.2V$$

Saturation

$$I_C = I_B = 0$$

Cutoff

- This is a piecewise model suitable for analytical calculations
- Can easily extend to reverse active mode but of little use
- Still need conditions for operating in the 3 regions

Simplified Multi-Region Model

Alternate equivalent model

$$I_C = \beta I_B \left(1 + \frac{V_{CE}}{V_{AF}} \right)$$

$$I_B = \frac{J_S A_E}{\beta} e^{\frac{V_{BE}}{V_t}}$$

$$V_t = \frac{kT}{q}$$

$$V_{BE} = 0.7V$$

$$V_{CE} = 0.2V$$

$$I_C = I_B = 0$$

Conditions

$$V_{BE} > 0.4V$$

$$V_{BC} < 0$$

Forward Active

$$I_C < \beta I_B$$

Saturation

$$V_{BE} < 0$$

$$V_{BC} < 0$$

Cutoff

A small portion of the operating region is missed with this model but seldom operate in the missing region

Further Simplified Multi-Region dc Model

Equivalent Further Simplified Multi-Region Model

$$I_C = \beta I_B$$

$$V_{BE} = 0.6V$$

$$V_t = \frac{kT}{q}$$

$$V_{BE} > 0.4V$$

$$V_{BC} < 0$$

Forward Active

$$V_{BE} = 0.7V$$

$$V_{CE} = 0.2V$$

$$I_C < \beta I_B$$

Saturation

$$I_C = I_B = 0$$

$$V_{BE} < 0$$

$$V_{BC} < 0$$

Cutoff

A small portion of the operating region is missed with this model but seldom operate in the missing region

Bipolar Process Description

p-substrate epi

Components Shown

- Vertical npn BJT
- Lateral pnp BJT
- JFET
- Diffusion Resistor
- Diode (and varactor)

Note: Features intentionally not to scale to make it easier to convey more information on small figures

- Much processing equipment is same as used for MOS processes so similar minimum-sized features can be made
- But will see that there are some fundamental issues that typically make bipolar circuits large

TABLE 2C.1

Process scenario of major process steps in typical bipolar process^a

1. Clean wafer (p-type)
 2. GROW THIN OXIDE
 3. Apply photoresist
 4. PATTERN n⁺ BURIED LAYER
 5. Develop photoresist
 6. DEPOSITION AND DIFFUSION OF n-BURIED LAYER
 7. Strip photoresist
 8. Strip oxide
 9. GROW EPITAXIAL LAYER (n-type)
 10. Grow oxide
 11. Apply photoresist
 12. PATTERN p⁺ ISOLATION REGIONS
 13. Develop photoresist
 14. Etch oxide
 15. DEPOSITION AND DIFFUSION OF p⁺ ISOLATION
 16. Strip photoresist
 17. Grow oxide
 - Optional high-resistance p-diffusion*
 - A.1 Apply photoresist
 - A.2 PATTERN p-RESISTORS
 - A.3 Develop photoresist
 - A.4 Etch oxide
 - A.5 DEPOSITION AND DIFFUSION OF p-RESISTORS
 - A.6 Strip photoresist
 - A.7 Grow oxide
 18. Apply photoresist
 19. PATTERN BASE REGIONS
 20. Develop photoresist
 21. Etch oxide
 22. DEPOSITION AND DIFFUSION OF p-TYPE BASE
 23. Strip photoresist
 24. Grow oxide
 25. Apply photoresist
- (MASK #1)
- (MASK #2)
- (MASK #A)
- (MASK #3)

26. PATTERN n-TYPE EMITTER REGIONS
27. Develop photoresist
28. Etch Oxide
29. n⁺ DEPOSITION AND DIFFUSION
30. Strip photoresist
31. Grow oxide
32. Apply photoresist
33. PATTERN CONTACT OPENINGS
34. Develop photoresist
35. Etch oxide
36. Strip Photoresist
37. APPLY METAL
38. Apply photoresist
39. PATTERN METAL
40. Develop photoresist
41. ETCH METAL
42. Strip photoresist
43. APPLY PASSIVATION
44. Apply photoresist
45. PATTERN PAD OPENINGS
46. Develop photoresist
47. Etch passivation
48. Strip photoresist
49. ASSEMBLE, PACKAGE, AND TEST

(MASK #4)

(MASK #5)

(MASK #6)

(MASK #7)

- Small number of masks
- Most not critical alignment / size

TABLE 2C.2
Design rules for a typical bipolar process ($\lambda = 2.5 \mu$)
(See Table 2C.3 in color plates for graphical interpretation)

	Dimension
1. n^+ buried collector diffusion (Yellow, Mask #1)	
1.1 Width	3λ
1.2 Overlap of p-base diffusion (for vertical npn)	2λ
1.3 Overlap of n^+ emitter diffusion (for collector contact of vertical npn)	2λ
1.4 Overlap of p-base diffusion (for collector and emitter of lateral pnp)	2λ
1.5 Overlap of n^+ emitter diffusion (for base contact of lateral pnp)	2λ
2. Isolation diffusion (Orange, Mask #2)	
2.1 Width	4λ
2.2 Spacing	24λ
2.3 Distance to n^+ buried collector	14λ
3. p-base diffusion (Brown, Mask #3)	
3.1 Width	3λ
3.2 Spacing	5λ
3.3 Distance to isolation diffusion	14λ
3.4 Width (resistor)	3λ
3.5 Spacing (as resistor)	3λ
4. n^+ emitter diffusion (Green, Mask #4)	
4.1 Width	3λ
4.2 Spacing	3λ
4.3 p-base diffusion overlap of n^+ emitter diffusion (emitter in base)	2λ
4.4 Spacing to isolation diffusion (for collector contact)	12λ
4.5 Spacing to p-base diffusion (for base contact of lateral pnp)	6λ
4.6 Spacing to p-base diffusion (for collector contact of vertical npn)	6λ

- Note some features have very large design rules
- Will discuss implication of this later

5. Contact (Black, Mask #5)	
5.1 Size (exactly)	$4\lambda \times 4\lambda$
5.2 Spacing	2λ
5.3 Metal overlap of contact	λ
5.4 n^+ emitter diffusion overlap of contact	2λ
5.5 p-base diffusion overlap of contact	2λ
5.6 p-base to n^+ emitter	3λ
5.7 Spacing to isolation diffusion	4λ
6. Metalization (Blue, Mask #6)	
6.1 Width	2λ
6.2 Spacing	2λ
6.3 Bonding pad size	$100\ \mu \times 100\ \mu$
6.4 Probe pad size	$75\ \mu \times 75\ \mu$
6.5 Bonding pad separation	$50\ \mu$
6.6 Bonding to probe pad	$30\ \mu$
6.7 Probe pad separation	$30\ \mu$
6.8 Pad to circuitry	$40\ \mu$
6.9 Maximum current density	$0.8\ \text{mA}/\mu\ \text{width}$
7. Passivation (Purple, Mask #7)	
7.1 Minimum bonding pad opening	$90\ \mu \times 90\ \mu$
7.2 Minimum probe pad opening	$65\ \mu \times 65\ \mu$

TABLE 2C.4
Process parameters for a typical bipolar process^a

Parameter	Typical	Tolerance ^b	Units
Ebers-Moll model parameters			
β_F (forward β)			
npn—vertical	100	50 to 200	
pnp—lateral			
(at $I_C = 500 \mu\text{A}$)	10	$\pm 20\%$	
(at $I_C = 200 \mu\text{A}$)	6	$\pm 20\%$	
β_R (reverse β)			
npn—vertical	1.5	± 0.5	
pnp—lateral			
(at $I_C = 500 \mu\text{A}$)	5	$\pm 20\%$	
(at $I_C = 200 \mu\text{A}$)	3	$\pm 20\%$	
V_{AF} (forward Early voltage)			
npn—vertical	100	$\pm 30\%$	V
pnp—lateral	150	$\pm 30\%$	V
V_{AR} (reverse Early voltage)			
npn—vertical	150	$\pm 30\%$	V
pnp—lateral	150	$\pm 30\%$	V
J_S (saturation current density)			
npn—vertical	2.6×10^{-7}	-50% to + 100%	pA/μ^2
pnp—lateral	1.3×10^{-5}	-50% to + 100%	pA/μ emitter perimeter

Parameter	Typical	Tolerance ^b	Units
Doping			
n ⁺ emitter	10 ⁴	± 30%	10 ¹⁶ /cm ³
p-base			
Surface	10 ⁵	± 20%	10 ¹⁶ /cm ³
Junction	1	± 20%	10 ¹⁶ /cm ³
Epitaxial layer	0.3	± 20%	10 ¹⁶ /cm ³
Substrate	0.08	± 25%	10 ¹⁶ /cm ³
Physical feature size			
Diffusion depth			
n ⁺ emitter diffusion	1.3	± 5%	μ
p-base diffusion	2.6	± 5%	μ
p-resistive diffusion	0.3	± 5%	μ
n-epitaxial layer	10.4	± 5%	μ
n ⁺ buried collector diffusion			
Into epitaxial	3.9	± 5%	μ
Into substrate	7.8	± 5%	μ
Oxide thickness			
Metal to epitaxial	1.4	± 30%	μ
Metal to p-base	0.65	± 30%	μ
Metal to n ⁺ emitter	0.4	± 30%	μ

Capacitances

Metal to epitaxial	0.022	$\pm 30\%$	fF/ μ^2
Metal to p-base diffusion	0.045	$\pm 30\%$	fF/ μ^2
Metal to n ⁺ emitter diffusion	0.078	$\pm 30\%$	fF/ μ^2
n ⁺ buried collector to substrate (junction, bottom)	0.062	$\pm 30\%$	fF/ μ^2
Epitaxial to substrate (junction, bottom)	0.062	$\pm 30\%$	fF/ μ^2
Epitaxial to substrate (junction, sidewall)	1.6	$\pm 30\%$	fF/ μ perimeter
Epitaxial to p-base diffusion (junction, bottom)	0.14	$\pm 30\%$	fF/ μ^2
Epitaxial to p-base diffusion (junction, sidewall)	7.9	$\pm 30\%$	fF/ μ perimeter
p-base diffusion to n ⁺ emitter diffusion (junction, bottom)	0.78	$\pm 30\%$	fF/ μ^2
p-base diffusion to n ⁺ emitter diffusion (junction, sidewall)	3.1	$\pm 30\%$	fF/ μ perimeter

Parameter	Typical	Tolerance ^b	Units
Resistance and resistivity			
Substrate resistivity	16	±25%	Ω · cm
n ⁺ buried collector diffusion	17	±35%	Ω / □
Epitaxial layer	1.6	±20%	Ω · cm
p-base diffusion	160	±20%	Ω / □
p-resistive diffusion (optional)	1500	±40%	Ω / □
n ⁺ emitter diffusion	4.5	±30%	Ω / □
Metal	0.003		Ω / □
Contacts (3μ × 3μ)	<4		Ω
Metal-n ⁺ emitter (contact plus series resistance to BE junction)	<1		Ω
Metal-p-base ^c (contact plus series resistance)	70		Ω
Metal-Epitaxial ^d (contact plus series resistance to BC junction)	120		Ω
Breakdown voltages, leakage currents, migration currents, and operating conditions			
Reverse breakdown voltages			
n ⁺ emitter to p-base	6.9	±50 mV	V
p-base to epitaxial	70	±10	V
Epitaxial to substrate	>80		V
Maximum operating voltage	40		V
Substrate leakage current	0.16		fA/μ ²
Maximum metal current density	0.8		mA/μ width
Maximum device operating temperature (design)	125		°C
Maximum device operating temperature (physical)	225		°C

SPICE model parameters of typical bipolar process

Parameter ^{a,b,c}	Vertical npn	Lateral pnp	Units
IS ^c	0.1	0.78	fA
BF	80	225	
NF	1	1	
VAF	100	150	V
IKF	100	0.1	mA
ISE	0.11	0.15	fA
NE	1.44	1.28	
BR	1.5		
NR	1	1	
VAR ^b	19	38	V
ISC		1.5	fA
NC	1.44	1.28	
RB	70	250	Ω
RE	1	4	Ω
RC	120	130	Ω
CJE	0.62	0.48	pF
VTE	0.69	0.65	V
MJE	0.33	0.40	
TF	0.45	40	ns
CJC	1.9	0.48	pF
VJC	0.65	0.65	V
MJC	0.4	0.4	
XCJC	0.5	0	
TR	22.5	2000	ns
CJS ^d	1.30	0	pF
VJS	0.49	0	pF
MJS	0.38	0	

Recall:

Simplified Multi-Region Model

“Forward” Regions : $\beta = \beta_F$

$$I_C = J_S A_E e^{\frac{V_{BE}}{V_t}} \left(1 + \frac{V_{CE}}{V_{AF}} \right)$$

$$I_B = \frac{J_S A_E}{\beta} e^{\frac{V_{BE}}{V_t}}$$

Conditions

$$V_{BE} > 0.4V \quad V_{BC} < 0$$

Forward Active

$$V_{BE} = 0.7V$$
$$V_{CE} = 0.2V$$

$$I_C < \beta I_B$$

Saturation

$$I_C = I_B = 0$$

$$V_{BE} < 0 \quad V_{BC} < 0$$

Cutoff

Process Parameters: $\{J_S, \beta, V_{AF}\}$

$$V_t = \frac{kT}{q}$$

Design Parameters: $\{A_E\}$

- Process parameters highly process dependent
- J_S highly temperature dependent as well, β modestly temperature dependent
- This model is dependent only upon emitter area, independent of base and collector area !
- Currents scale linearly with A_E and not dependent upon shape of emitter
- A small portion of the operating region is missed with this model but seldom operate in the missing region

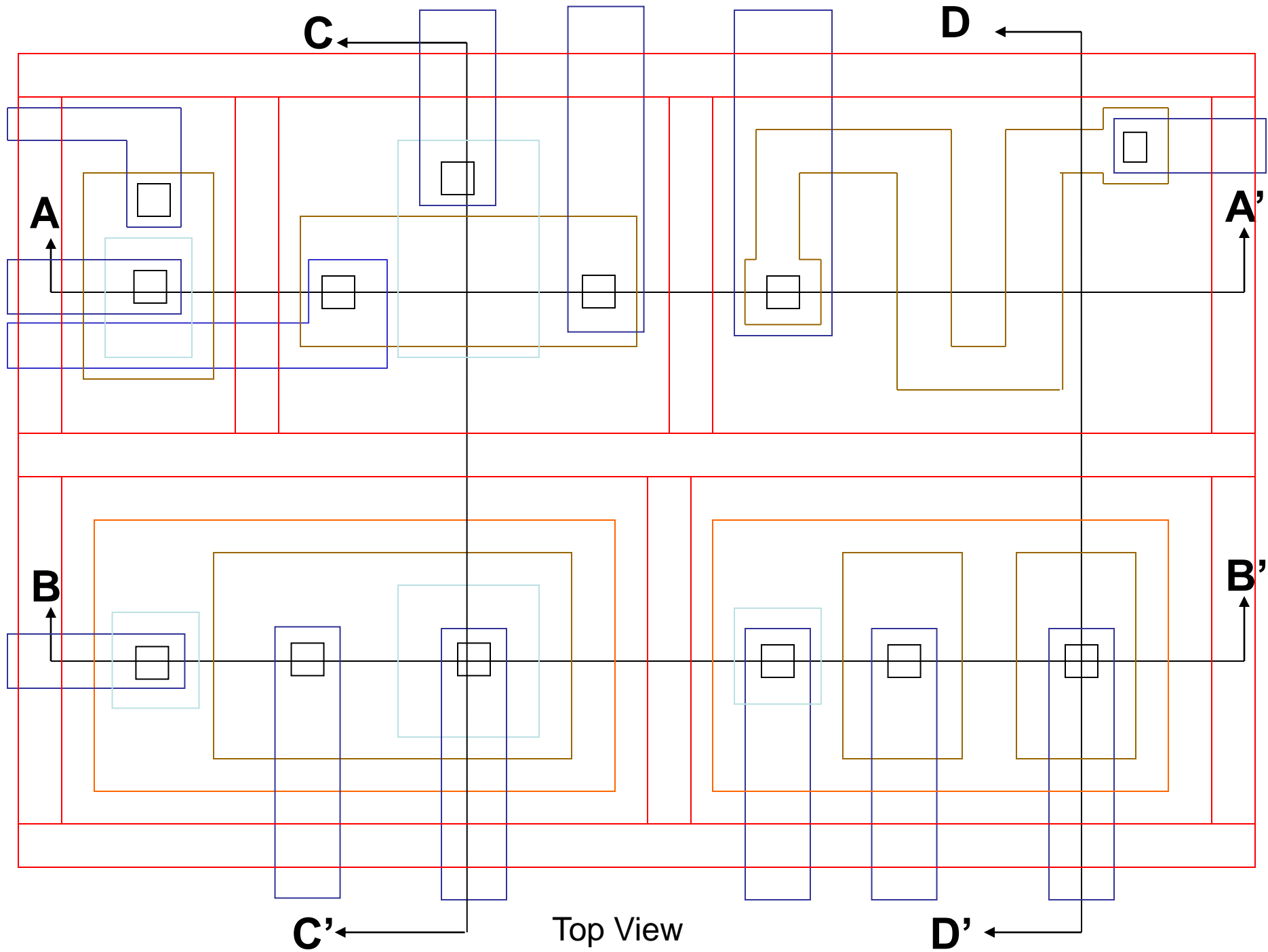
^aParameters are defined in Chapters 3 and 4.

^bSome of these Gummel-Poon parameters differ considerably from those given in Table 2C.4. They have been obtained from curve fitting and should give good results with computer simulations. The parameters of Table 2C.4 should be used for hand analysis.








^cParameters that are strongly area-dependent are based upon an npn emitter area of $390 \mu^2$ and perimeter of 80μ , a base area of $2200 \mu^2$ and perimeter of 200μ , and a collector area of $10,500 \mu^2$ and perimeter of 425μ . The lateral pnp has rectangular collectors and emitters spaced 10μ apart with areas of $230 \mu^2$ and perimeters of 60μ . The base area of the pnp is $7400 \mu^2$ and the base perimeter is 345μ .

^dCJS is set to zero for the lateral transistor because it is essentially nonexistent. The parasitic capacitance from base to substrate, which totals 1.0 pF for this device, must be added externally to the BJT.

- In contrast to the MOSFET where process parameters are independent of geometry, the bipolar transistor model is for a specific transistor !
- Area emitter factor is used to model other devices
- Often multiple specific device models are given and these devices are used directly
- Often designer can not arbitrarily set A_E but rather must use parallel combinations of specific devices and layouts

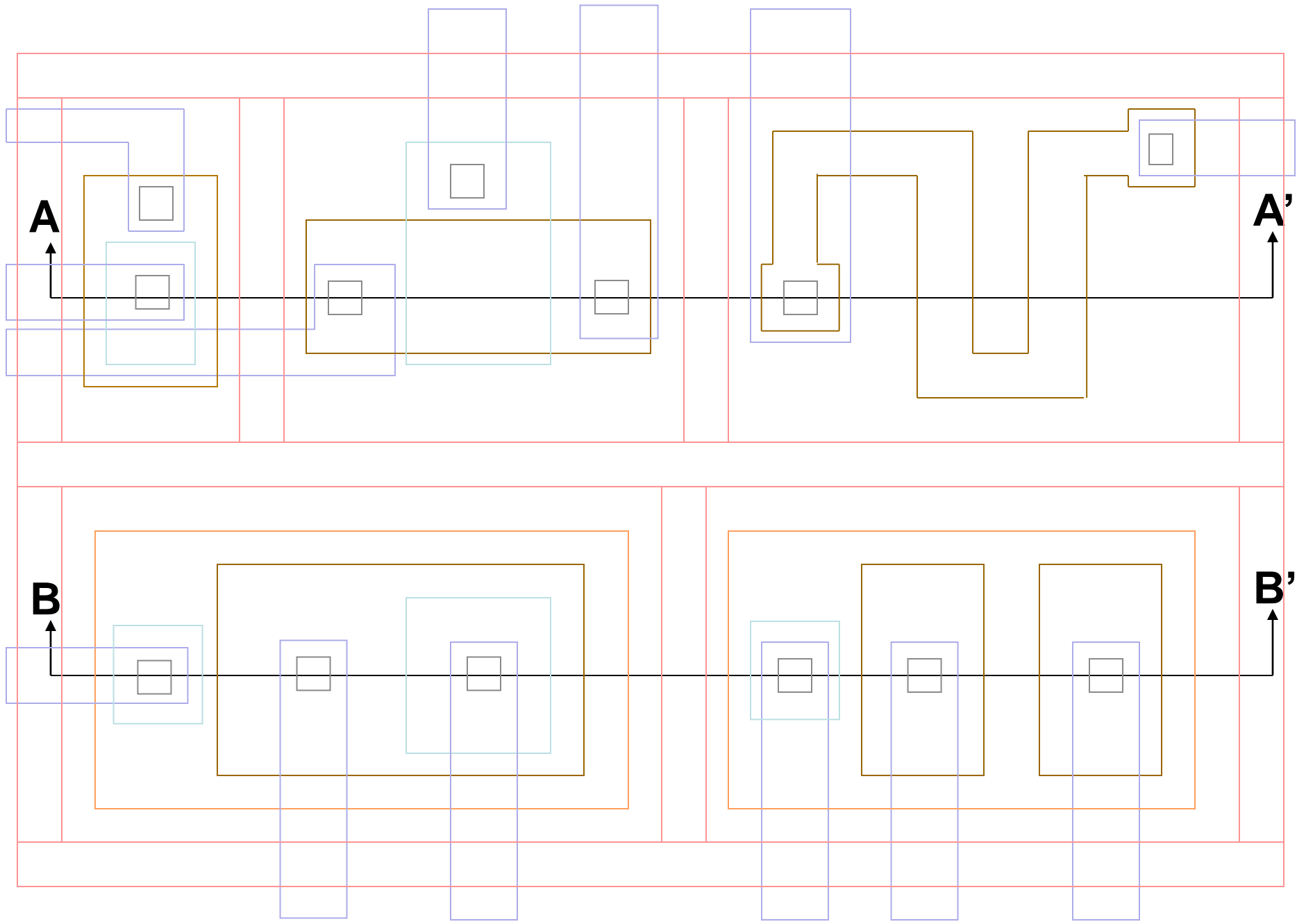


Layer Mappings

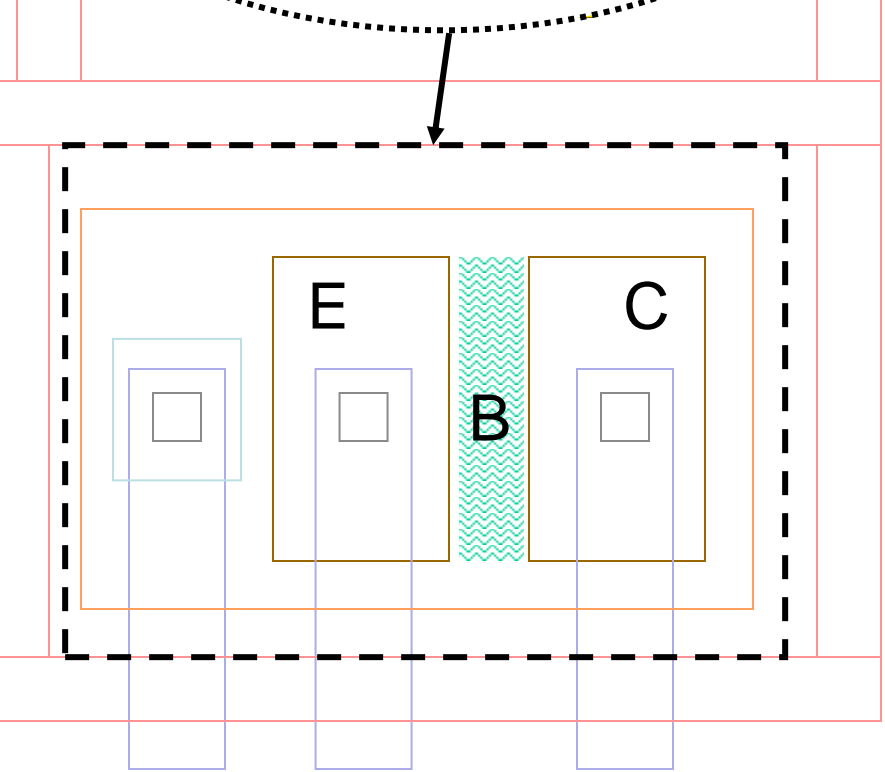
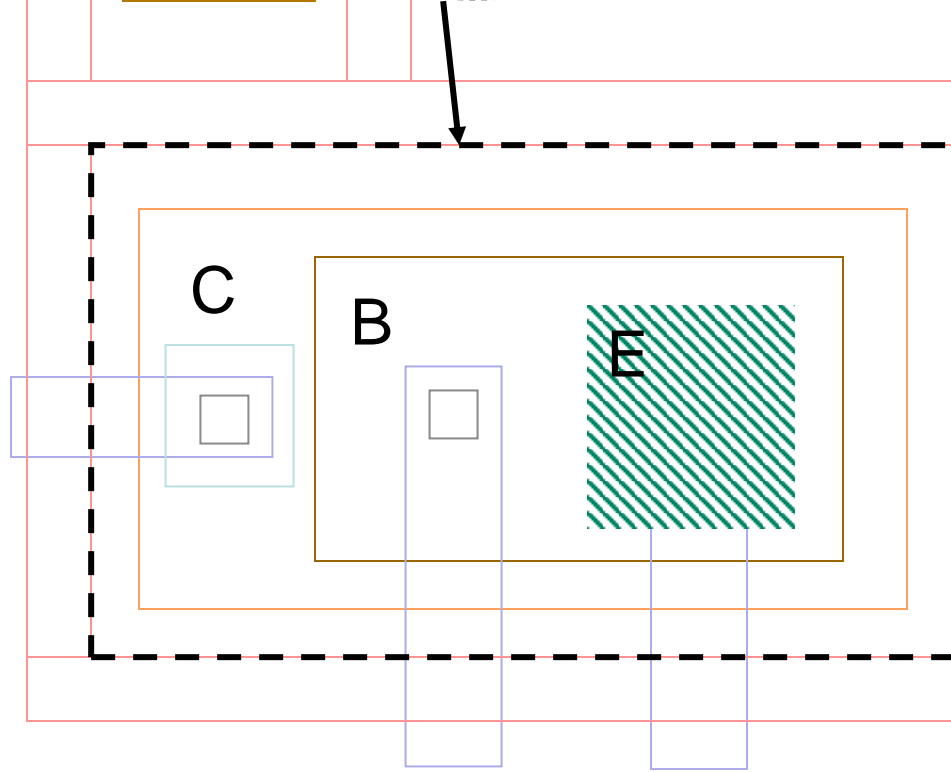
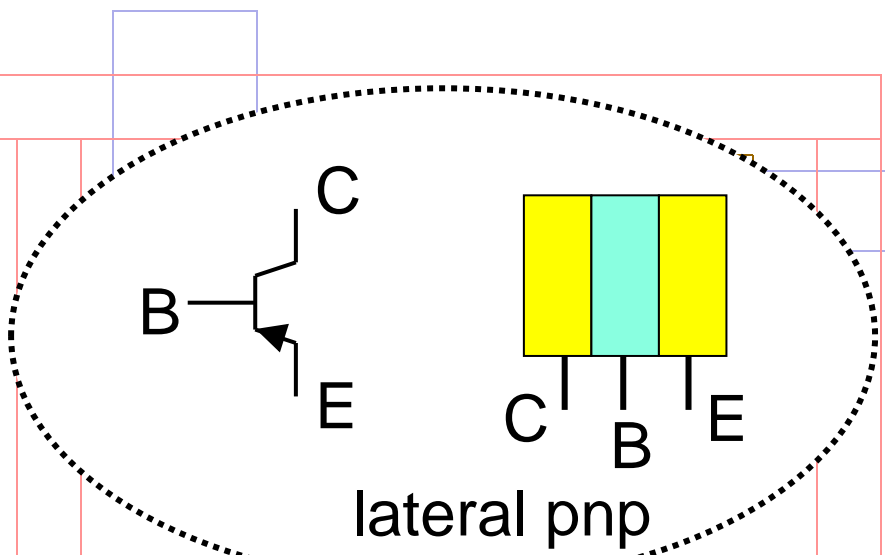
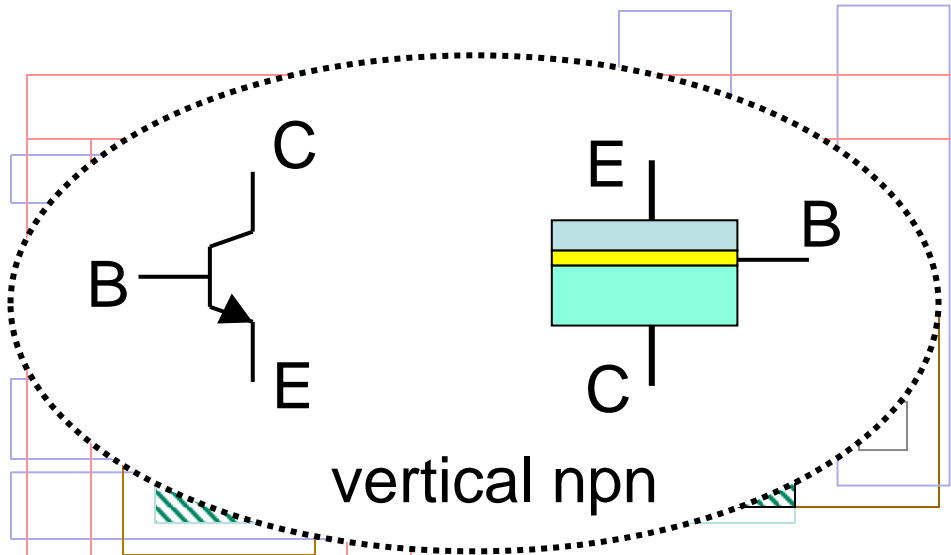
	n ⁺ buried collector
	isolation diffusion (p ⁺)
	p-base diffusion
	n ⁺ emitter
	contact
	metal
	passivation opening

Notes:

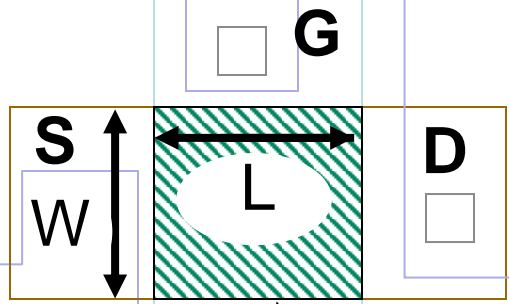
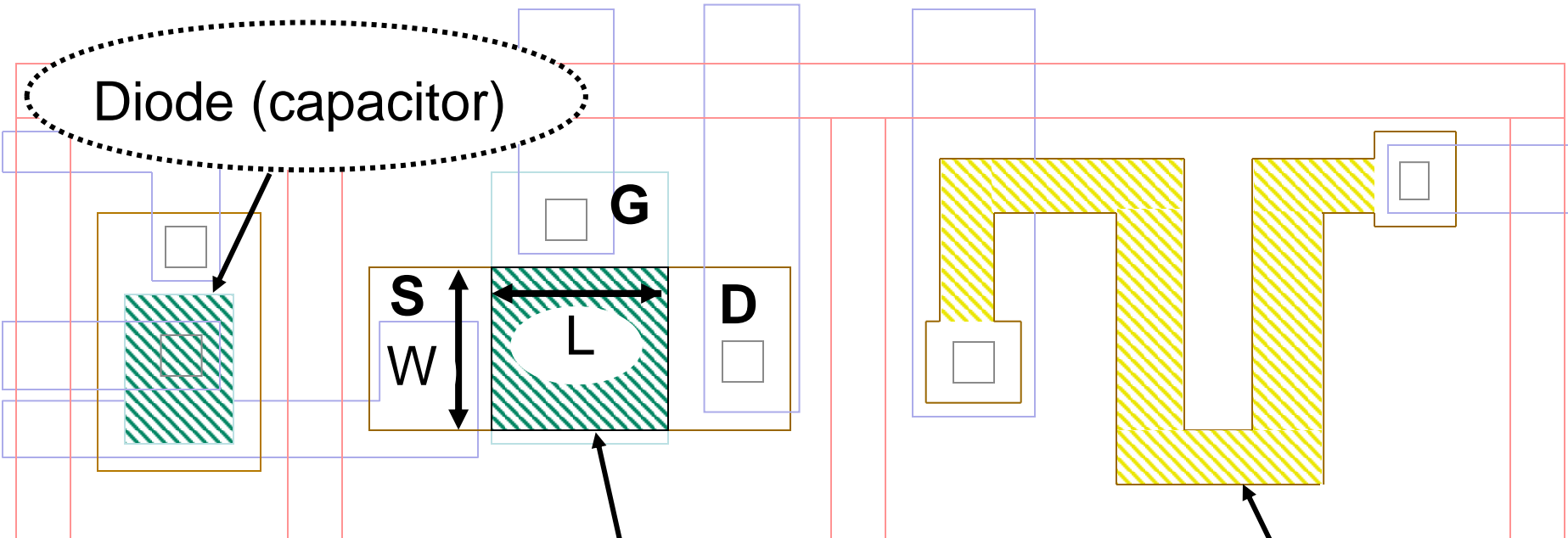
- passivation opening for contacts not shown
- isolation diffusion intentionally not shown to scale



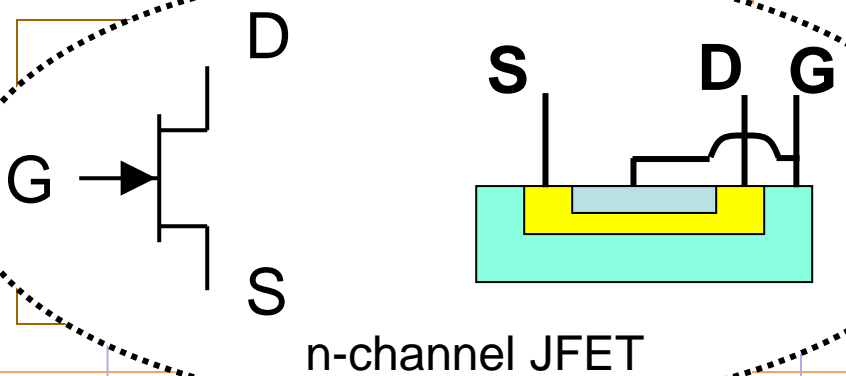
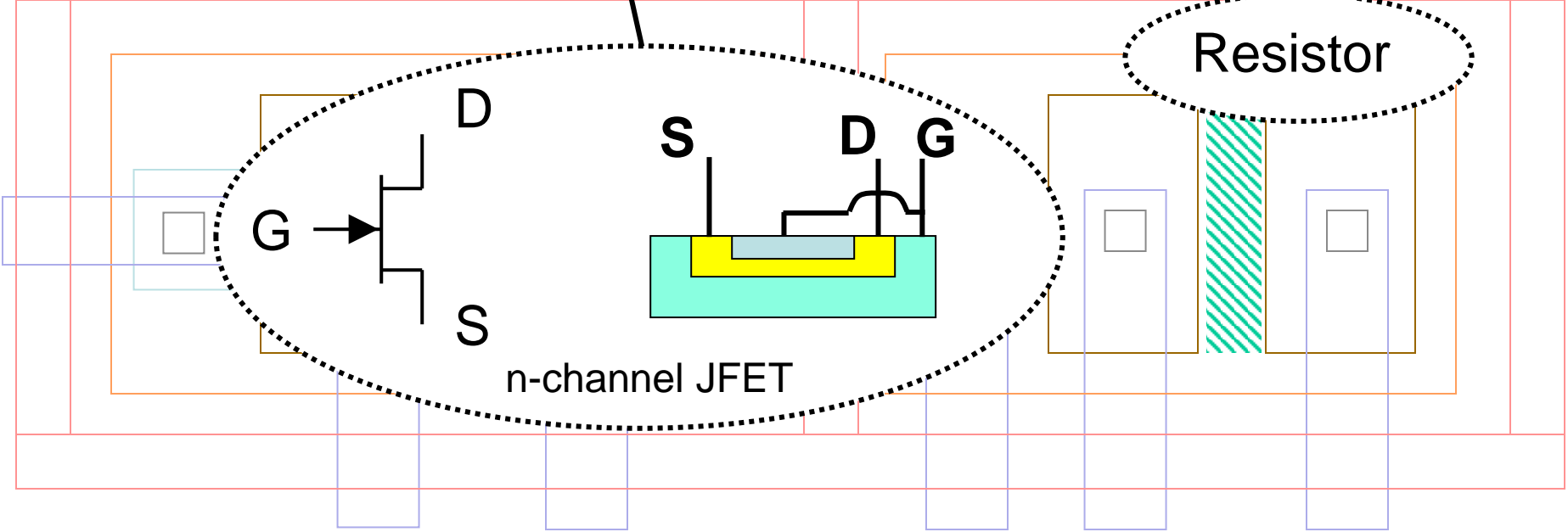
Dimmed features with A-A' and B-B' cross sections



Diode (capacitor)



Resistor










Detailed Description of First Photolithographic Steps Only

- Top View
- Cross-Section View

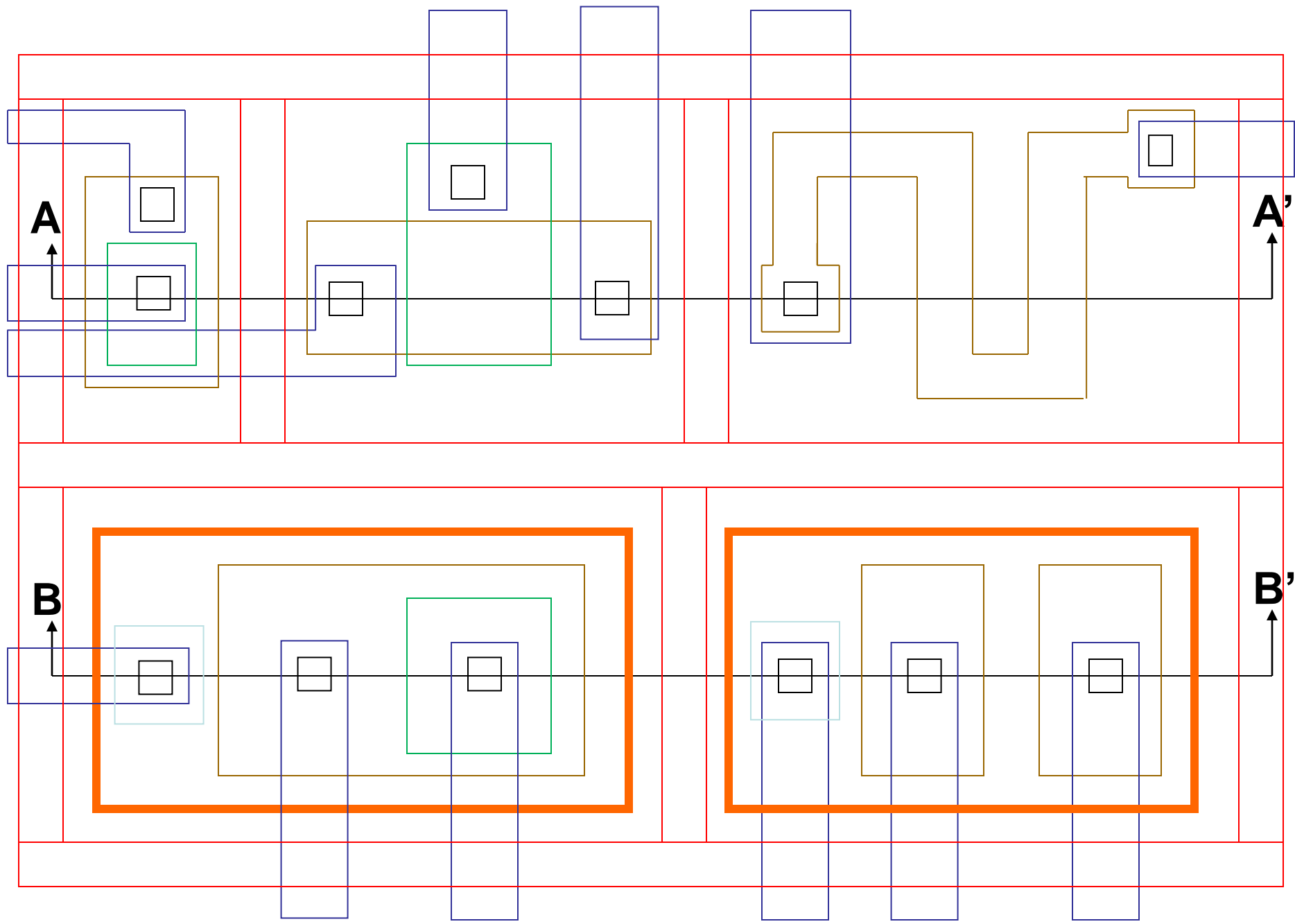
Mask Numbering and Mappings



Mask 1		n ⁺ buried collector
Mask 2		isolation diffusion (p ⁺)
Mask 3		p-base diffusion
Mask 4		n ⁺ emitter
Mask 5		contact
Mask 6		metal
Mask 7		passivation opening

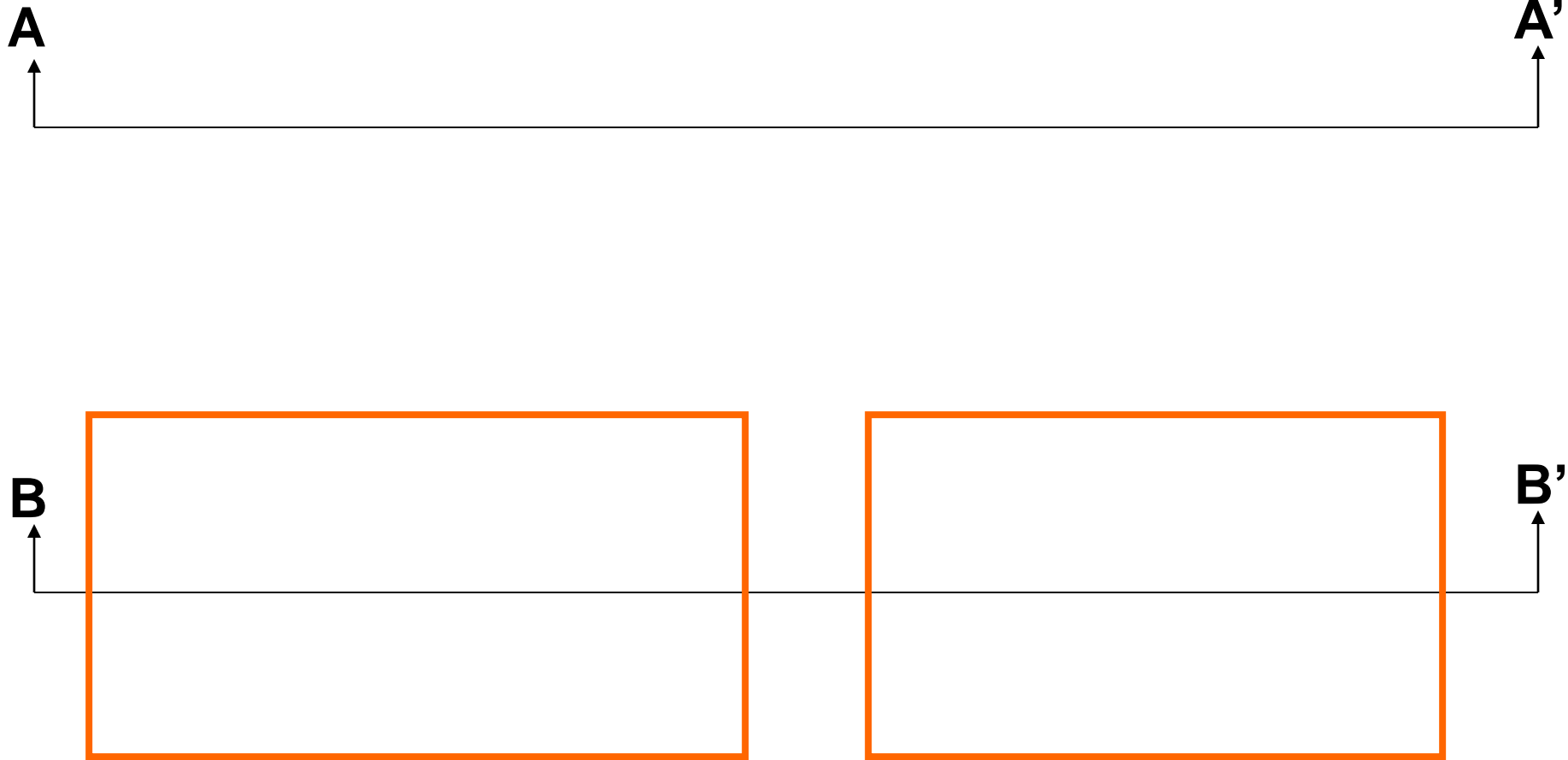
Notes:

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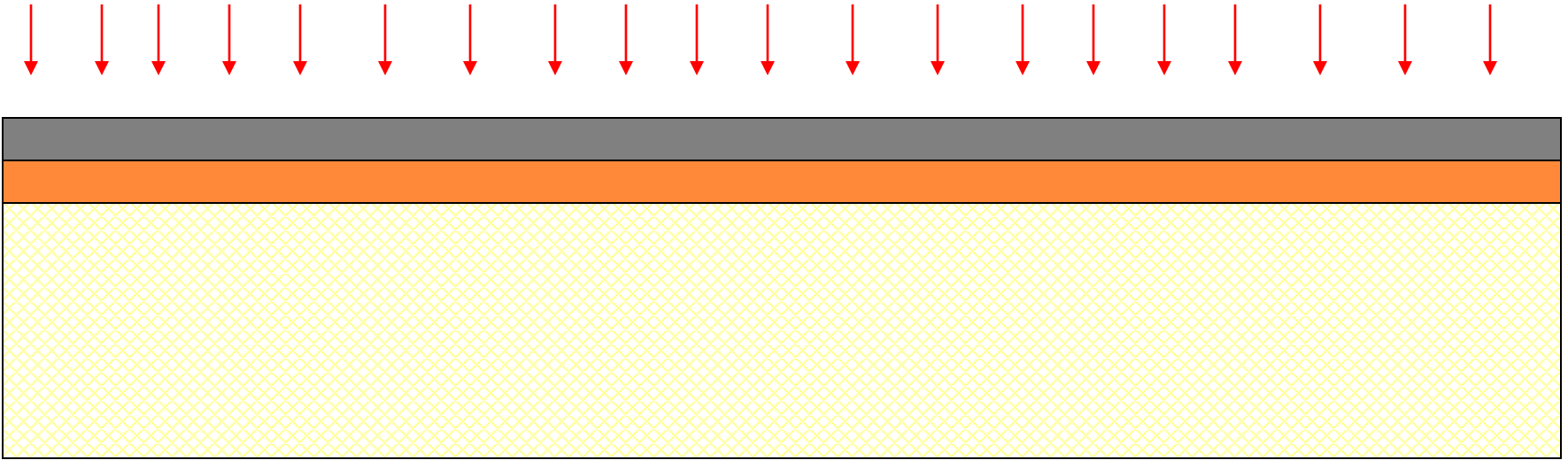


n^+ buried collector

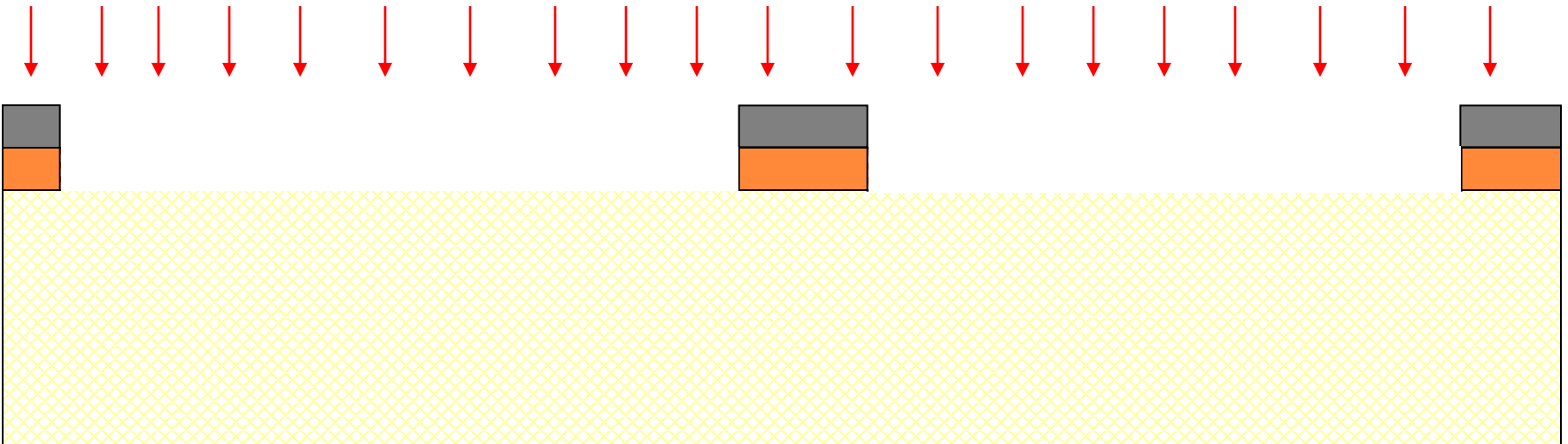
Mask 1: n^+ buried collector



Develop

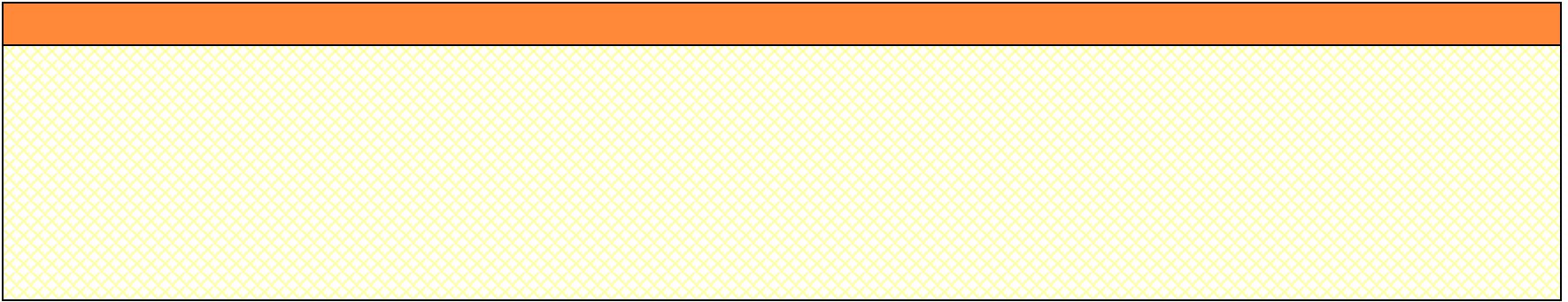


A-A' Section

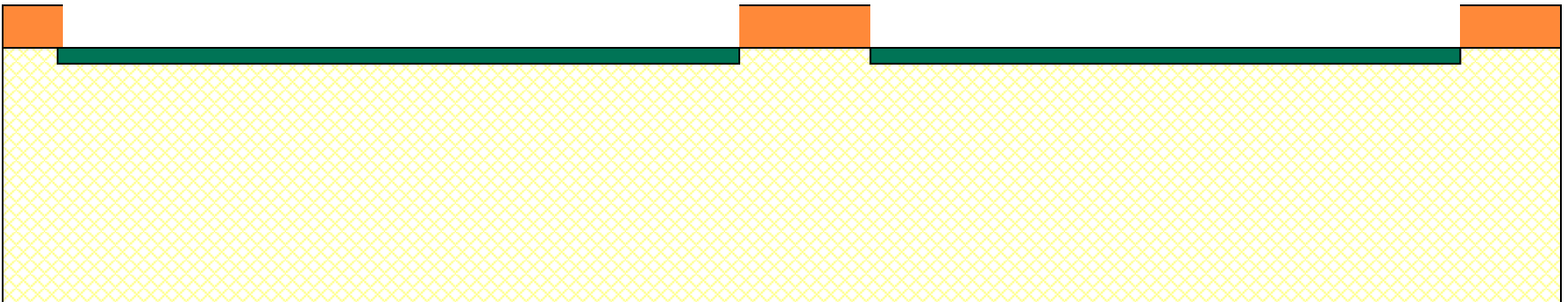


B-B' Section

Implant

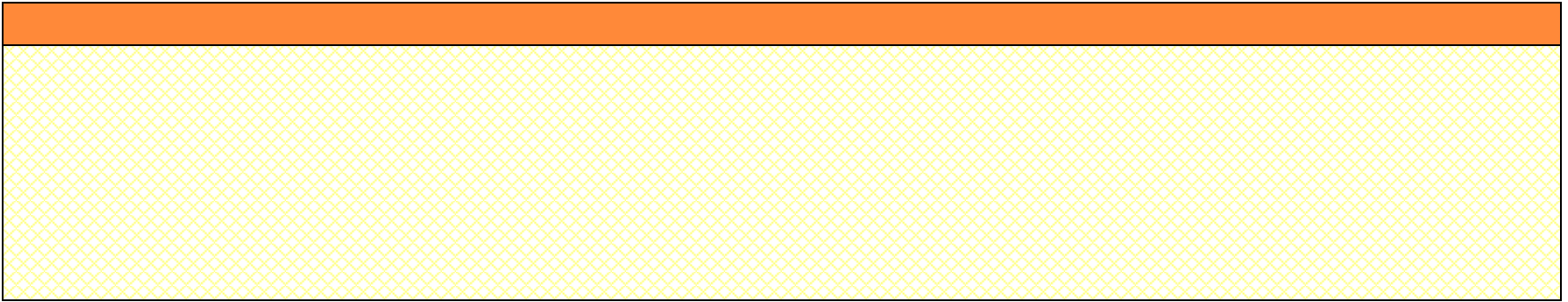


A-A' Section

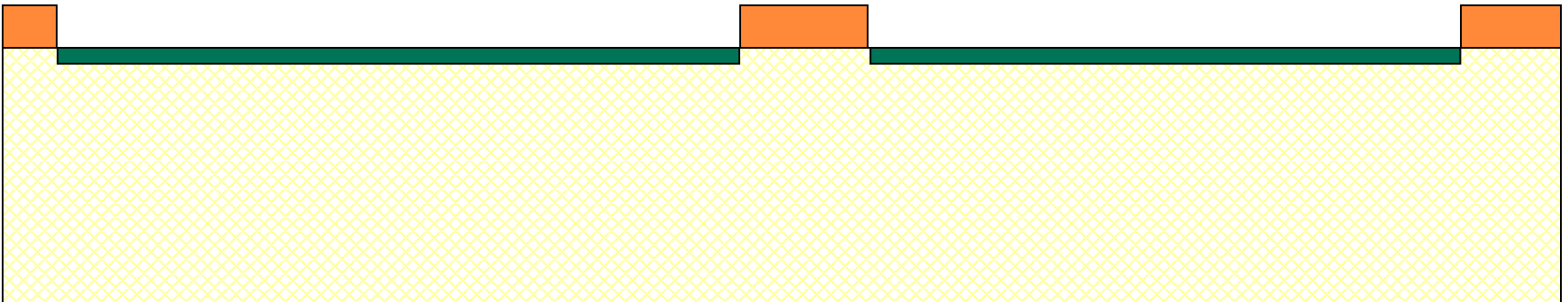


B-B' Section

Strip Photoresist



A-A' Section



B-B' Section

A



p-substrate

A'



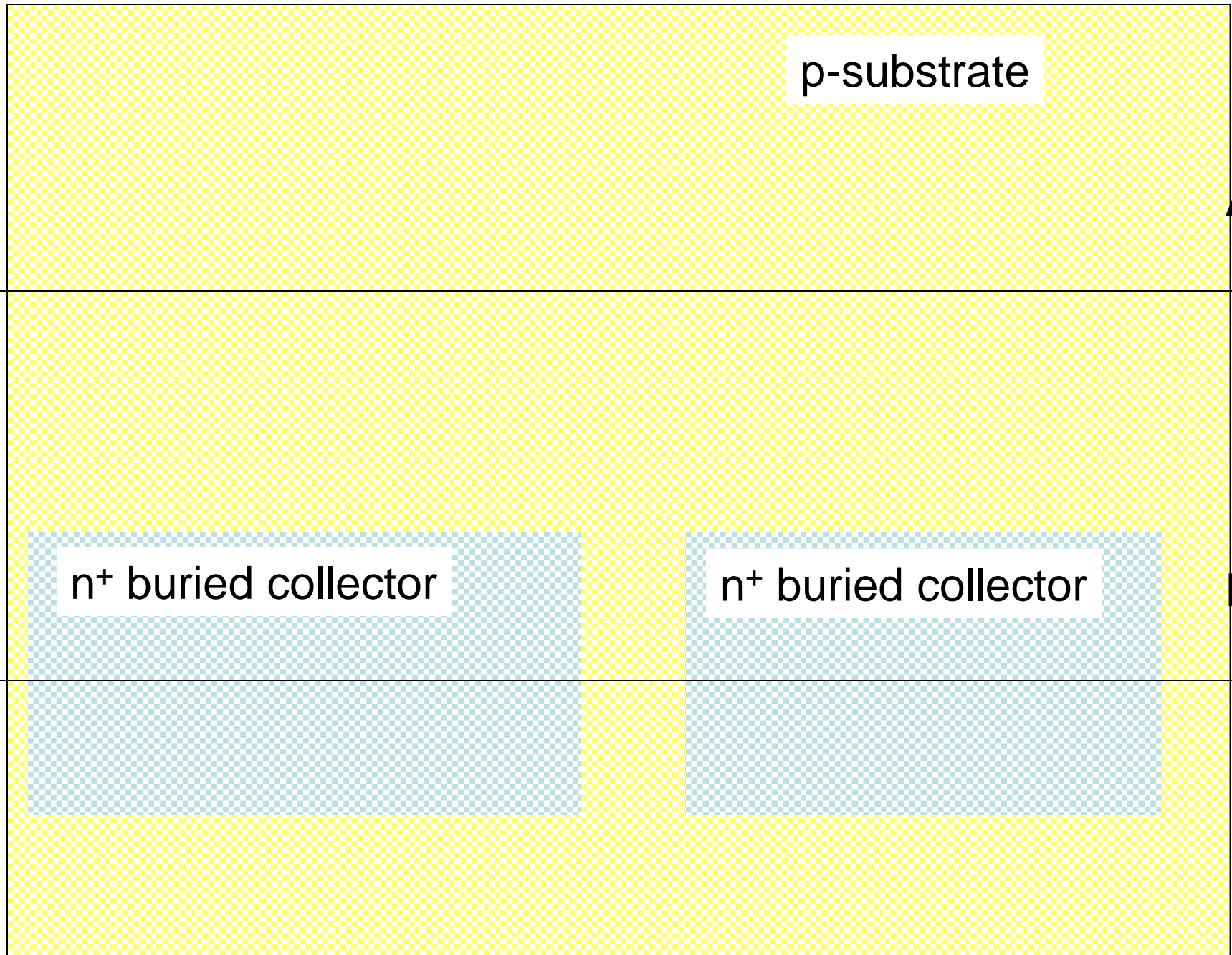
B



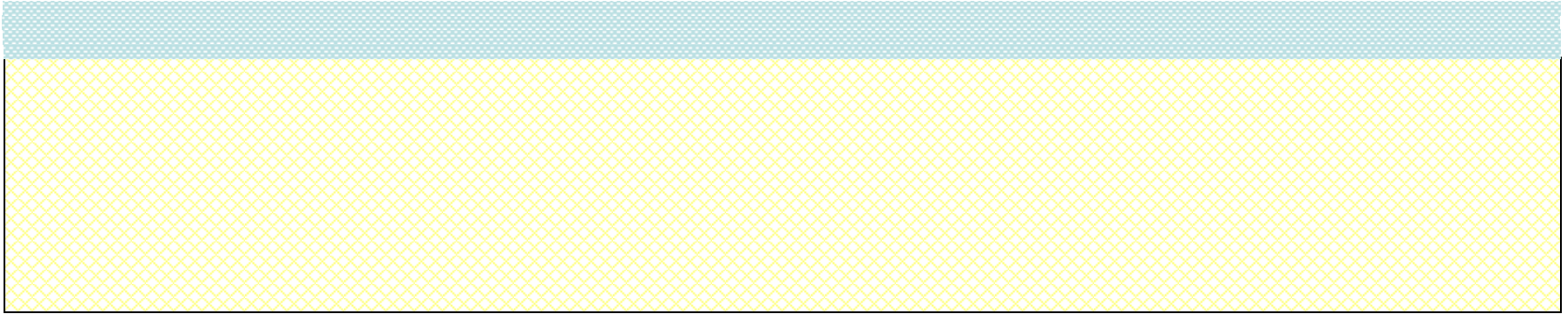
n⁺ buried collector

n⁺ buried collector

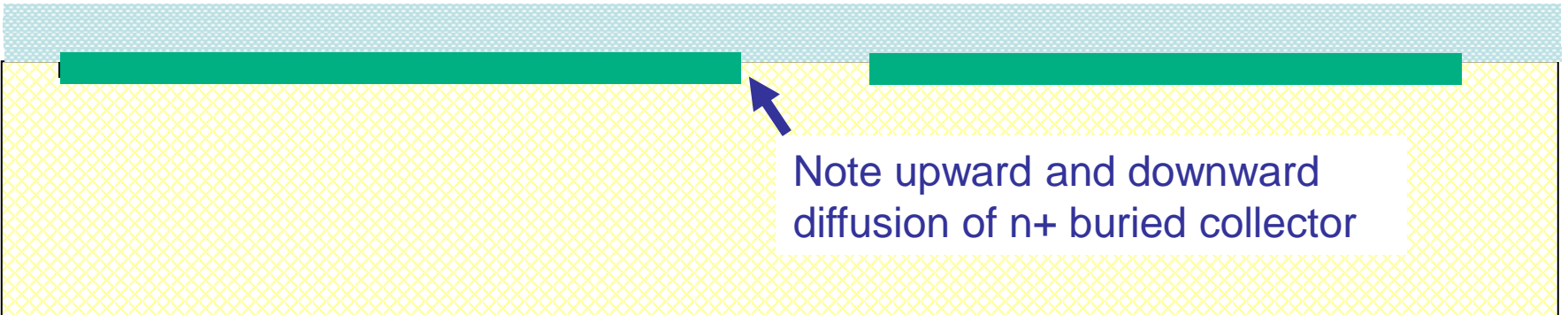
B'



Grow Epitaxial Layer



A-A' Section



B-B' Section

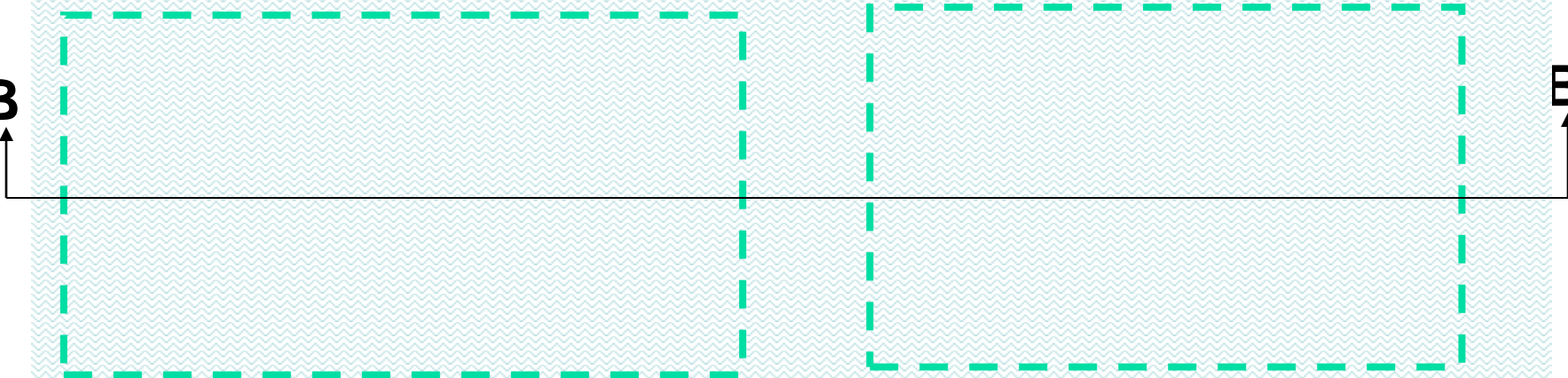
Grow Epitaxial Layer

A









A'

B

B'

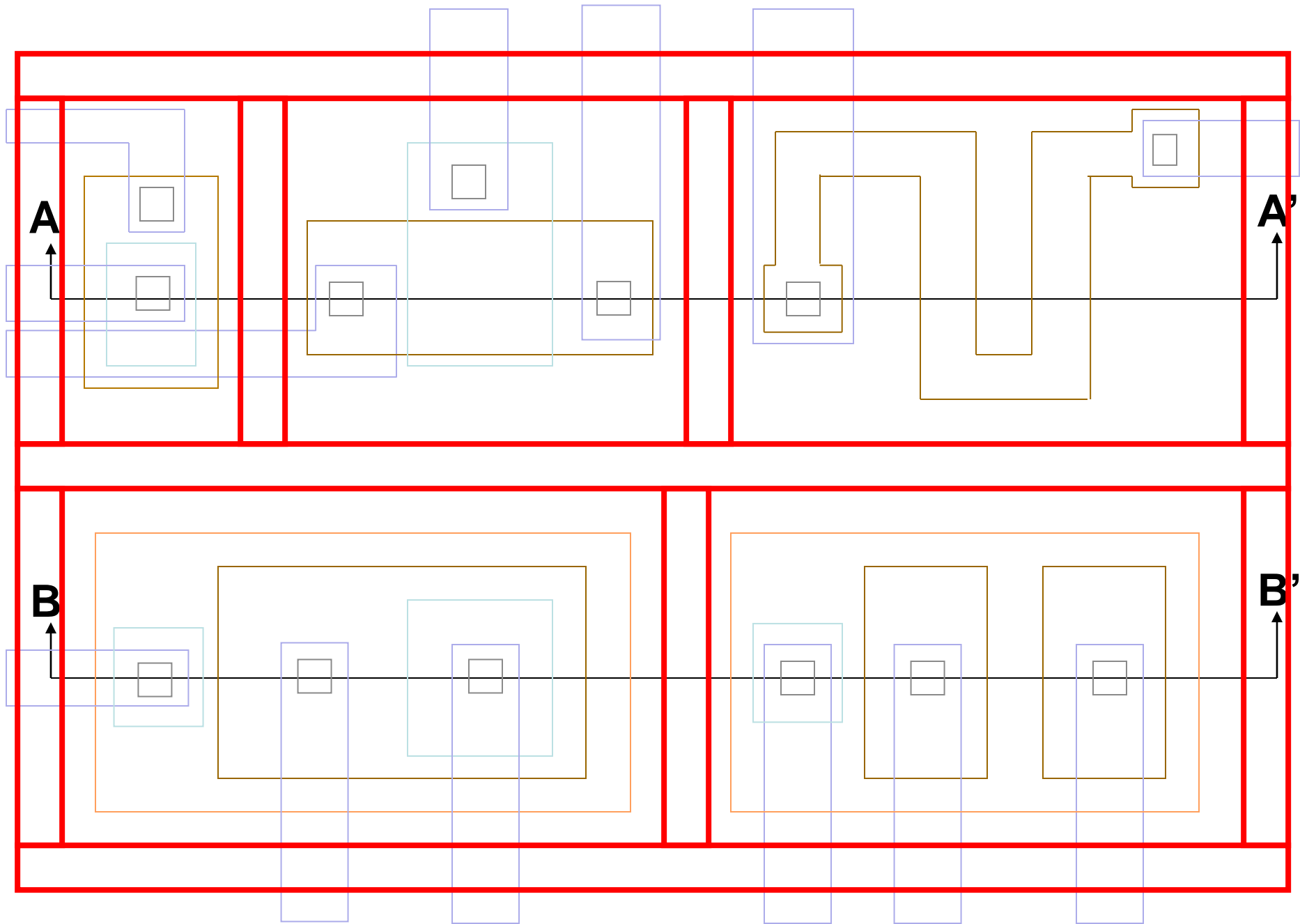


Mask Numbering and Mappings

	Mask 1		n ⁺ buried collector
	Mask 2		isolation diffusion (p ⁺)
	Mask 3		p-base diffusion
	Mask 4		n ⁺ emitter
	Mask 5		contact
	Mask 6		metal
	Mask 7		passivation opening

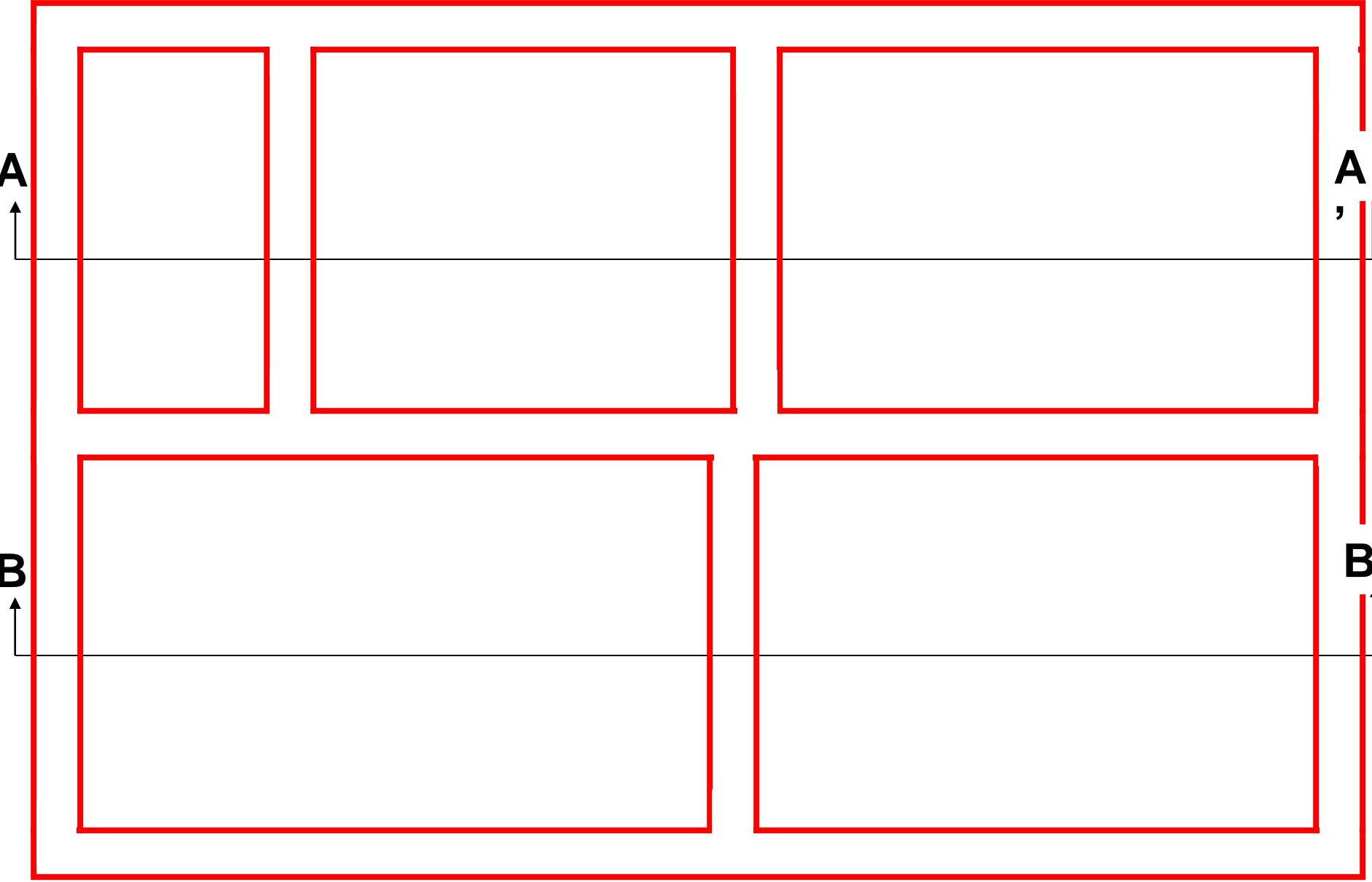
Notes:

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- isolation diffusion intentionally not shown to scale



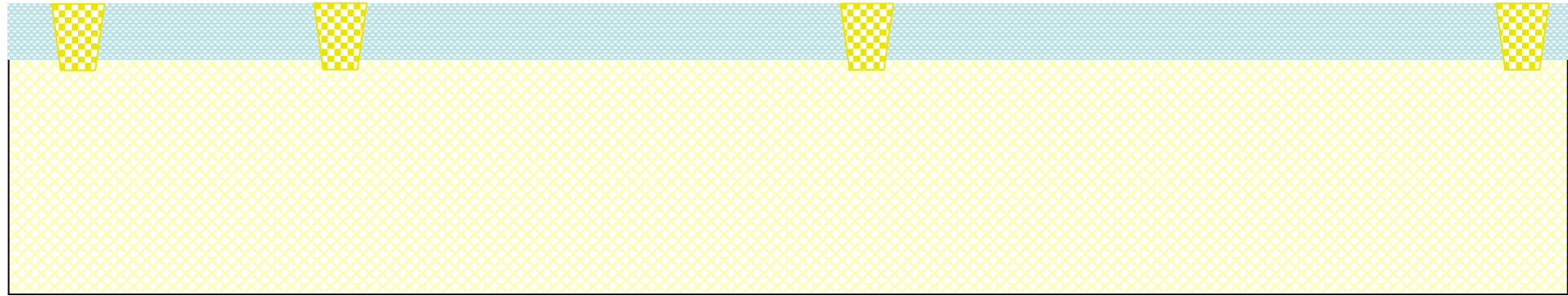
Isolation Diffusion

Mask 2: Isolation Deposition/Diffusion

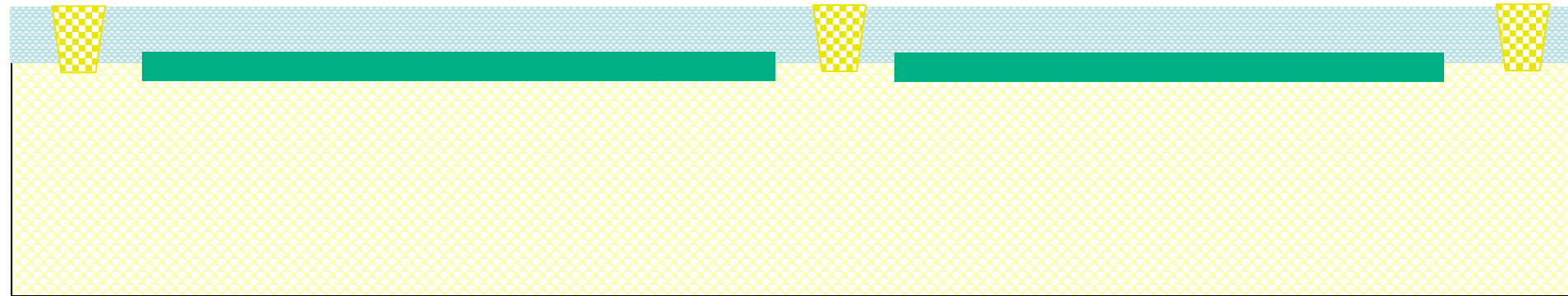


Isolation Deposition/Diffusion

- Photoresist present but not shown
- Deposition and diffusion combined in slides

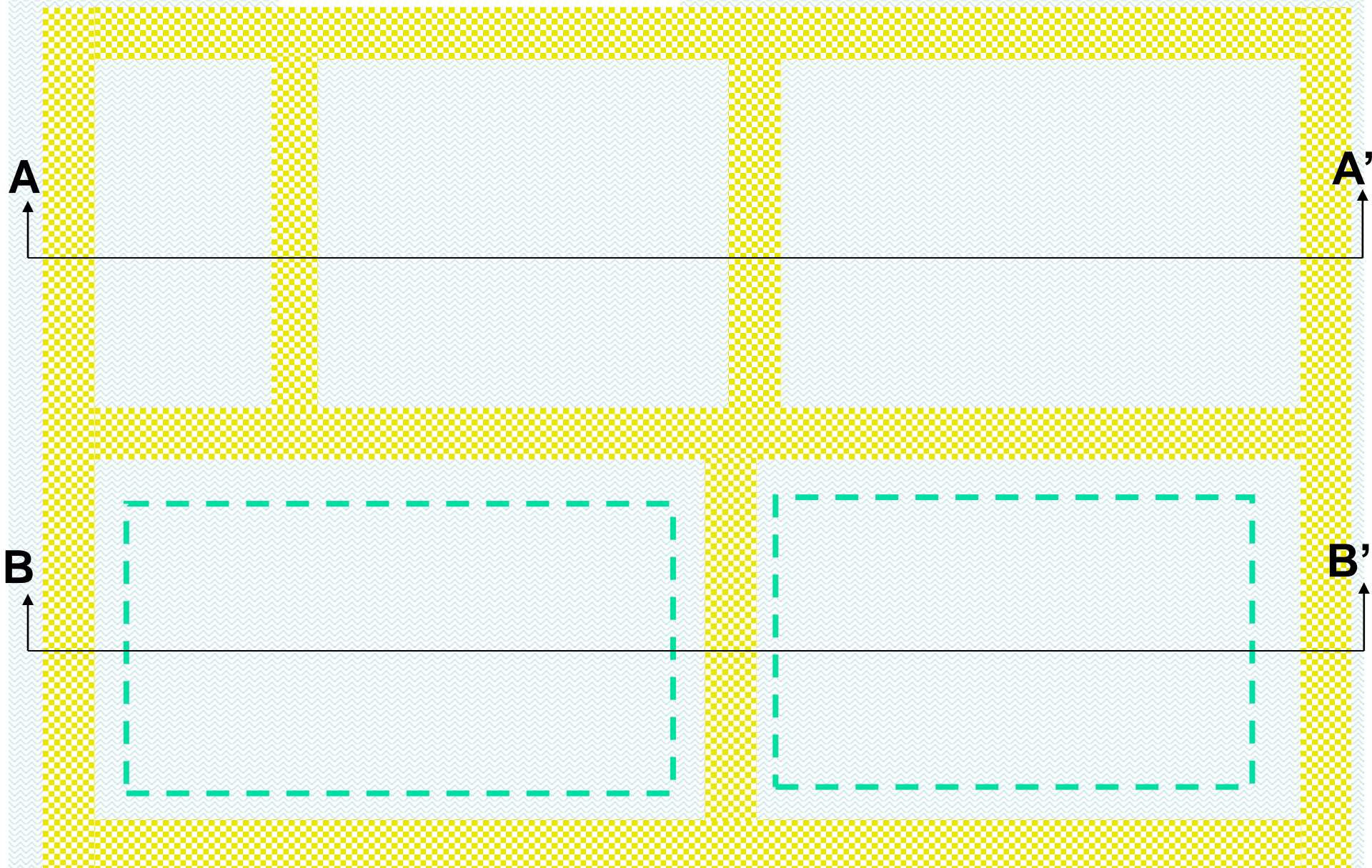


A-A' Section











B-B' Section

Isolation Diffusion



Have created 5 "islands" of n⁻ material on top of p⁻ substrate

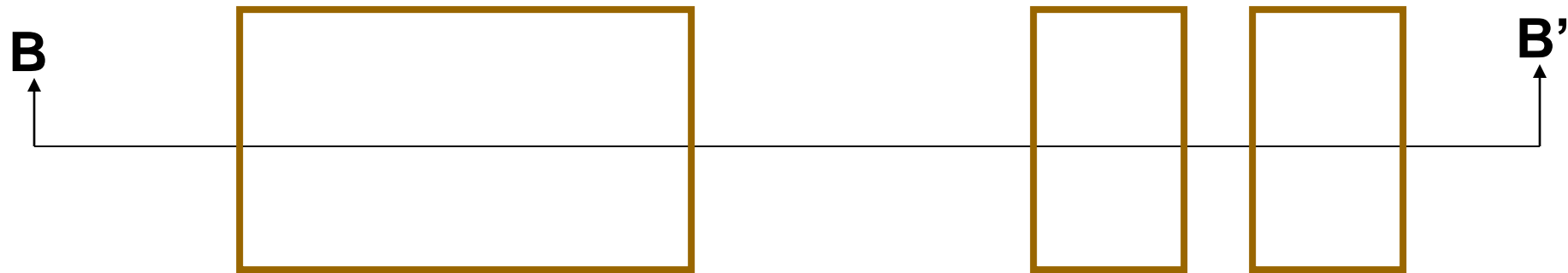
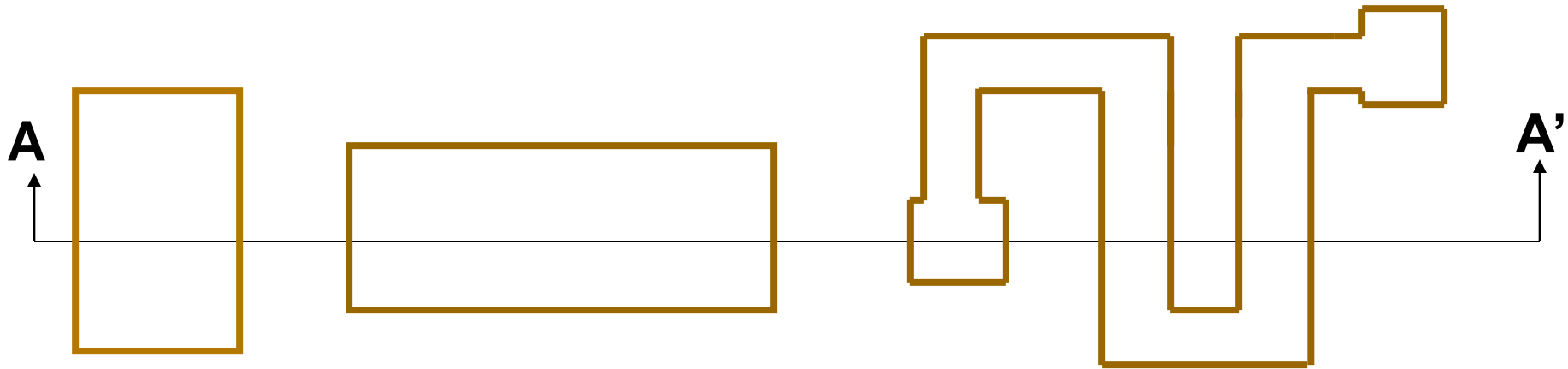
Mask Numbering and Mappings

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Mask 6		metal
Mask 7		passivation opening

Notes:

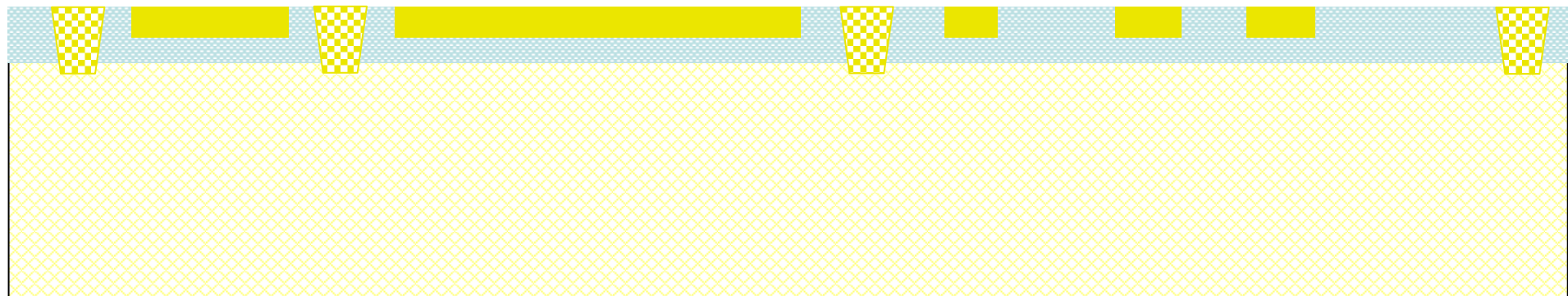
- passivation opening for contacts not shown
- isolation diffusion intentionally not shown to scale

Mask 3: p-base diffusion

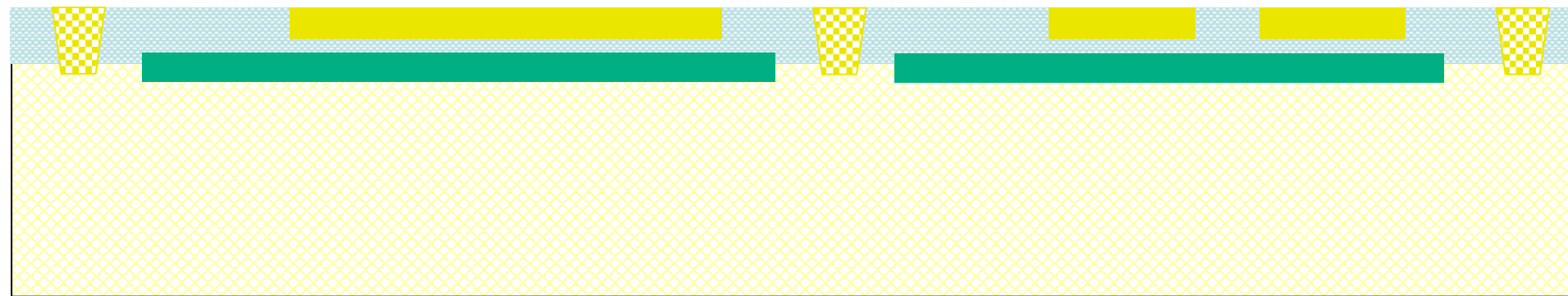


p-base Diffusion

- Photoresist present but not shown
- Deposition and diffusion combined in slides

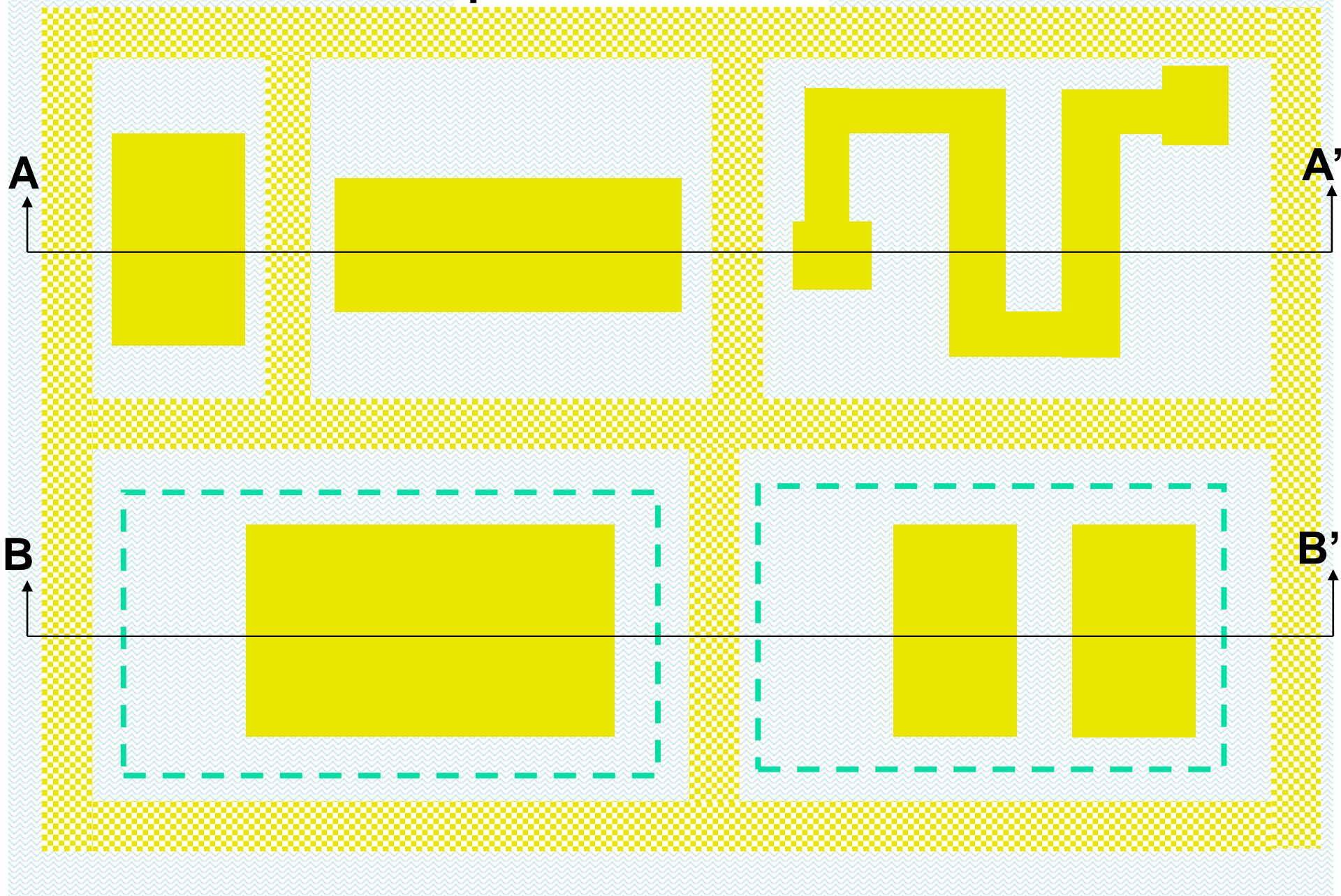


A-A' Section











B-B' Section

p-base Diffusion

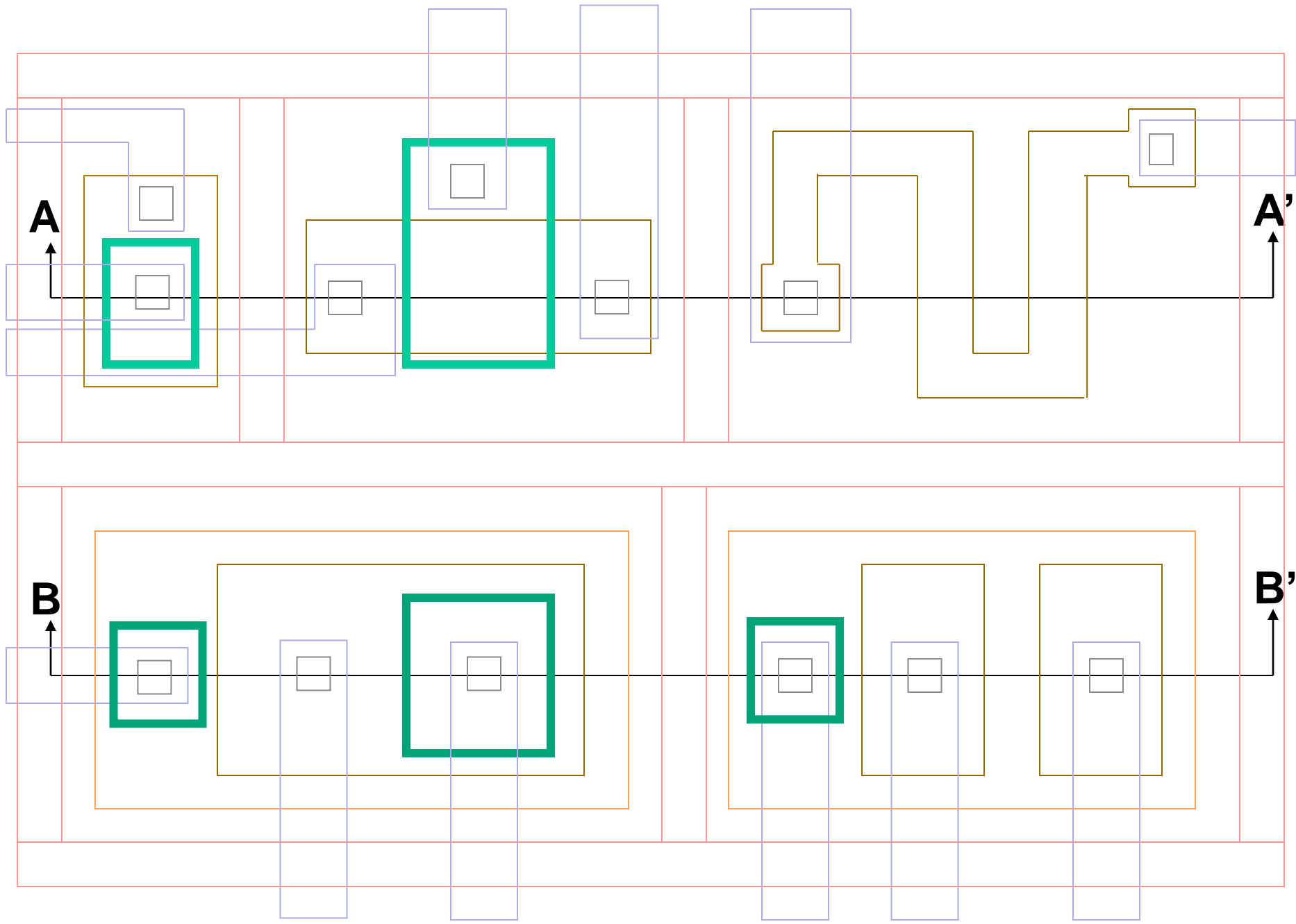


Mask Numbering and Mappings

Mask 1		n ⁺ buried collector
Mask 2		isolation diffusion (p ⁺)
Mask 3		p-base diffusion
 Mask 4		n ⁺ emitter
Mask 5		contact
Mask 6		metal
Mask 7		passivation opening

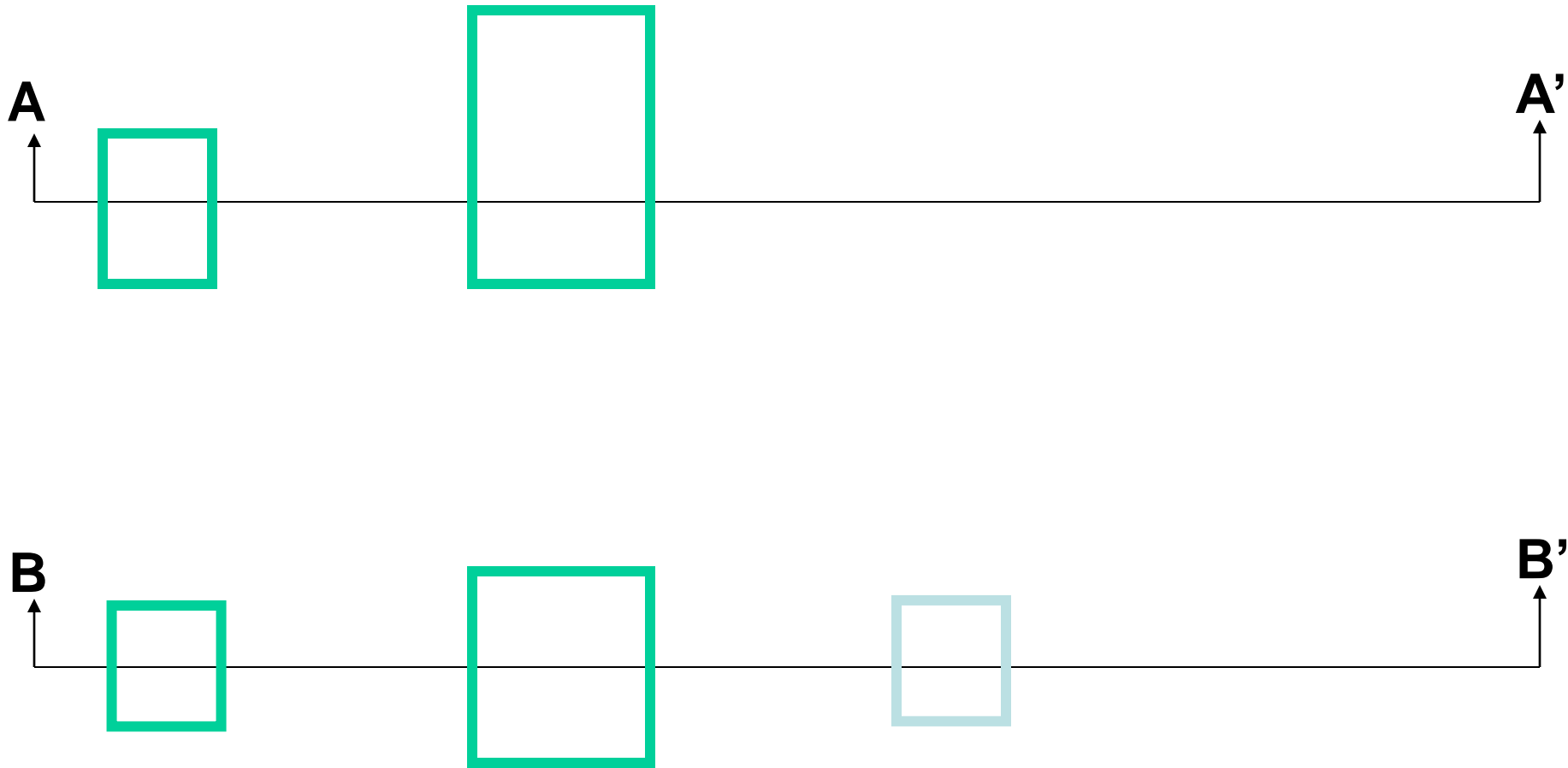
Notes:

- passivation opening for contacts not shown
- isolation diffusion intentionally not shown to scale



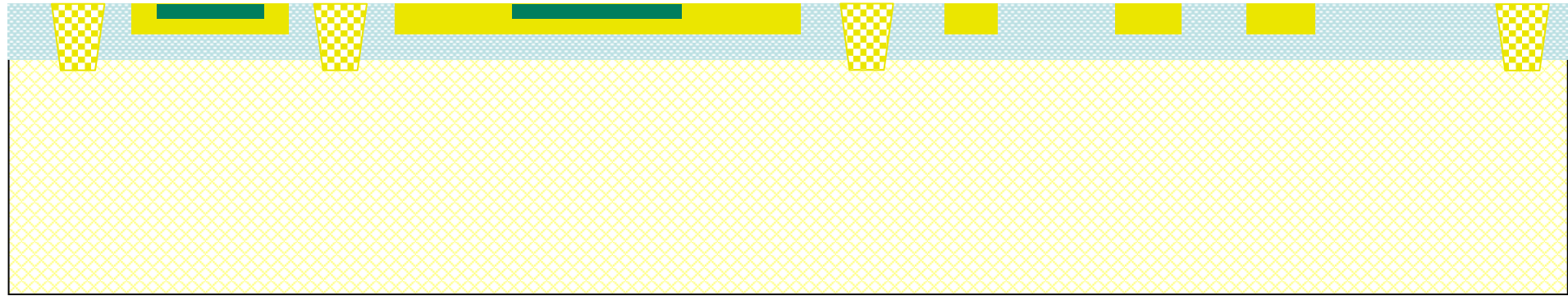
n^+ emitter diffusion

Mask 4: n⁺ emitter diffusion

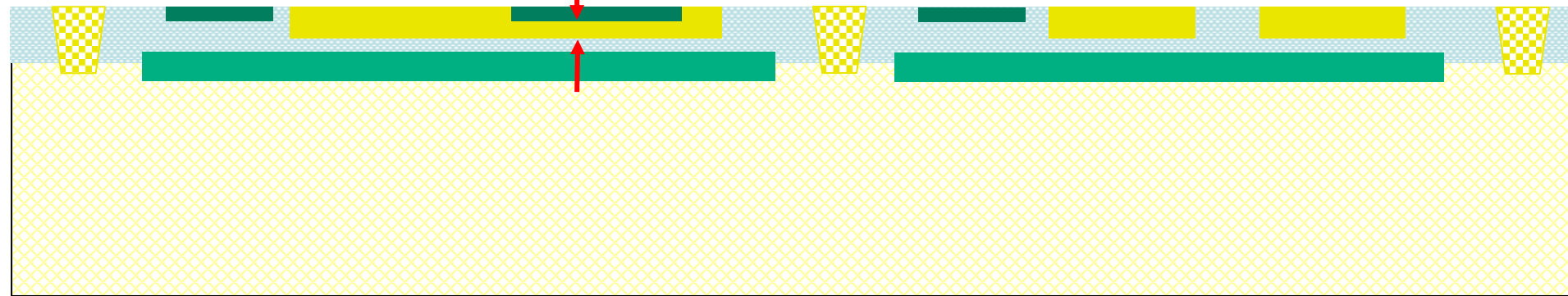


n⁺ emitter Diffusion

- Photoresist present but not shown
- Deposition and diffusion combined in slides



A-A' Section

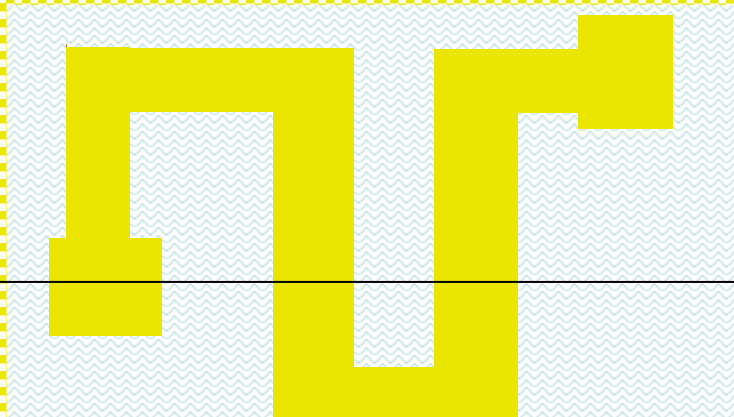
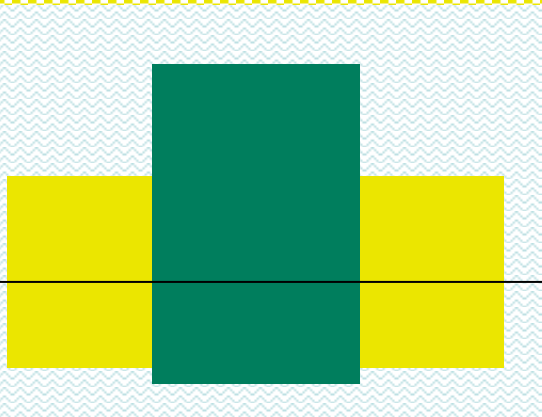
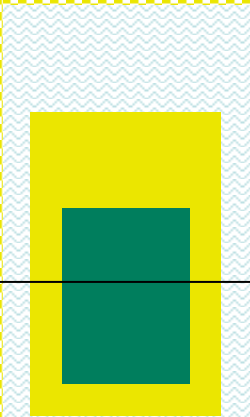


B-B' Section

Emitter diffusion typically leaves only thin base area underneath

n^+ emitter Diffusion

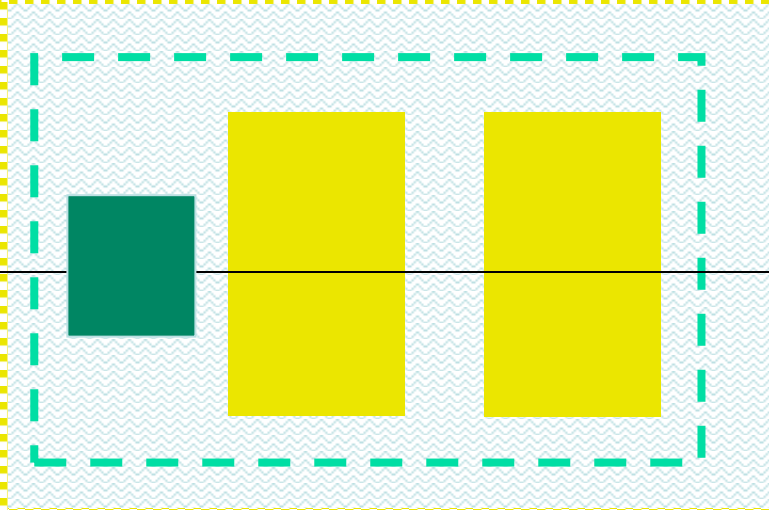
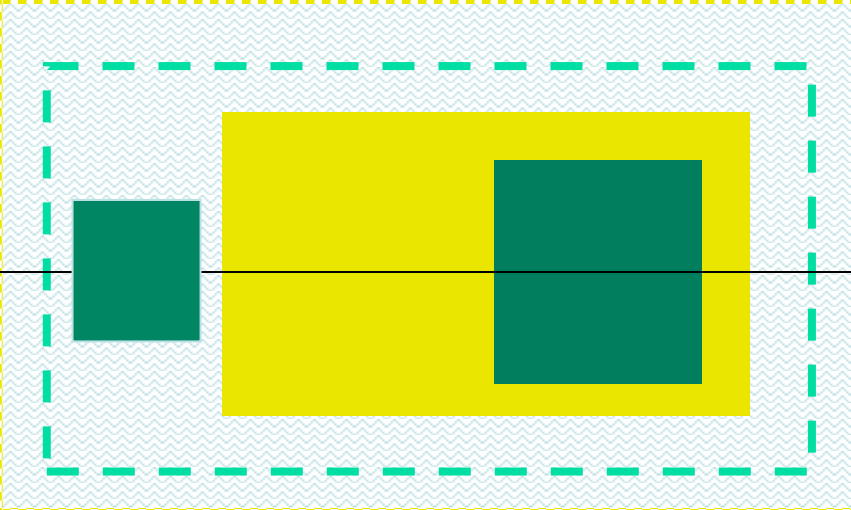
A



A'



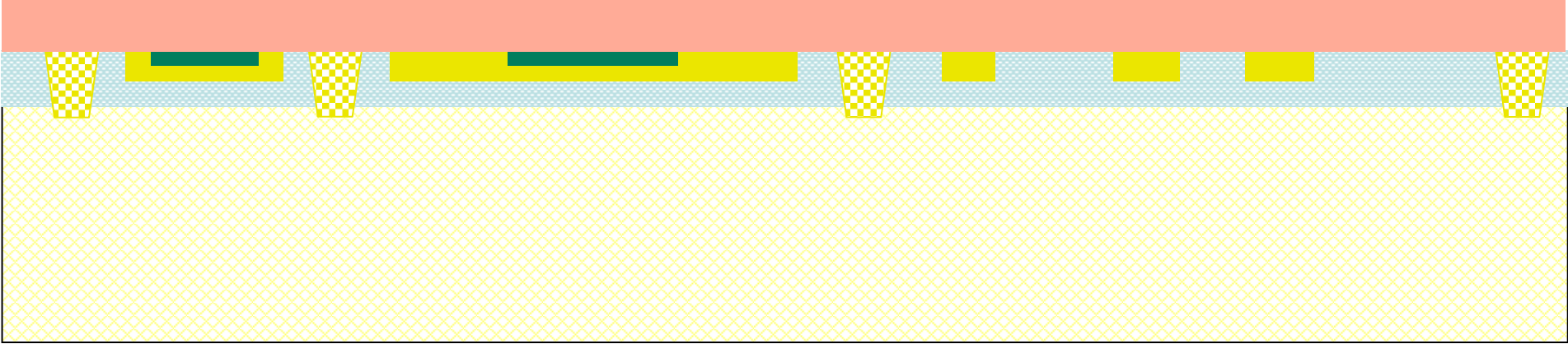
B



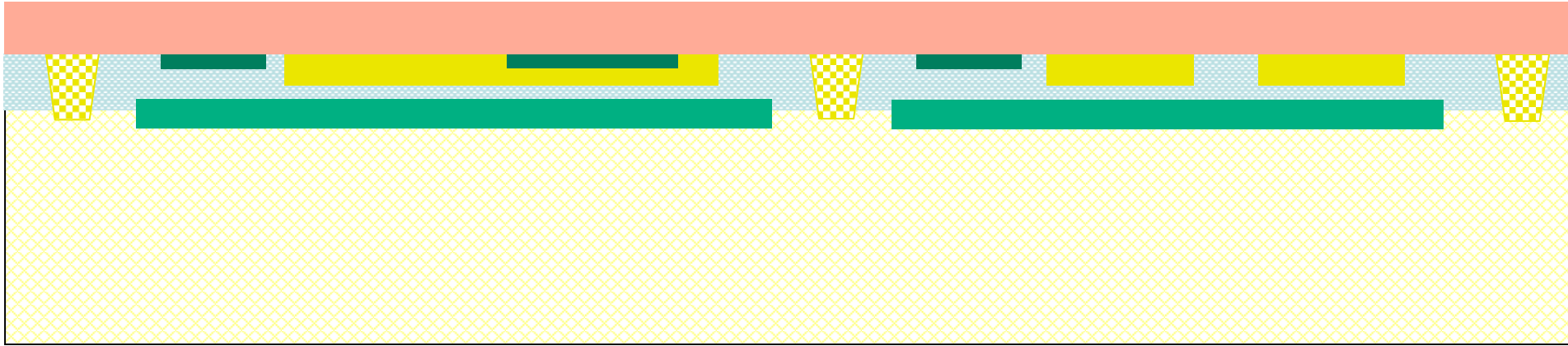
B'



Oxidation



A-A' Section



B-B' Section

Oxidation

A









A'

B

B'

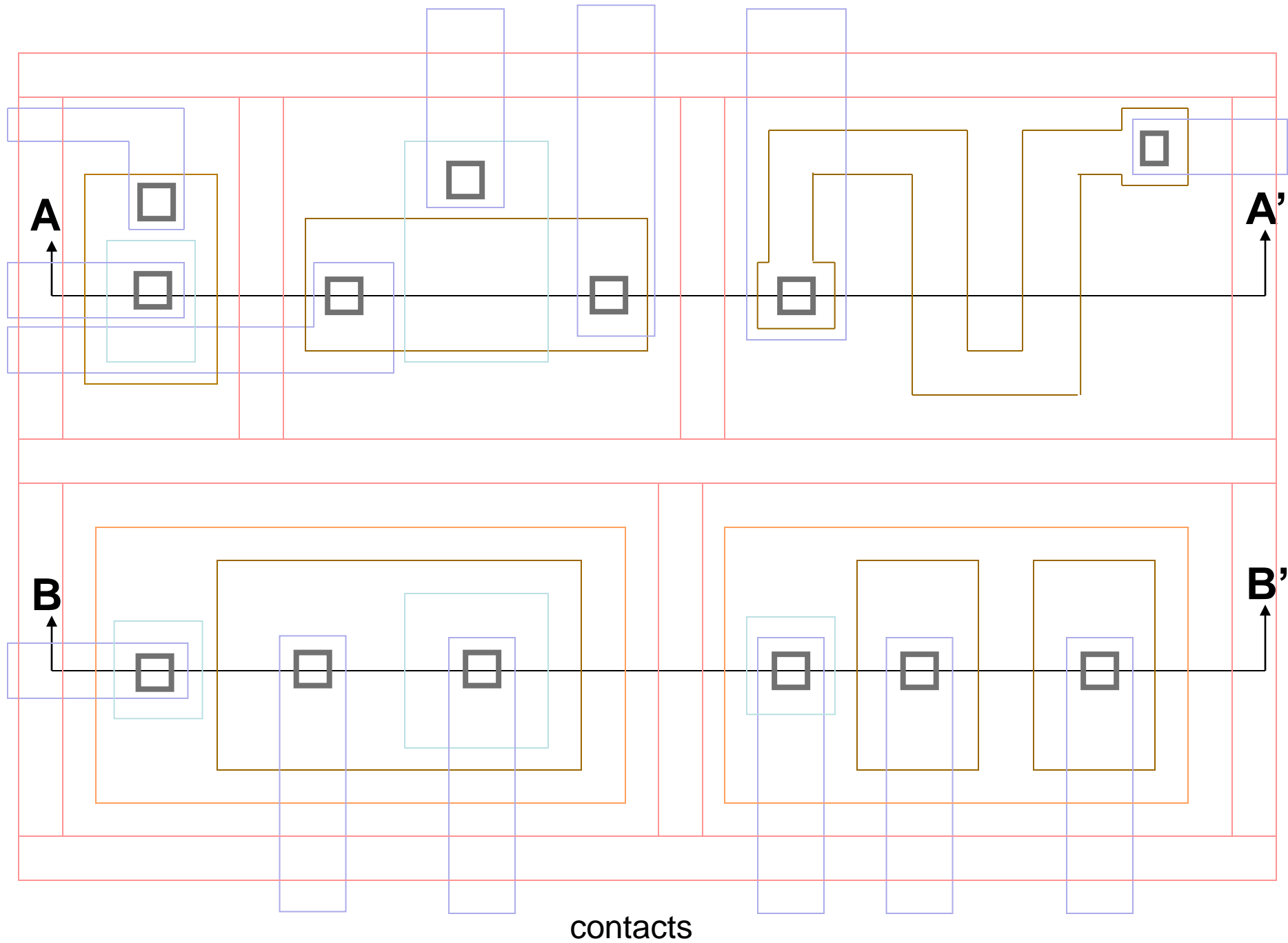


Mask Numbering and Mappings

Mask 1		n ⁺ buried collector
Mask 2		isolation diffusion (p ⁺)
Mask 3		p-base diffusion
Mask 4		n ⁺ emitter
 Mask 5		contact
Mask 6		metal
Mask 7		passivation opening

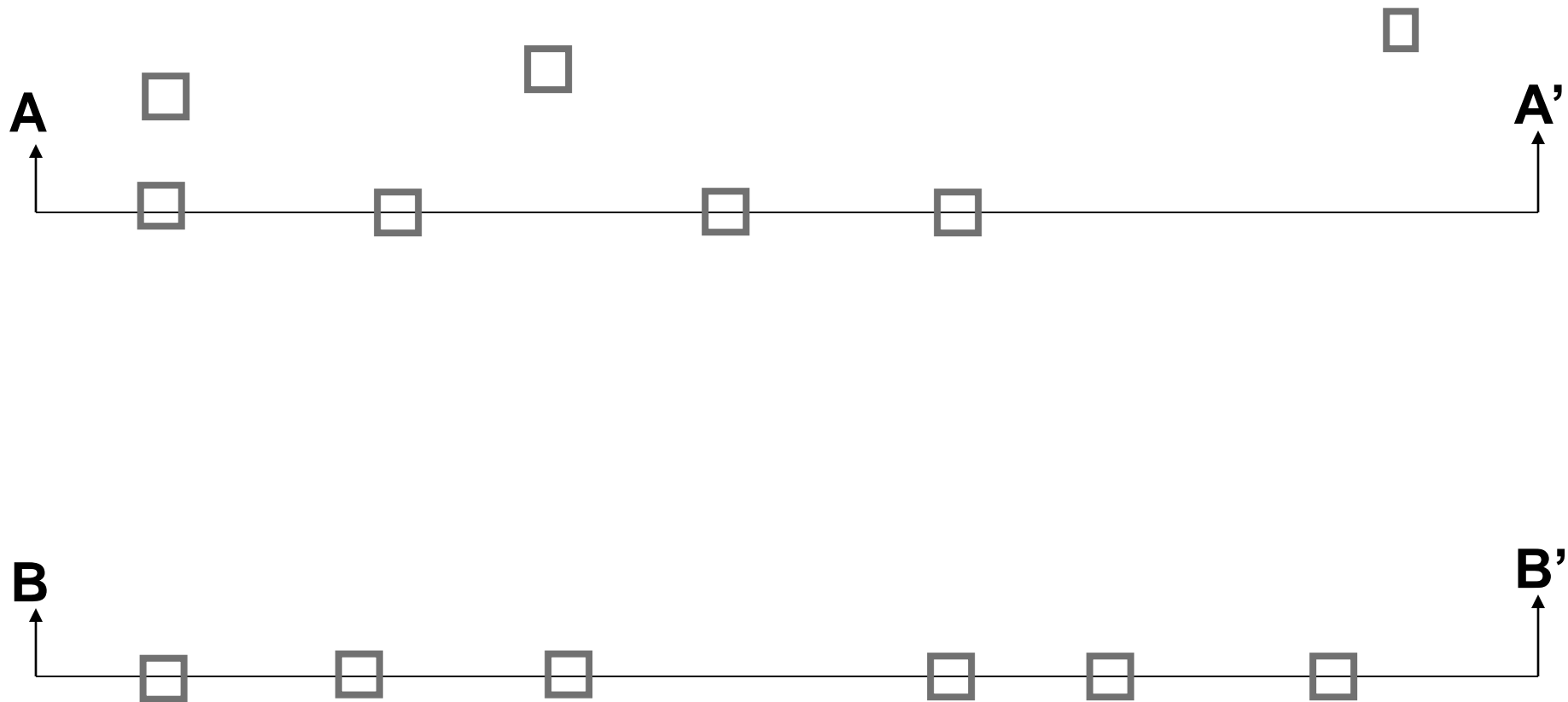
Notes:

- passivation opening for contacts not shown
- isolation diffusion intentionally not shown to scale



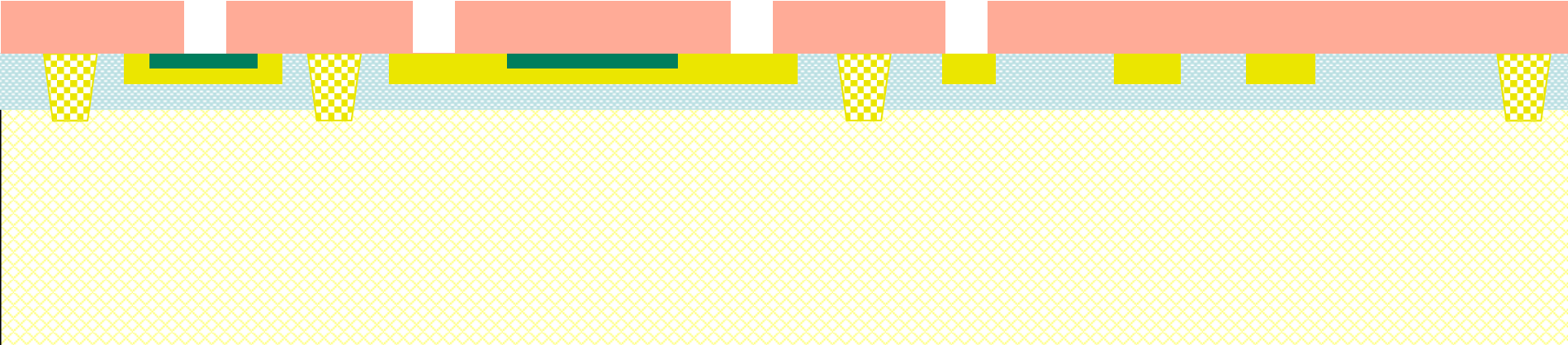
contacts

Mask 5: contacts

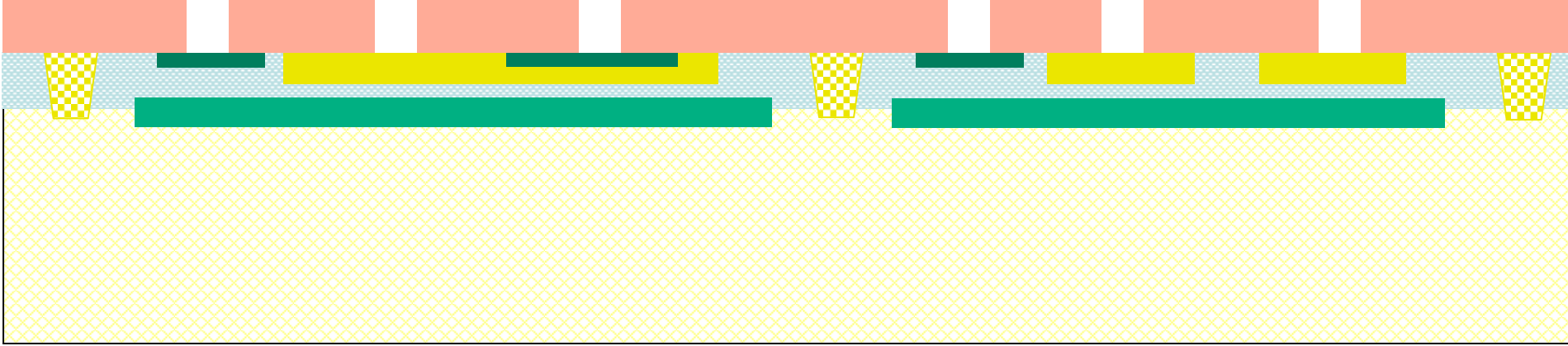


Contact Openings

- Photoresist present but not shown
- Deposition and diffusion combined in slides

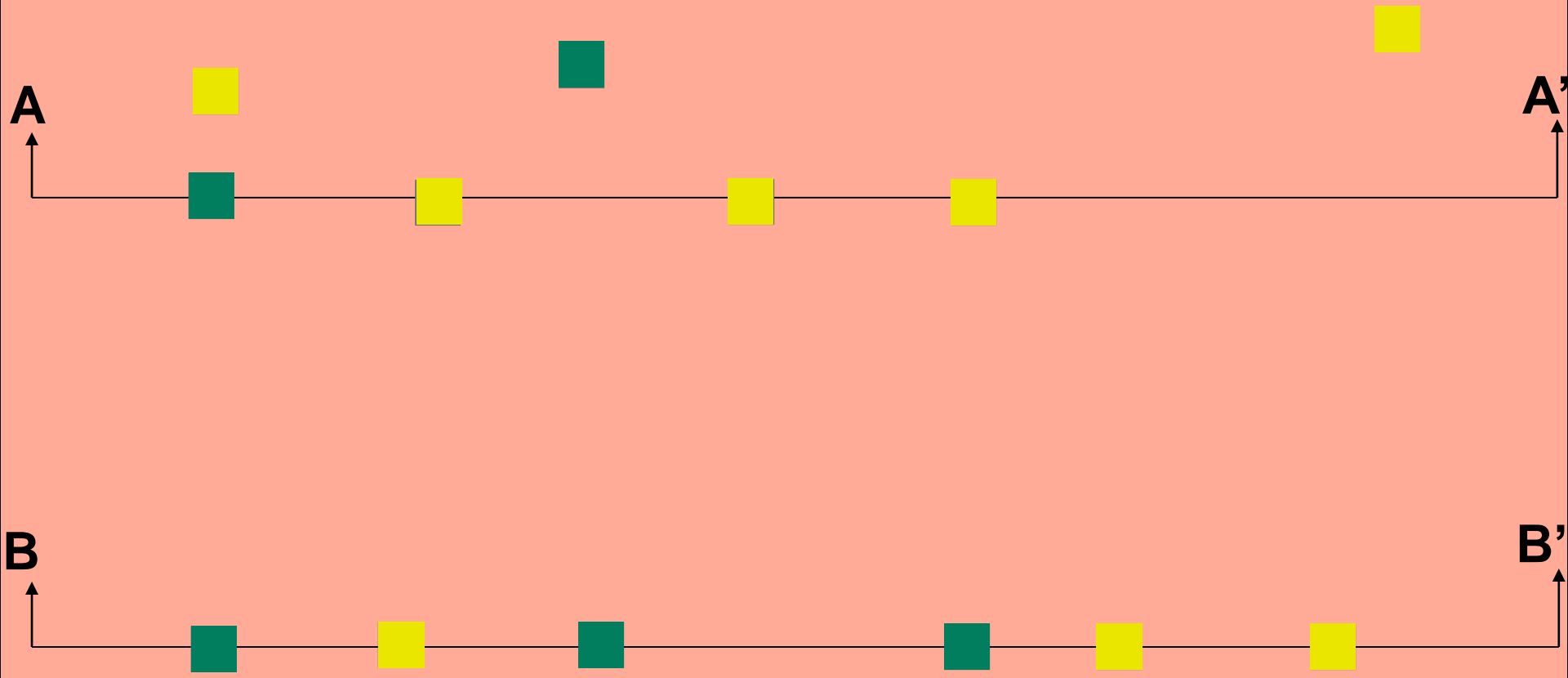


A-A' Section











B-B' Section

Contact Openings

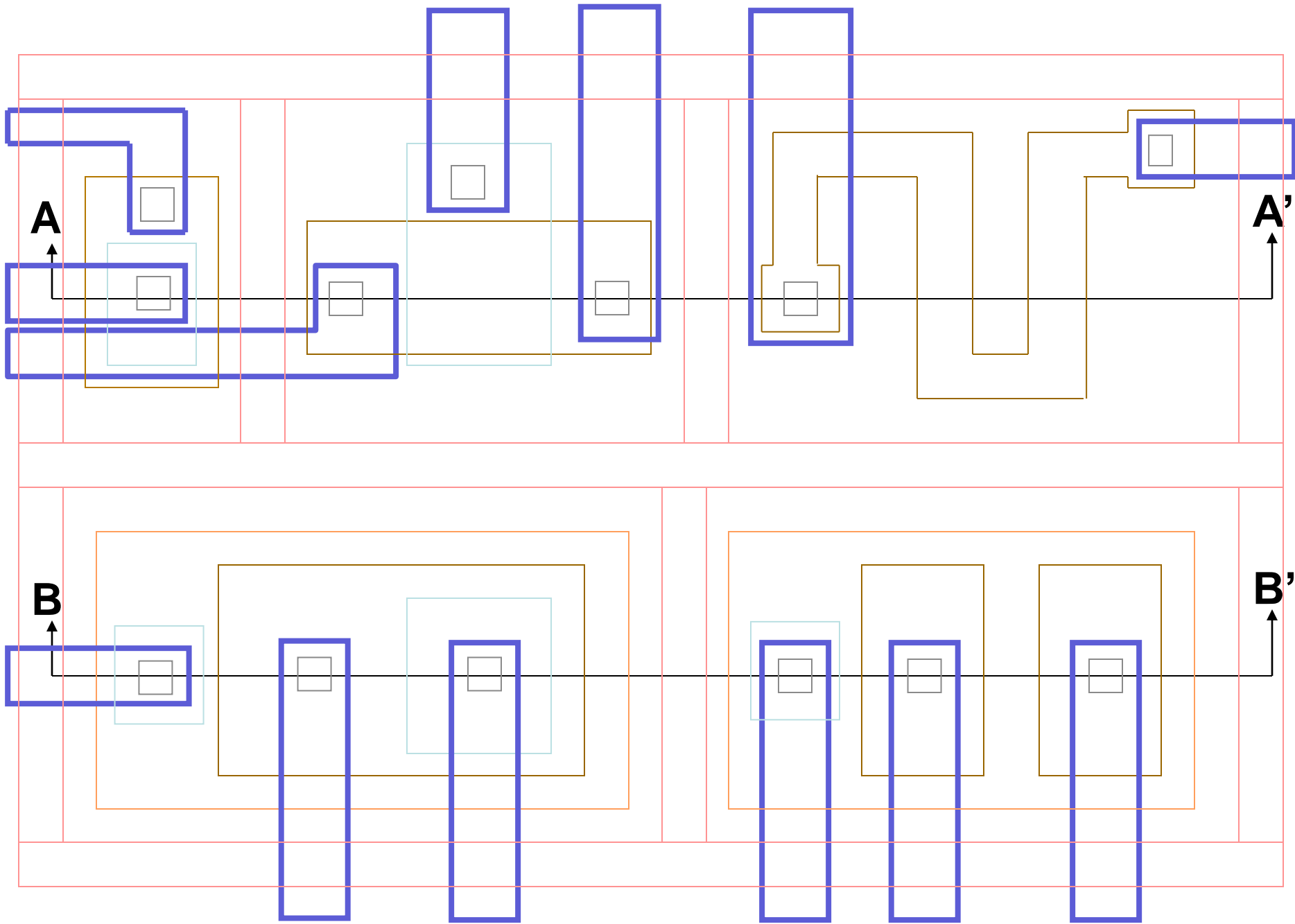


Mask Numbering and Mappings

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Mask 2		isolation diffusion (p ⁺)
Mask 3		p-base diffusion
Mask 4		n ⁺ emitter
Mask 5		contact
 Mask 6		metal
Mask 7		passivation opening

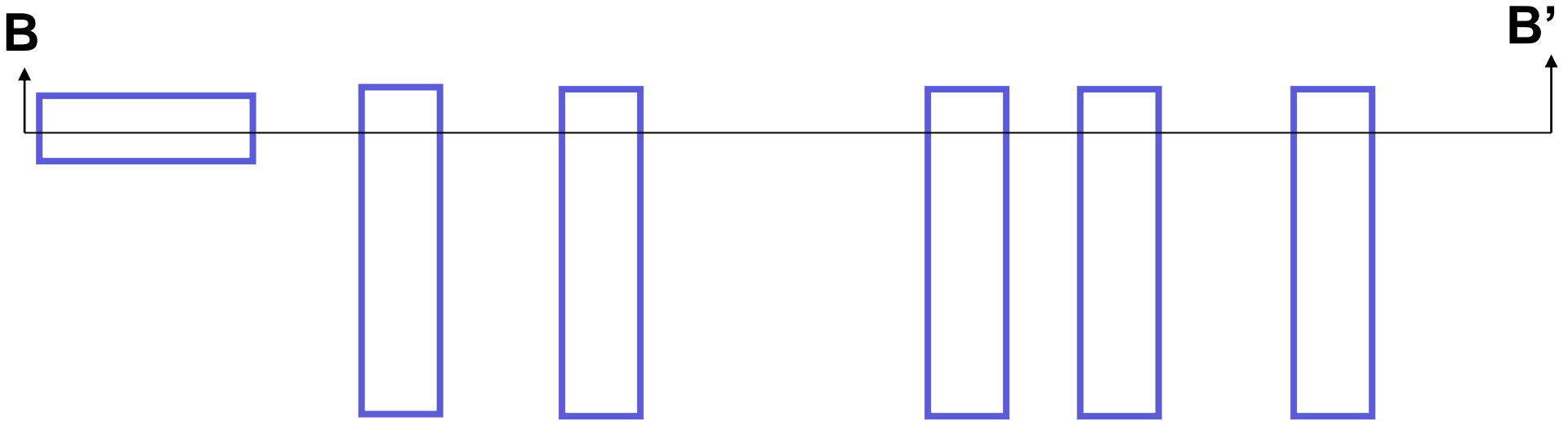
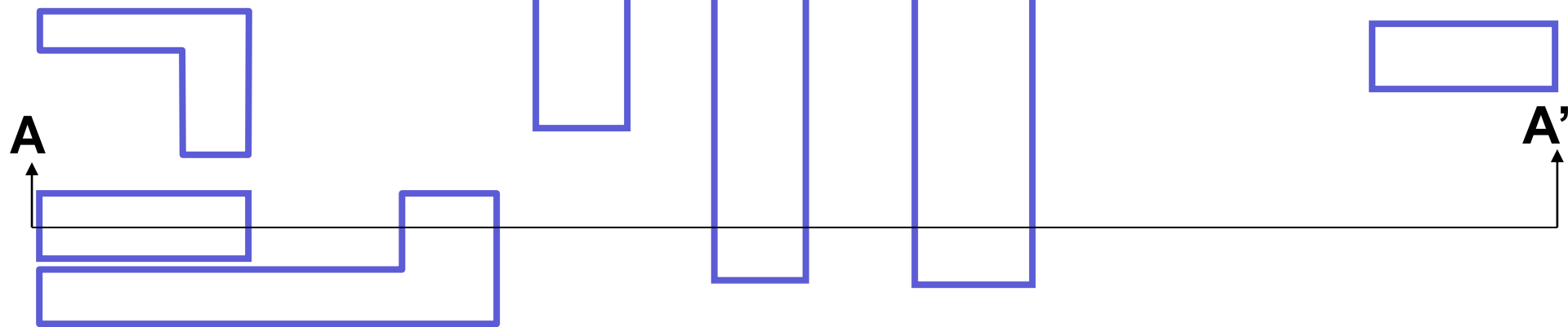
Notes:

- passivation opening for contacts not shown
- isolation diffusion intentionally not shown to scale



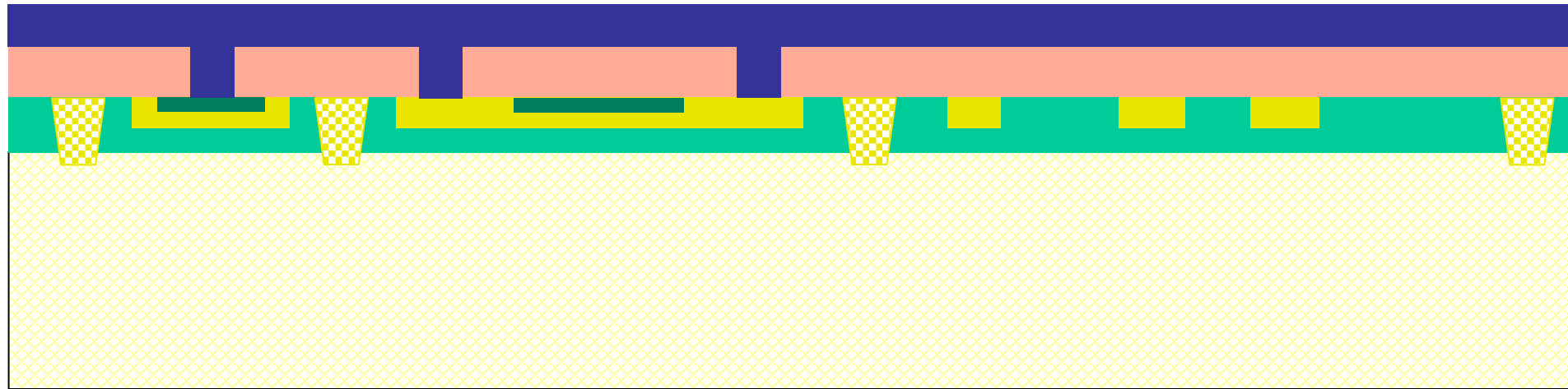
metal

Mask 6: metal

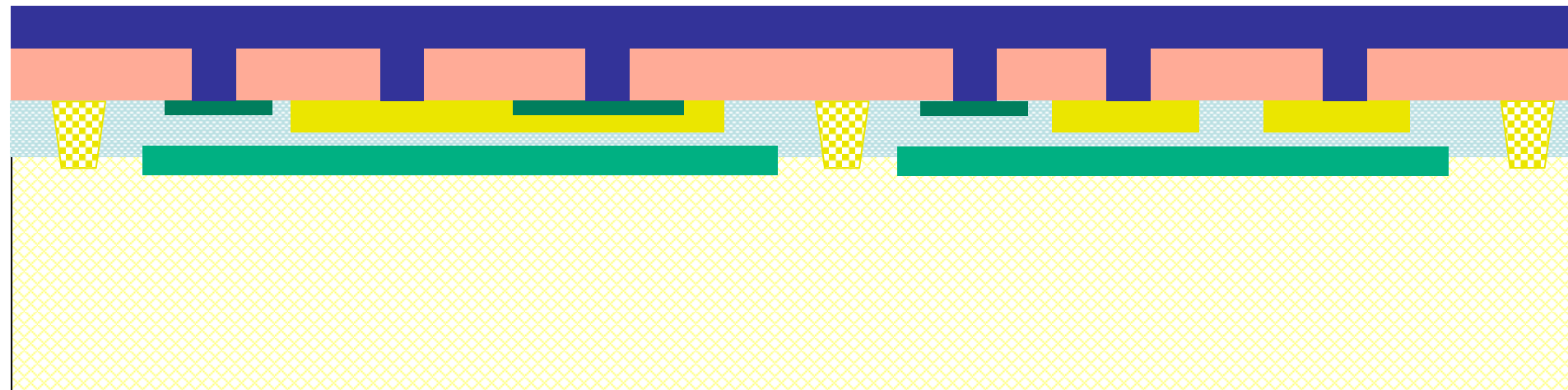


Metalization

- Photoresist present but not shown

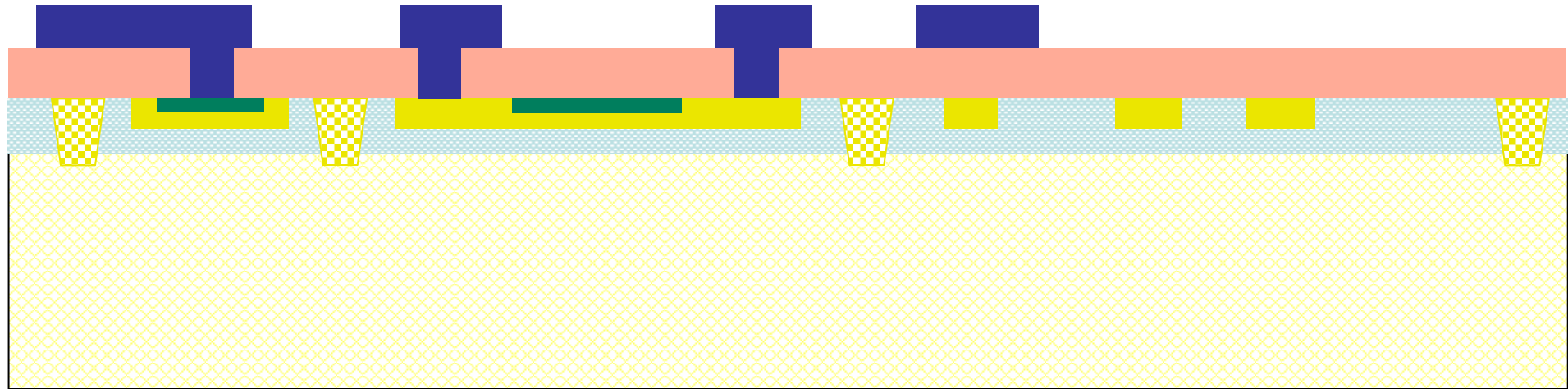


A-A' Section

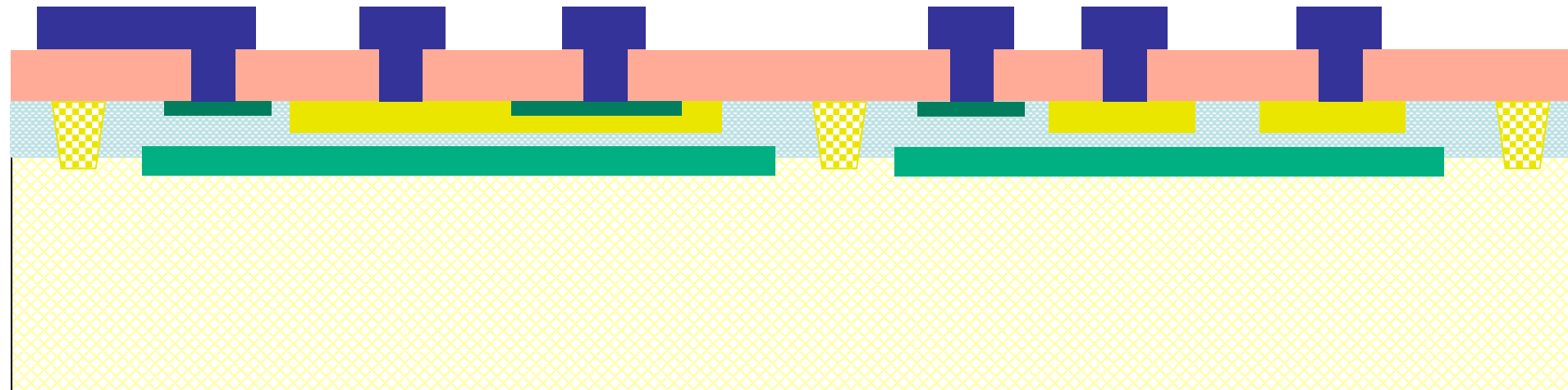


B-B' Section

Pattern Metal



A-A' Section



B-B' Section

Metalization

A

A'



B

B'



Pattern Metal

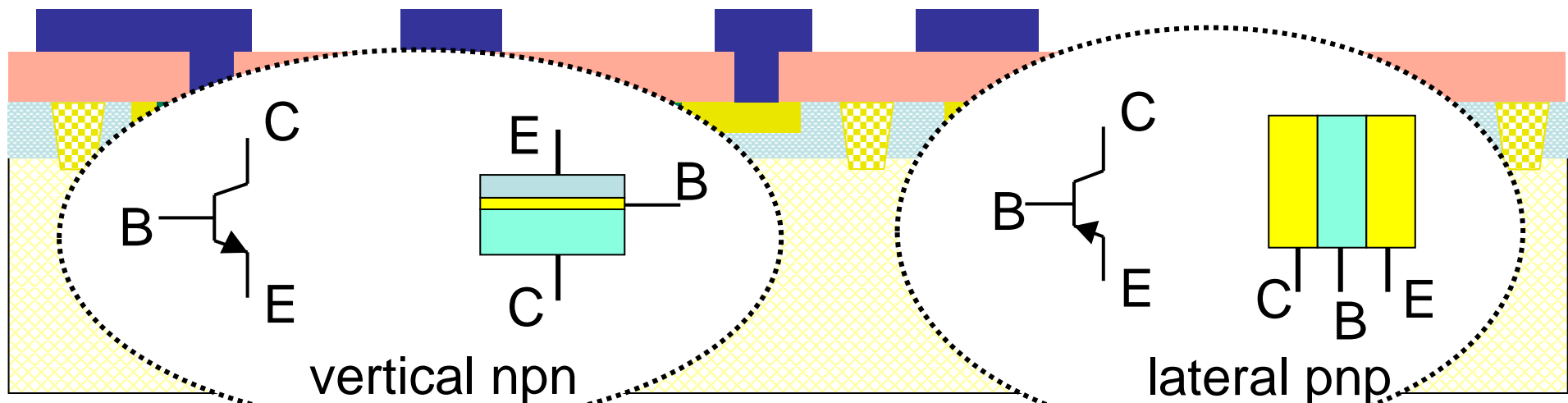
A

A'

B

B'

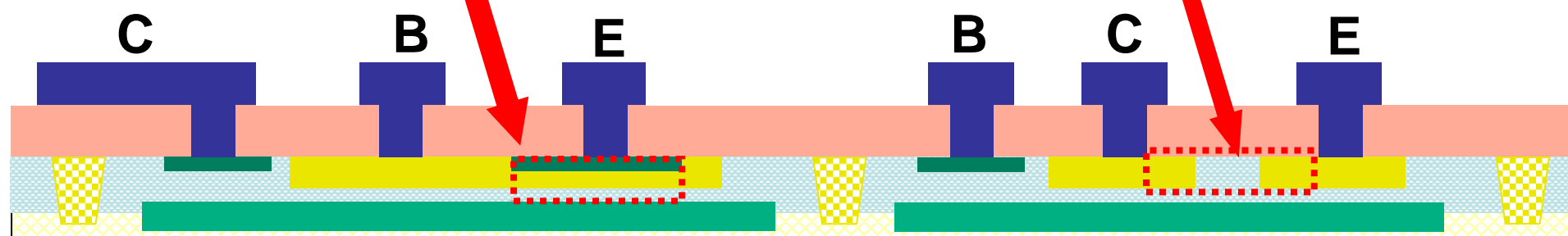




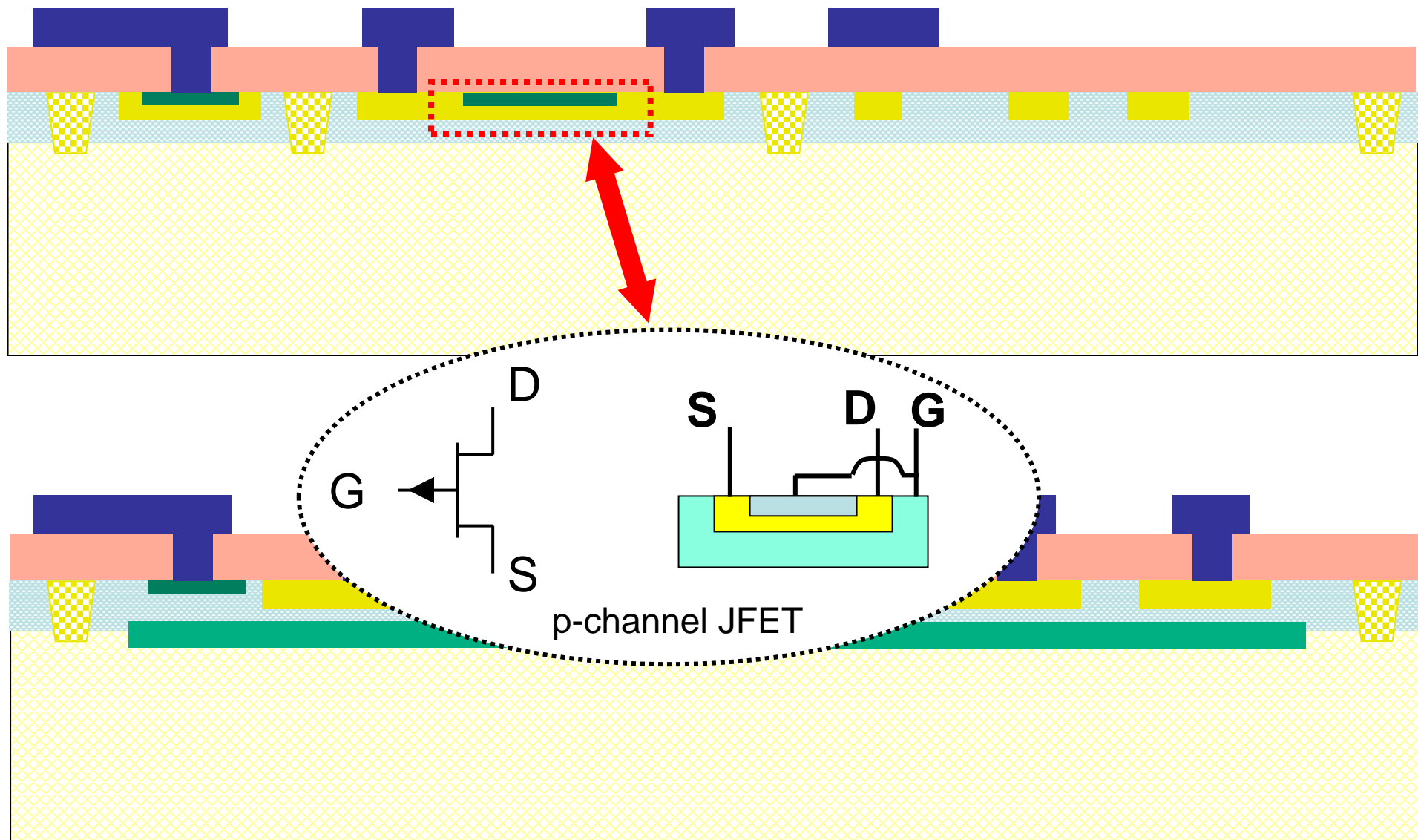
vertical npn

lateral pnp

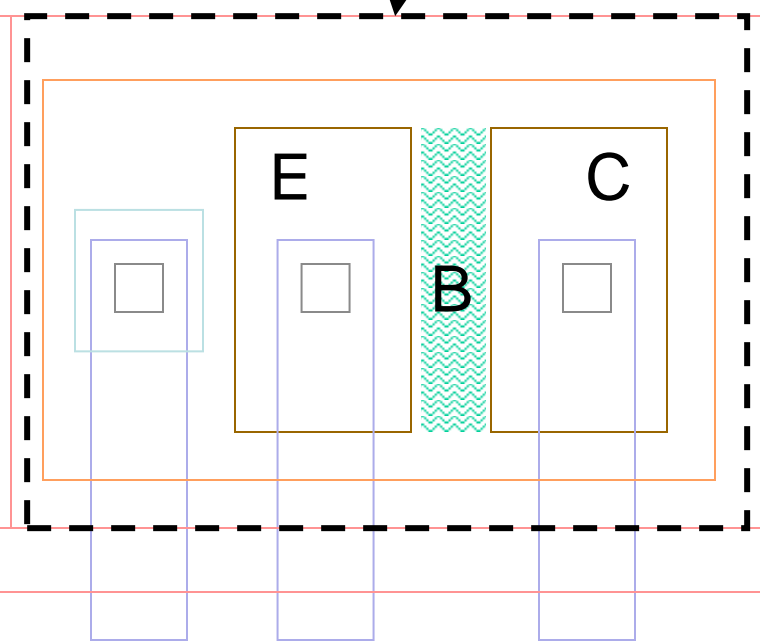
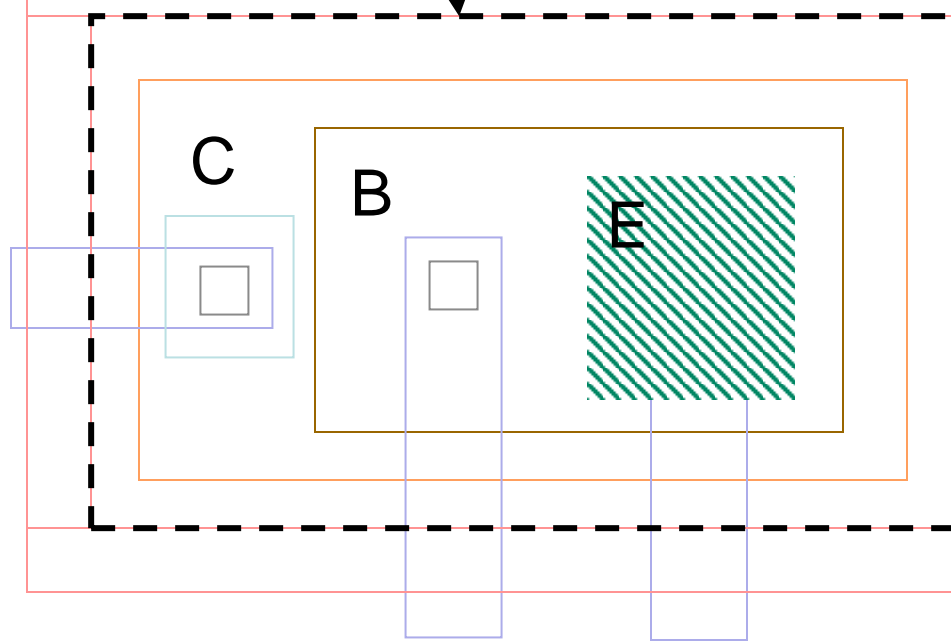
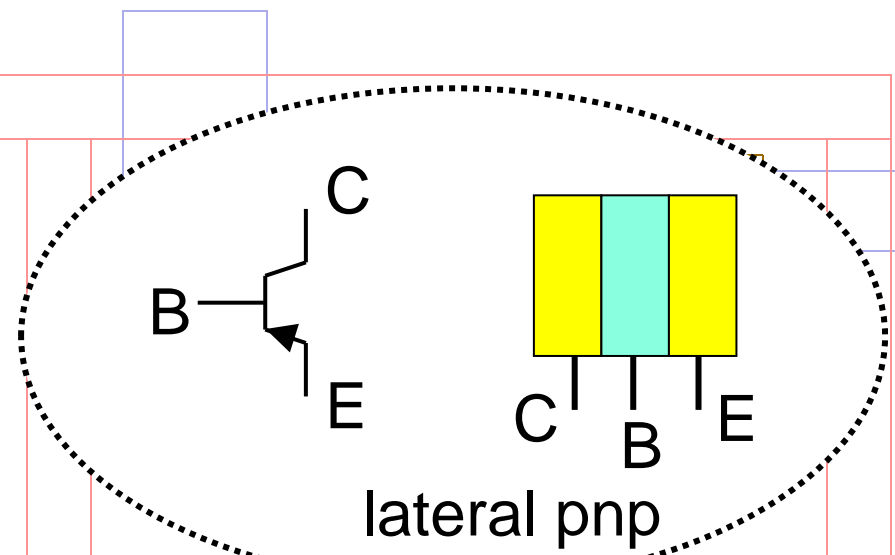
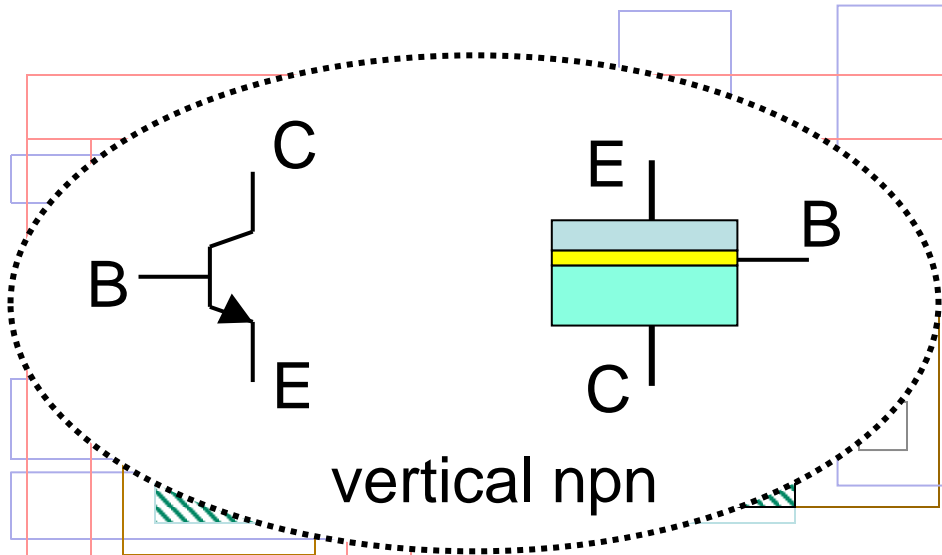
A-A' Section



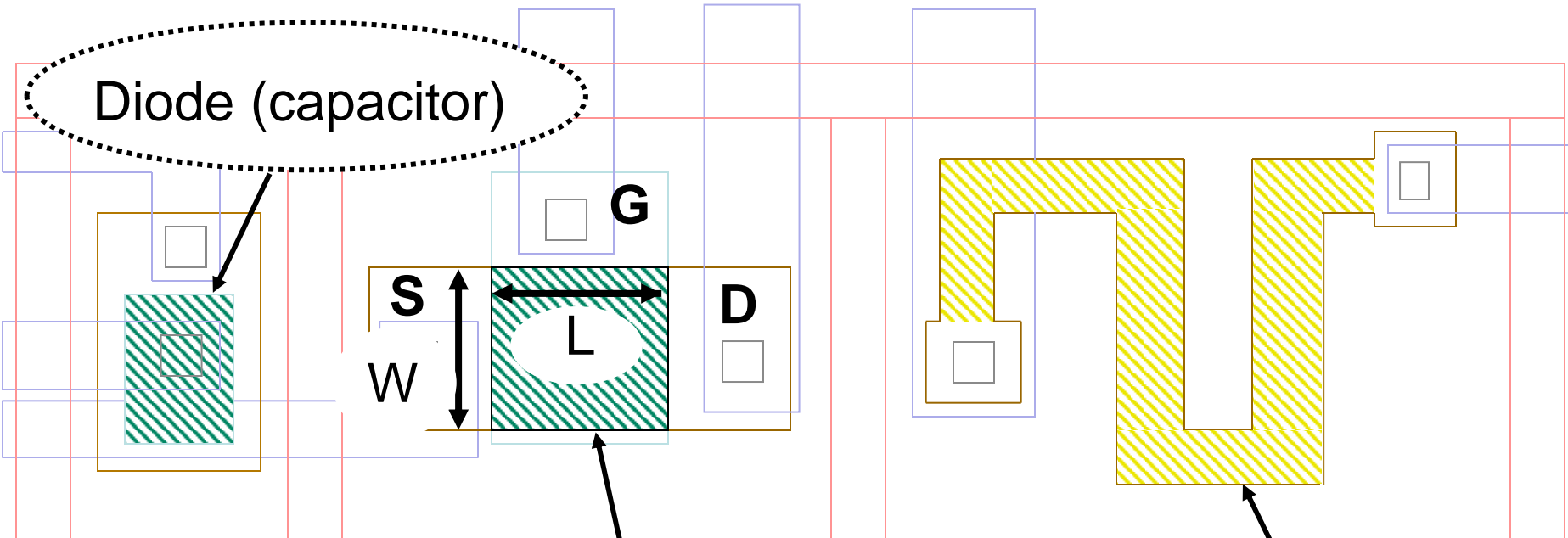
B-B' Section



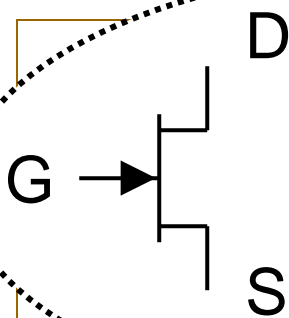
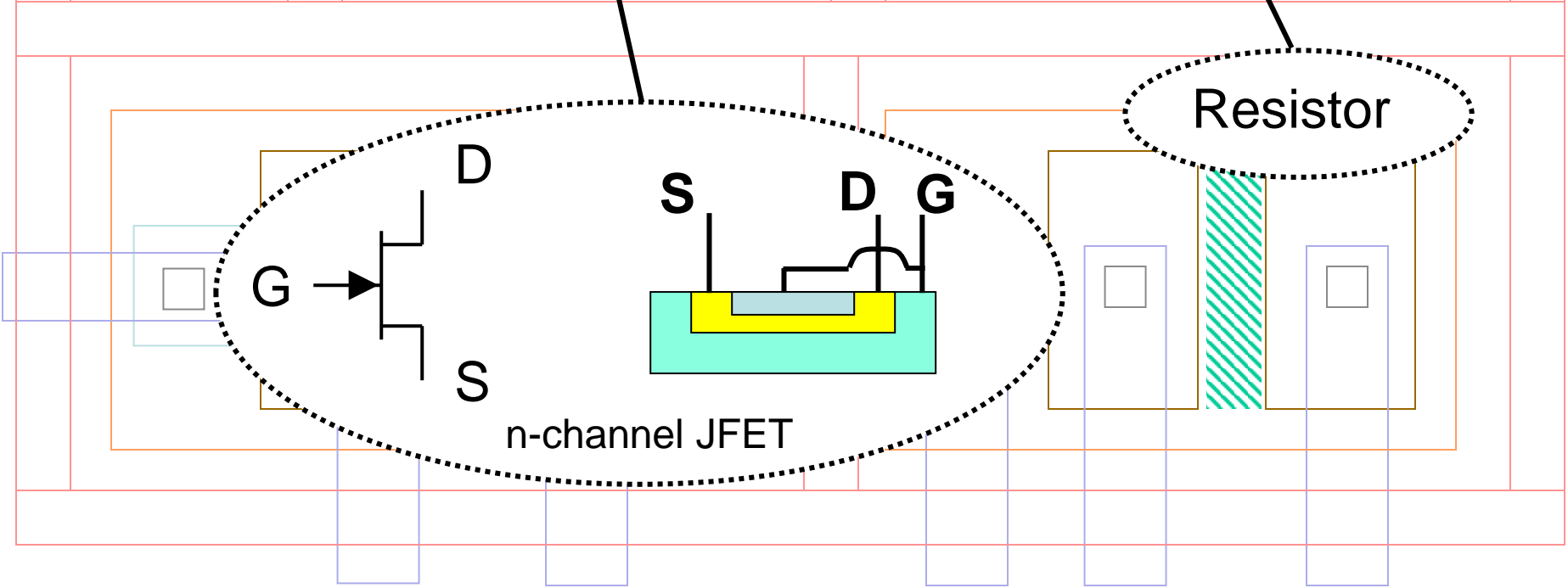
B-B' Section



Diode (capacitor)











Resistor



n-channel JFET

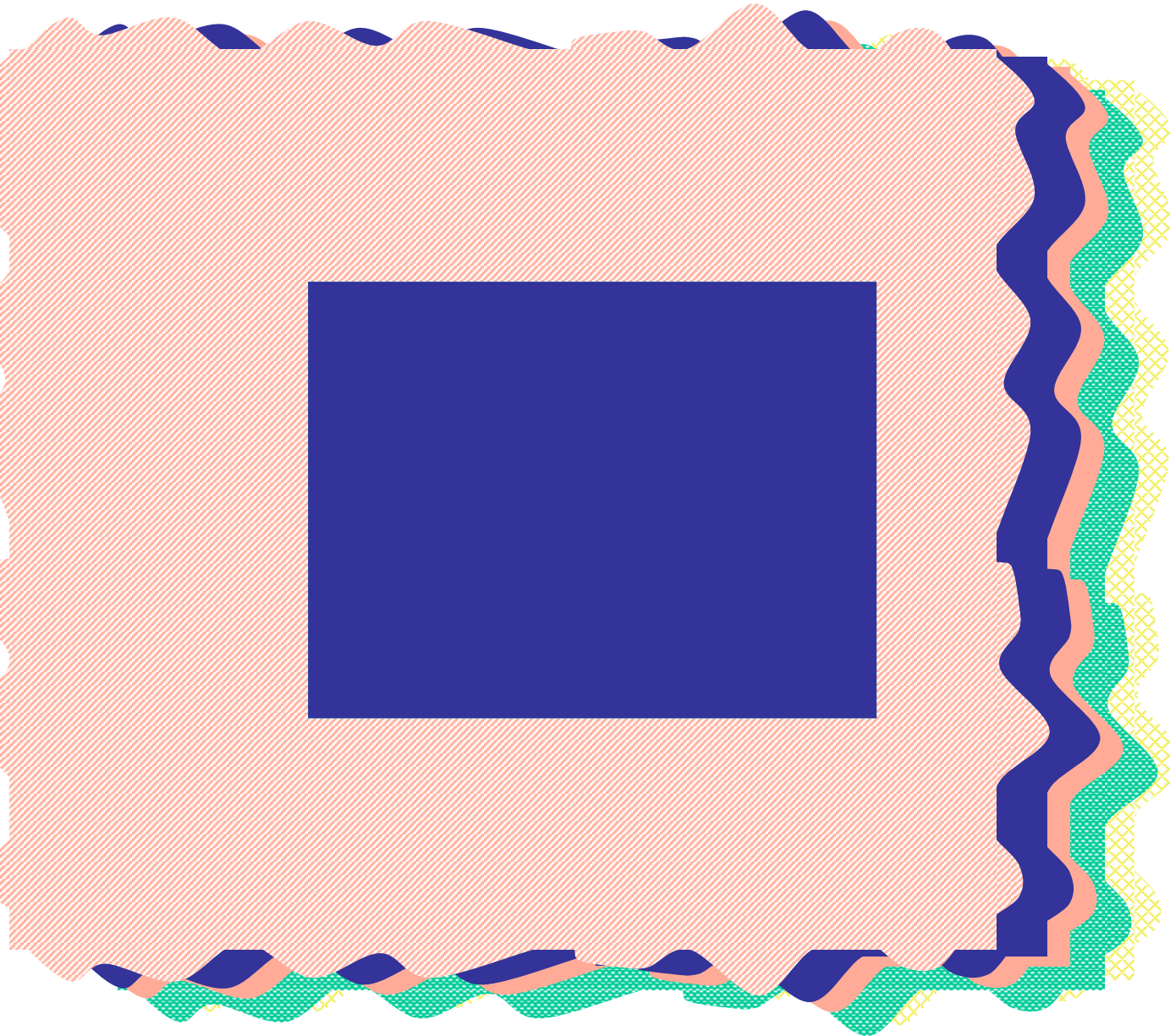
Mask Numbering and Mappings

Mask 1		n ⁺ buried collector
Mask 2		isolation diffusion (p ⁺)
Mask 3		p-base diffusion
Mask 4		n ⁺ emitter
Mask 5		contact
Mask 6		metal
 Mask 7		passivation opening

Notes:

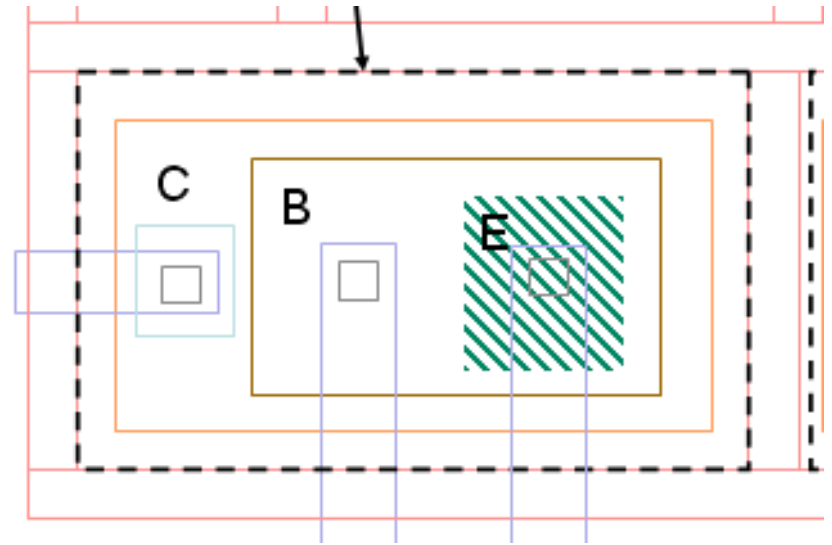
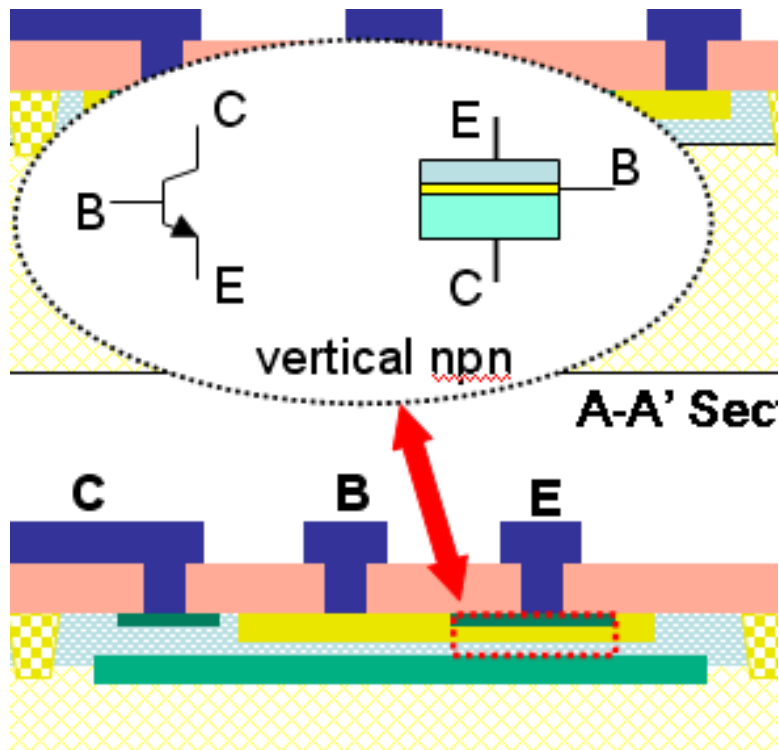
- passivation opening for contacts not shown
- isolation diffusion intentionally not shown to scale

Pad and Pad Opening



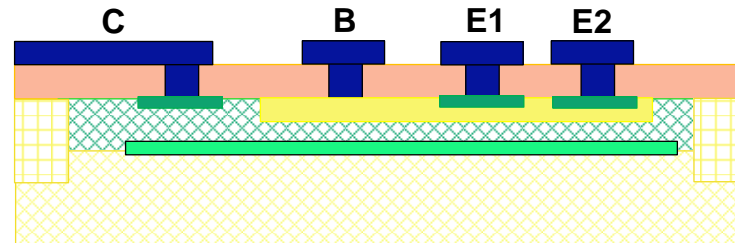
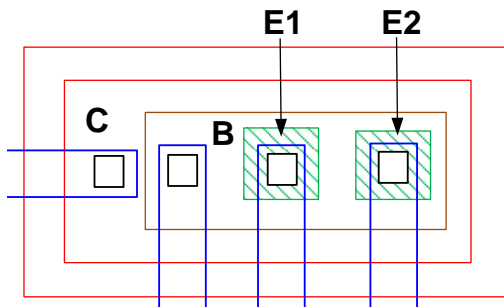
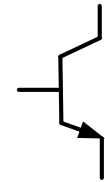
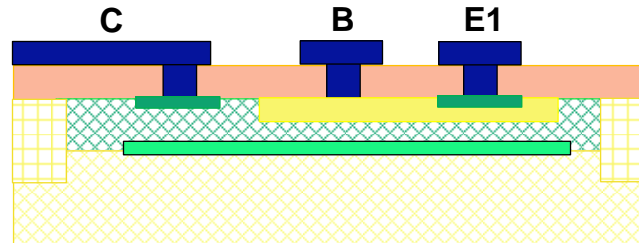
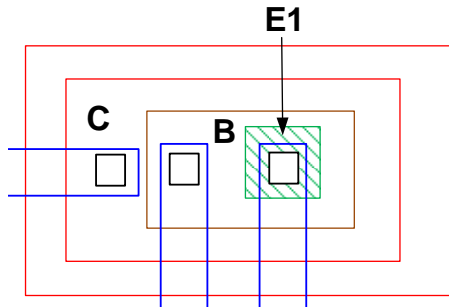
- p-substrate
- Epitaxial Layer
- Oxidation
- Metalization
- Protective Layer
- Pad Opening Mask
- Pad Opening

The vertical npn transistor



- Emitter area only geometric parameter that appears in basic device model !
- B and C areas large to get top contact to these regions
- Transistor much larger than emitter
- Multiple-emitter devices often used (TTL Logic) and don't significantly increase area
- Multiple B and C contacts often used (and multiple E contacts as well if A_E large)

The vertical npn transistor



Single-emitter and Double-Emitter Transistor

Base and Collector are shared

Quirks in modeling the BJT

^aParameters are defined in Chapters 3 and 4.

^bSome of these Gummel-Poon parameters differ considerably from those given in Table 2C.4. They have been obtained from curve fitting and should give good results with computer simulations. The parameters of Table 2C.4 should be used for hand analysis.

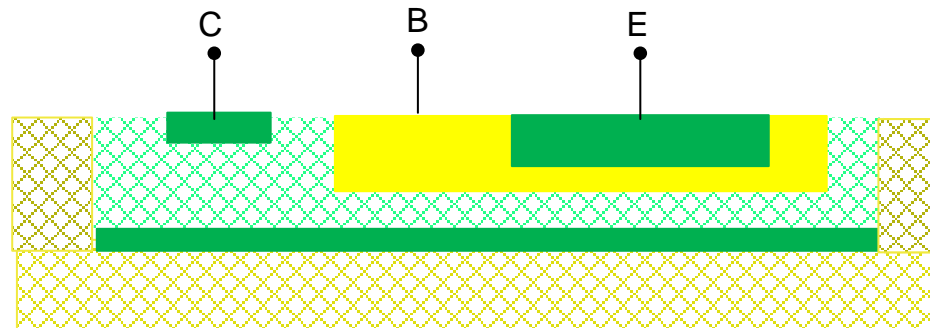
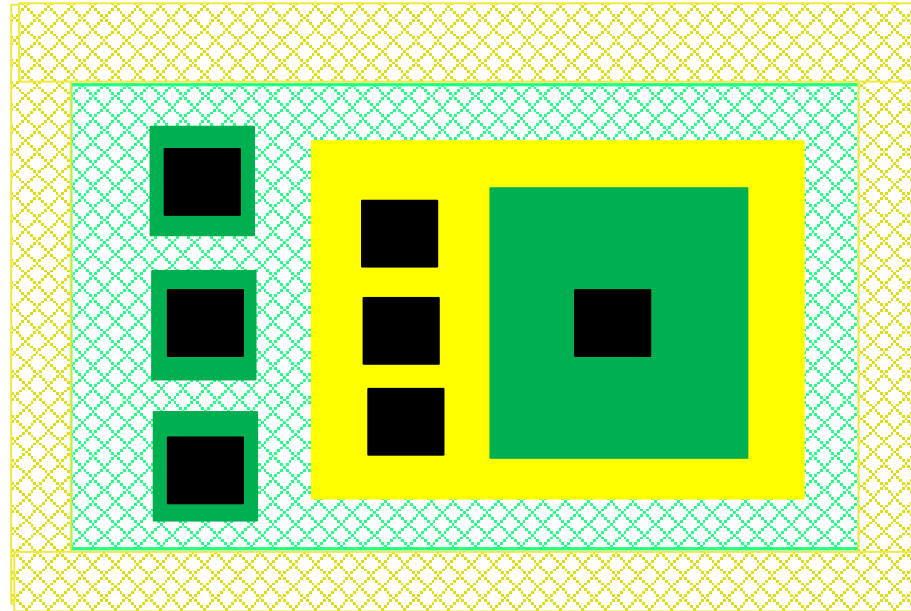
^cParameters that are strongly area-dependent are based upon an npn emitter area of 390 μ^2 and perimeter of 80 μ , a base area of 2200 μ^2 and perimeter of 200 μ , and a collector area of 10,500 μ^2 and perimeter of 425 μ . The lateral pnp has rectangular collectors and emitters spaced 10 μ apart with areas of 230 μ^2 and perimeters of 60 μ . The base area of the pnp is 7400 μ^2 and the base perimeter is 345 μ .

^dCJS is set to zero for the lateral transistor because it is essentially nonexistent. The parasitic capacitance from base to substrate, which totals 1.0 pF for this device, must be added externally to the BJT.

- In contrast to the MOSFET where process parameters are independent of geometry, the bipolar transistor model is for a specific transistor !
- Area emitter factor is used to model other devices
- Often multiple specific device models are given and these devices are used directly
- Often designer can not arbitrarily set A_E but rather must use parallel combinations of specific devices and layouts

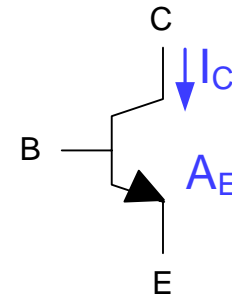
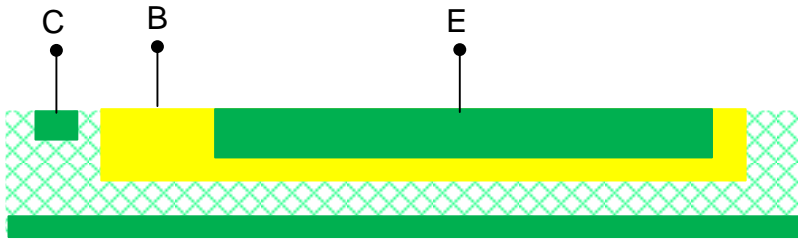
A challenge in modeling the BJT

Top View of Vertical npn

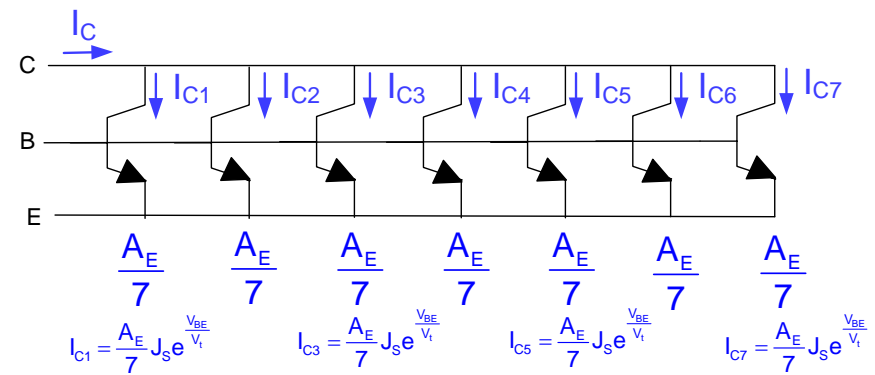
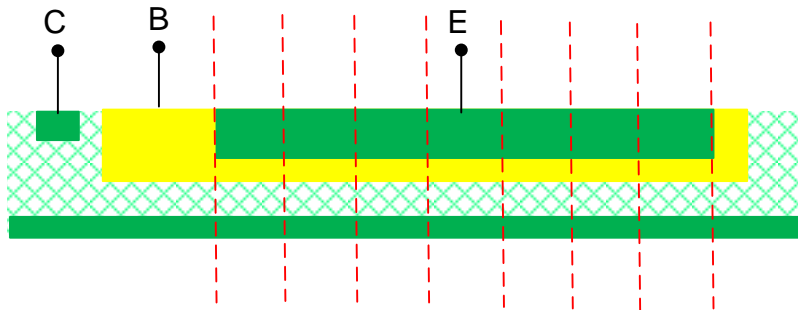


Cross-Sectional View

A challenge in modeling the BJT



$$I_C = A_E J_S e^{\frac{V_{BE}}{V_t}}$$

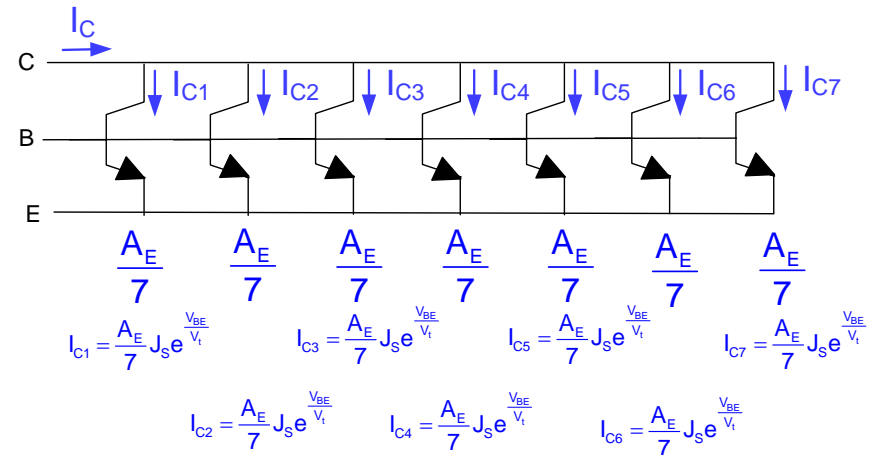
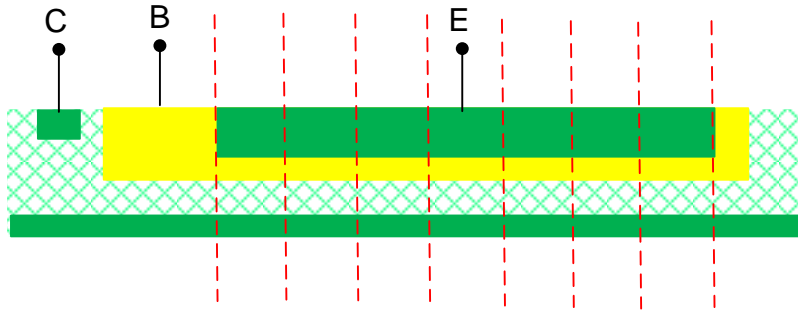


$$I_{C2} = \frac{A_E}{7} J_S e^{\frac{V_{BE}}{V_t}} \quad I_{C4} = \frac{A_E}{7} J_S e^{\frac{V_{BE}}{V_t}} \quad I_{C6} = \frac{A_E}{7} J_S e^{\frac{V_{BE}}{V_t}}$$

$$I_C = \sum_{i=1}^7 \frac{A_E}{7} J_S e^{\frac{V_{BE}}{V_t}} = A_E J_S e^{\frac{V_{BE}}{V_t}}$$

This looks consistent but ...

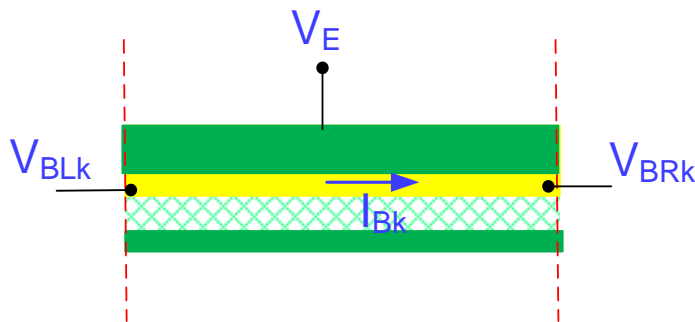
A challenge in modeling the BJT



$$I_C = \sum_{i=1}^7 \frac{A_E}{7} J_S e^{\frac{V_{BE}}{V_t}} = A_E J_S e^{\frac{V_{BE}}{V_t}}$$

This looks consistent but ...

consider an individual slice

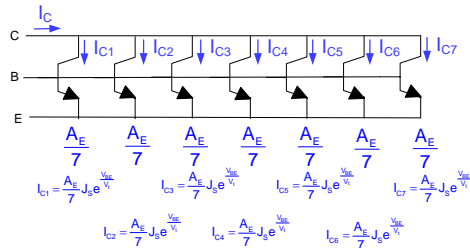


Lateral flow of base current causes a drop in base voltage across the base region

$$V_{BRK} \neq V_{BLK} \quad I_{Ck} = \frac{A_E}{7} J_S e^{\frac{V_{BEk}}{V_t}}$$

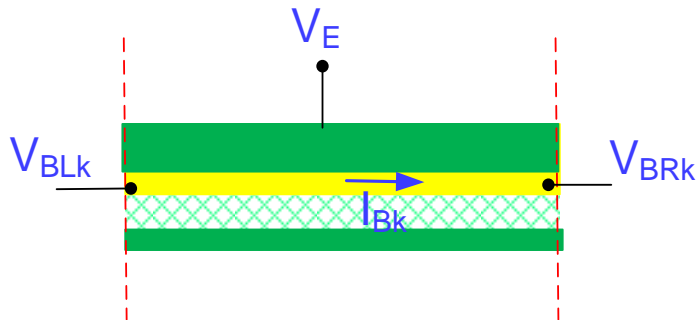
What is V_{BEk} ?

A challenge in modeling the BJT



$$I_C = \sum_{i=1}^7 \frac{A_E}{7} J_S e^{\frac{V_{BE}}{V_t}} = A_E J_S e^{\frac{V_{BE}}{V_t}}$$

This looks consistent but ...



- Lateral flow of base current causes a drop in base voltage across the base region
- And that drop differs from one slice to the next
- So V_{BE} is not fixed across the slices
- Since current is exponentially related to V_{BE} , affects can be significant
- Termed **base spreading resistance** problem
- Strongly dependent upon layout and contact placement
- No good models to include this effect
- Major reason designer does not have control of transistor layout detail in some bipolar processes
- Similar issue does not exist in MOSFET because the corresponding gate voltage does not change with position since $I_G=0$

A challenge in modeling the BJT

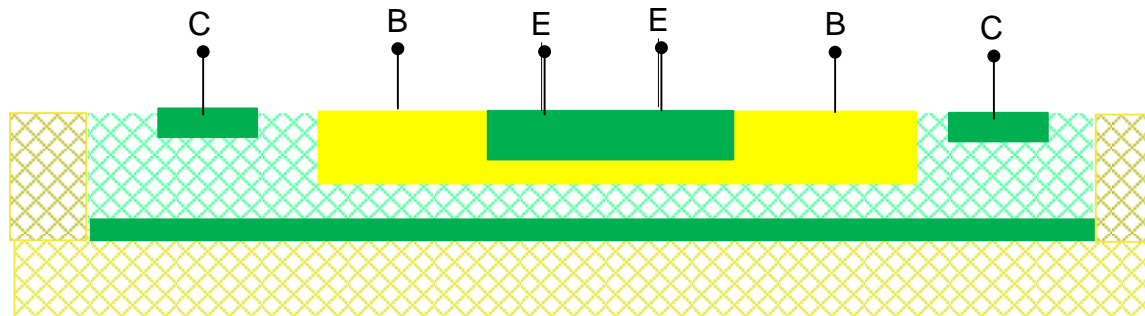
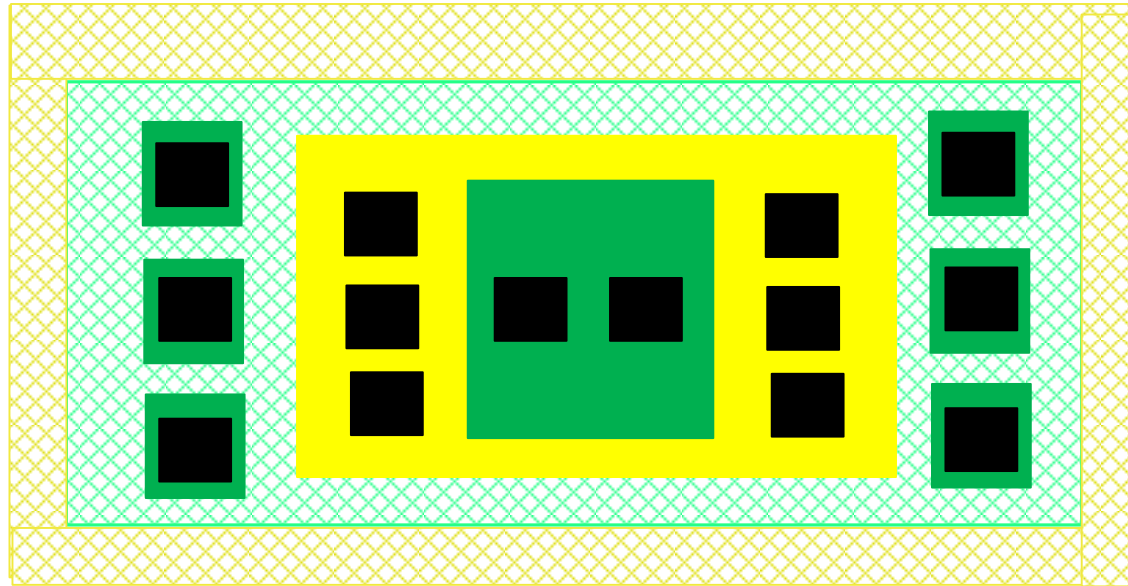
Top View of Vertical npn

Cross-Sectional View

A challenge in modeling the BJT

What can be done about this problem ?

Top View of Vertical npn

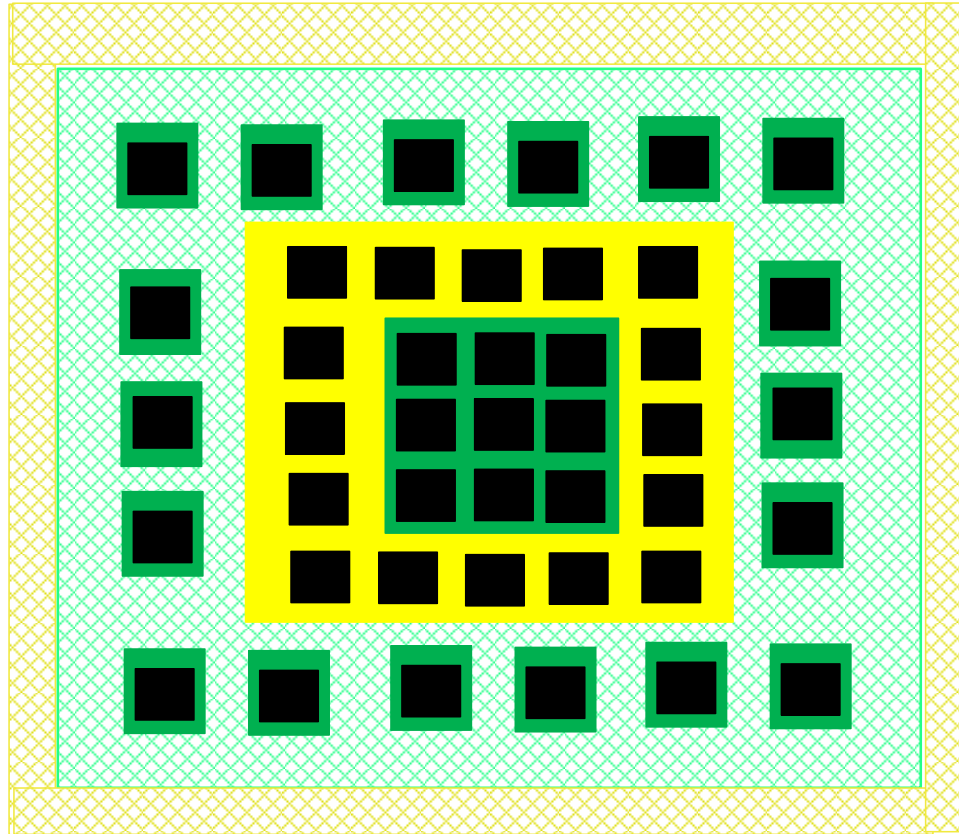


Cross-Sectional View

A challenge in modeling the BJT

What can be done about this problem ?

Top View of Vertical npn



- Often double rows of contacts used
- Area overhead can be significant
- Effects can be reduced but current flow paths are irregular

MOS and Bipolar Area Comparisons

How does the area required to realize a MOSFET compare to that required to realize a BJT?

Will consider a minimum-sized device in both processes

TABLE 2C.2
Design rules for a typical bipolar process ($\lambda = 2.5 \mu$)
(See Table 2C.3 in color plates for graphical interpretation)

	Dimension
1. n^+ buried collector diffusion (Yellow, Mask #1)	
1.1 Width	3λ
1.2 Overlap of p-base diffusion (for vertical npn)	2λ
1.3 Overlap of n^+ emitter diffusion (for collector contact of vertical npn)	2λ
1.4 Overlap of p-base diffusion (for collector and emitter of lateral pnp)	2λ
1.5 Overlap of n^+ emitter diffusion (for base contact of lateral pnp)	2λ
2. Isolation diffusion (Orange, Mask #2)	
2.1 Width	4λ
2.2 Spacing	24λ
2.3 Distance to n^+ buried collector	14λ
3. p-base diffusion (Brown, Mask #3)	
3.1 Width	3λ
3.2 Spacing	5λ
3.3 Distance to isolation diffusion	14λ
3.4 Width (resistor)	3λ
3.5 Spacing (as resistor)	3λ
4. n^+ emitter diffusion (Green, Mask #4)	
4.1 Width	3λ
4.2 Spacing	3λ
4.3 p-base diffusion overlap of n^+ emitter diffusion (emitter in base)	2λ
4.4 Spacing to isolation diffusion (for collector contact)	12λ
4.5 Spacing to p-base diffusion (for base contact of lateral pnp)	6λ
4.6 Spacing to p-base diffusion (for collector contact of vertical npn)	6λ

5. Contact (Black, Mask #5)	
5.1 Size (exactly)	$4\lambda \times 4\lambda$
5.2 Spacing	2λ
5.3 Metal overlap of contact	λ
5.4 n^+ emitter diffusion overlap of contact	2λ
5.5 p-base diffusion overlap of contact	2λ
5.6 p-base to n^+ emitter	3λ
5.7 Spacing to isolation diffusion	4λ
6. Metalization (Blue, Mask #6)	
6.1 Width	2λ
6.2 Spacing	2λ
6.3 Bonding pad size	$100 \mu \times 100 \mu$
6.4 Probe pad size	$75 \mu \times 75 \mu$
6.5 Bonding pad separation	50μ
6.6 Bonding to probe pad	30μ
6.7 Probe pad separation	30μ
6.8 Pad to circuitry	40μ
6.9 Maximum current density	$0.8 \text{ mA}/\mu \text{ width}$
7. Passivation (Purple, Mask #7)	
7.1 Minimum bonding pad opening	$90 \mu \times 90 \mu$
7.2 Minimum probe pad opening	$65 \mu \times 65 \mu$

Consider Initially the Emitter in the BJT surrounded by a base region

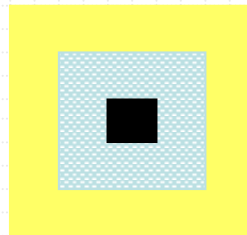


TABLE 2C.2
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(See Table 2C.3 in color plates for graphical interpretation)

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1.4 Overlap of p-base diffusion (for collector and emitter of lateral pnp)	2λ
1.5 Overlap of n^+ emitter diffusion (for base contact of lateral pnp)	2λ
2. Isolation diffusion (Orange, Mask #2)	
2.1 Width	4λ
2.2 Spacing	24λ
2.3 Distance to n^+ buried collector	14λ
3. p-base diffusion (Brown, Mask #3)	
3.1 Width	3λ
3.2 Spacing	5λ
3.3 Distance to isolation diffusion	14λ
3.4 Width (resistor)	3λ
3.5 Spacing (as resistor)	3λ
4. n^+ emitter diffusion (Green, Mask #4)	
4.1 Width	3λ
4.2 Spacing	3λ
4.3 p-base diffusion overlap of n^+ emitter diffusion (emitter in base)	2λ
4.4 Spacing to isolation diffusion (for collector contact)	12λ
4.5 Spacing to p-base diffusion (for base contact of lateral pnp)	6λ
4.6 Spacing to p-base diffusion (for collector contact of vertical npn)	6λ

5. Contact (Black, Mask #5)	
5.1 Size (exactly)	$4\lambda \times 4\lambda$
5.2 Spacing	2λ
5.3 Metal overlap of contact	λ
5.4 n^+ emitter diffusion overlap of contact	2λ
5.5 p-base diffusion overlap of contact	2λ
5.6 p-base to n^+ emitter	3λ
5.7 Spacing to isolation diffusion	4λ
6. Metalization (Blue, Mask #6)	
6.1 Width	2λ
6.2 Spacing	2λ
6.3 Bonding pad size	$100\ \mu \times 100\ \mu$
6.4 Probe pad size	$75\ \mu \times 75\ \mu$
6.5 Bonding pad separation	$50\ \mu$
6.6 Bonding to probe pad	$30\ \mu$
6.7 Probe pad separation	$30\ \mu$
6.8 Pad to circuitry	$40\ \mu$
6.9 Maximum current density	$0.8\ \text{mA}/\mu\ \text{width}$
7. Passivation (Purple, Mask #7)	
7.1 Minimum bonding pad opening	$90\ \mu \times 90\ \mu$
7.2 Minimum probe pad opening	$65\ \mu \times 65\ \mu$

From design rules (left to right) 4.3, 5.1, 5.4, 5.6, 5.5

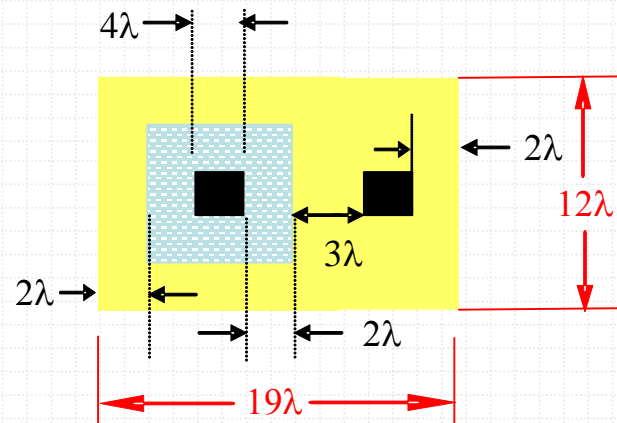


TABLE 2C.2
Design rules for a typical bipolar process ($\lambda = 2.5 \mu$)
(See Table 2C.3 in color plates for graphical interpretation)

	Dimension
1. n^+ buried collector diffusion (Yellow, Mask #1)	
1.1 Width	3λ
1.2 Overlap of p-base diffusion (for vertical npn)	2λ
1.3 Overlap of n^+ emitter diffusion (for collector contact of vertical npn)	2λ
1.4 Overlap of p-base diffusion (for collector and emitter of lateral pnp)	2λ
1.5 Overlap of n^+ emitter diffusion (for base contact of lateral pnp)	2λ
2. Isolation diffusion (Orange, Mask #2)	
2.1 Width	4λ
2.2 Spacing	24λ
2.3 Distance to n^+ buried collector	14λ
3. p-base diffusion (Brown, Mask #3)	
3.1 Width	3λ
3.2 Spacing	5λ
3.3 Distance to isolation diffusion	14λ
3.4 Width (resistor)	3λ
3.5 Spacing (as resistor)	3λ
4. n^+ emitter diffusion (Green, Mask #4)	
4.1 Width	3λ
4.2 Spacing	3λ
4.3 p-base diffusion overlap of n^+ emitter diffusion (emitter in base)	2λ
4.4 Spacing to isolation diffusion (for collector contact)	12λ
4.5 Spacing to p-base diffusion (for base contact of lateral pnp)	6λ
4.6 Spacing to p-base diffusion (for collector contact of vertical npn)	6λ

Add n+ buried for collector
From design rule 1.2

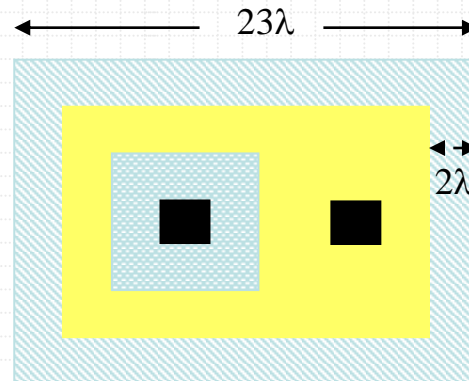
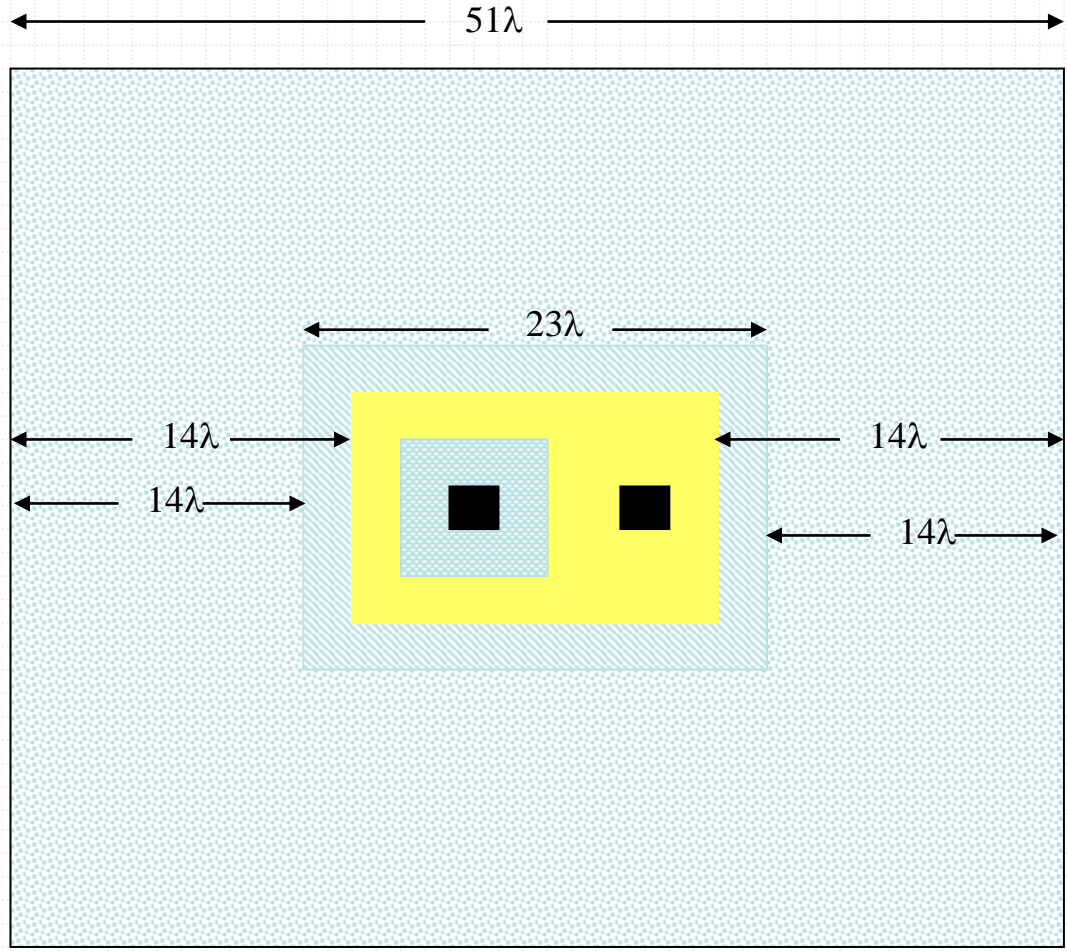


TABLE 2C.2
Design rules for a typical bipolar process ($\lambda = 2.5 \mu$)
(See Table 2C.3 in color plates for graphical interpretation)

	Dimension
1. n^+ buried collector diffusion (Yellow, Mask #1)	
1.1 Width	3λ
1.2 Overlap of p-base diffusion (for vertical npn)	2λ
1.3 Overlap of n^+ emitter diffusion (for collector contact of vertical npn)	2λ
1.4 Overlap of p-base diffusion (for collector and emitter of lateral pnp)	2λ
1.5 Overlap of n^+ emitter diffusion (for base contact of lateral pnp)	2λ
2. Isolation diffusion (Orange, Mask #2)	
2.1 Width	4λ
2.2 Spacing	24λ
2.3 Distance to n^+ buried collector	14λ
3. p-base diffusion (Brown, Mask #3)	
3.1 Width	3λ
3.2 Spacing	5λ
3.3 Distance to isolation diffusion	14λ
3.4 Width (resistor)	3λ
3.5 Spacing (as resistor)	3λ
4. n^+ emitter diffusion (Green, Mask #4)	
4.1 Width	3λ
4.2 Spacing	3λ
4.3 p-base diffusion overlap of n^+ emitter diffusion (emitter in base)	2λ
4.4 Spacing to isolation diffusion (for collector contact)	12λ
4.5 Spacing to p-base diffusion (for base contact of lateral pnp)	6λ
4.6 Spacing to p-base diffusion (for collector contact of vertical npn)	6λ

1 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75

Add n-epi region from design rules 2.3 and 3.3



5. Contact (Black, Mask #5)	
5.1 Size (exactly)	$4\lambda \times 4\lambda$
5.2 Spacing	2λ
5.3 Metal overlap of contact	λ
5.4 n^+ emitter diffusion overlap of contact	2λ
5.5 p-base diffusion overlap of contact	2λ
5.6 p-base to n^+ emitter	3λ
5.7 Spacing to isolation diffusion	4λ
6. Metalization (Blue, Mask #6)	
6.1 Width	2λ
6.2 Spacing	2λ
6.3 Bonding pad size	$100\ \mu \times 100\ \mu$
6.4 Probe pad size	$75\ \mu \times 75\ \mu$
6.5 Bonding pad separation	$50\ \mu$
6.6 Bonding to probe pad	$30\ \mu$
6.7 Probe pad separation	$30\ \mu$
6.8 Pad to circuitry	$40\ \mu$
6.9 Maximum current density	$0.8\ \text{mA}/\mu\ \text{width}$
7. Passivation (Purple, Mask #7)	
7.1 Minimum bonding pad opening	$90\ \mu \times 90\ \mu$
7.2 Minimum probe pad opening	$65\ \mu \times 65\ \mu$

Add contact to n-epi region from design rules 2.3 and 3.3

1 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75

5

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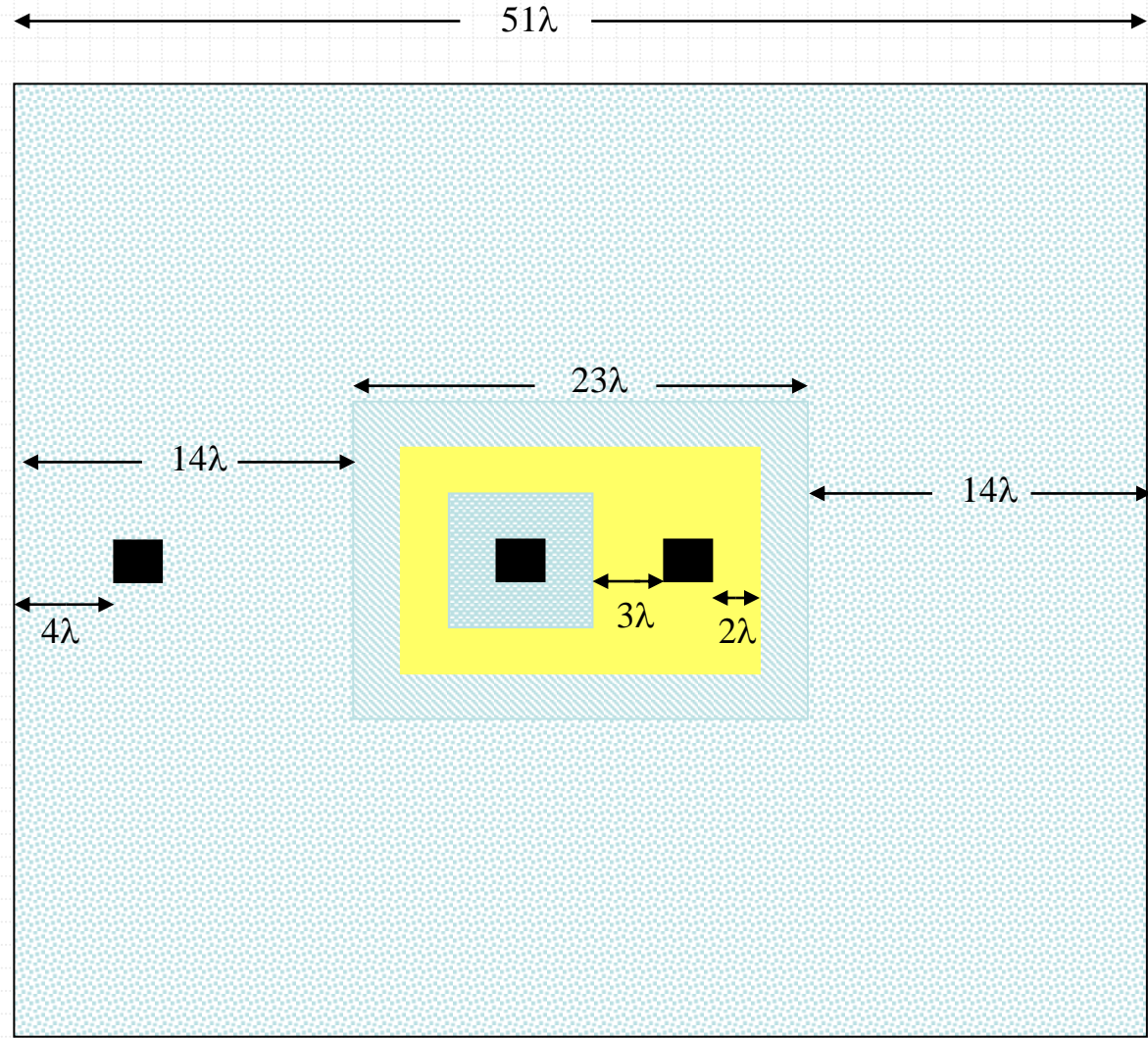


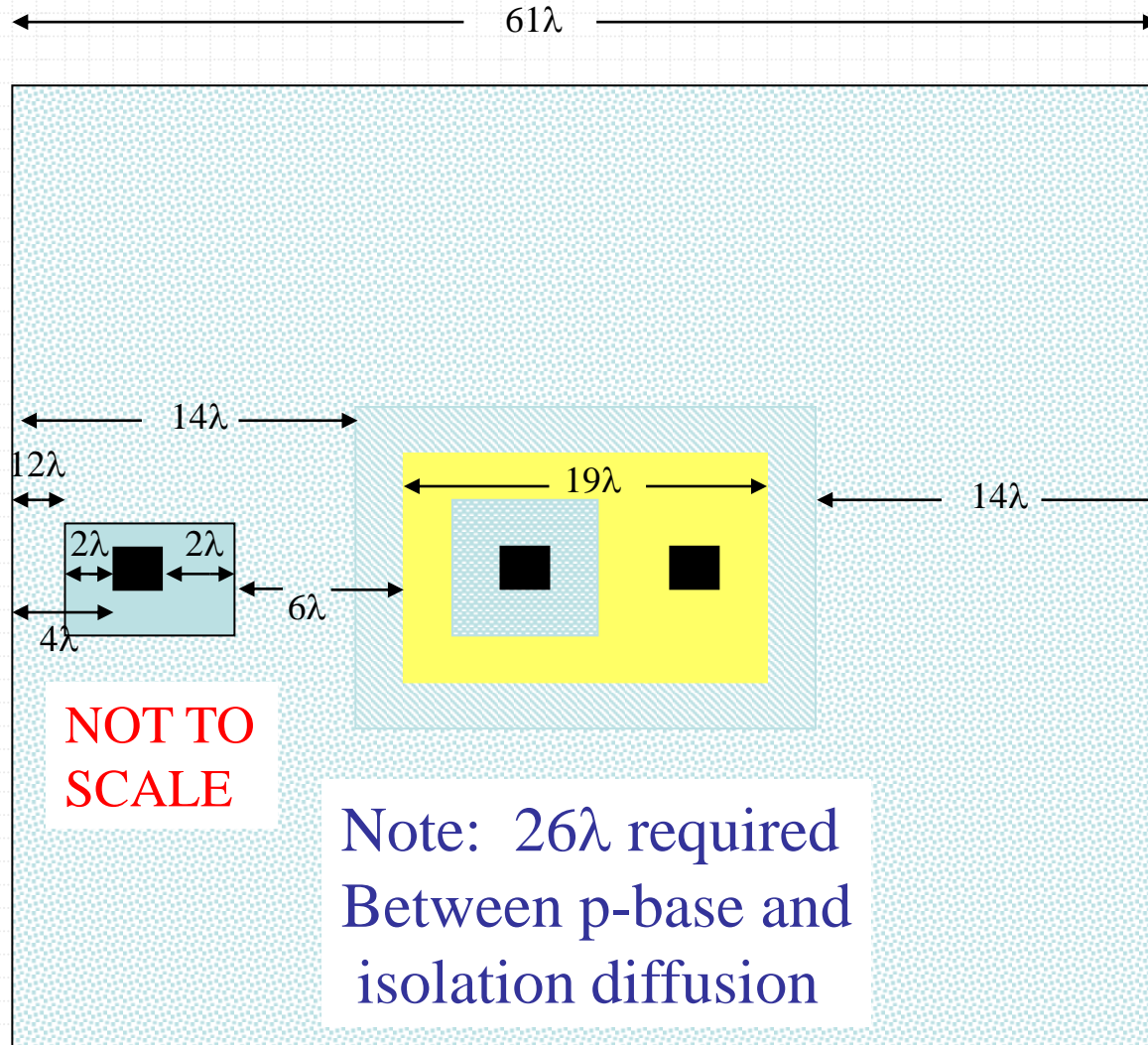
TABLE 2C.2
Design rules for a typical bipolar process ($\lambda = 2.5 \mu$)
(See Table 2C.3 in color plates for graphical interpretation)

	Dimension
1. n^+ buried collector diffusion (Yellow, Mask #1)	
1.1 Width	3λ
1.2 Overlap of p-base diffusion (for vertical npn)	2λ
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2. Isolation diffusion (Orange, Mask #2)	
2.1 Width	4λ
2.2 Spacing	24λ
2.3 Distance to n^+ buried collector	14λ
3. p-base diffusion (Brown, Mask #3)	
3.1 Width	3λ
3.2 Spacing	5λ
3.3 Distance to isolation diffusion	14λ
3.4 Width (resistor)	3λ
3.5 Spacing (as resistor)	3λ
4. n^+ emitter diffusion (Green, Mask #4)	
4.1 Width	3λ
4.2 Spacing	3λ
4.3 p-base diffusion overlap of n^+ emitter diffusion (emitter in base)	2λ
4.4 Spacing to isolation diffusion (for collector contact)	12λ
4.5 Spacing to p-base diffusion (for base contact of lateral pnp)	6λ
4.6 Spacing to p-base diffusion (for collector contact of vertical npn)	6λ

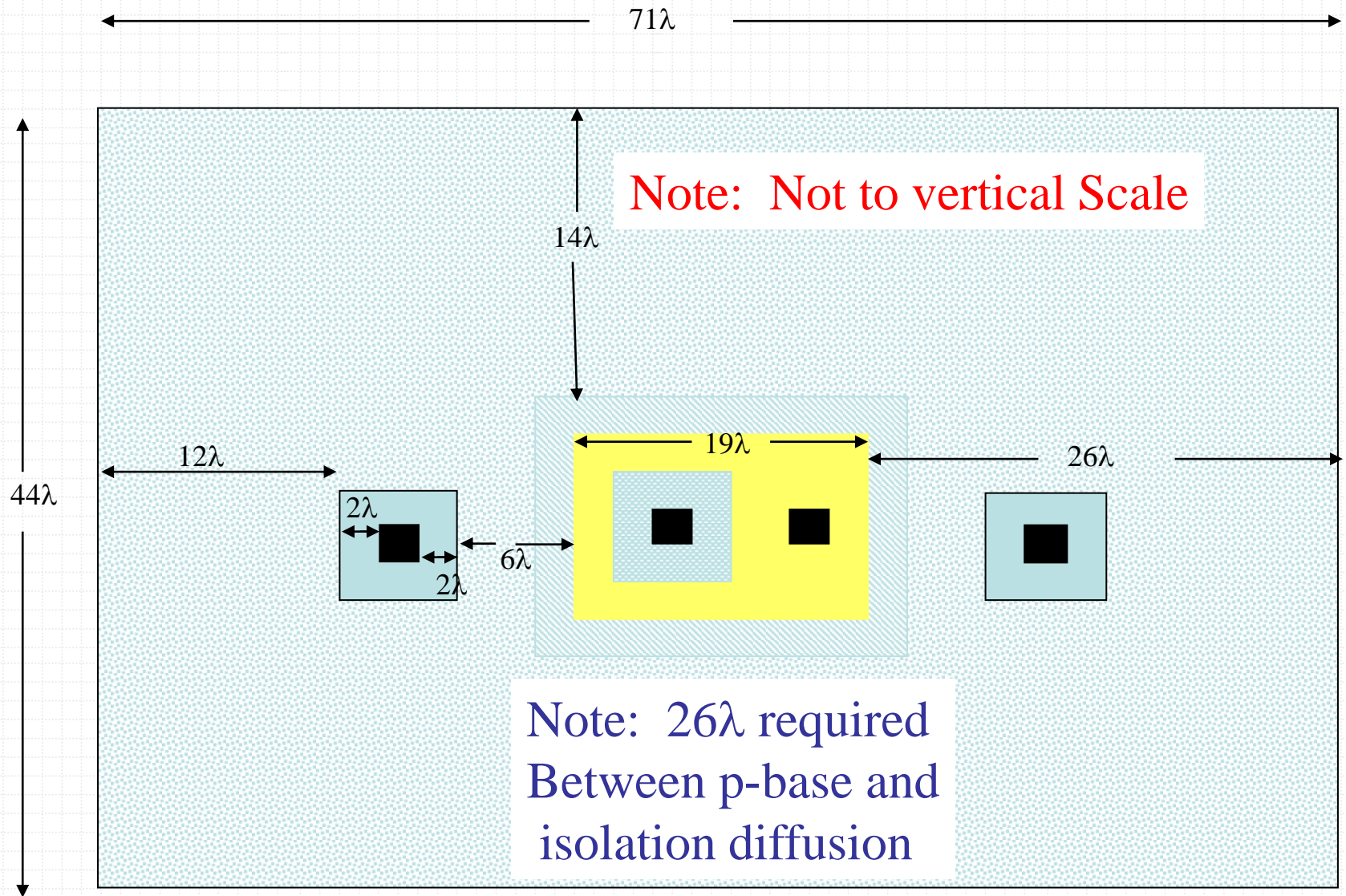
5. Contact (Black, Mask #5)	
5.1 Size (exactly)	$4\lambda \times 4\lambda$
5.2 Spacing	2λ
5.3 Metal overlap of contact	λ
5.4 n^+ emitter diffusion overlap of contact	2λ
5.5 p-base diffusion overlap of contact	2λ
5.6 p-base to n^+ emitter	3λ
5.7 Spacing to isolation diffusion	4λ
6. Metalization (Blue, Mask #6)	
6.1 Width	2λ
6.2 Spacing	2λ
6.3 Bonding pad size	$100\ \mu \times 100\ \mu$
6.4 Probe pad size	$75\ \mu \times 75\ \mu$
6.5 Bonding pad separation	$50\ \mu$
6.6 Bonding to probe pad	$30\ \mu$
6.7 Probe pad separation	$30\ \mu$
6.8 Pad to circuitry	$40\ \mu$
6.9 Maximum current density	$0.8\ \text{mA}/\mu\ \text{width}$
7. Passivation (Purple, Mask #7)	
7.1 Minimum bonding pad opening	$90\ \mu \times 90\ \mu$
7.2 Minimum probe pad opening	$65\ \mu \times 65\ \mu$

1 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75
But, there are some rather strict rules relating to the epi contact

5 from (left to right) rules 4.4, 5.4, 4.6



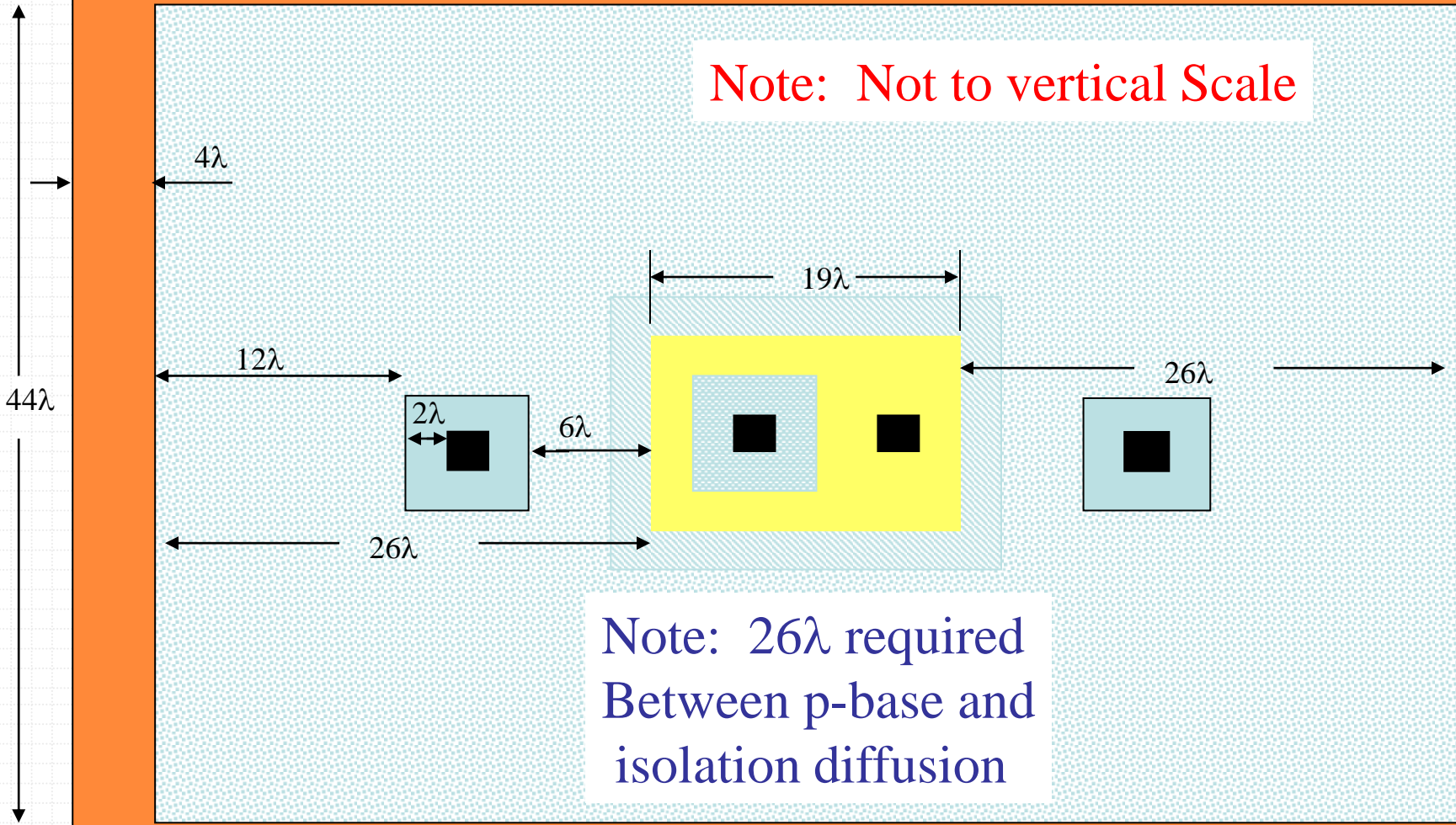
Consider a structure with a collector contact on both sides of epi



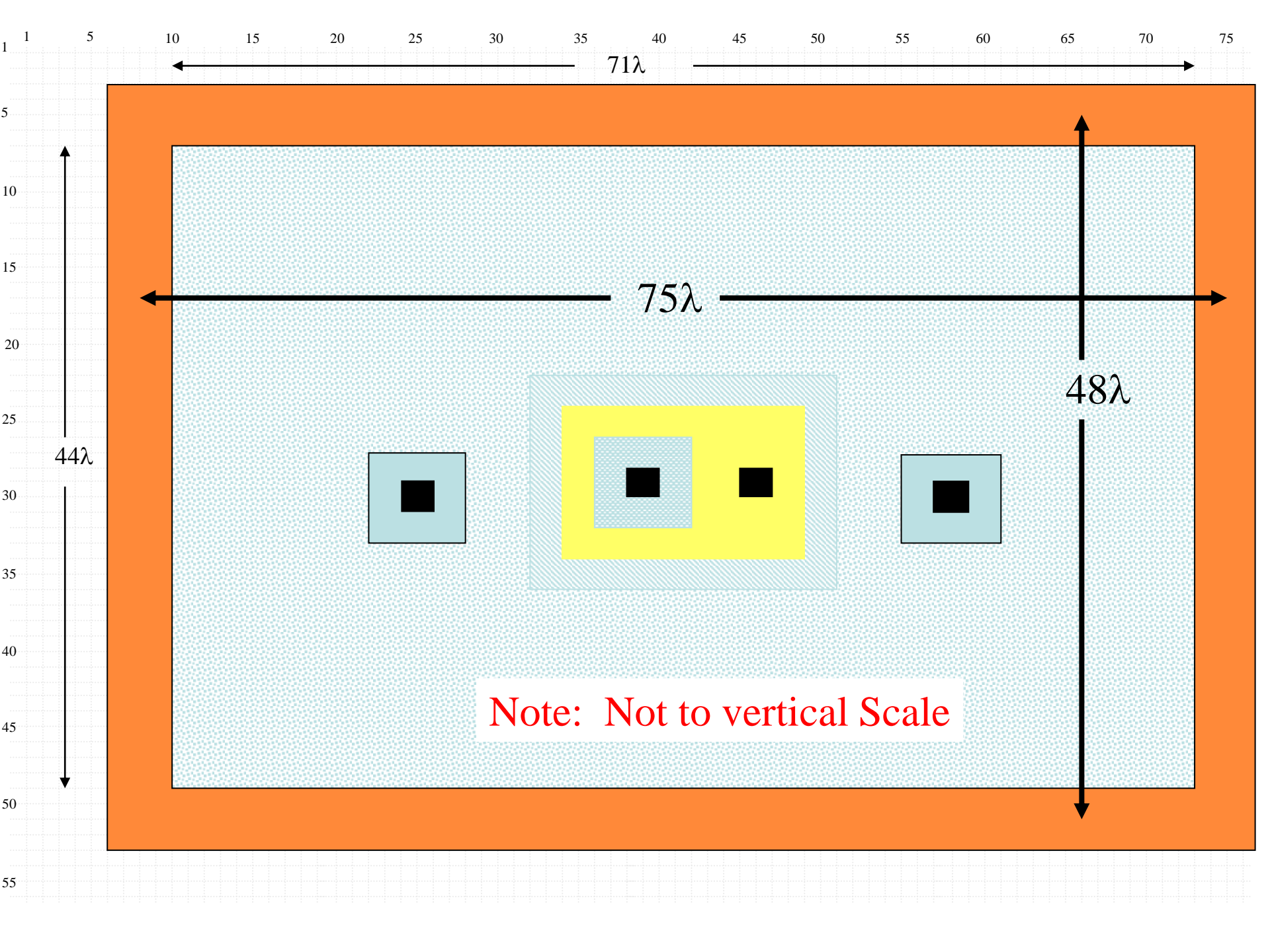
1 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75

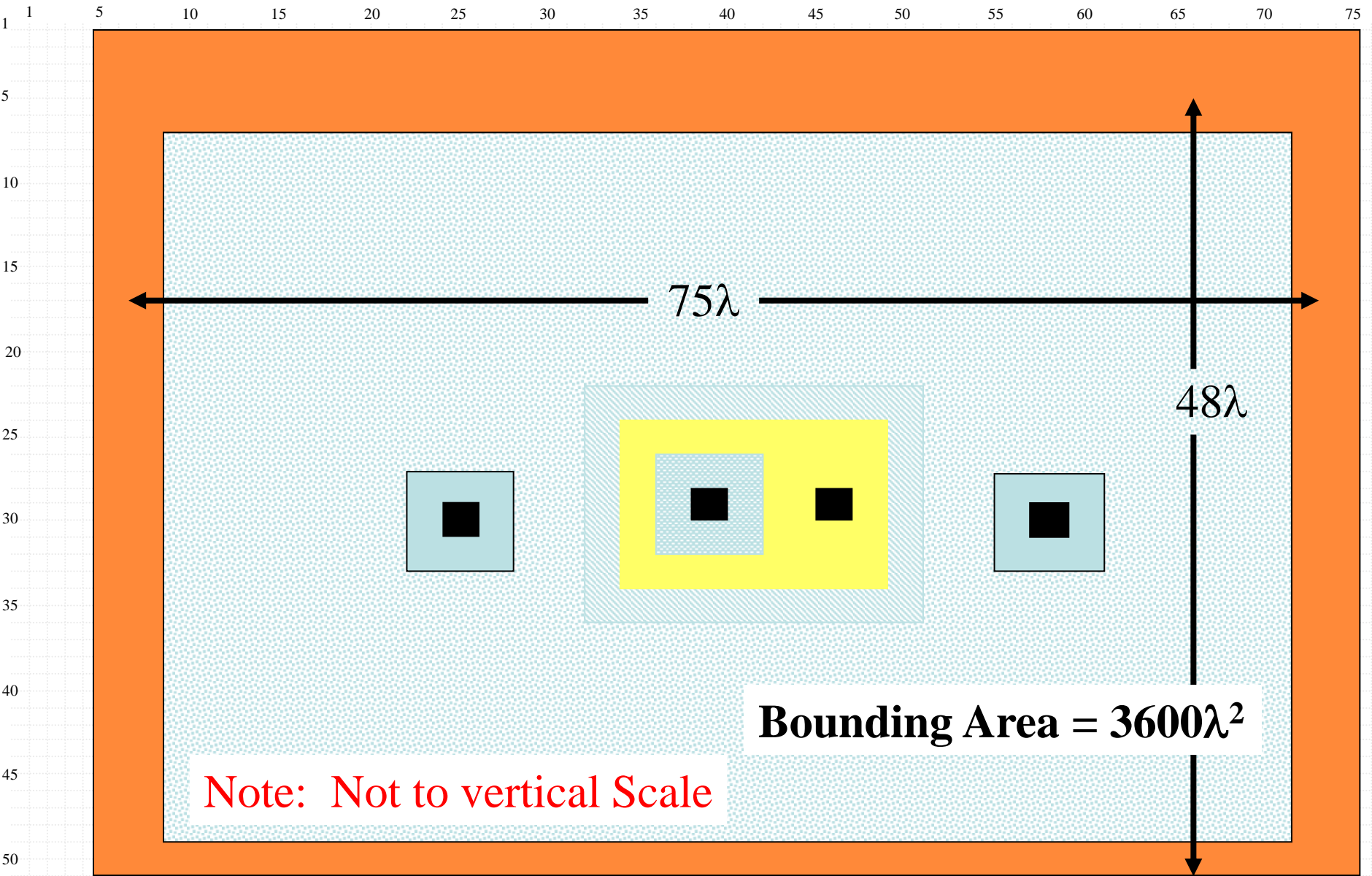
71λ

Note: Not to vertical Scale



Note: 26λ required
Between p-base and
isolation diffusion

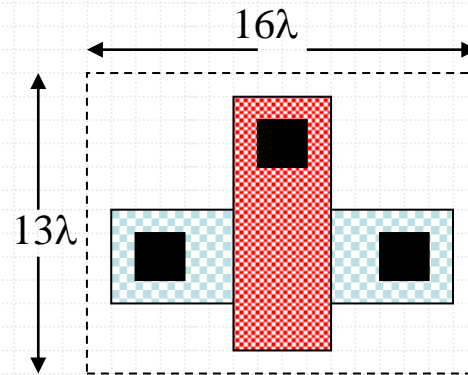




55

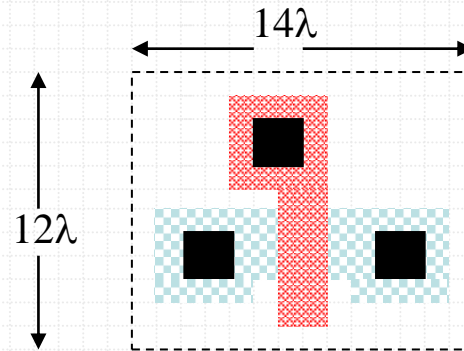
Major contributor to large size of BJT is the isolation diffusion which diffuses laterally a large distance beyond the drawn edges of the isolation mask

Comparison with Area for n-channel MOSFET in Bulk CMOS



Bounding Area = $208\lambda^2$

Minimum-Sized MOSFET



Bounding Area = $168\lambda^2$

Active Area = $6\lambda^2$

1 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75

1

5

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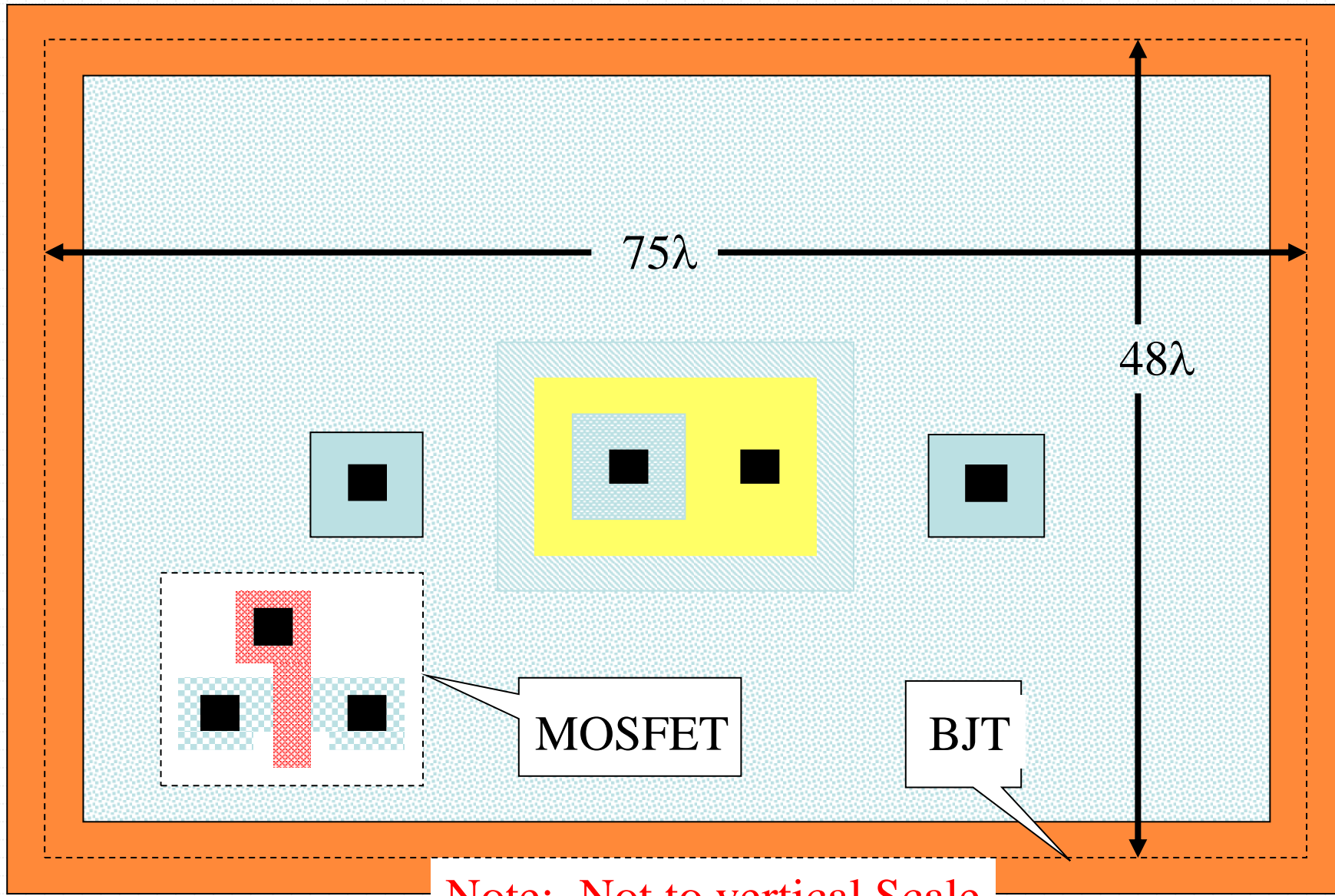
35

40

45

50

55



MOSFET

BJT

Note: Not to vertical Scale

Area Comparison between BJT and MOSFET

- BJT Area = $3600 \lambda^2$
- n-channel MOSFET Area = $168 \lambda^2$
- Area Ratio = 21:1



Stay Safe and Stay Healthy !

End of Lecture 21