Organische Transistoren

Wahlfach in der Fakultät
Informatik, Elektrotechnik und Informationstechnik

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http://www.fkf.mpg.de/oe/vorlesung

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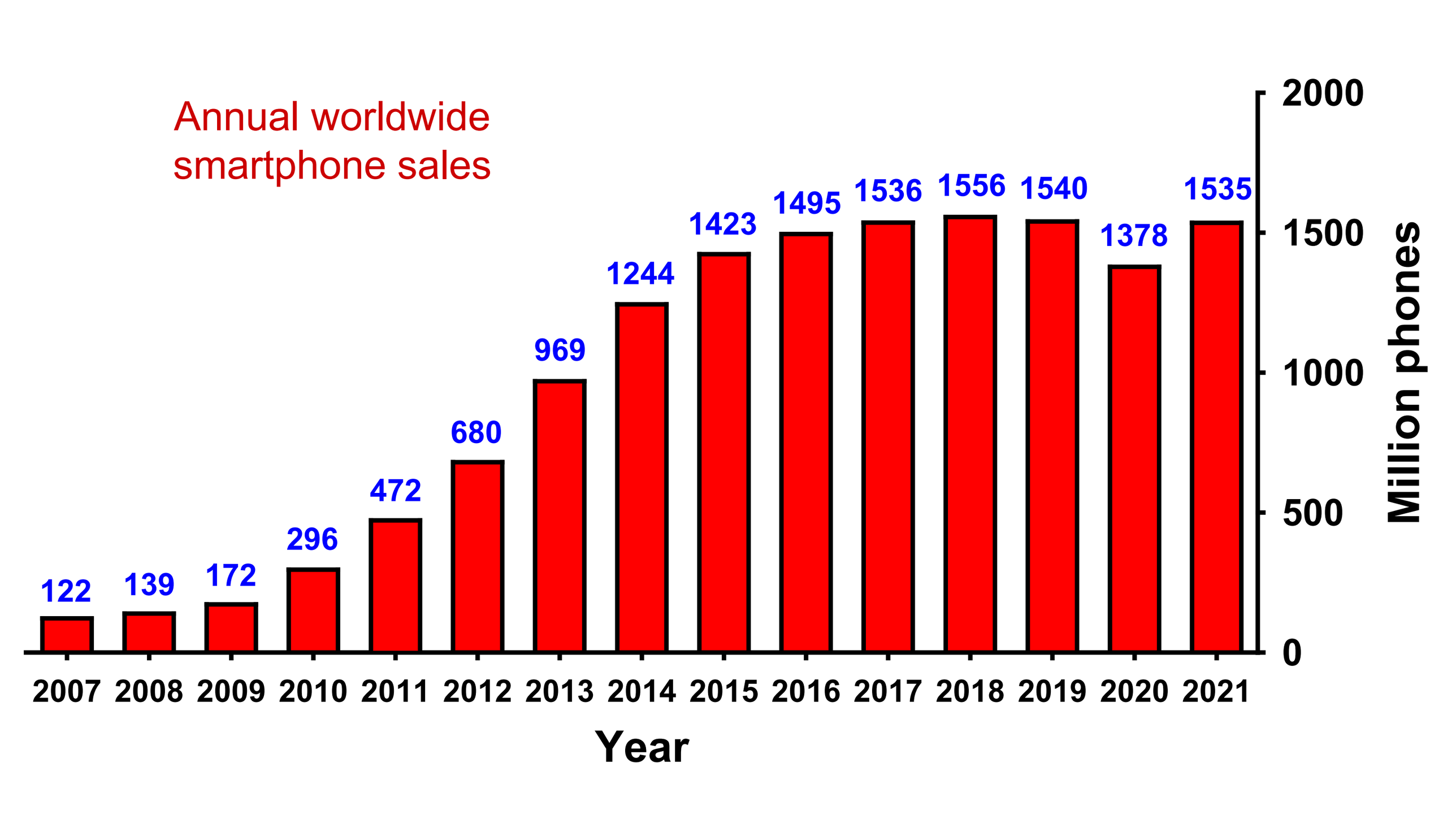
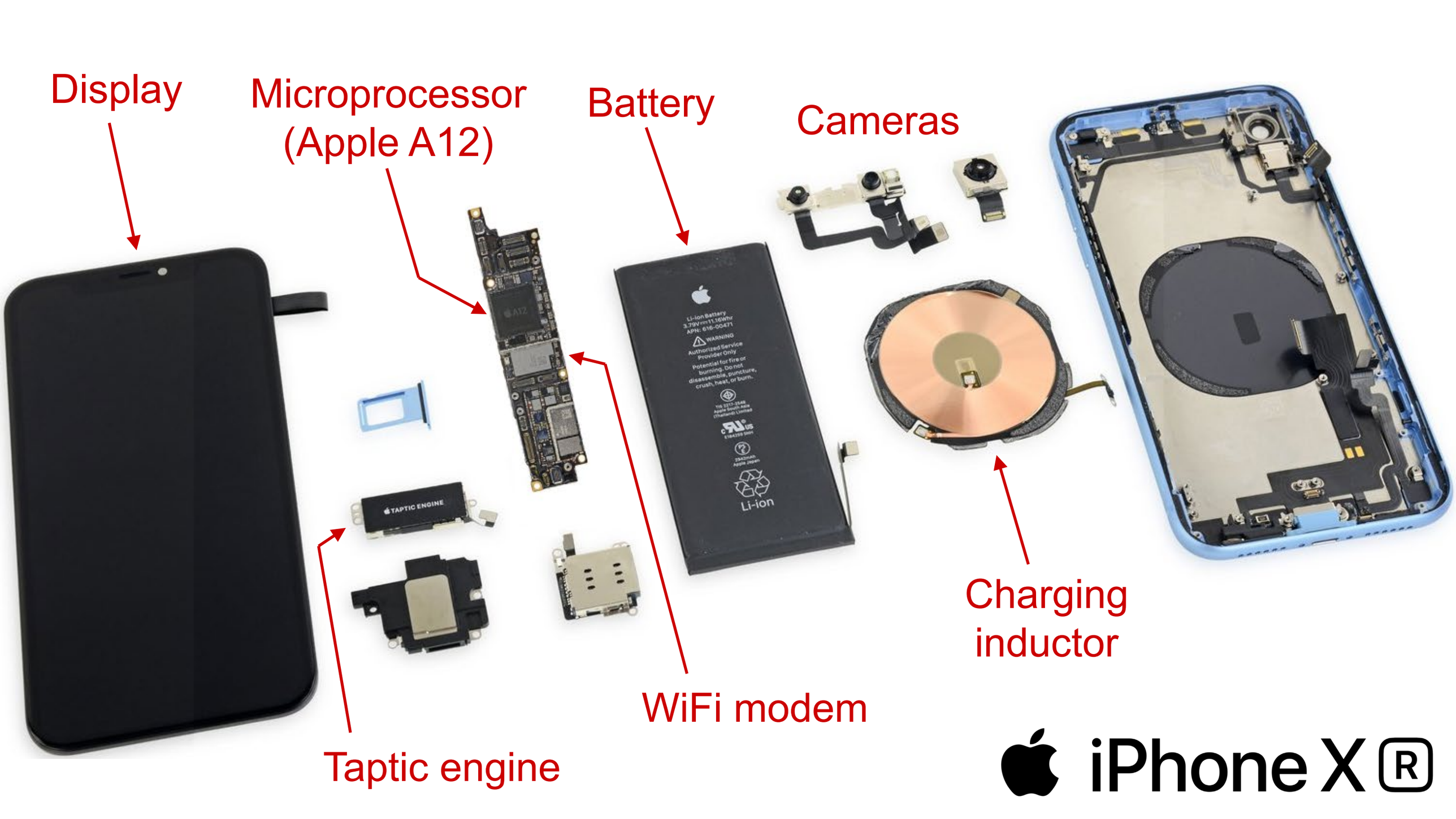
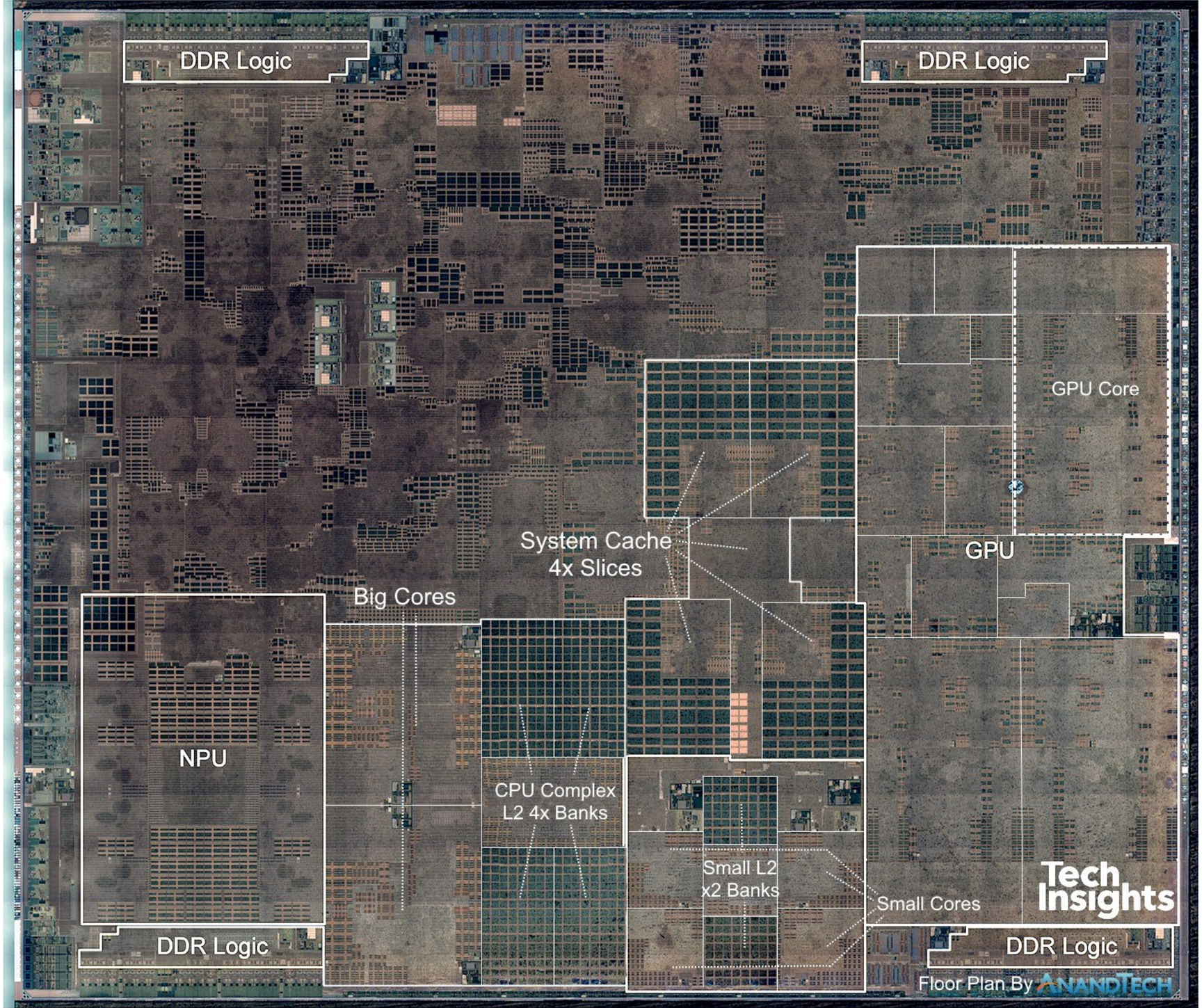
iPhone XR


Annual worldwide
smartphone sales
122
139
172
296
472
680
969
1244
1423
1495
1536
1556
1540
1378
1535
2000
1500
1000
500
0
Million phones
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
Year


Display
Microprocessor (Apple A12)
Battery
Cameras
Charging inductor
WiFi modem
Taptic engine
TAPTIC ENGINE
Li-ion
iPhone XR

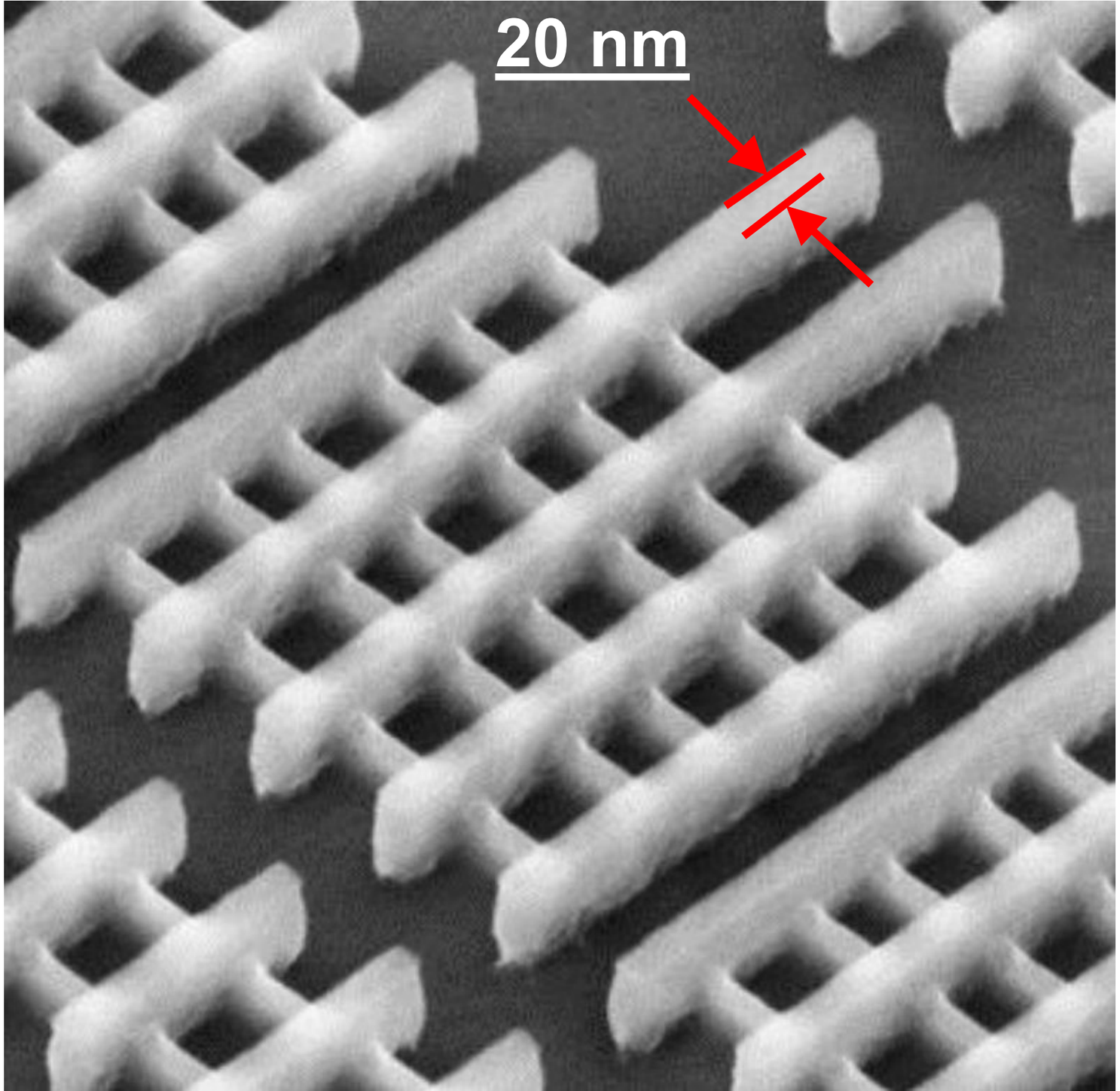
Apple A12 microprocessor

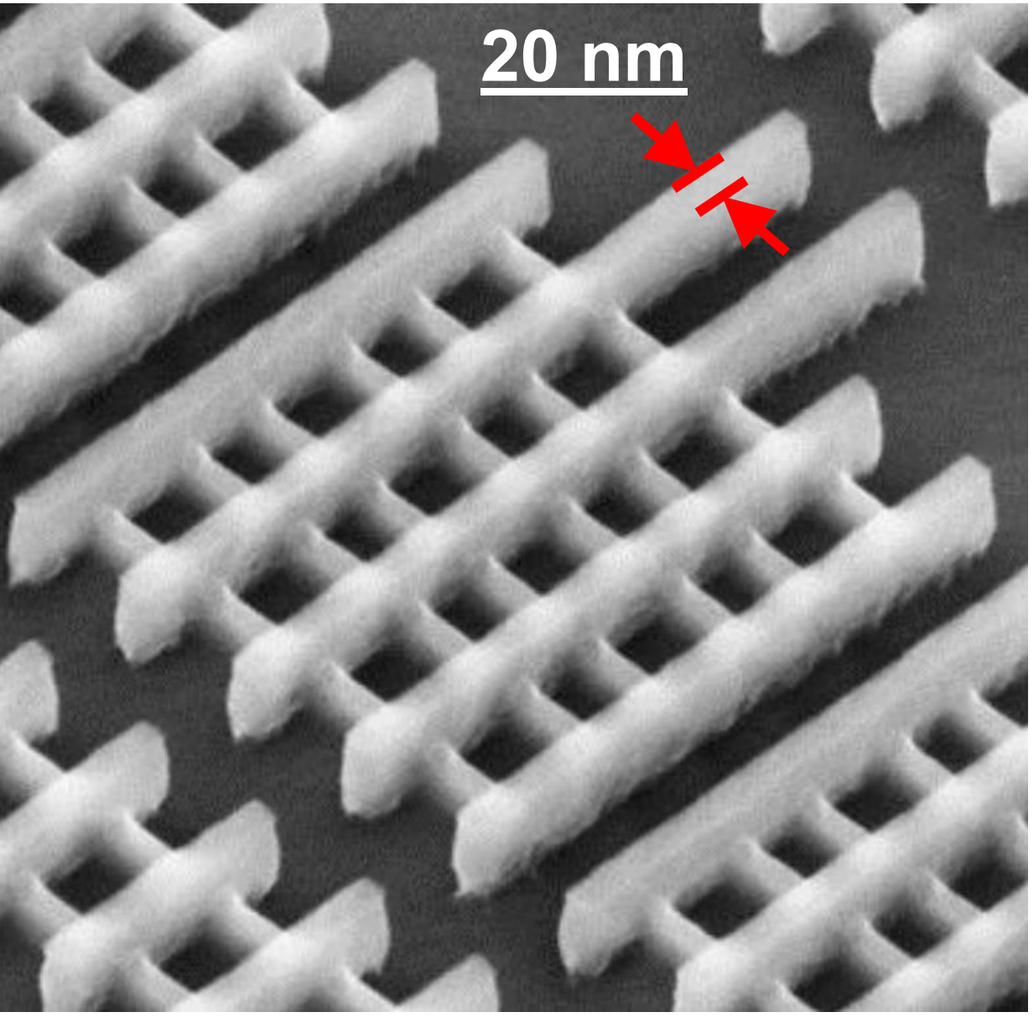
7 billion FETs

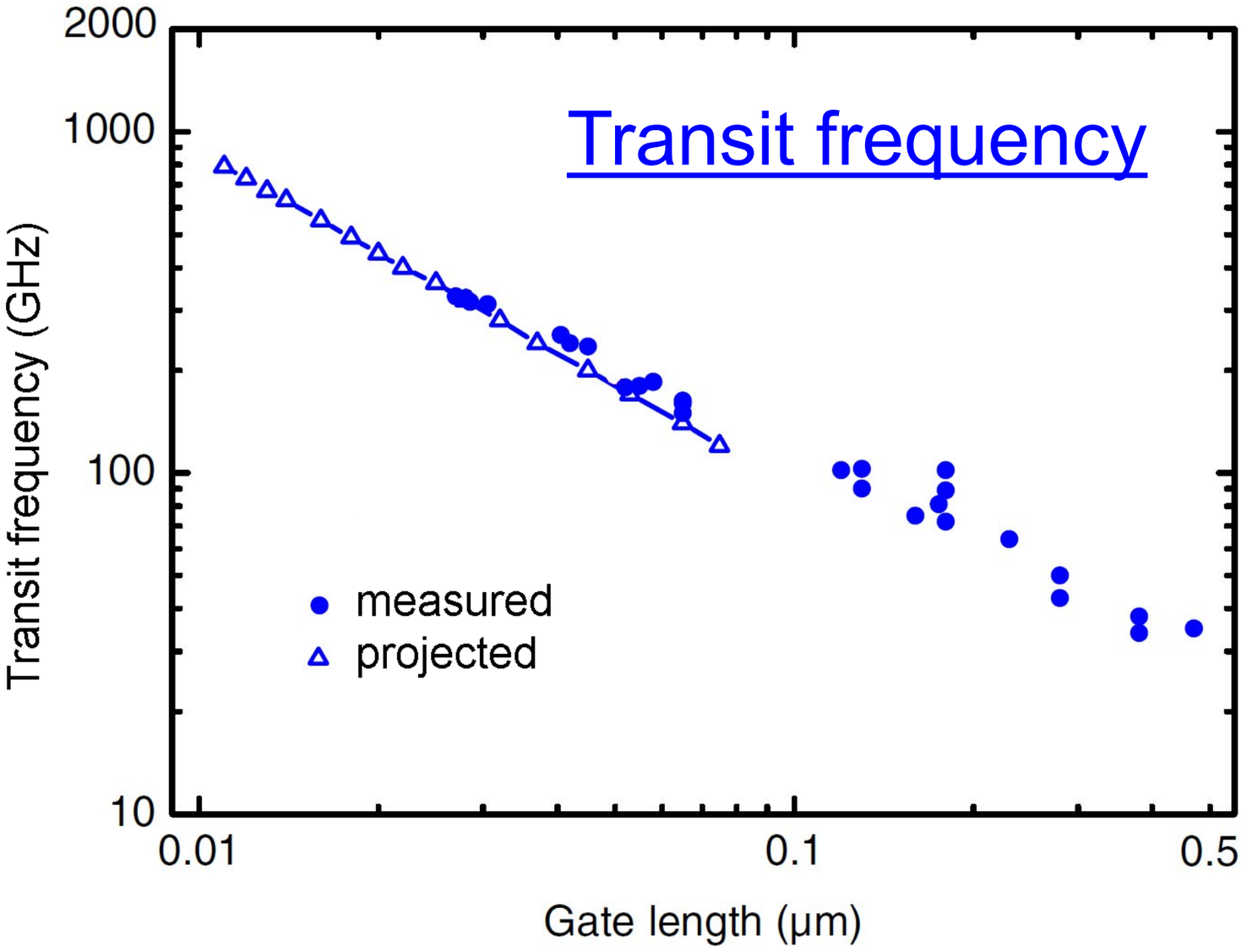


1 cm

Tri-gate silicon MOSFET

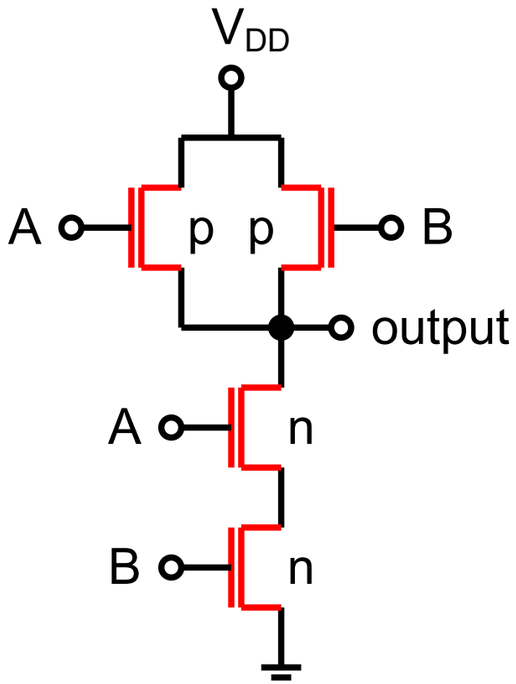


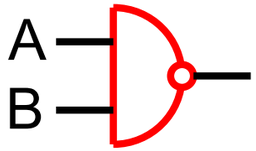




f_T (L = 10 nm) ~ 1 THz

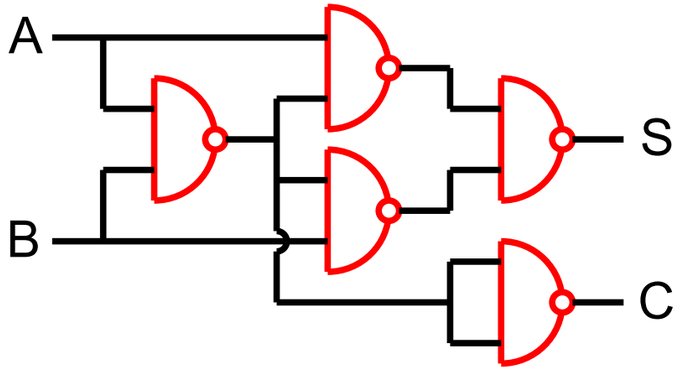
NAND (4 FETs)





A	B	output
0	0	1
0	1	1
1	0	1
1	1	0

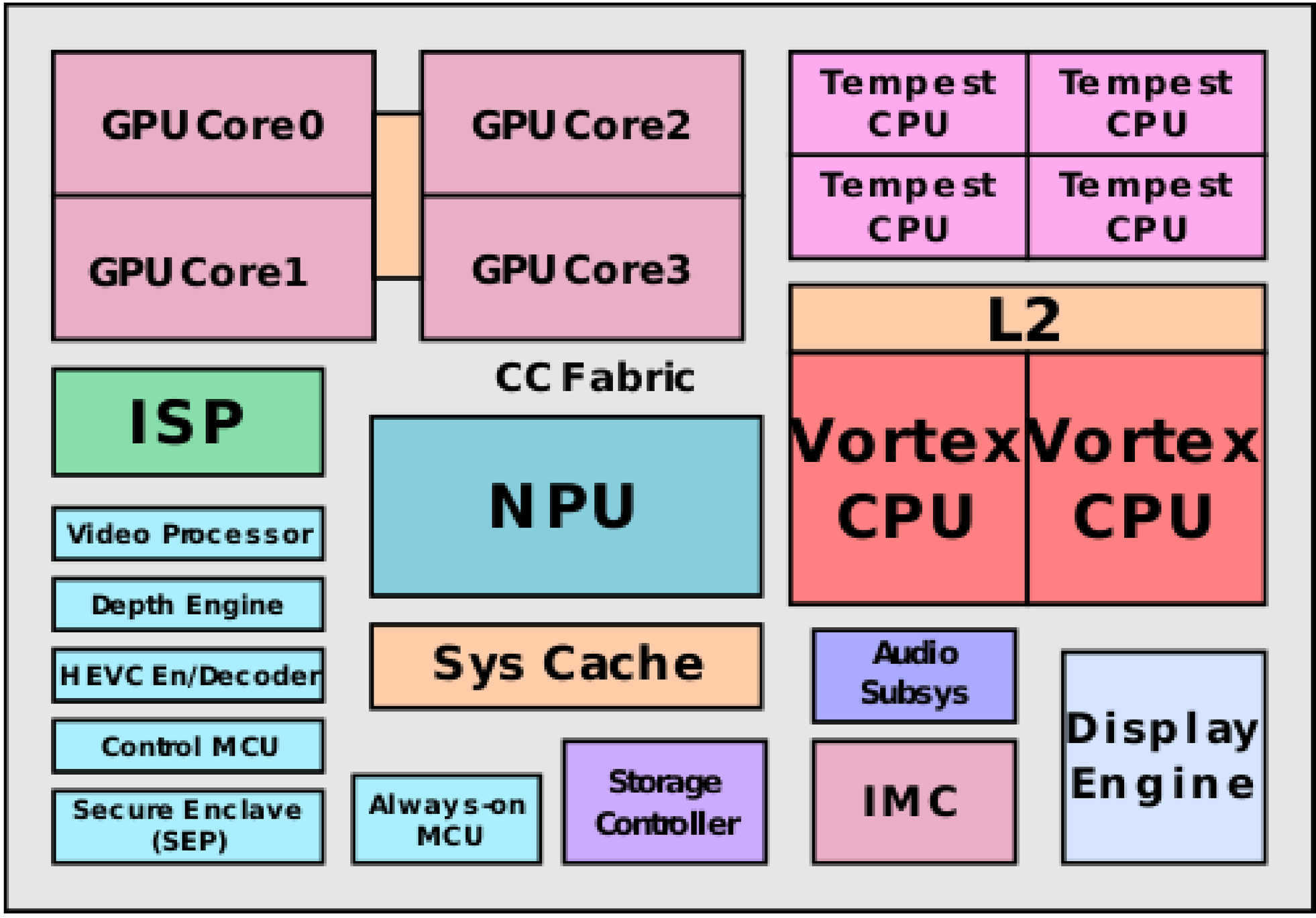
Half-adder (20 FETs)



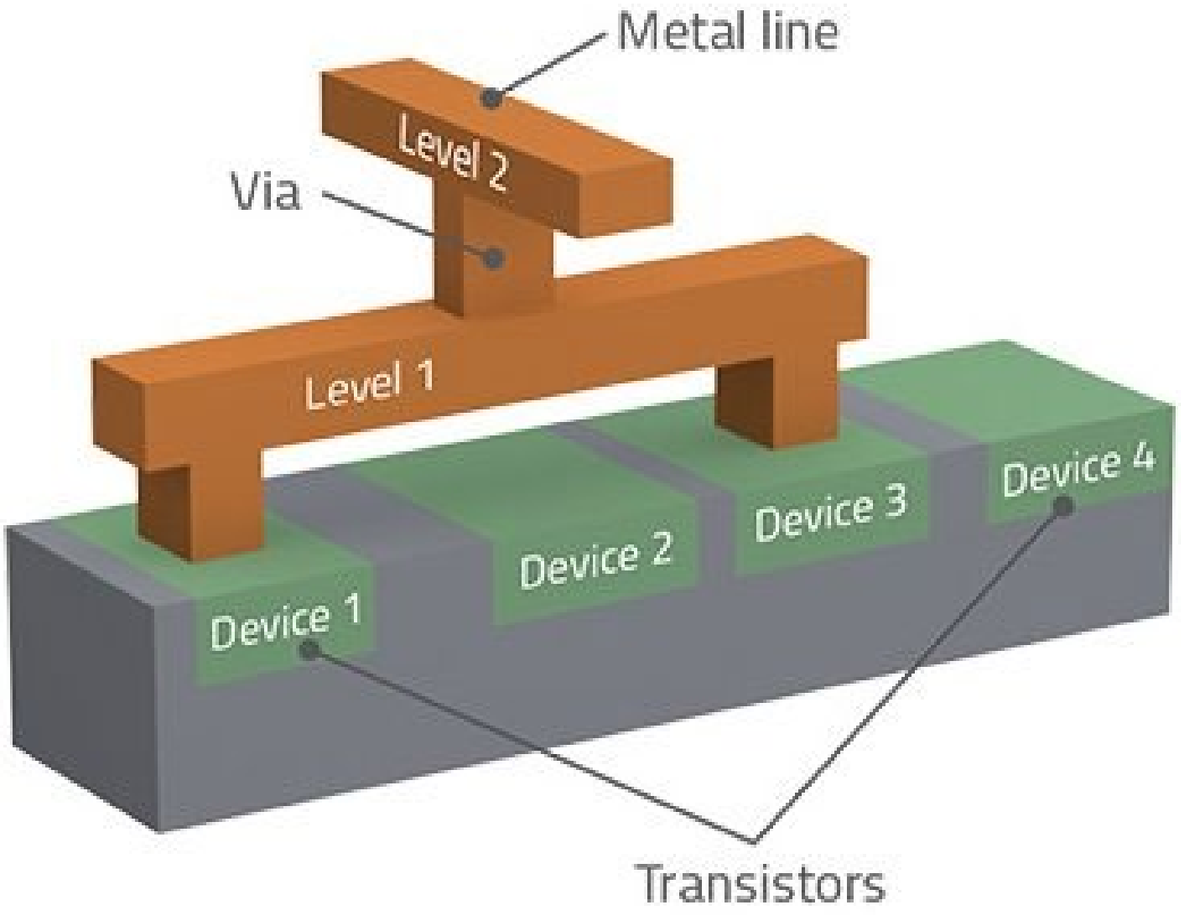
A	B	S (sum)	C (carry)
0	0	0	0
0	1	1	0
1	0	1	0
1	1	0	1

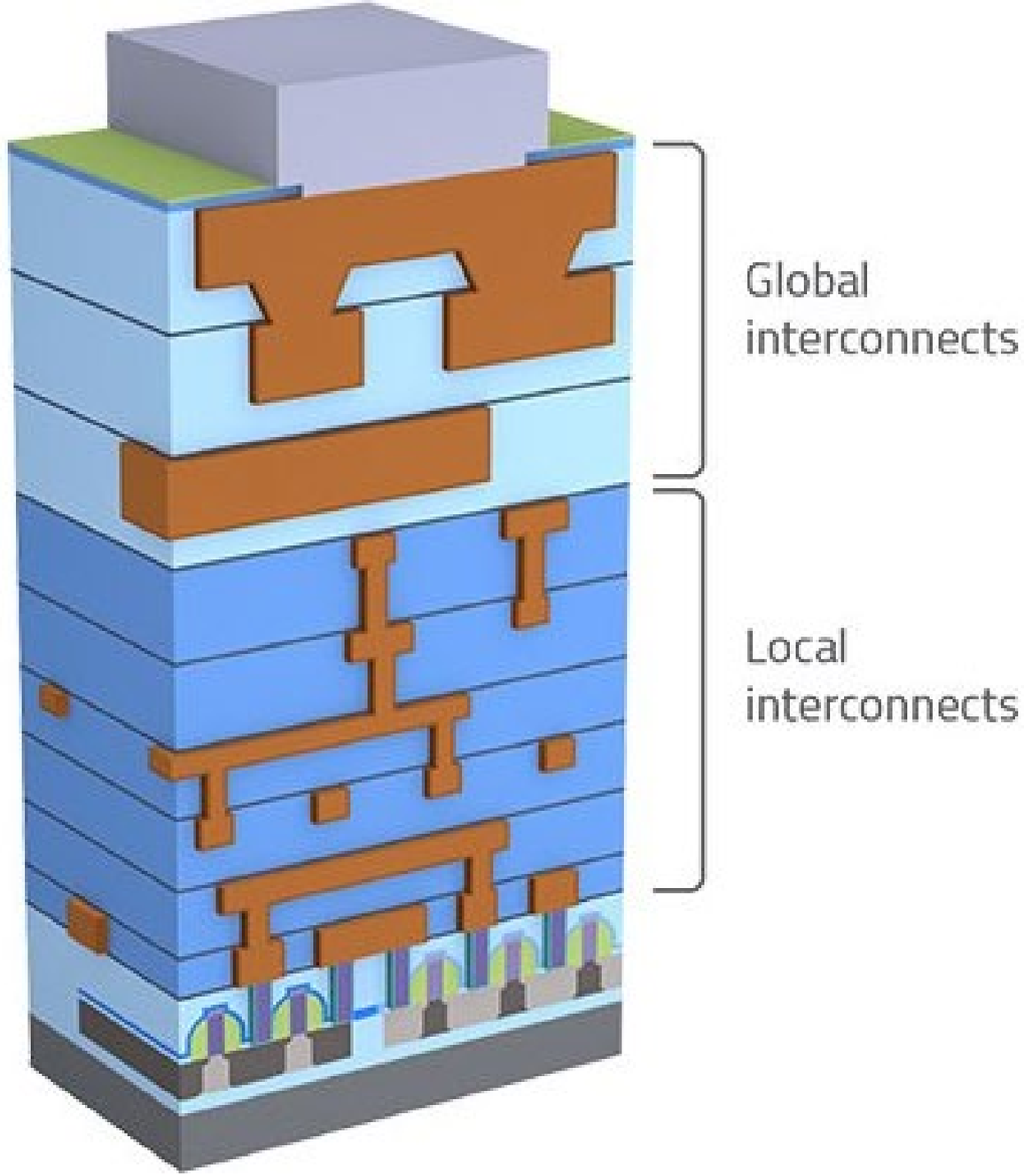
Apple A12
64-bit
microprocessor

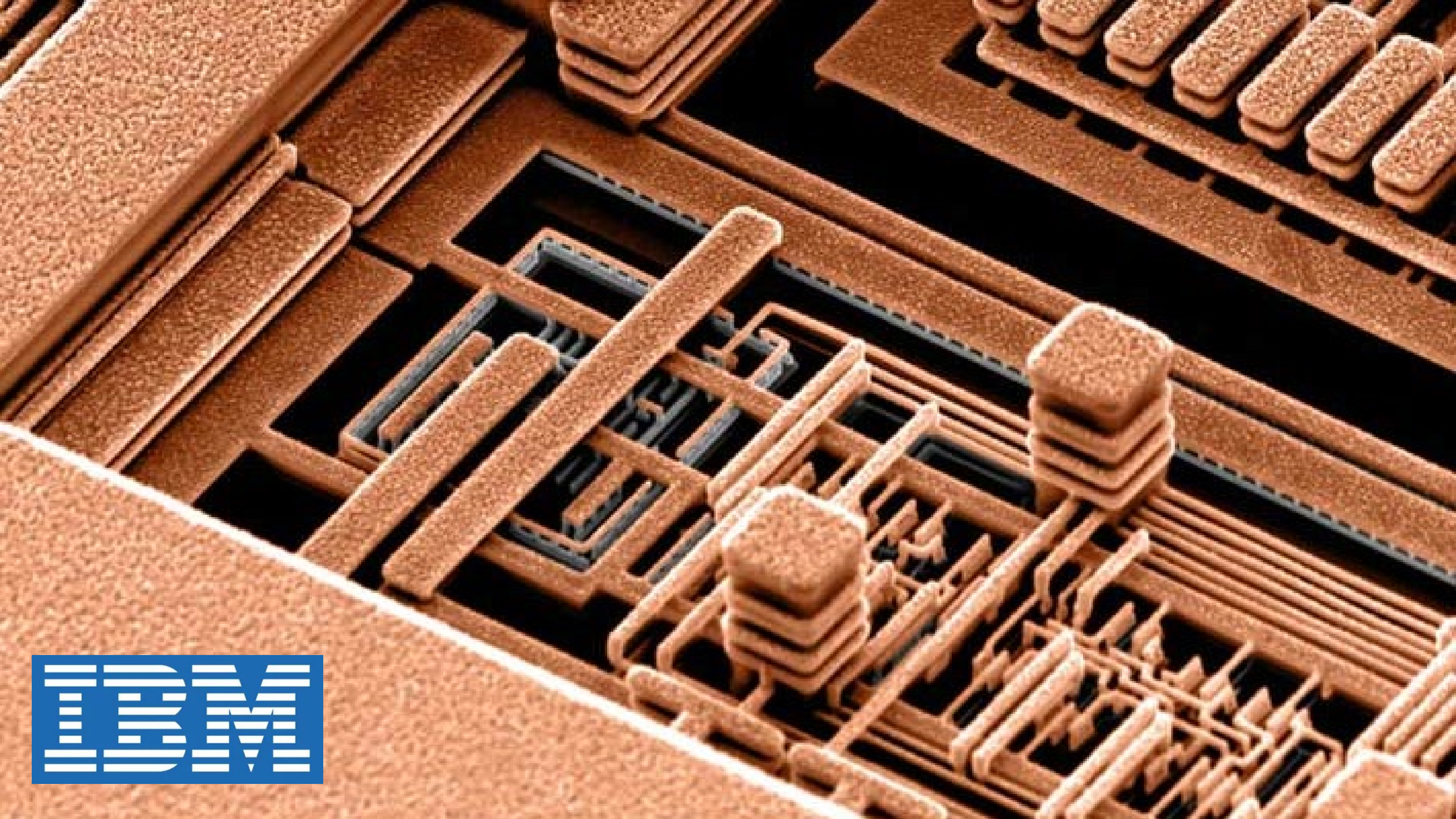
7 billion FETs

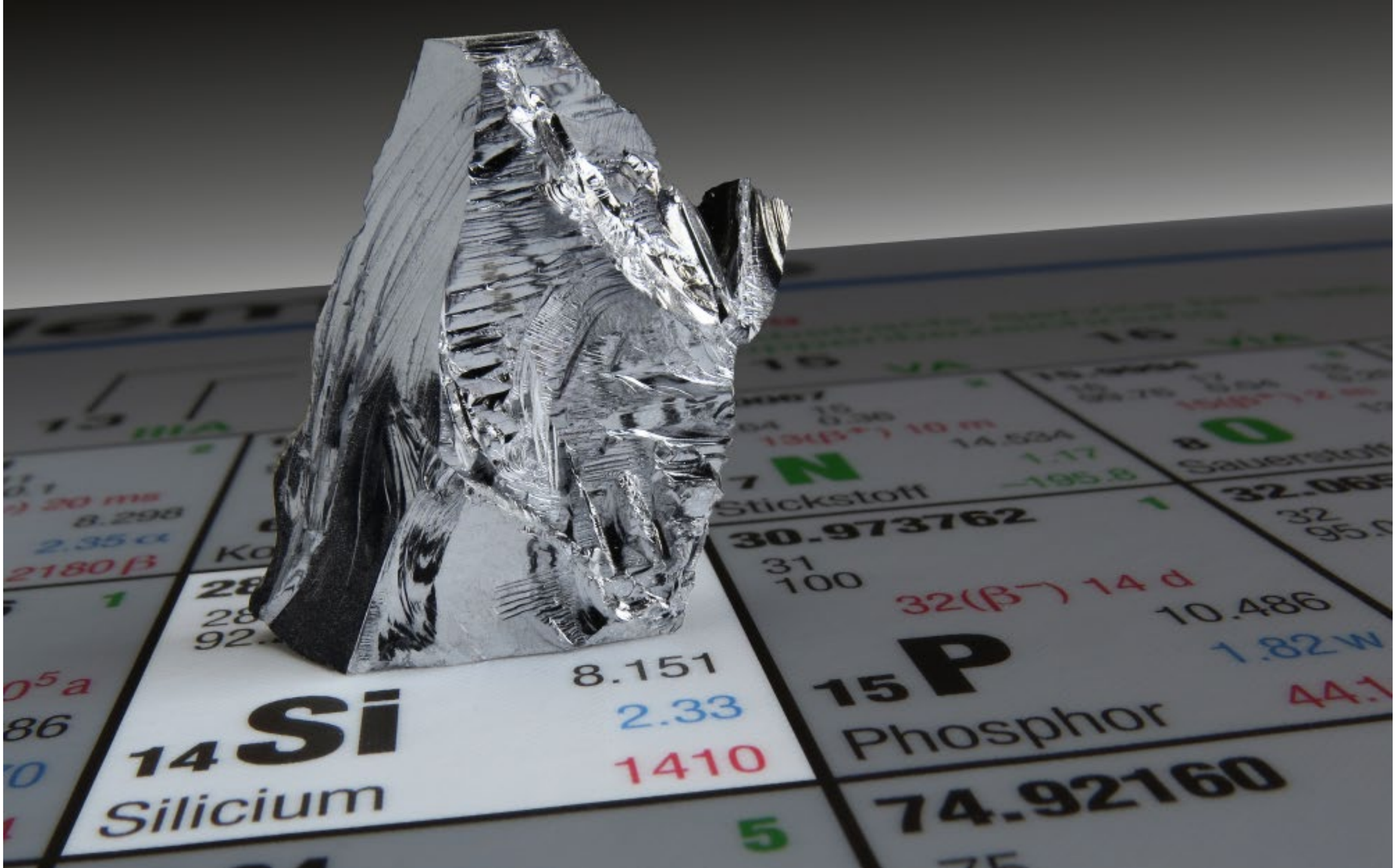


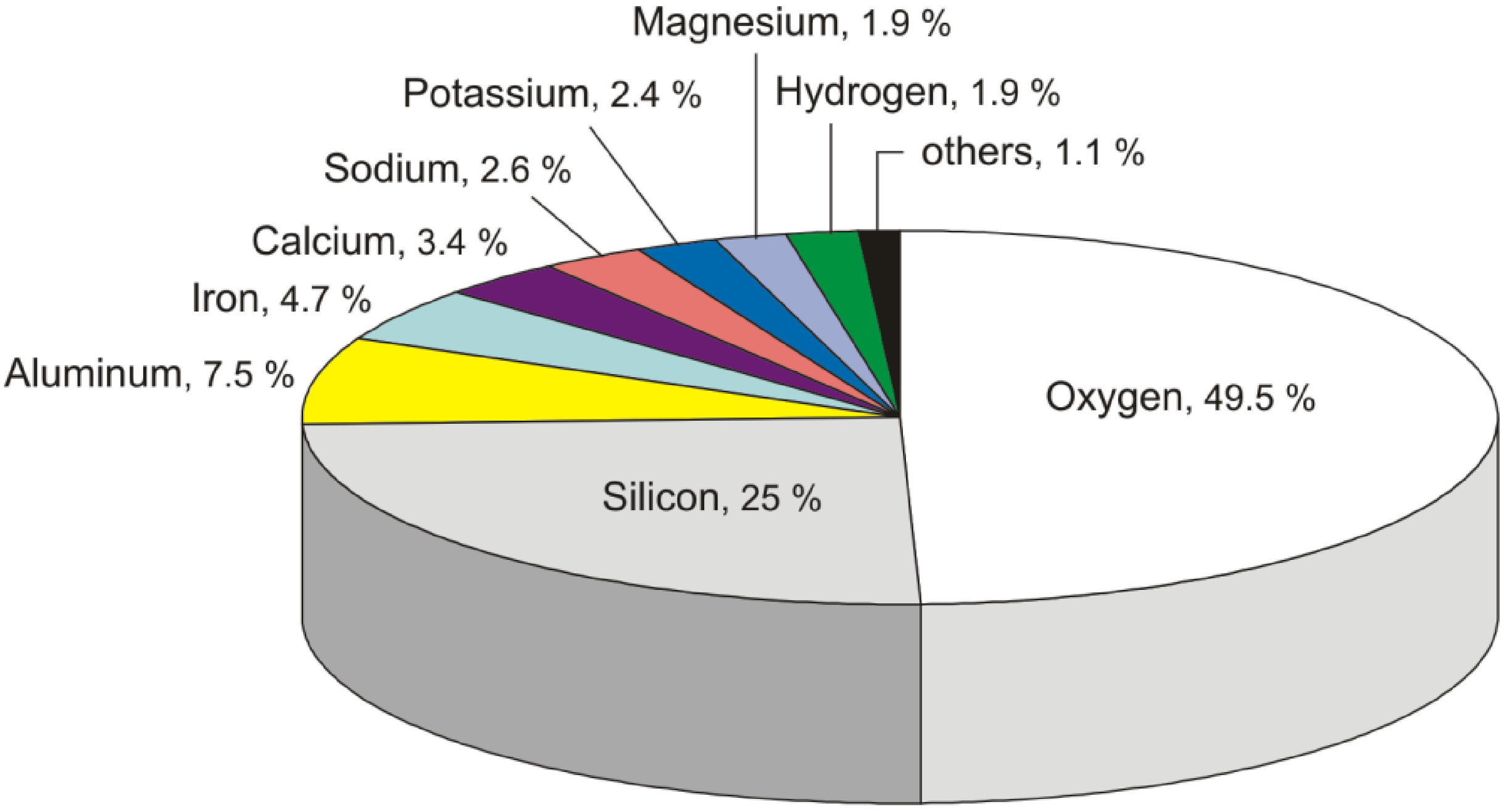
Multi-level interconnects

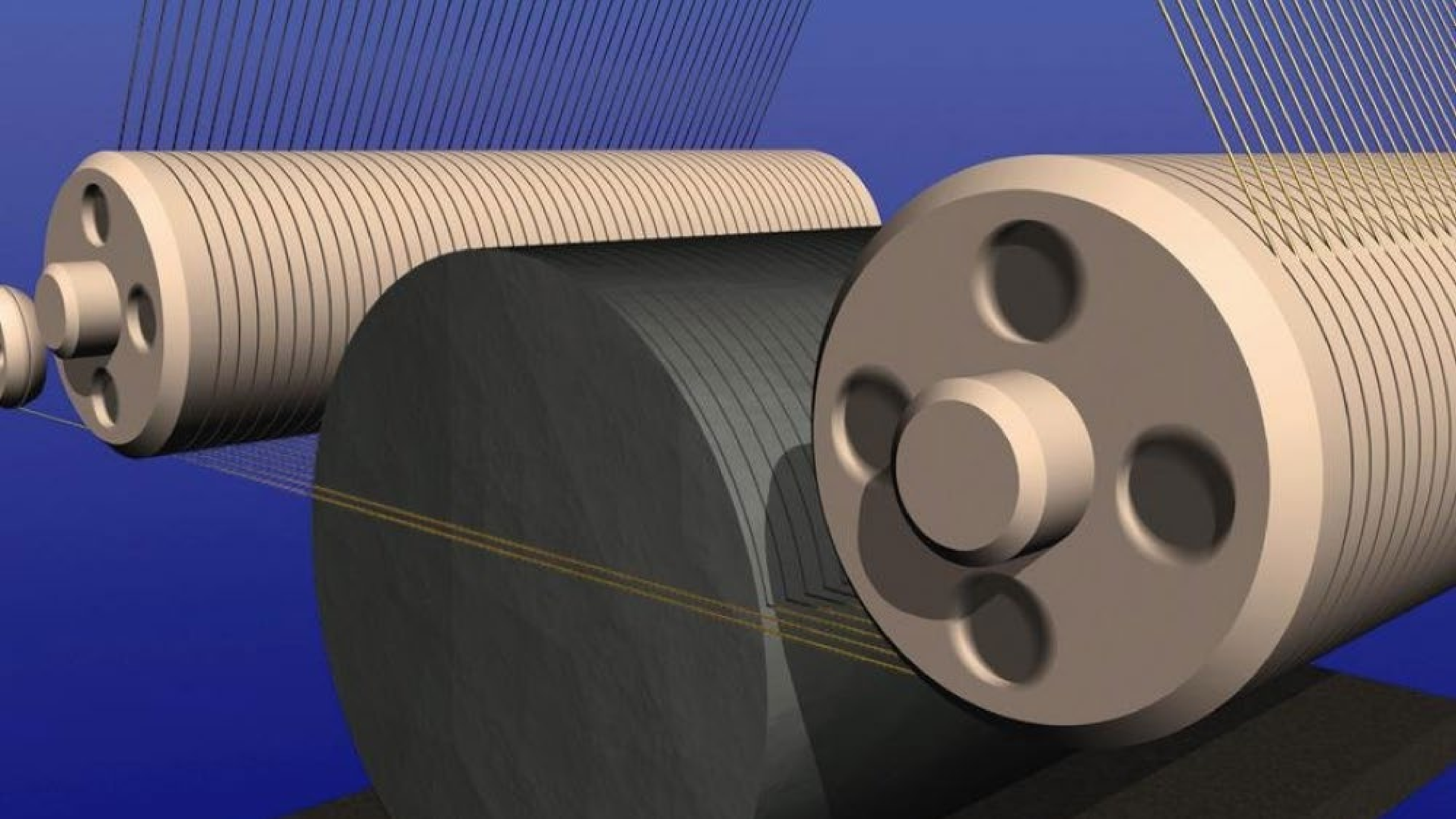


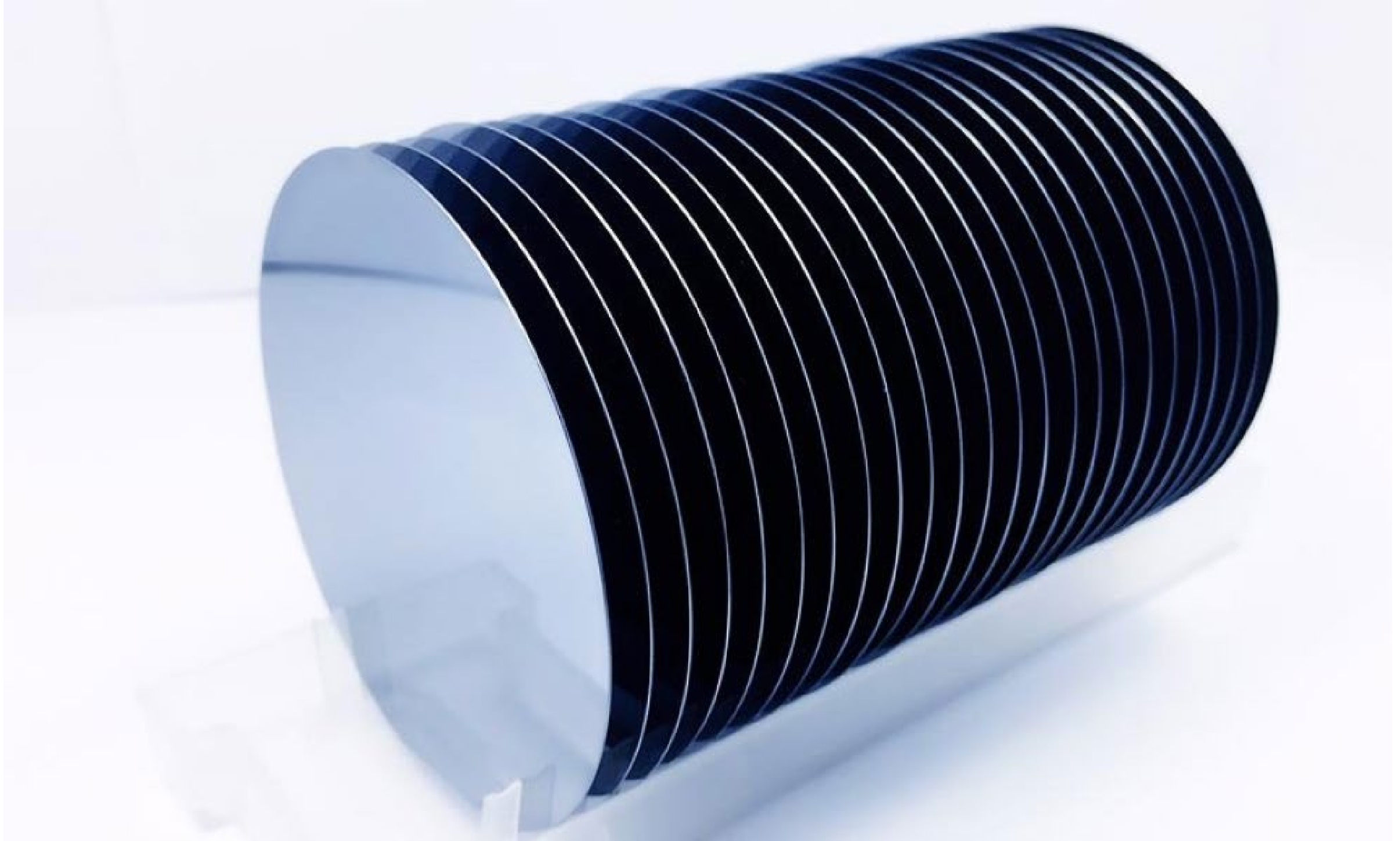


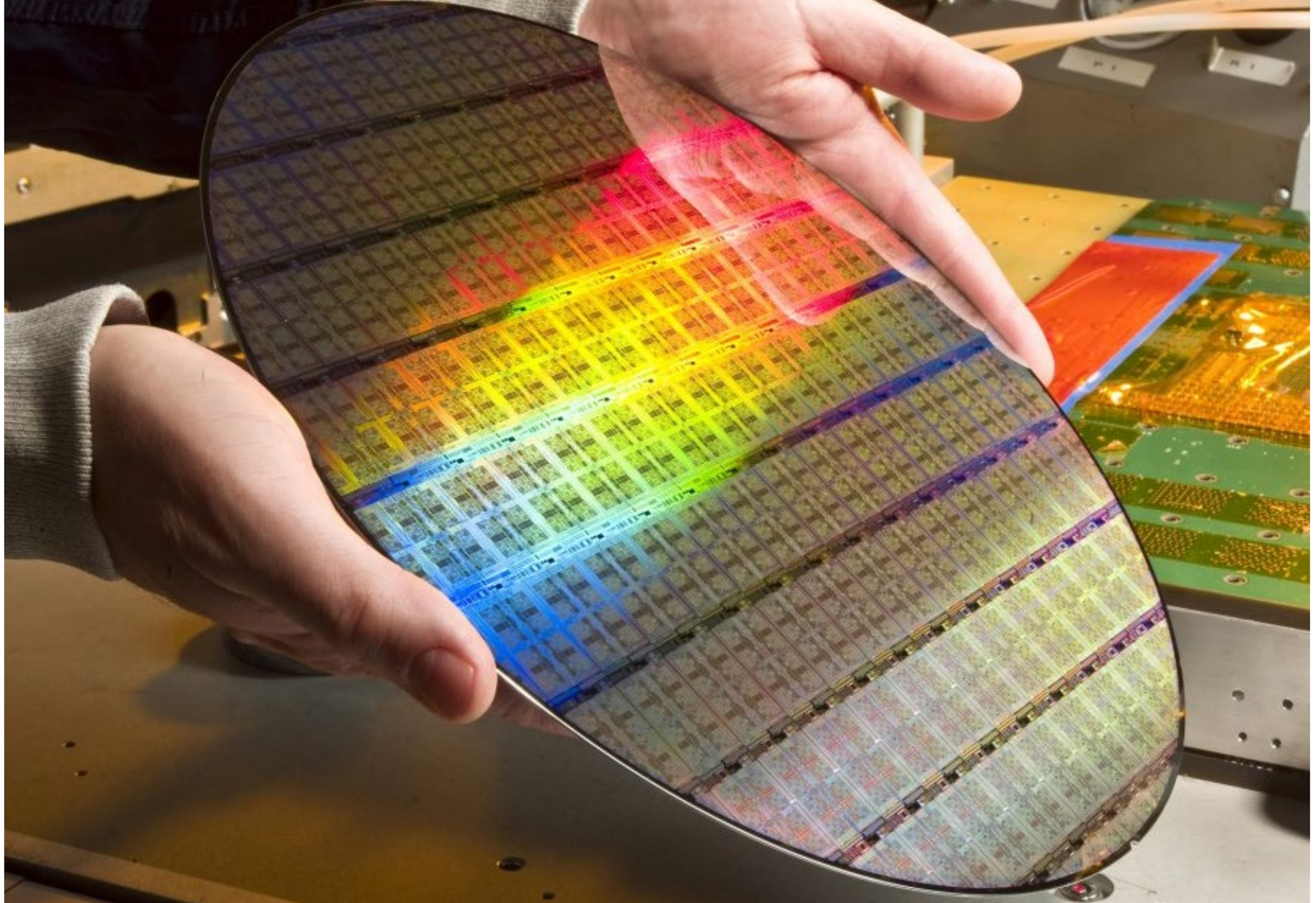


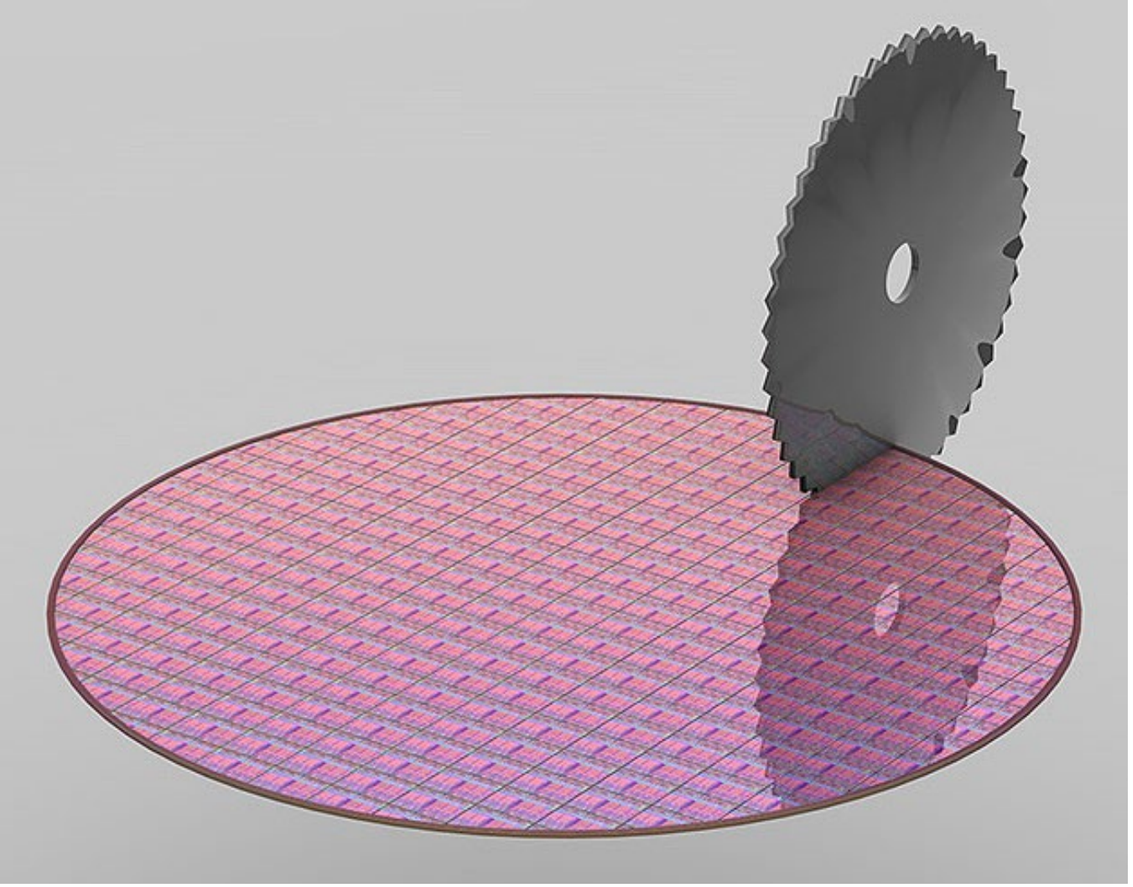

14 Si
Silicium
8.151
2.33
1410
15 P
Phosphor
30.973762
31
100
32(β⁻) 14 d
10.486
1.82 W
74.92160
7 N
Stickstoff
8 O
Sauerstoff

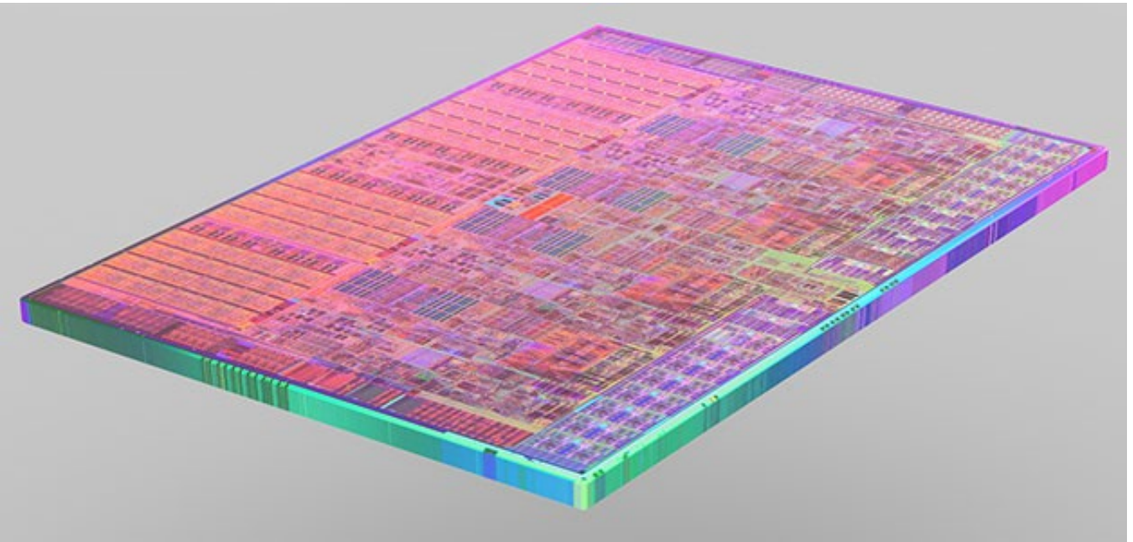

Magnesium, 1.9 %
Potassium, 2.4 %
Hydrogen, 1.9 %
Sodium, 2.6 %
others, 1.1 %
Calcium, 3.4 %
Iron, 4.7 %
Aluminum, 7.5 %
Oxygen, 49.5 %
Silicon, 25 %

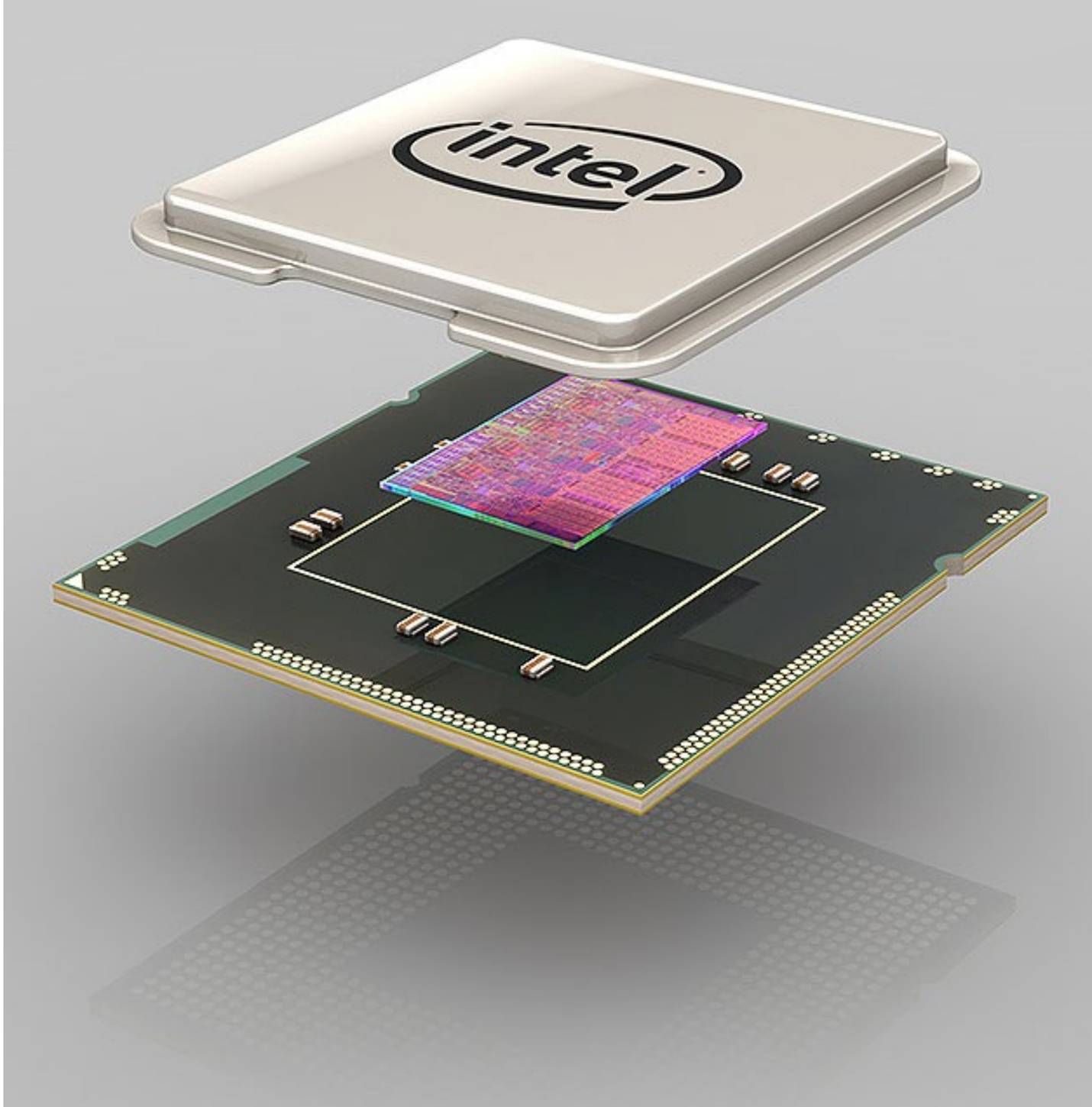


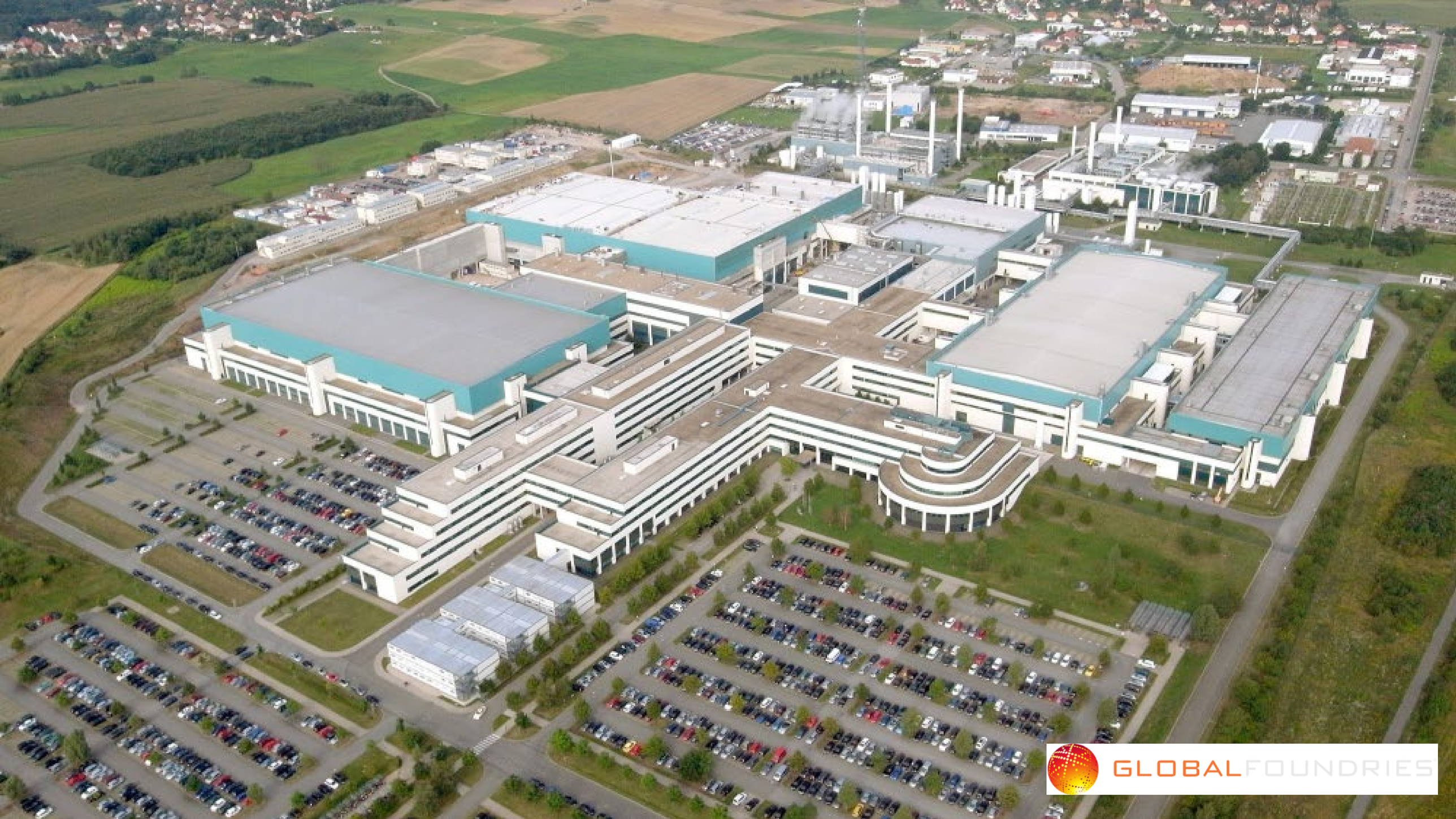


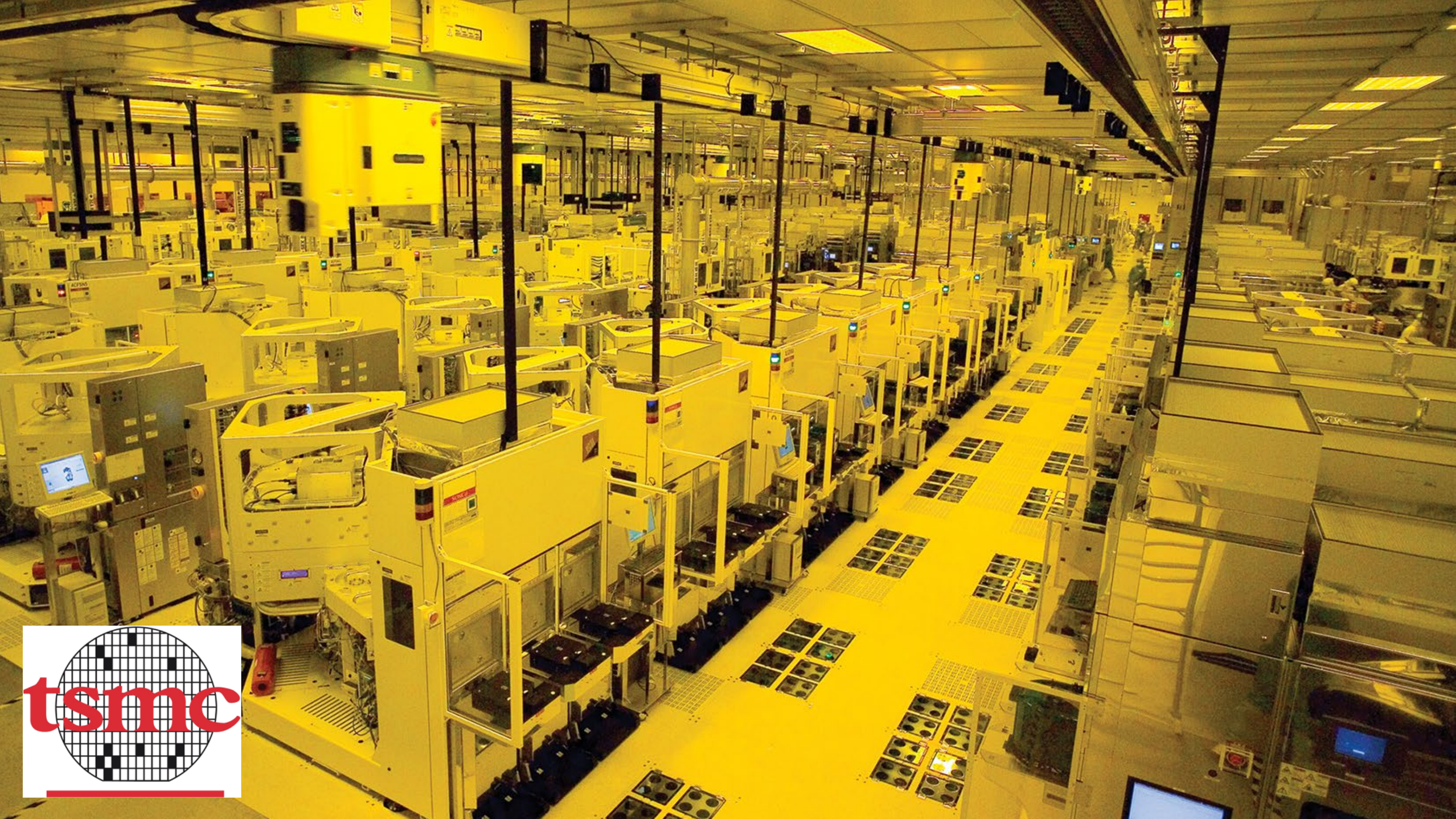


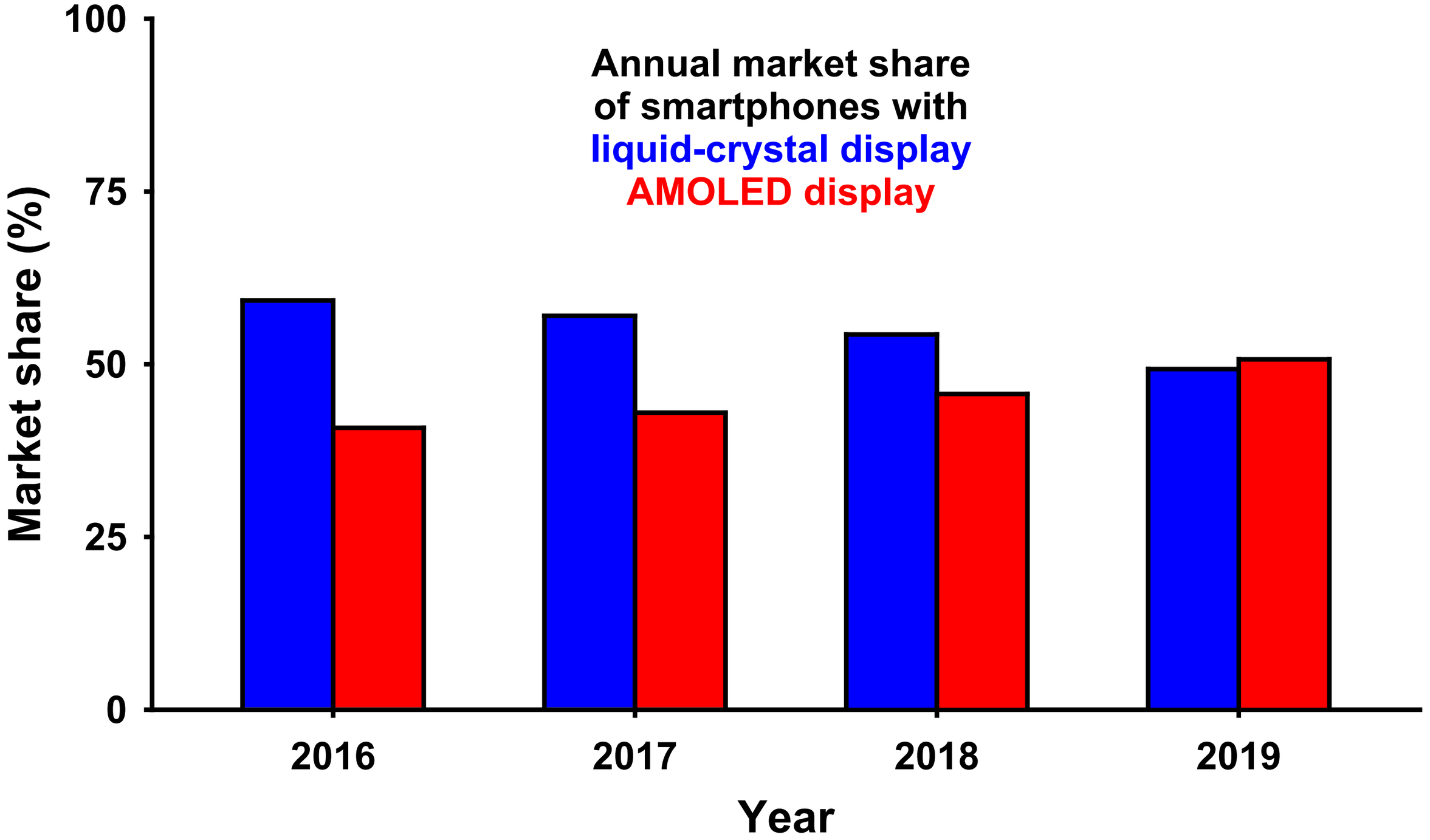




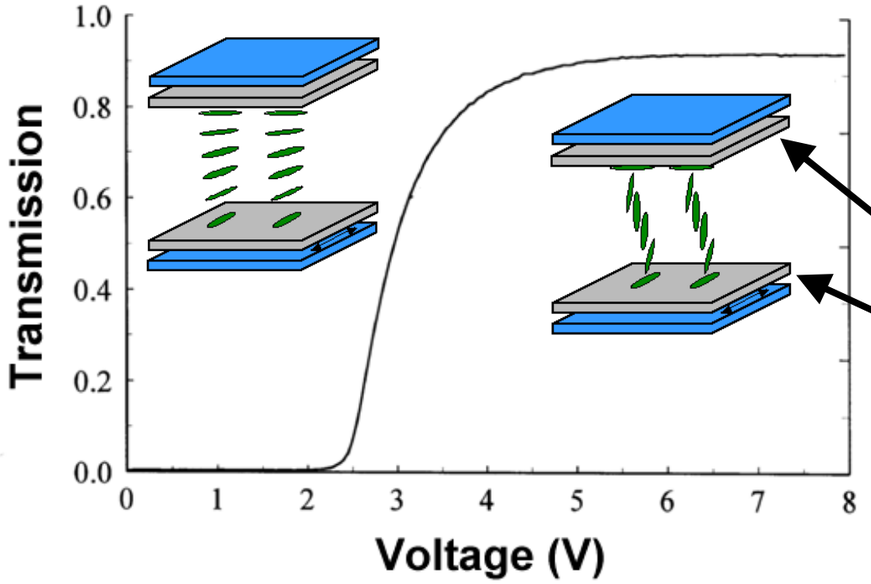

intel


GLOBALFOUNDRIES

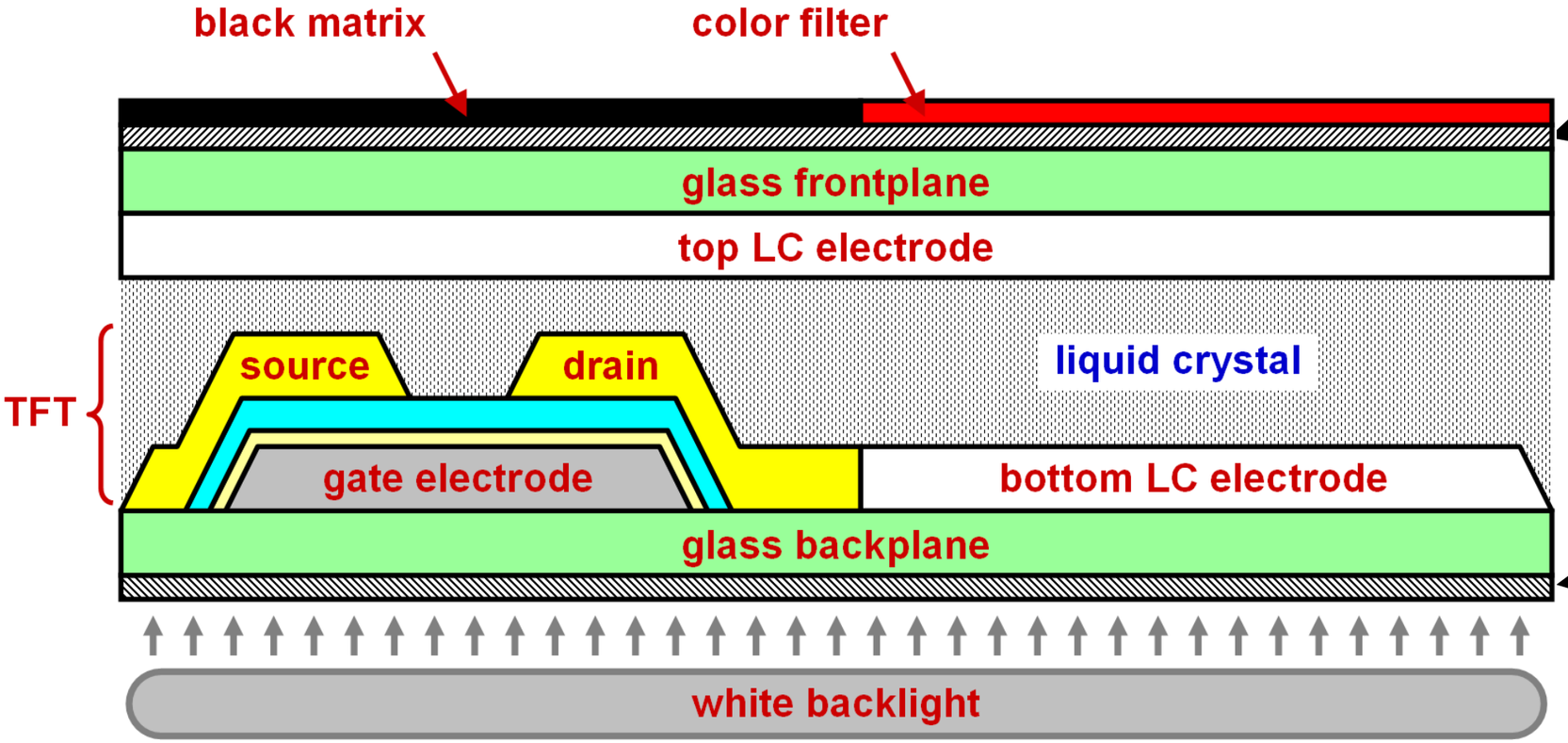

tsmc

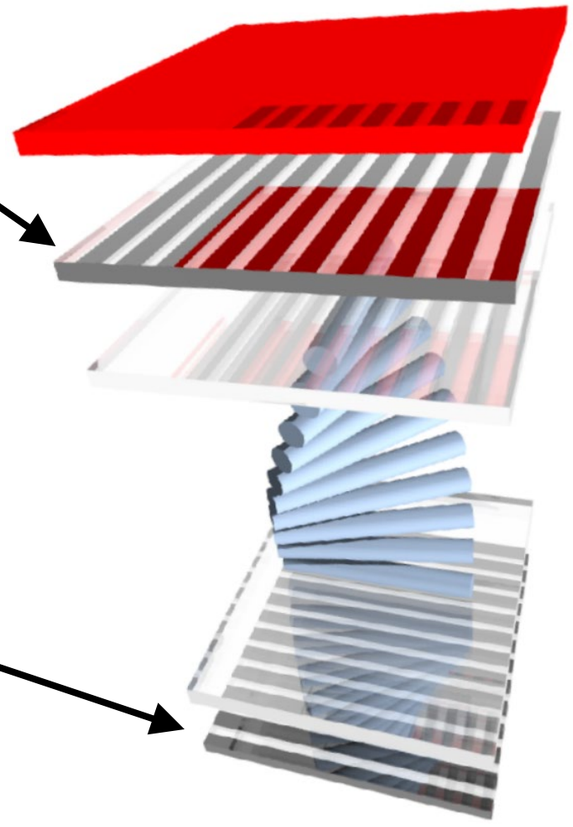

Annual market share
of smartphones with
liquid-crystal display
AMOLED display
Market share (%)
100
75
50
25
0
2016
2017
2018
2019
Year

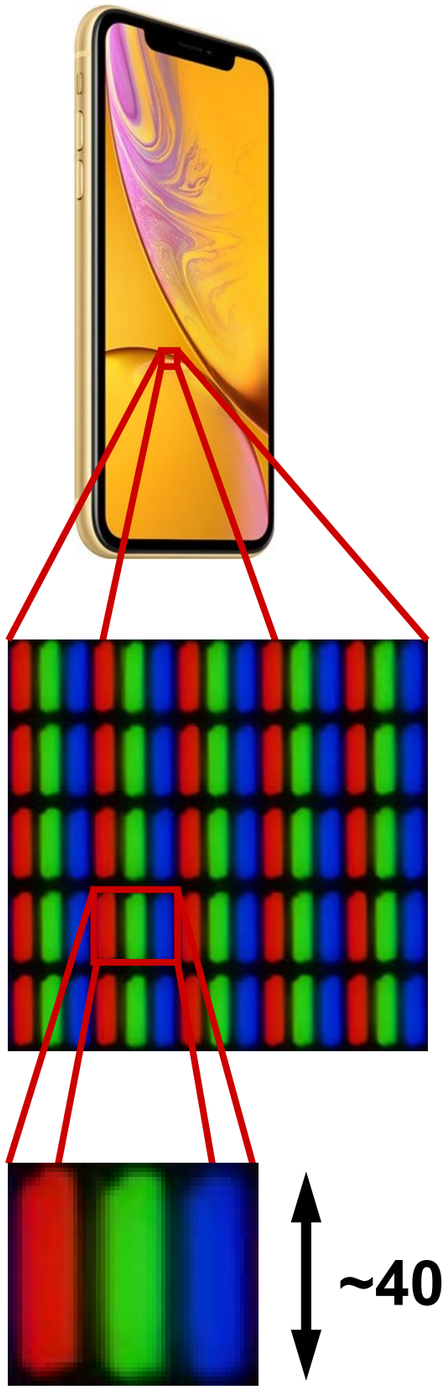
Active-matrix liquid-crystal display (AMLCD)

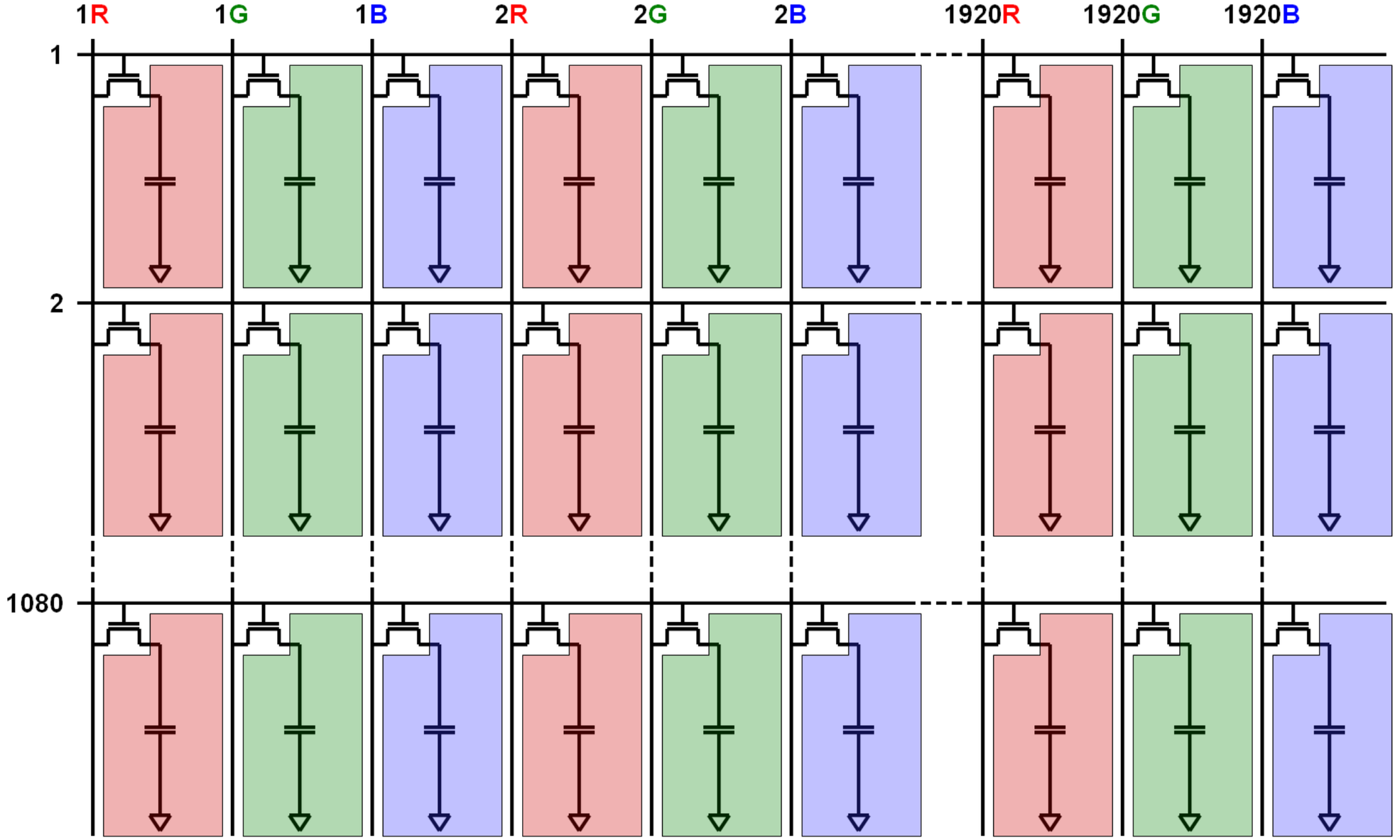


Polarizers

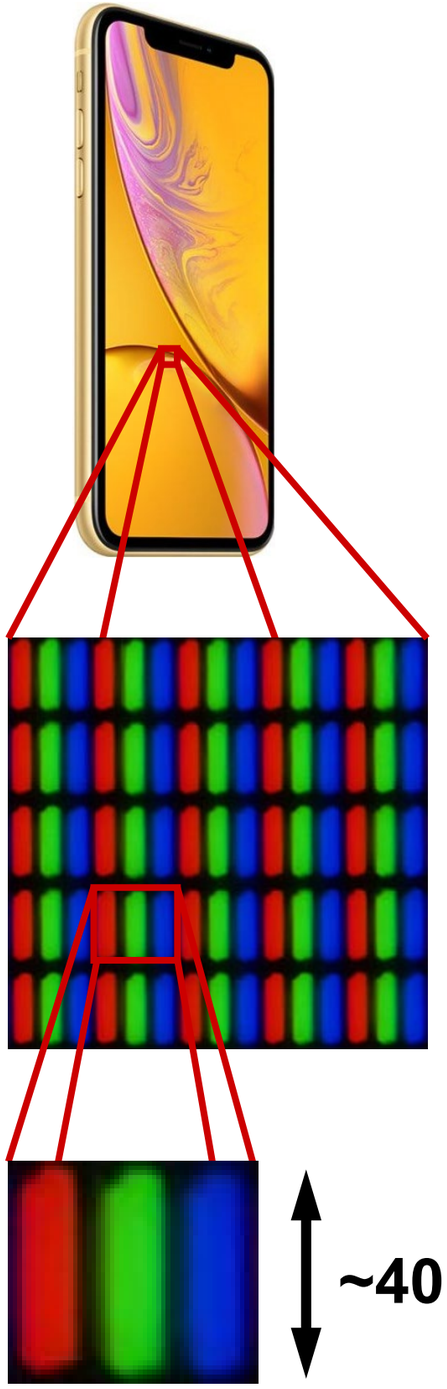


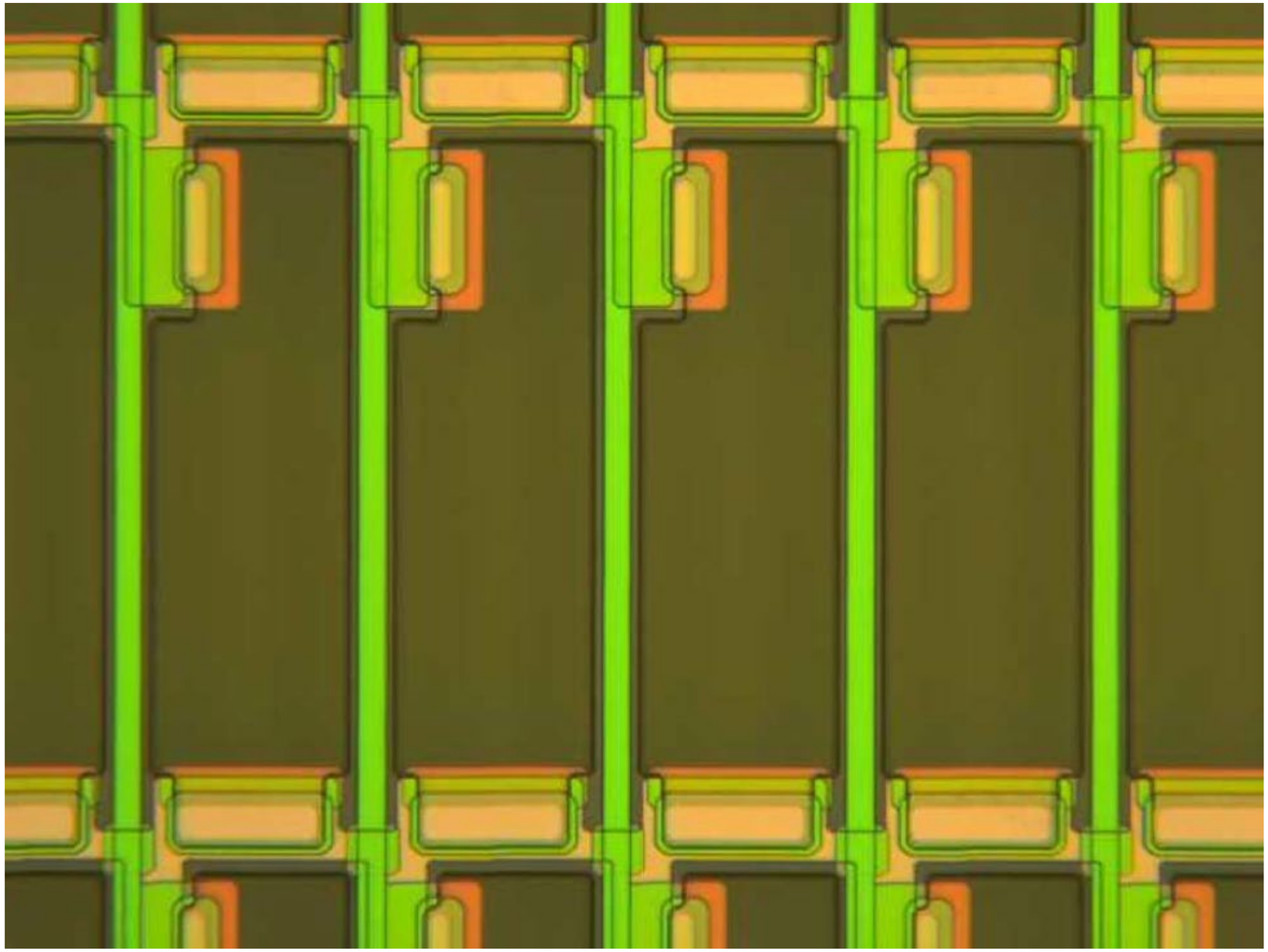




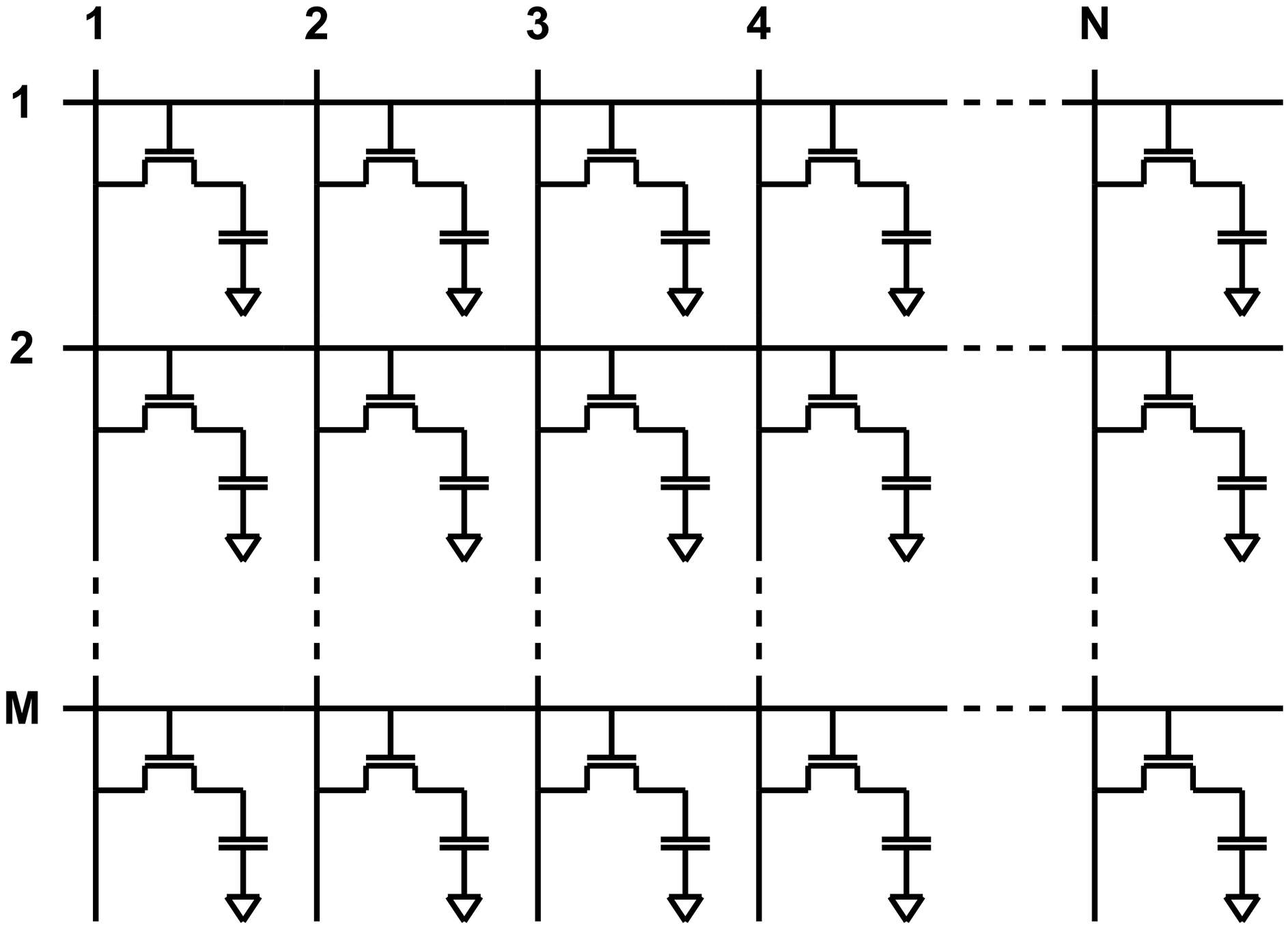


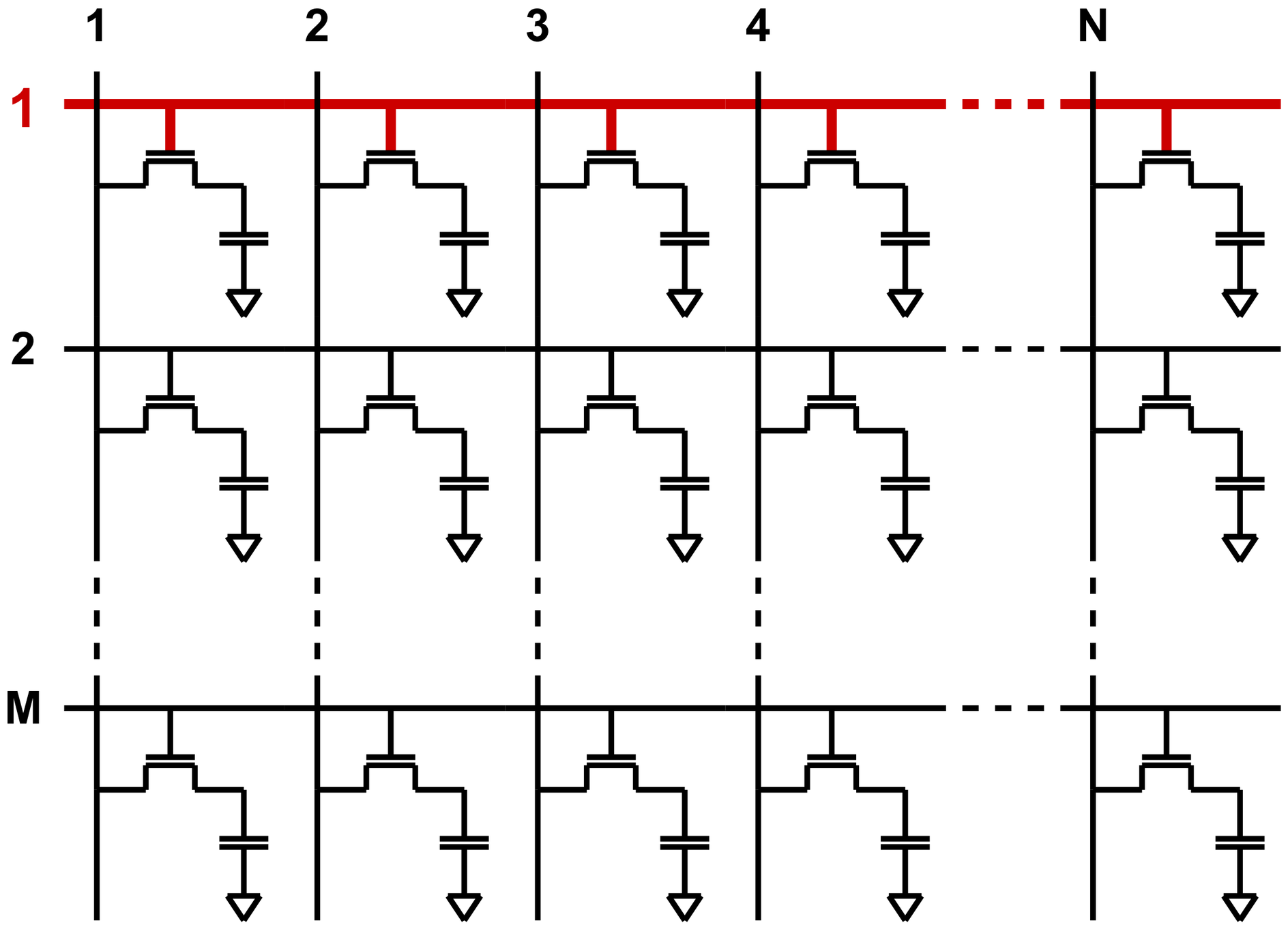
Active-matrix displays require the integration of the electro-optic elements with thin-film transistors (TFTs).



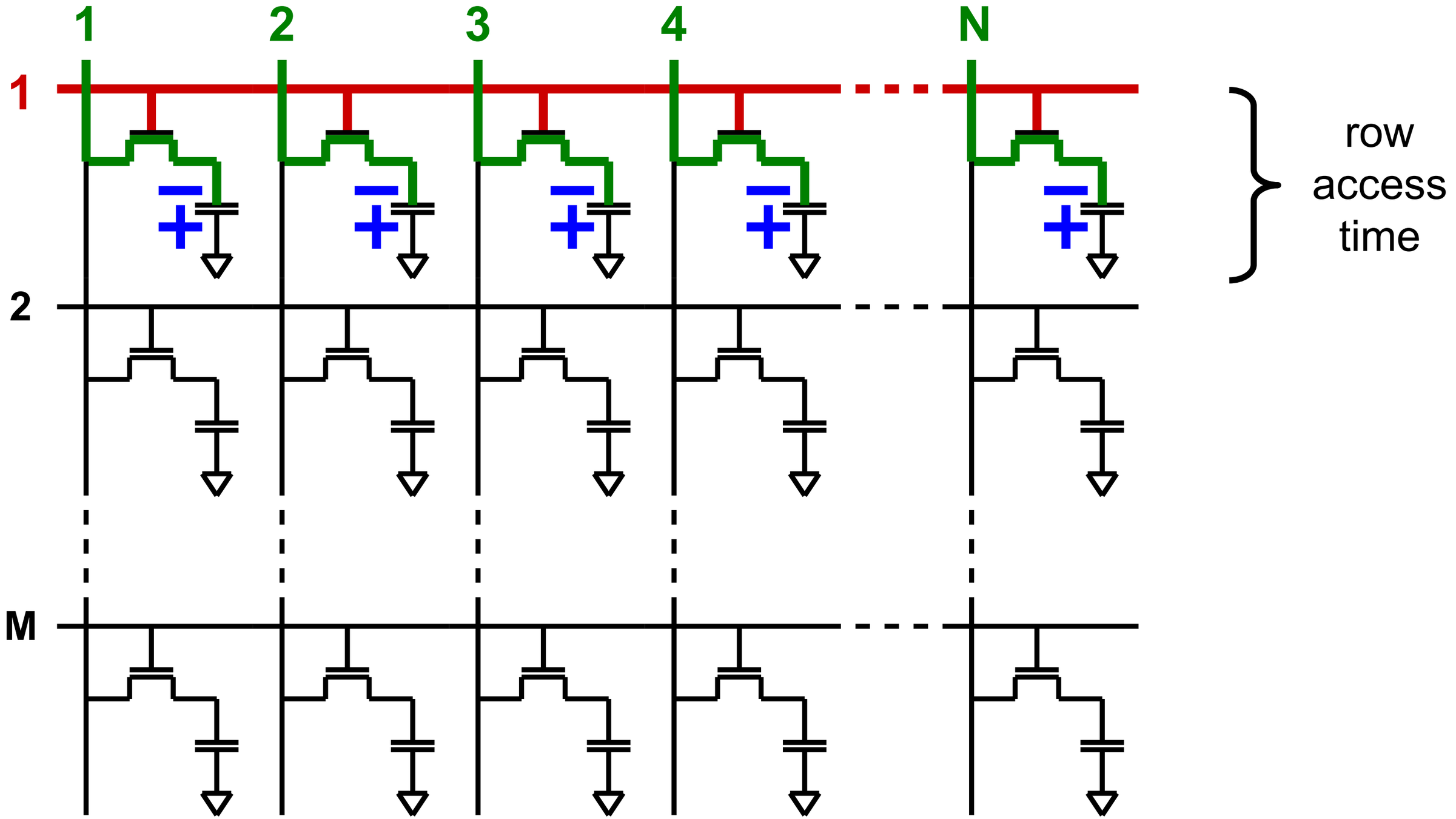


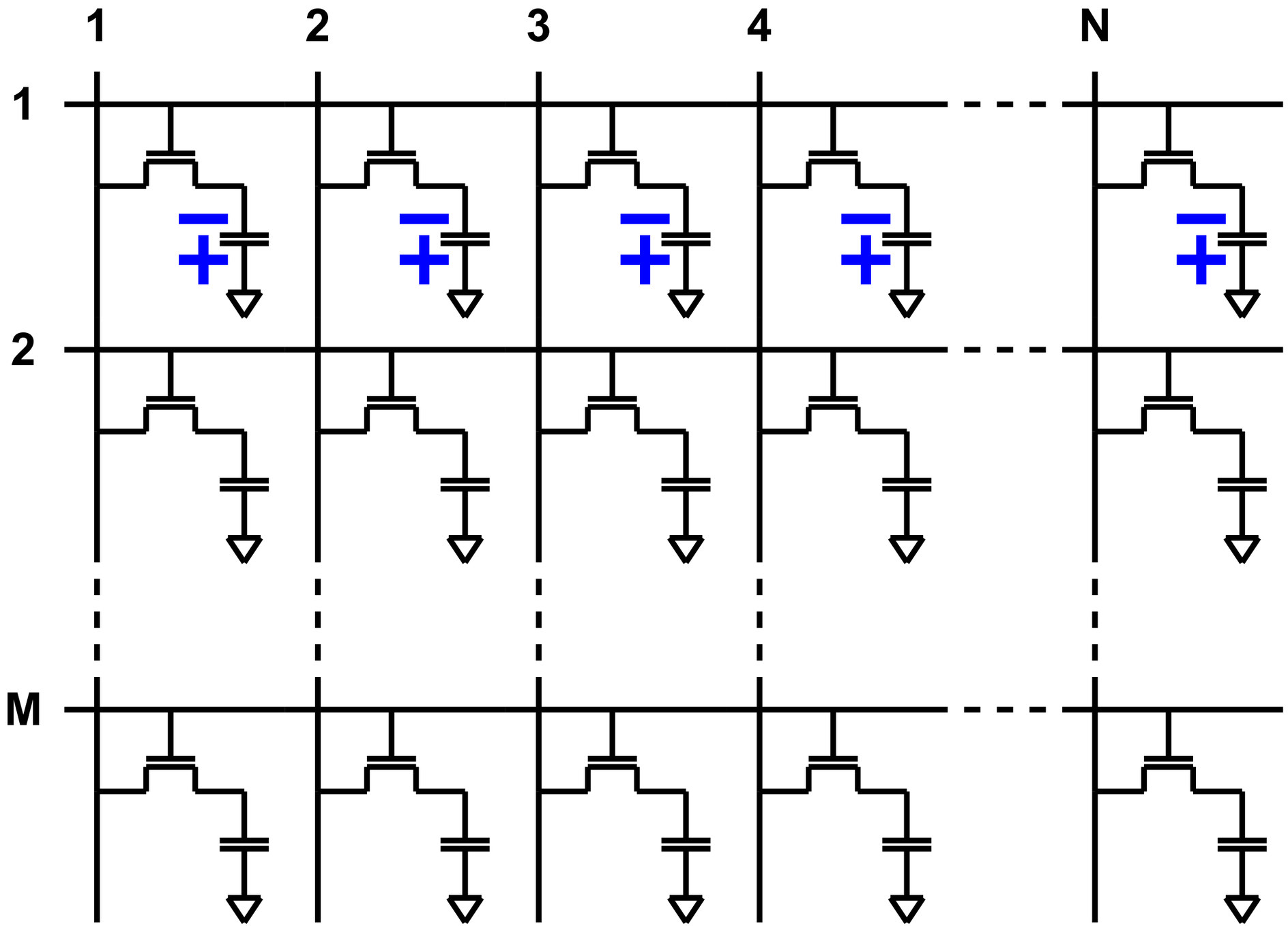
Steffen Höhla, Norbert Frühauf
Institut für Großflächige Mikroelektronik, Universität Stuttgart


1
2
3
4
N
1
2
M



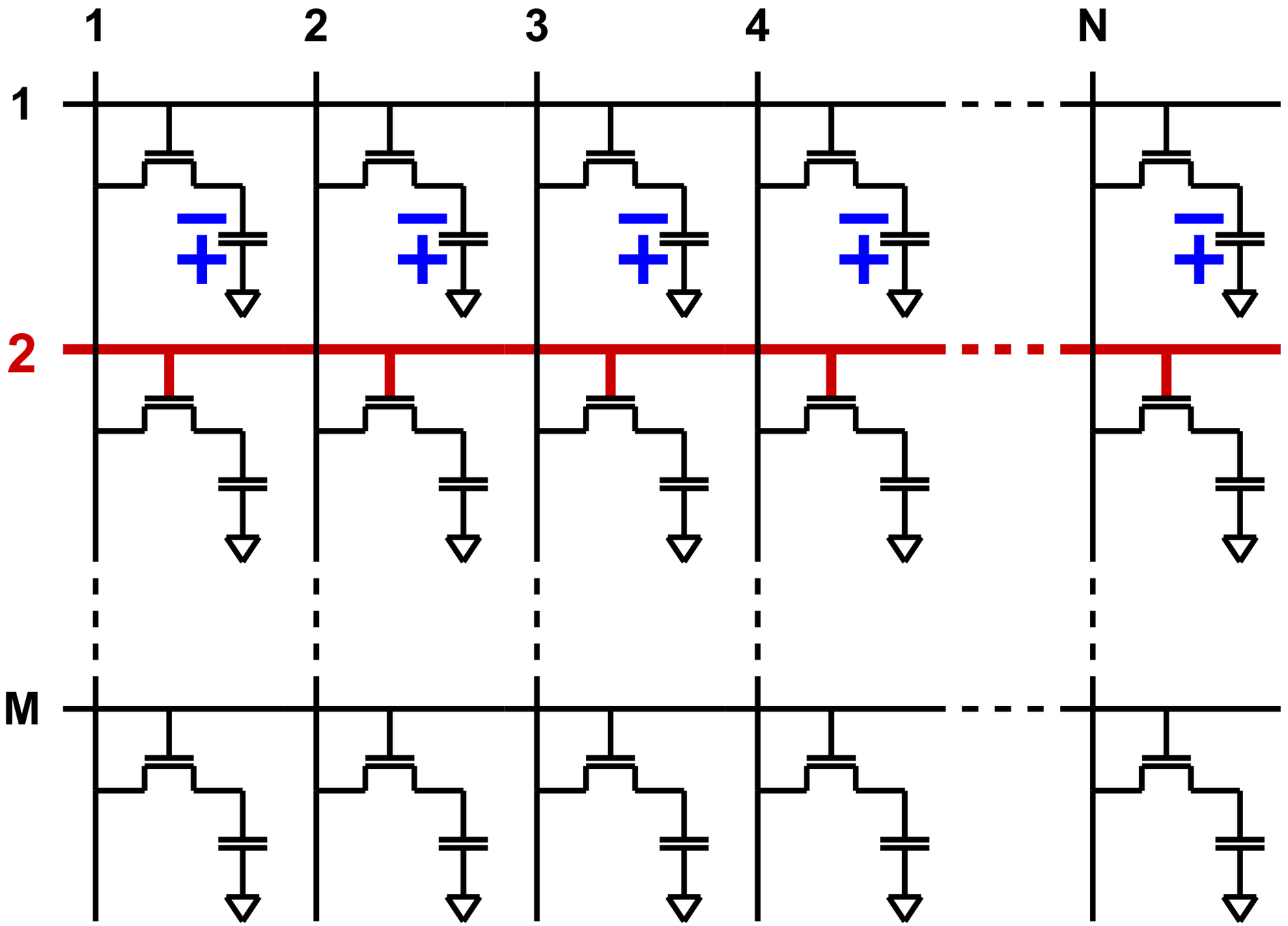
t = 0

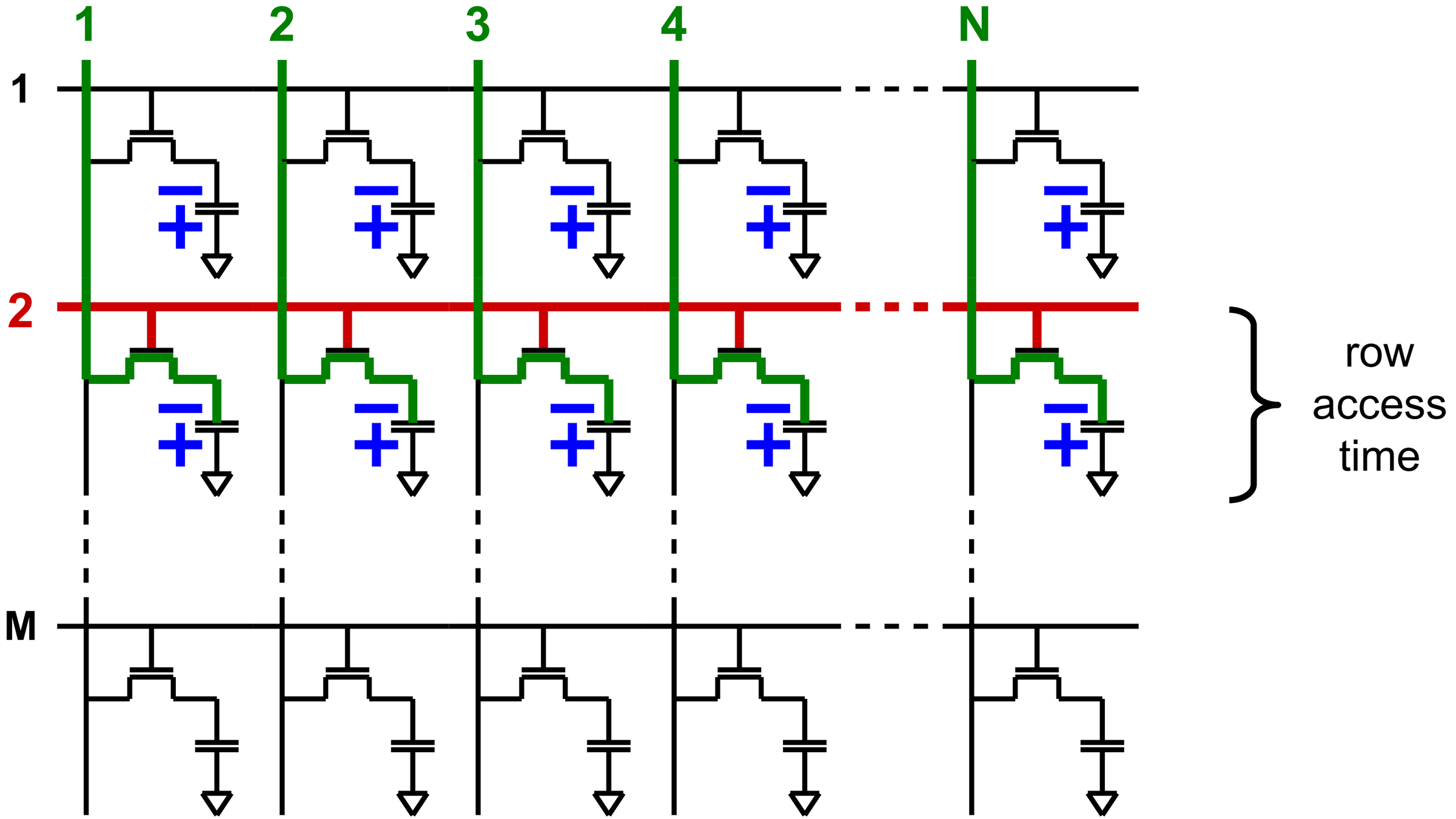

1
2
3
4
N
1
2
M
row
access
time

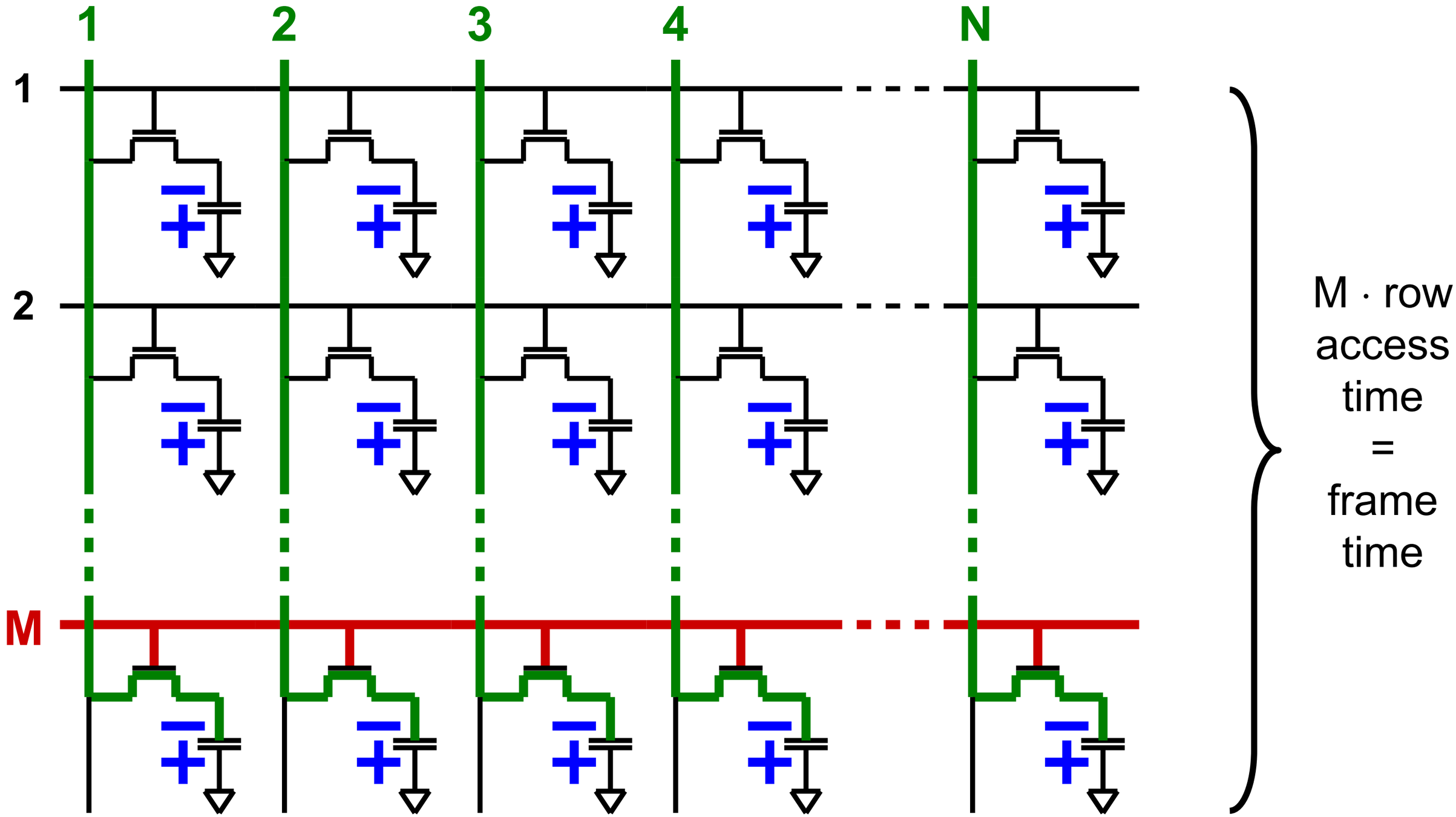


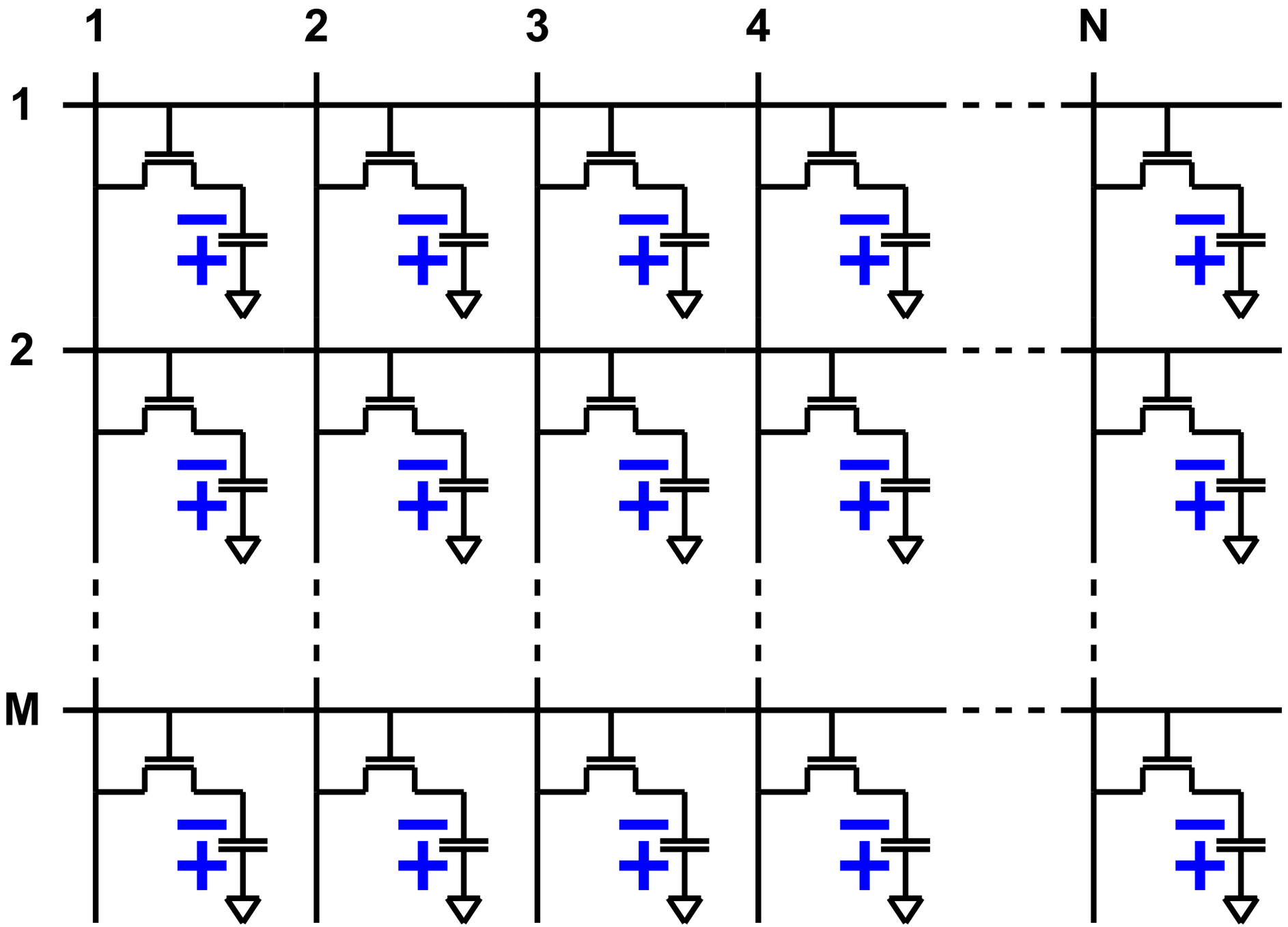
off-state:

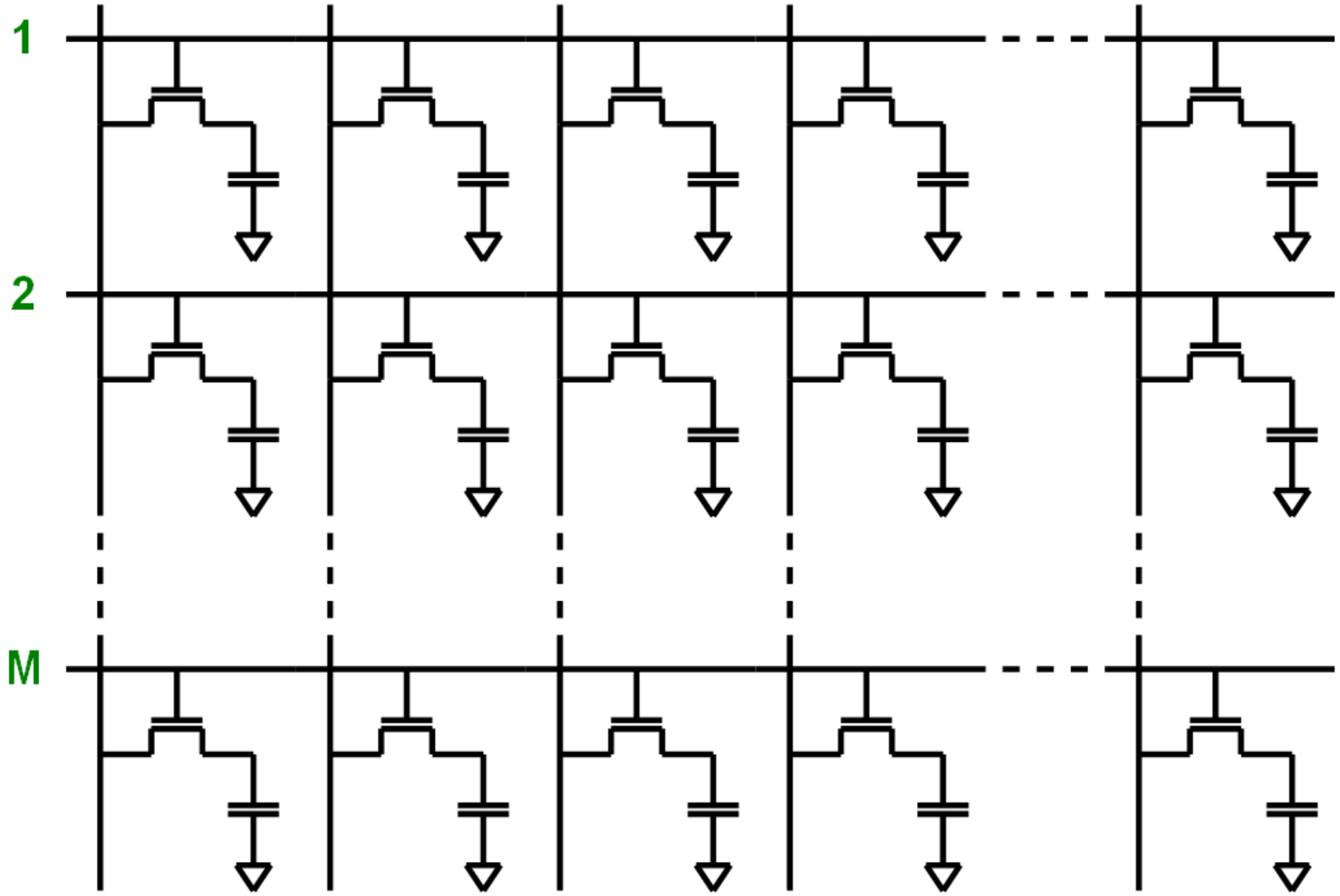
$I_D < 1$ pA


1
2
3
4
N
1
2
M


1
2
3
4
N
1
2
M
row
access
time

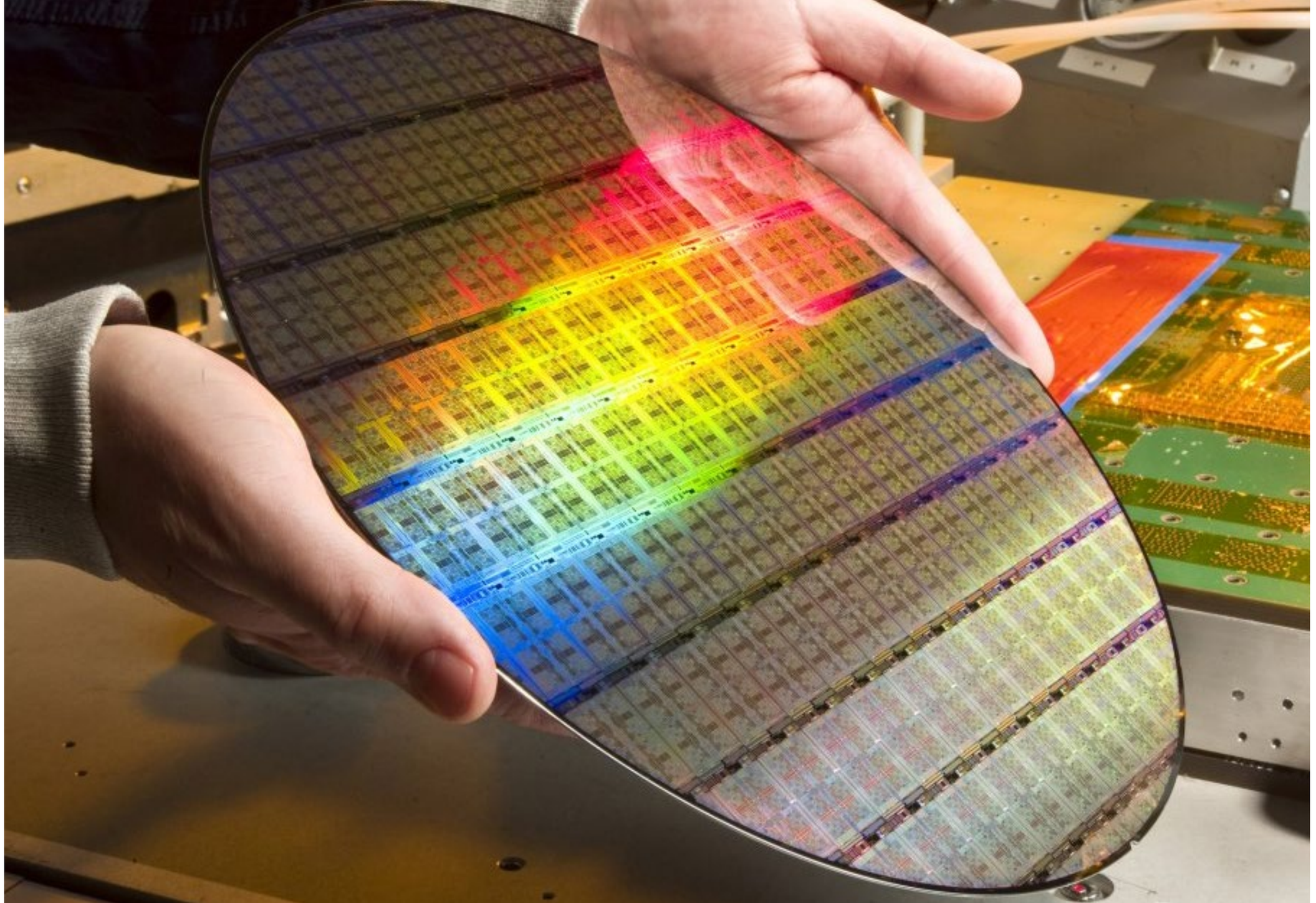

1
2
3
4
N
1
2
M
M · row access time = frame time

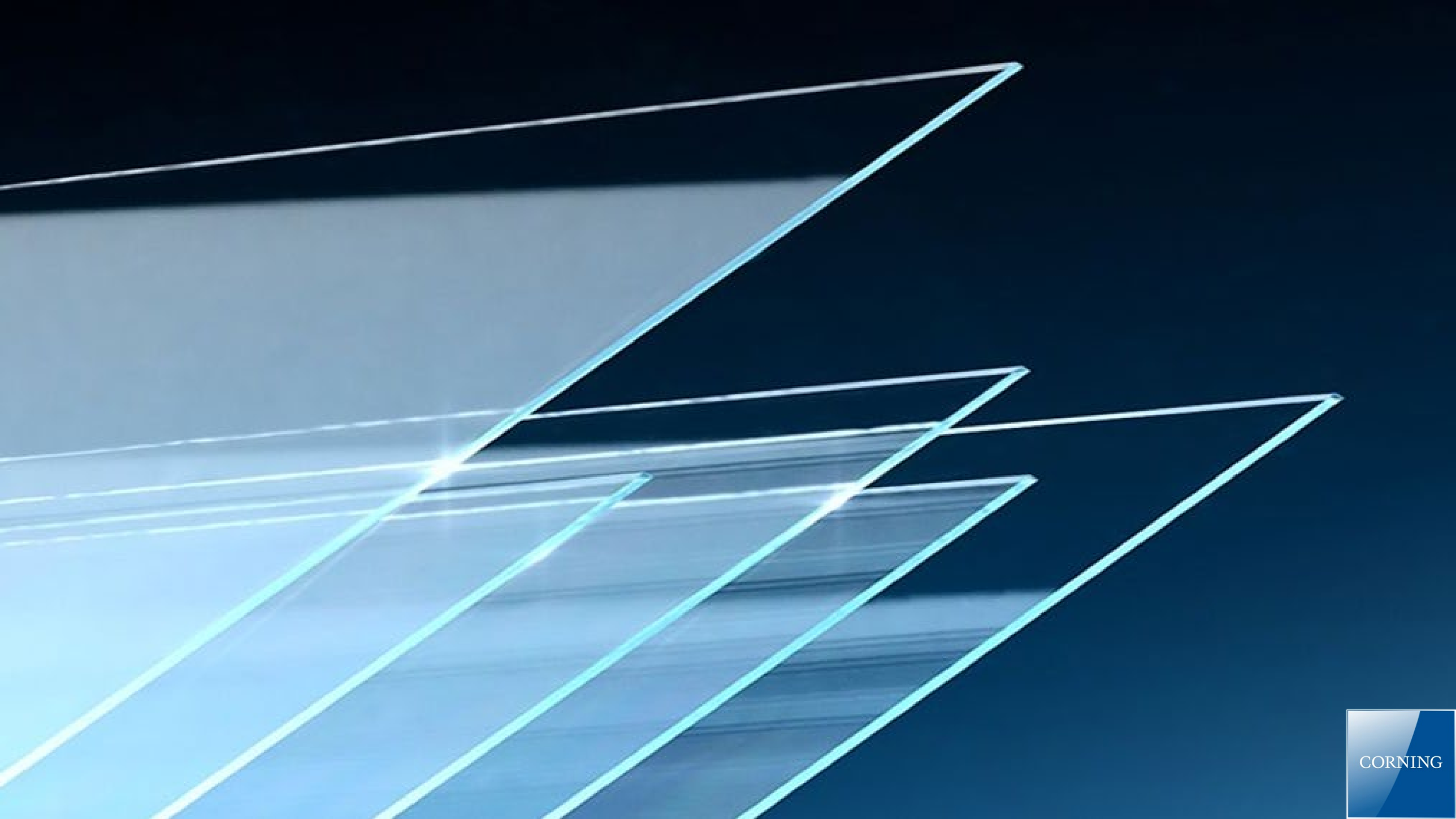

1
2
3
4
N
1
2
M



frame time = row access time x # of rows

display resolution	# of rows (M)	frame rate	row access time	TFT transit frequency
HD	1080	100 Hz	8 µsec	~1 MHz
8K UHD	4320	200 Hz	1 µsec	~10 MHz

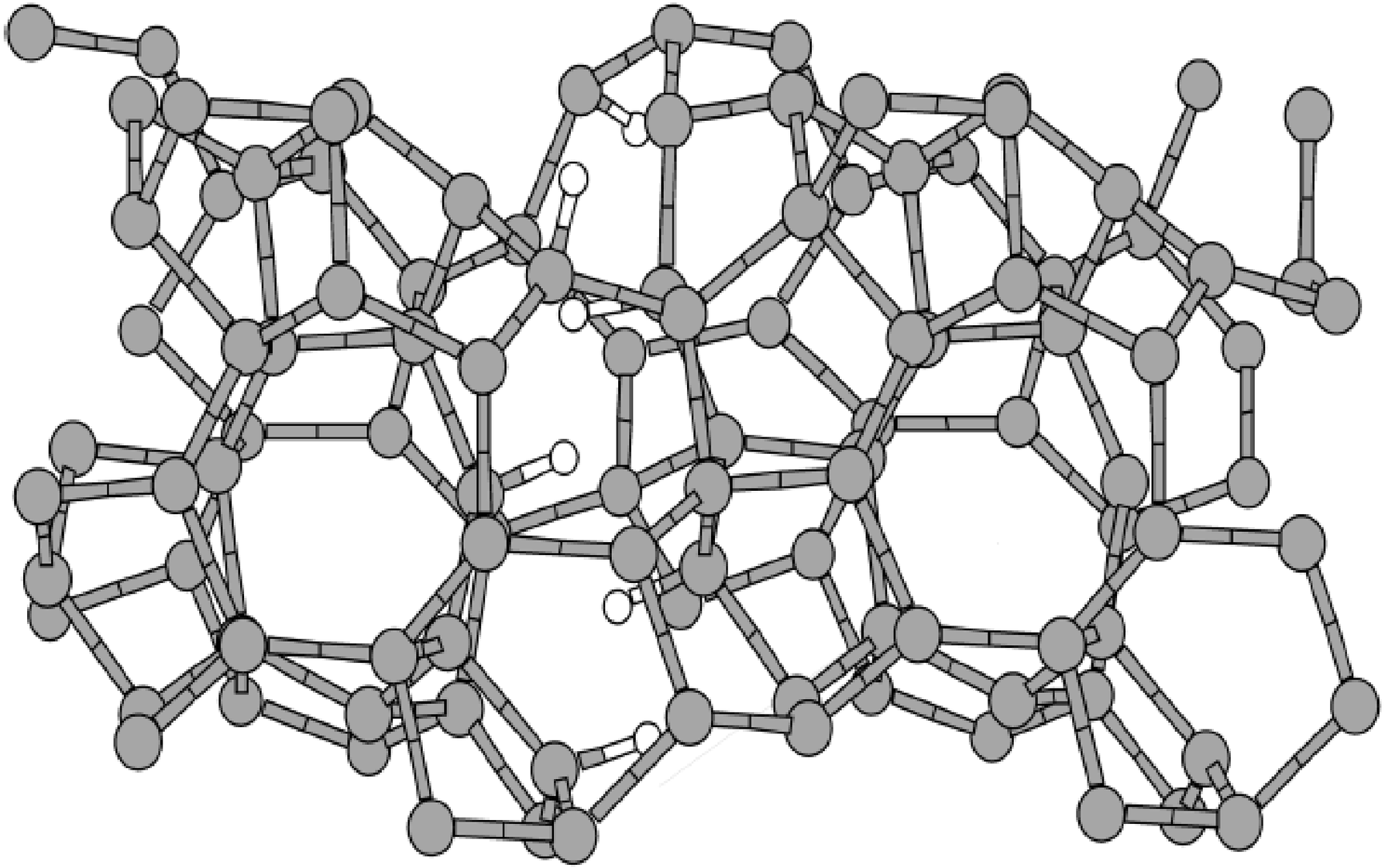



CORNING


CORNING

Hydrogenated amorphous silicon (a-Si:H) by PECVD:

SiH_4 (gas) $\rightarrow$ Si:H (solid) + H_2 (gas)



Si atom

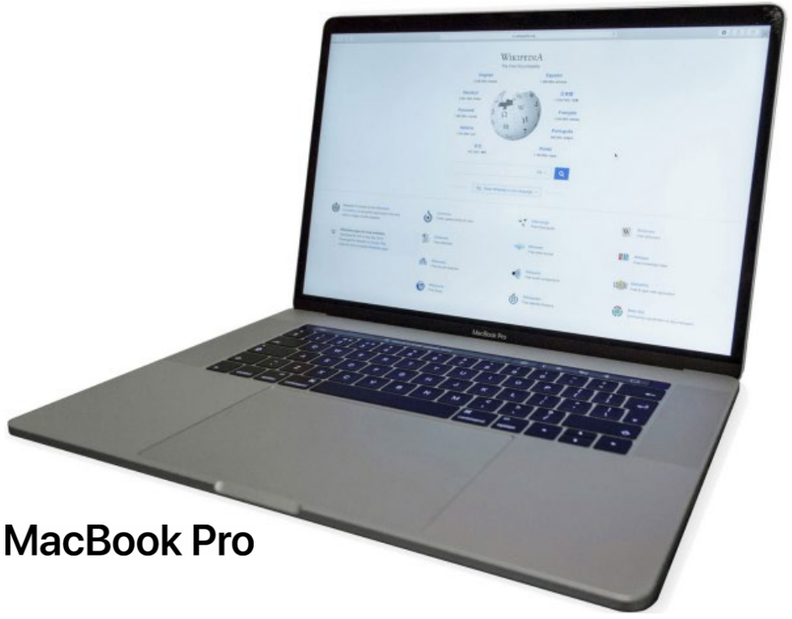
H atom

Tuttle,
Phys. Rev. B
57 12859 (1998)


APPLIED
MATERIALS

iPhone X®

MacBook Air

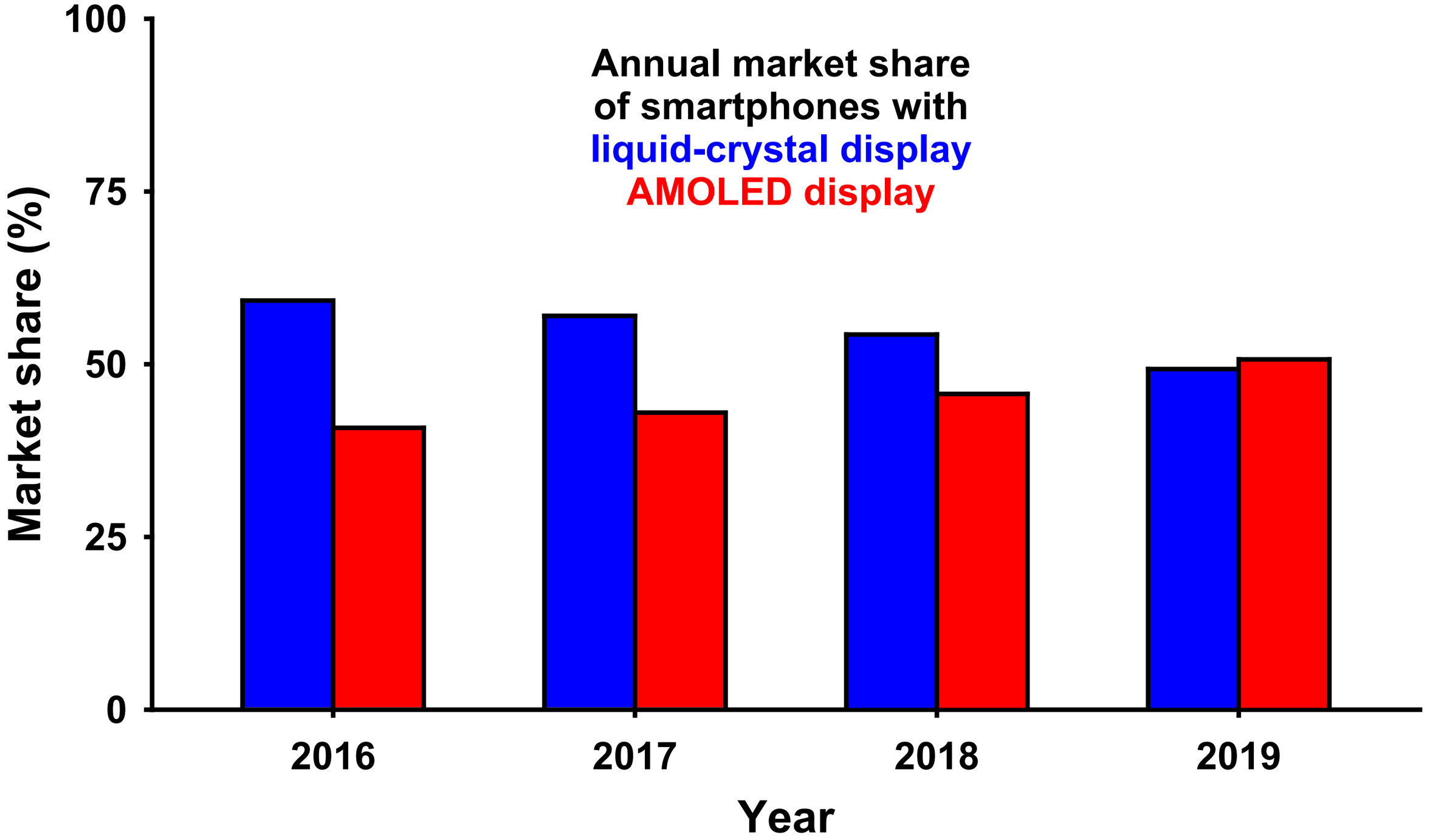


MacBook Pro

iPad Air

SONY

CASIO

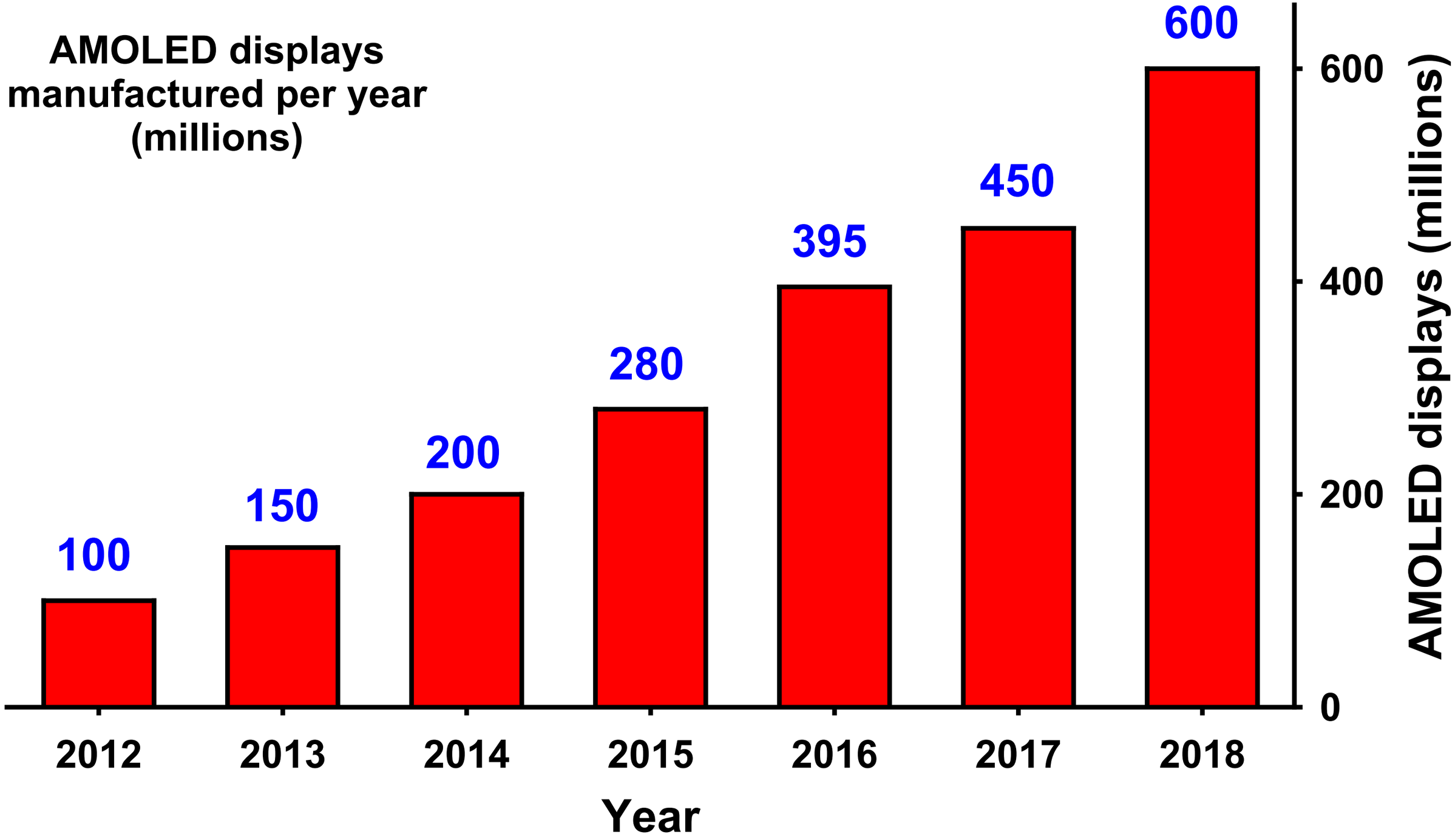

Annual market share
of smartphones with
liquid-crystal display
AMOLED display
Market share (%)
100
75
50
25
0
2016
2017
2018
2019
Year

SAMSUNG
Galaxy S10

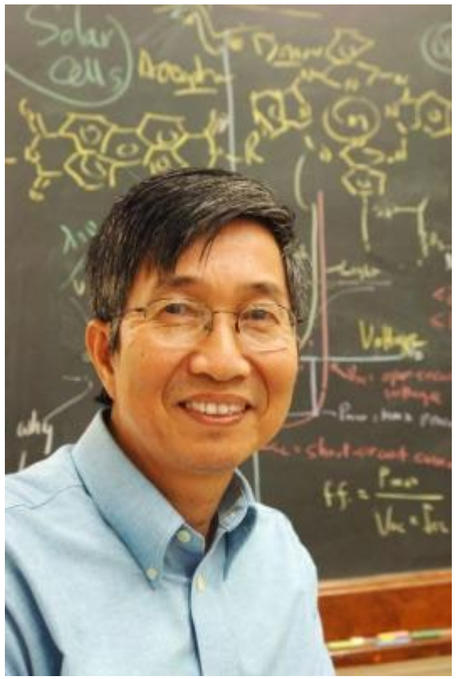
HUAWEI P30

iPhone XS

ONEPLUS 7


AMOLED displays manufactured per year (millions)
100
150
200
280
395
450
600
2012
2013
2014
2015
2016
2017
2018
Year
0
200
400
600
AMOLED displays (millions)

1987



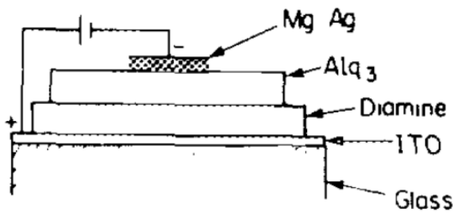
Ching W. Tang

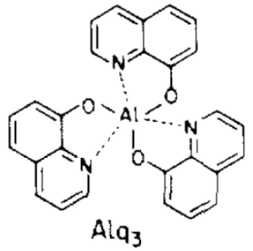
Steven Van Slyke

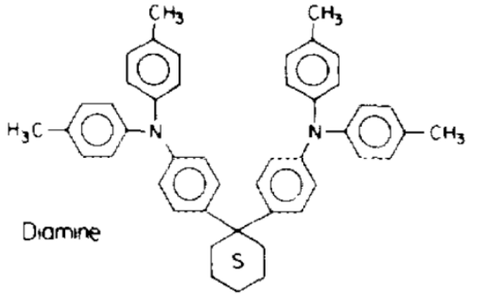
Organic electroluminescent diodes

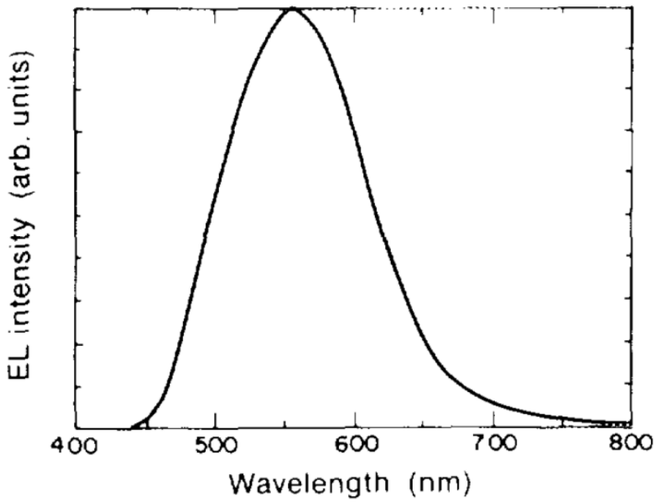
C. W. Tang and S. A. VanSlyke
Research Laboratories, Corporate Research Group, Eastman Kodak Company, Rochester, New York 14650

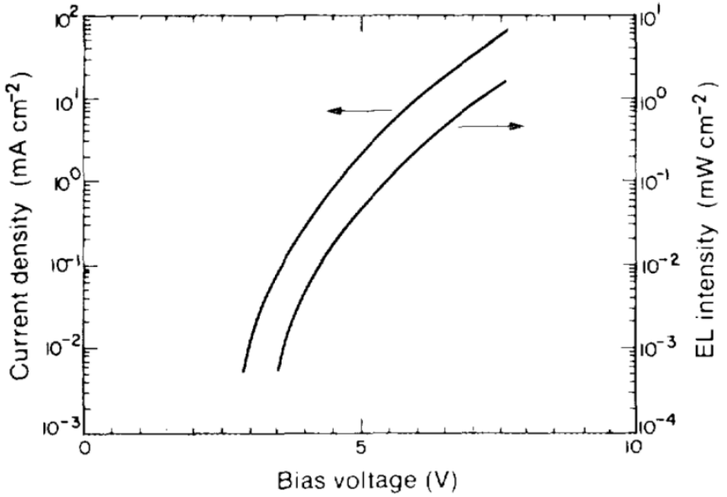
(Received 12 May 1987; accepted for publication 20 July 1987)



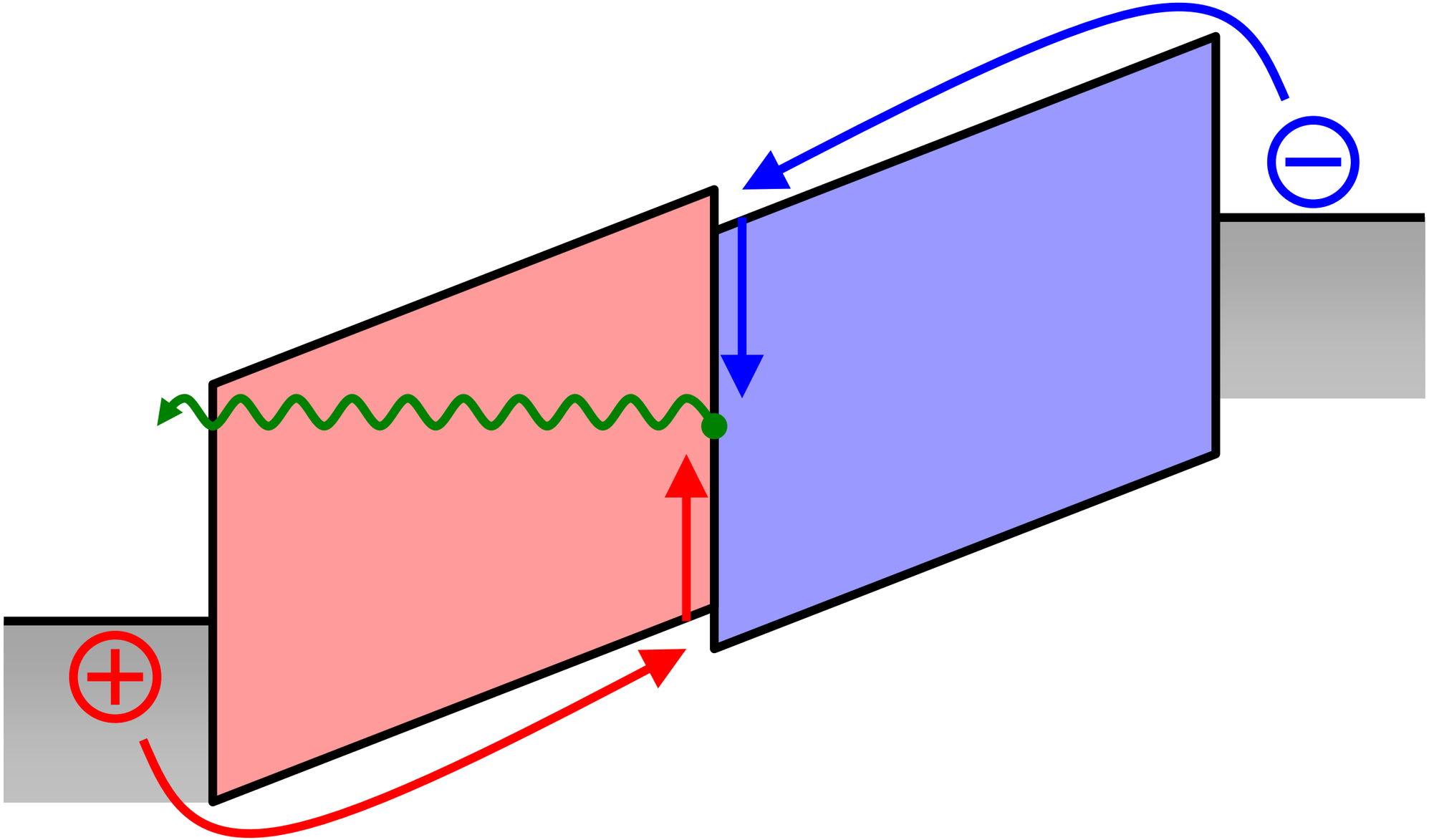


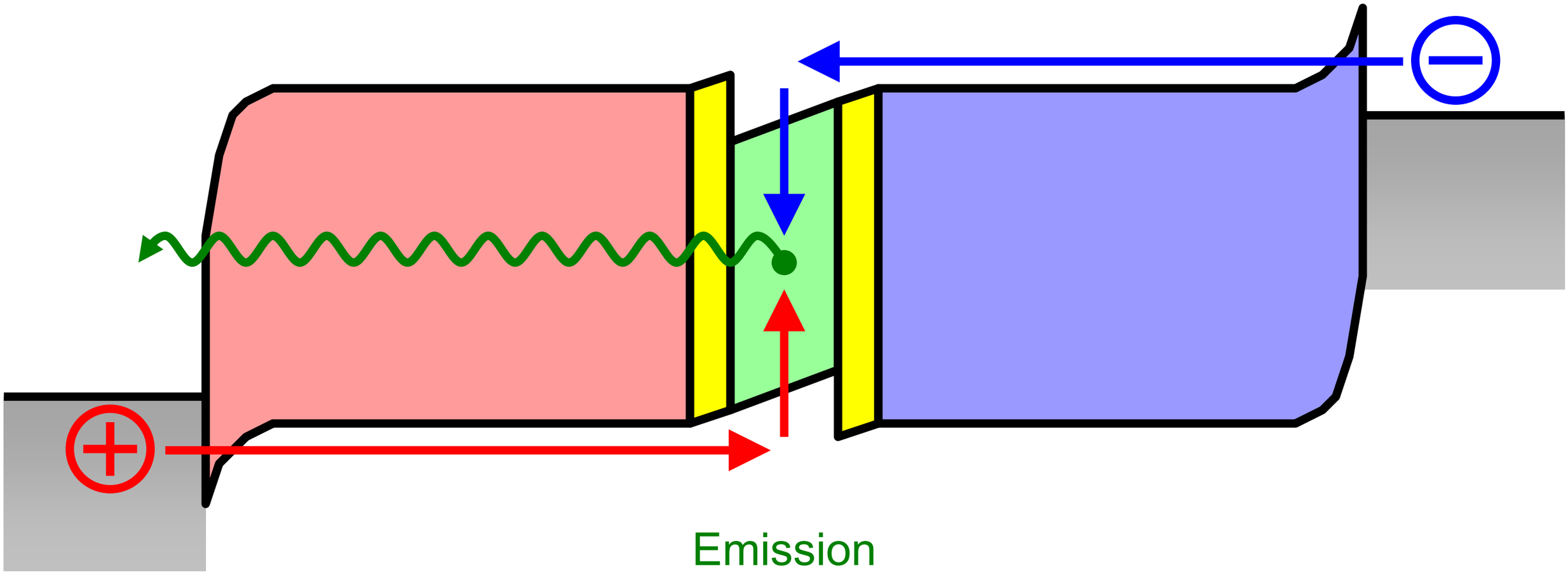






Tang & Van Slyke, *Appl. Phys. Lett.* 51 913 (1987)


Hole-transporting layer
Electron-transporting layer



Hole-injection layer

Doped hole-transport layer

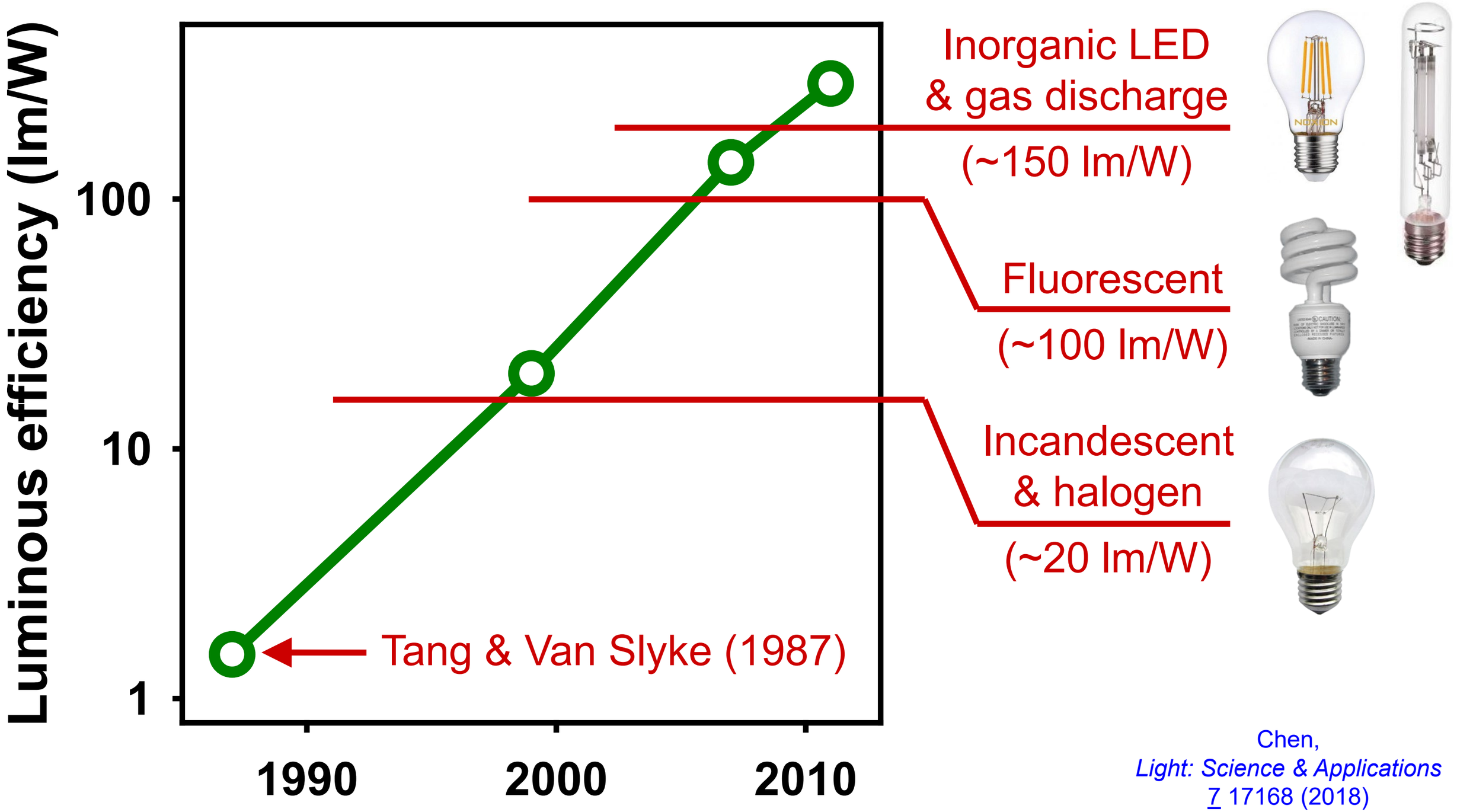
Electron-blocking layer

Emission layer

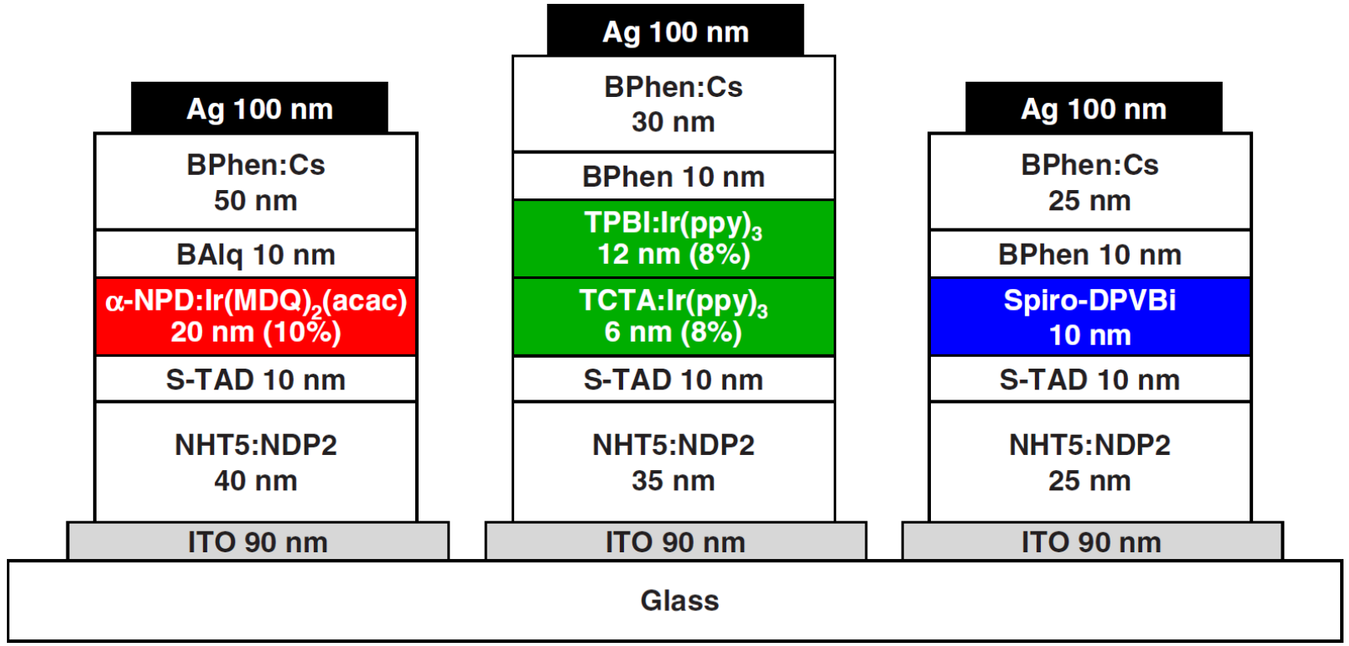
Hole-blocking layer

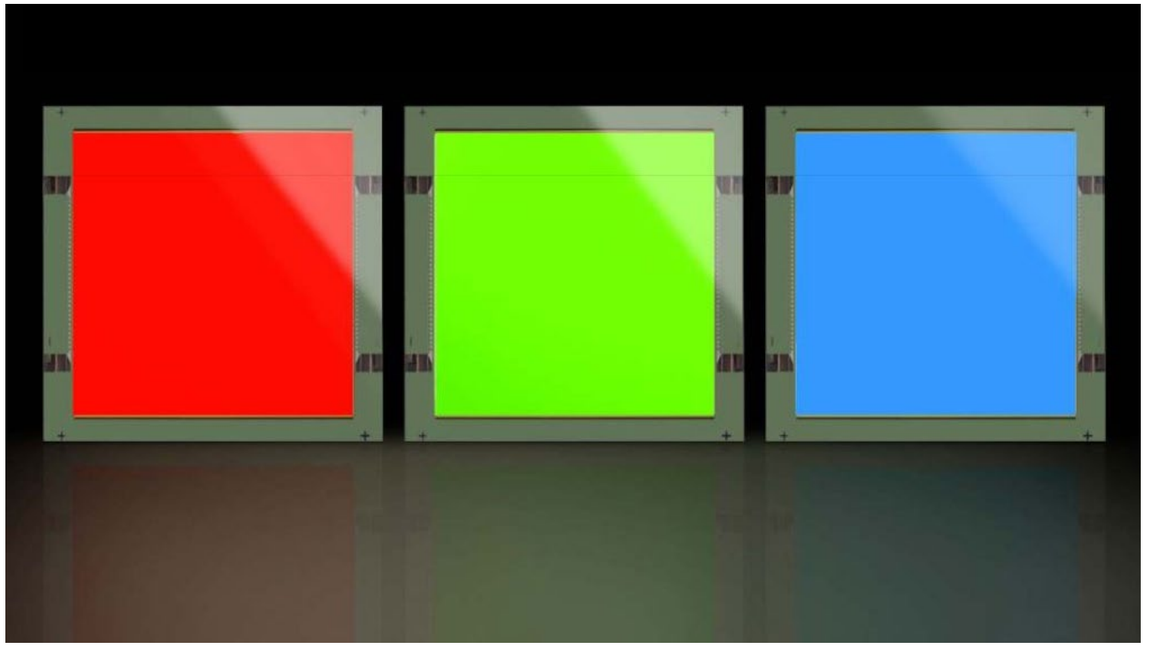
Doped electron-transport layer

Electron-injection layer



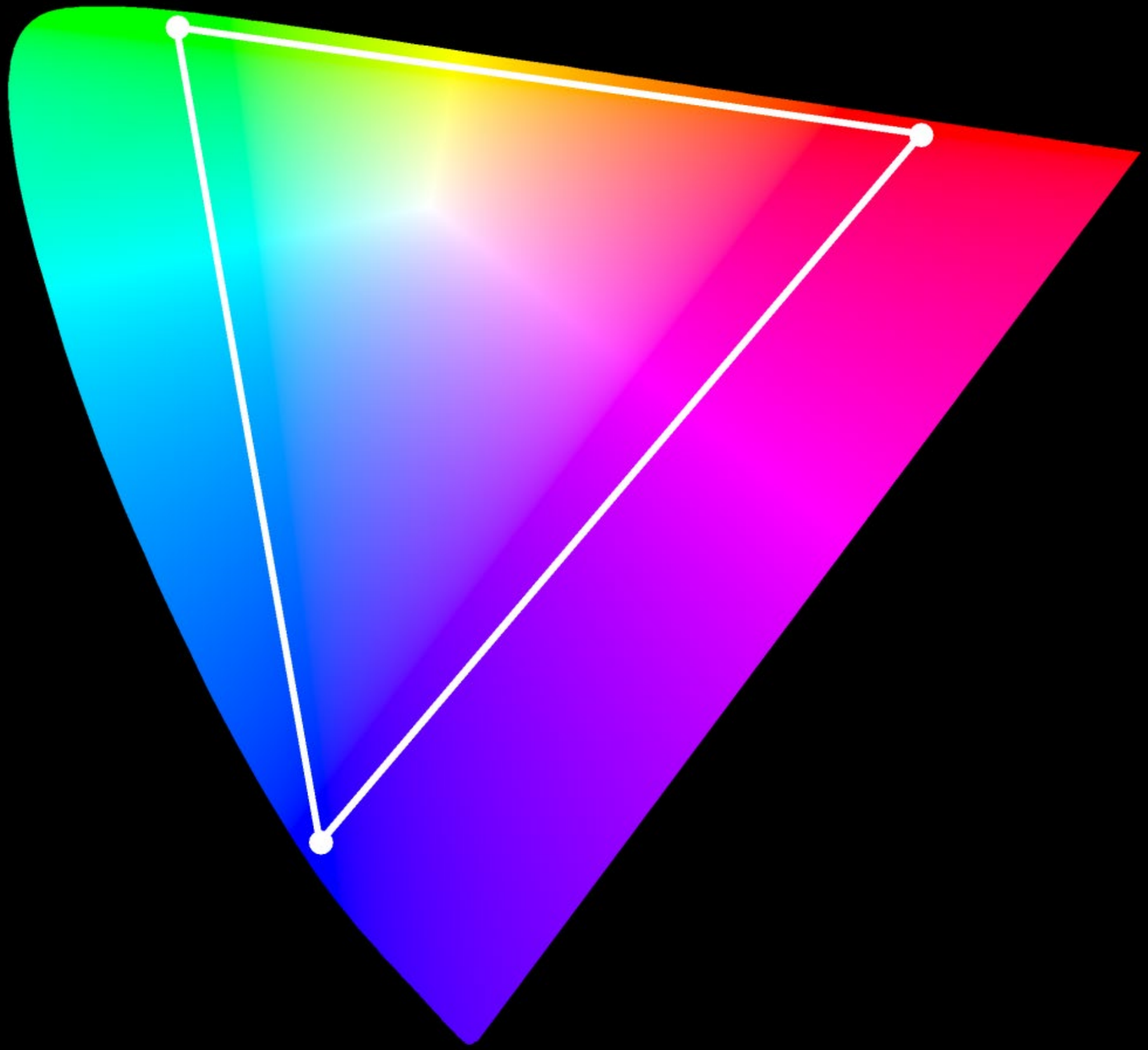
Chen,
Light: Science & Applications
7 17168 (2018)



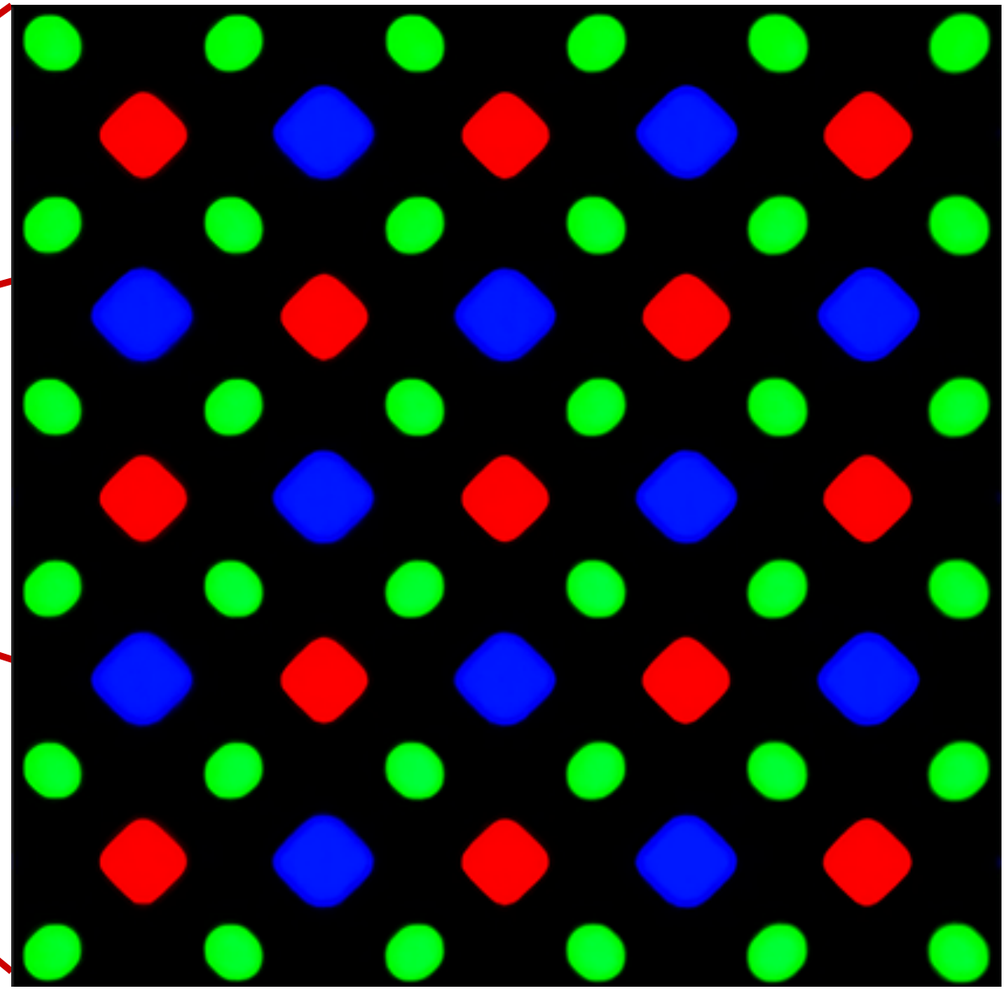


Meerheim,
Appl. Phys. Lett.
93 043310 (2008)

PHILIPS



SAMSUNG
Galaxy S10



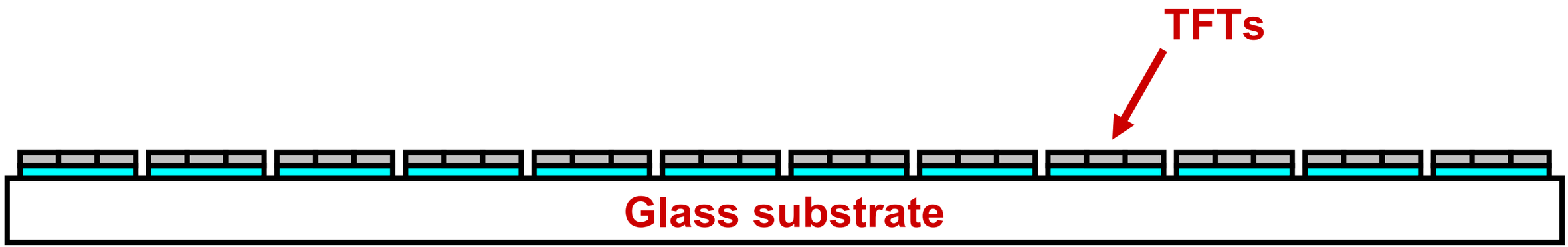
3040 x 1440 pixels
x 2 OLEDs/pixel
= 9 million OLEDs

600 million displays

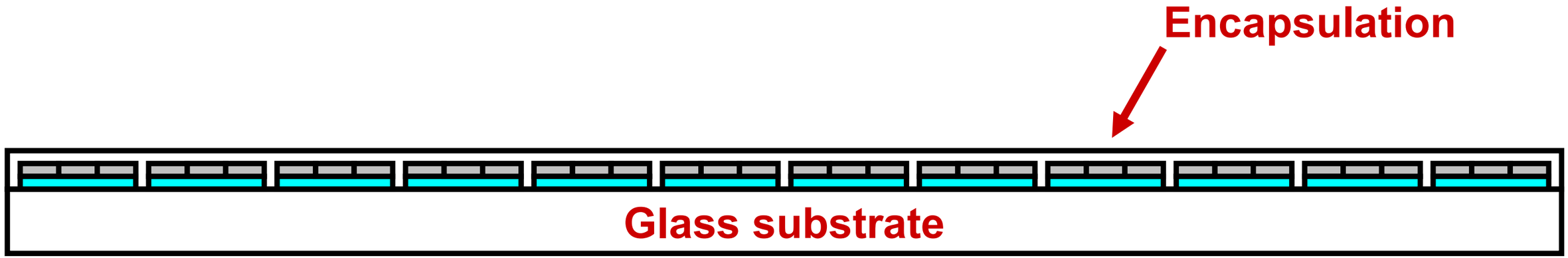
x 9 million OLEDs

> 10^{15} OLEDs

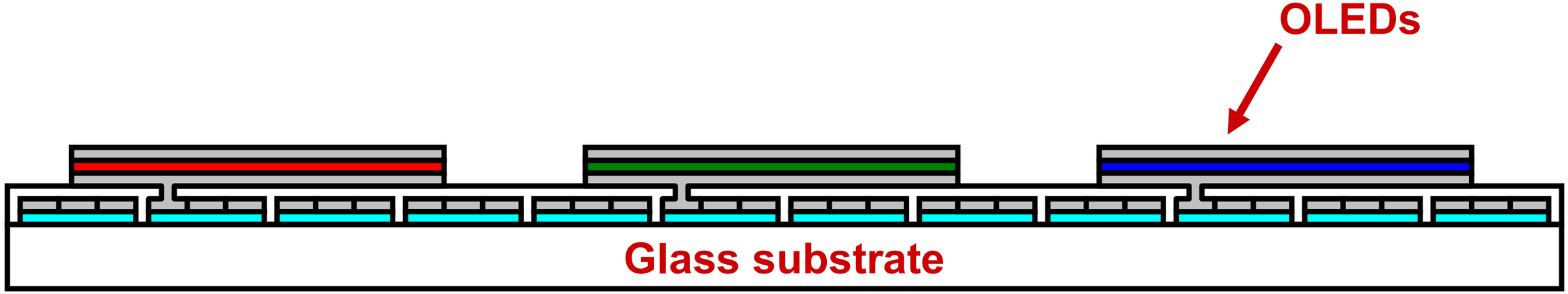
1. Deposition and patterning of TFTs



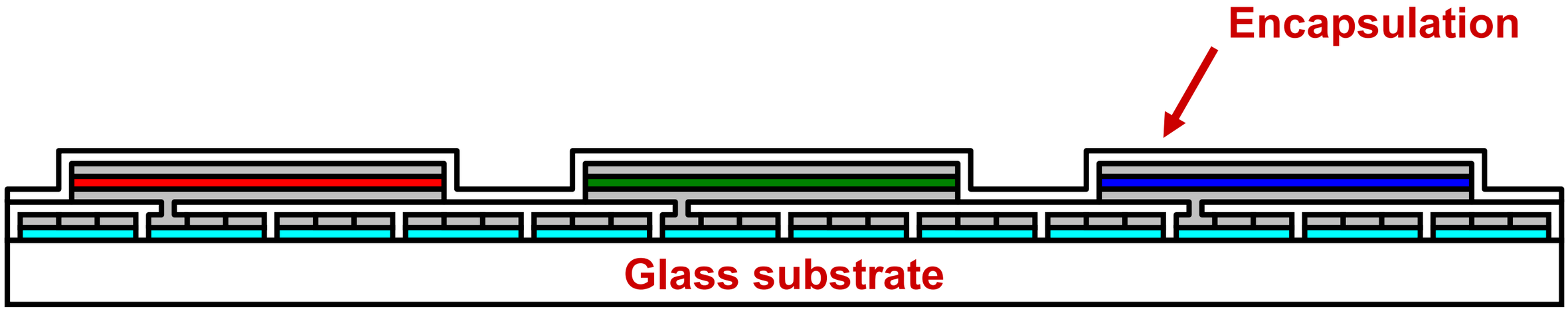
2. Thin-film encapsulation of TFTs

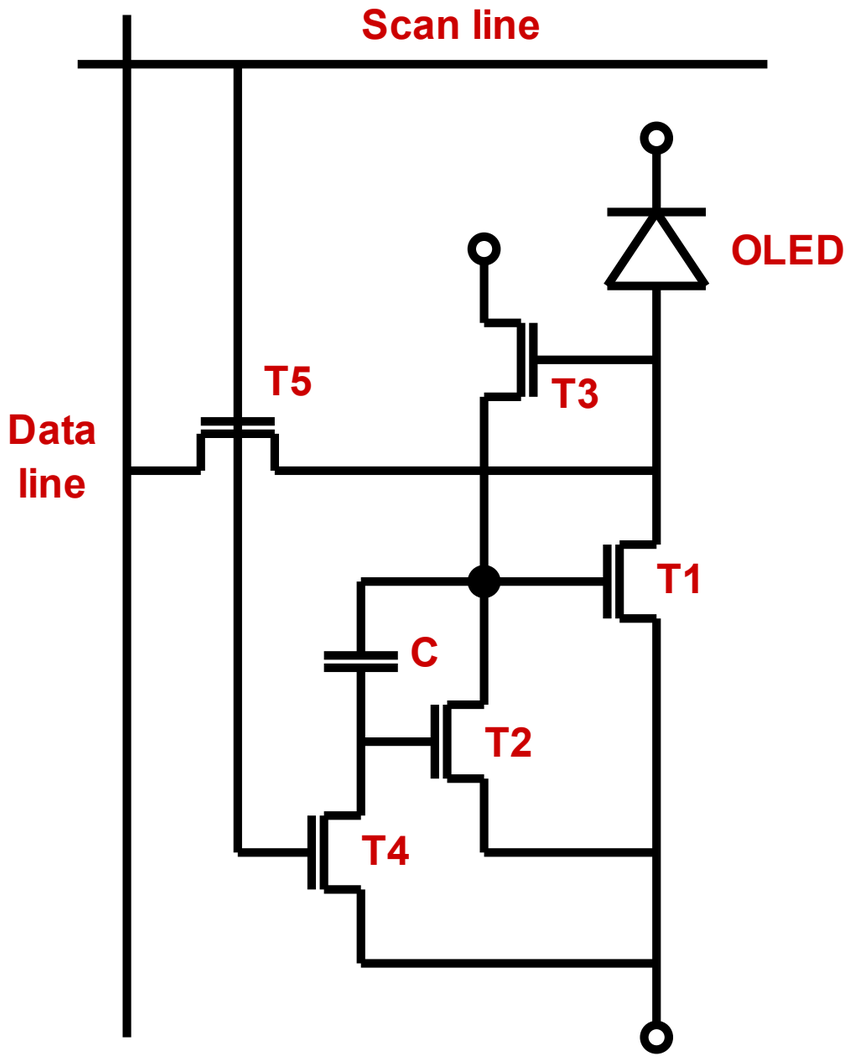


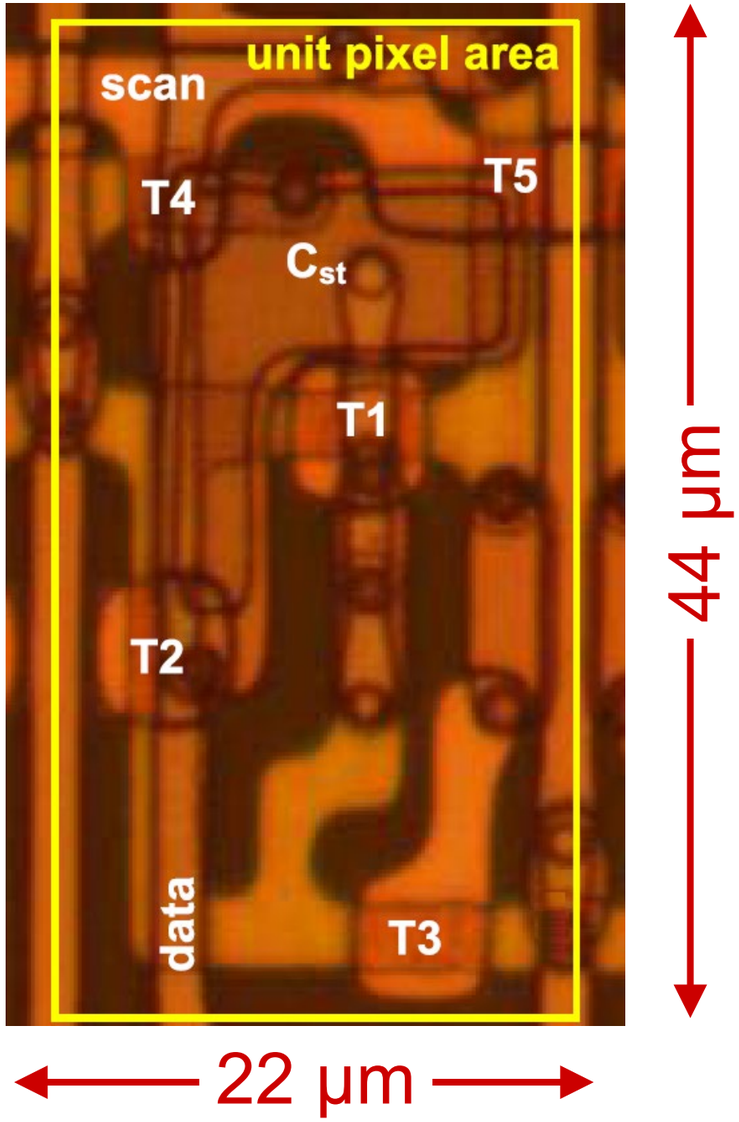
3. Deposition and patterning of OLEDs

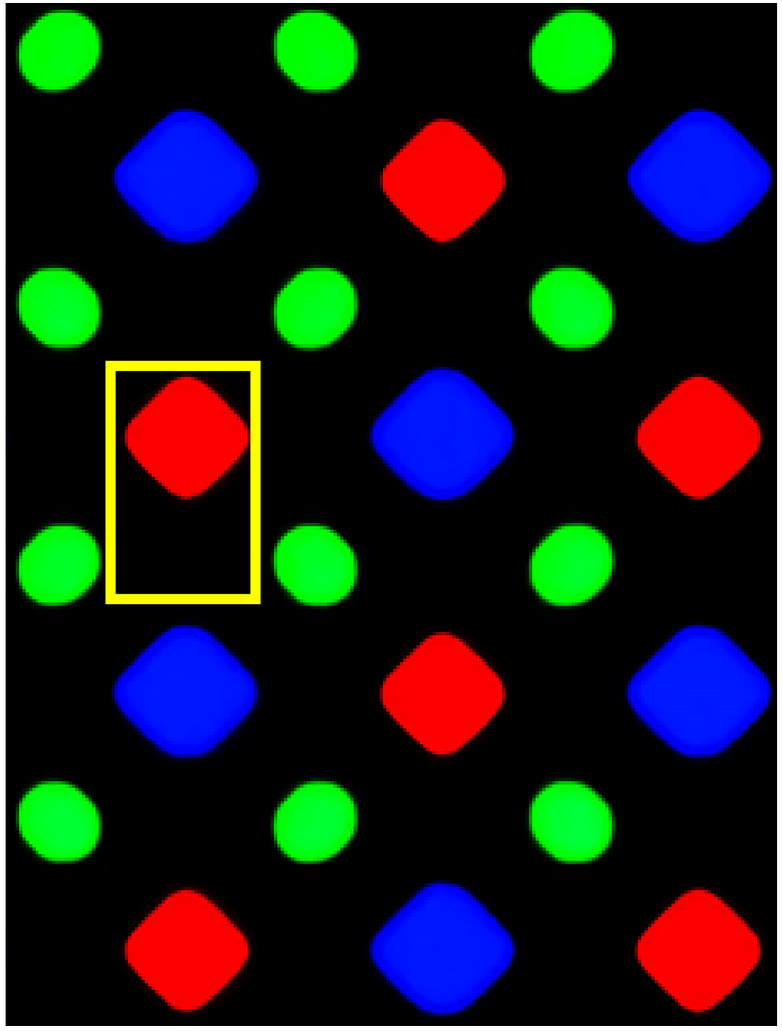


4. Thin-film encapsulation of OLEDs





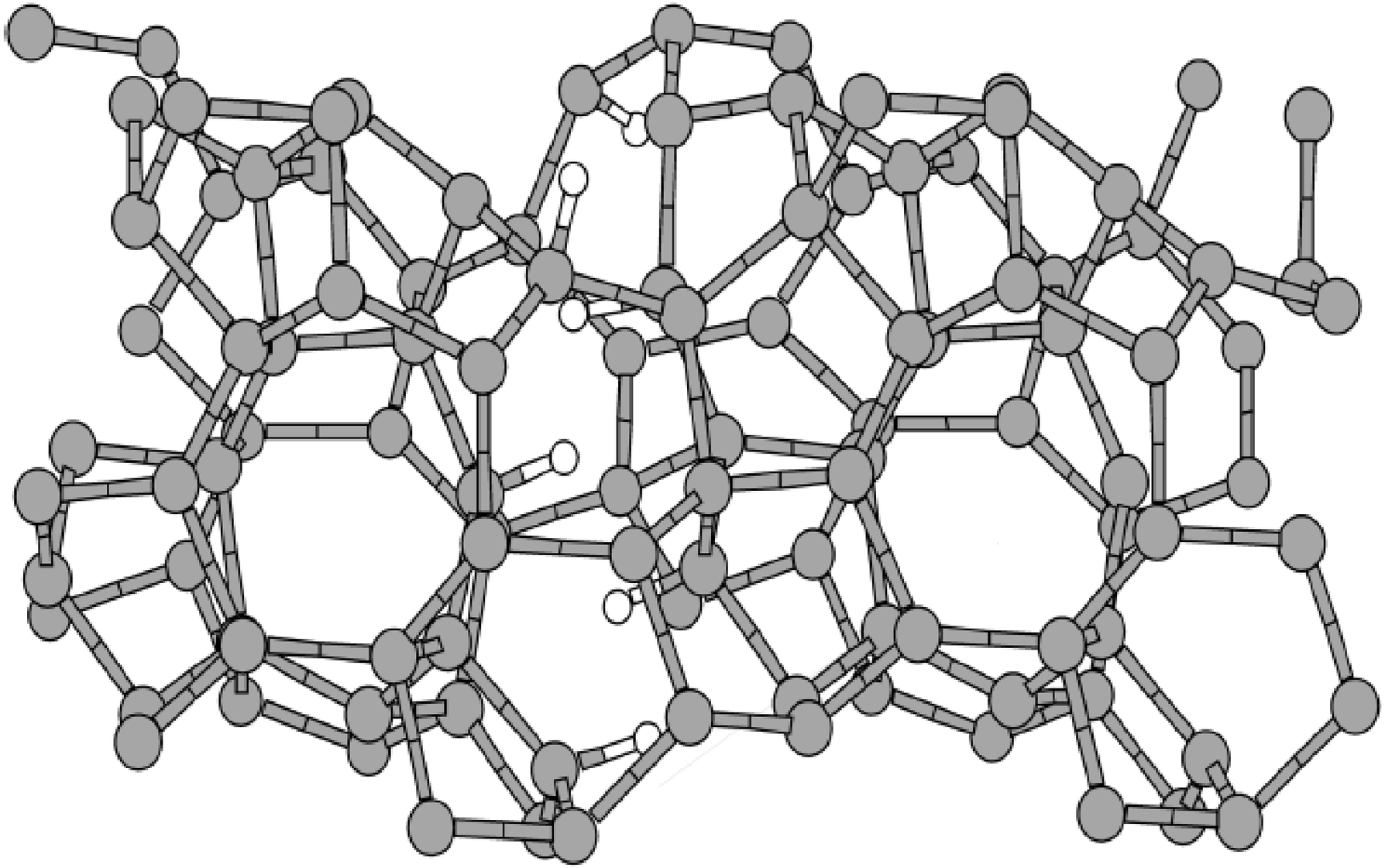




Keum,
J. Electr. Dev. Soc.
7 462 (2019)

Hydrogenated amorphous silicon (a-Si:H) by PECVD:

SiH_4 (gas) $\rightarrow$ Si:H (solid) + H_2 (gas)

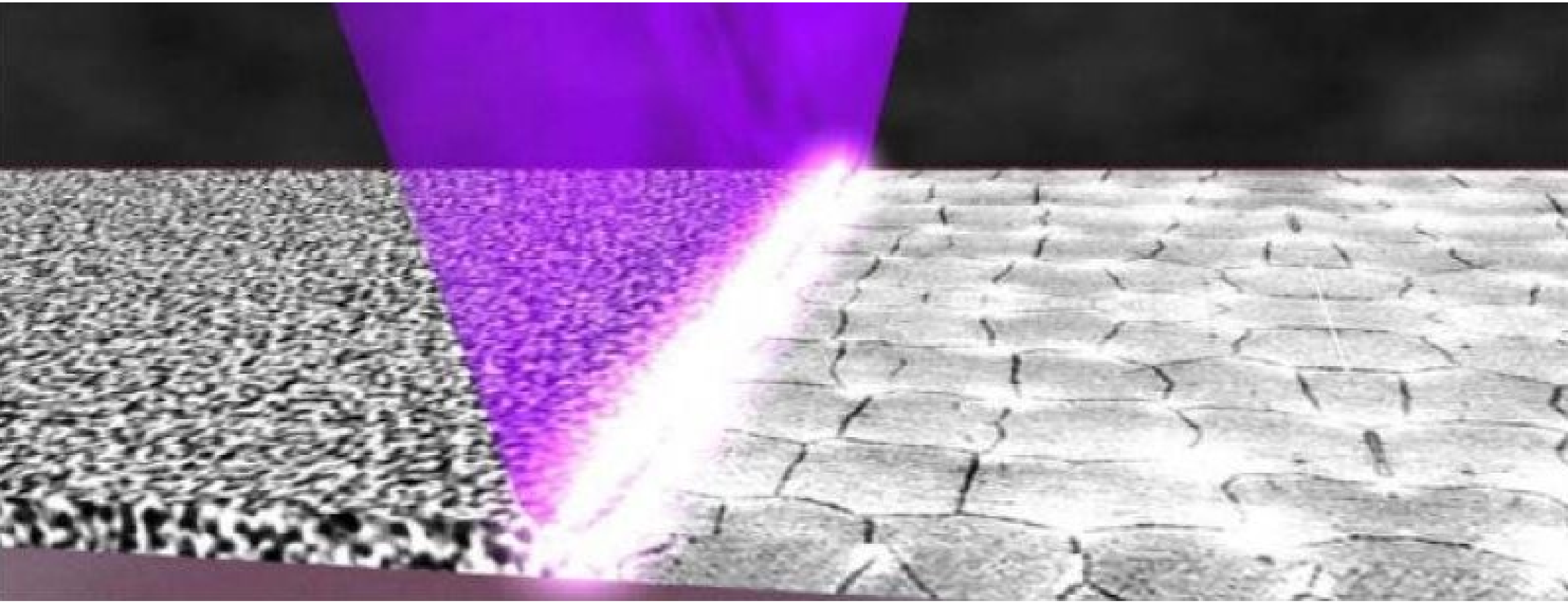


Si atom

H atom

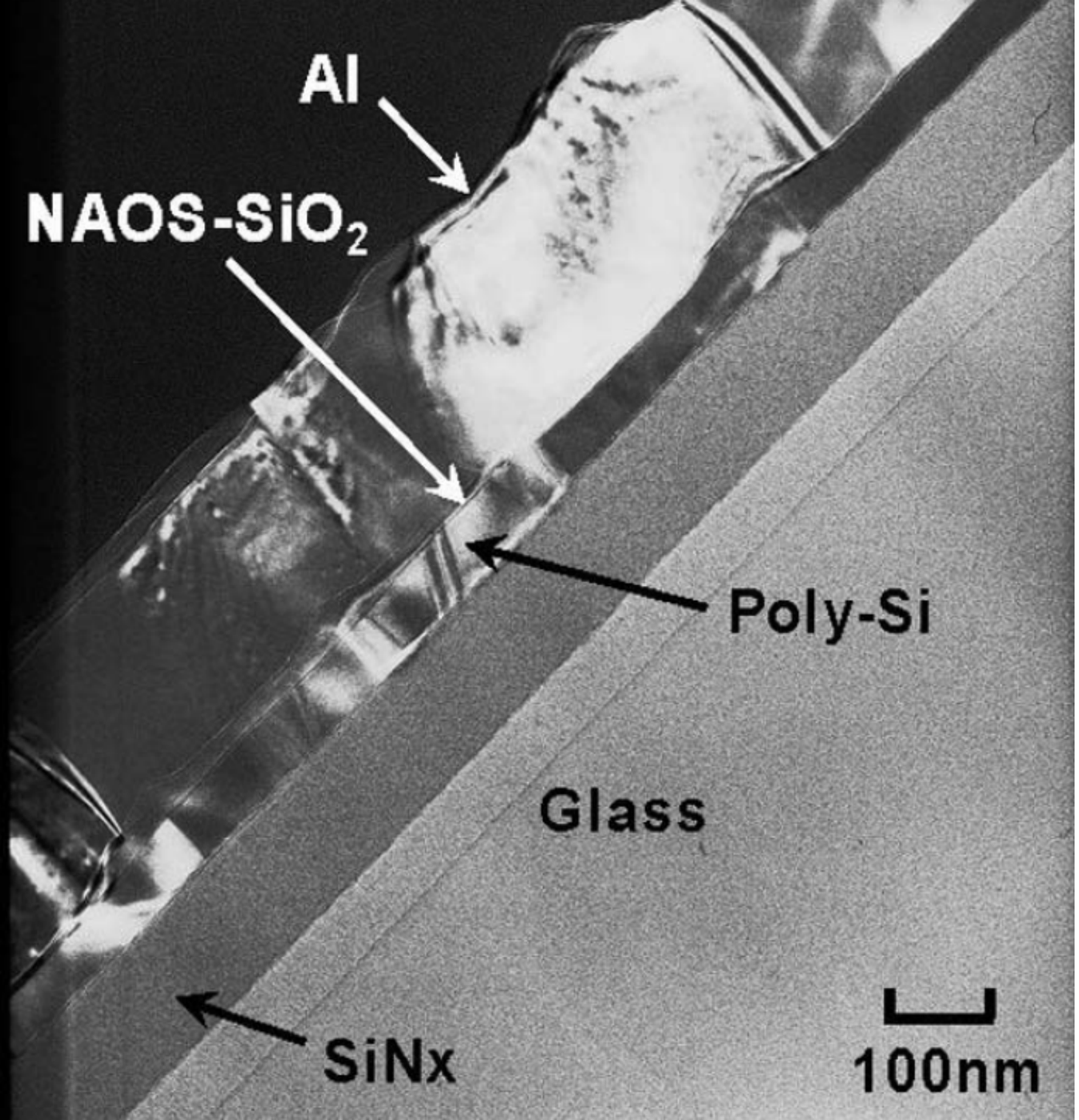
Tuttle,
Phys. Rev. B
57 12859 (1998)

Laser crystallization of a-Si:H to form polycrystalline silicon



amorphous silicon
$\mu \sim 1\ cm^2/Vs$

polycrystalline silicon
$\mu \sim 100\ cm^2/Vs$



Excimer-laser annealing (ELA)

Low-temperature polycrystalline silicon (LTPS)

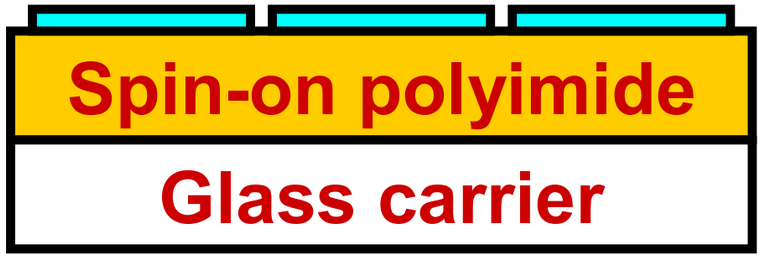
T ~ 450 .. 550 ºC

Kubota,
IEEE Trans. Electr. Dev. 59 385 (2012)

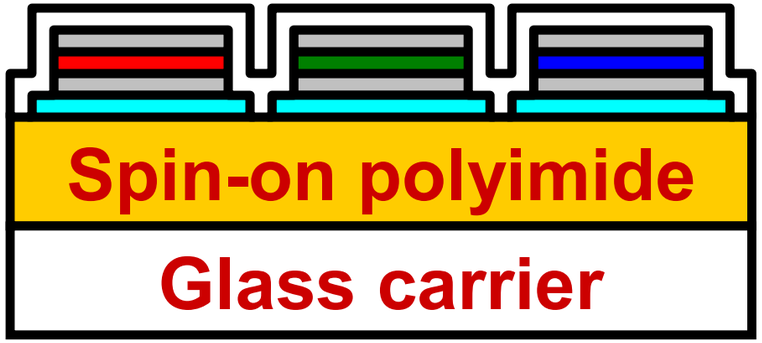
Holst Centre

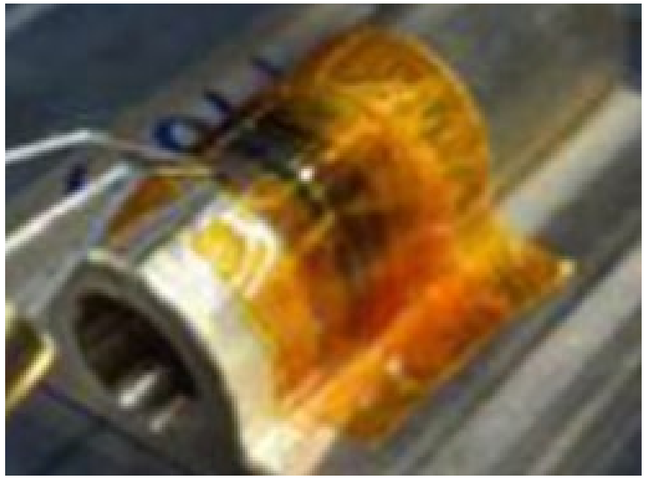
Open Innovation by IMEC and TNO

Thin-film transistors (TFTs)

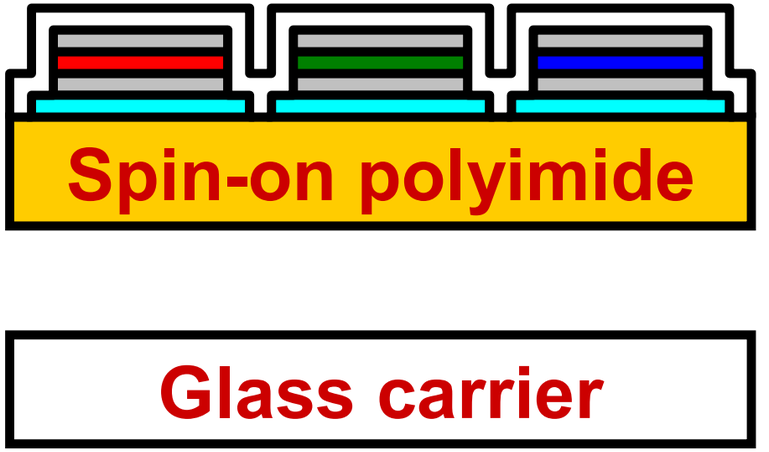


OLEDs and encapsulation





Release of polyimide substrate from carrier



Lee,
J. SID
26 200 (2018)

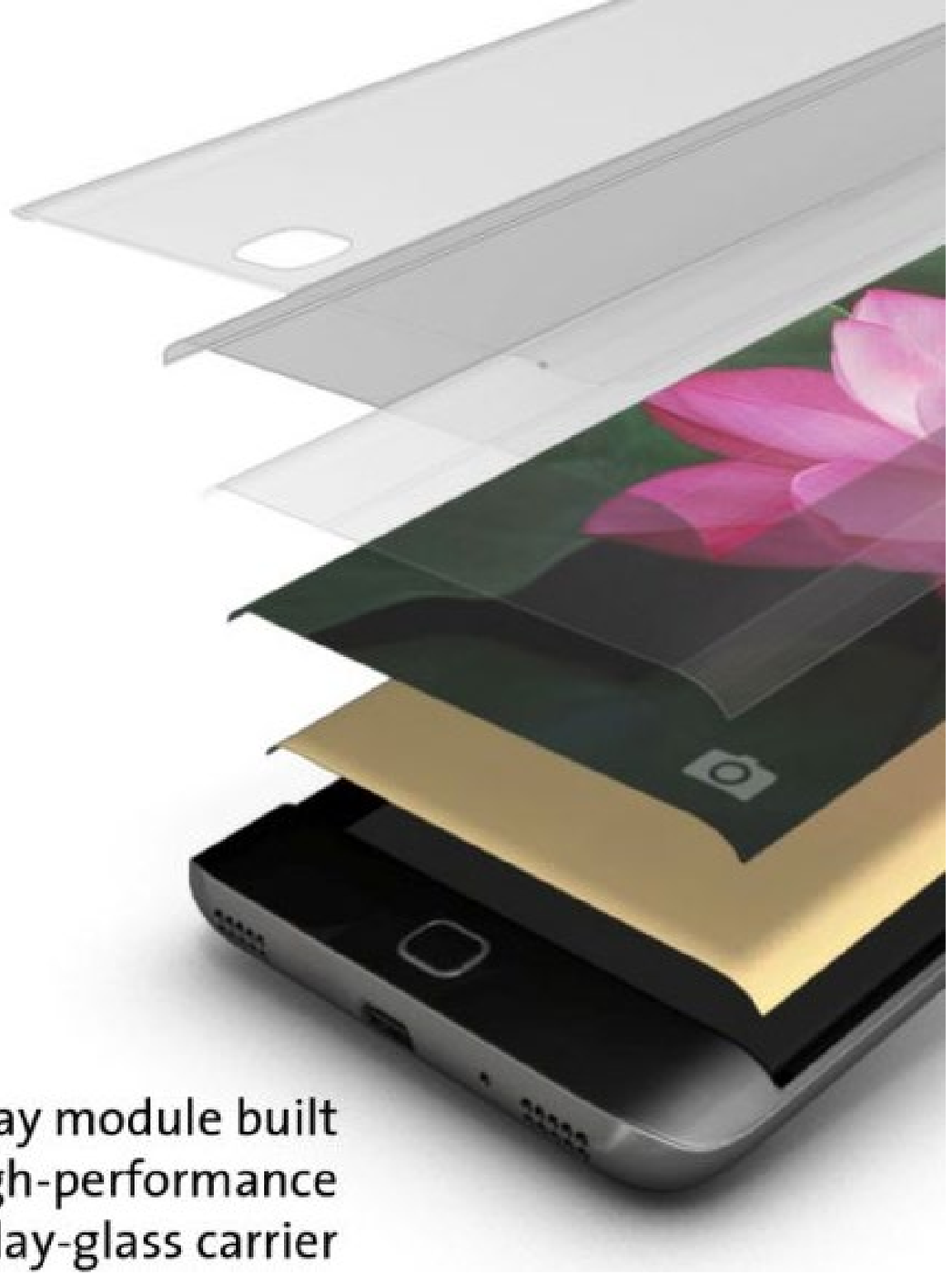
Cover Glass

Circular Polarizer

Transparent Encapsulation

Plastic TFT Backplane with OLED

Heat Sink



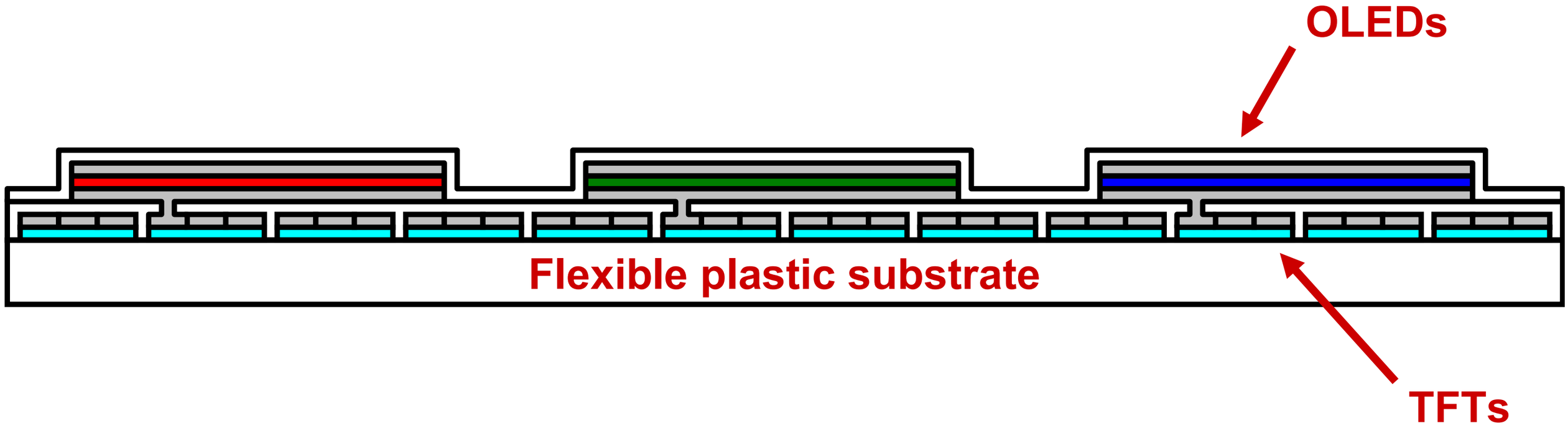
Display module built upon a high-performance display-glass carrier

CORNING

Samsung
GALAXY **Note** *4*

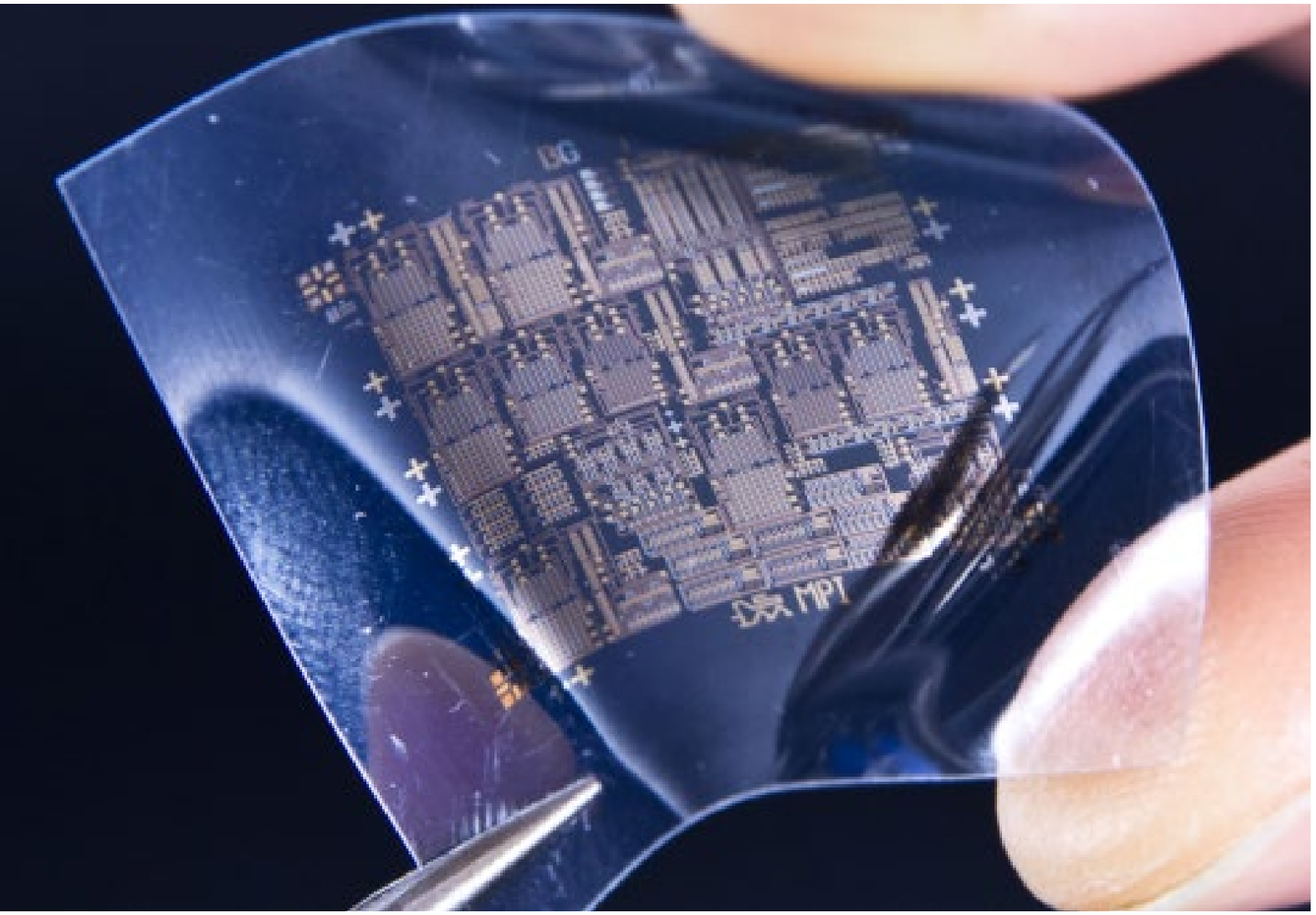
SAMSUNG

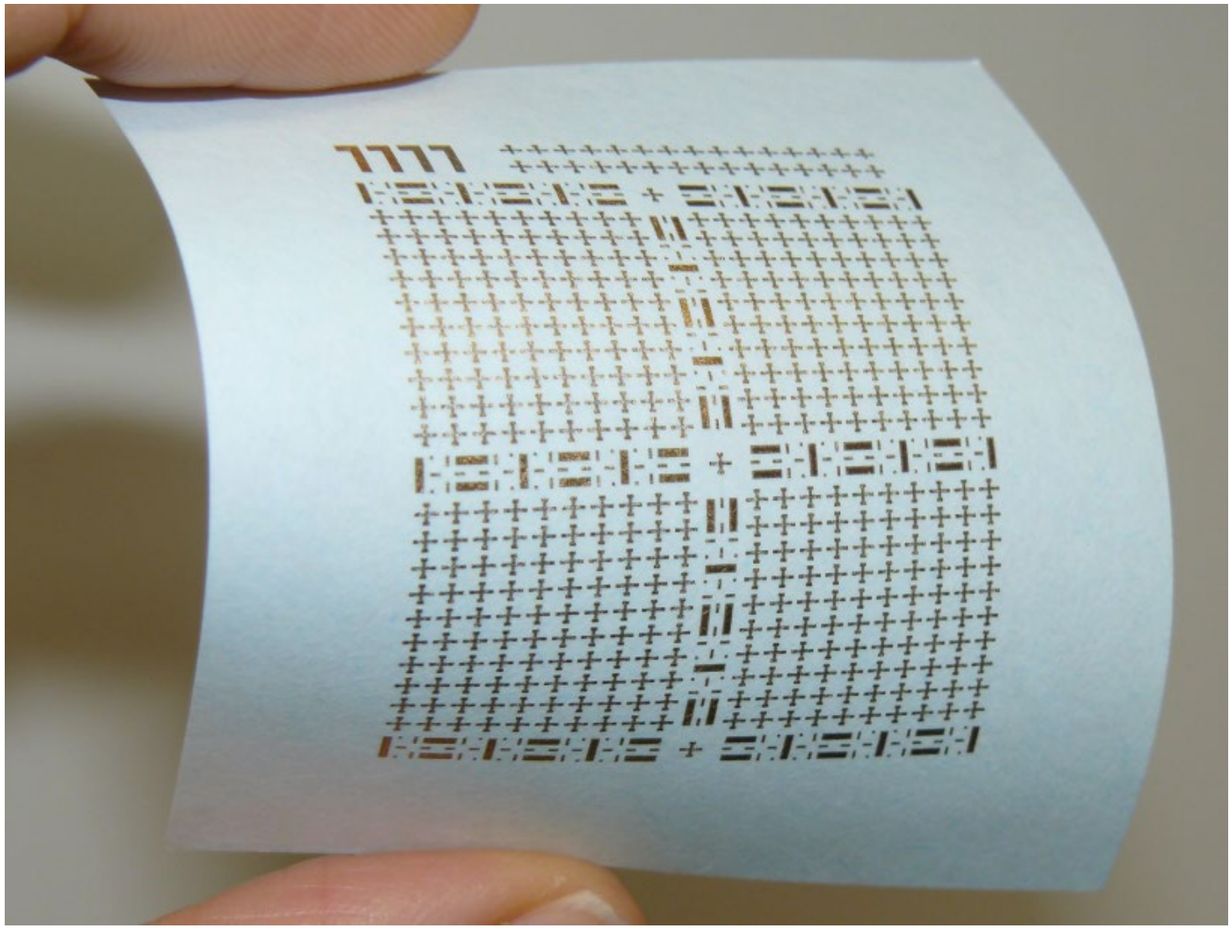

Edge Slim
Transparent


OLEDs
Flexible plastic substrate
TFTs

semiconductor	carrier type	process temperature (ºC)	carrier mobility (cm^2/Vs)	reference
single-crystalline Si (CMOS)	n-channel	900	800	[1]
	p-channel	900	200	[1]
polycrystalline Si (LTPS)	n-channel	500	200	[2]
	p-channel	500	100	[2]
amorphous Si (a-Si:H)	n-channel	150	2	[3]
	p-channel	250	0.1	[4]
metal oxides (ZnO, InGaZnO)	n-channel	150	20	[5]
	p-channel	200	2	[6]
organic	n-channel	120	1	[7]
	p-channel	80	5	[8]

[1] Takagi, *IEEE Trans. Electr. Dev.* 41 2357 (1994)
[2] Kubota, *IEEE Trans. Electr. Dev.* 59 385 (2012)
[3] Han, *Appl. Phys. Lett.* 96 042111 (2010)
[4] Han, *Appl. Phys. Lett.* 94 162105 (2009)
[5] Münzenrieder, *IEEE Trans. Electr. Dev.* 59 2153 (2012)
[6] Khan, *Org. Electronics* 16 9 (2015)
[7] Kraft, *Adv. Mater.* 27 207 (2015)
[8] Borchert, *Nature Commun.* 10 1119 (2019)

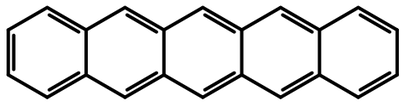


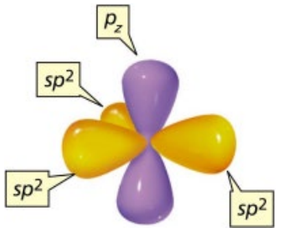


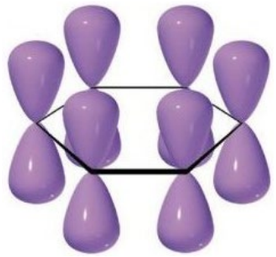
Kraft,
Adv. Mater.
27 207 (2015)

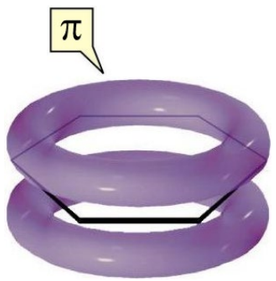
Zschieschang,
Org. Electronics
25 340 (2015)

Zschieschang,
J. Mater. Chem. C
7 5522 (2019)

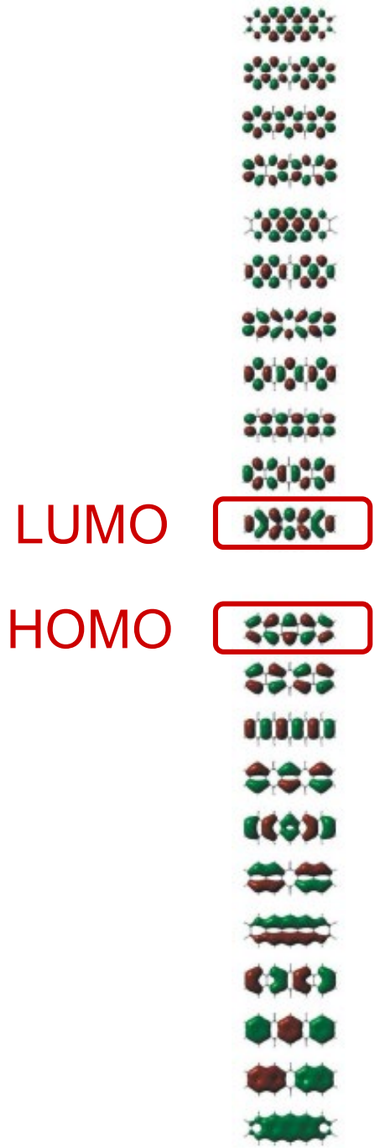




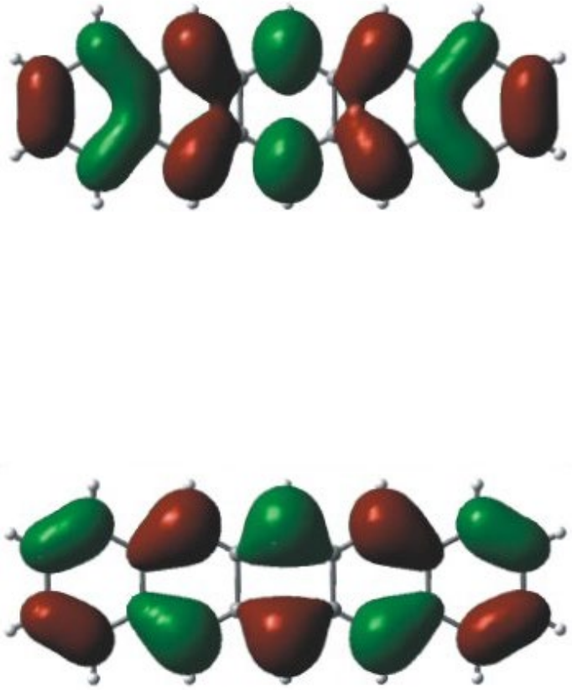




Bruice,
Organic Chemistry
(Pearson)

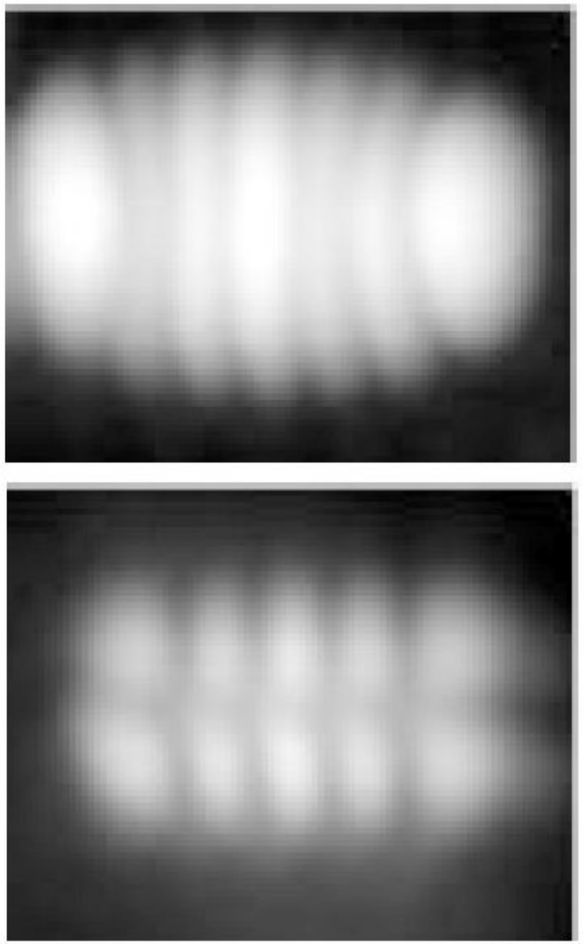


density functional theory (DFT)

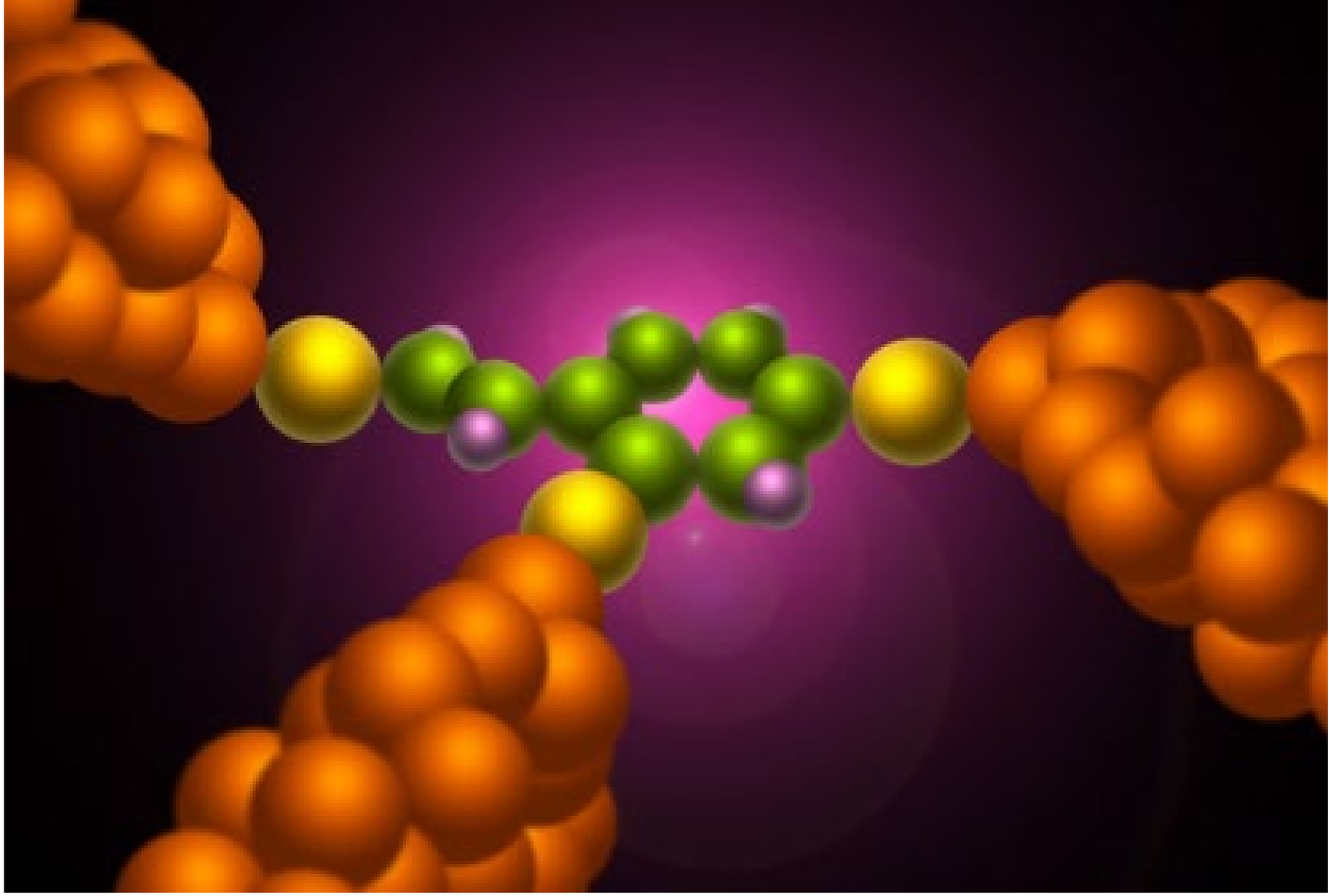


Winkler,
J. Am. Chem. Soc.
129 1805 (2007)

scanning tunneling spectroscopy (STS)



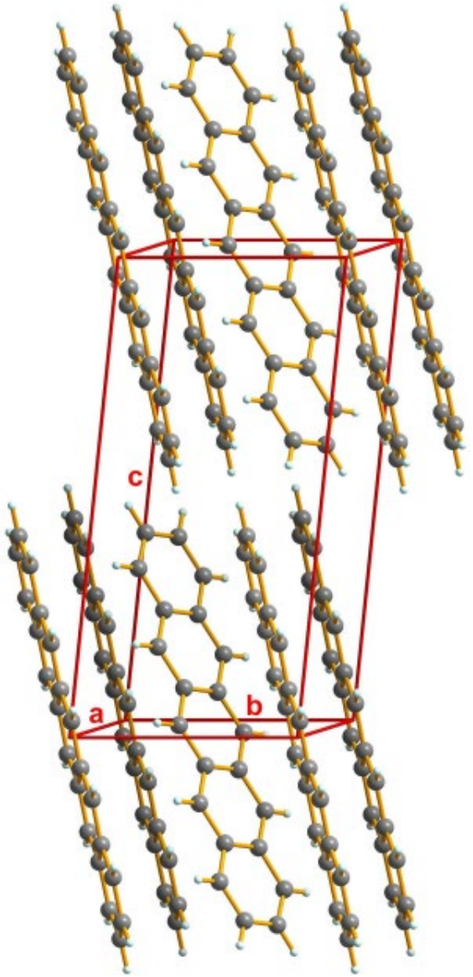
Repp,
Phys. Rev. Lett.
94 026803 (2005)



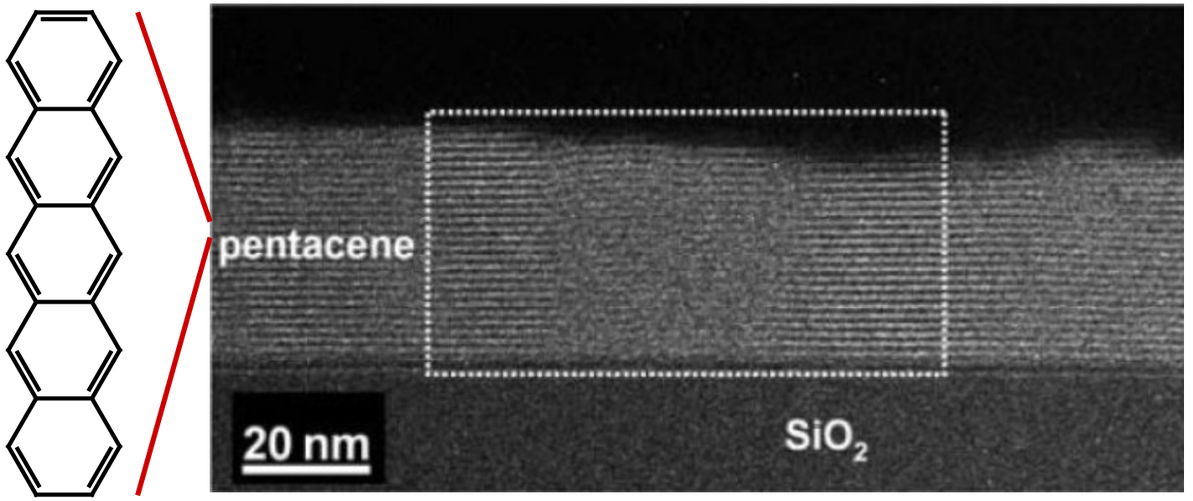
~ 1 nm

Cardamone,
Nano Lett.
6 2422 (2006)

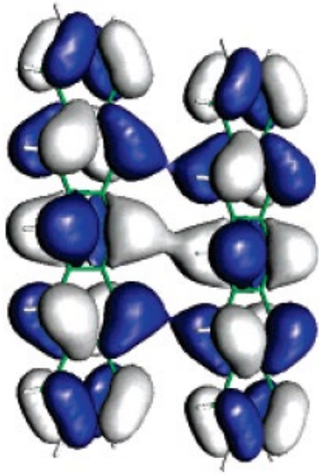
Charge transport in organic semiconductors



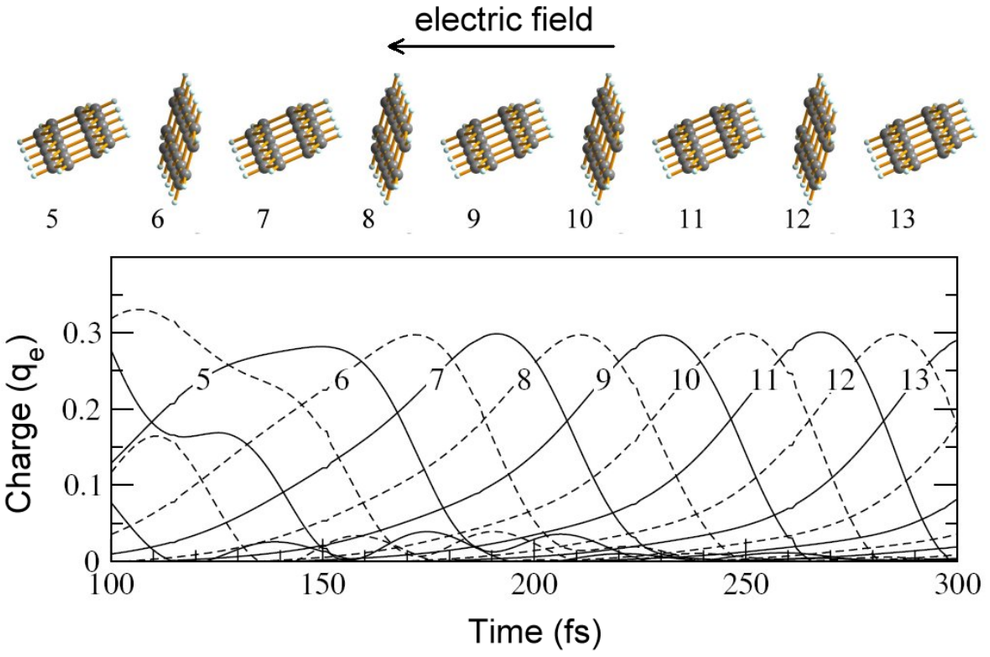
a = 0.596 nm
b = 0.760 nm
c = 1.56 nm



Murakami,
Phys. Rev. Lett.
103 146102 (2009)

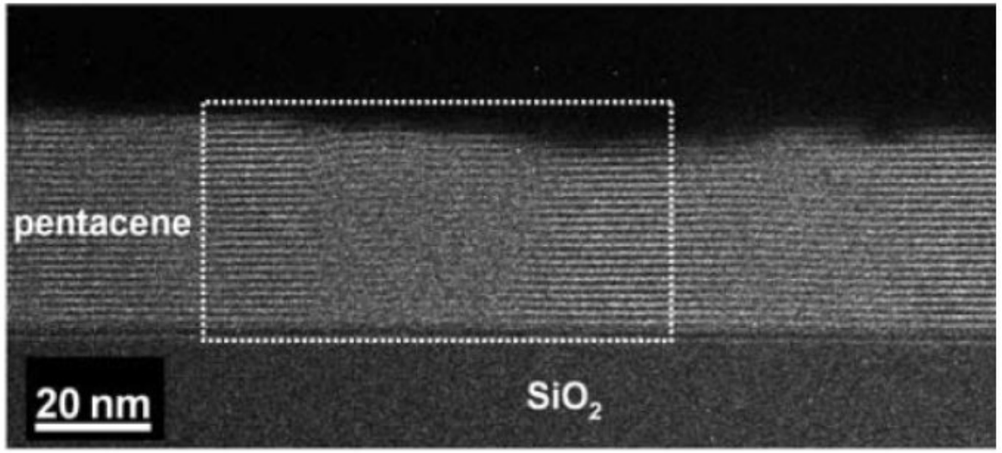


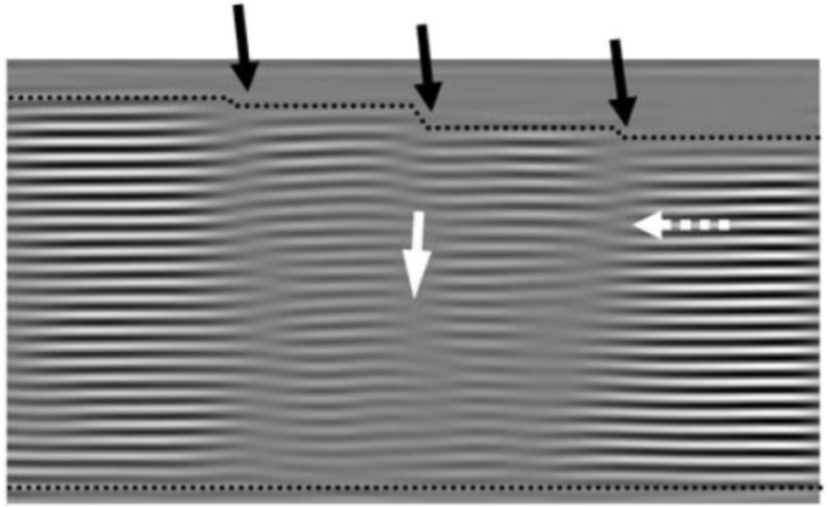
Troisi,
J. Phys. Chem. B
109 1849 (2005)



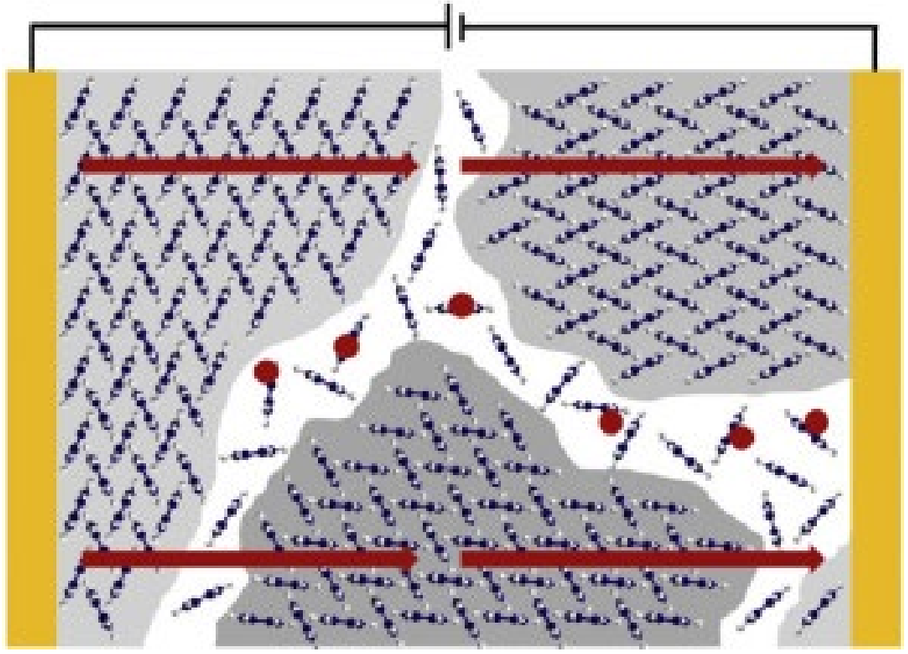
Hultell,
Chem. Phys. Lett.
428 446 (2006)

Charge transport in organic semiconductors: Effects of Disorder

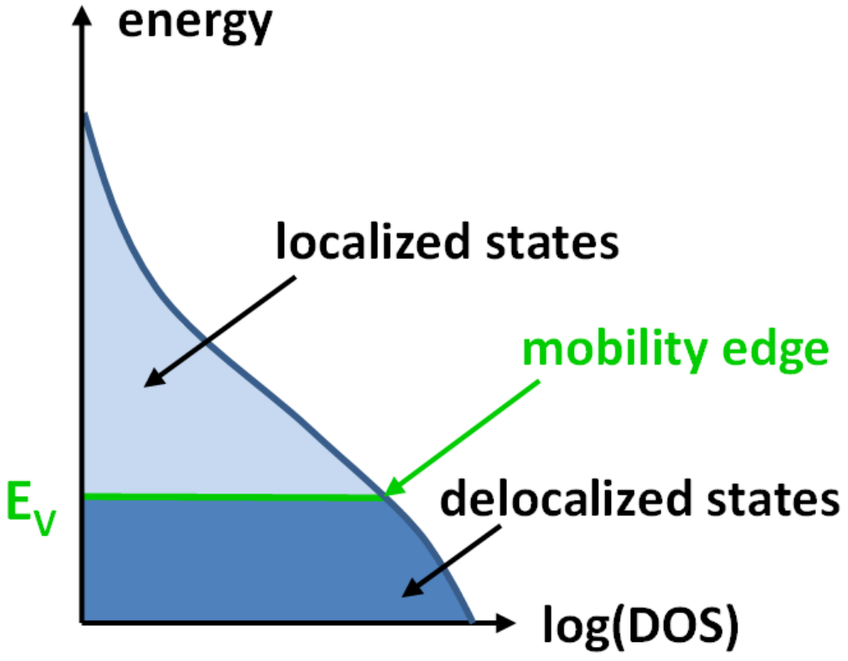




Murakami,
Phys. Rev. Lett.
103 146102 (2009)

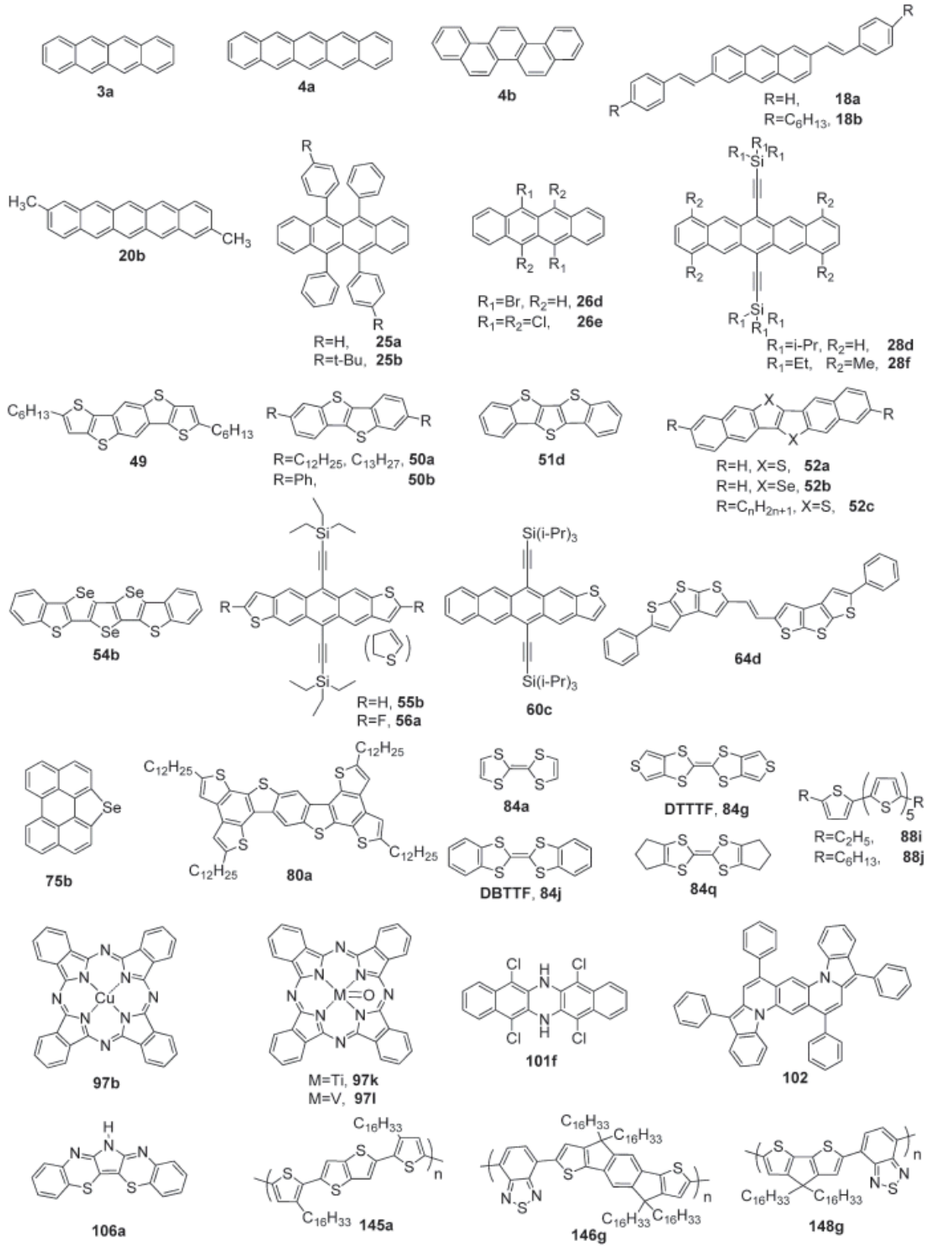


Rösner,
Org. Electronics
15 435 (2014)

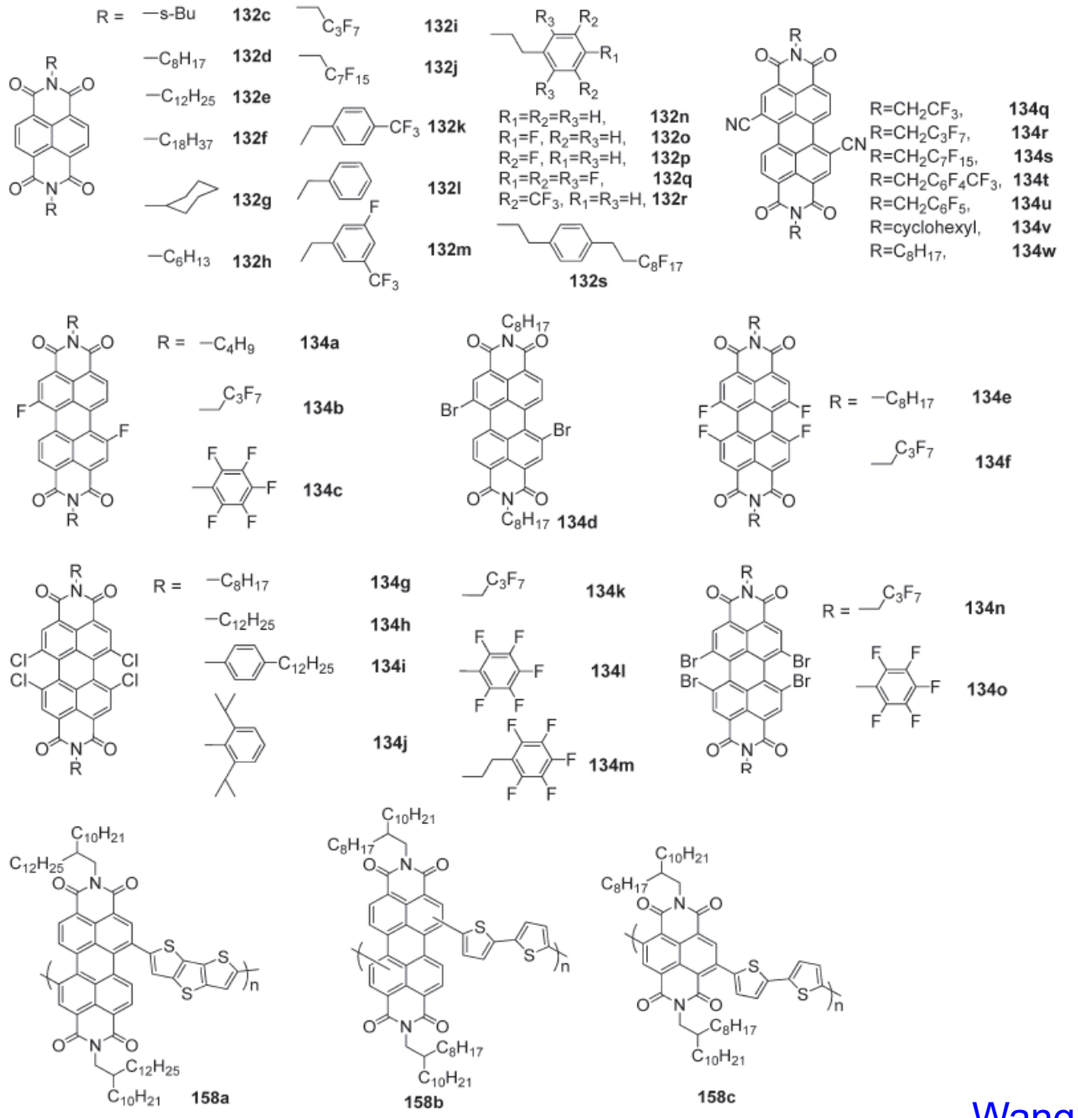


Geiger,
Phys. Rev. Appl.
10 044023 (2018)

p-channel semiconductors

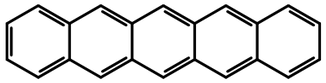


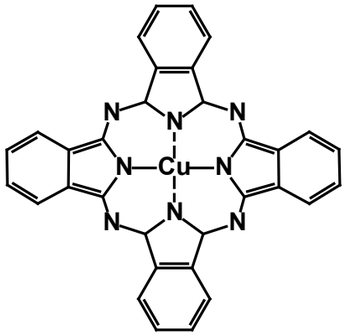
n-channel semiconductors



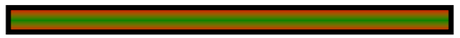
Wang,
Chem. Rev.
112 2208 (2012)

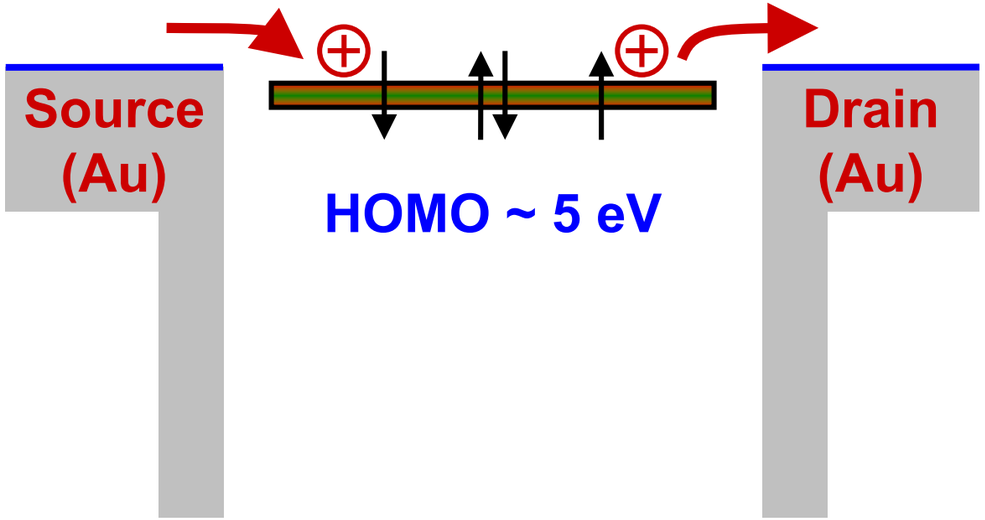
p-channel TFTs





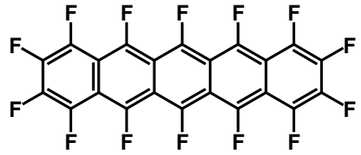
LUMO ~ 2 eV

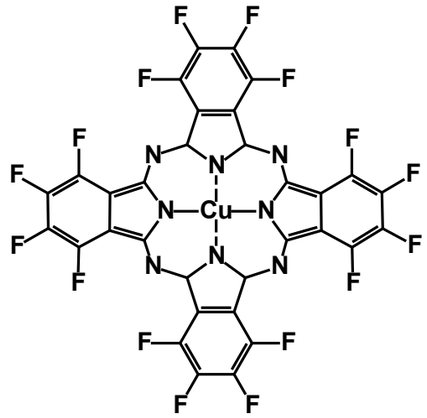




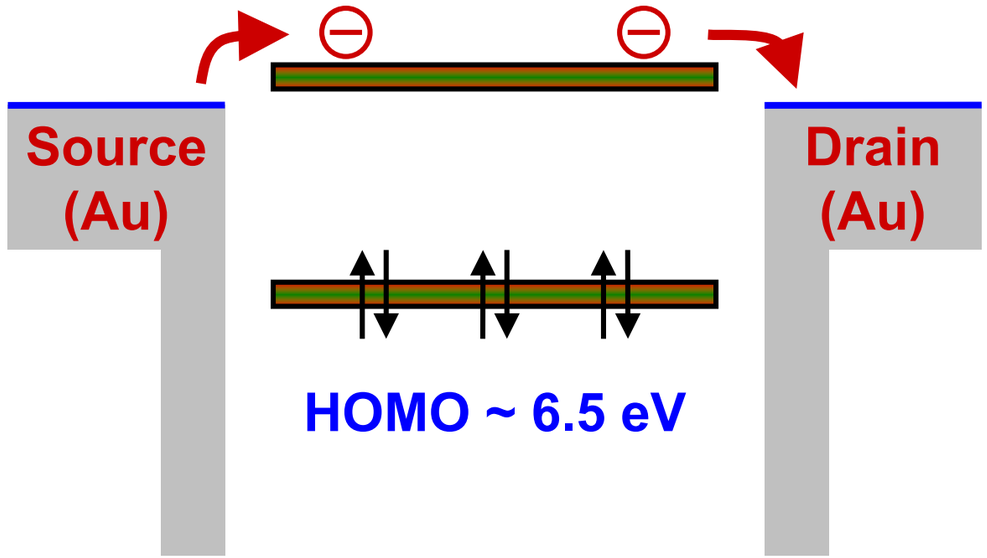
HOMO ~ 5 eV

n-channel TFTs





LUMO ~ 4.5 eV



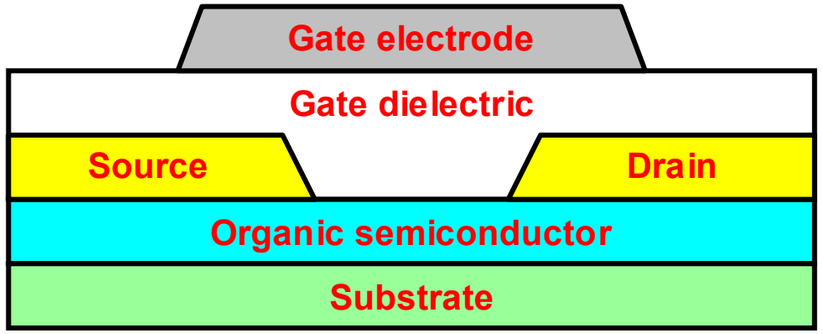
HOMO ~ 6.5 eV

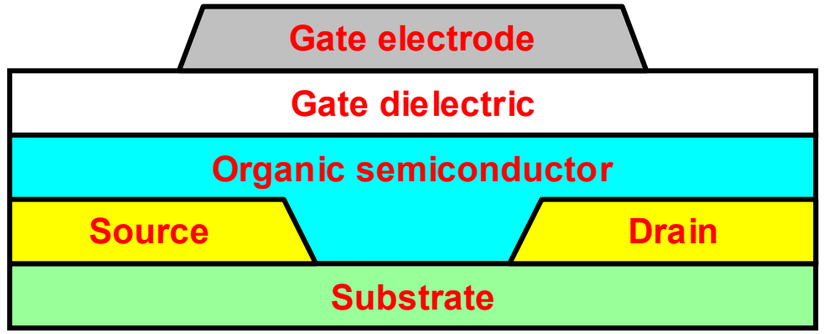
Organic TFT device architectures

coplanar

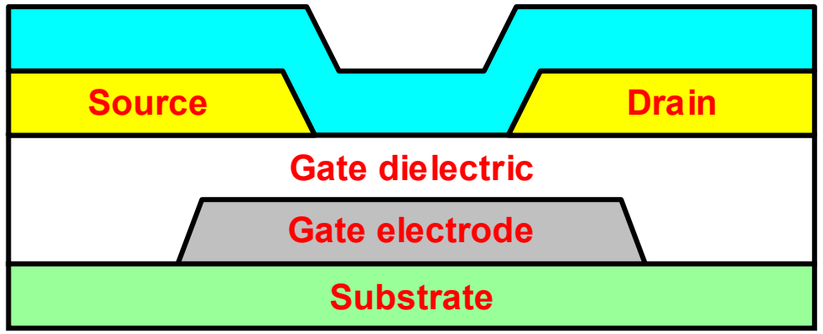
staggered

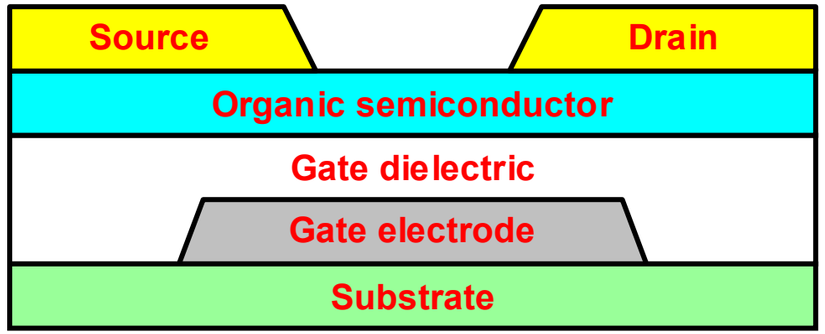
top-gate

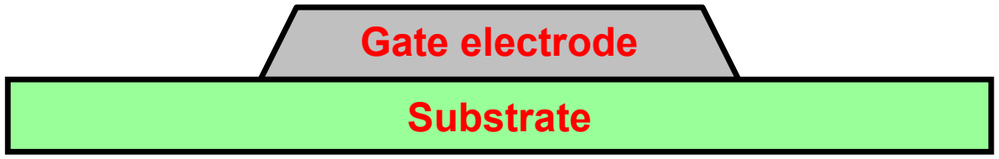


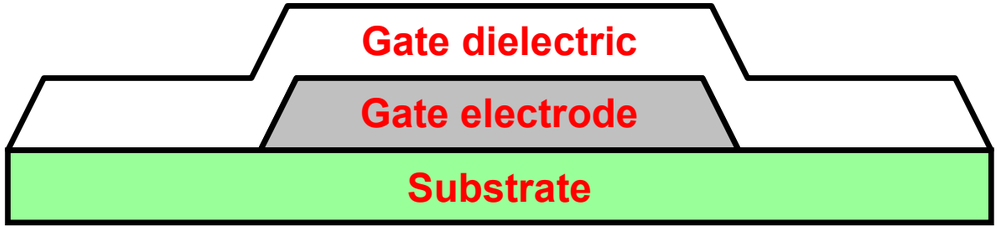


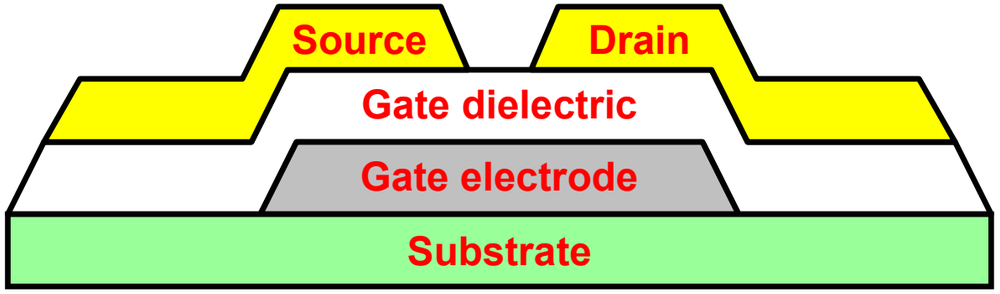
bottom-gate
(inverted)

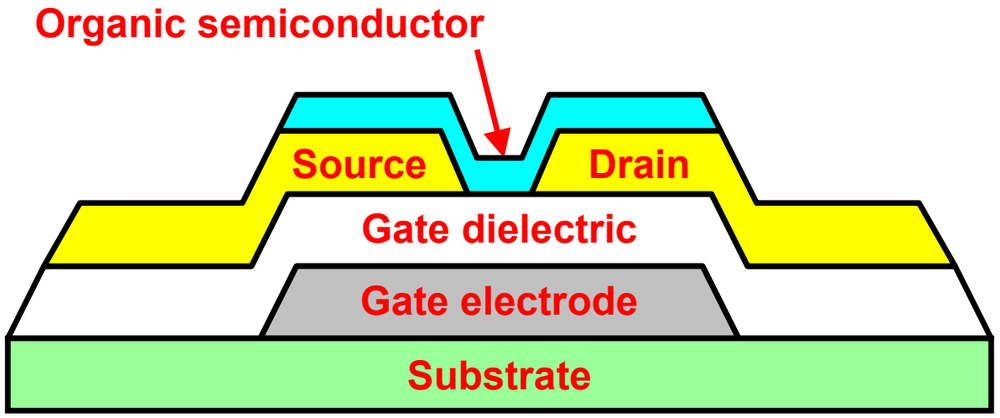












Gate electrodes:

- vacuum-deposited metals
- printed metal nanoparticle inks
- printed PEDOT:PSS

Gate dielectric:

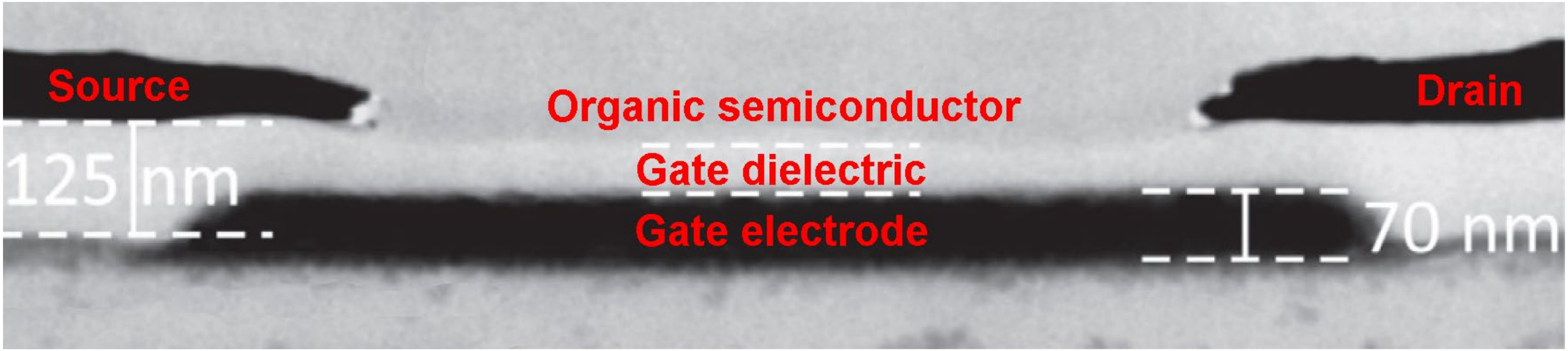
- PVD, ALD or sol-gel oxides (Al_2O_3, HfO_2, etc.)
- spin-coated or printed polymers

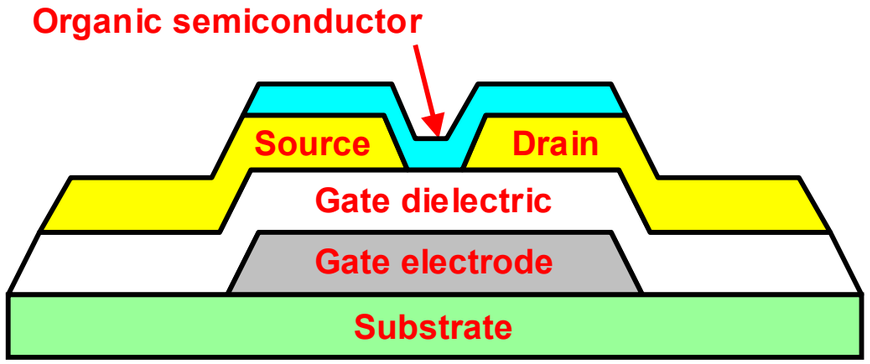
Source and drain contacts:

- vacuum-deposited metals
- printed metal nanoparticle inks
- printed PEDOT:PSS

Organic semiconductor layer:

- vacuum-deposited small-molecule materials
- spin-coated or printed small-molecule materials
- spin-coated or printed semiconducting polymers





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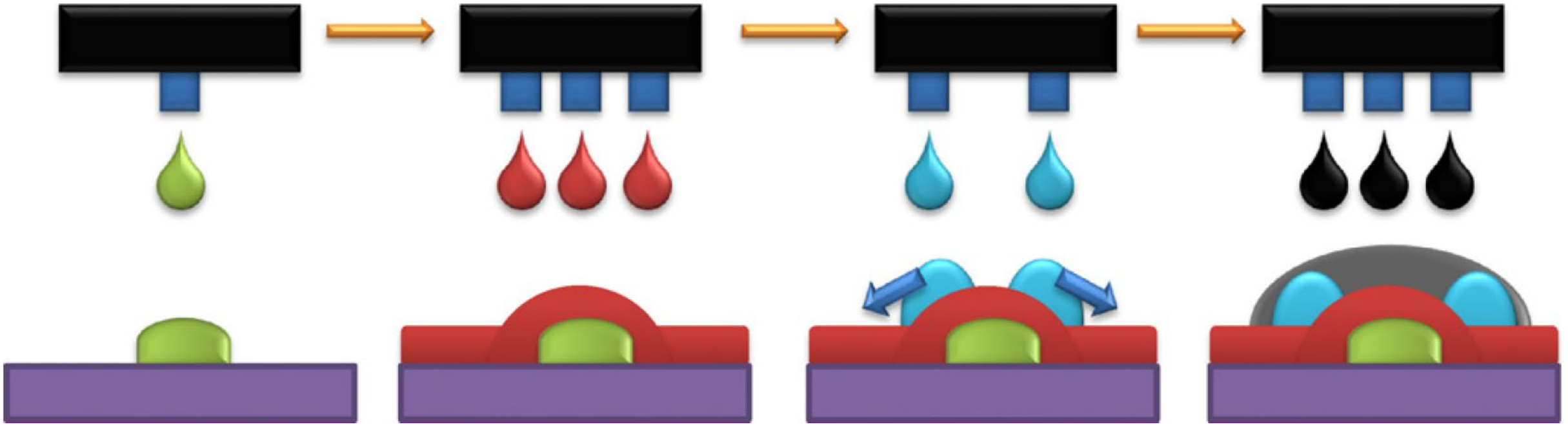
Gold,
Org. Electronics
22 140 (2015)

Inkjet printing

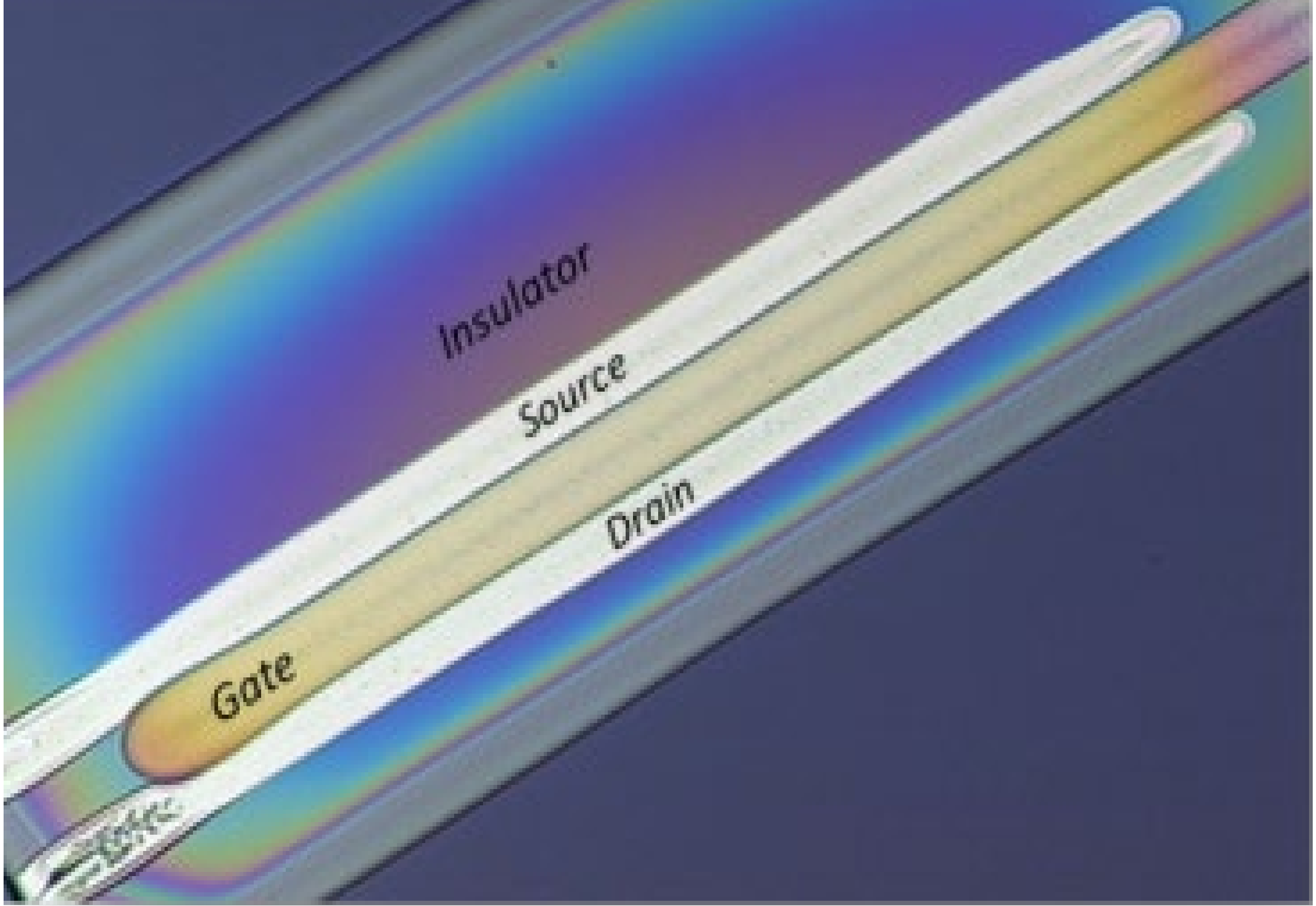


gate electrode

gate dielectric

source and drain contacts

organic semiconductor



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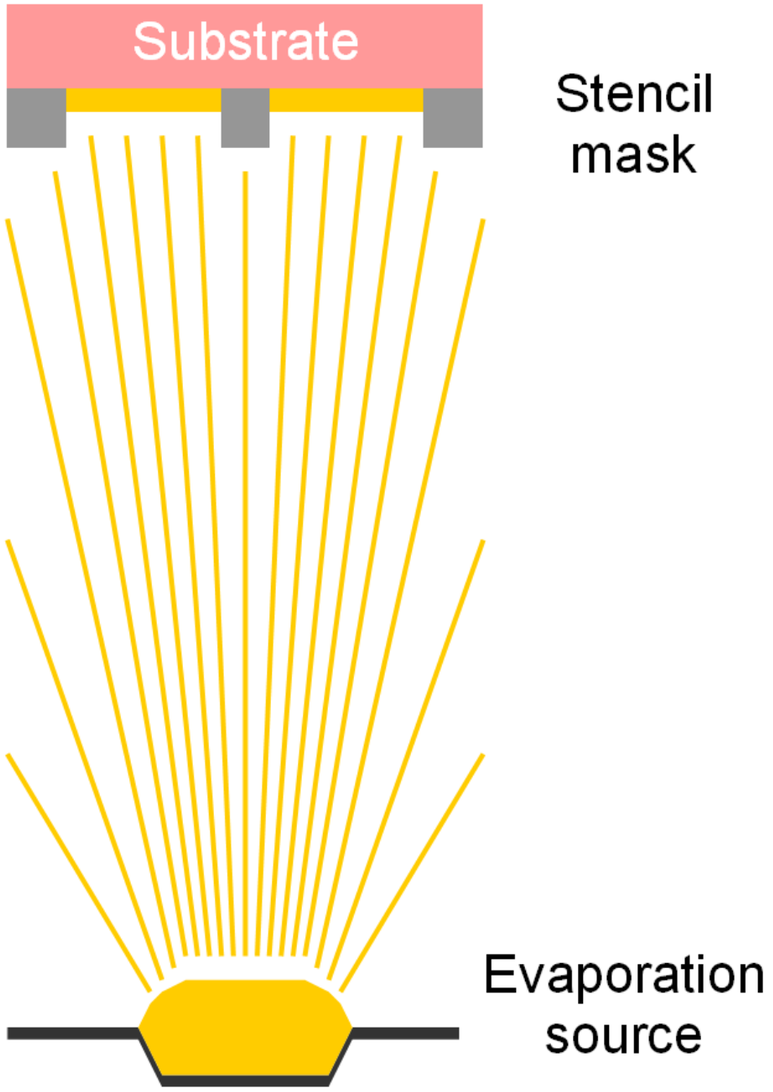
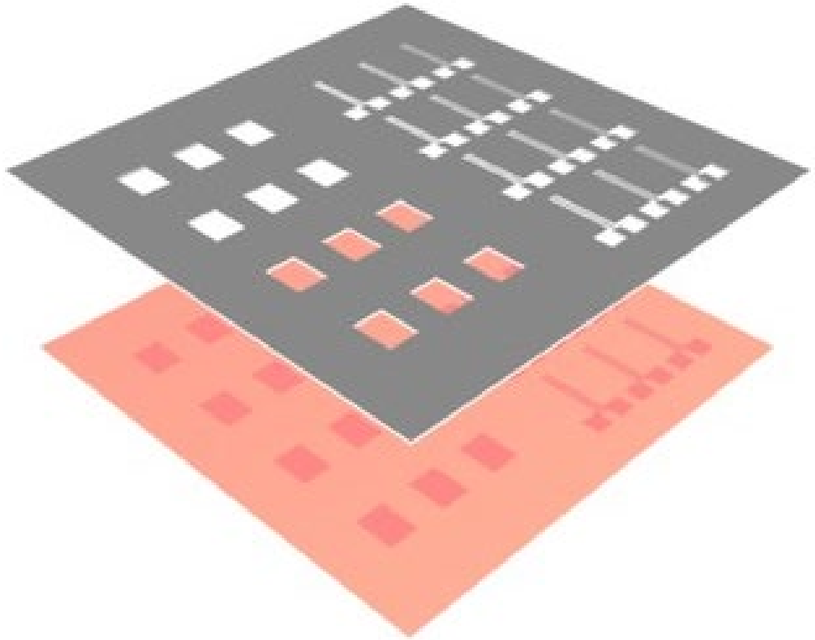
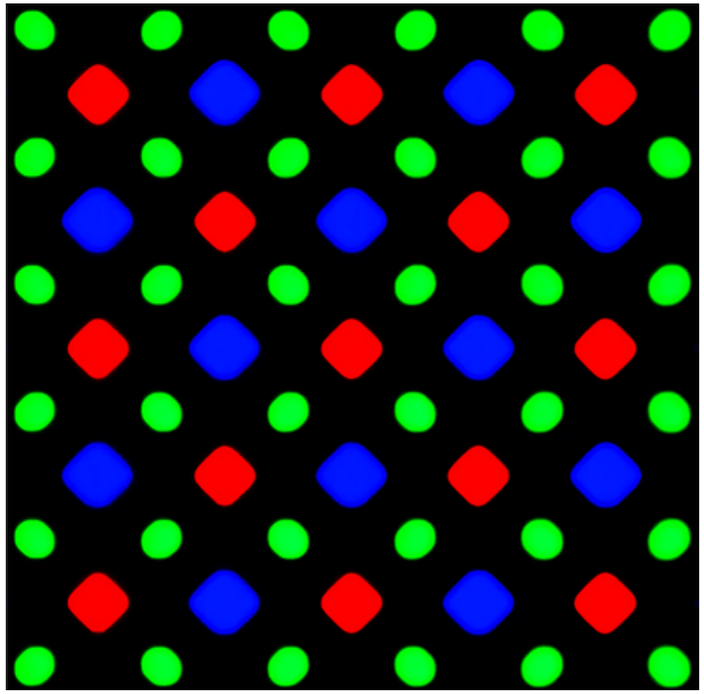
UNIVERSITY OF CALIFORNIA

Vacuum deposition / stencil lithography



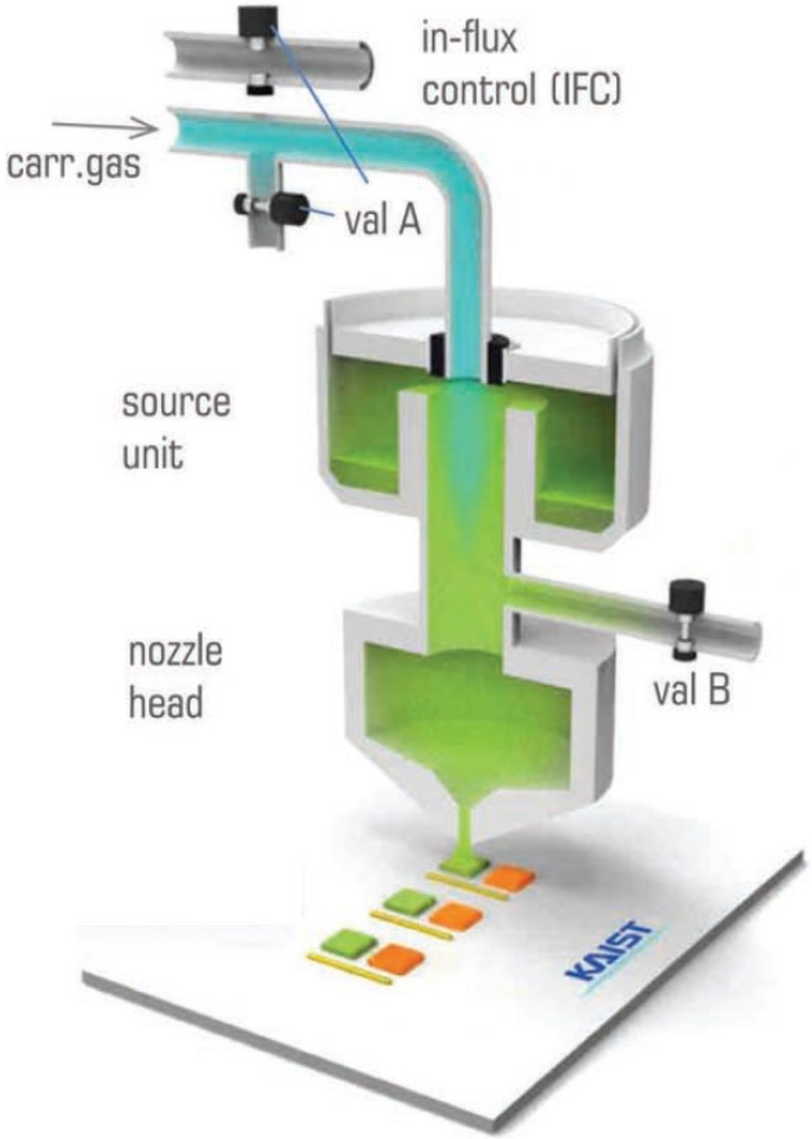


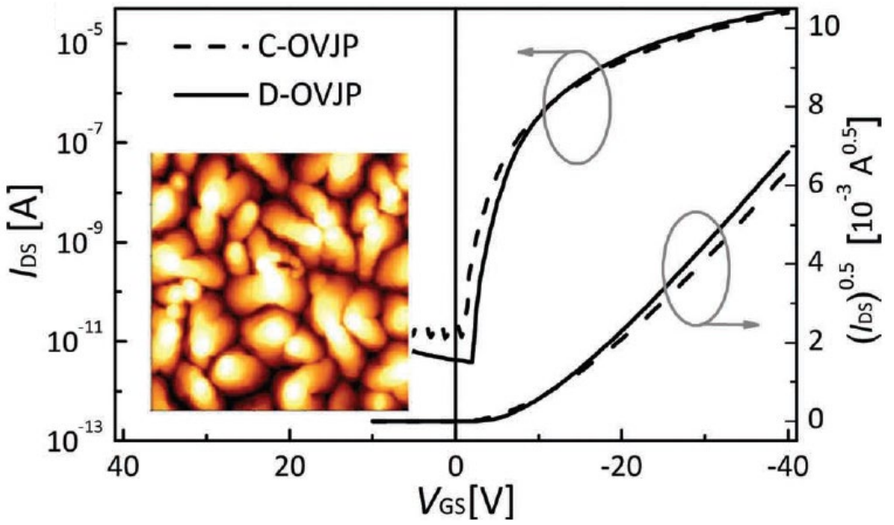


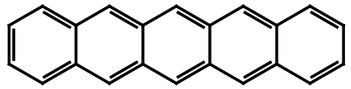
OLEDs patterned by stencil lithography and vacuum deposition

Muyres,
J. Vac. Sci. Technol. A
22 1892 (2004)

Organic vapor jet printing







Shtein,
Adv. Mater.
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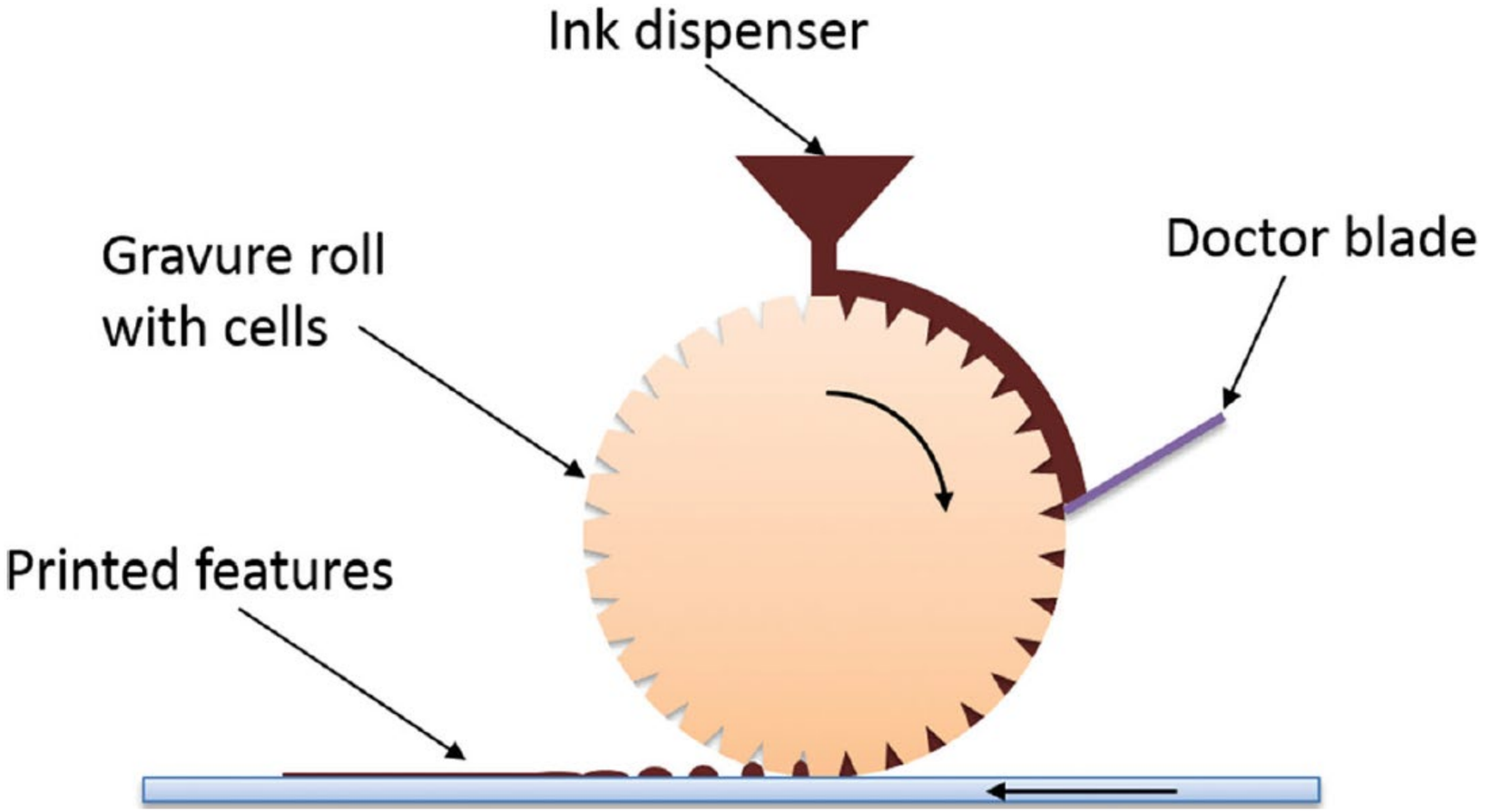
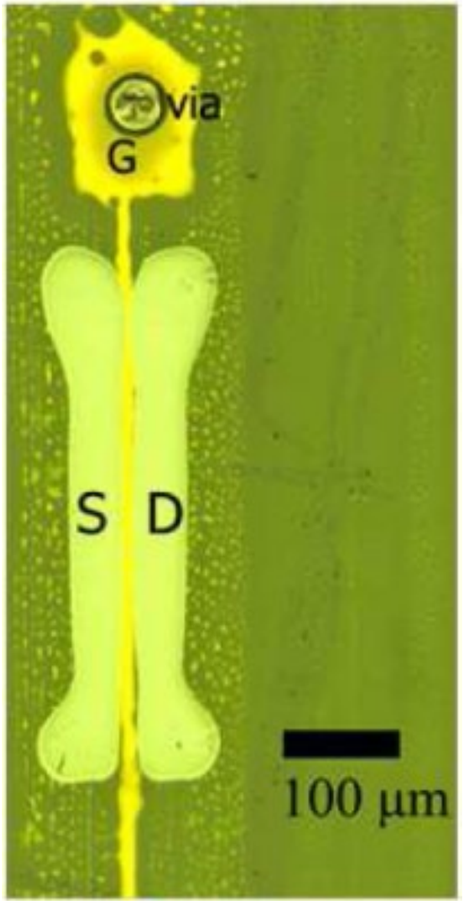
Yun,
Adv. Mater.
24 2857 (2012)

Roll-to-roll gravure printing





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Kang,
Adv. Mater.
24 3065 (2012)

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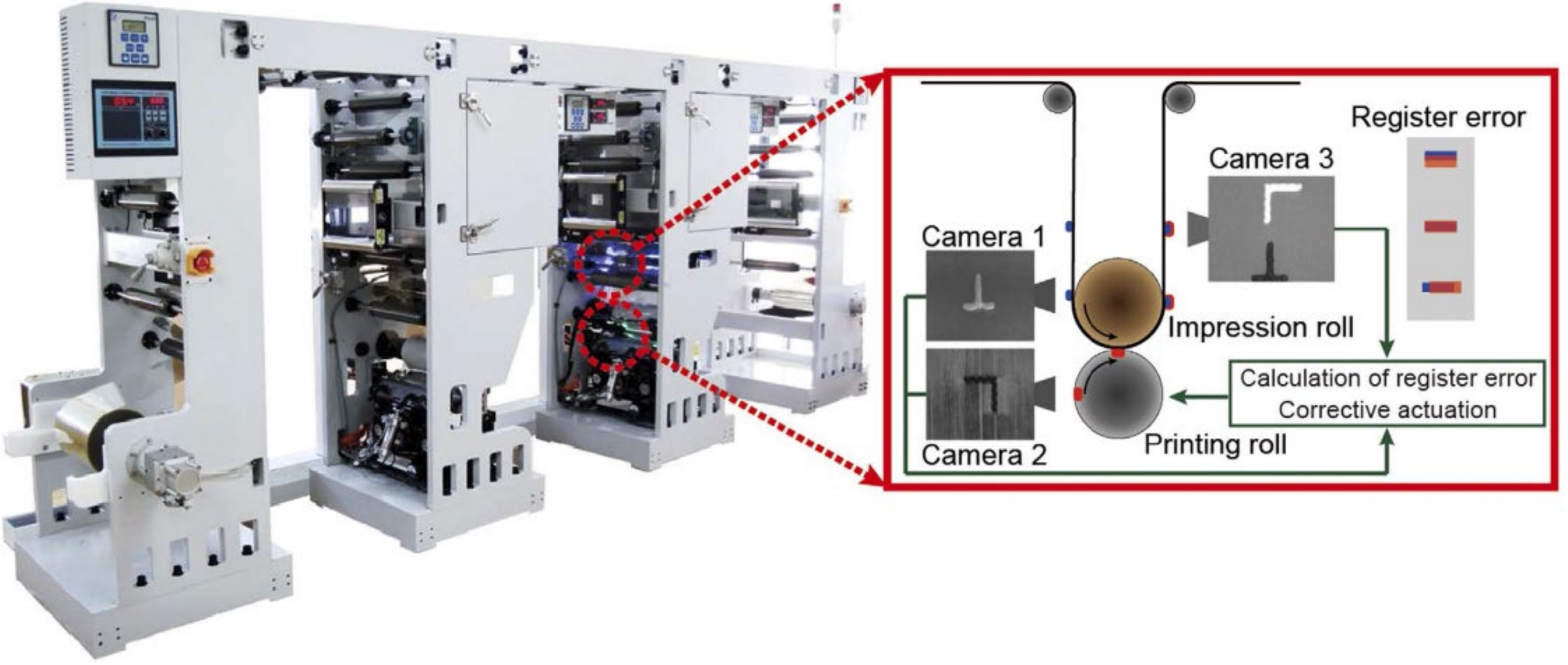
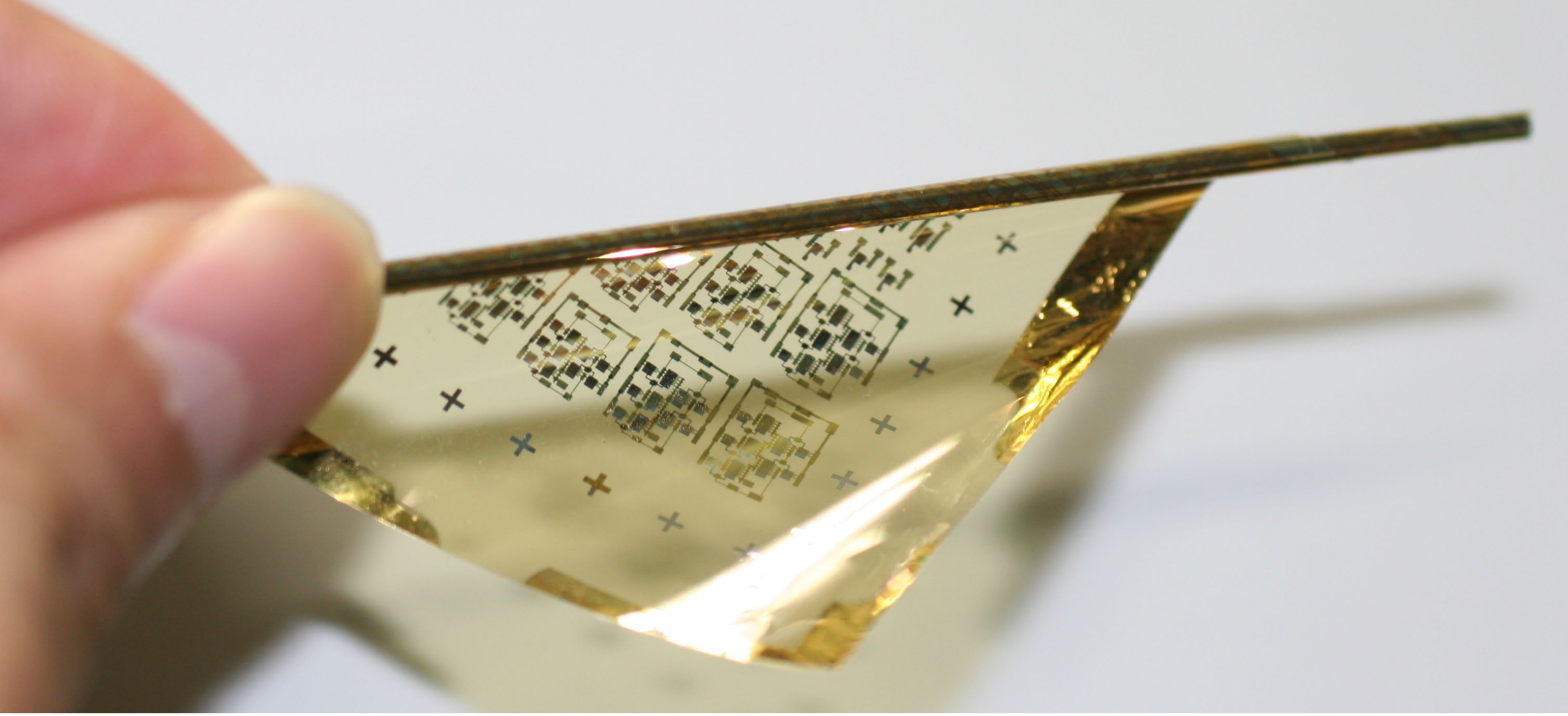

Register error
Camera 3
Camera 1
Impression roll
Calculation of register error
Corrective actuation
Printing roll
Camera 2



東京大学
THE UNIVERSITY OF TOKYO

Sekitani,
Nature Mater.
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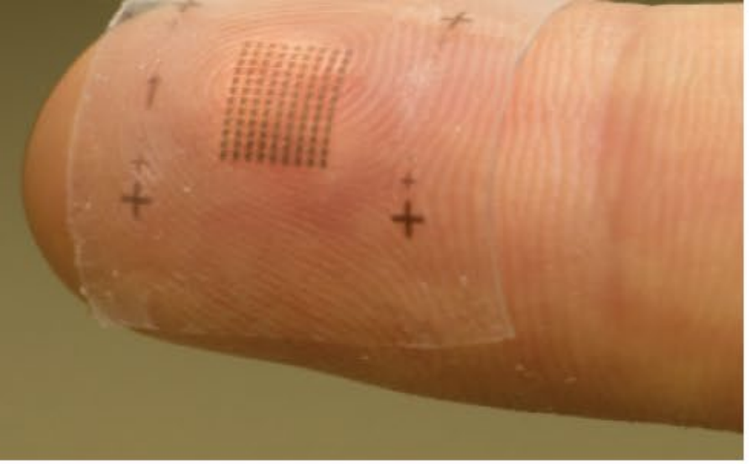
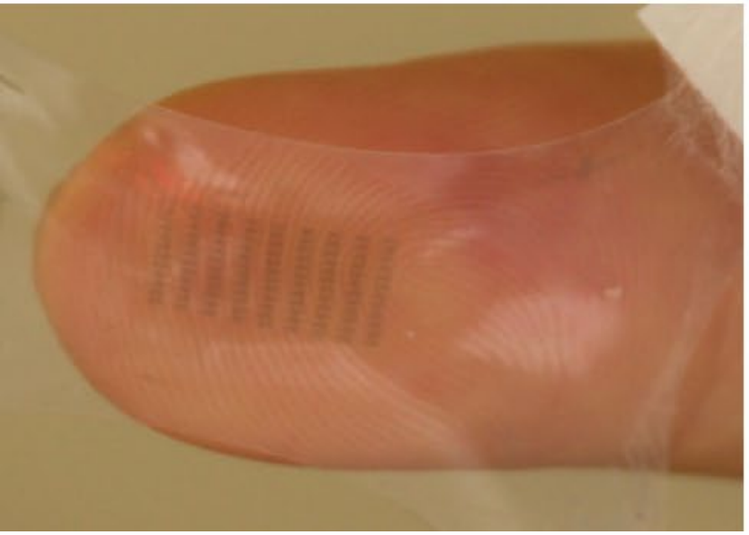
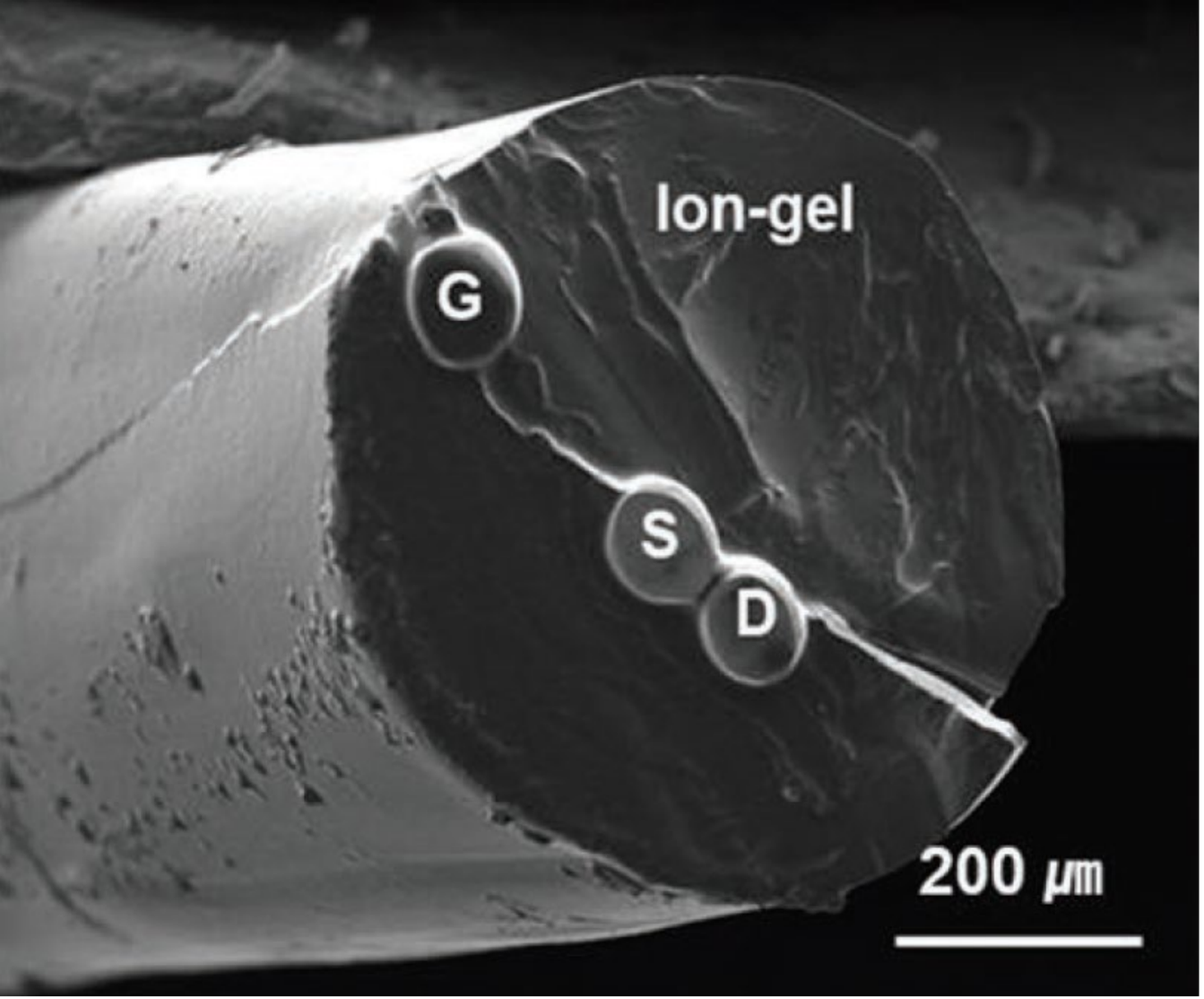
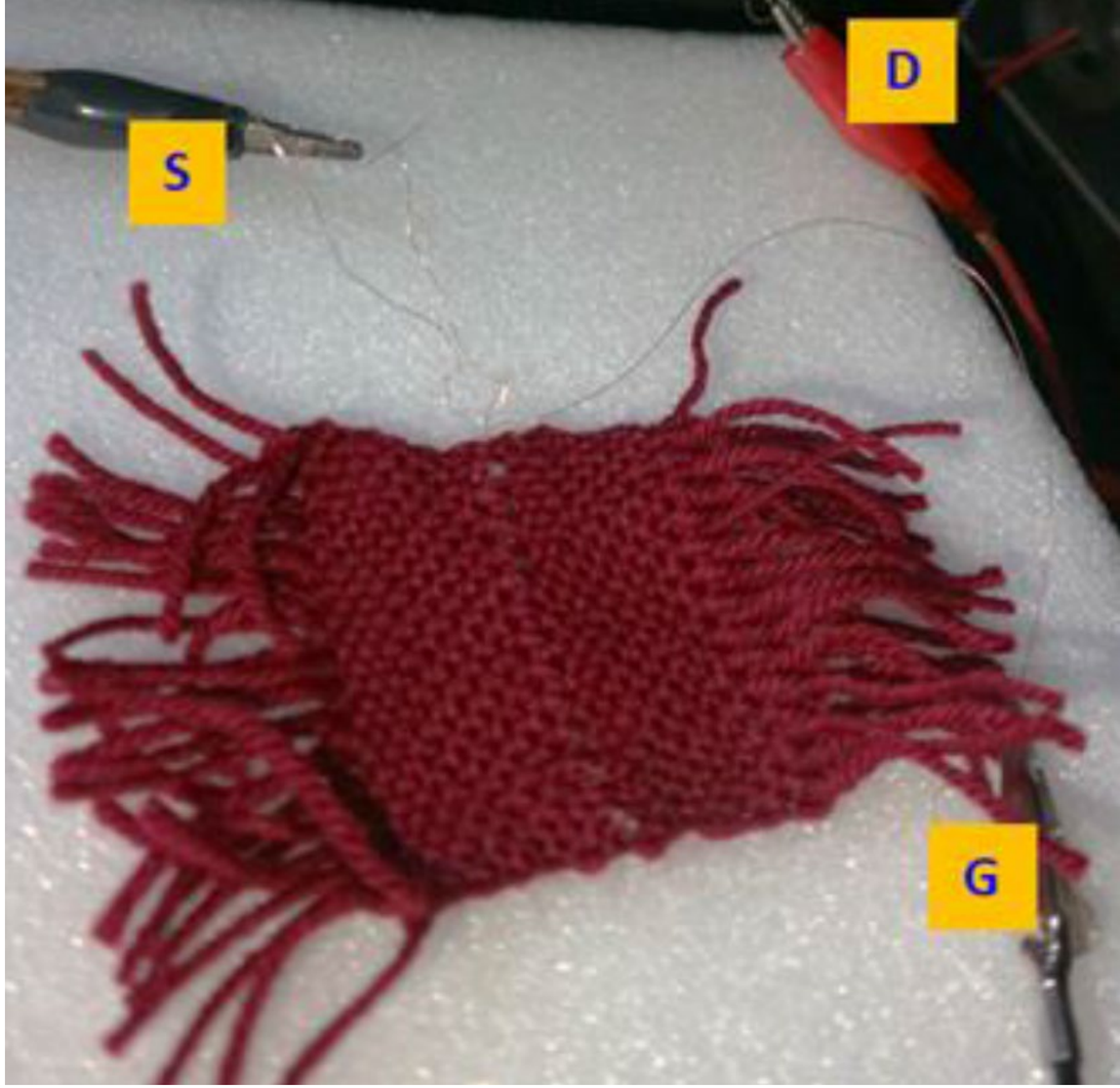




STANFORD
UNIVERSITY

Wang,
Nature
555 83 (2018)





Korea Institute of Science and Technology

Kim,
Adv. Mater.
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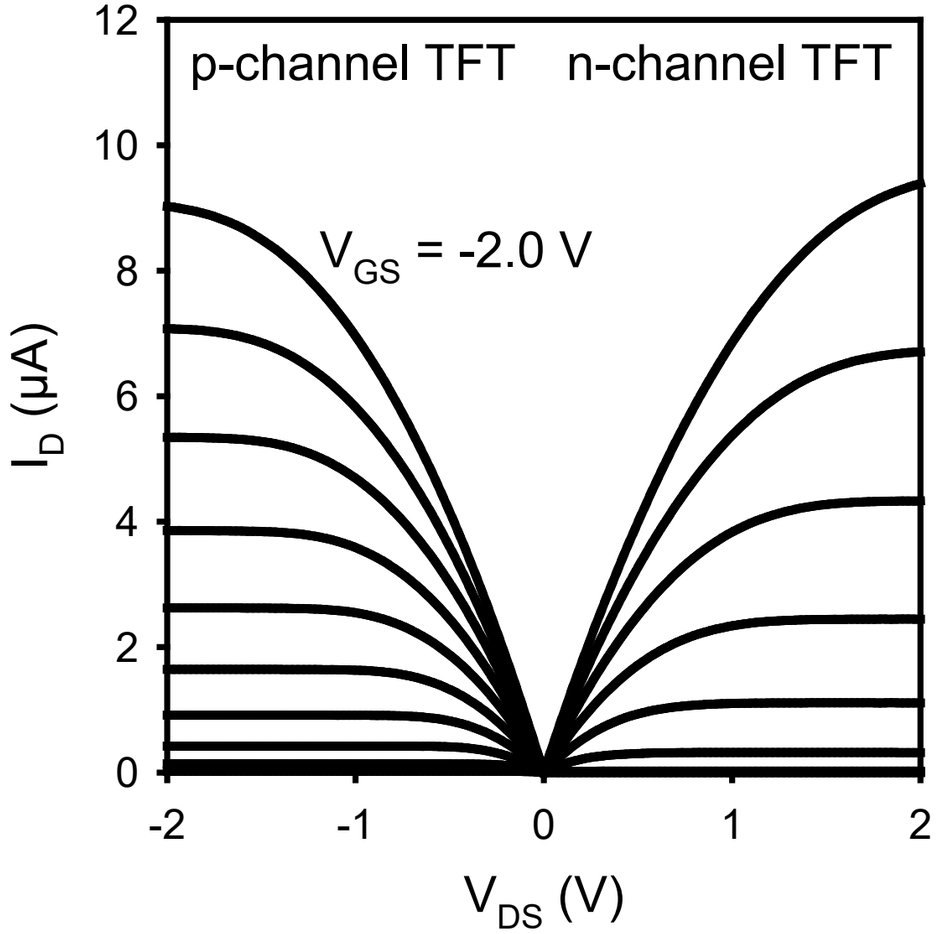
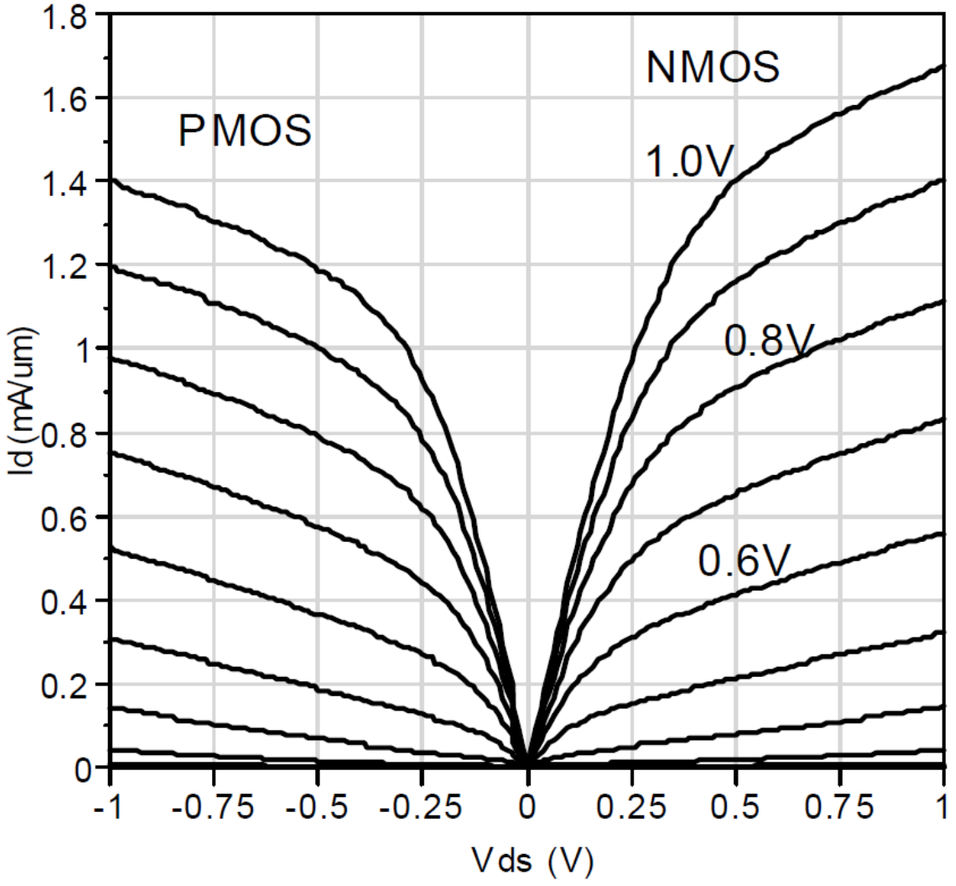
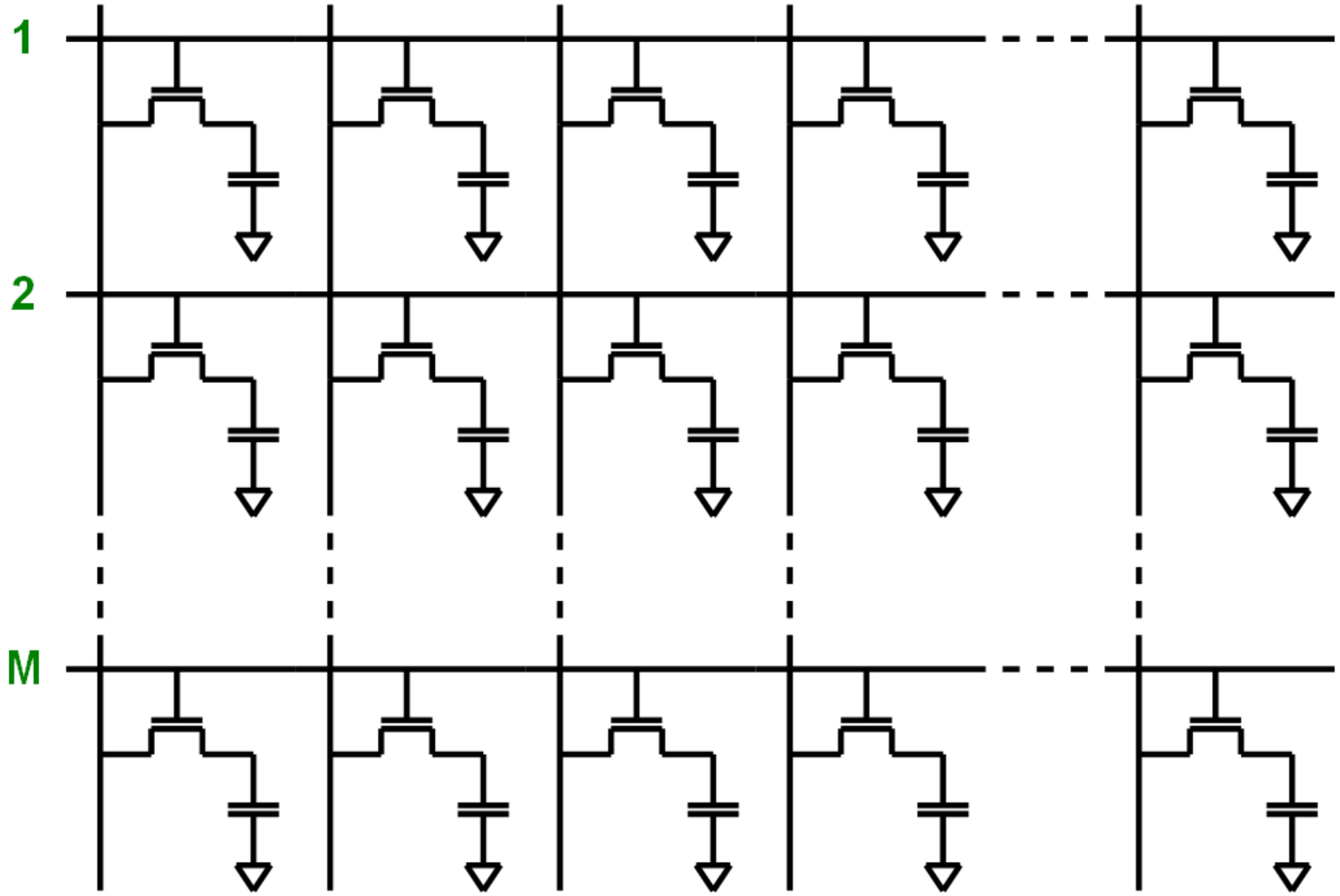
Organic TFTs



Silicon MOSFETs

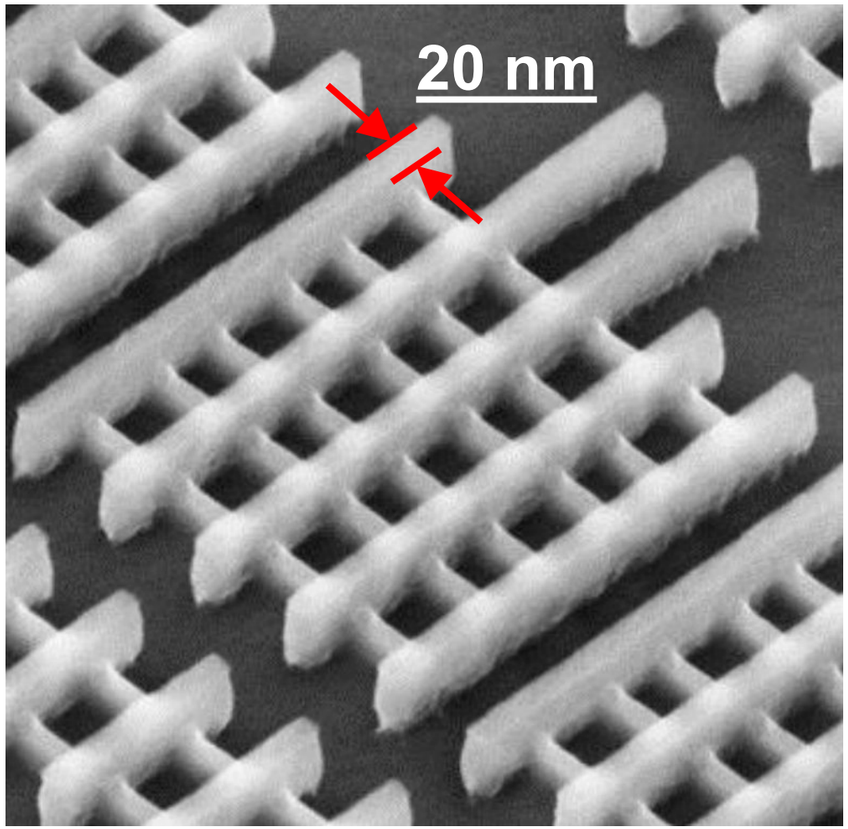


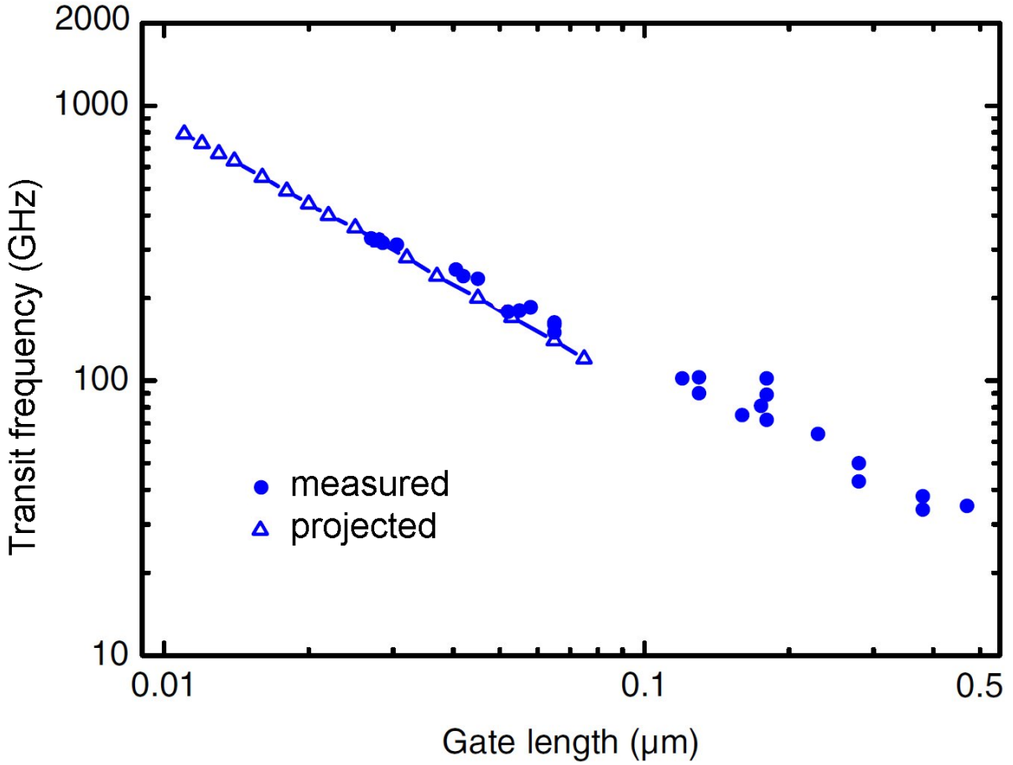


frame time = row access time x # of rows

display model	# of rows (M)	frame rate	row access time	TFT transit frequency
iPhone X S	1125	200 Hz	4 μsec	~10 MHz

$$f_T = \frac{\mu_{eff}\left(V_{GS} - V_{th}\right)}{2\pi L\left(\frac{2}{3}L + 2L_{ov}\right)}$$





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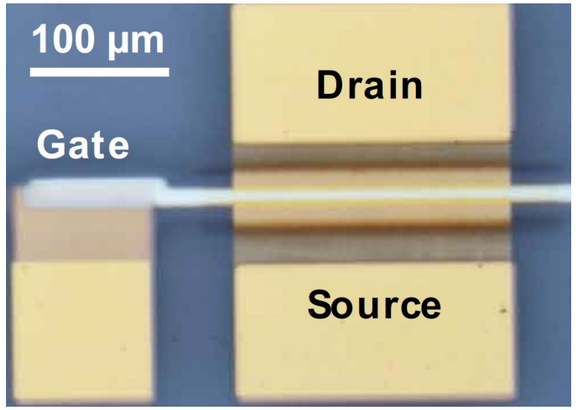

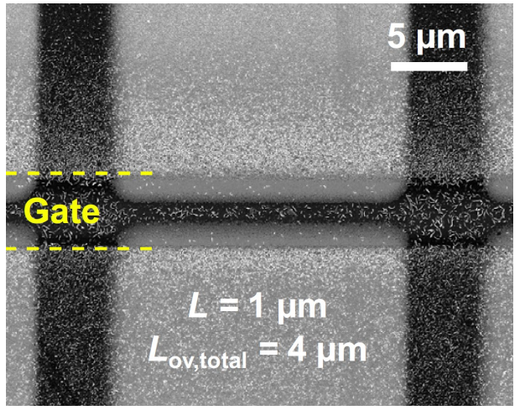

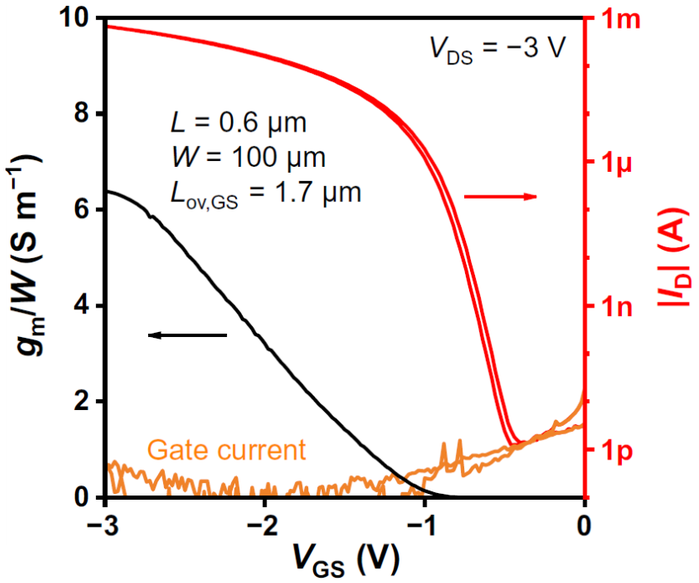

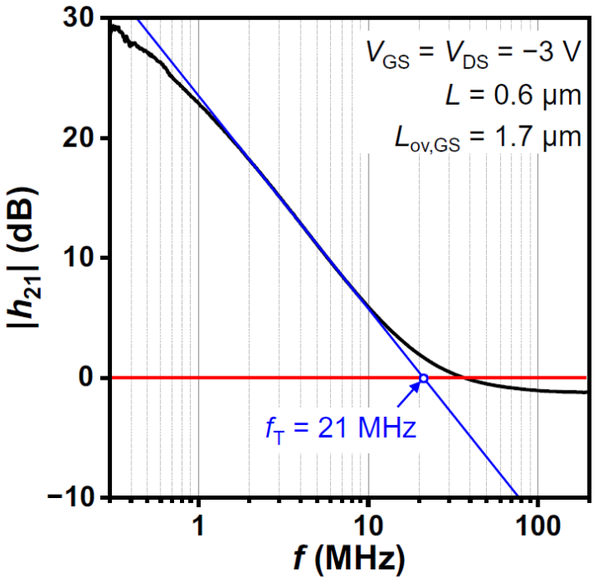

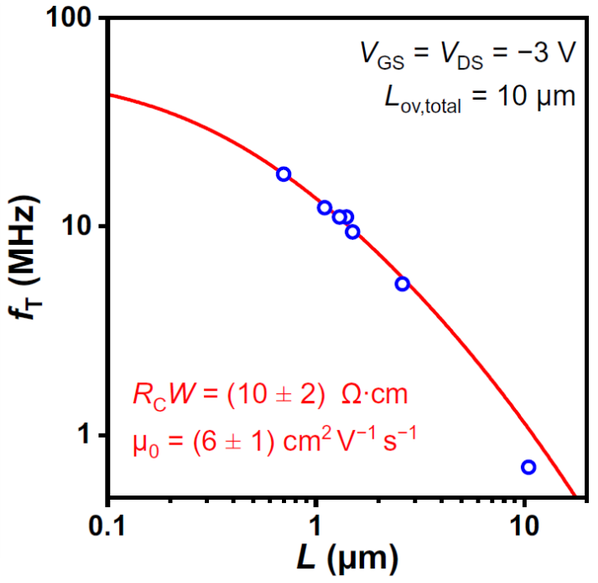

Borchert,
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6 eaaz5156 (2020)