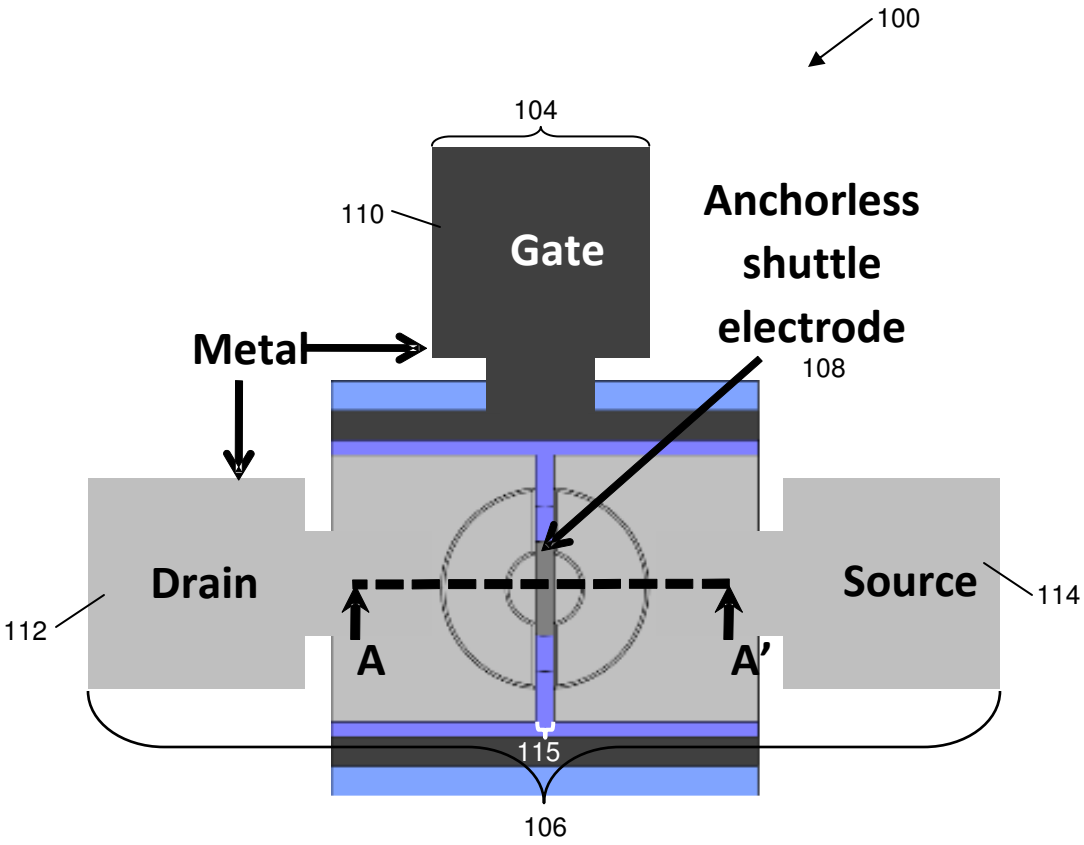

100
104
110
Gate
Anchorless
shuttle
electrode
108
Metal
Drain
112
Source
114
A
A'
115
106

Figure 1a

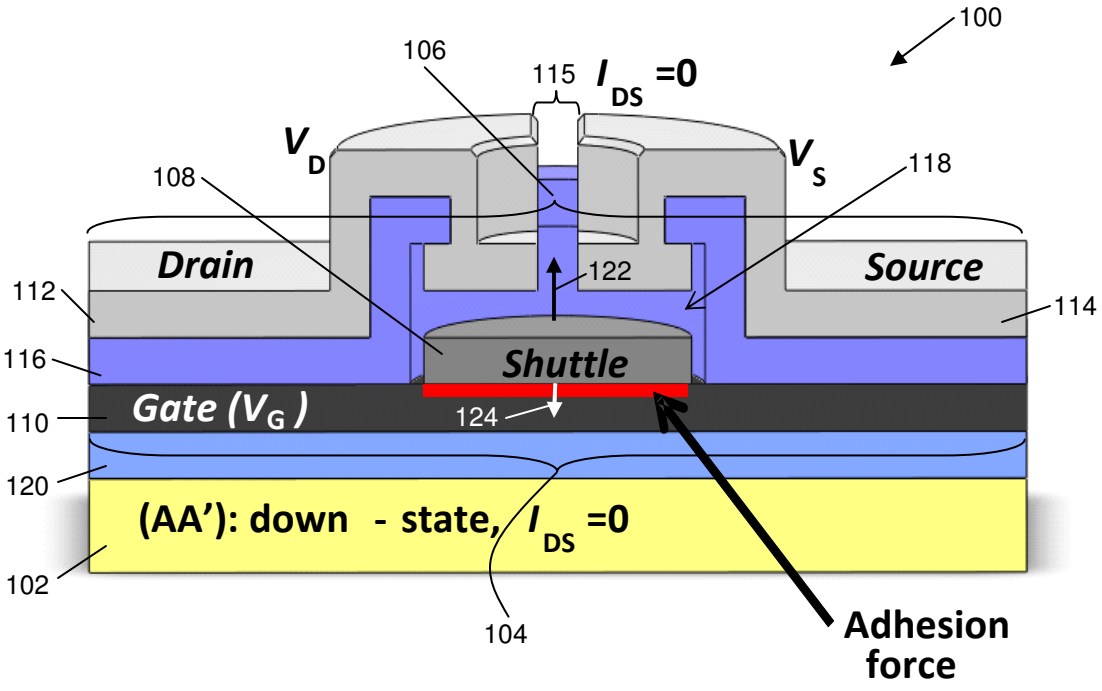


Figure 1b

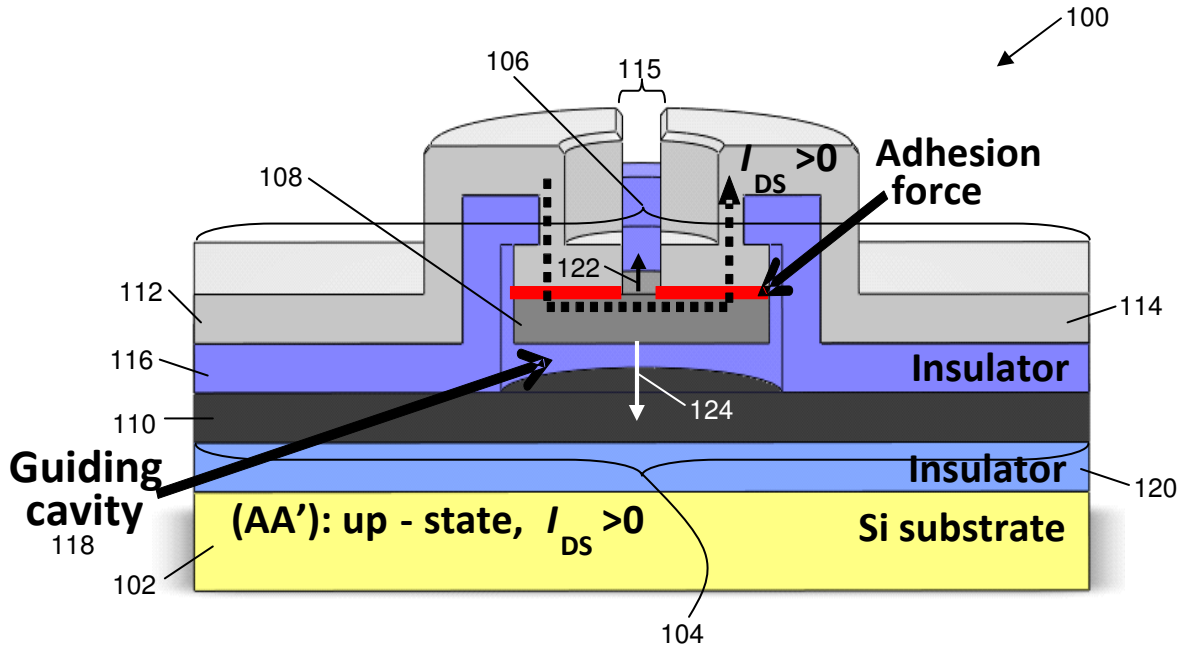


Figure 1c

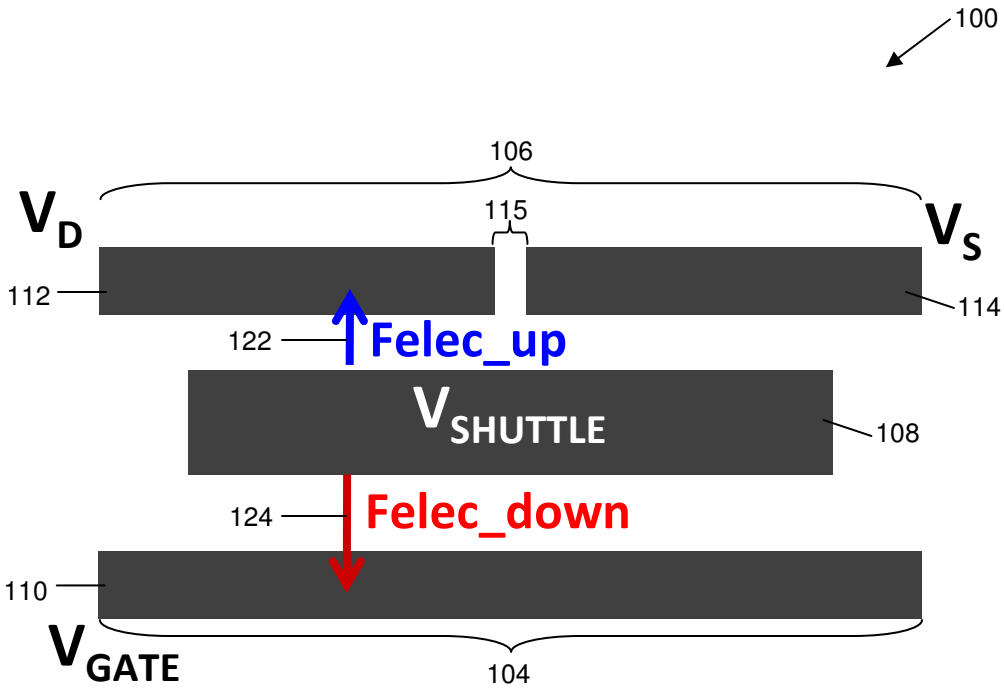

100
106
V_D
115
V_S
112
114
122
Felec_up
$V_{SHUTTLE}$
108
124
Felec_down
110
V_{GATE}
104

Figure 1d

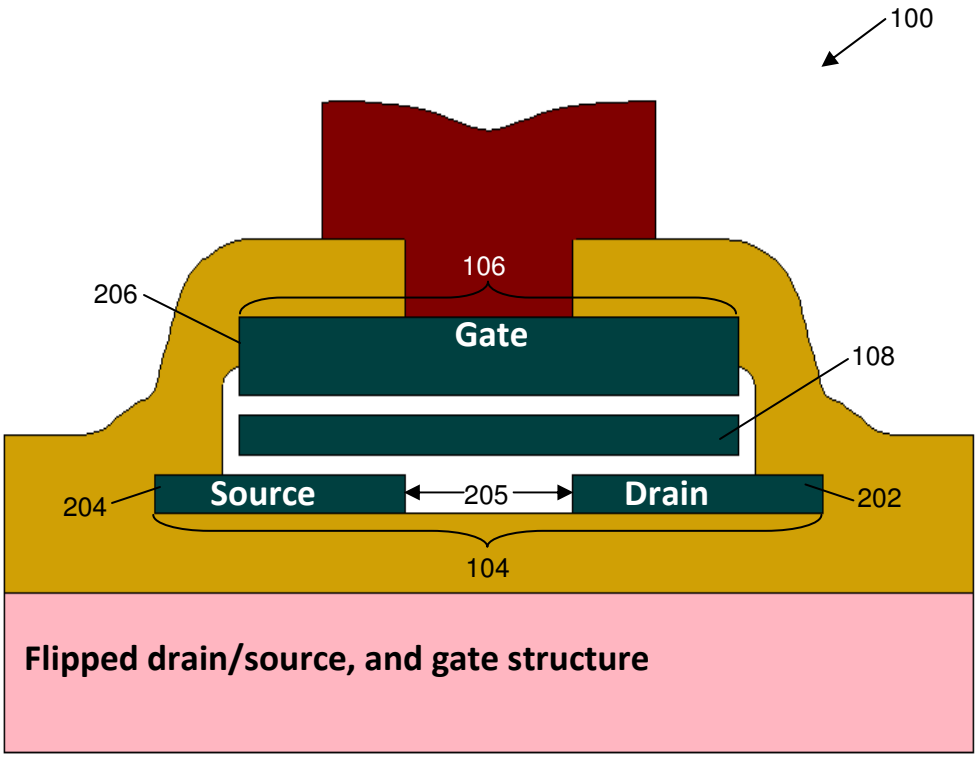

100
106
206
Gate
108
204
Source
205
Drain
202
104
Flipped drain/source, and gate structure

Figure 2

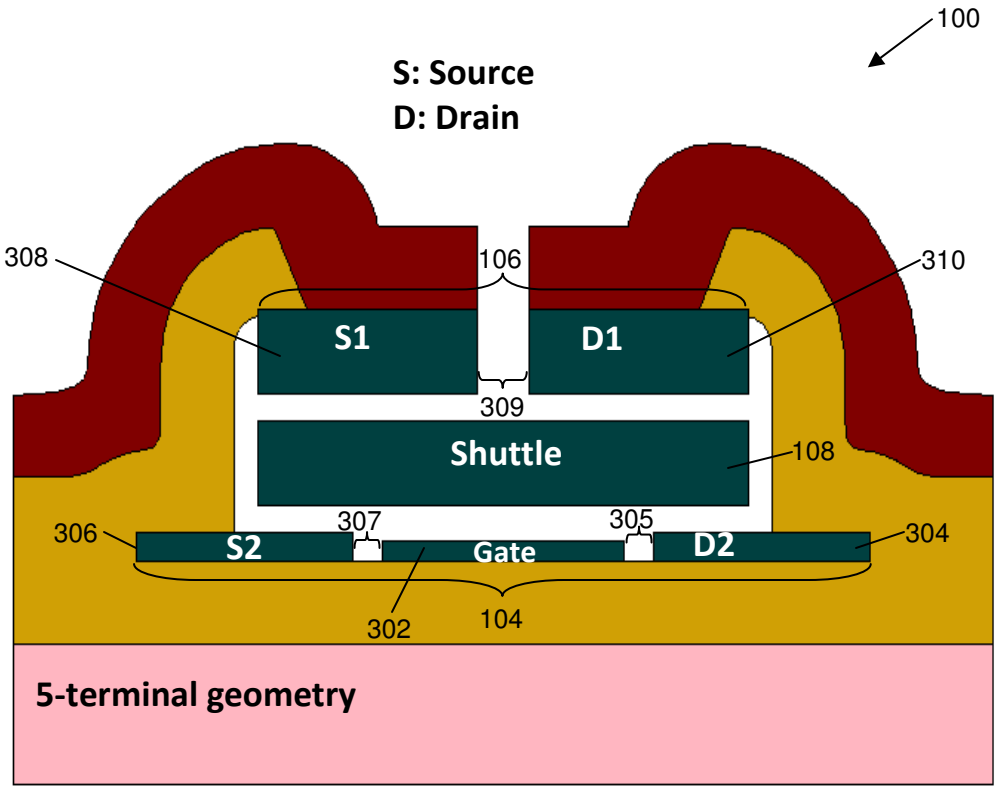

100
S: Source
D: Drain
308
106
310
S1
D1
309
Shuttle
108
306
307
305
304
S2
Gate
D2
302
104
5-terminal geometry

Figure 3

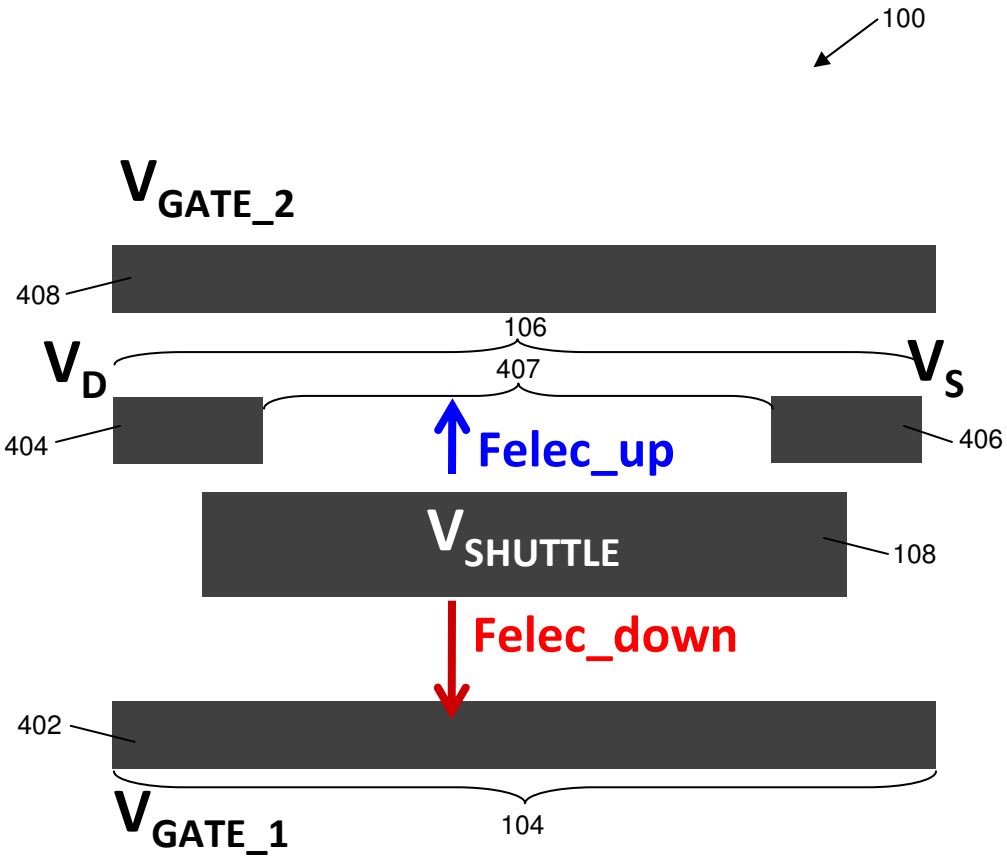

100
V_{GATE_2}
408
106
V_D
407
V_S
404
406
Felec_up
$V_{SHUTTLE}$
108
Felec_down
402
V_{GATE_1}
104

Figure 4

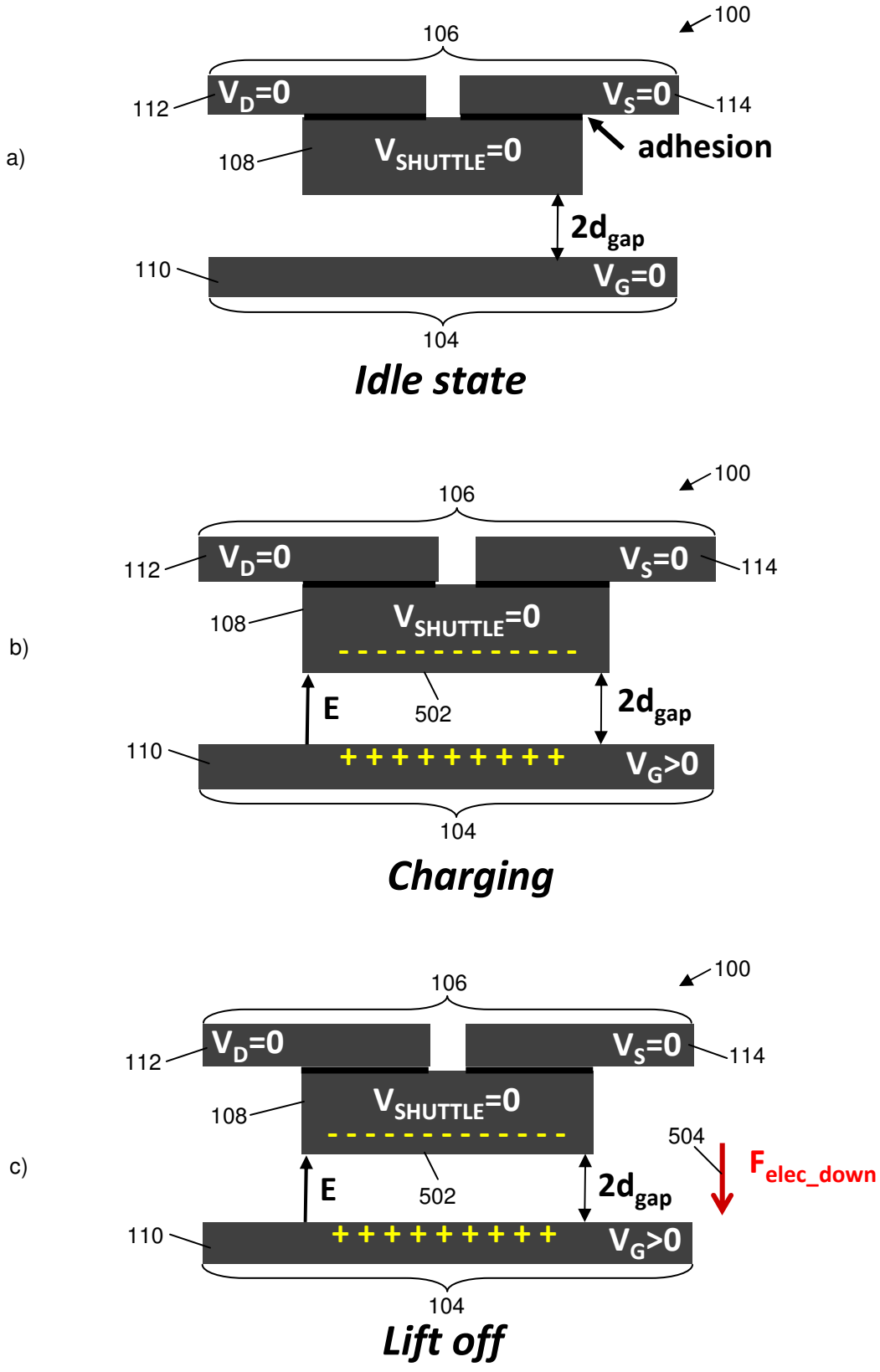
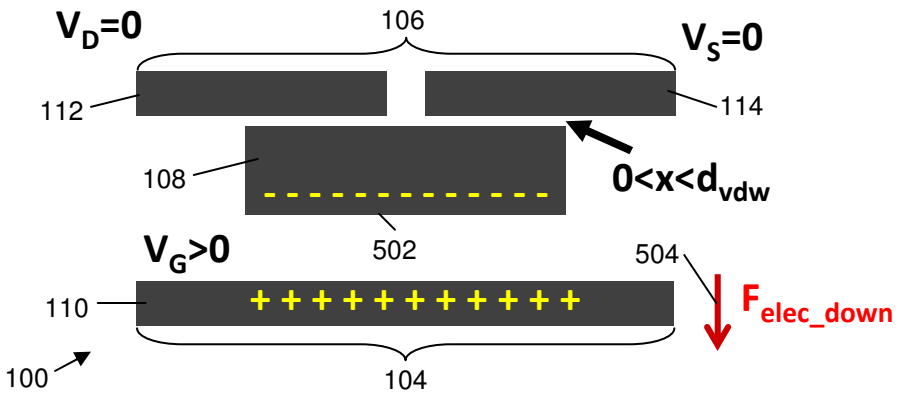

a)
100
106
112
V_D=0
V_S=0
114
adhesion
108
$V_{SHUTTLE}$=0
$2d_{gap}$
110
V_G=0
104
Idle state
b)
100
106
112
V_D=0
V_S=0
114
108
$V_{SHUTTLE}$=0
E
502
$2d_{gap}$
110
V_G>0
104
Charging
c)
100
106
112
V_D=0
V_S=0
114
108
$V_{SHUTTLE}$=0
504
F_{elec_down}
E
502
$2d_{gap}$
110
V_G>0
104
Lift off

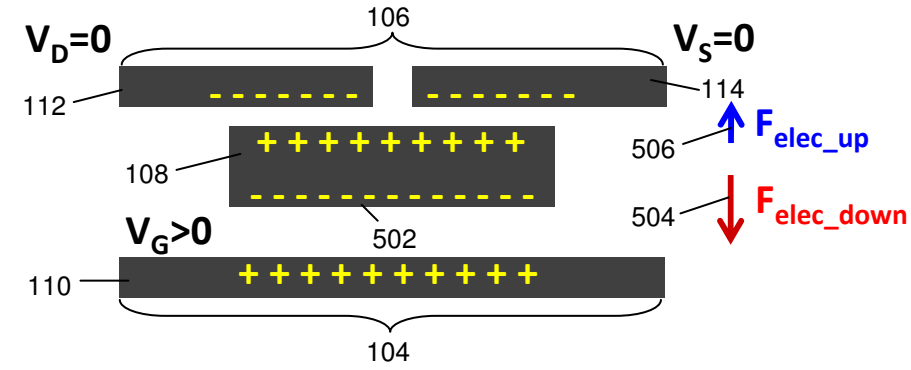
Figure 5

d)



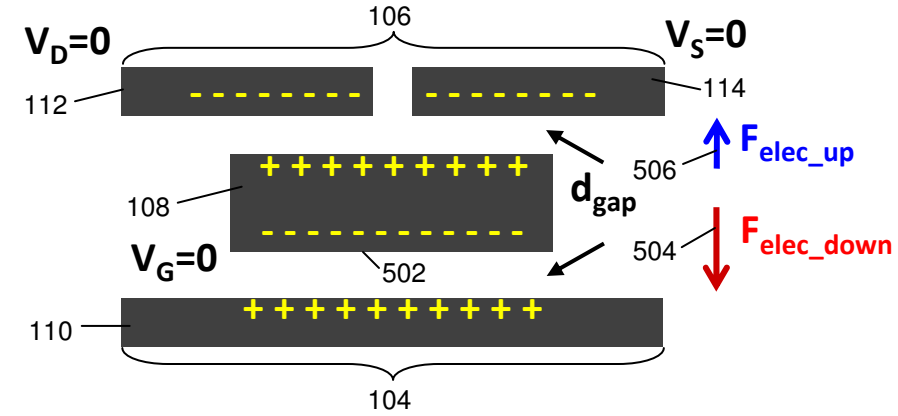
Van der Waals flight

e)



Acceleration phase

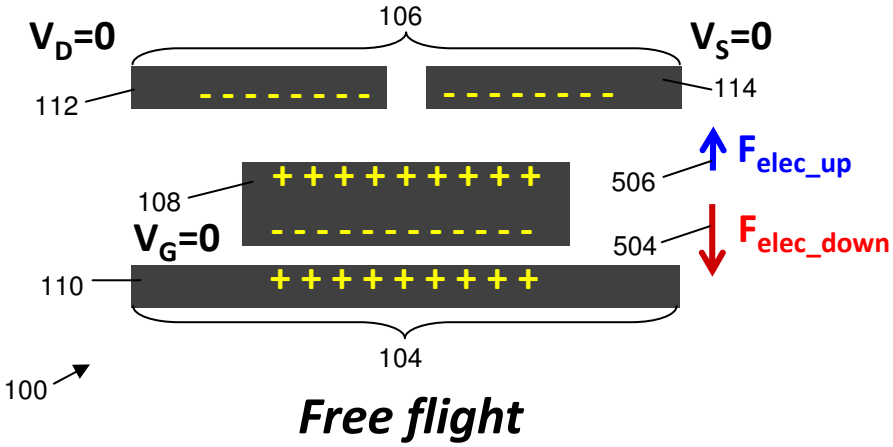
f)



Middle flight

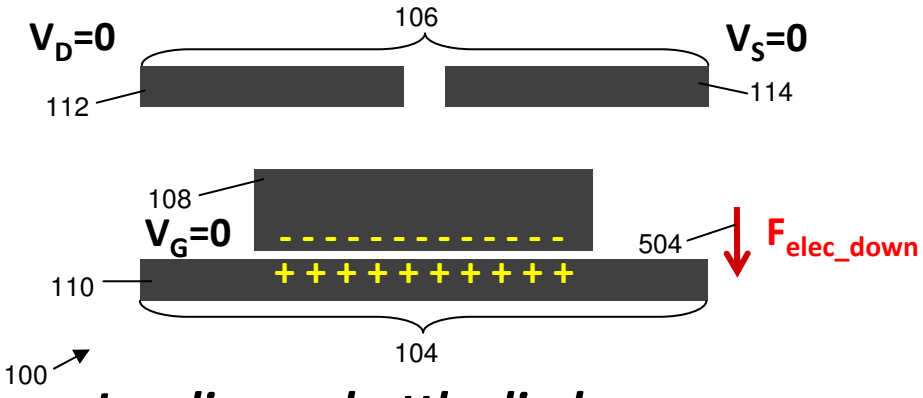
Figure 5

g)



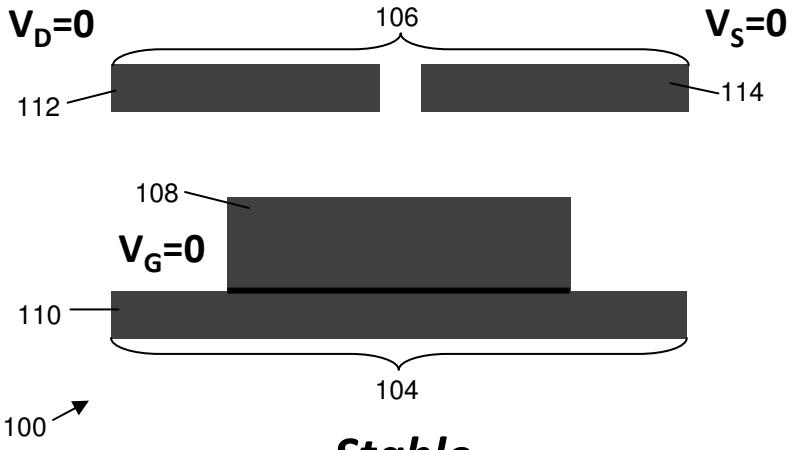
Free flight

h)



Landing + shuttle discharge

i)



Stable

Figure 5

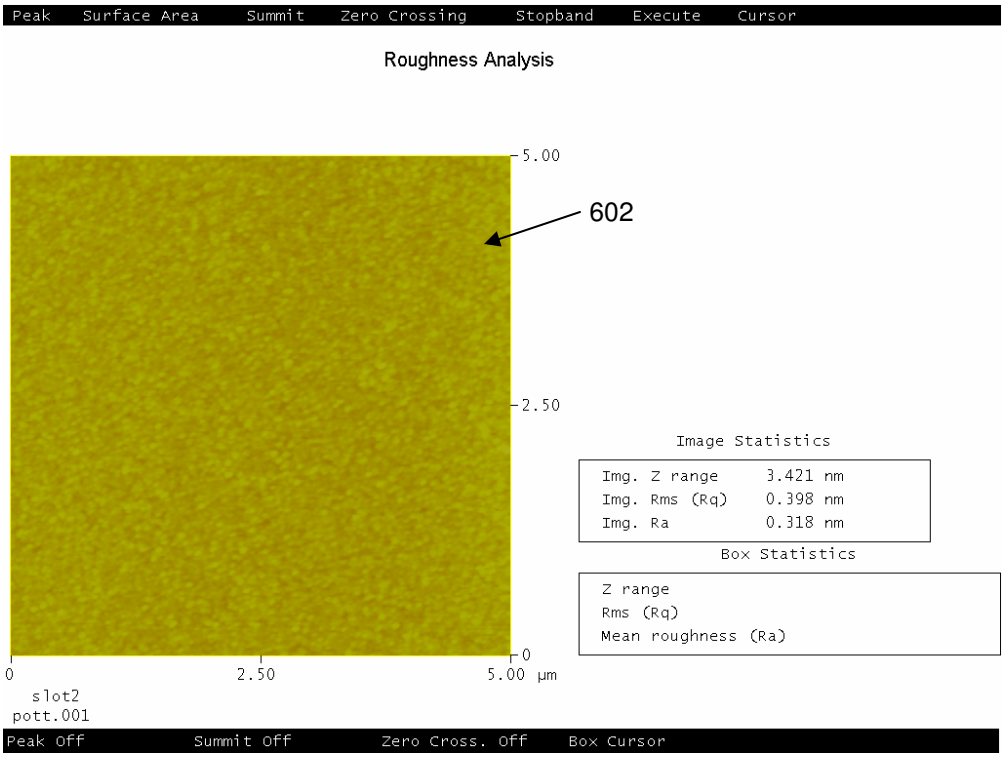

Peak
Surface Area
Summit
Zero Crossing
Stopband
Execute
Cursor
Roughness Analysis
5.00
602
2.50
0
0
2.50
5.00 µm
slot2
pott.001
Image Statistics
Img. Z range 3.421 nm
Img. Rms (Rq) 0.398 nm
Img. Ra 0.318 nm
Box Statistics
Z range
Rms (Rq)
Mean roughness (Ra)
Peak Off
Summit Off
Zero Cross. Off
Box Cursor

Figure 6

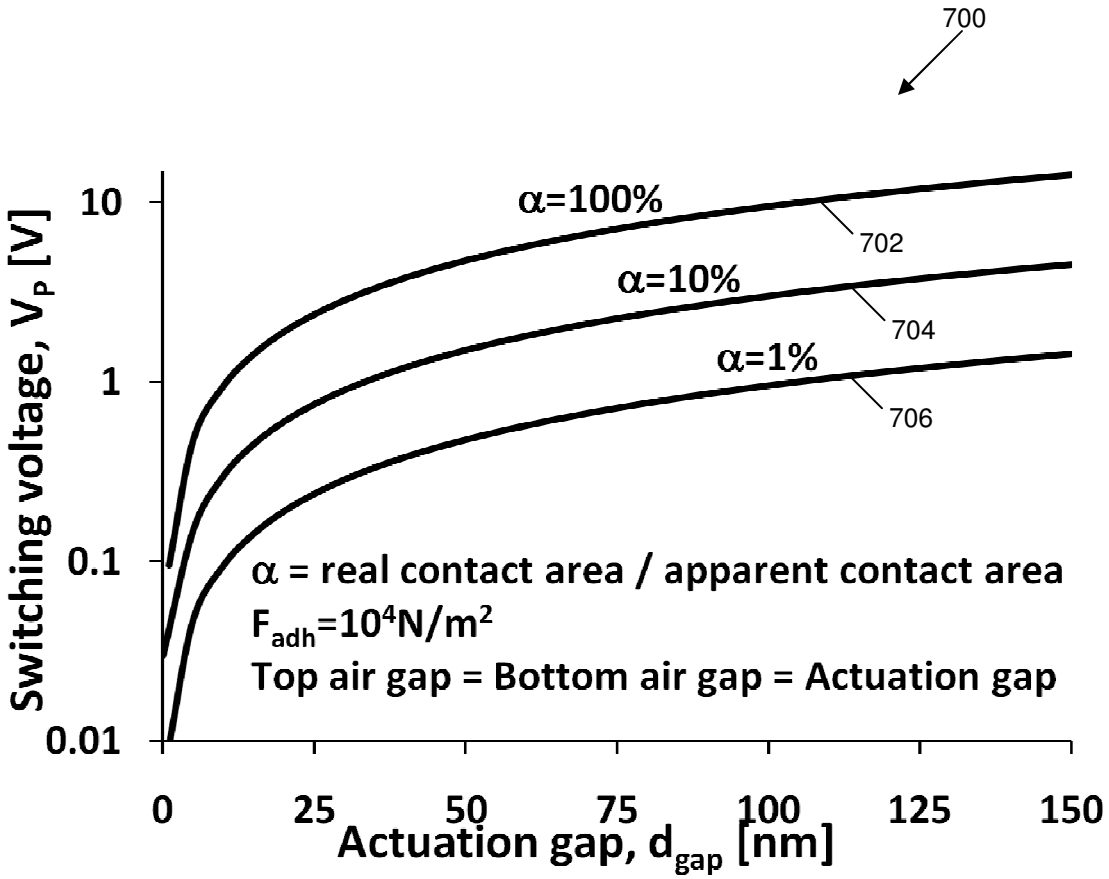

700
Switching voltage, V_P [V]
10
1
0.1
0.01
α=100%
α=10%
α=1%
702
704
706
α = real contact area / apparent contact area
$F_{adh}=10^4 N/m^2$
Top air gap = Bottom air gap = Actuation gap
0
25
50
75
100
125
150
Actuation gap, d_{gap} [nm]

Figure 7

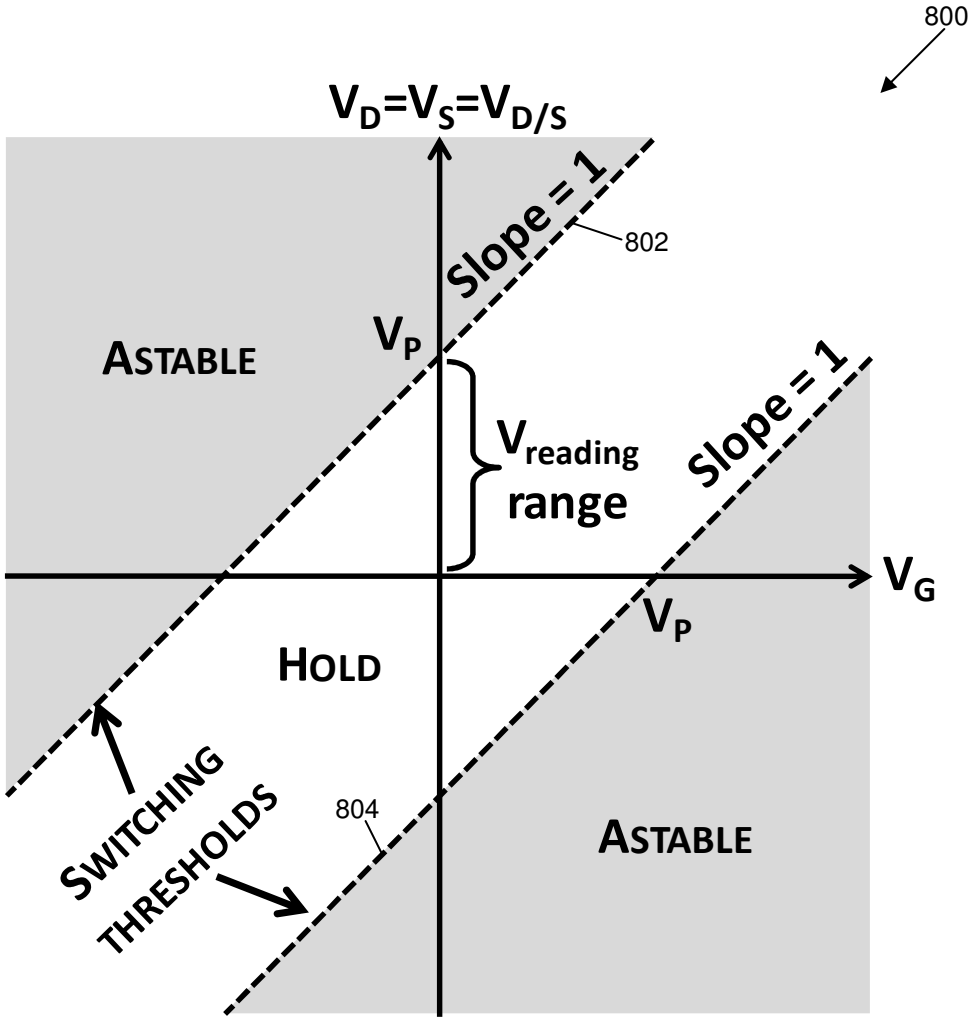

800
$V_D=V_S=V_{D/S}$
Slope = 1
802
ASTABLE
V_P
$V_{reading}$ range
Slope = 1
V_G
V_P
HOLD
SWITCHING THRESHOLDS
804
ASTABLE

Figure 8

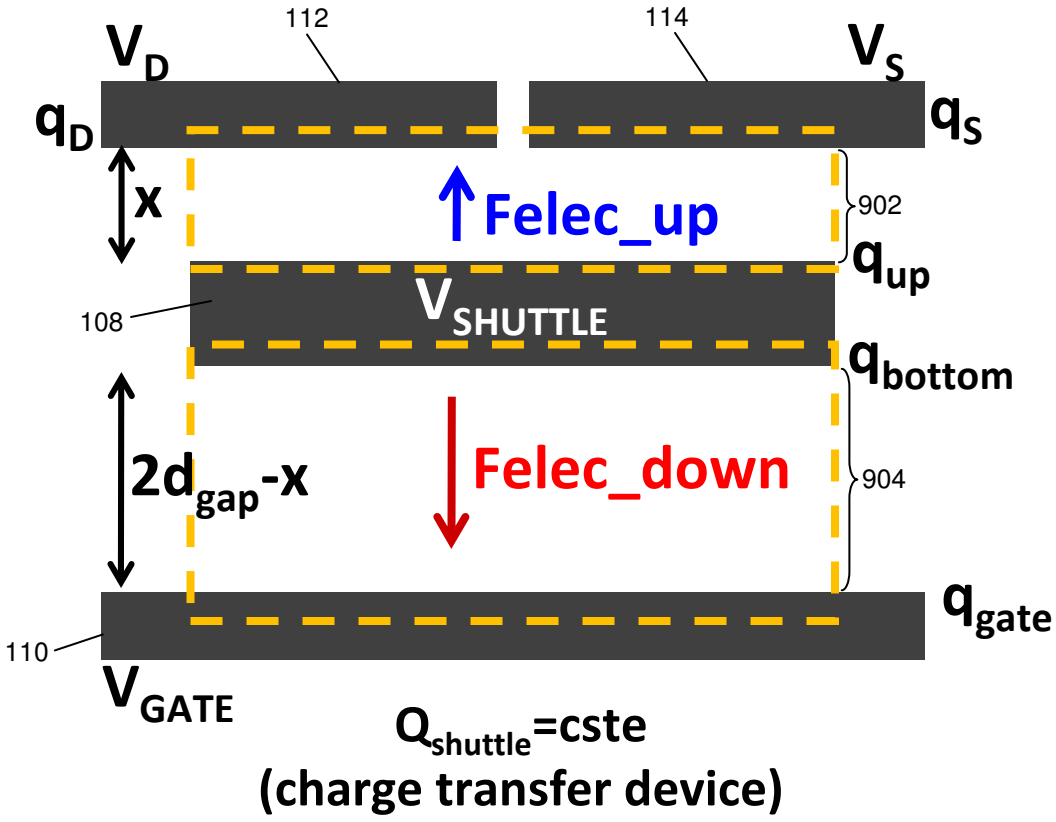
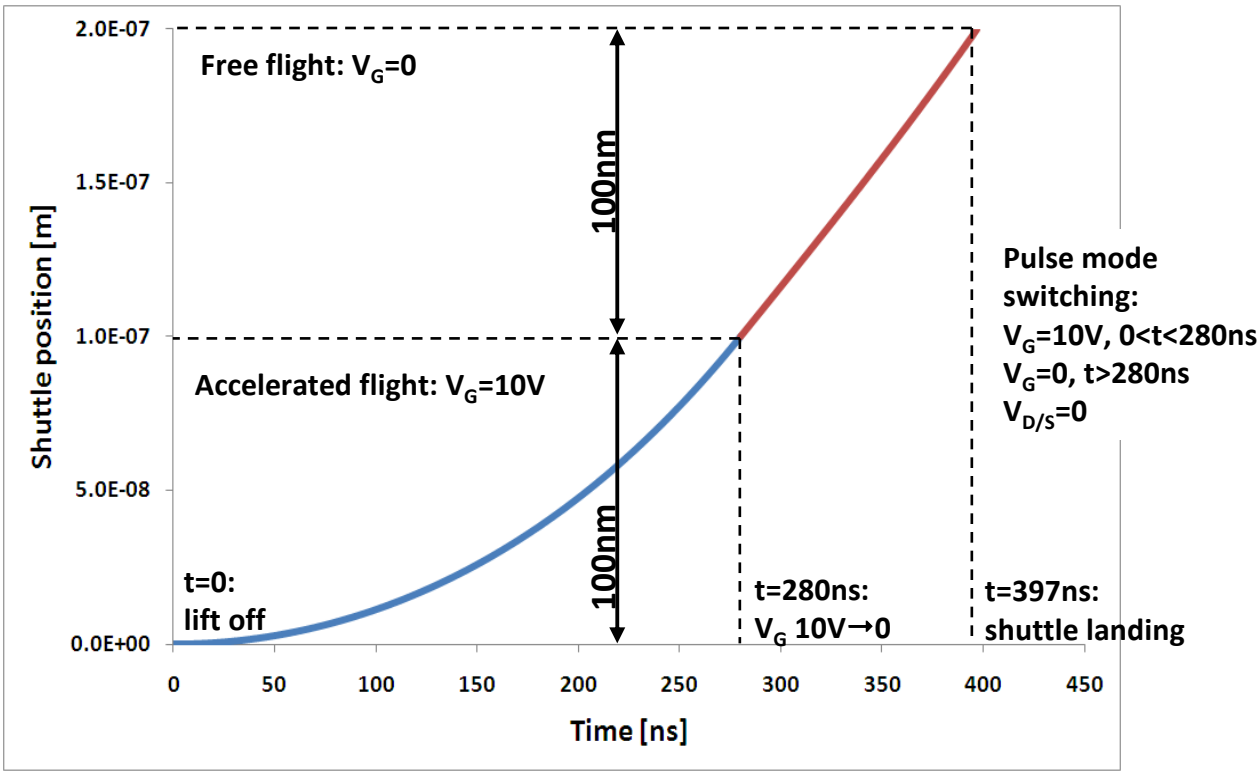
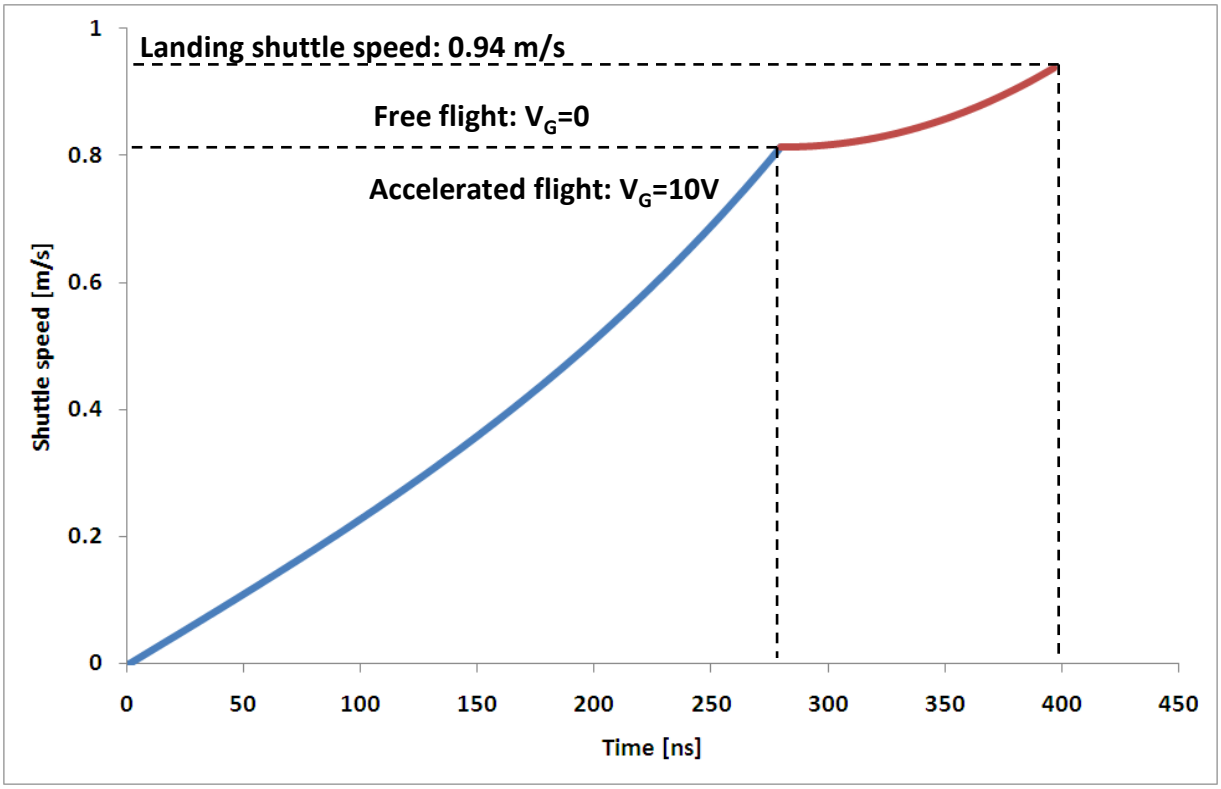

112
114
V_D
V_S
q_D
q_S
x
Felec_up
902
q_{up}
108
$V_{SHUTTLE}$
q_{bottom}
$2d_{gap}$-x
Felec_down
904
q_{gate}
110
V_{GATE}
$Q_{shuttle}$=cste
(charge transfer device)

Figure 9



1000

Figure 10



1100

Figure 11

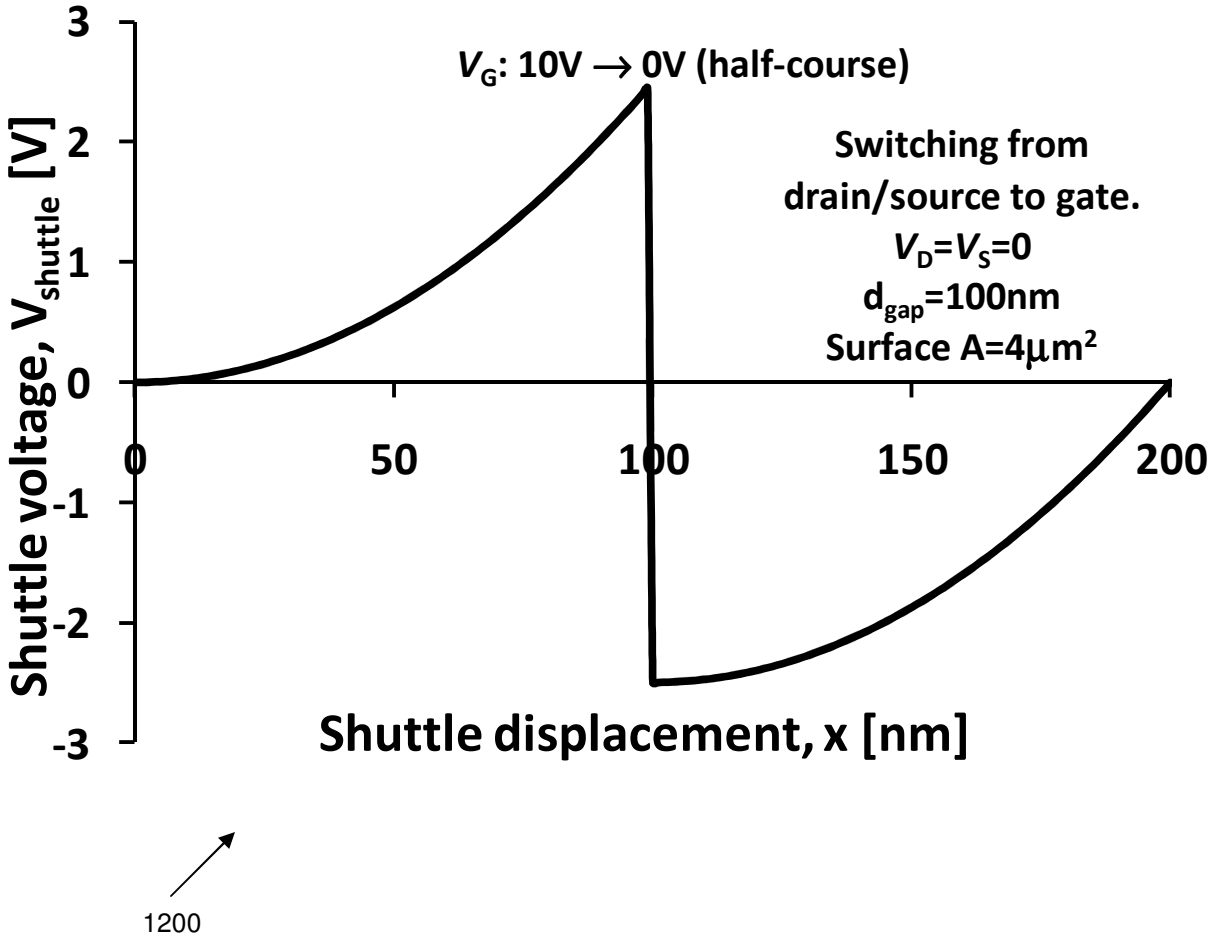

V_G: 10V → 0V (half-course)
Switching from drain/source to gate.
V_D=V_S=0
d_{gap}=100nm
Surface A=4μm²
Shuttle voltage, $V_{shuttle}$ [V]
Shuttle displacement, x [nm]
3
2
1
0
-1
-2
-3
0
50
100
150
200
1200

Figure 12

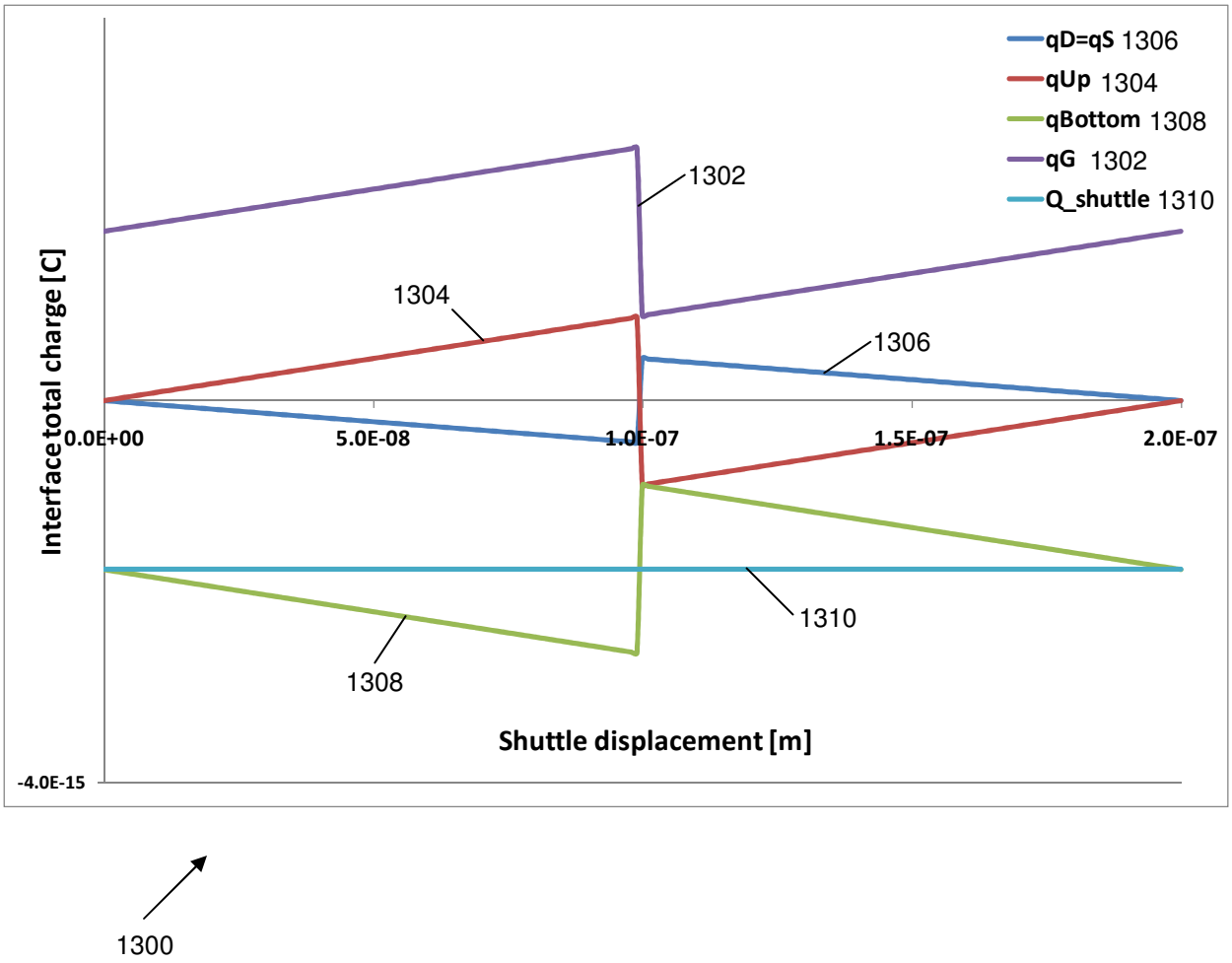

qD=qS 1306
qUp 1304
qBottom 1308
qG 1302
Q_shuttle 1310
1302
1304
1306
1310
1308
Interface total charge [C]
Shuttle displacement [m]
0.0E+00
5.0E-08
1.0E-07
1.5E-07
2.0E-07
-4.0E-15
1300

Figure 13

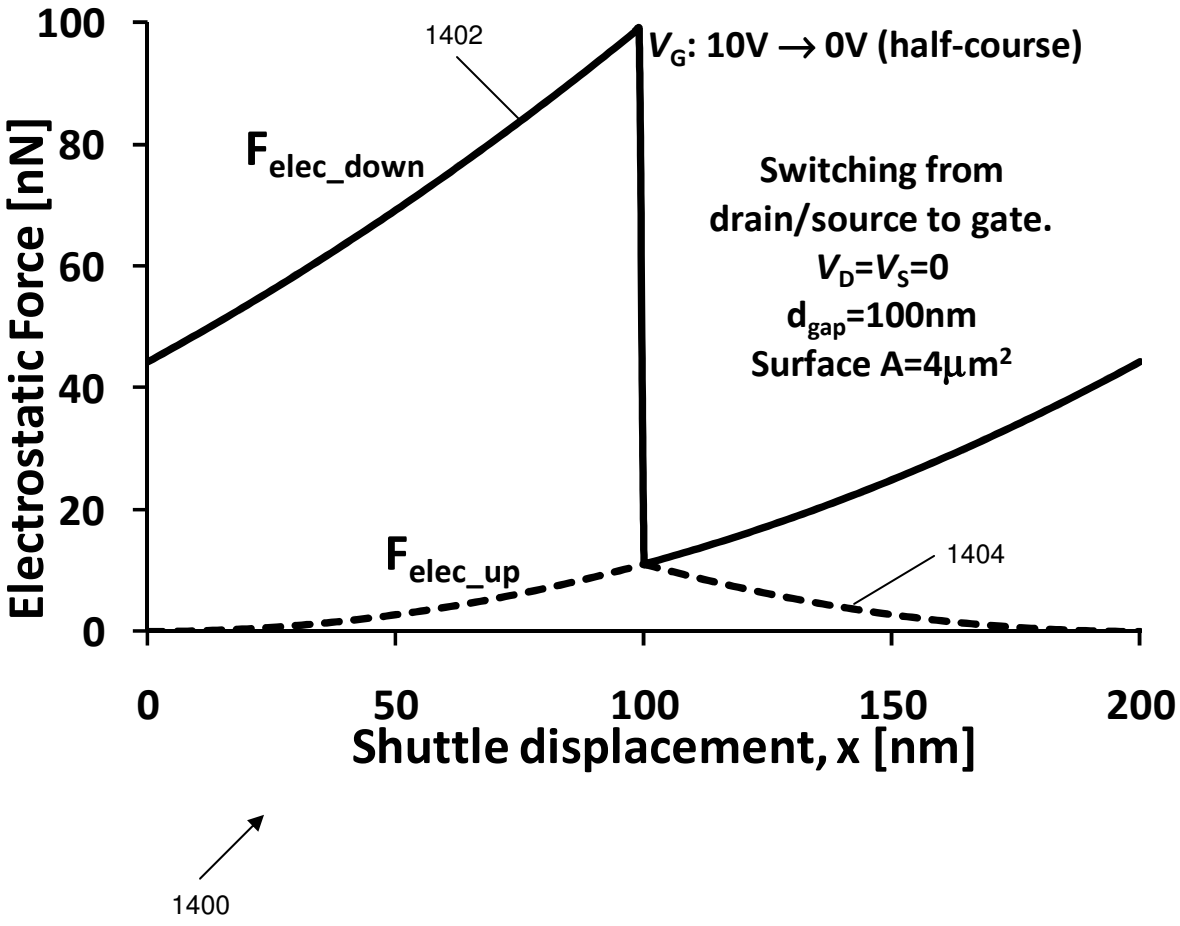

100
80
60
40
20
0
Electrostatic Force [nN]
1402
V_G: 10V → 0V (half-course)
F_{elec_down}
Switching from
drain/source to gate.
V_D=V_S=0
d_{gap}=100nm
Surface A=4μm²
F_{elec_up}
1404
0
50
100
150
200
Shuttle displacement, x [nm]
1400

Figure 14

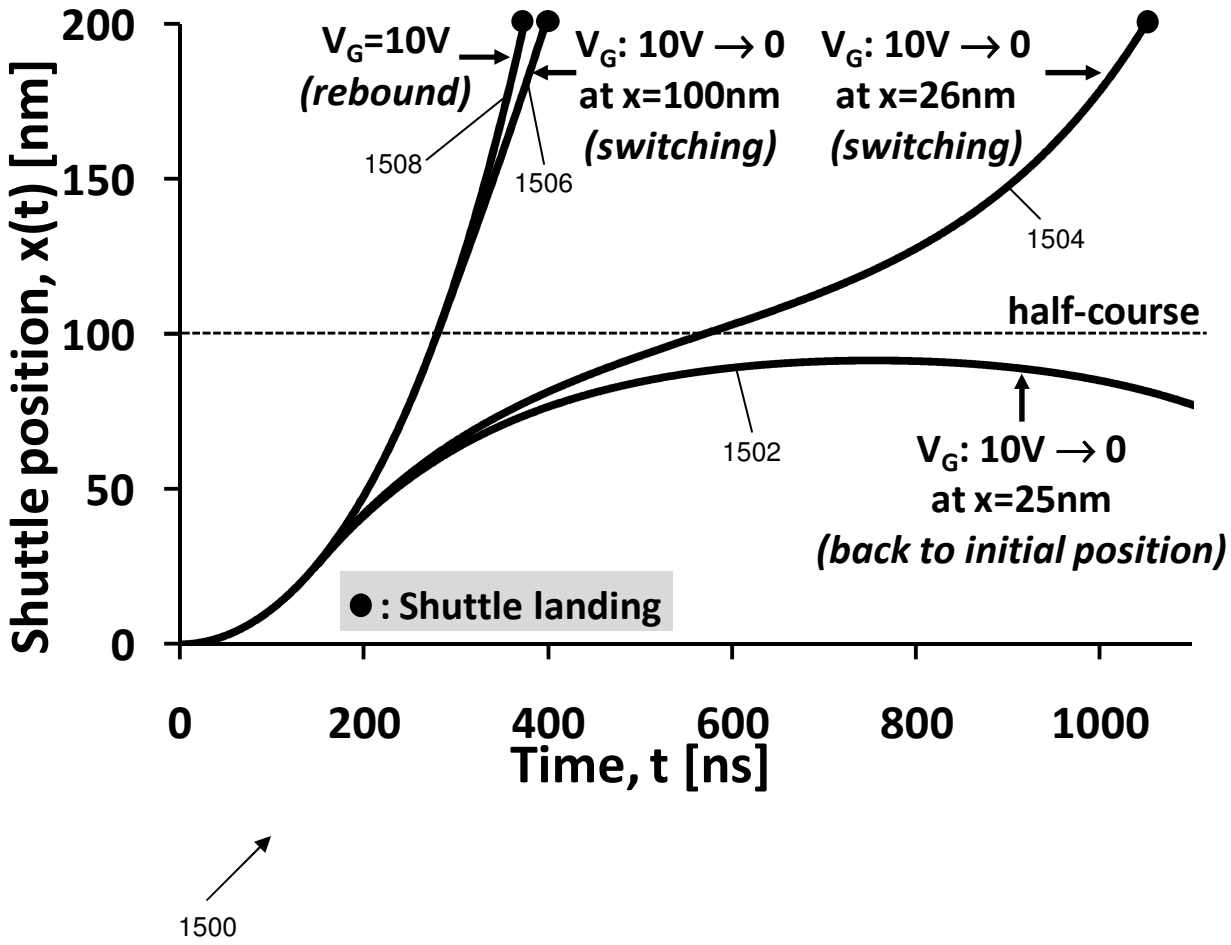
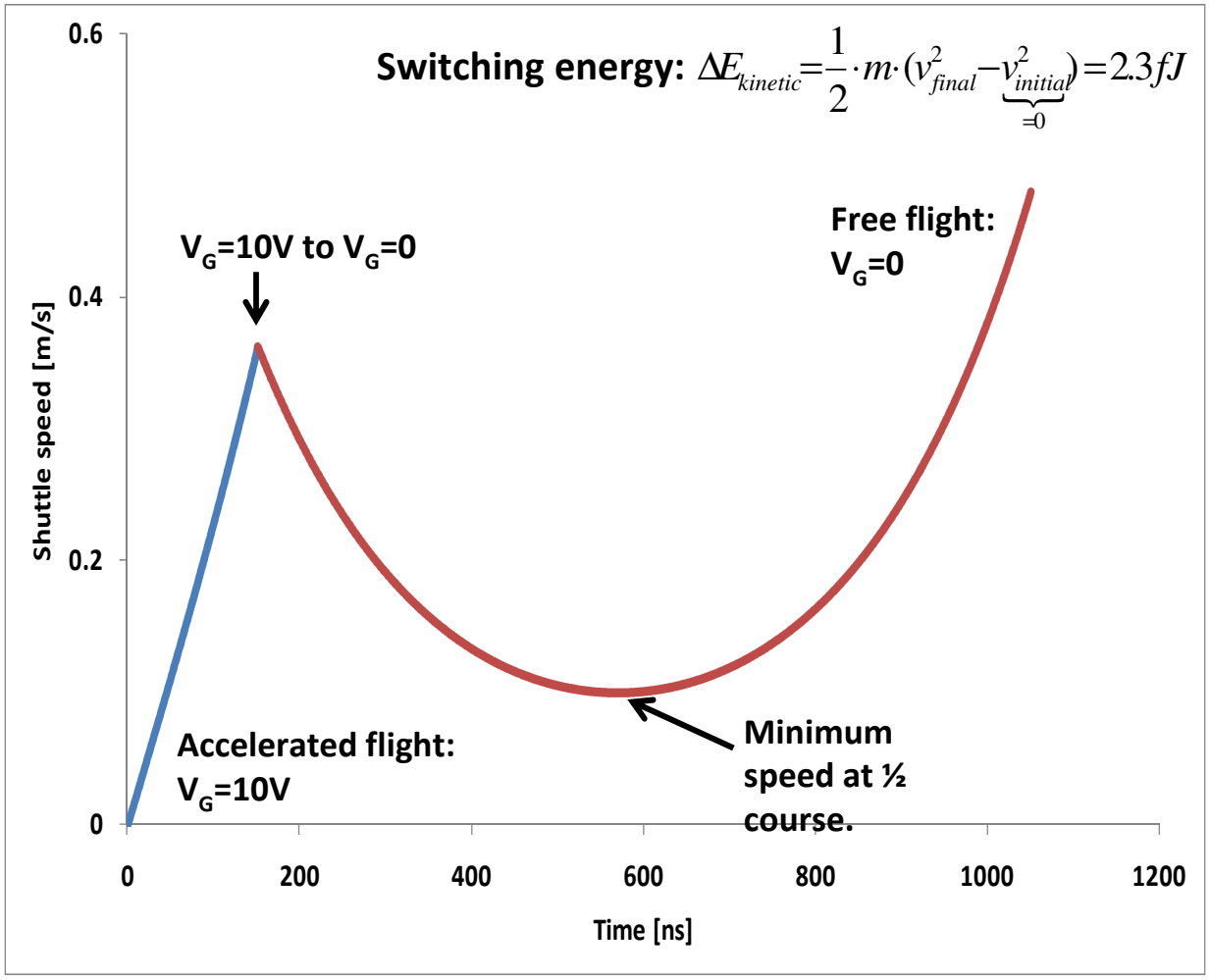

200
150
100
50
0
Shuttle position, x(t) [nm]
V_G=10V
(rebound)
V_G: 10V → 0
at x=100nm
(switching)
V_G: 10V → 0
at x=26nm
(switching)
1508
1506
1504
half-course
1502
V_G: 10V → 0
at x=25nm
(back to initial position)
● : Shuttle landing
0
200
400
600
800
1000
Time, t [ns]
1500

Figure 15a



1510

Figure 15b

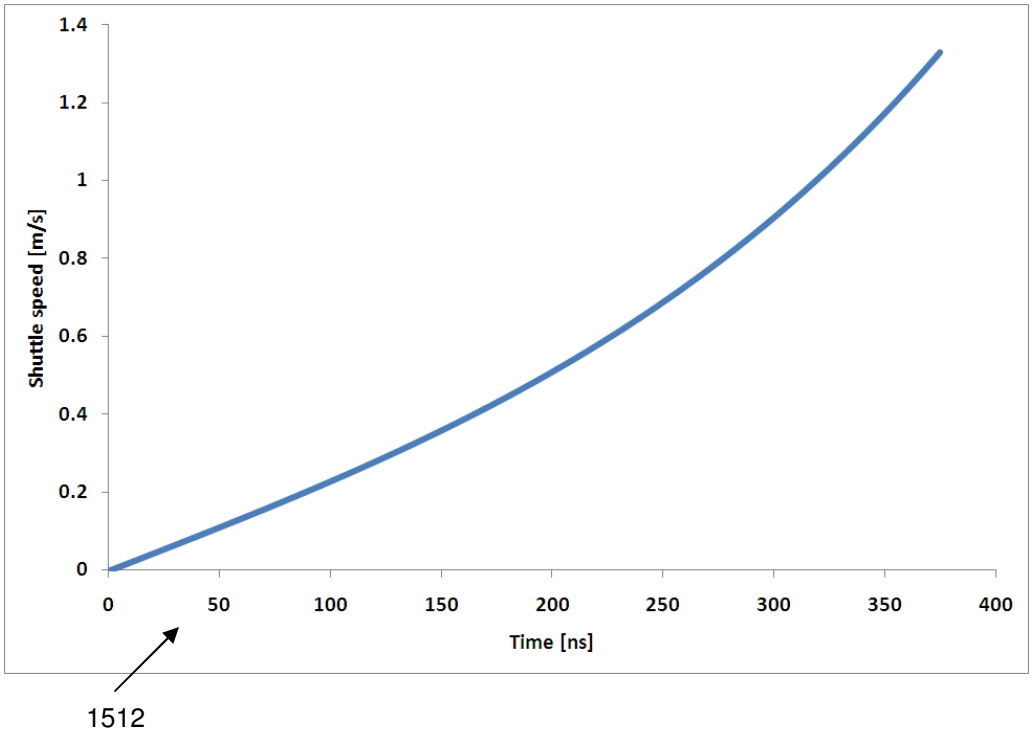


Figure 15c

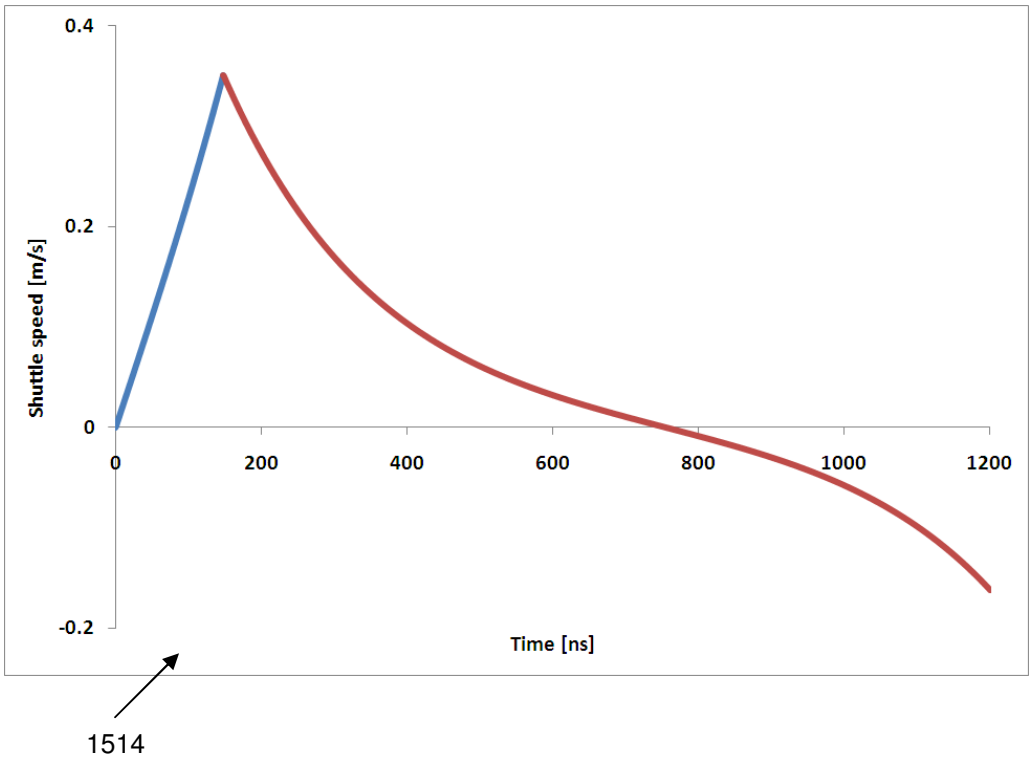


Figure 15d

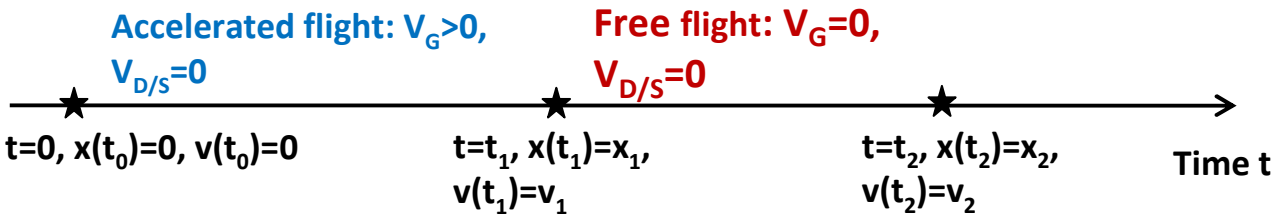

Accelerated flight: $V_G>0$, $V_{D/S}=0$
Free flight: $V_G=0$, $V_{D/S}=0$
$t=0, x(t_0)=0, v(t_0)=0$
$t=t_1, x(t_1)=x_1, v(t_1)=v_1$
$t=t_2, x(t_2)=x_2, v(t_2)=v_2$
Time t

Figure 16

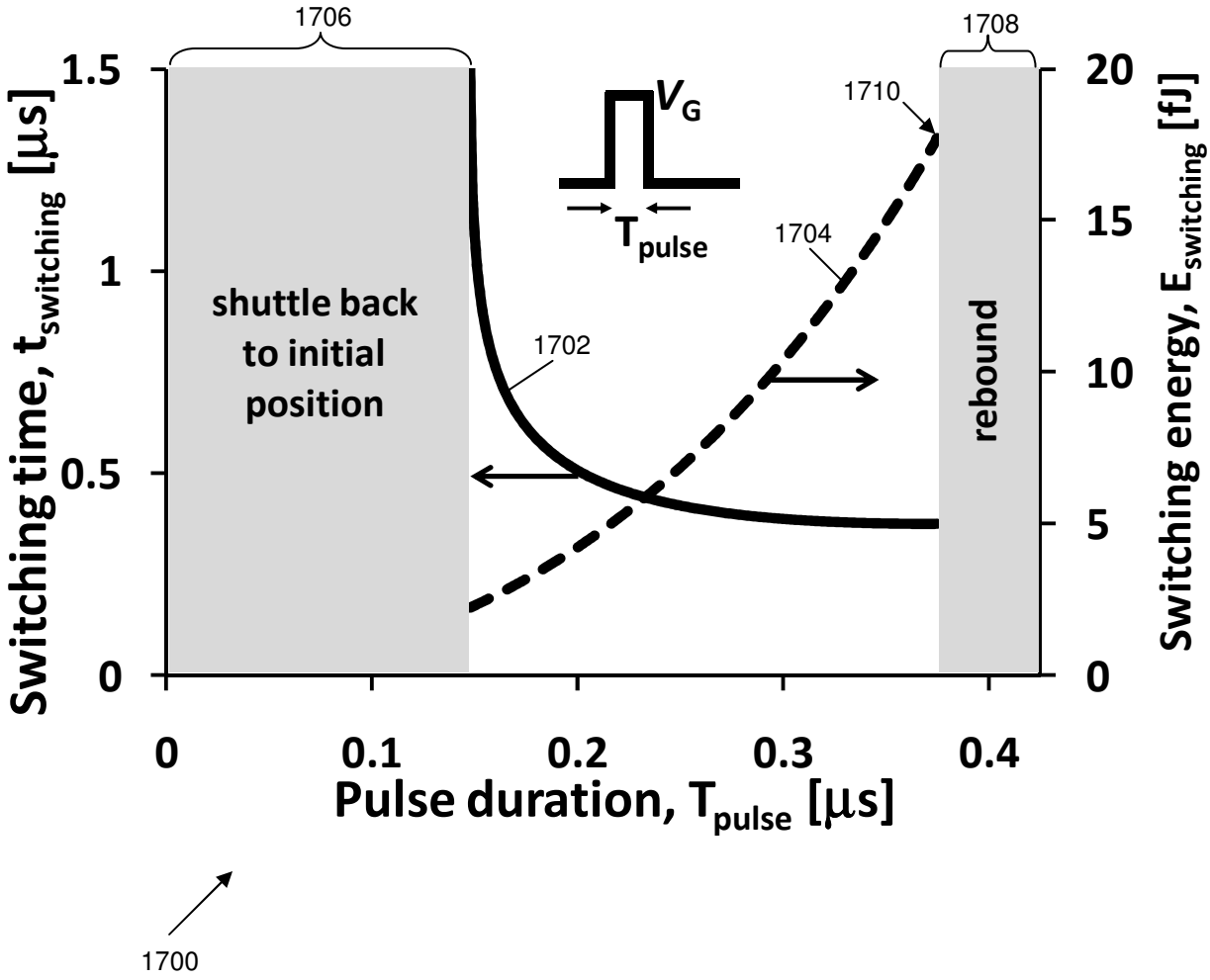

1706
1708
1710
1704
1702
1700
V_G
T_{pulse}
shuttle back to initial position
rebound
Switching time, $t_{switching}$ [μs]
Switching energy, $E_{switching}$ [fJ]
Pulse duration, T_{pulse} [μs]
1.5
1
0.5
0
20
15
10
5
0
0
0.1
0.2
0.3
0.4

Figure 17

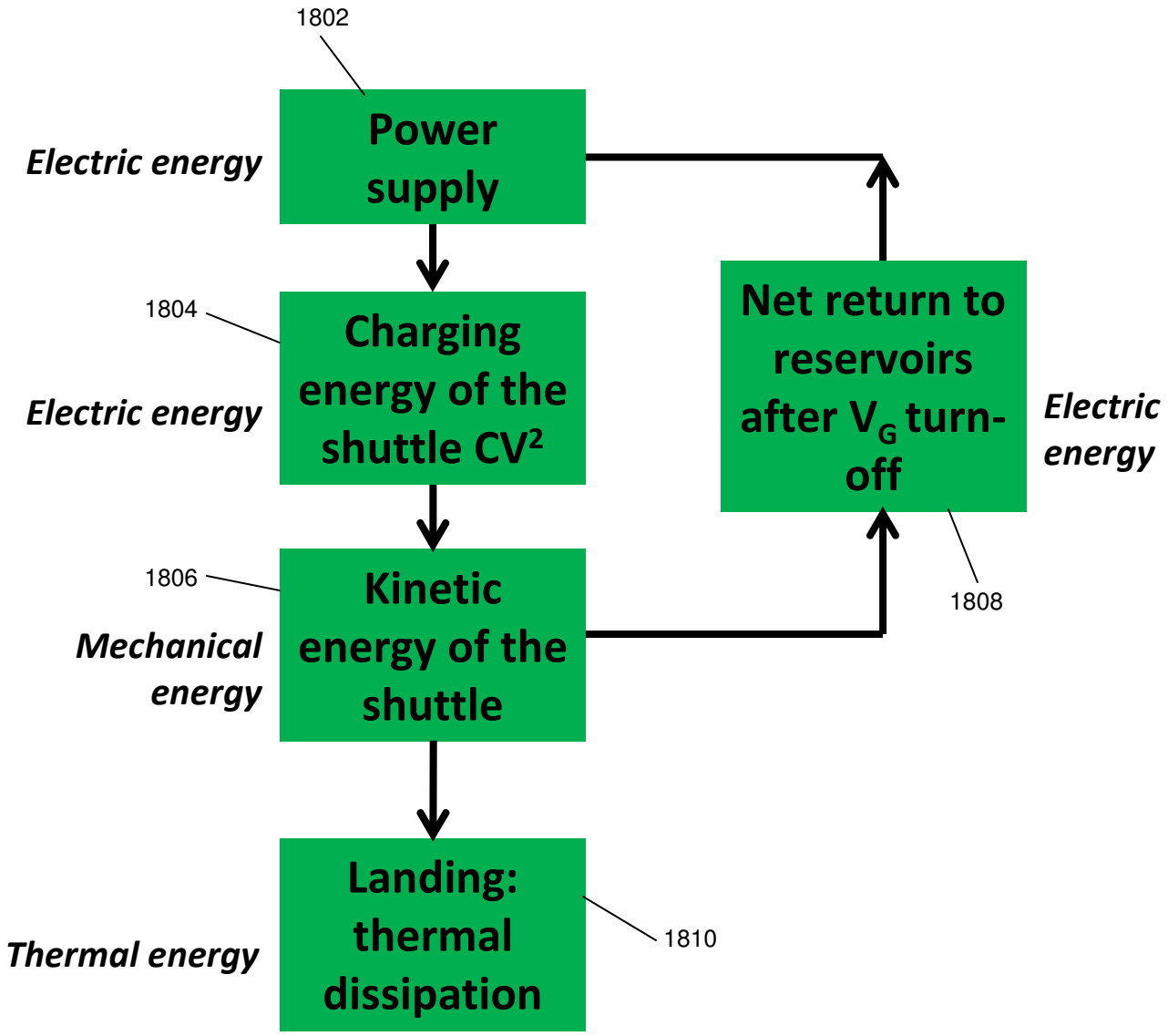

1802
Power supply
Electric energy
1804
Charging energy of the shuttle CV²
Electric energy
1806
Kinetic energy of the shuttle
Mechanical energy
Landing: thermal dissipation
Thermal energy
1810
Net return to reservoirs after V_G turn-off
Electric energy
1808

Figure 18

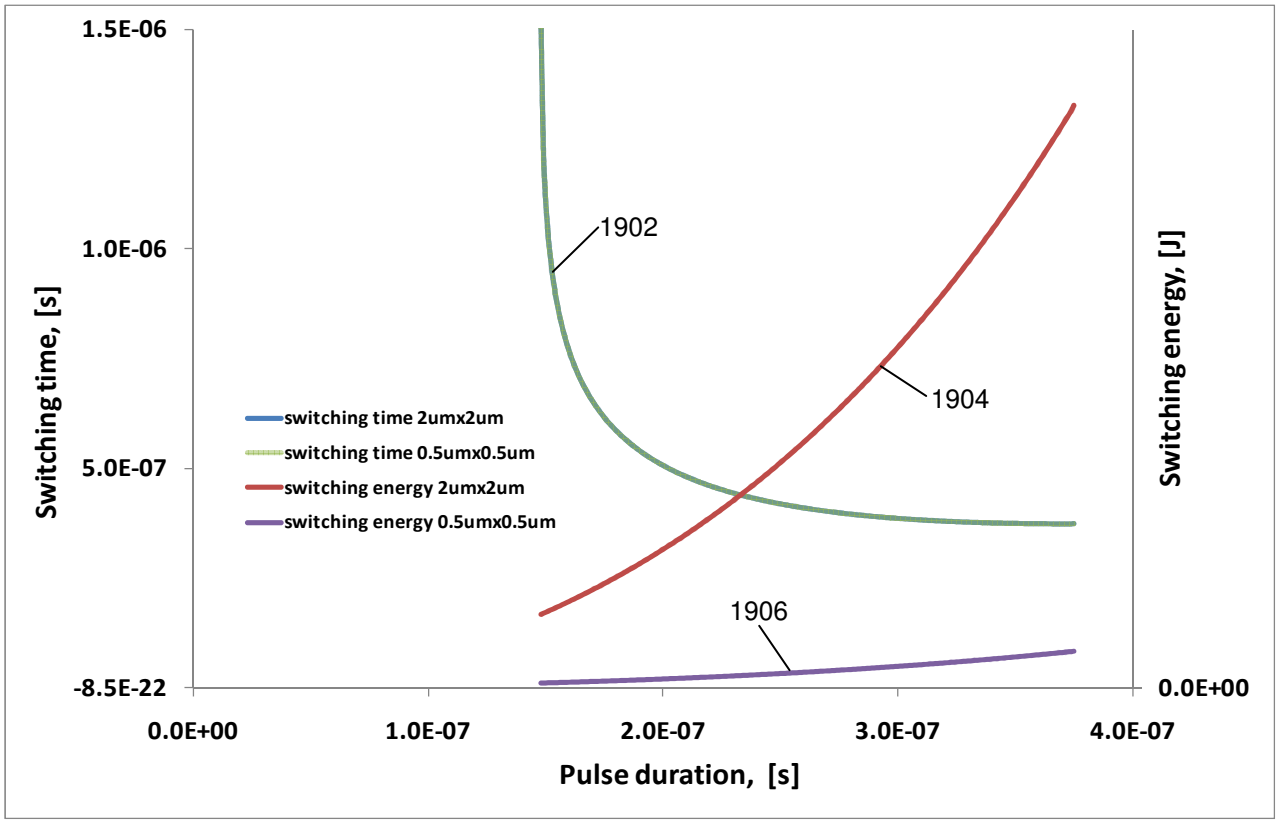

1.5E-06
1.0E-06
5.0E-07
-8.5E-22
Switching time, [s]
0.0E+00
1.0E-07
2.0E-07
3.0E-07
4.0E-07
Pulse duration, [s]
Switching energy, [J]
0.0E+00
switching time 2umx2um
switching time 0.5umx0.5um
switching energy 2umx2um
switching energy 0.5umx0.5um
1902
1904
1906
1900

Figure 19

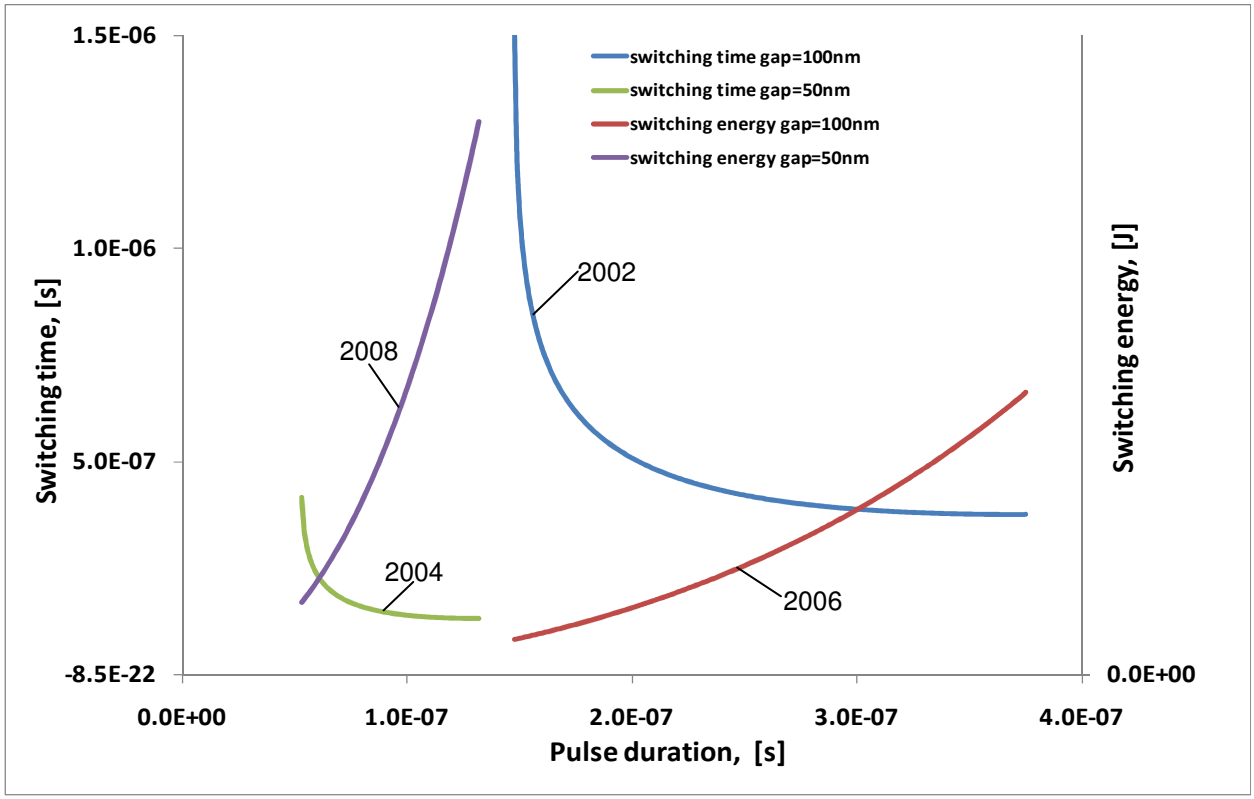

1.5E-06
1.0E-06
5.0E-07
-8.5E-22
0.0E+00
1.0E-07
2.0E-07
3.0E-07
4.0E-07
Pulse duration, [s]
Switching time, [s]
Switching energy, [J]
switching time gap=100nm
switching time gap=50nm
switching energy gap=100nm
switching energy gap=50nm
2002
2004
2006
2008
2000

Figure 20

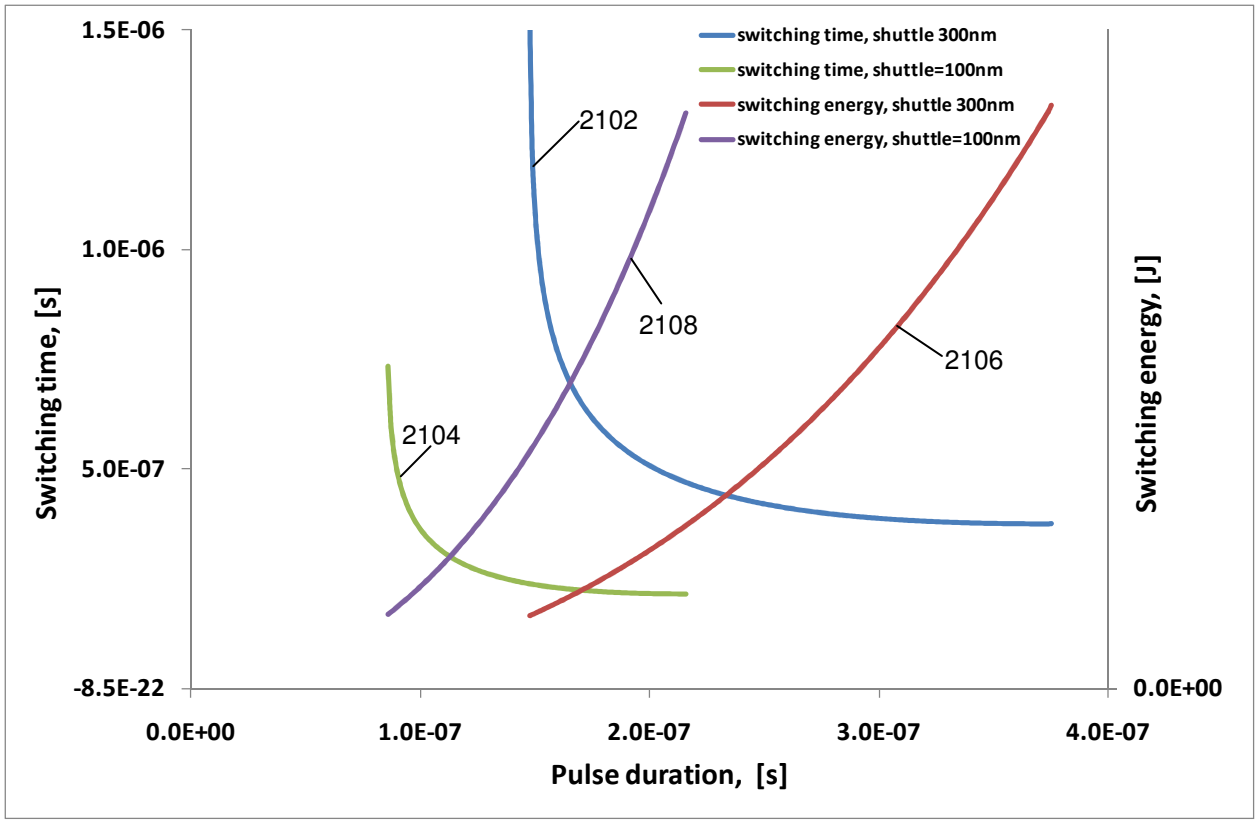

1.5E-06
1.0E-06
5.0E-07
-8.5E-22
0.0E+00
1.0E-07
2.0E-07
3.0E-07
4.0E-07
Switching time, [s]
Switching energy, [J]
Pulse duration, [s]
switching time, shuttle 300nm
switching time, shuttle=100nm
switching energy, shuttle 300nm
switching energy, shuttle=100nm
2102
2104
2106
2108
2100

Figure 21

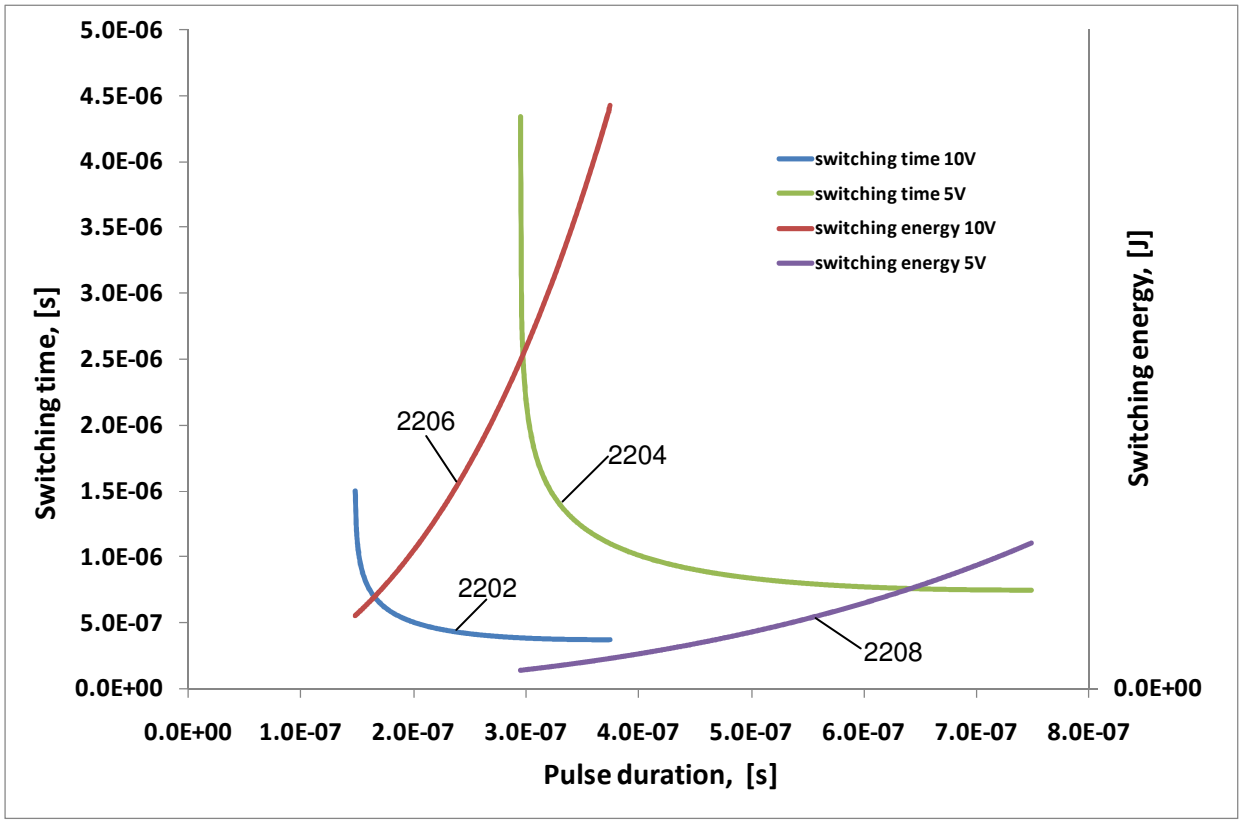

5.0E-06
4.5E-06
4.0E-06
3.5E-06
3.0E-06
2.5E-06
2.0E-06
1.5E-06
1.0E-06
5.0E-07
0.0E+00
Switching time, [s]
0.0E+00
1.0E-07
2.0E-07
3.0E-07
4.0E-07
5.0E-07
6.0E-07
7.0E-07
8.0E-07
Pulse duration, [s]
Switching energy, [J]
0.0E+00
switching time 10V
switching time 5V
switching energy 10V
switching energy 5V
2206
2204
2202
2208
2200

Figure 22

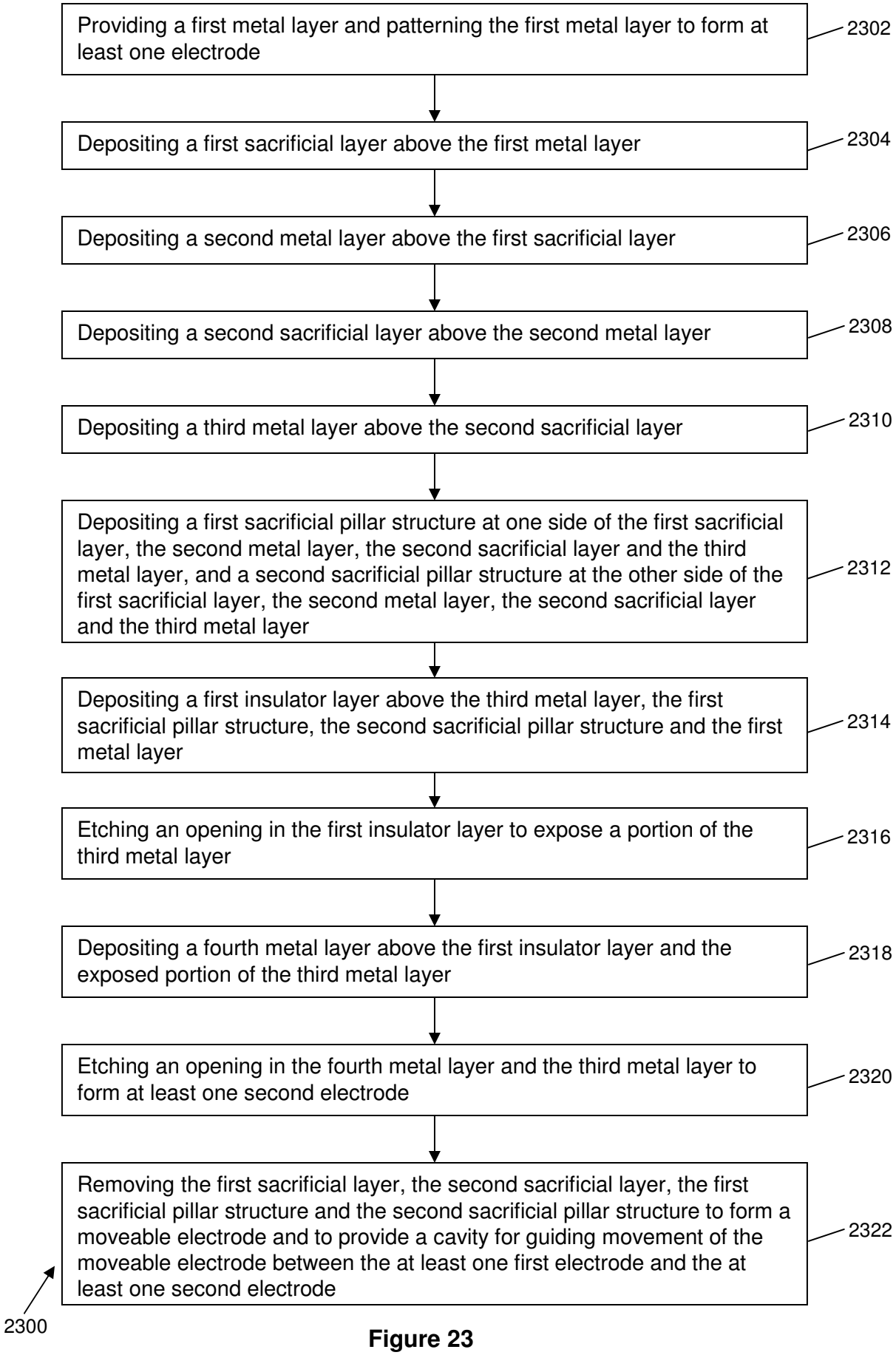

Providing a first metal layer and patterning the first metal layer to form at least one electrode
2302
Depositing a first sacrificial layer above the first metal layer
2304
Depositing a second metal layer above the first sacrificial layer
2306
Depositing a second sacrificial layer above the second metal layer
2308
Depositing a third metal layer above the second sacrificial layer
2310
Depositing a first sacrificial pillar structure at one side of the first sacrificial layer, the second metal layer, the second sacrificial layer and the third metal layer, and a second sacrificial pillar structure at the other side of the first sacrificial layer, the second metal layer, the second sacrificial layer and the third metal layer
2312
Depositing a first insulator layer above the third metal layer, the first sacrificial pillar structure, the second sacrificial pillar structure and the first metal layer
2314
Etching an opening in the first insulator layer to expose a portion of the third metal layer
2316
Depositing a fourth metal layer above the first insulator layer and the exposed portion of the third metal layer
2318
Etching an opening in the fourth metal layer and the third metal layer to form at least one second electrode
2320
Removing the first sacrificial layer, the second sacrificial layer, the first sacrificial pillar structure and the second sacrificial pillar structure to form a moveable electrode and to provide a cavity for guiding movement of the moveable electrode between the at least one first electrode and the at least one second electrode
2322
2300

Figure 23

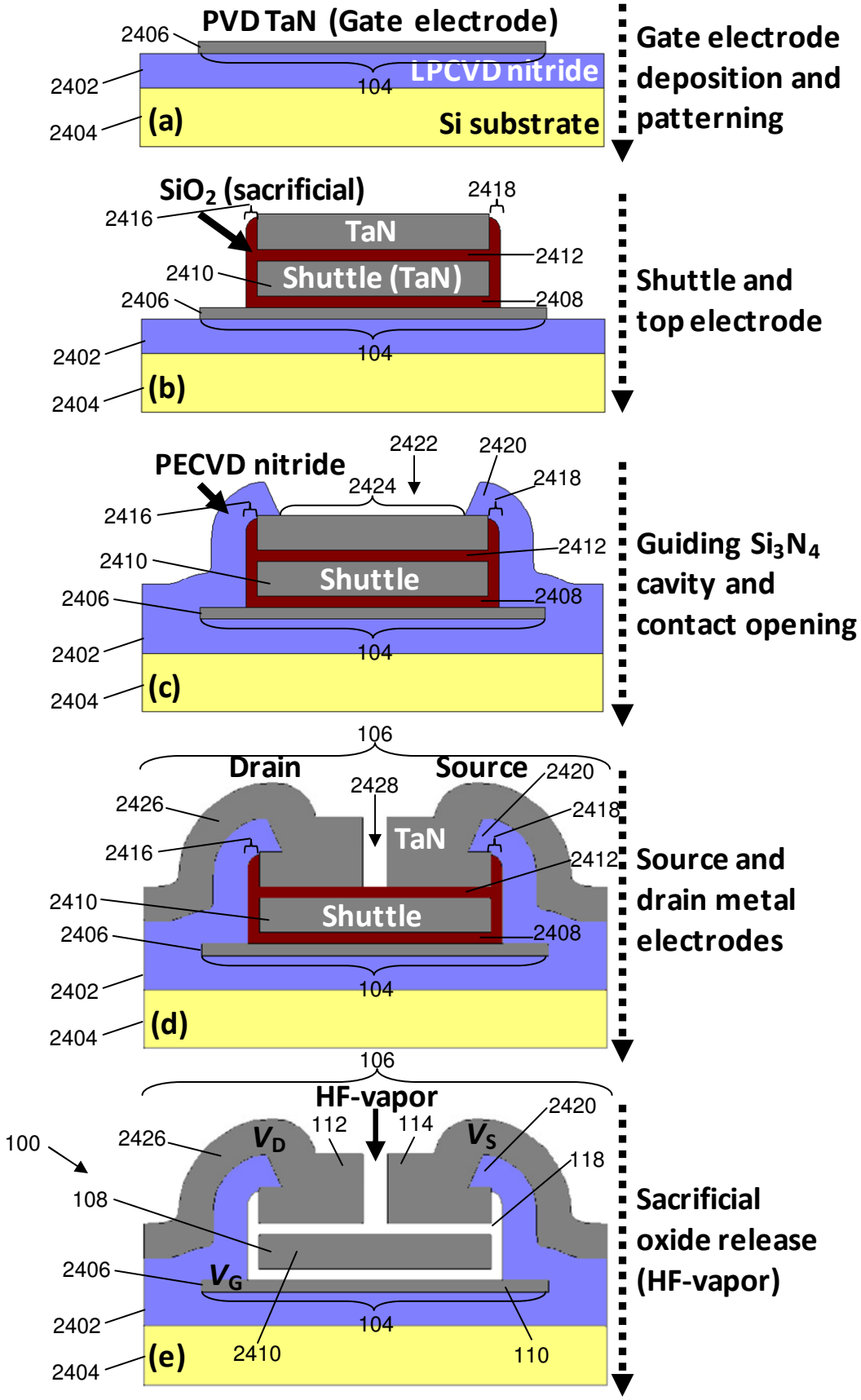

PVD TaN (Gate electrode)
2406
2402
2404
104
LPCVD nitride
Si substrate
(a)
Gate electrode deposition and patterning
SiO2 (sacrificial)
2418
2416
TaN
2412
2410
Shuttle (TaN)
2406
2408
104
2402
2404
(b)
Shuttle and top electrode
PECVD nitride
2422
2420
2424
2418
2416
2412
2410
Shuttle
2406
2408
104
2402
2404
(c)
Guiding Si3N4 cavity and contact opening
106
Drain
Source
2420
2428
2426
2418
2416
TaN
2412
2410
Shuttle
2406
2408
104
2402
2404
(d)
Source and drain metal electrodes
106
HF-vapor
2420
112
114
100
2426
VD
VS
118
108
2406
VG
104
2402
2404
(e)
2410
110
Sacrificial oxide release (HF-vapor)

Figure 24

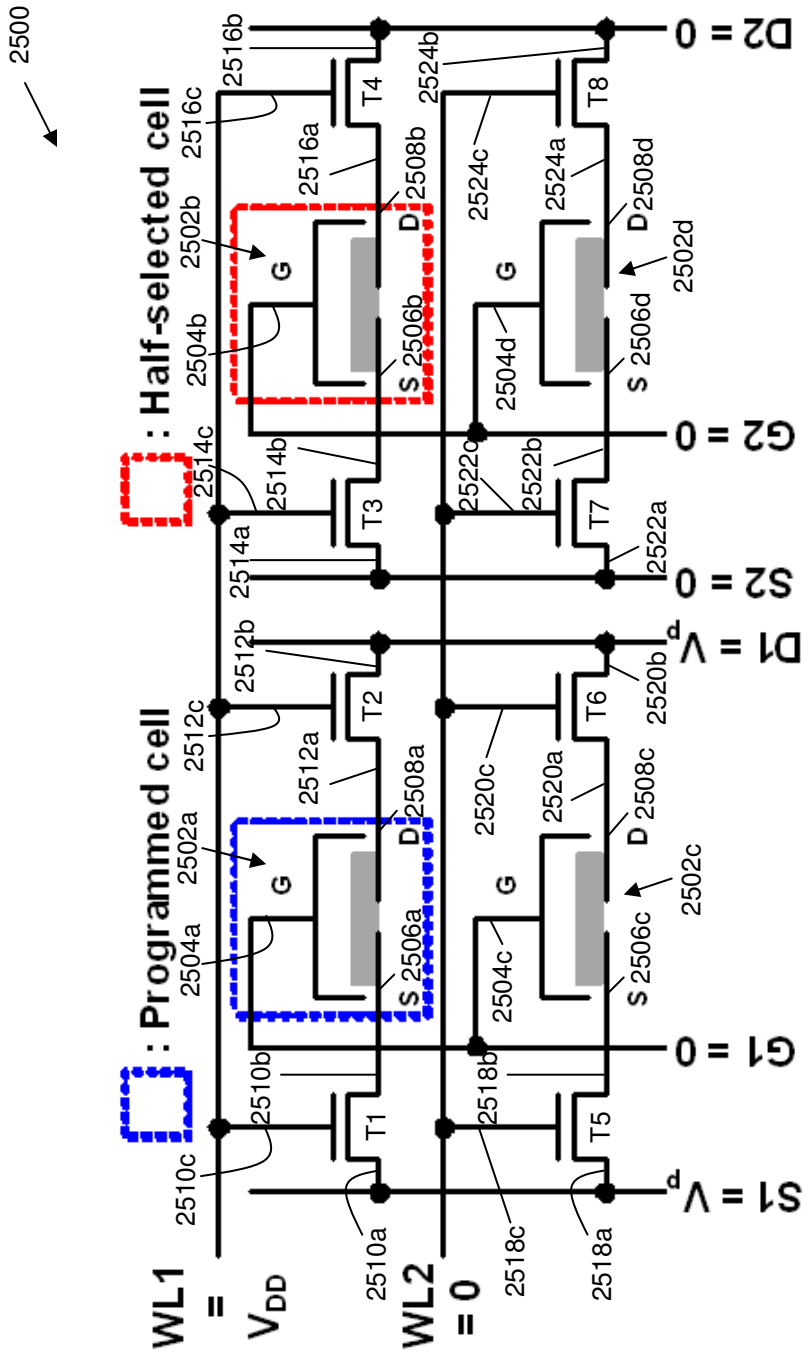

2500
: Half-selected cell
: Programmed cell
WL1 = V_{DD}
WL2 = 0
S1 = V_p
D1 = V_p
G1 = 0
S2 = 0
G2 = 0
D2 = 0
T1
T2
T3
T4
T5
T6
T7
T8
2502a
2502b
2502c
2502d
2504a
2504b
2504c
2504d
2506a
2506b
2506c
2506d
2508a
2508b
2508c
2508d
2510a
2510b
2510c
2512a
2512b
2512c
2514a
2514b
2514c
2516a
2516b
2516c
2518a
2518b
2518c
2520a
2520b
2520c
2522a
2522b
2522c
2524a
2524b
2524c
G
D
S

Figure 25

Writing 'down'	WL=V_{DD} & S1=D1=V_P & G1=0	$V_{DD} > V_p$	2602
Writing 'up'	WL=V_{DD} & S1=D1=0 & G1=V_P	$V_{DD} > V_p$	2604
Half-selected	WL=V_{DD} & S1=D1=G1=0	No potential difference between terminals	2606
Unselected	WL=0 & G1=0 or V_p	Floating source (S) / drain (D) following voltage changes in 'G'	2608

2600

Figure 26

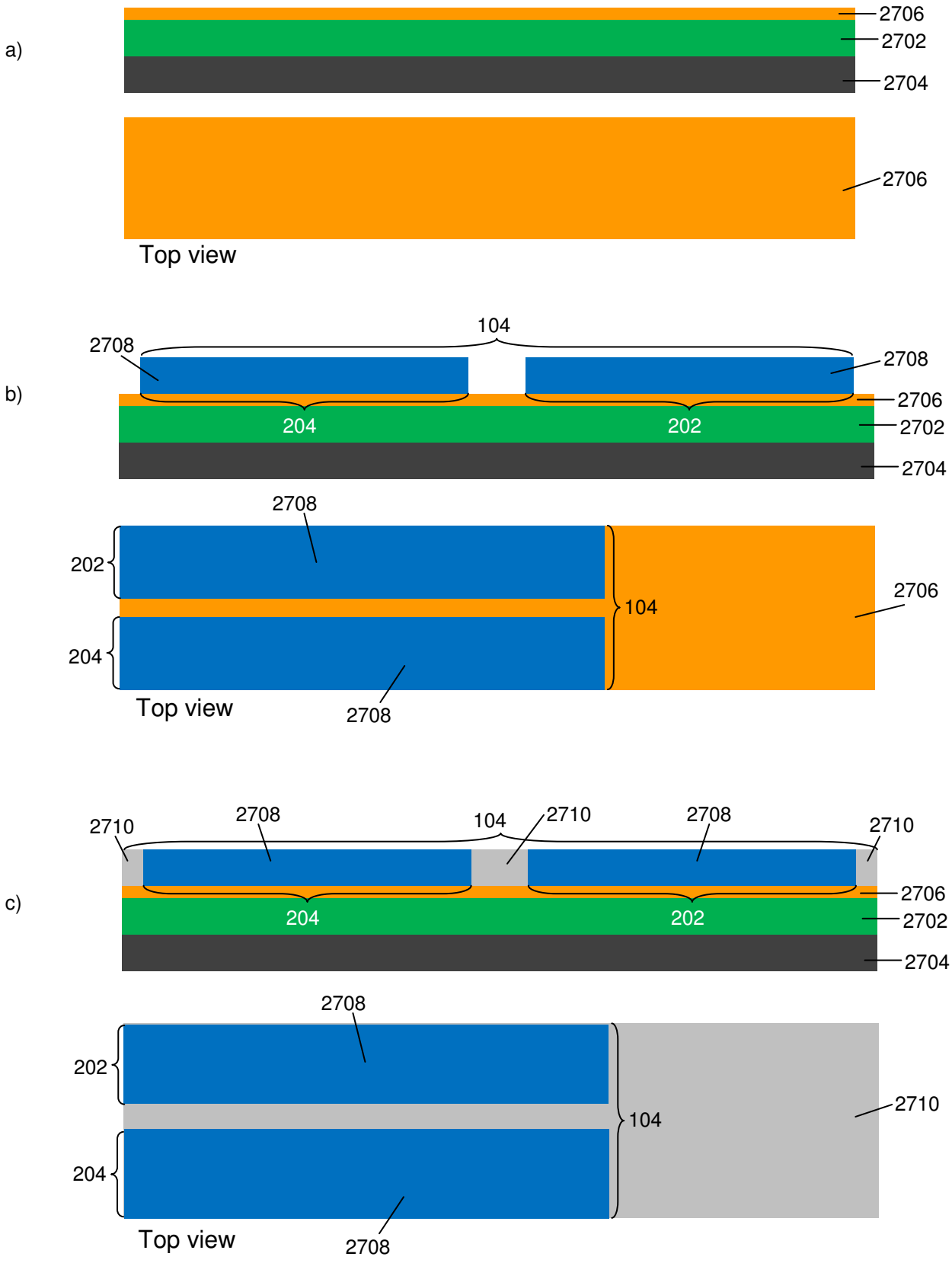

a)
2706
2702
2704
2706
Top view
b)
104
2708
2708
2706
204
202
2702
2704
2708
202
104
2706
204
Top view
2708
c)
2710
2708
104
2710
2708
2710
2706
204
202
2702
2704
2708
202
104
2710
204
Top view
2708

Figure 27

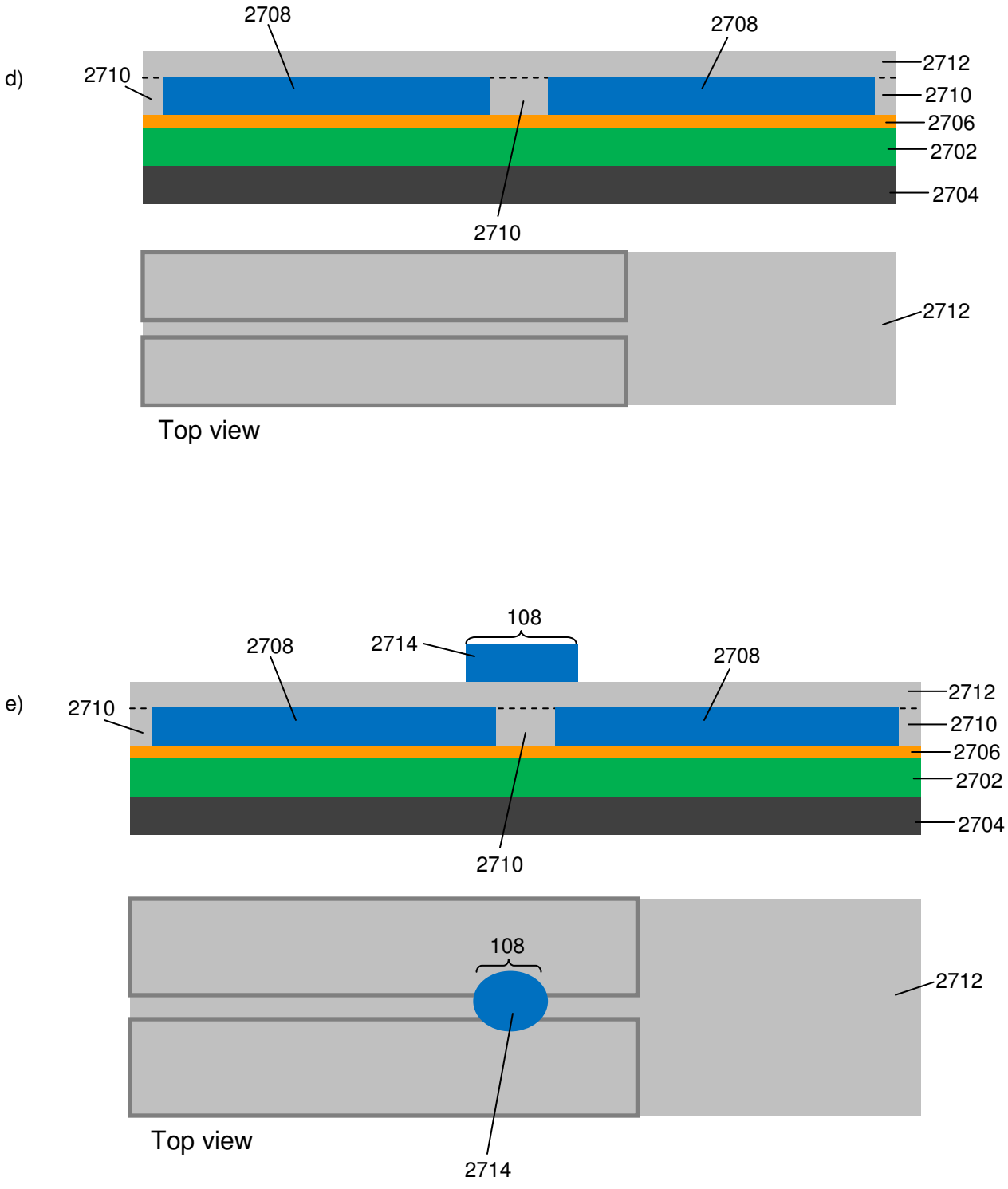
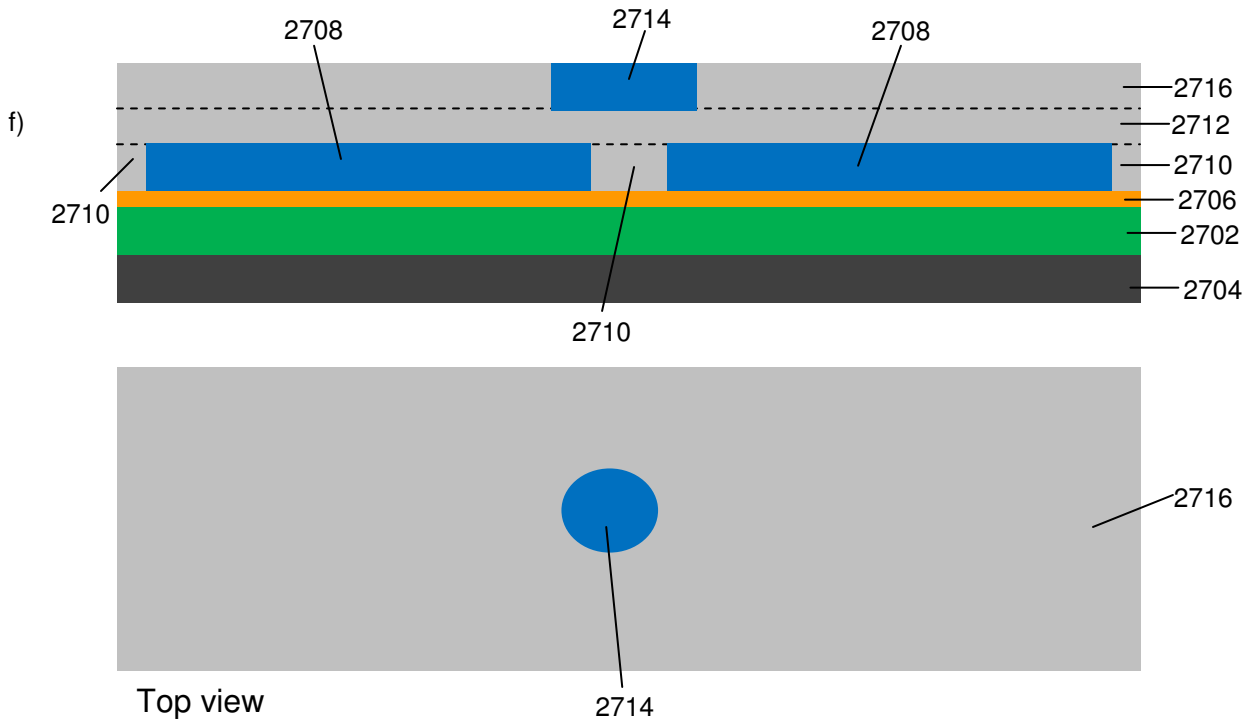

d)
2708
2708
2710
2712
2710
2706
2702
2704
2710
2712
Top view
e)
108
2708
2714
2708
2710
2712
2710
2706
2702
2704
2710
108
2712
Top view
2714

Figure 27


f)
2708
2714
2708
2716
2712
2710
2706
2702
2704
2710
2710
2716
2714
Top view

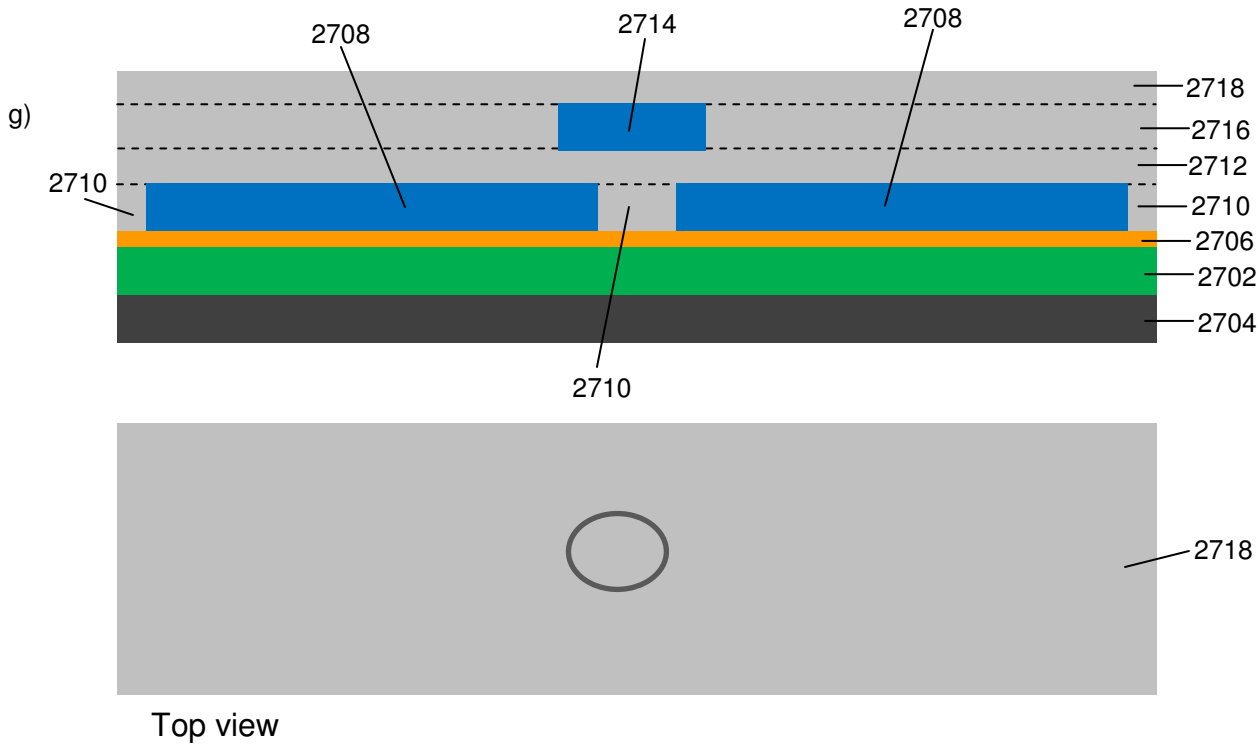
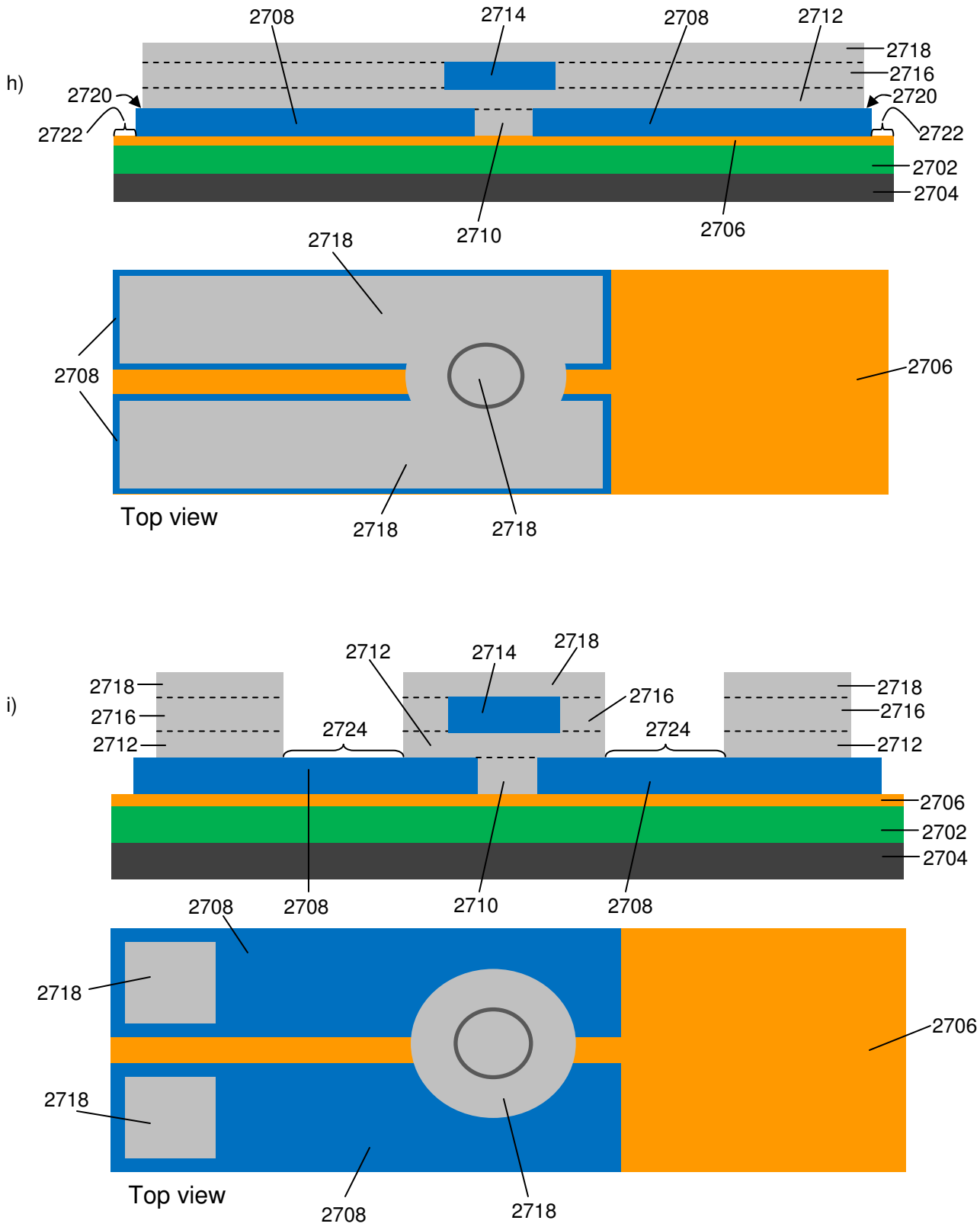

g)
2708
2714
2708
2718
2716
2712
2710
2706
2702
2704
2710
2710
2718
Top view

Figure 27


h)
2708
2714
2708
2712
2718
2716
2720
2720
2722
2722
2702
2704
2710
2706
2718
2708
2706
Top view
2718
2718
i)
2718
2712
2714
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2718
2716
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2712
2712
2706
2702
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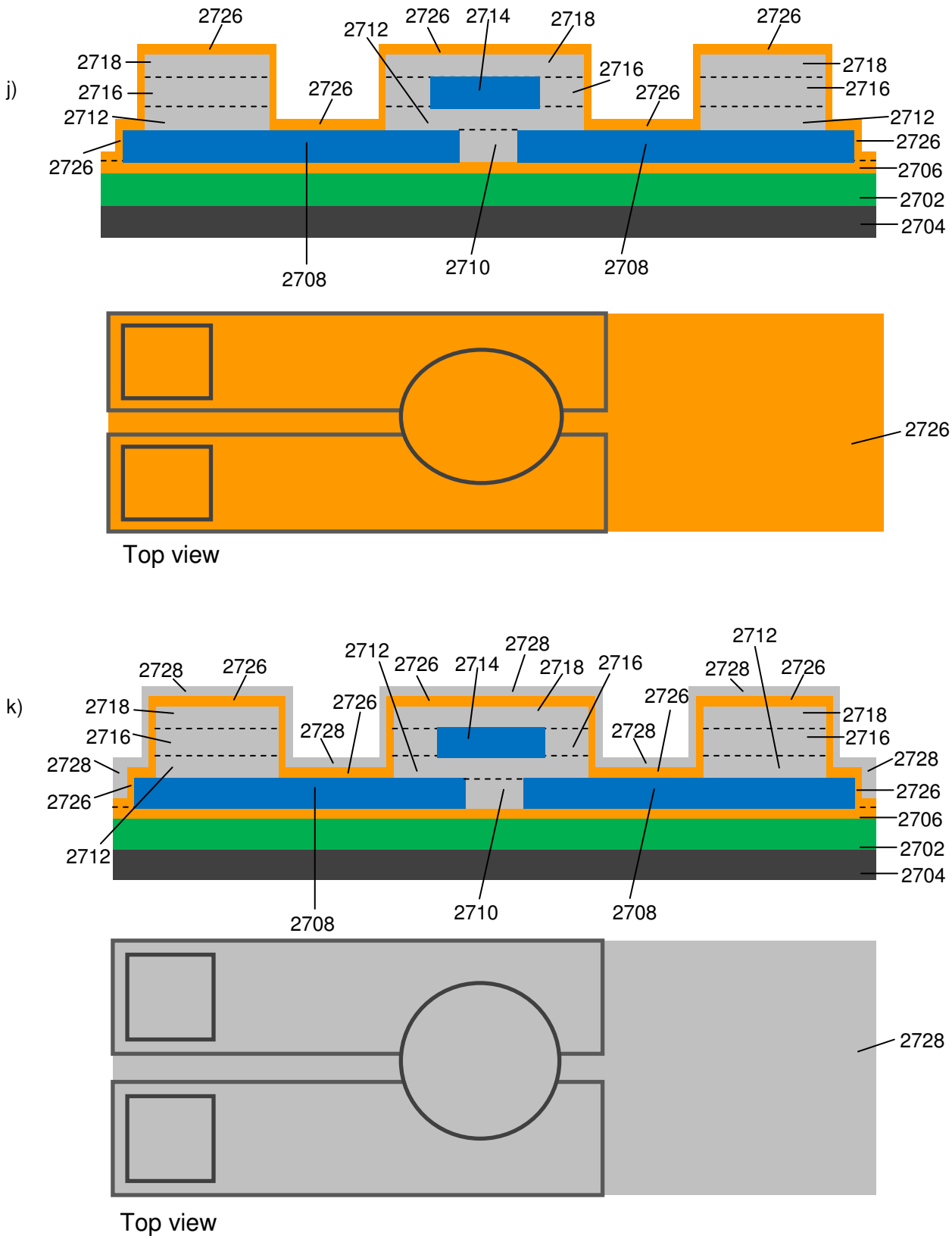
2710
2708
2718
2706
2718
Top view
2708
2718

Figure 27


j)
2726
2712
2726
2714
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2716
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2716
2712
2726
2726
2706
2702
2704
2708
2710
2708
2726
Top view
k)
2728
2726
2712
2726
2714
2728
2718
2716
2728
2726
2712
2728
2726
2718
2716
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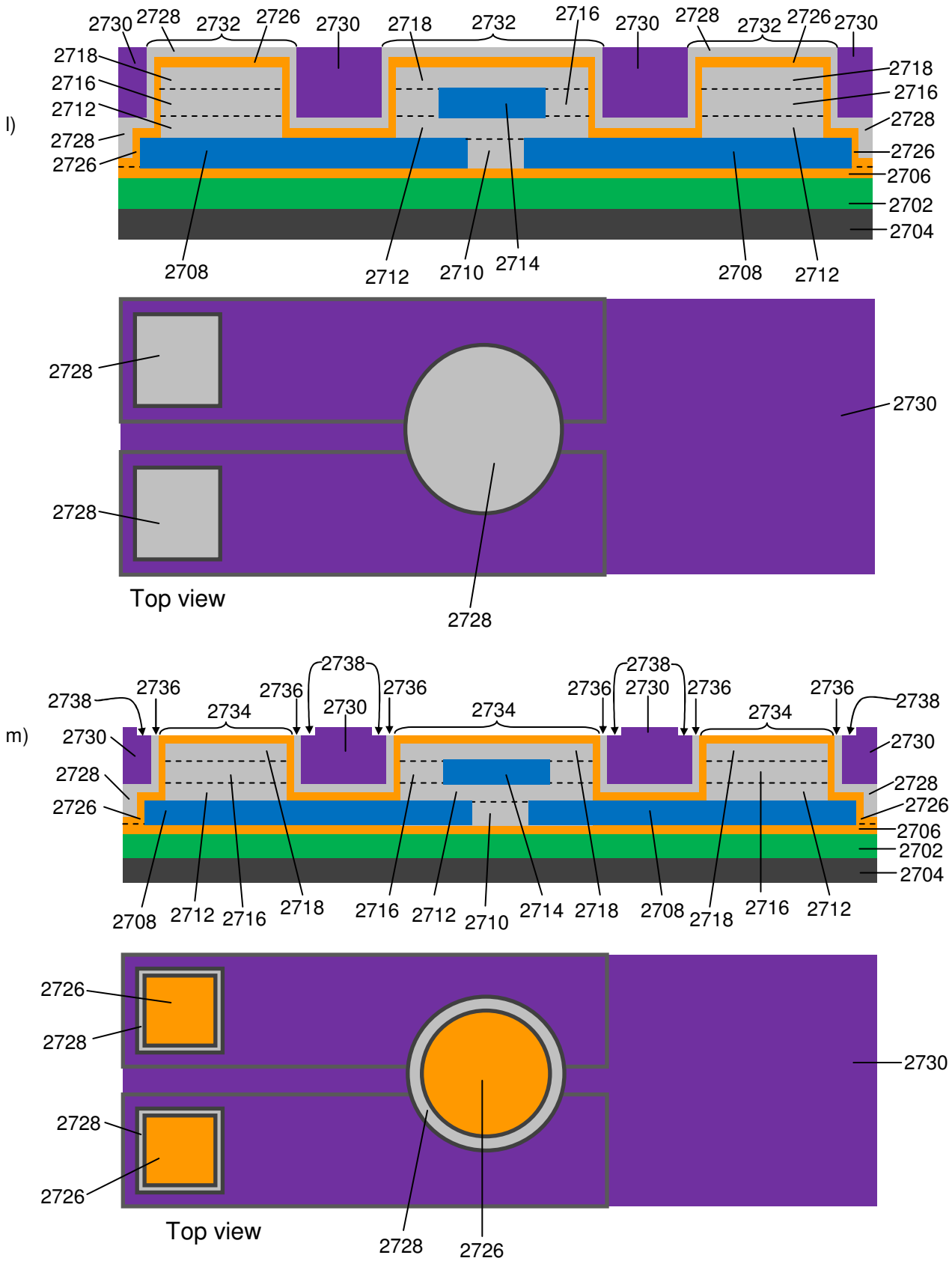
2706
2702
2704
2708
2710
2708
2728
Top view

Figure 27


l)
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2714
2708
2712
2728
2730
2728
Top view
2728
m)
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Top view
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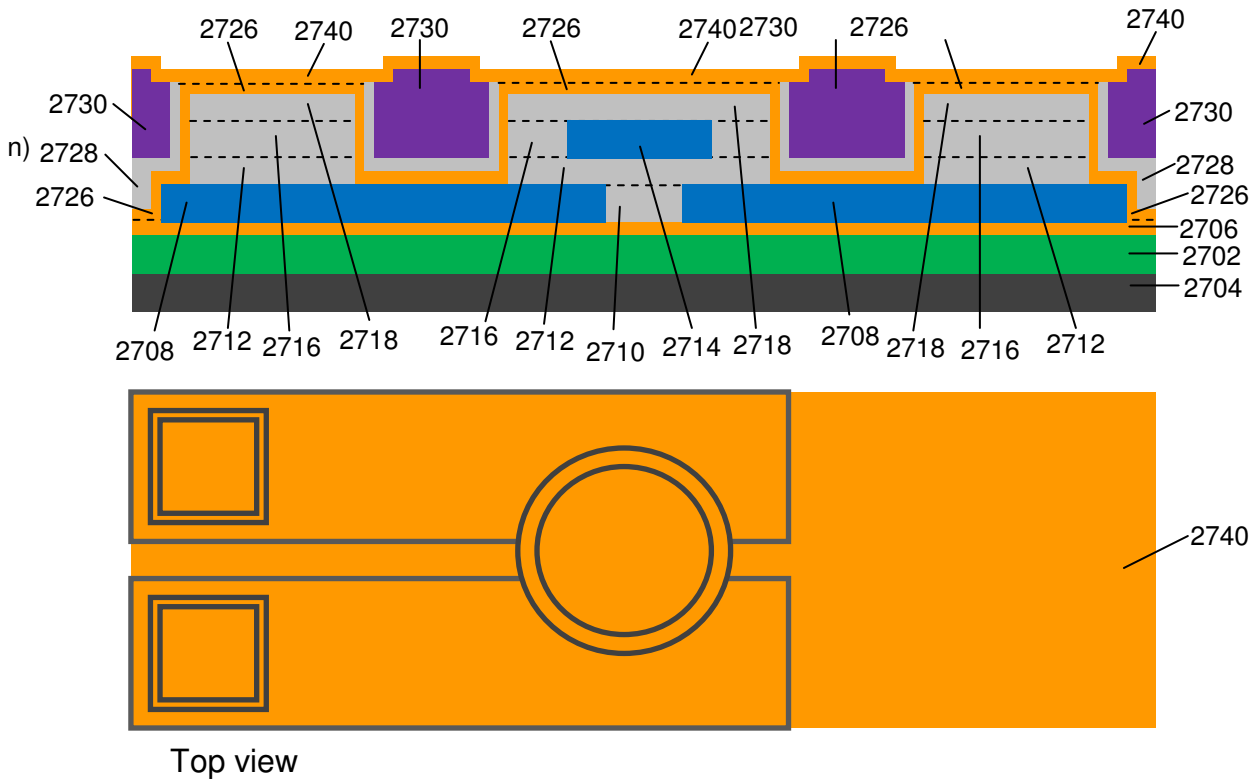
2726

Figure 27


n)
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2712
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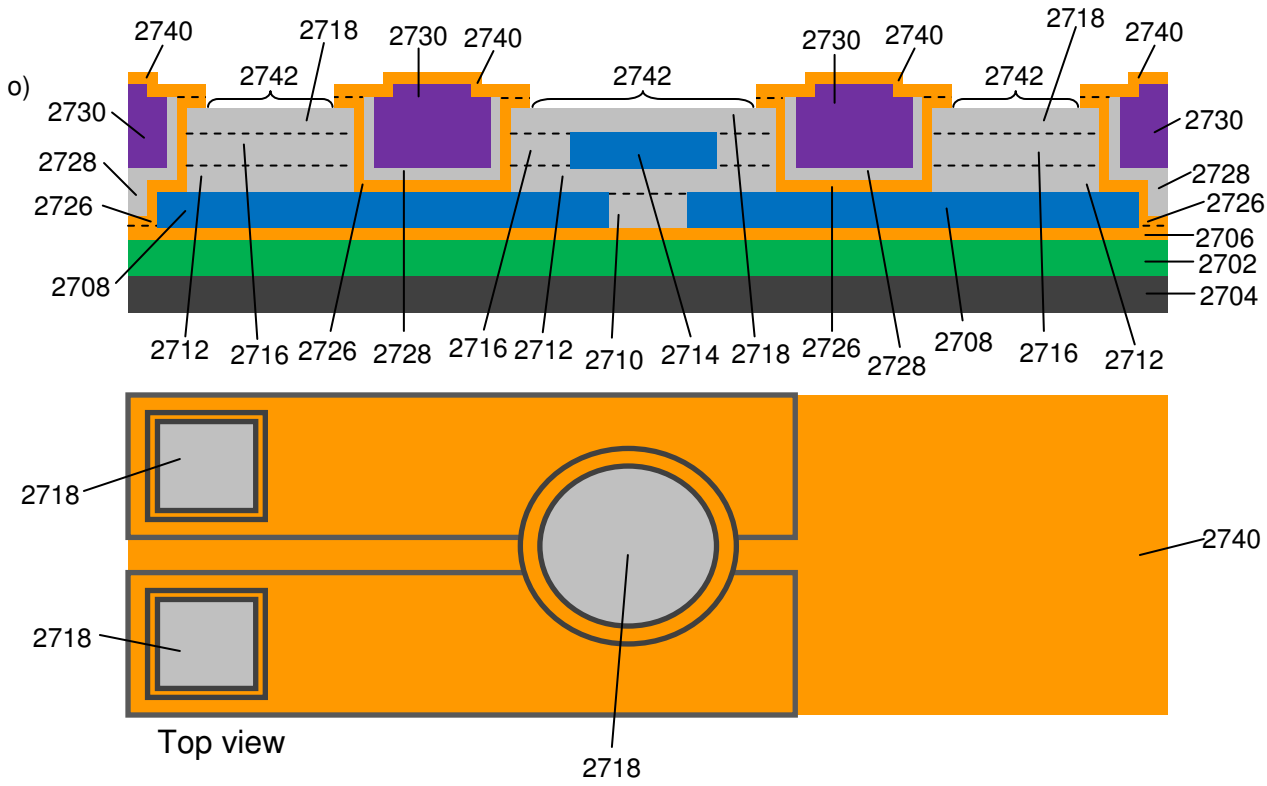
Top view


o)
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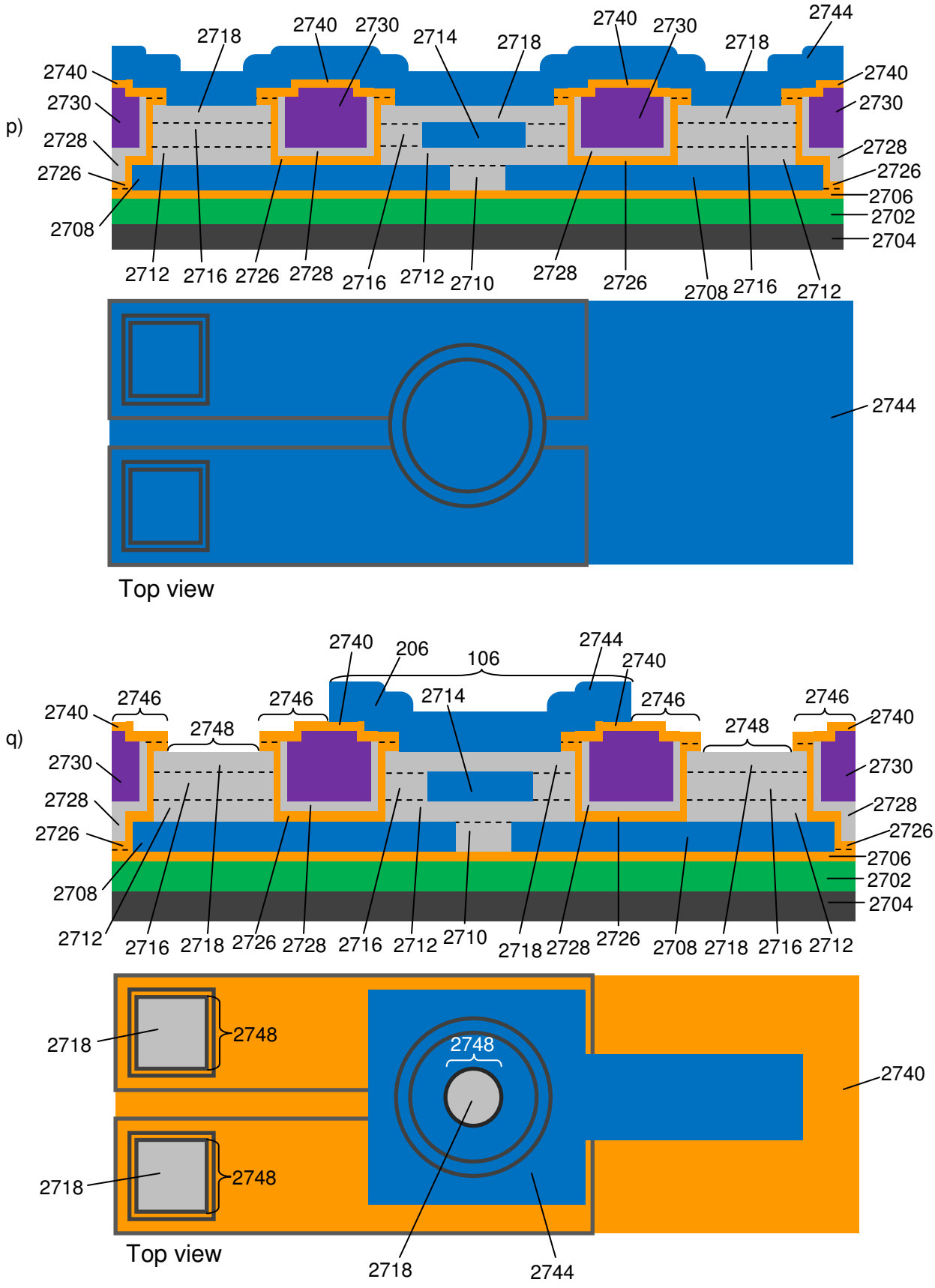
2740
Top view
2718

Figure 27


p)
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2726
2708
2716
2712
2744
Top view
q)
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106
2744
2740
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2748
Top view
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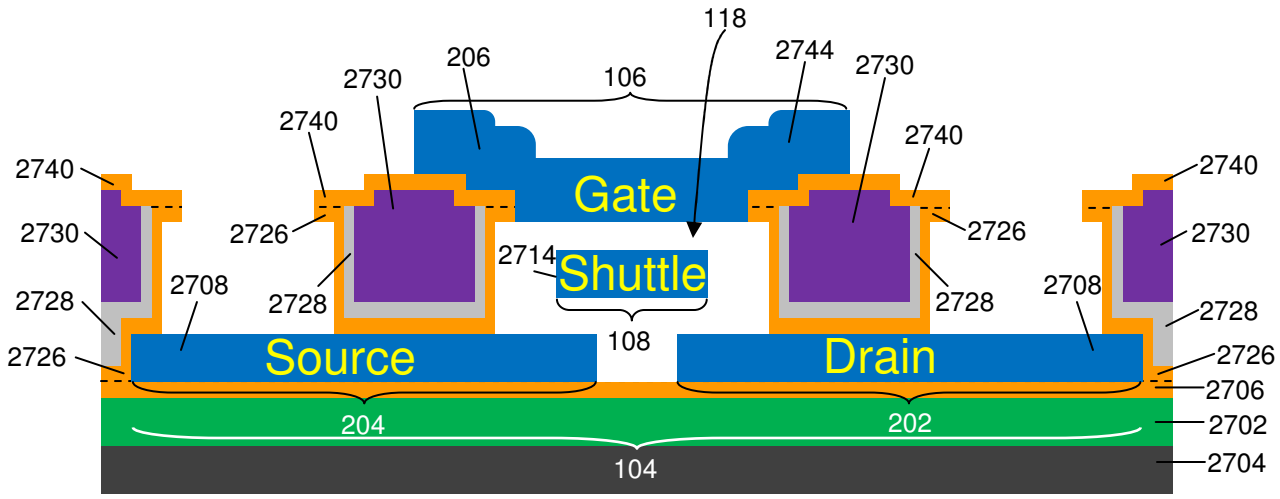
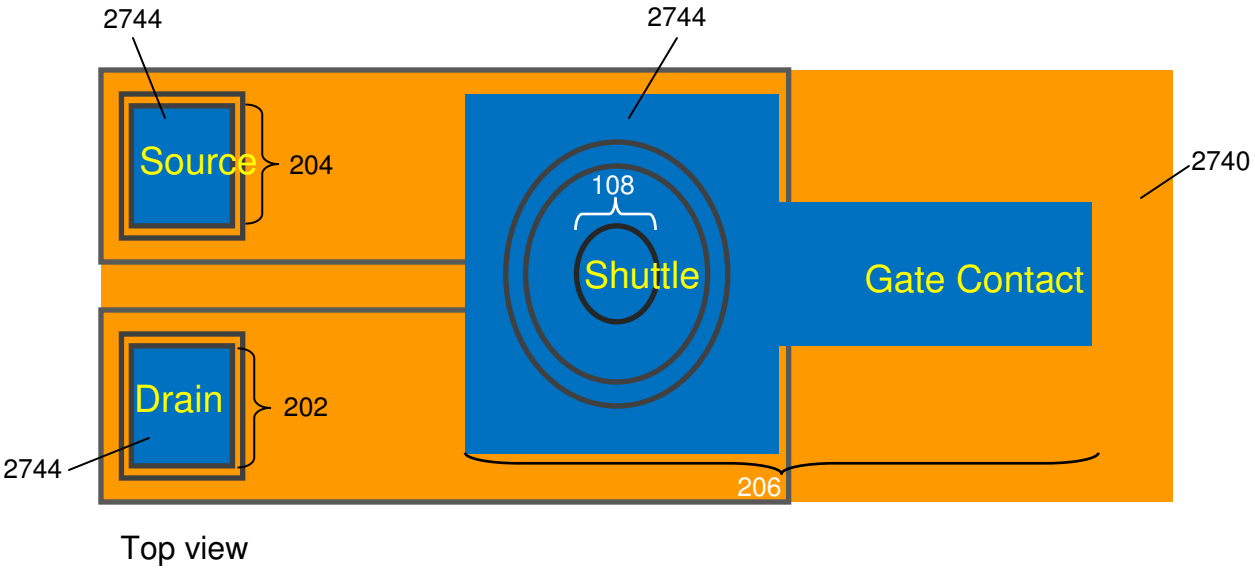
2744

Figure 27





Top view

Figure 27r