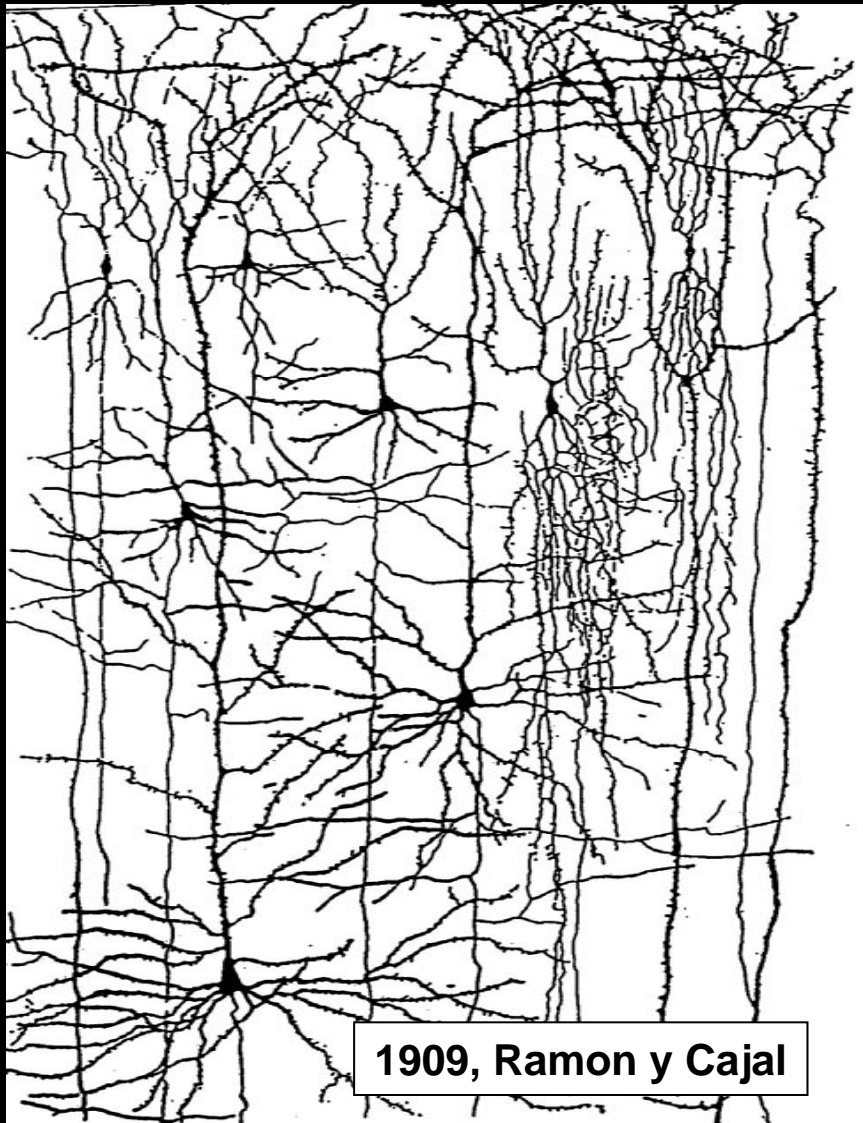




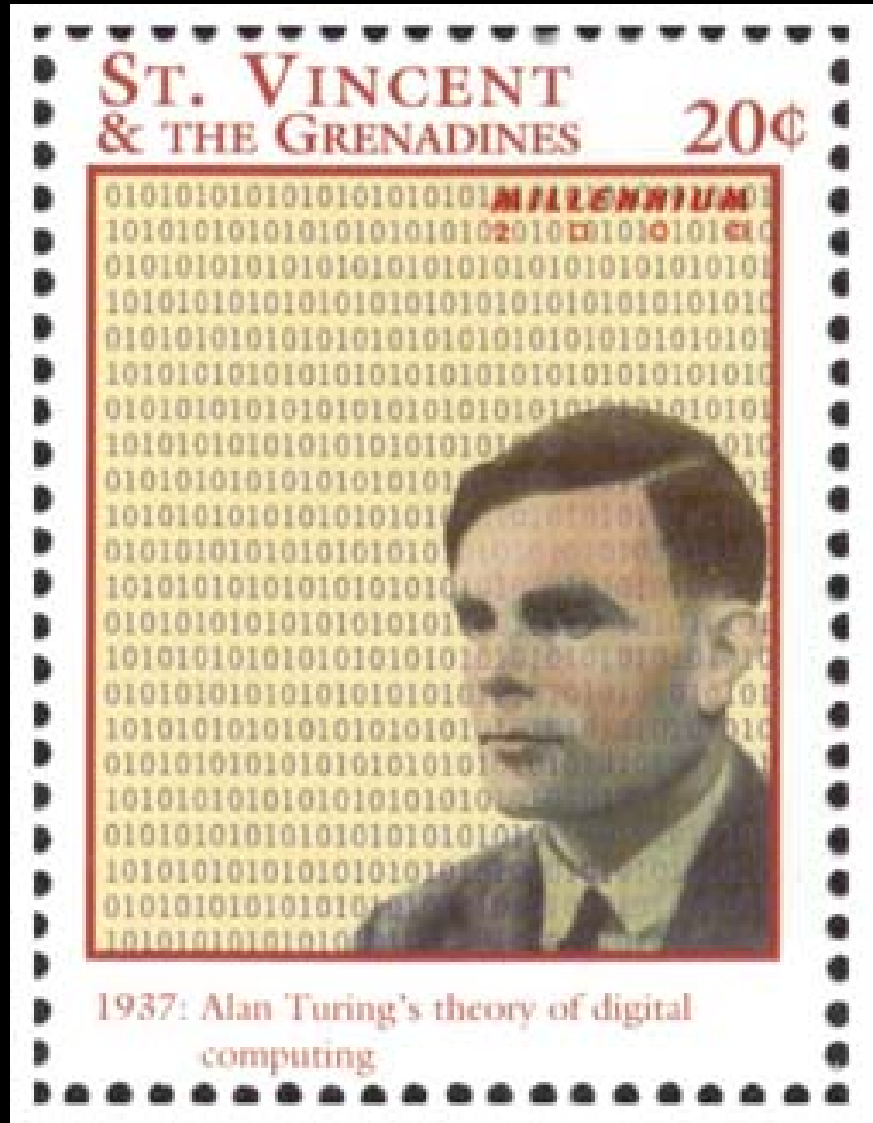
International Symposium on Contemporary Physics  
Islamabad, March 28, 2007

# Physical Problems of Brain-Computer Interfacing

Max Planck Institute for Biochemistry  
Department of Membrane and Neurophysics  
Peter Fromherz

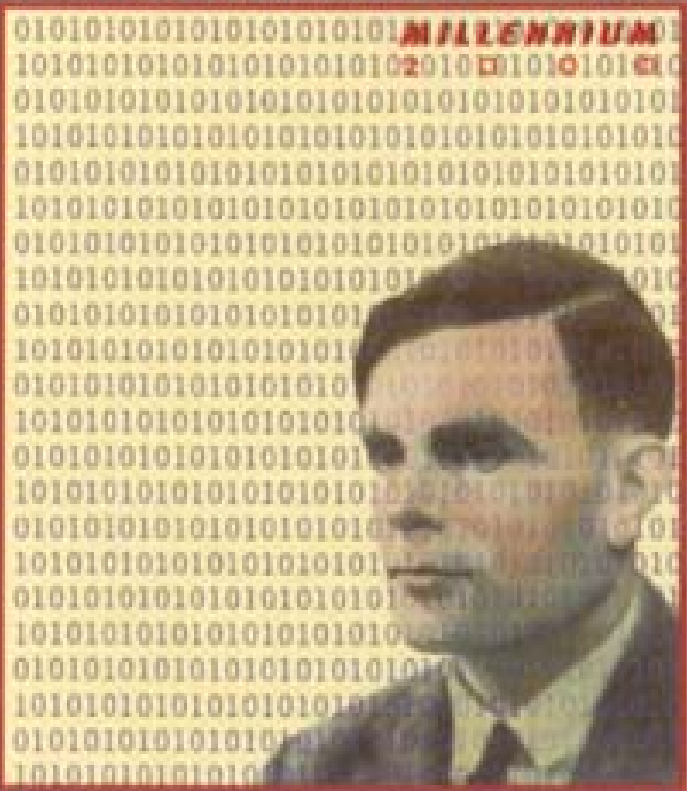


1909, Ramon y Cajal



ST. VINCENT  
& THE GRENADINES

20c



1937: Alan Turing's theory of digital  
computing

$$Q = C U$$

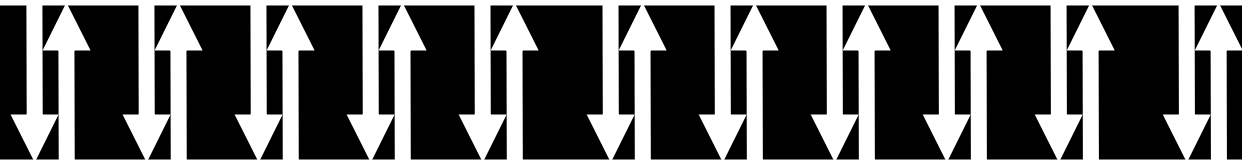
Coulomb

$$U = R I$$

Ohm

**ions  $10^{-3} \text{ cm}^2/\text{Vs}$**

thinking brain tissue

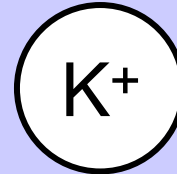
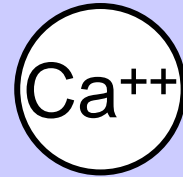
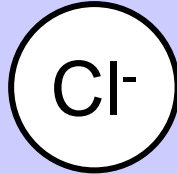
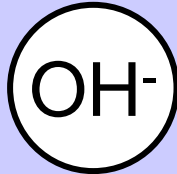
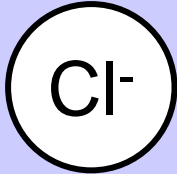
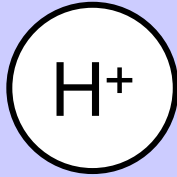


computing microprocessor

**electrons  $10^3 \text{ cm}^2/\text{Vs}$**

undefined electrochemistry

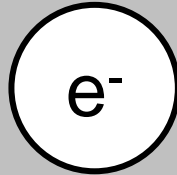
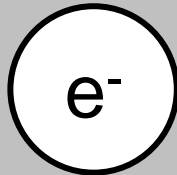
ions



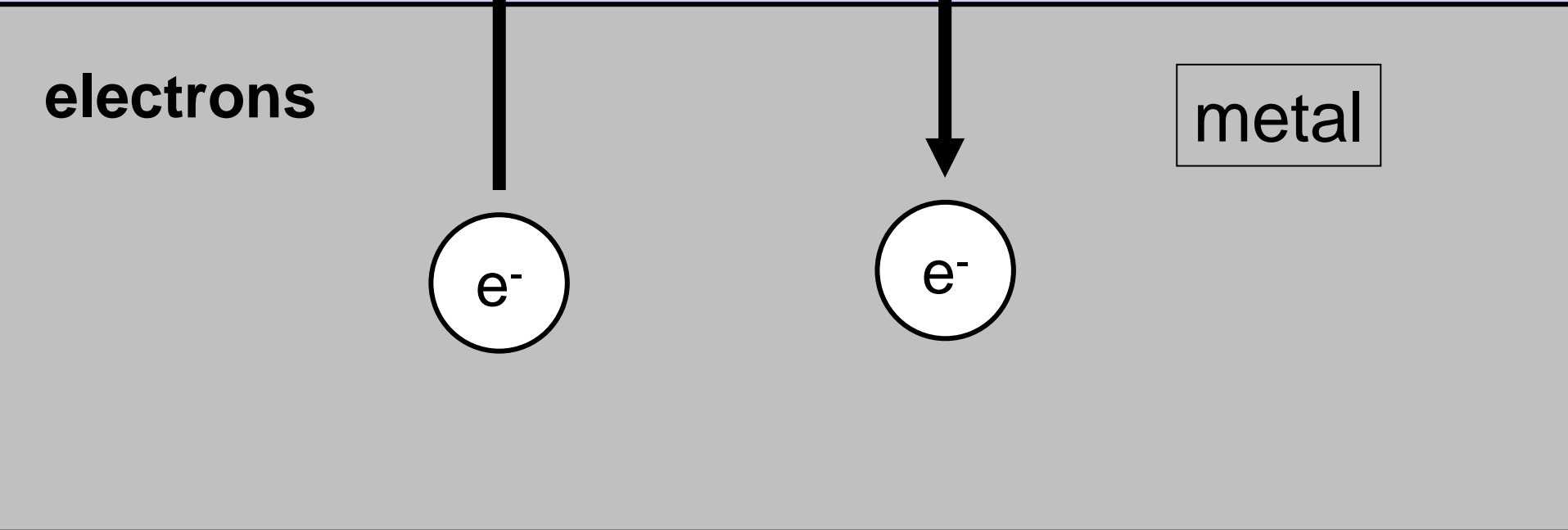
*Galvani*

electrolyte

electrons

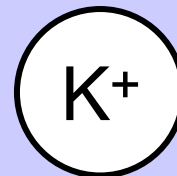
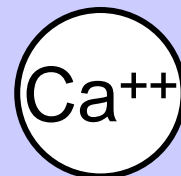
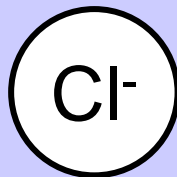
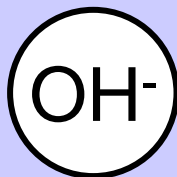
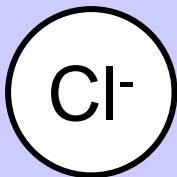
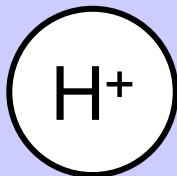


metal



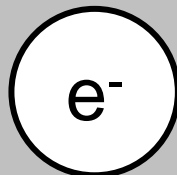
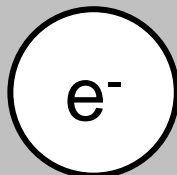
no electrochemistry

ions



insulator

electrons

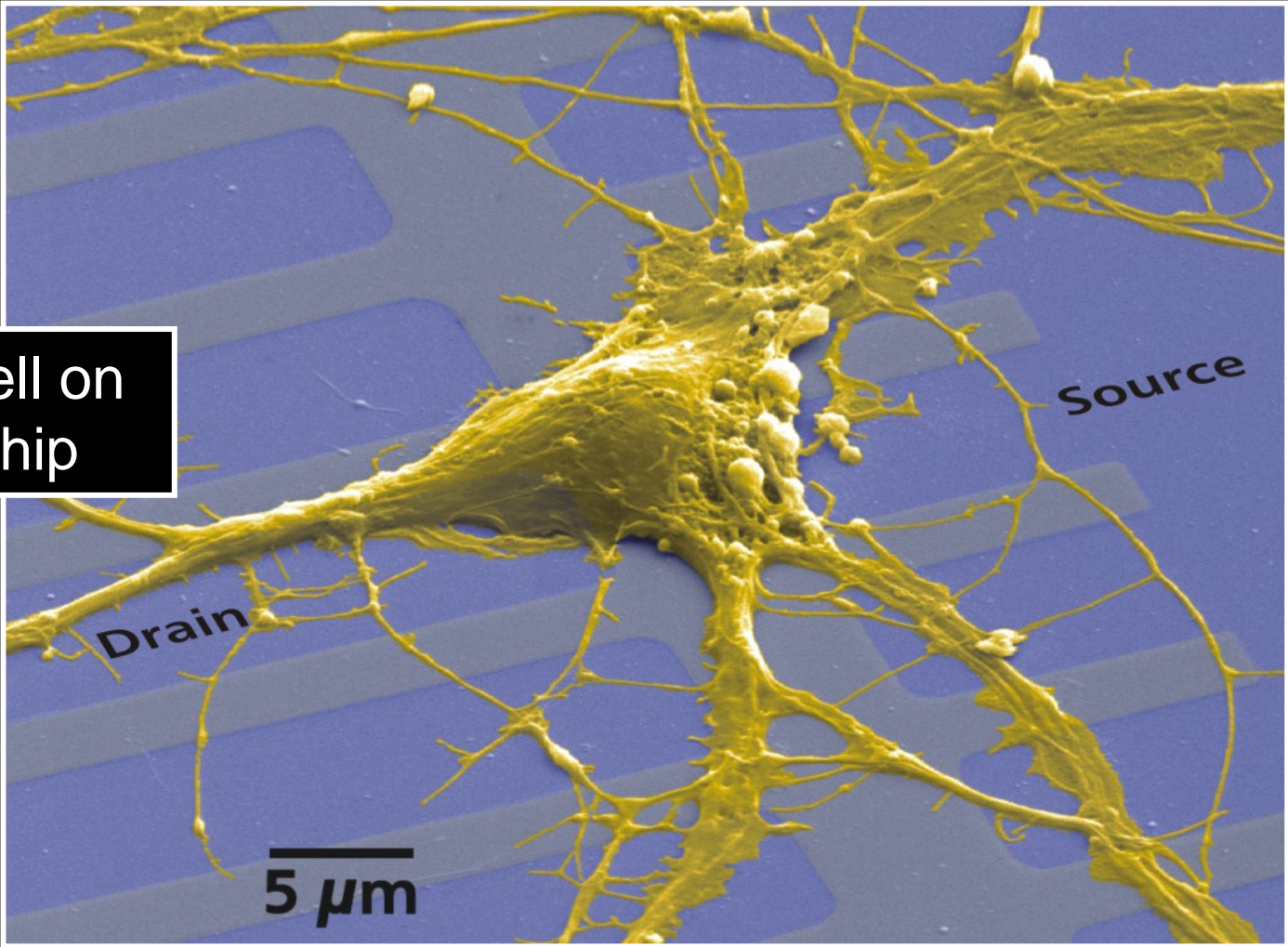


# Outline

1. Cell-Silicon Contact
2. Ions & Electrons
3. Nerve Cells on Silicon
4. Neuronal Networks on Chip
5. Brain Tissue on Chip

# 1. Cell-Silicon Contact

nerve cell on  
silicon chip



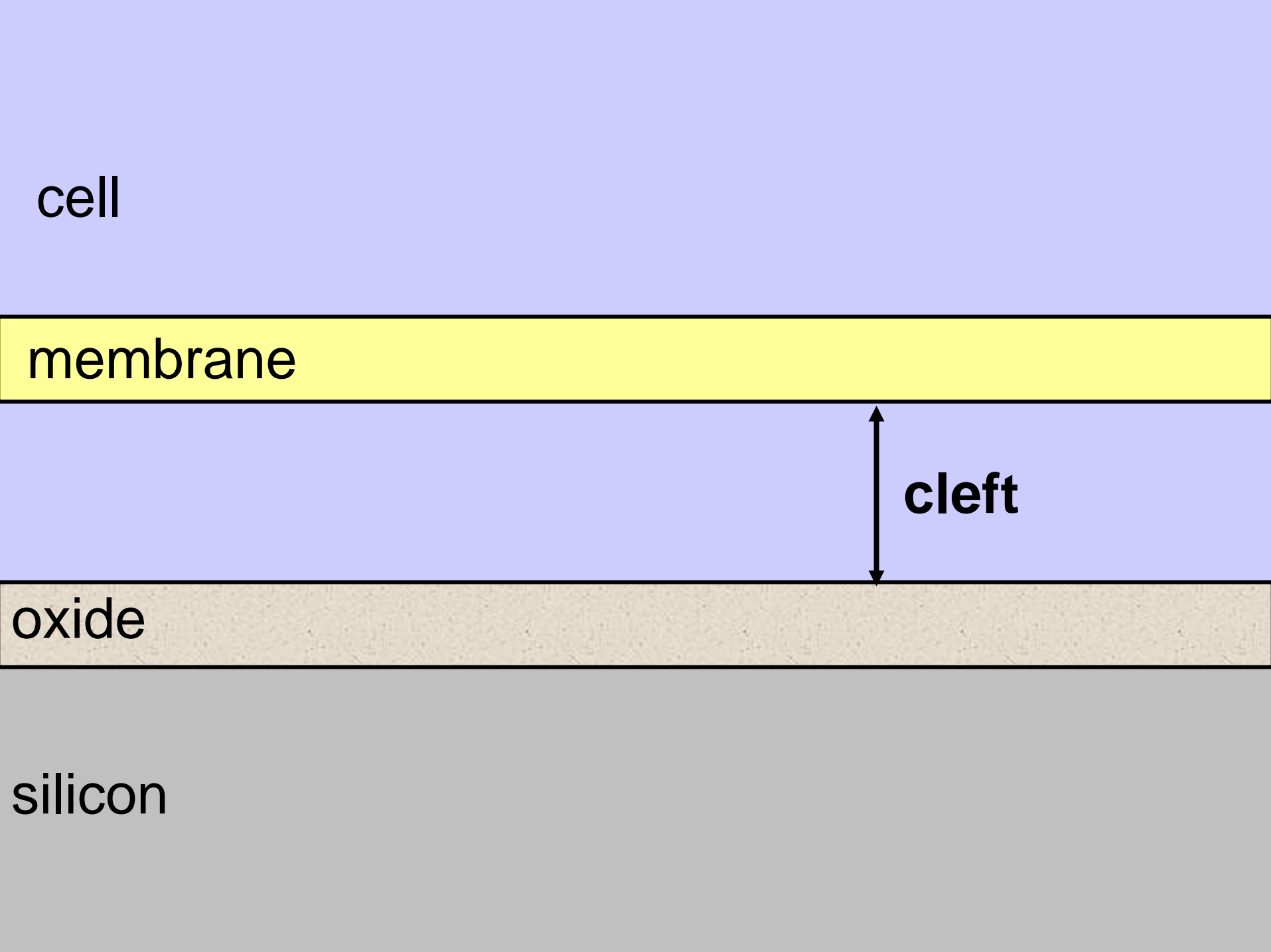
cell

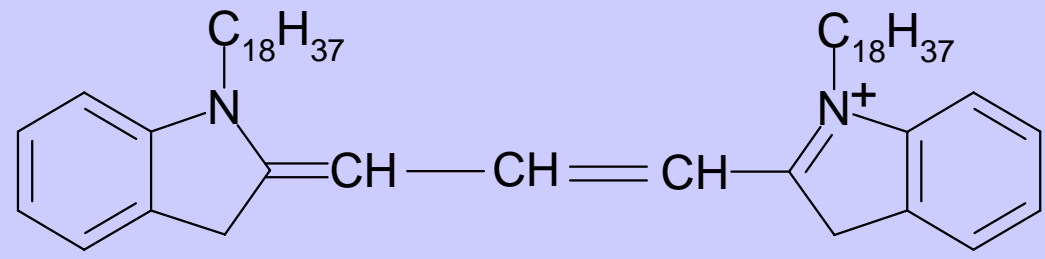
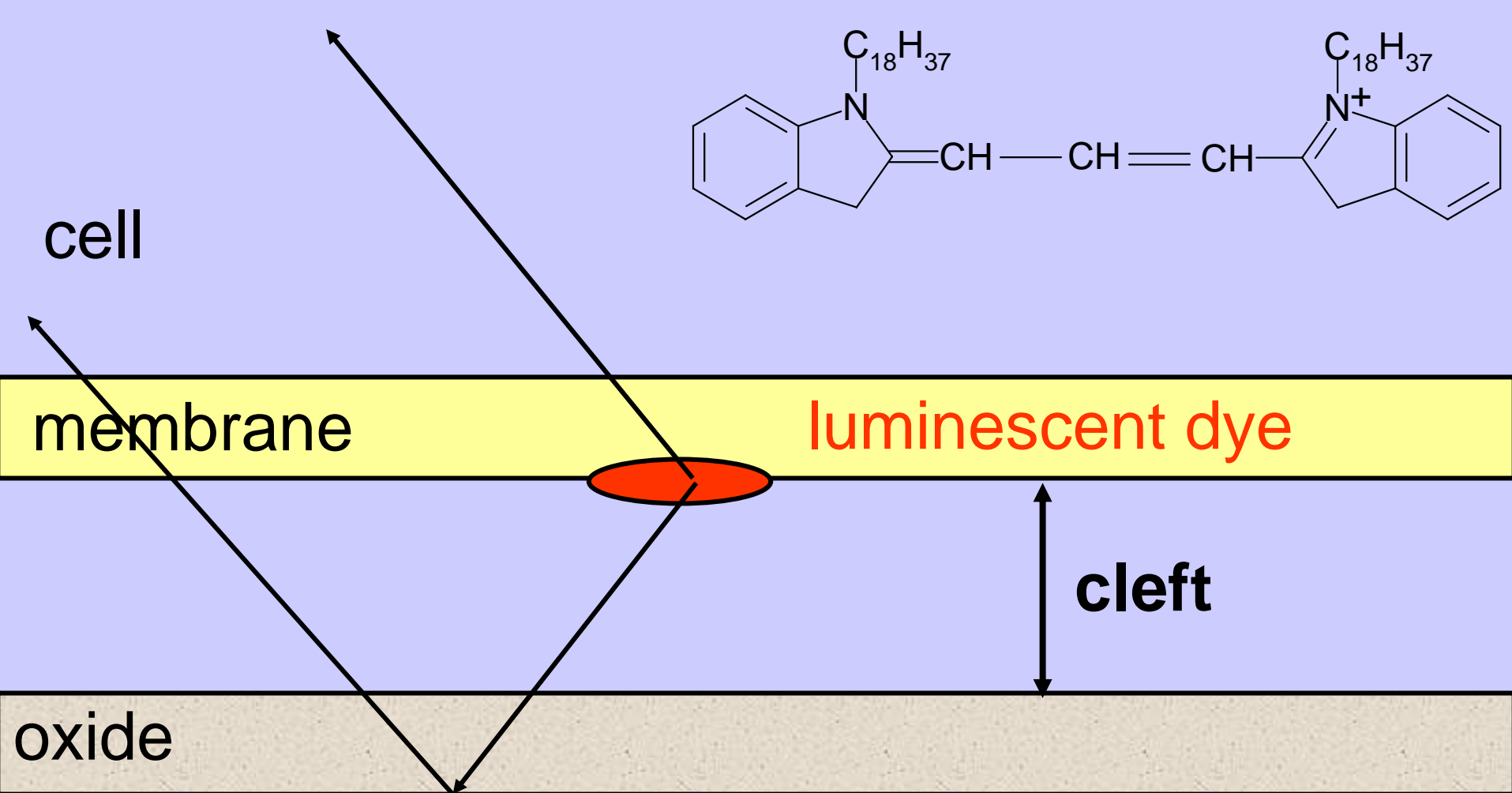
membrane

**cleft**

oxide

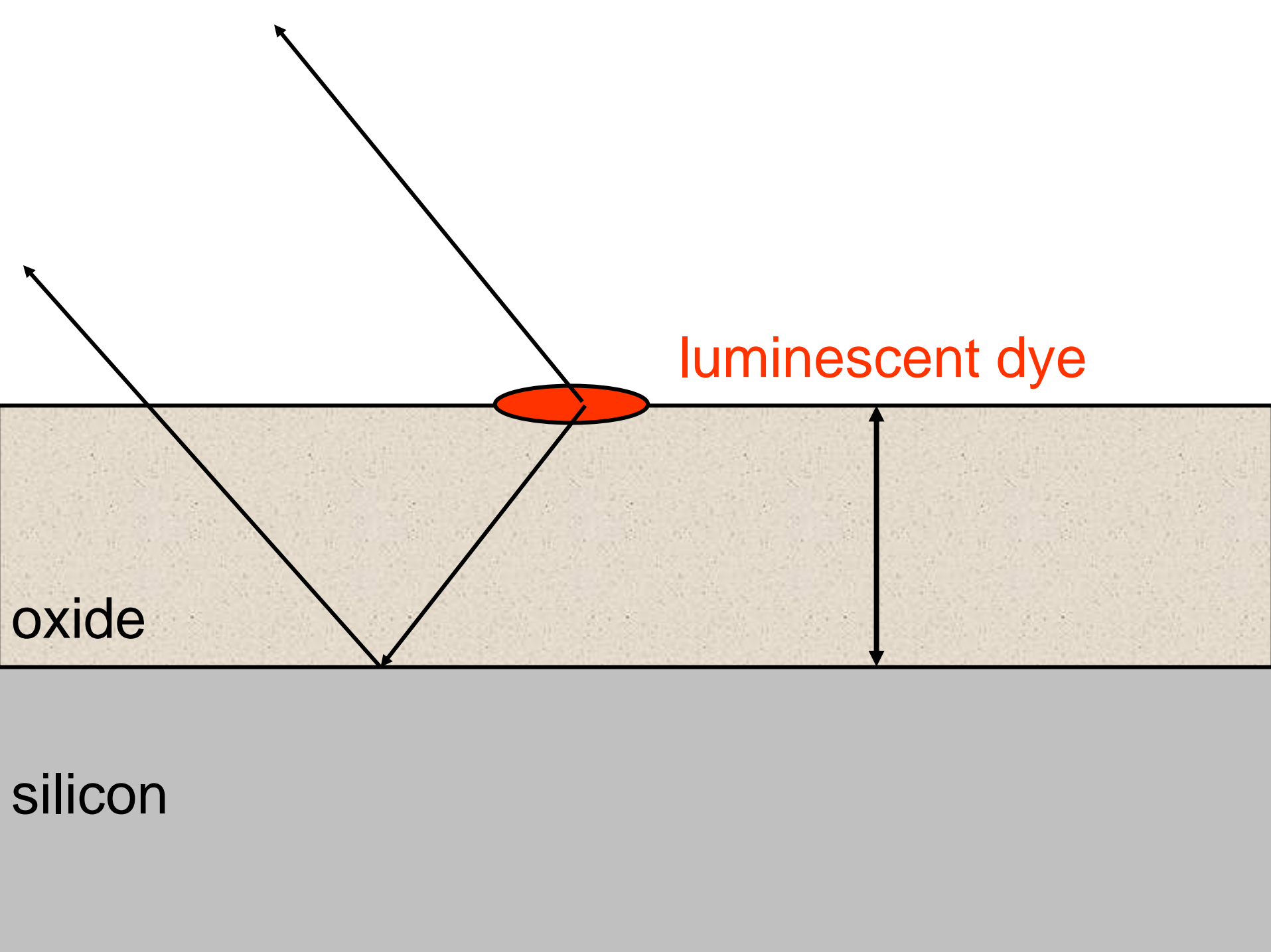
silicon





silicon

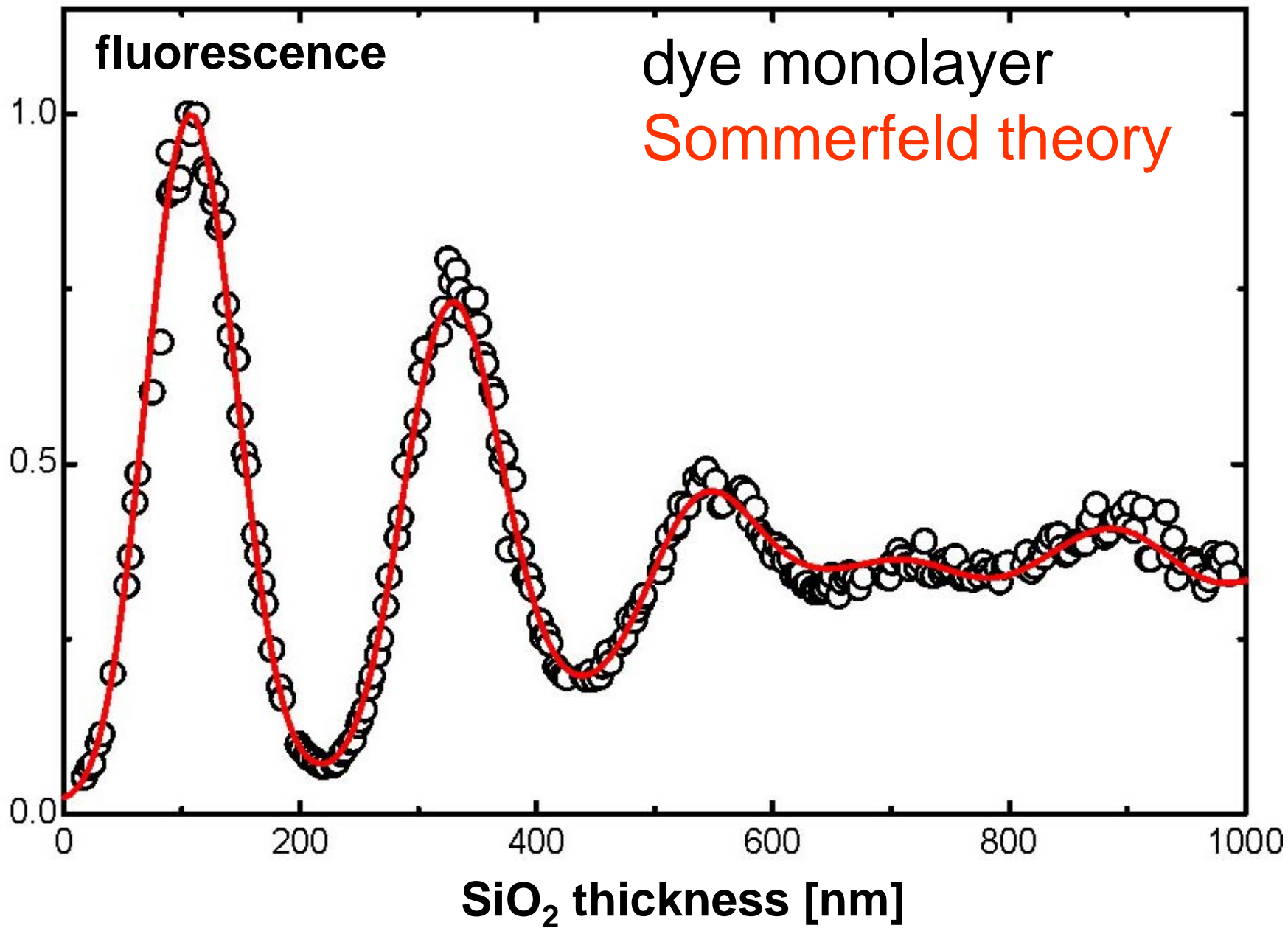
1



luminescent dye

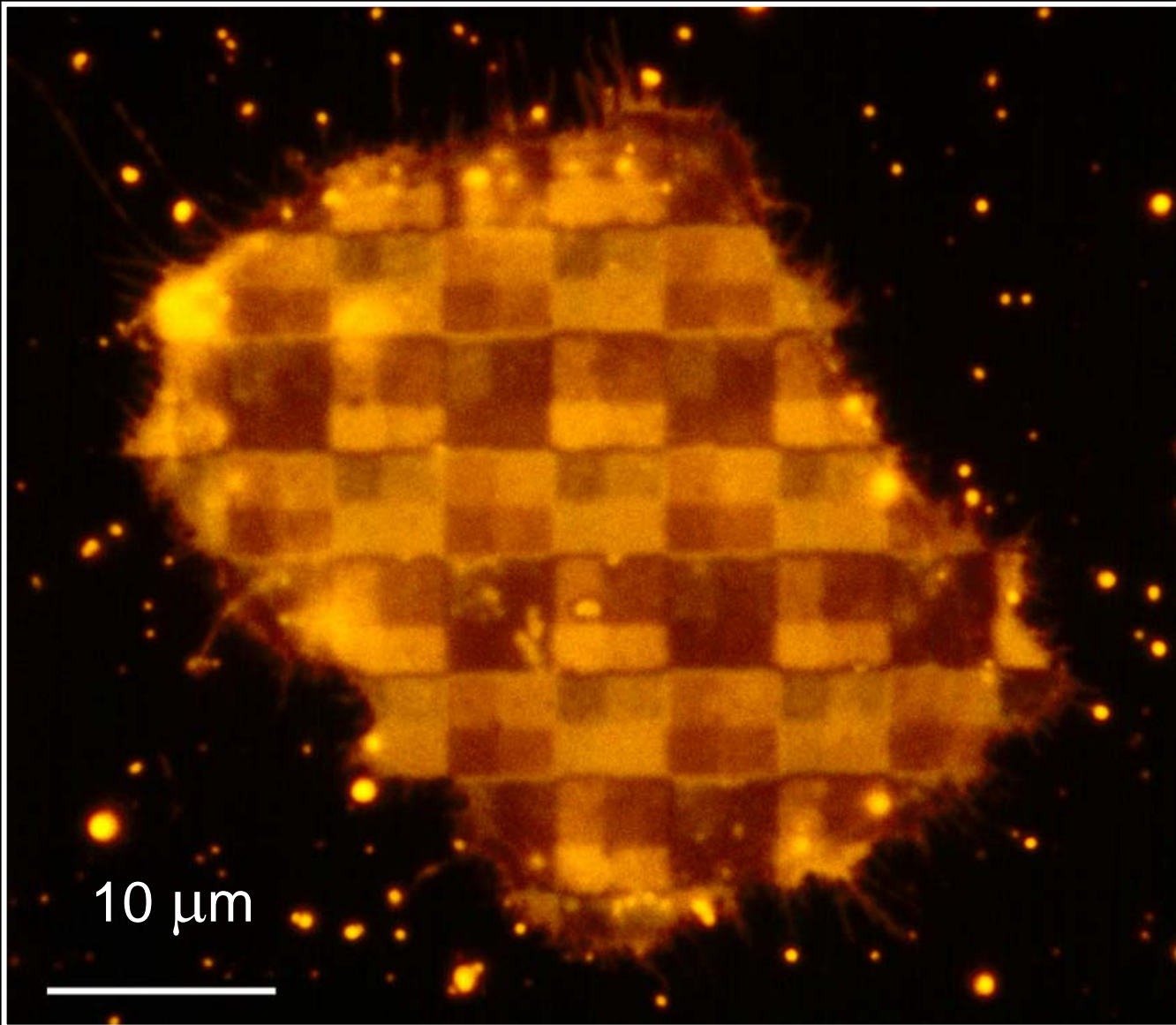
oxide

silicon

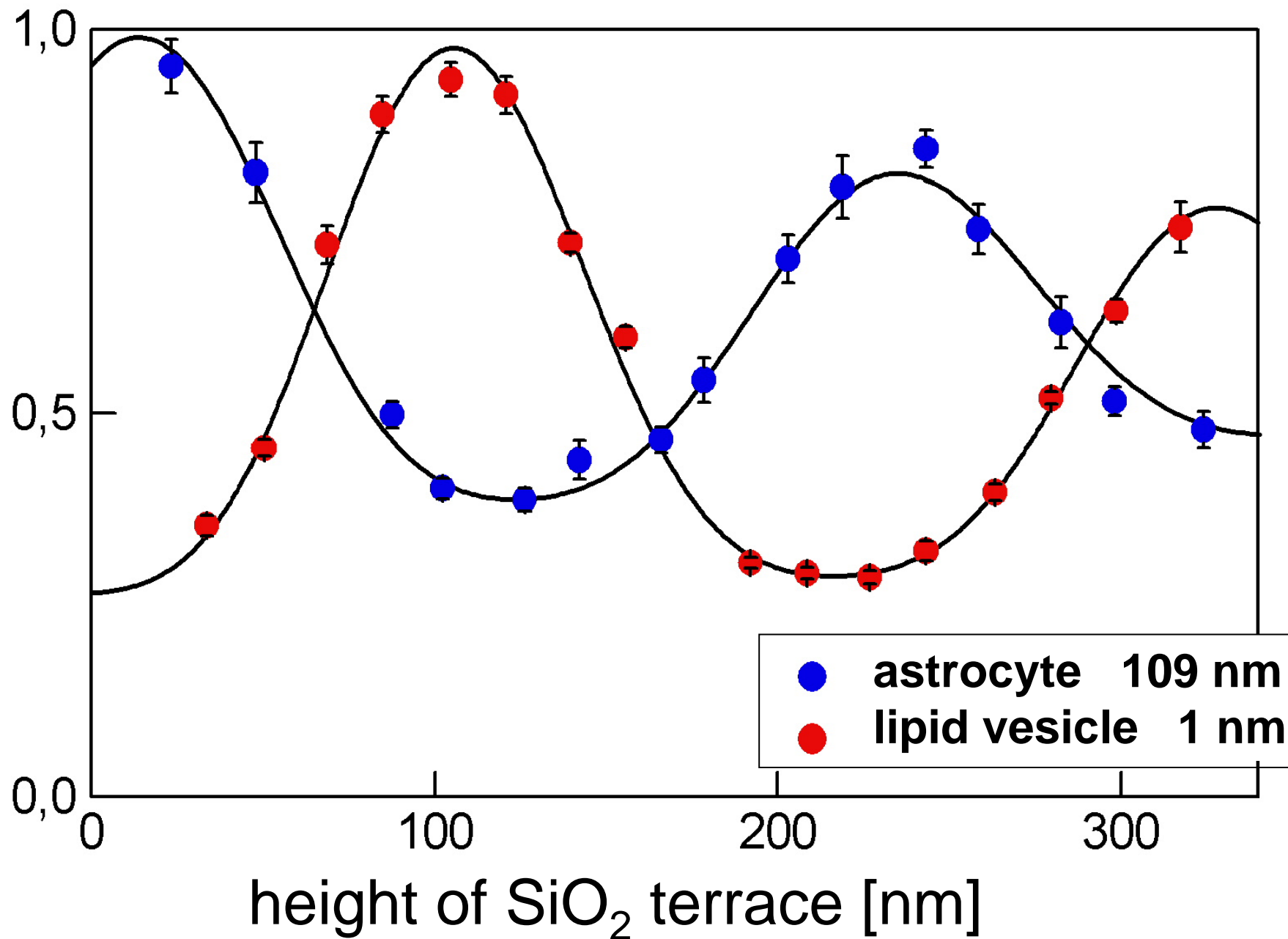


# FLuorescence Interference Microscopy

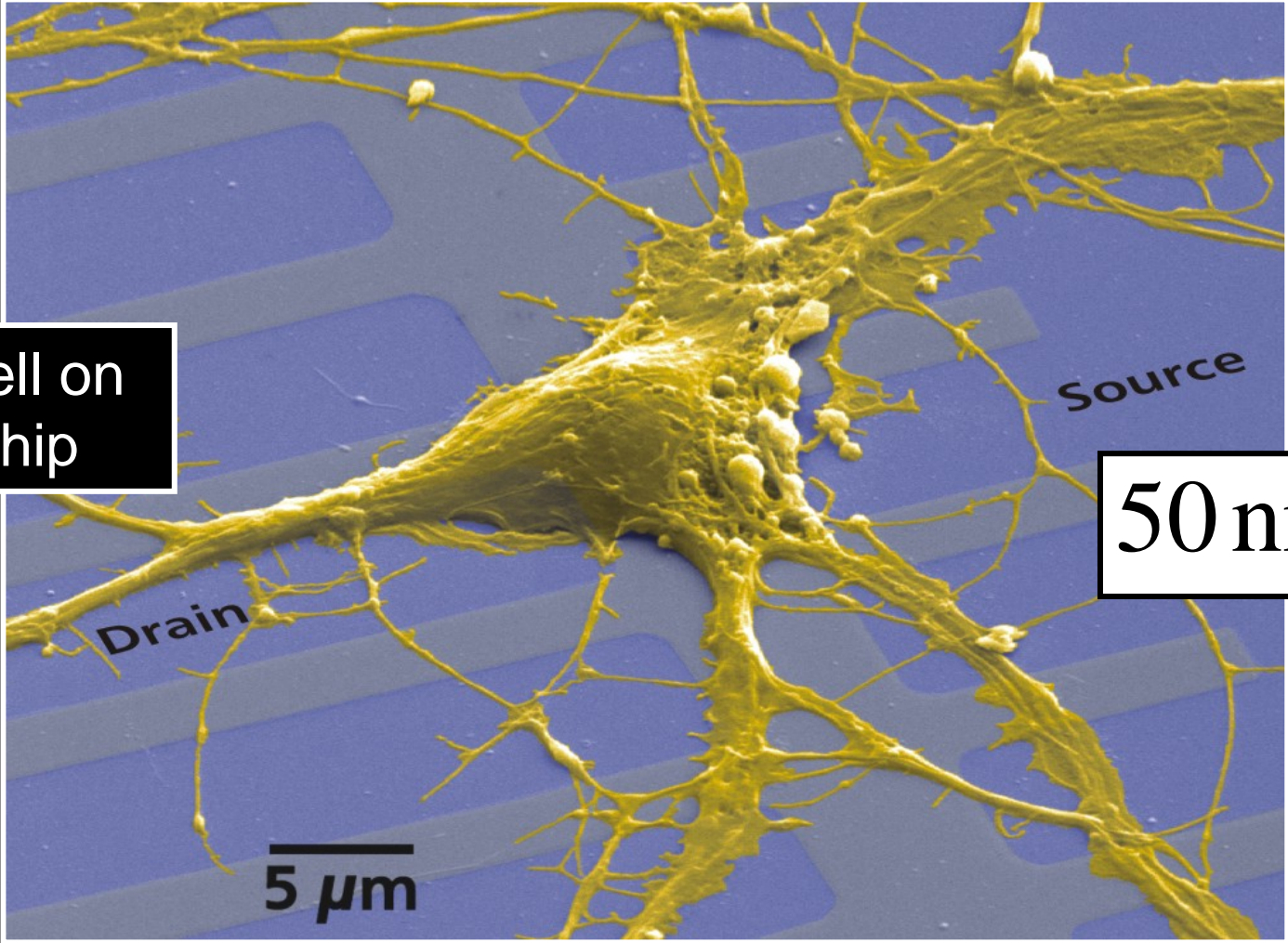
16 periodic  $\text{SiO}_2$  terraces with glia cell on laminin



# fluorescence



nerve cell on  
silicon chip



50 nm

cell

membrane

**resistance**

oxide

silicon

*Nyquist* :

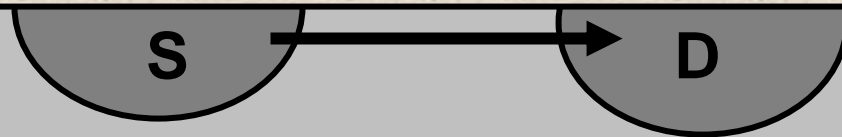
$$S_V = 4k_B T \cdot R$$

cell

membrane

**thermal noise**

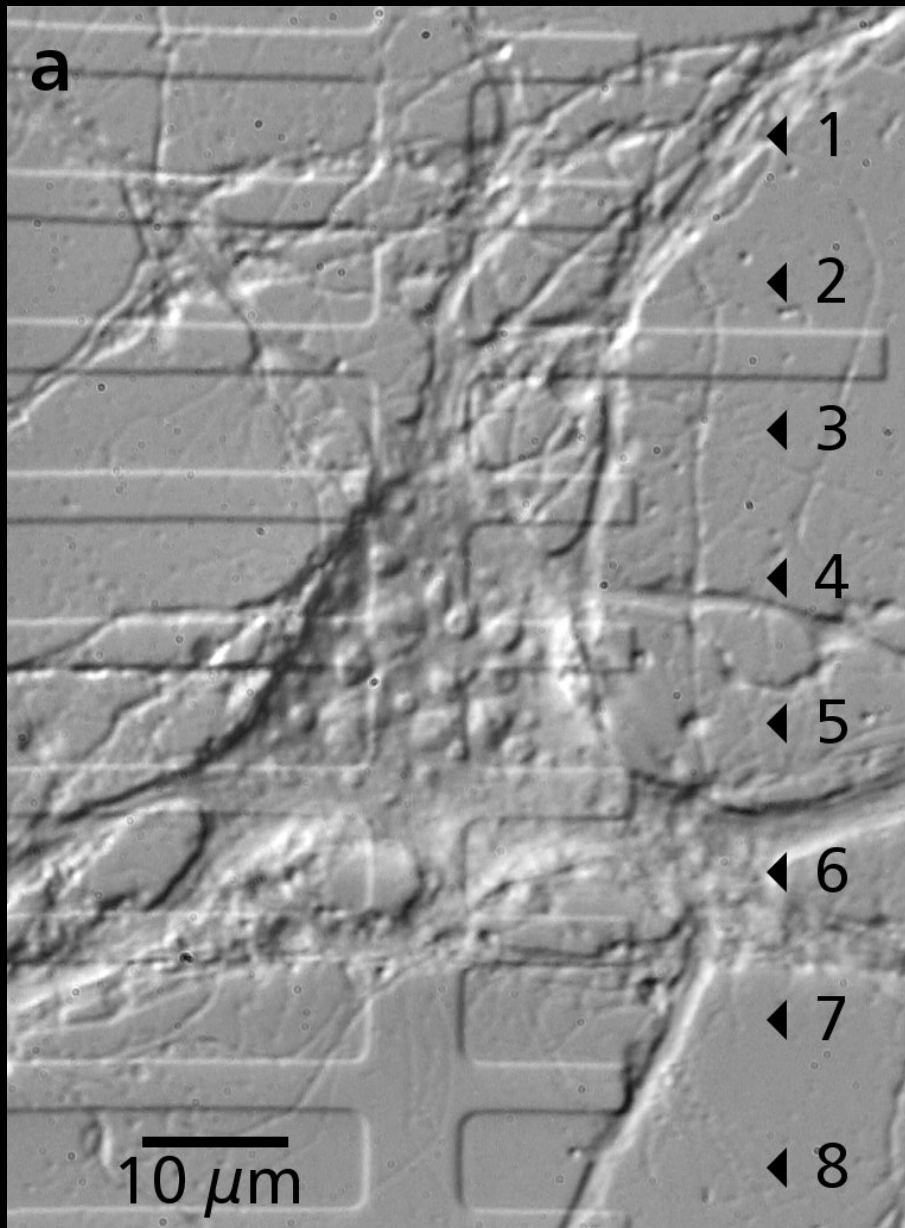
oxide



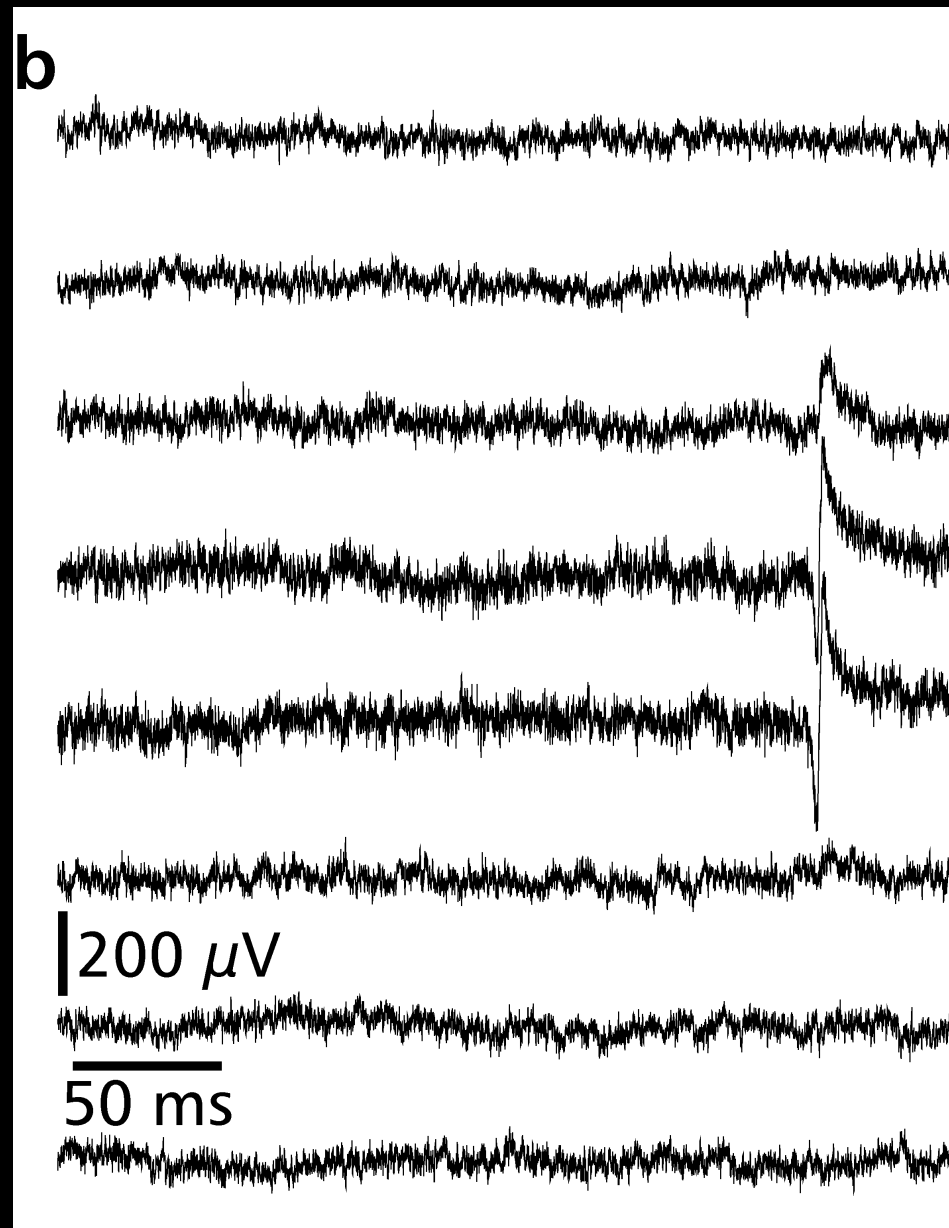
silicon

field-effect transistor

# nerve cell on transistor array

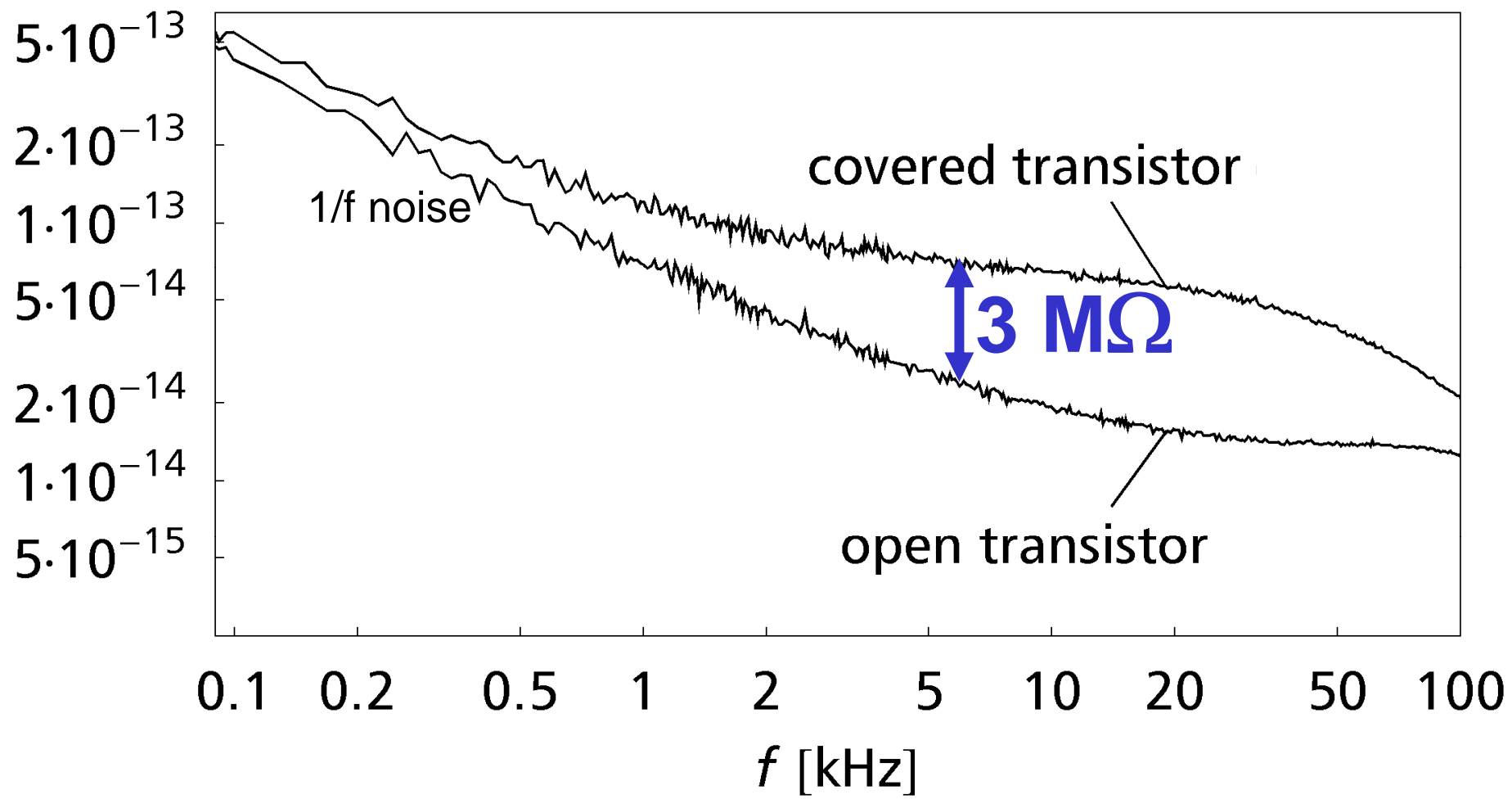


# voltage noise

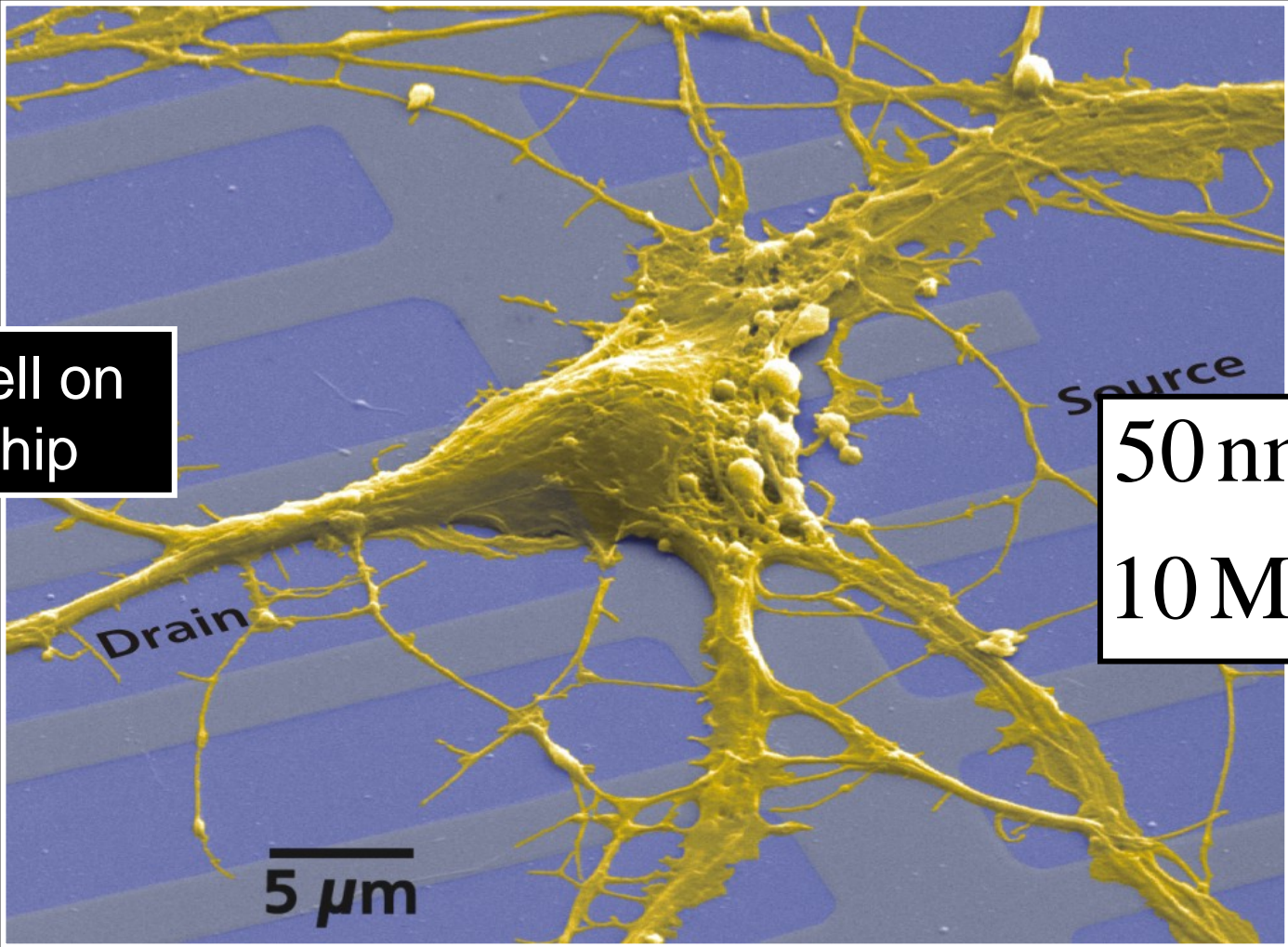


$[V^2/Hz]$

power spectrum of noise



nerve cell on  
silicon chip



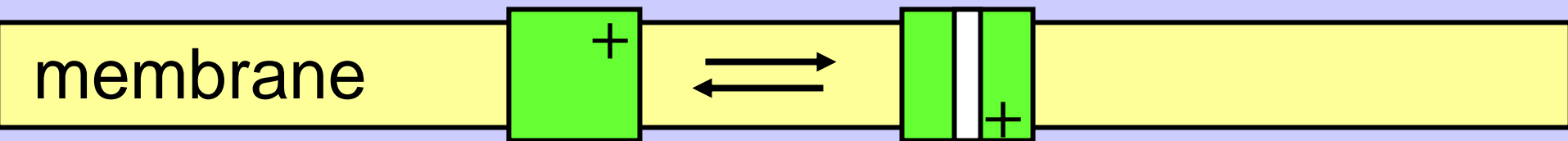
50 nm  
10 MΩ

## 2. Ions & Electrons

cell

ion channel

membrane



oxide



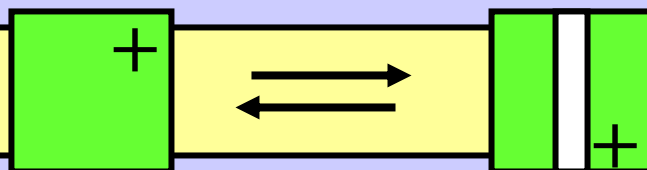
silicon



cell

ion channel

membrane



**50 nm electrolyte block electrostatic interaction.**

oxide



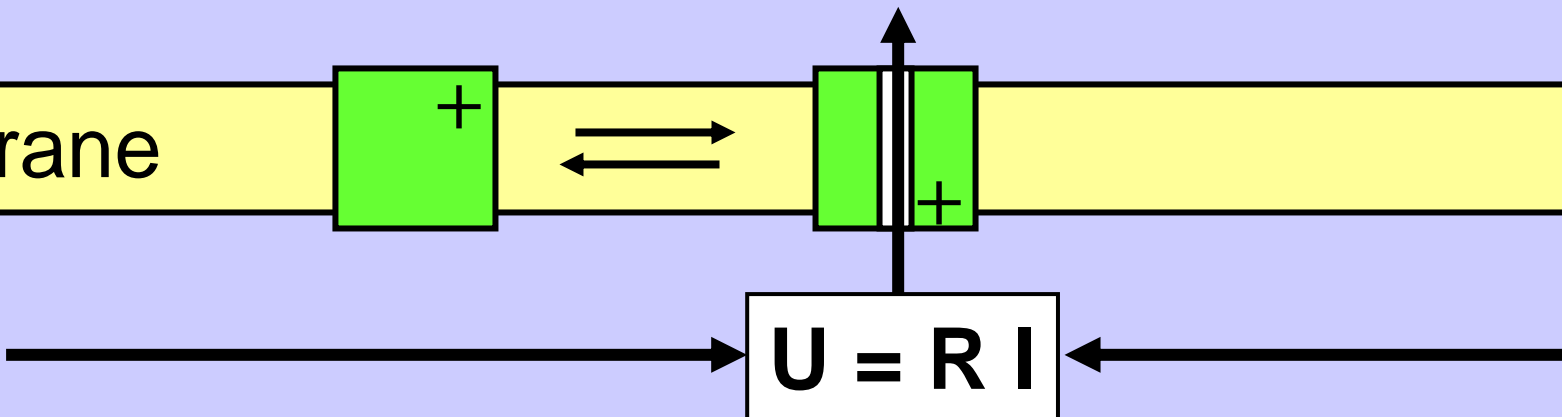
silicon

from ionics  
to electronics

cell

membrane

ion current



oxide



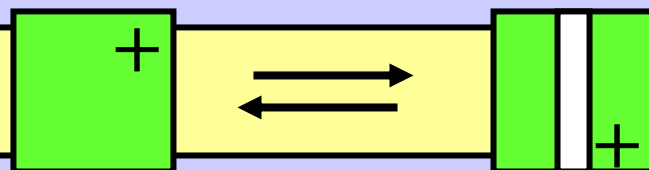
silicon

transistor

from electronics  
to ionics

cell

membrane



$$U = R I$$

oxide

capacitor

silicon

$$\dot{Q} = C \dot{U}$$

voltage ramp

TM electronmicrograph

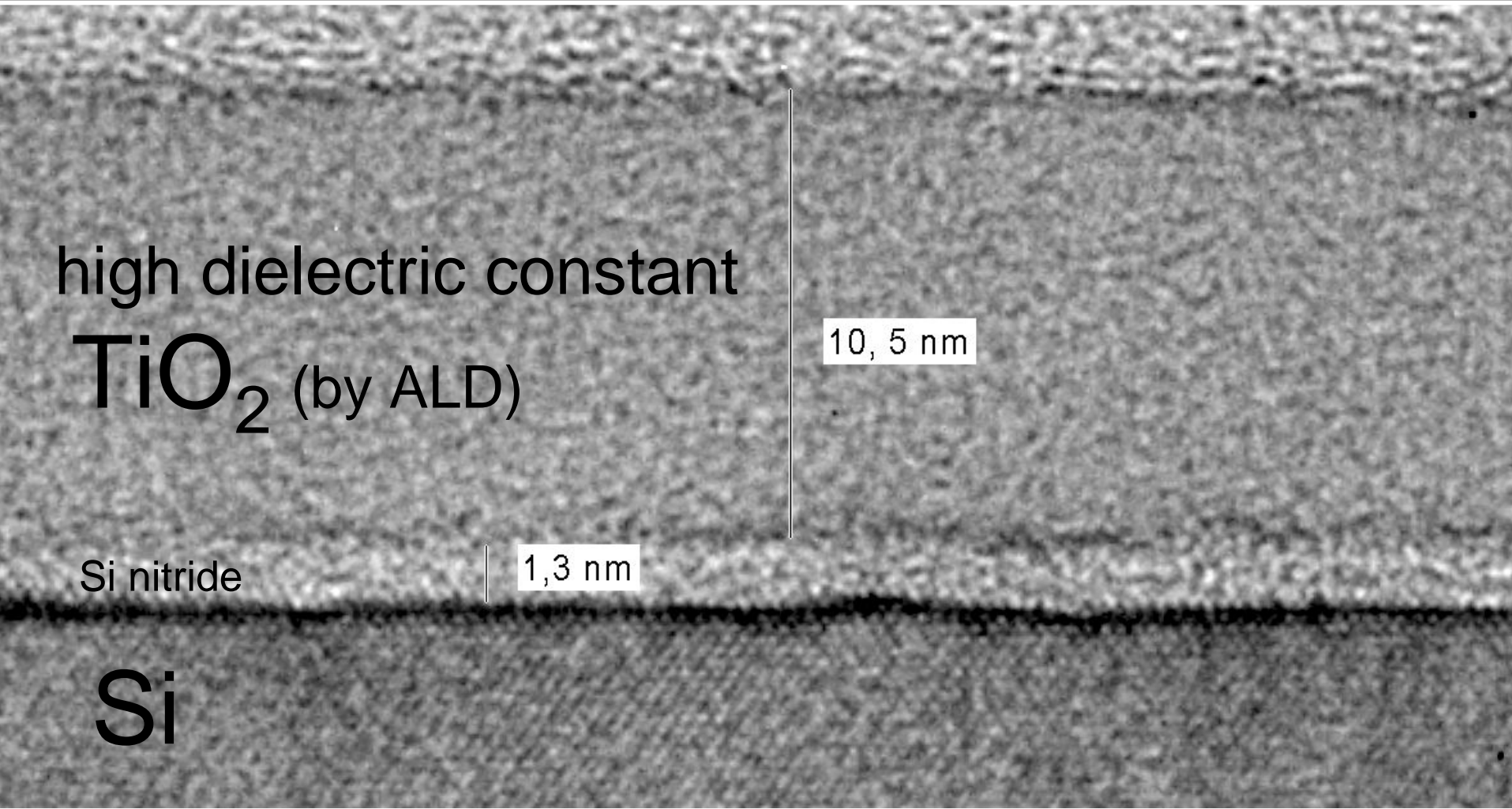
high dielectric constant  
 $\text{TiO}_2$  (by ALD)

10,5 nm

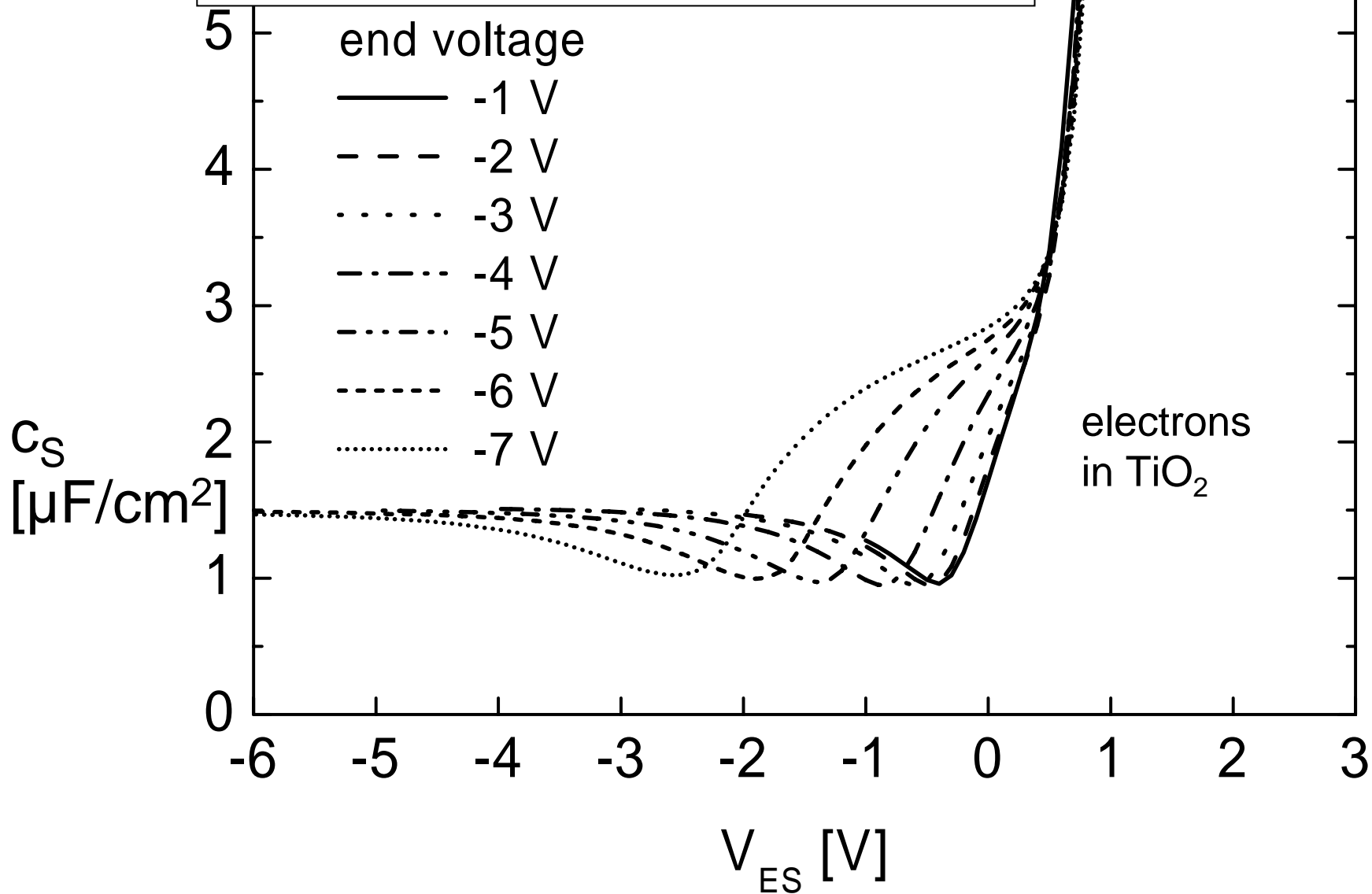
Si nitride

1,3 nm

Si

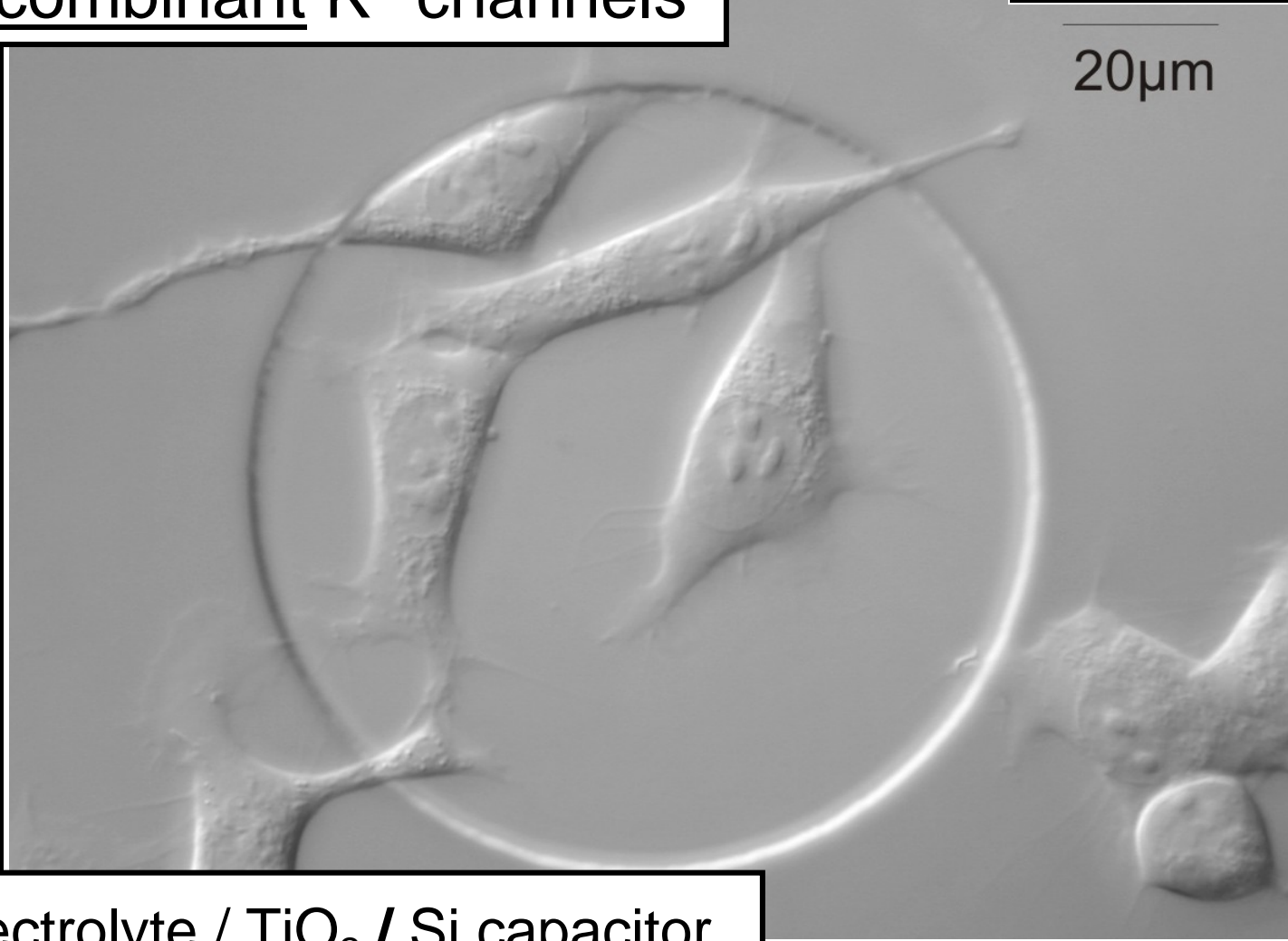


# differential capacitance of electrolyte / $\text{TiO}_2$ / $\text{p}^+$ silicon



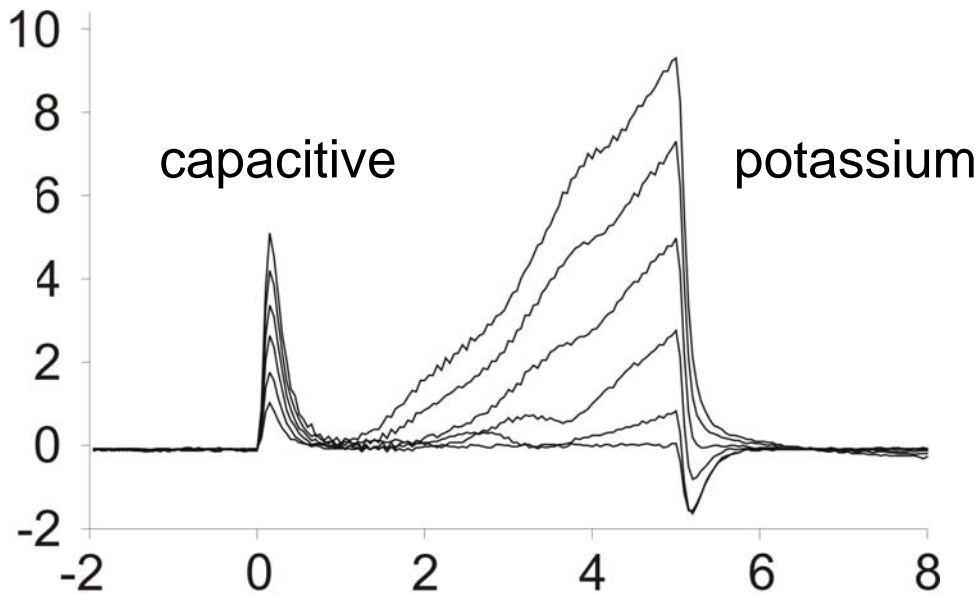
HEK293 cells with  
recombinant K<sup>+</sup> channels

from electronics  
to ionics



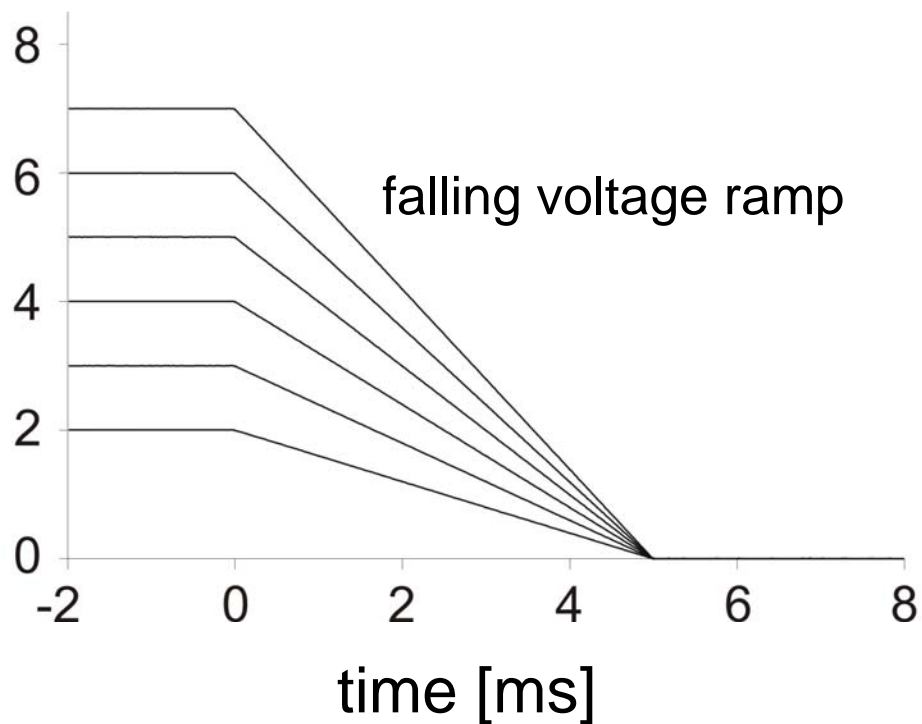
electrolyte / TiO<sub>2</sub> / Si capacitor

membrane current [nA]



**K<sub>v</sub>1.3 channel**

capacitor voltage [V]

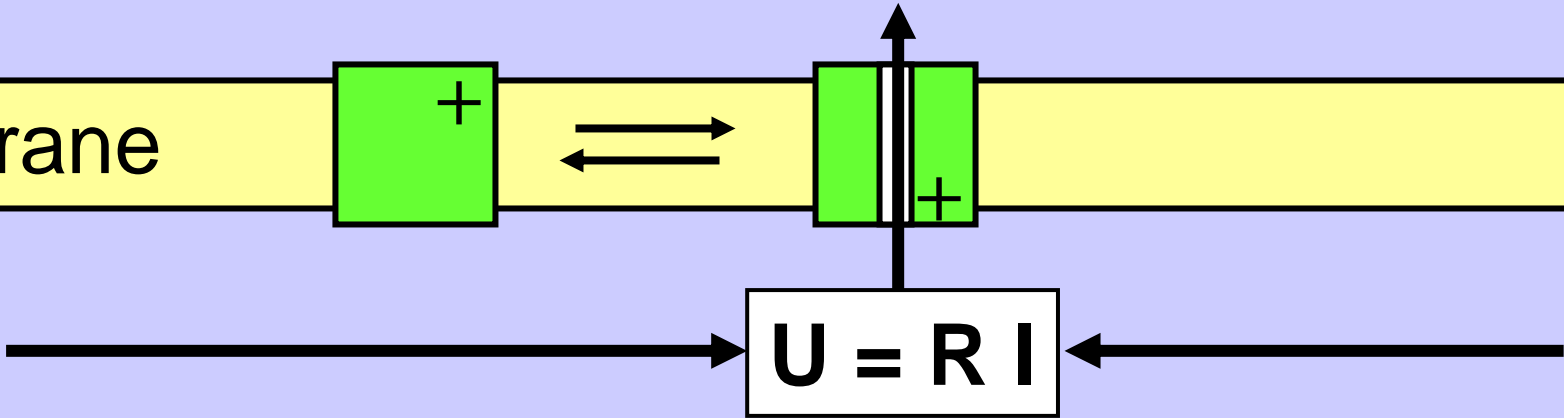


from ionics  
to electronics

cell

ion current

membrane



oxide



silicon

transistor



HEK293 cells with  
recombinant Na<sup>+</sup> channels

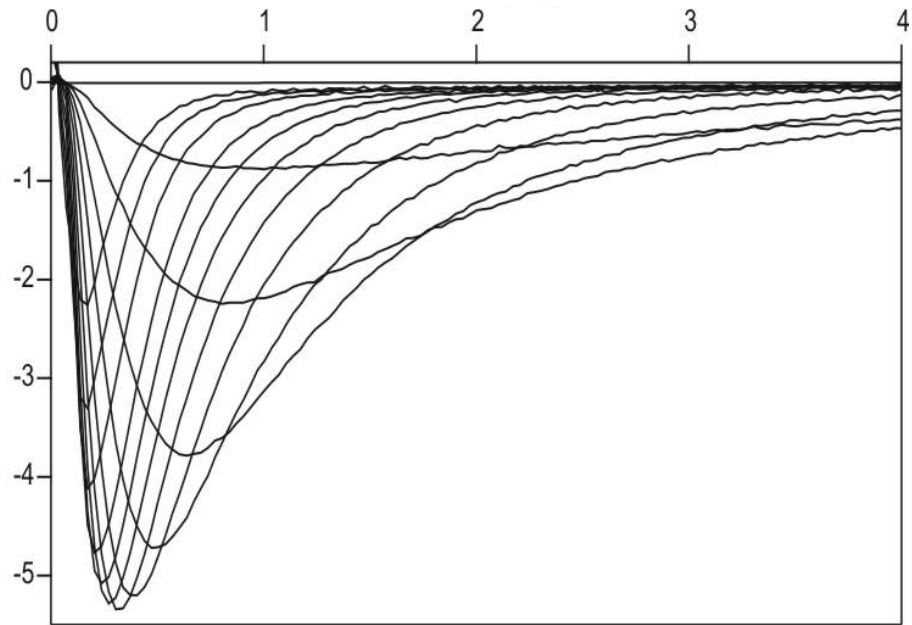
The image shows a grayscale micrograph of HEK293 cells cultured on a silicon transistor device. The device structure is visible as a series of parallel, raised lines forming a channel. A small white rectangular box highlights a specific cell within the channel. The cells are spread across the surface, with some showing distinct morphology. A scale bar in the bottom right corner indicates 20 micrometers.

from ionics  
to electronics

electrolyte/oxide silicon transistor

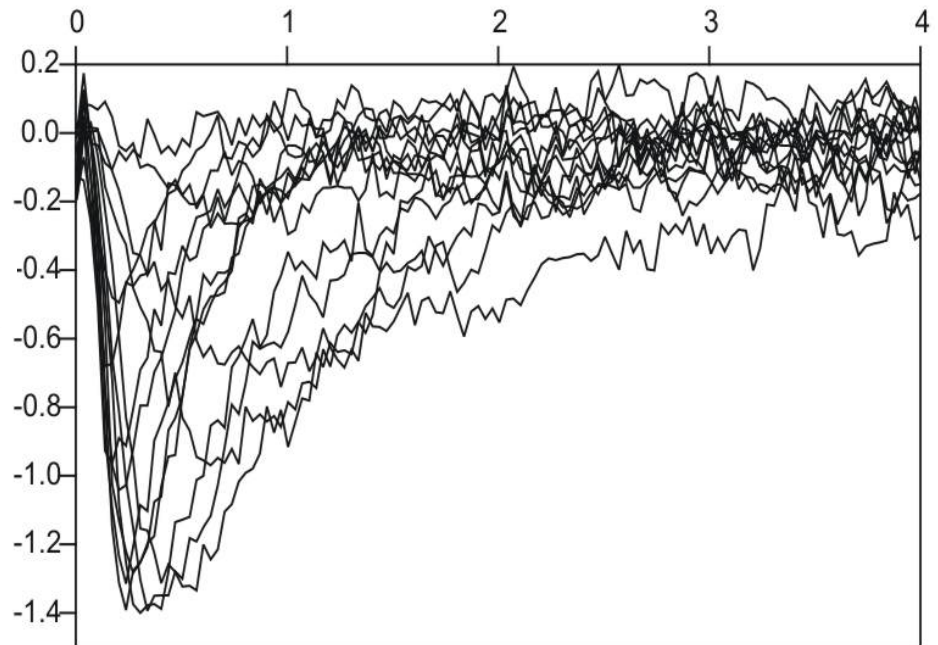
20  $\mu\text{m}$

time [ms]



membrane  
current [nA]

**Na<sub>v</sub>1.4 channel**

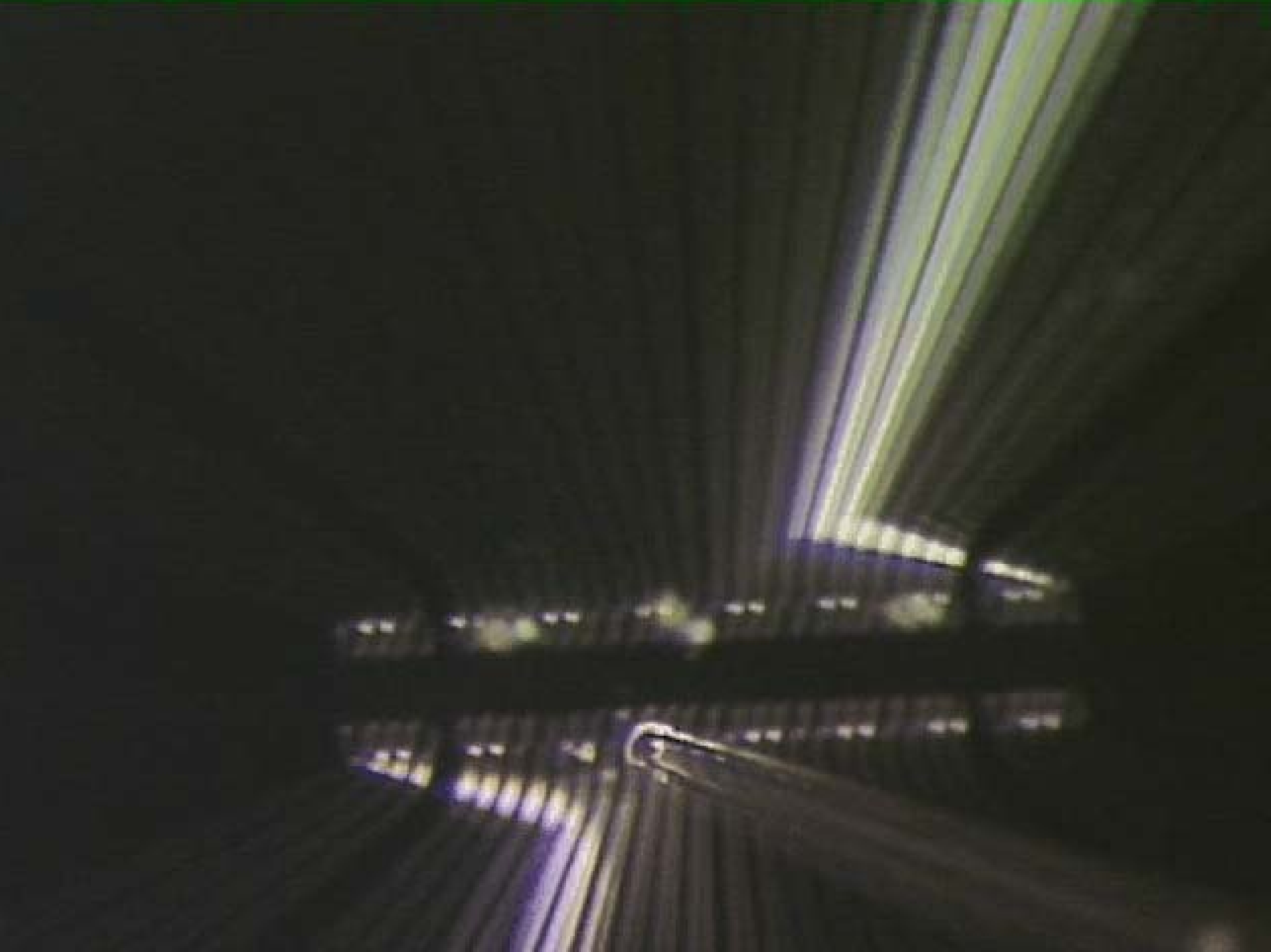


gate voltage [mV]

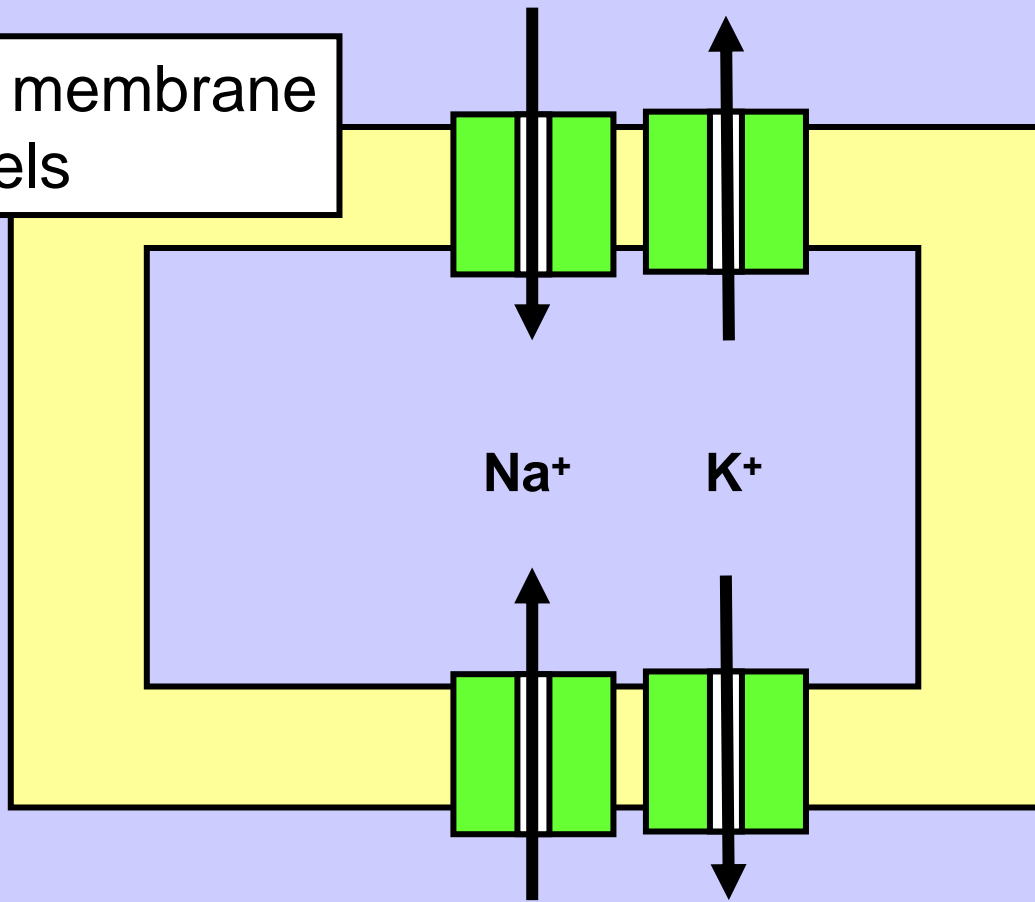
# 3. Nerve Cells on Silicon

brain of pond snail





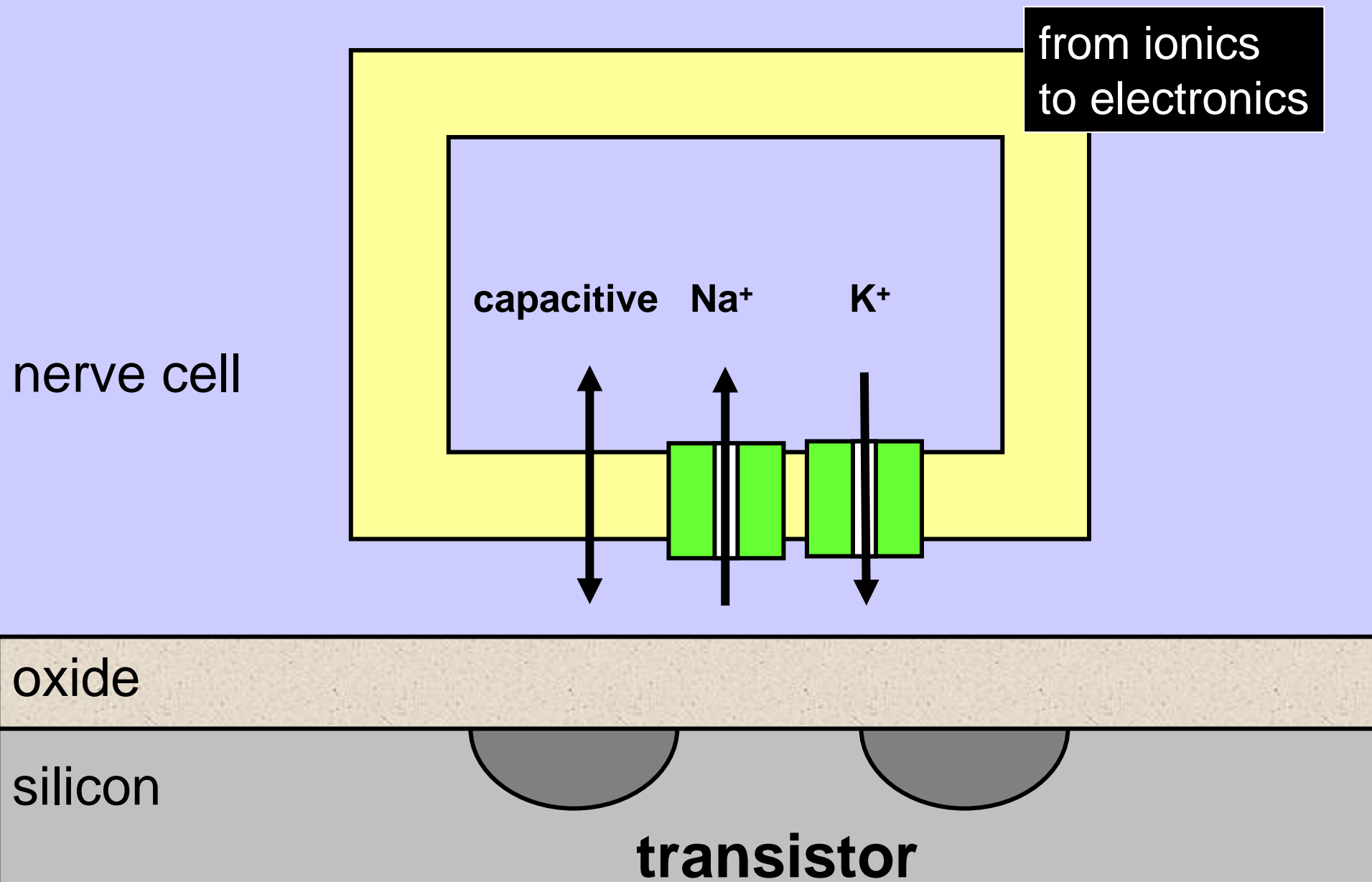
- attached/free membrane
- Na / K channels



nerve cell

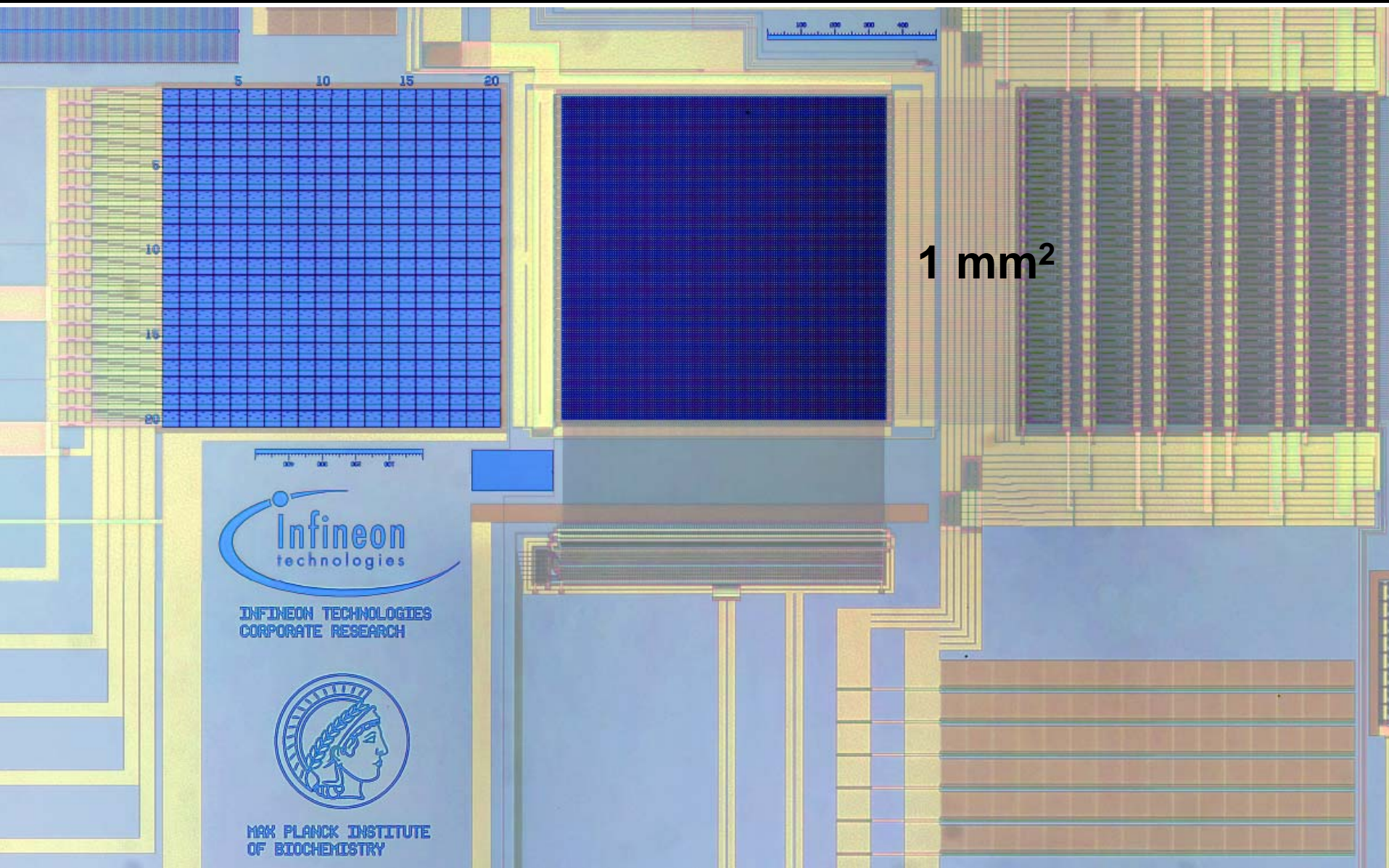
oxide

silicon



400 capacitors

16384 transistors



Electrolyte

Oxide

**TiO<sub>2</sub>/ZrO<sub>2</sub>**

Pt

metal layer

1 μm

**reset circuit**

metal layer

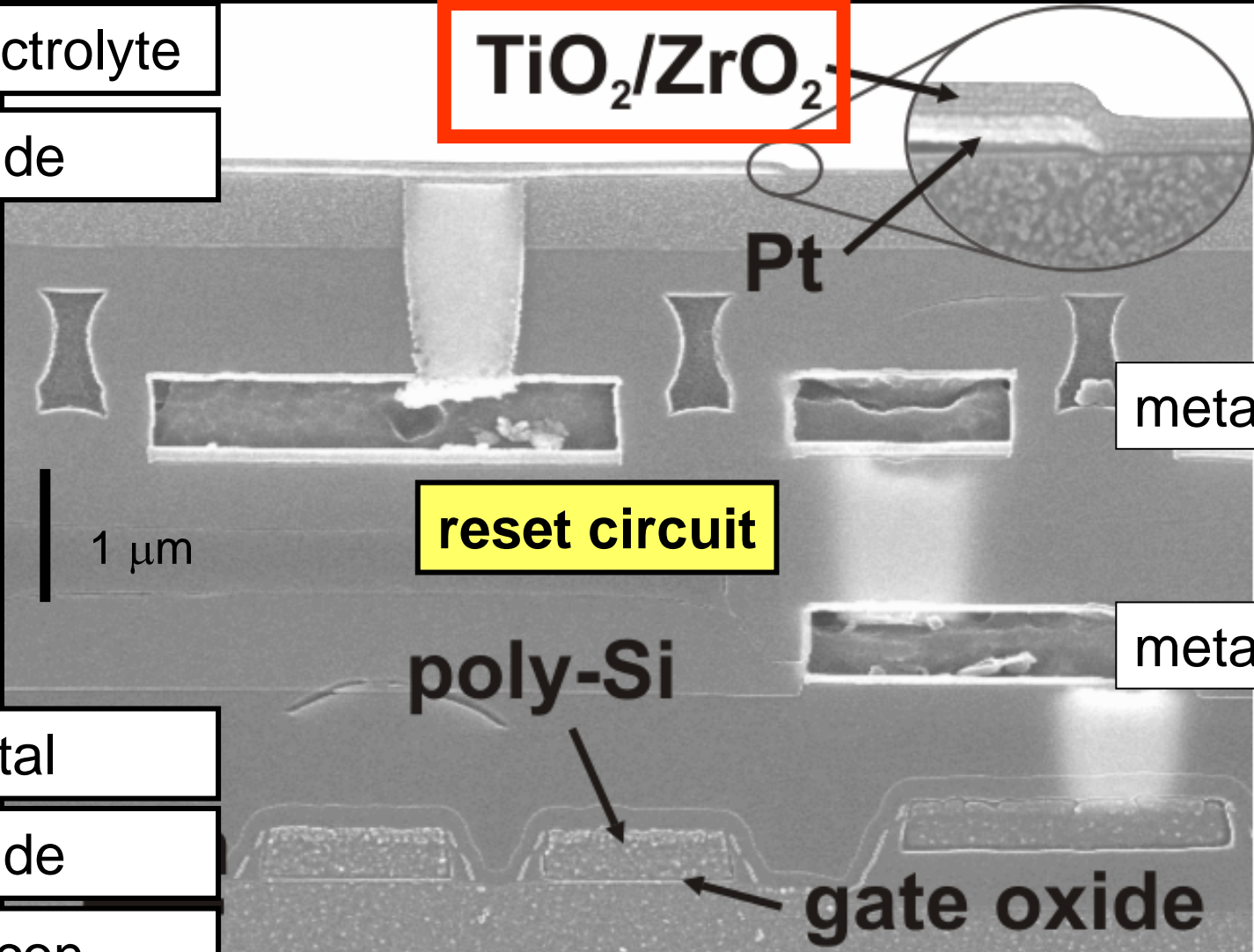
Metal

Oxide

Silicon

poly-Si

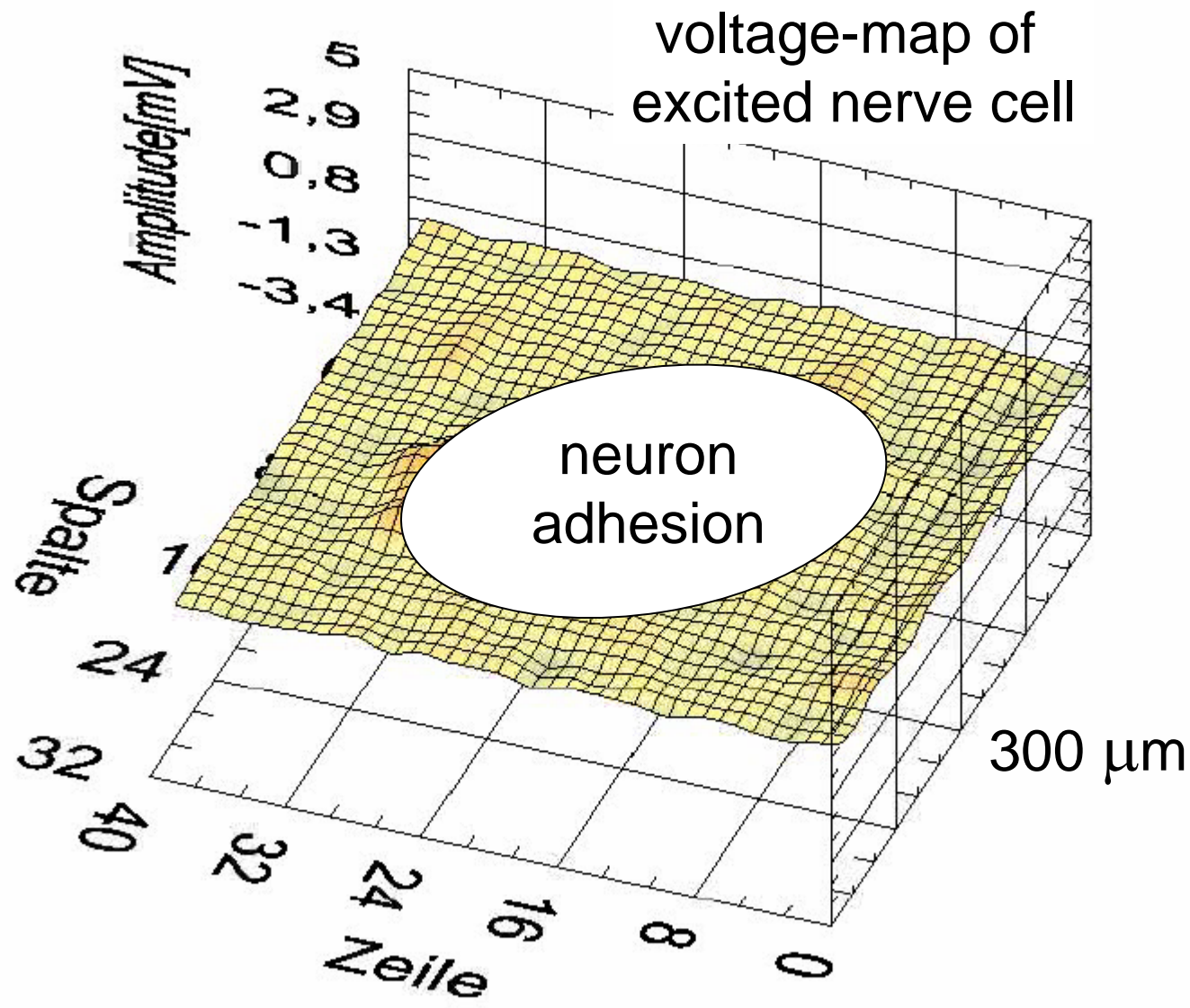
gate oxide

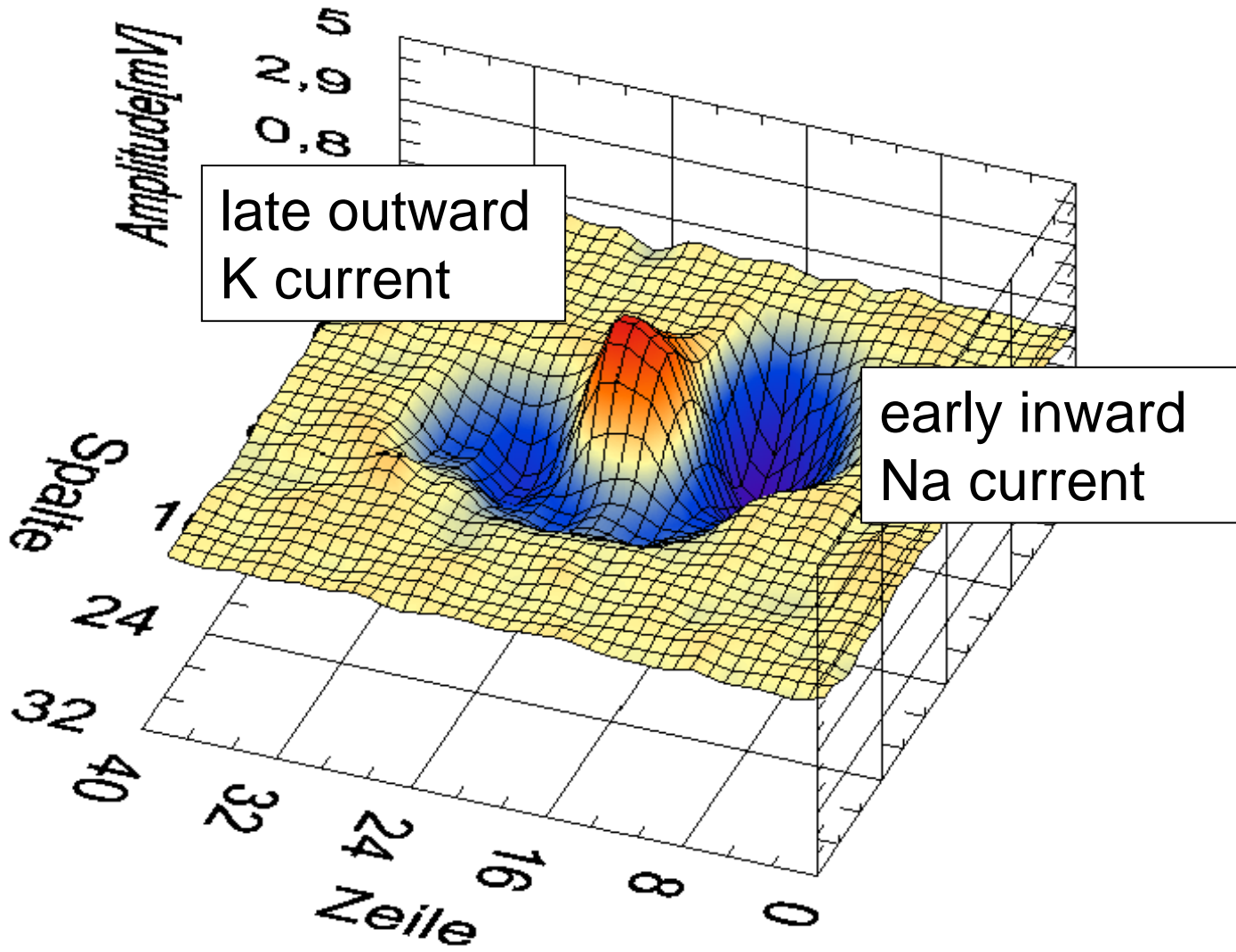


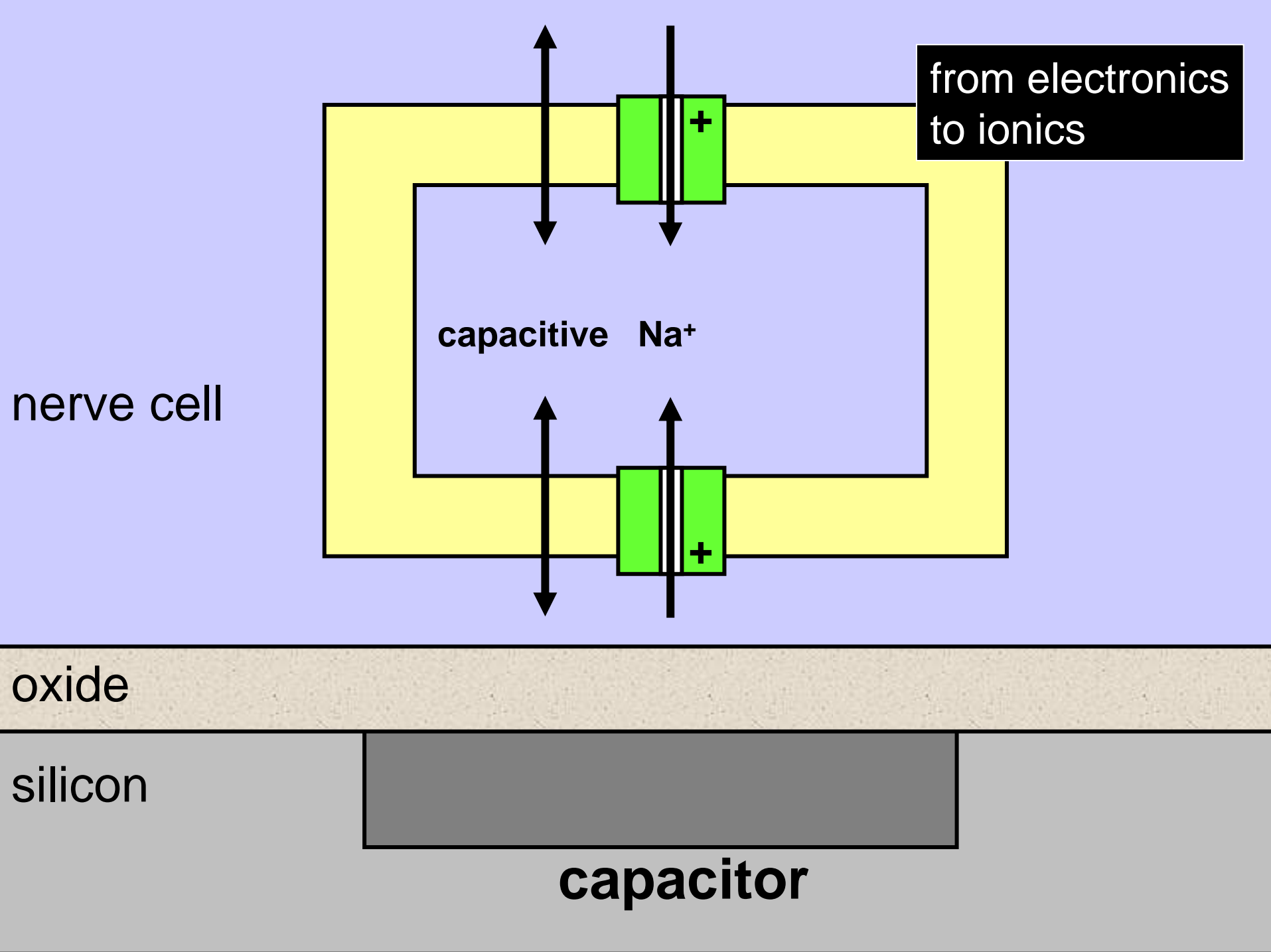
nerve cells from pond snail on  
transistor array (TiO<sub>2</sub> surface)

100μm

A scanning electron micrograph (SEM) showing several large, rounded, orange-colored nerve cells from a pond snail. The cells are situated on a blue, textured surface that is a transistor array made of TiO2. The cells have a bulbous, spherical appearance with some smaller protrusions and fine filaments extending from them. The background is a uniform blue color with a fine, grid-like texture. A scale bar in the bottom left corner indicates a length of 100 micrometers.

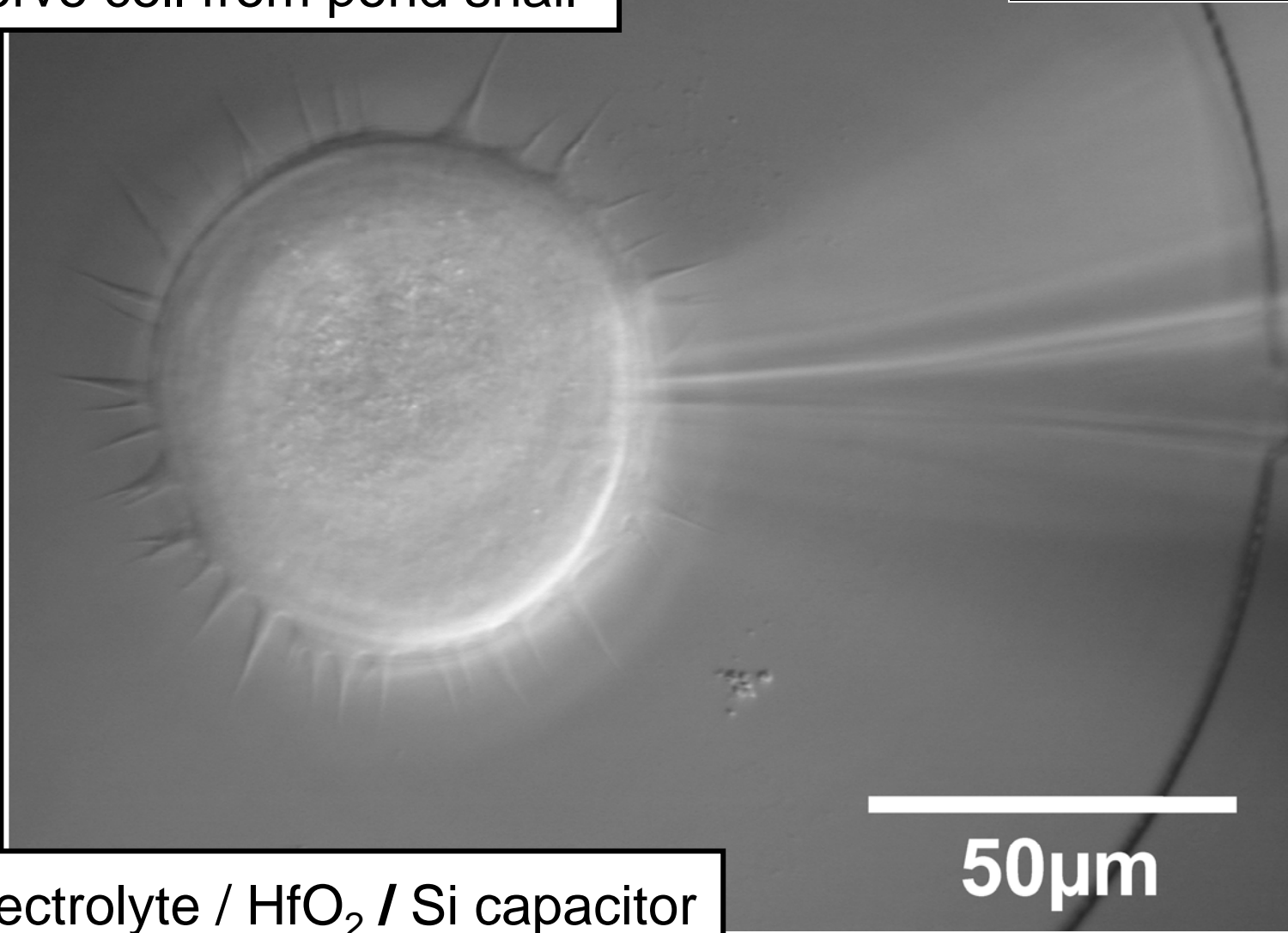






from electronics  
to ionics

nerve cell from pond snail

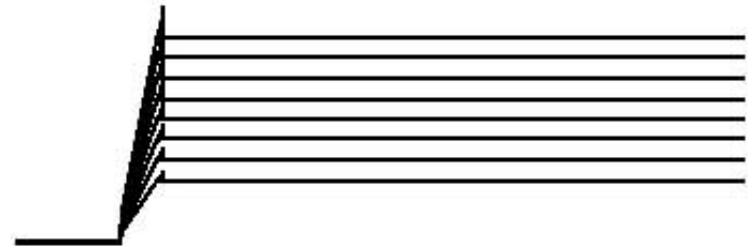
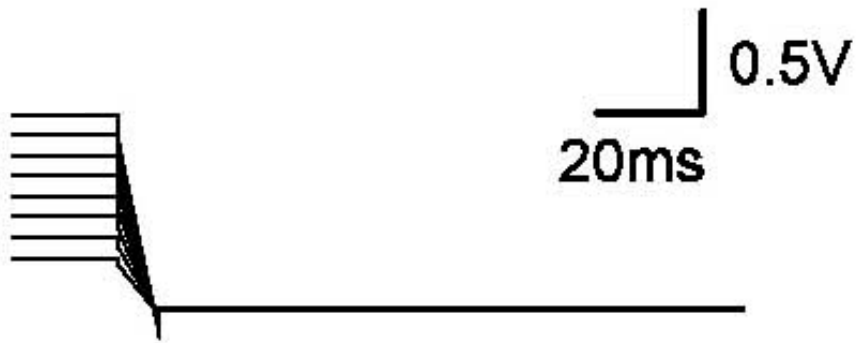


50 $\mu$ m

electrolyte / HfO<sub>2</sub> / Si capacitor

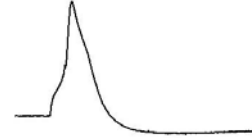
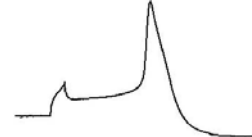
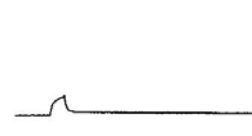
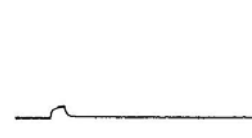
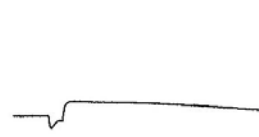
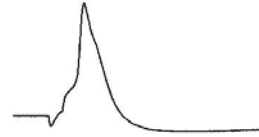
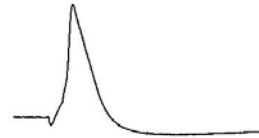
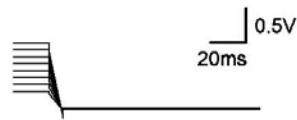
falling  
voltage ramp

rising  
voltage ramp



# falling voltage ramp

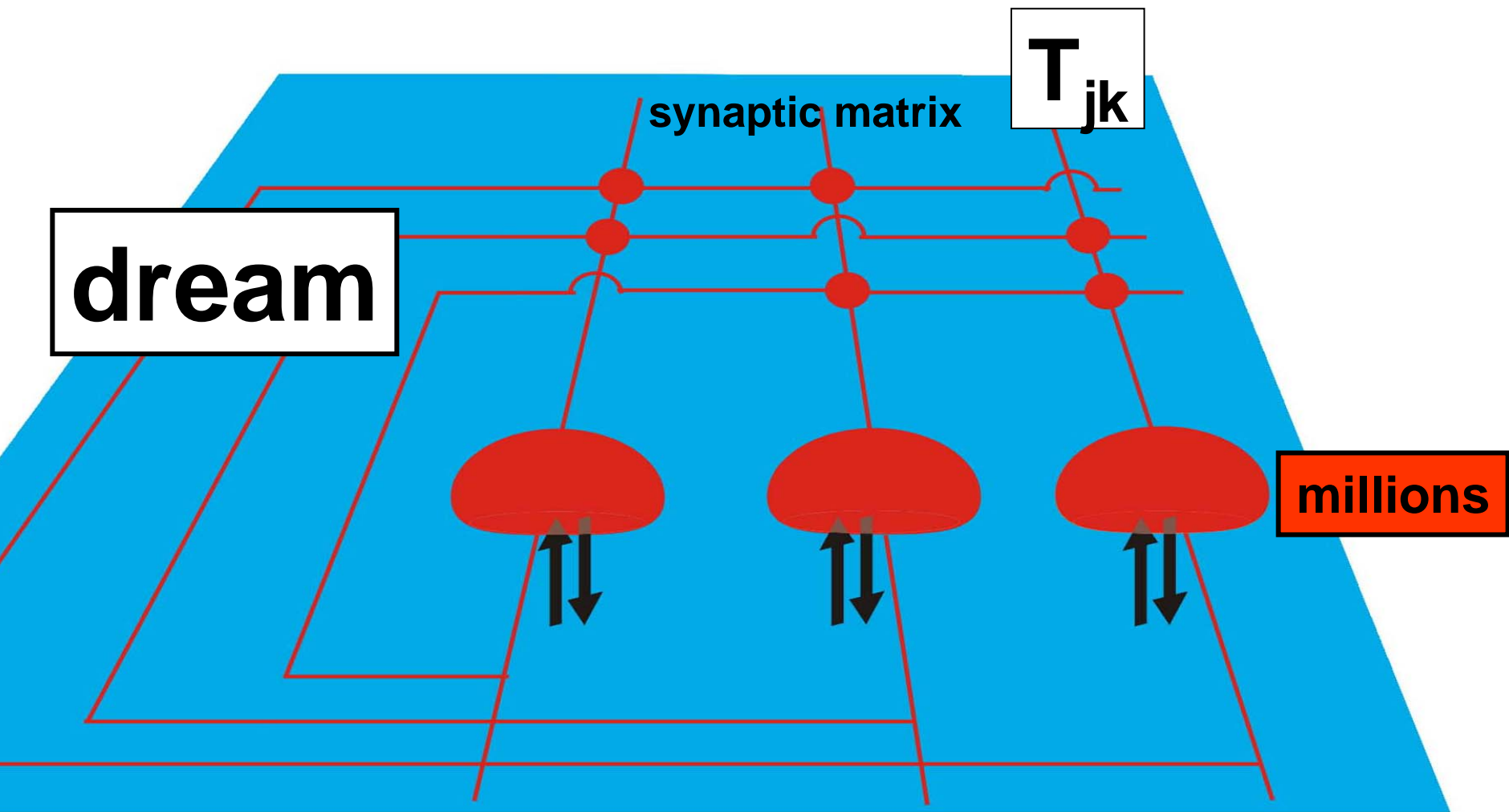
Stimulus opens  
Na channels in  
lower membrane.



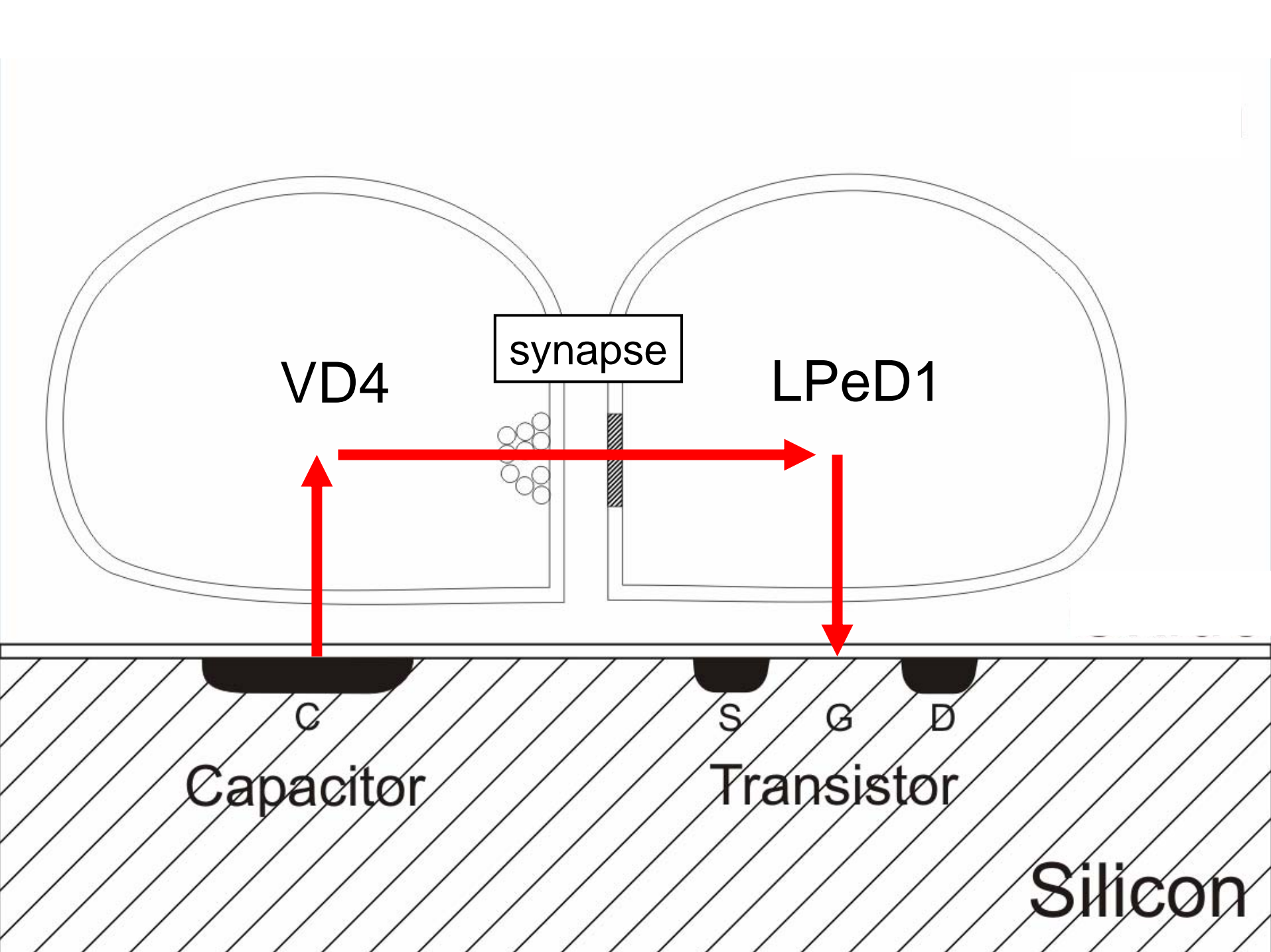
# rising voltage ramp

Stimulus opens  
Na channels in  
upper membrane.

# 4. Neuronal Networks on Chip



associative memory  
integrated with semiconductor chip



synapse on silicon

synapse

LPeD1

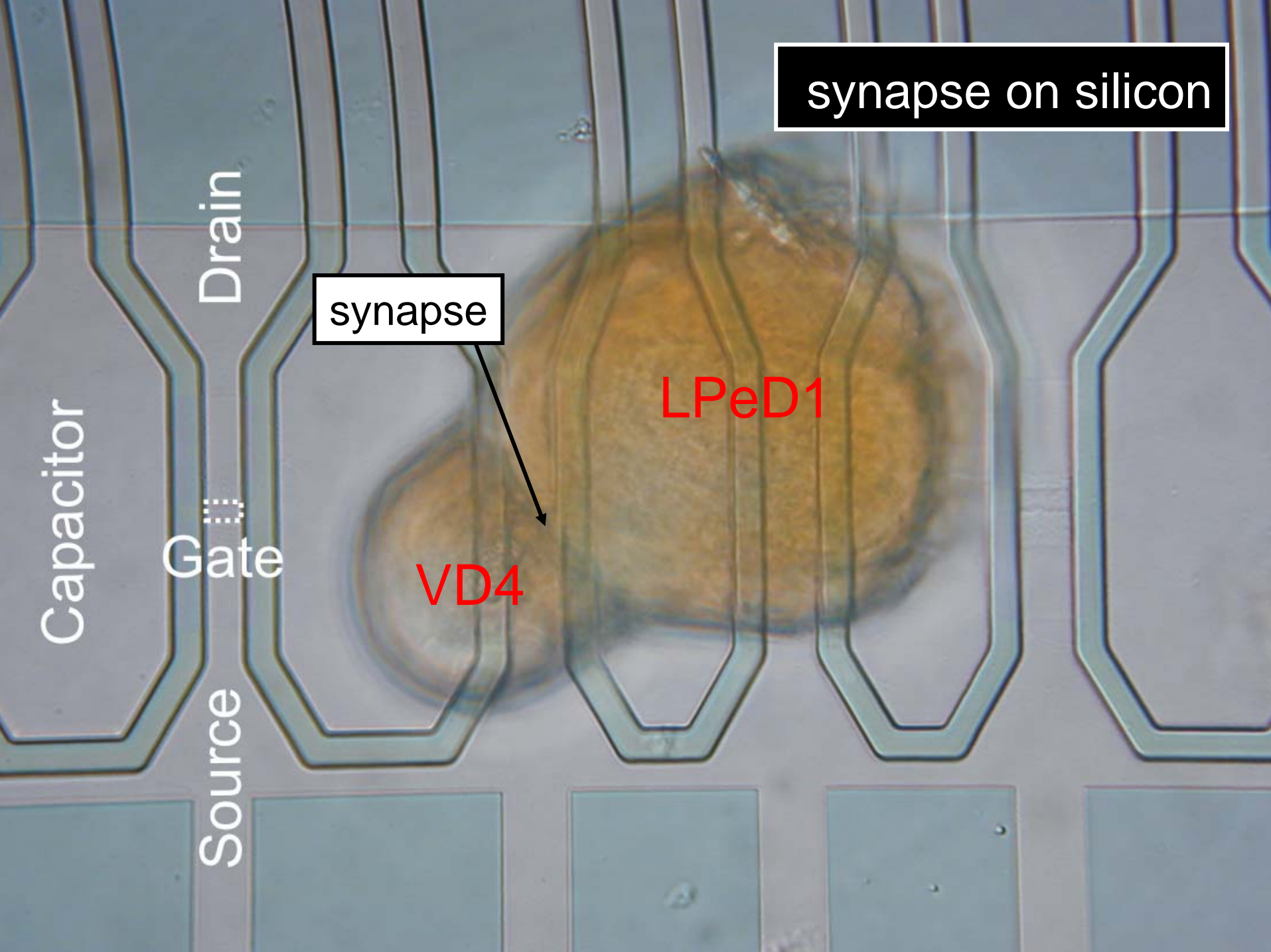
VD4

Capacitor

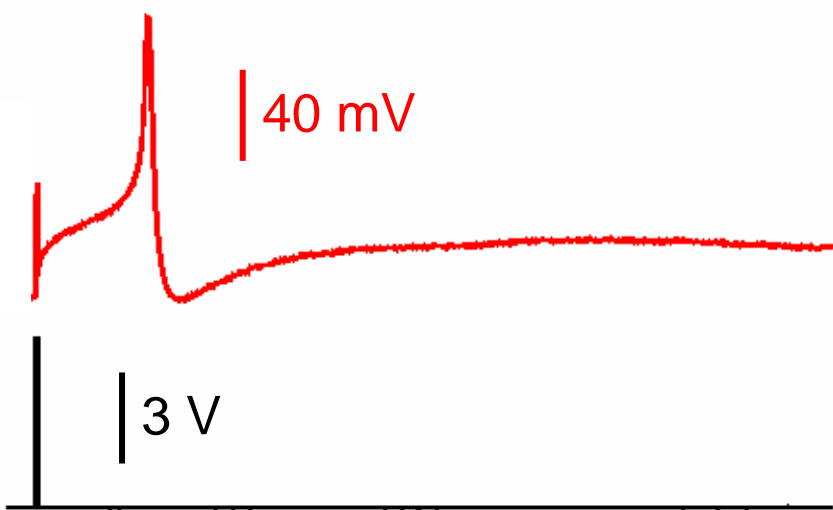
Drain

Gate

Source



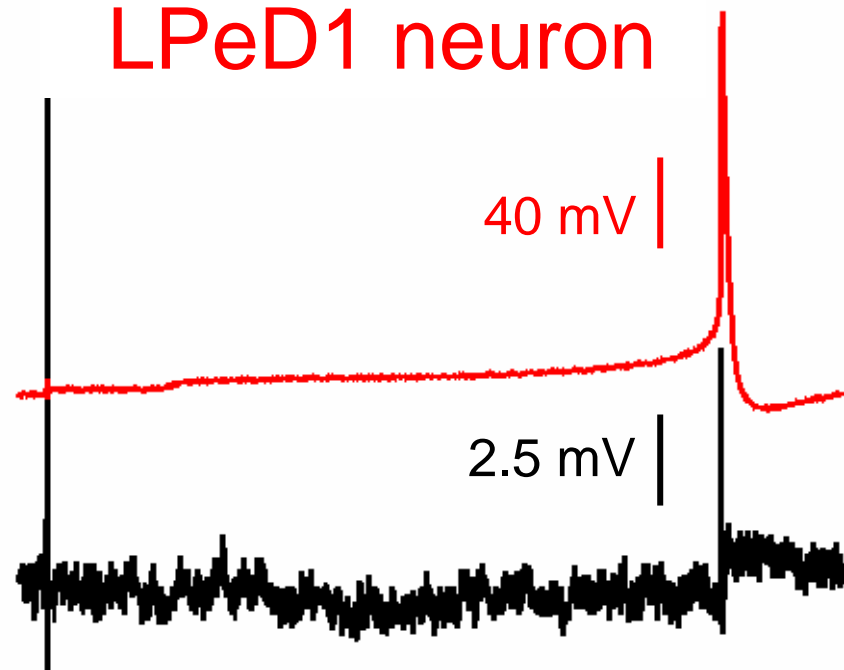
# VD4 neuron



capacitor

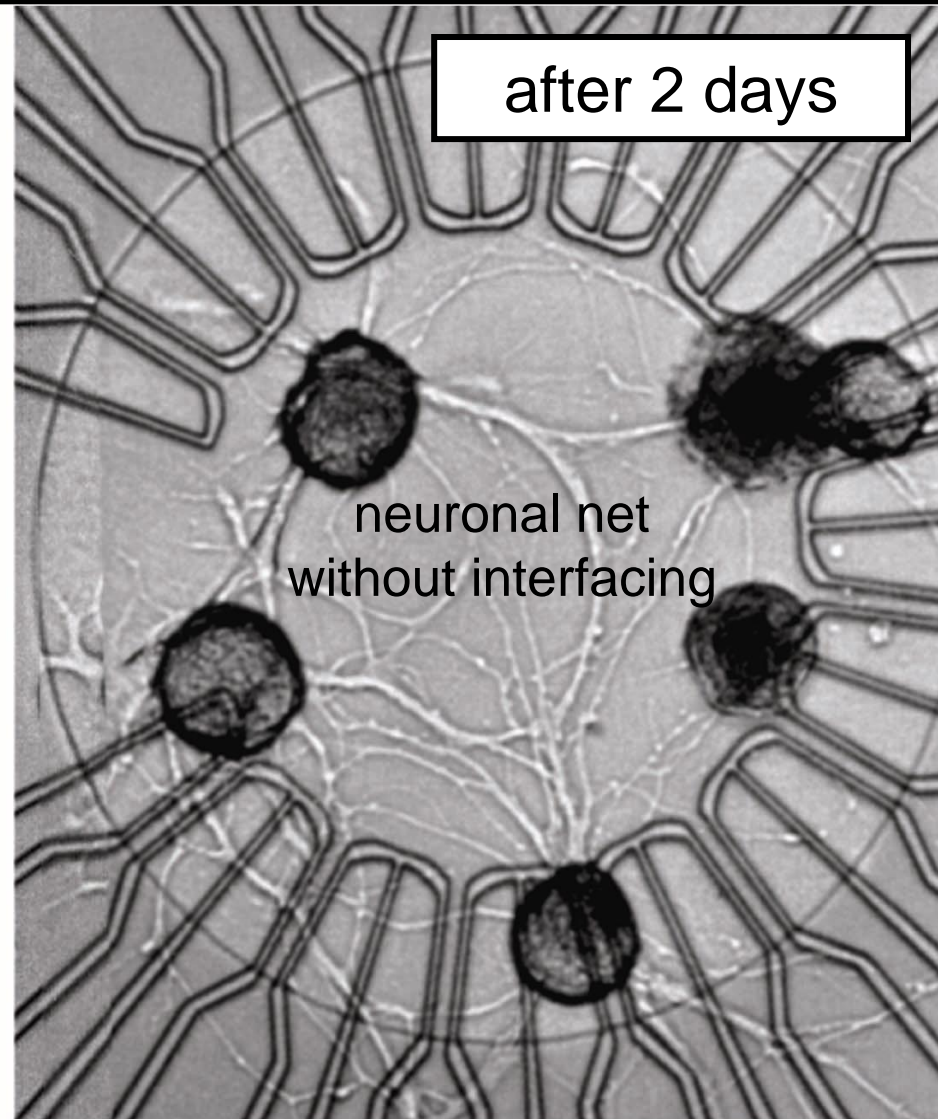
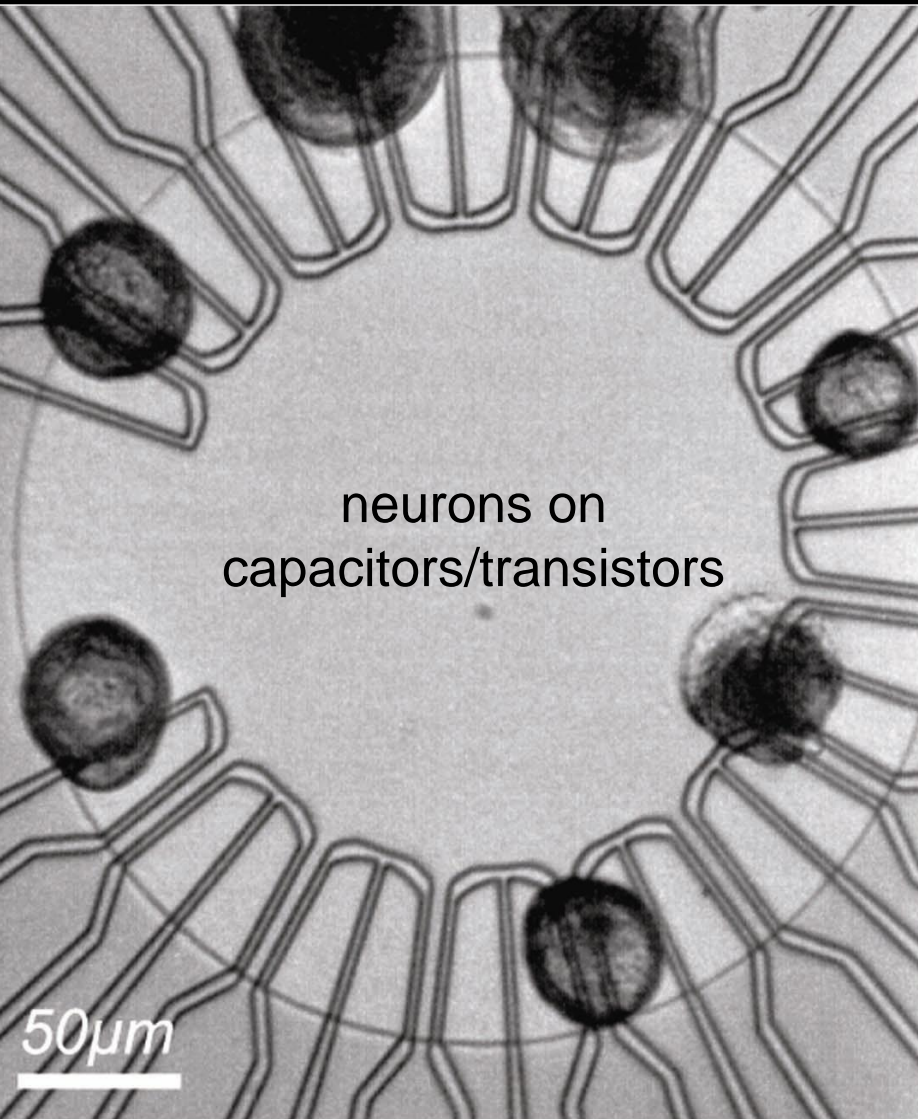
250 ms

# LPeD1 neuron

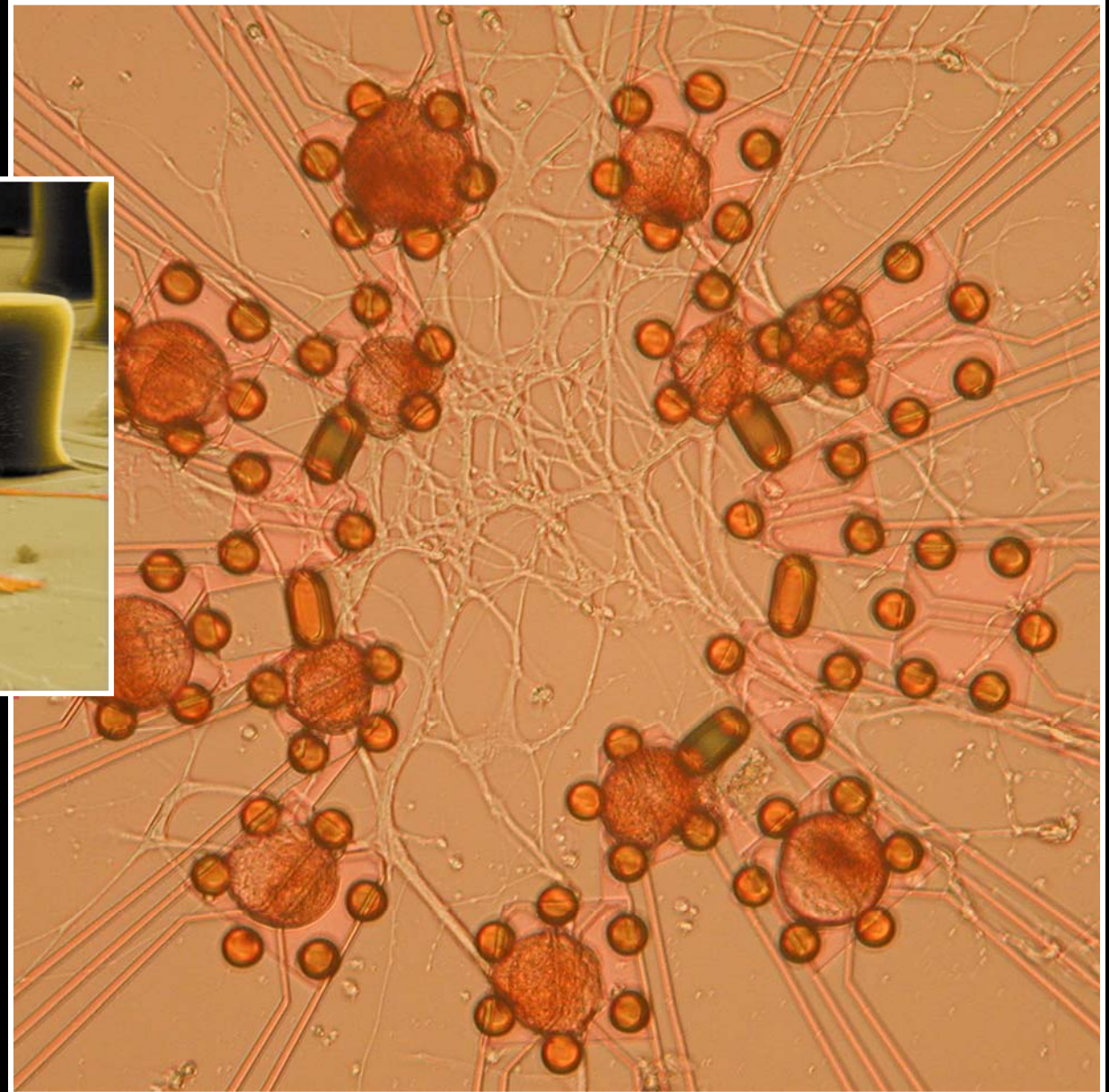
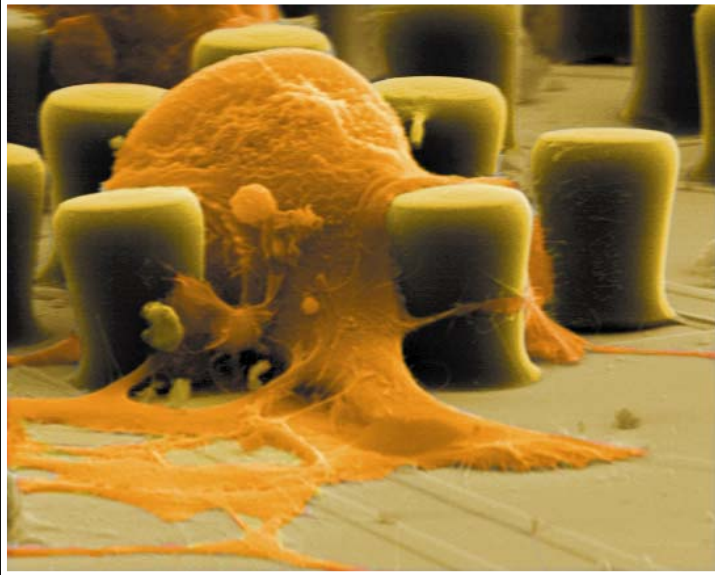


transistor

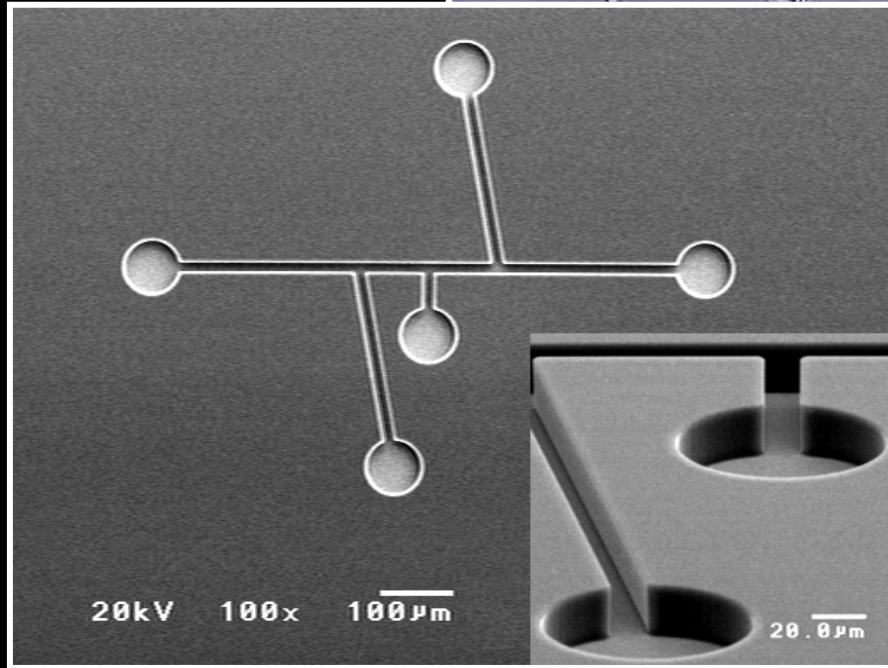
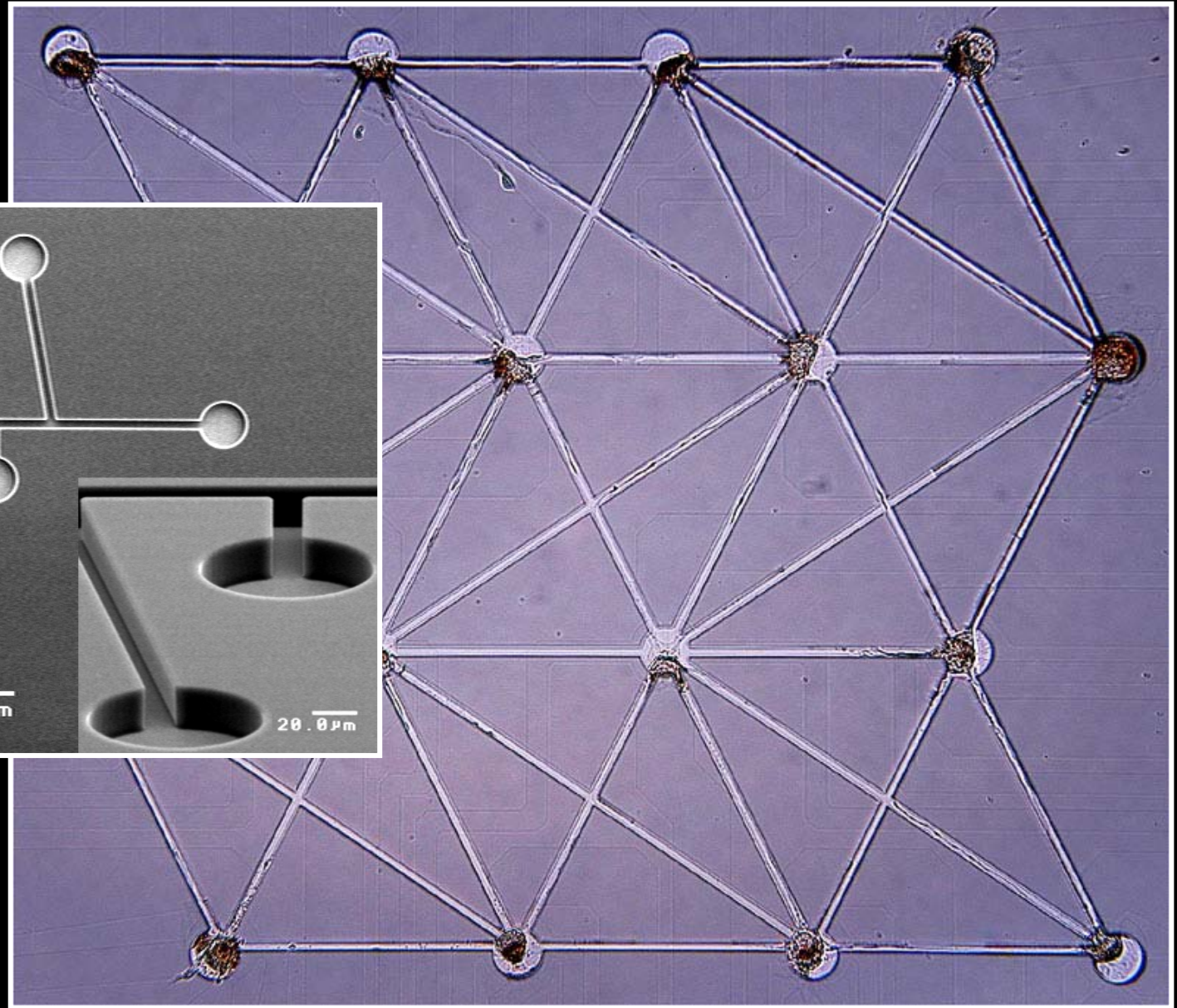
# Network interfacing is instable.



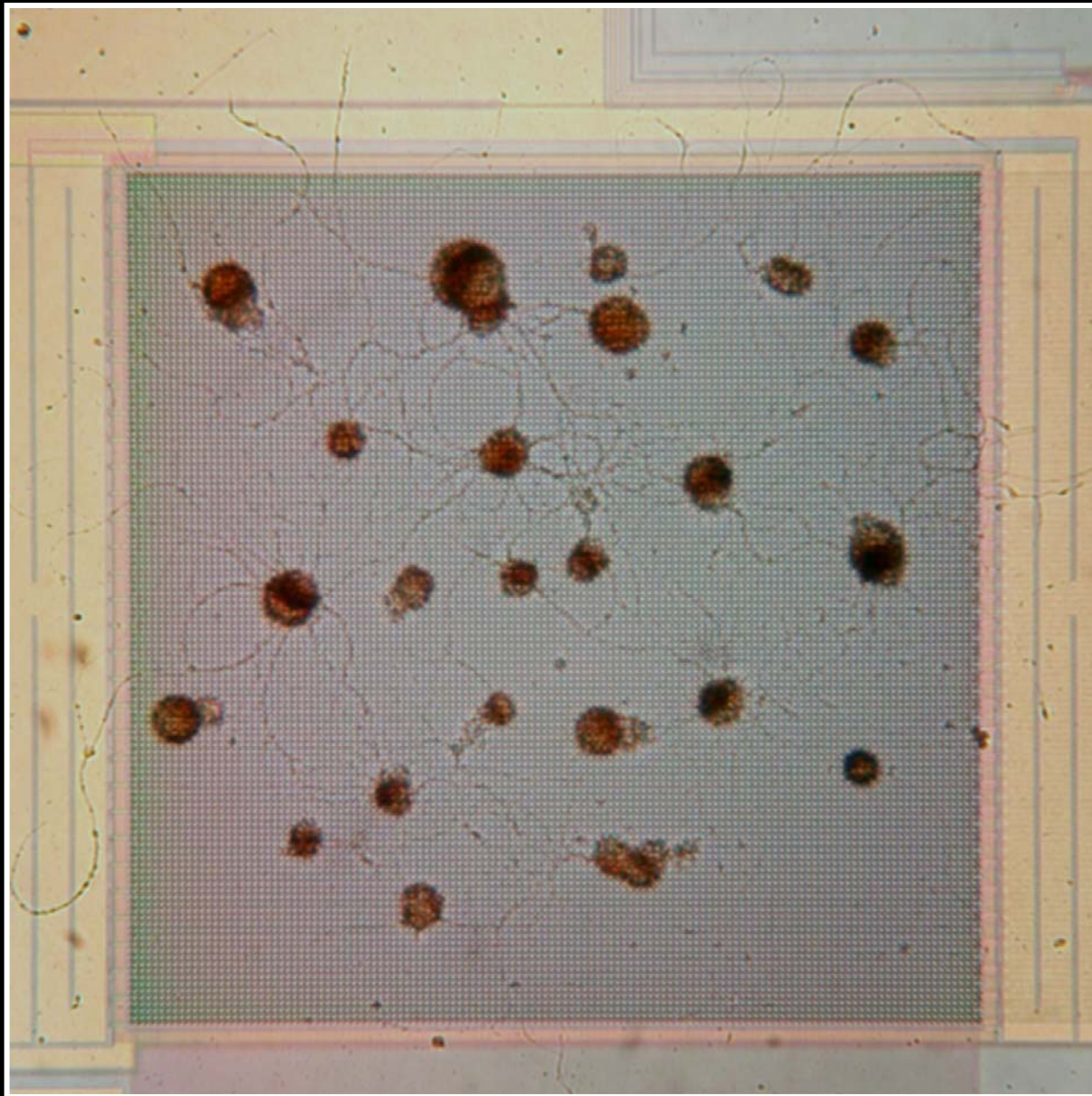
# network with mounted cells



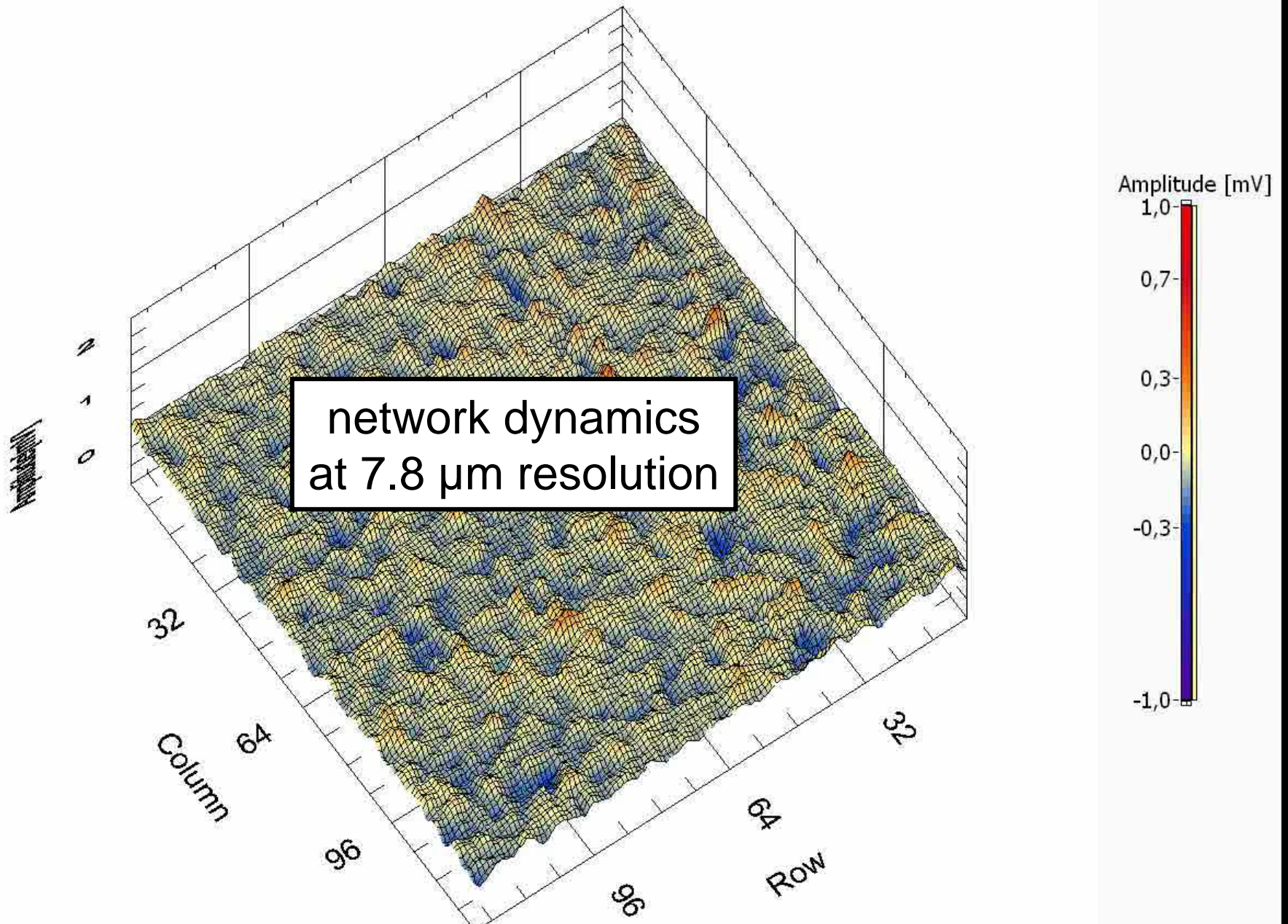
# defined network on chip



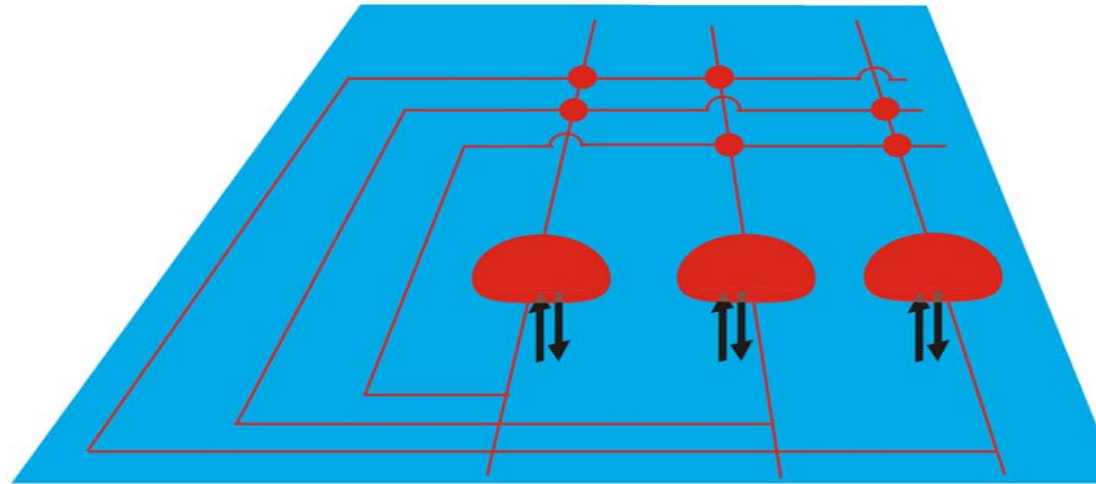
# random network on transistor array

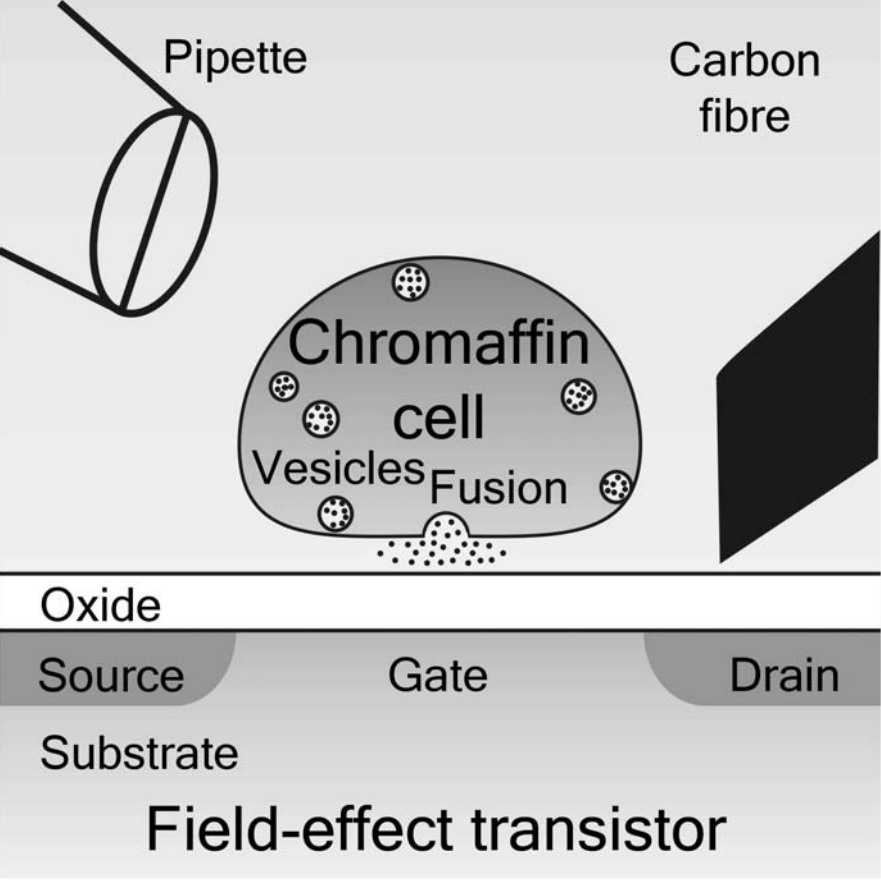


362,25 ms

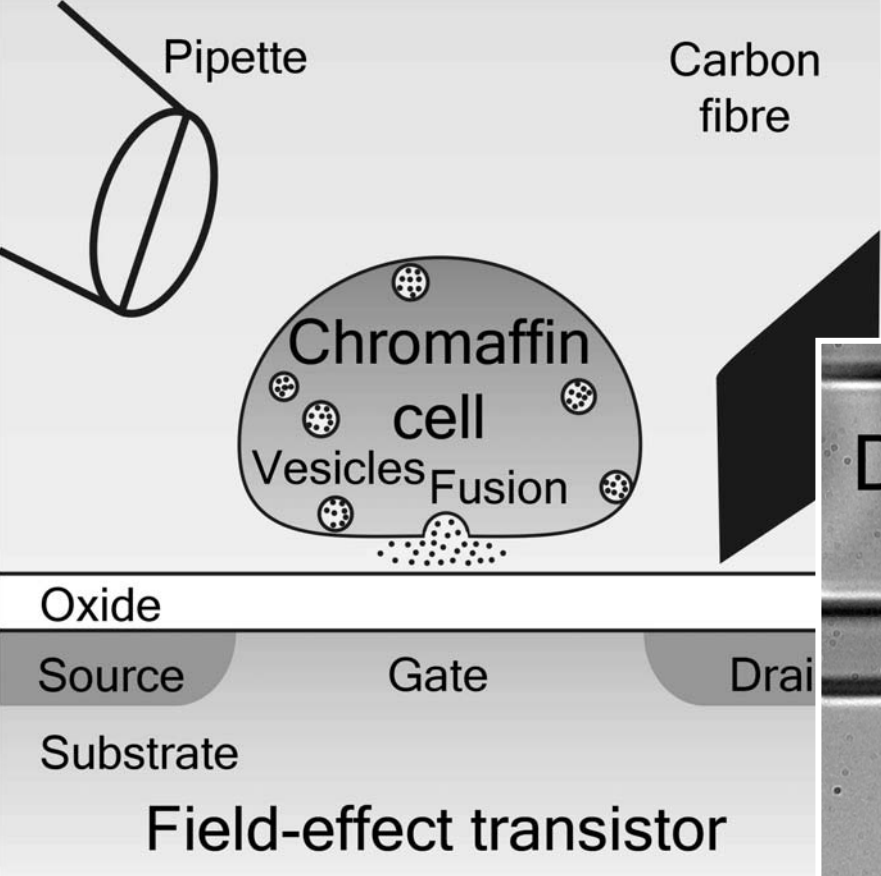


- Recording of neuron activity
- Recording of synapse activity ?

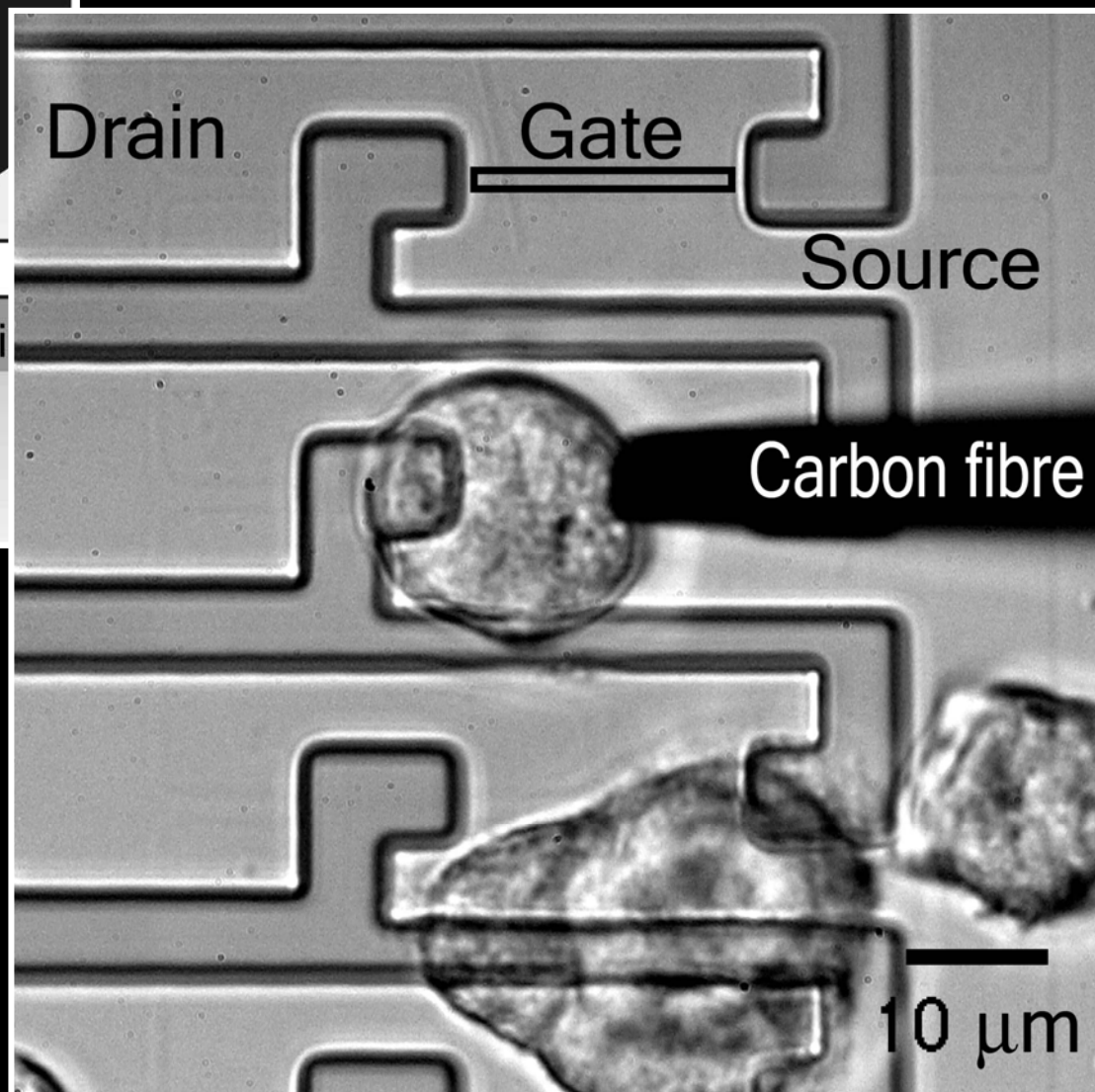




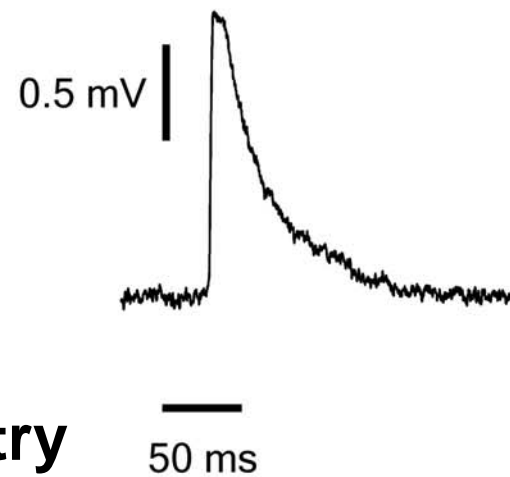
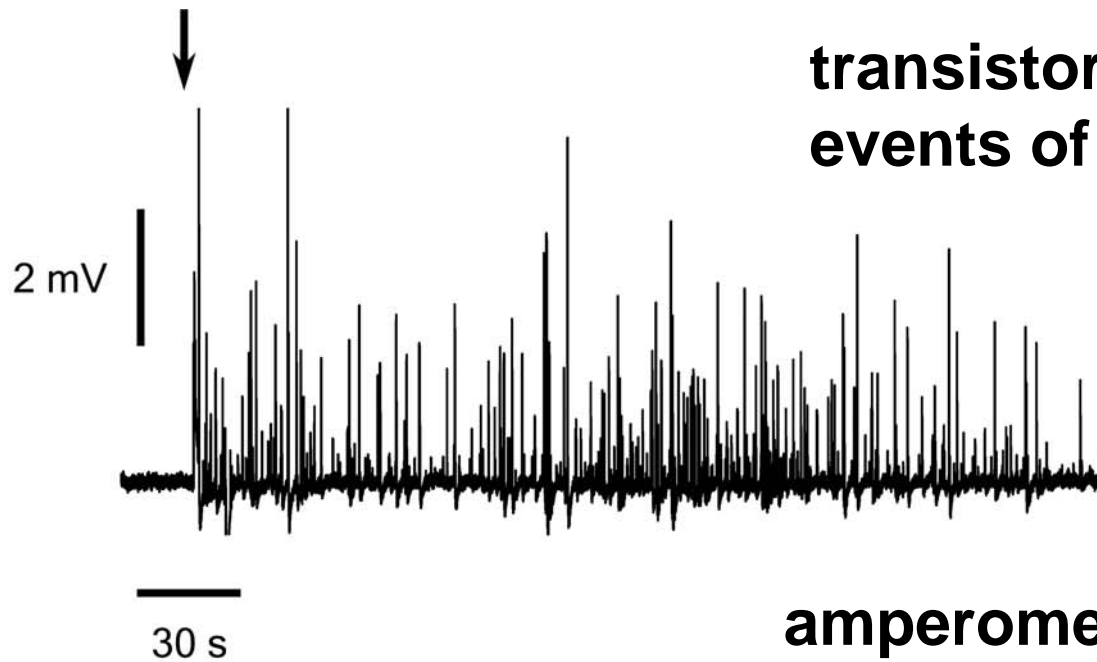
# Cell-Silicon Synapse



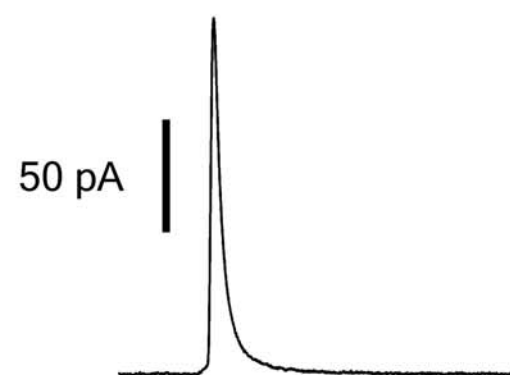
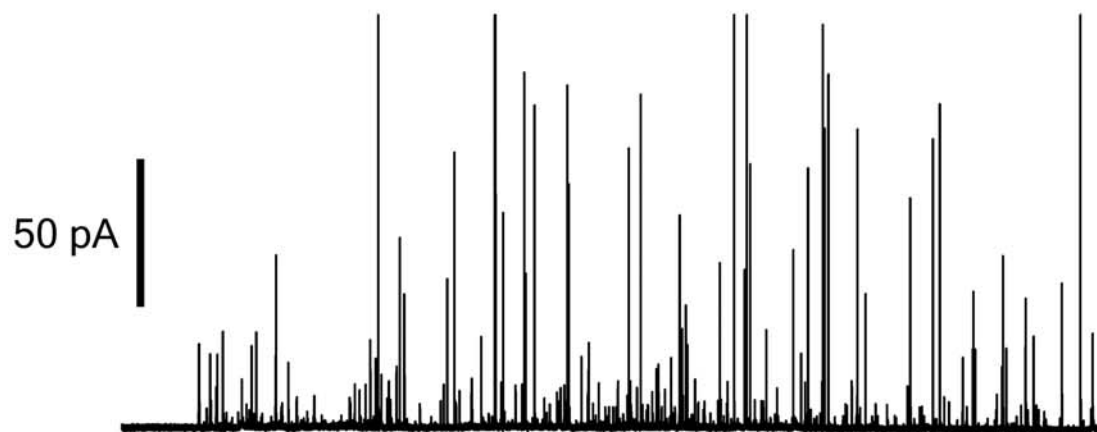
# Cell-Silicon Synapse



**transistor records  
events of vesicle release**



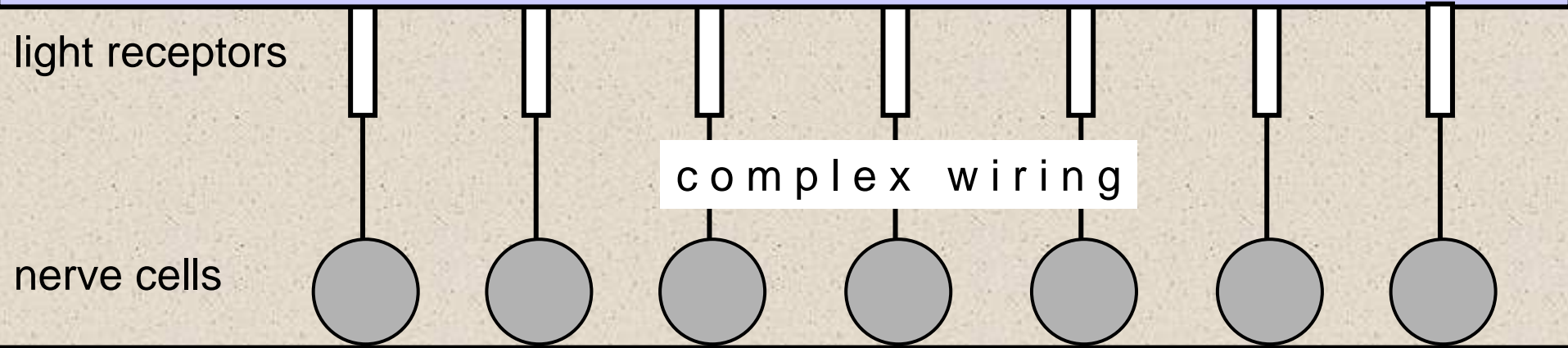
**amperometry**



# 6. Brain Tissue on Chip

electrolyte

# retina on chip



light receptors

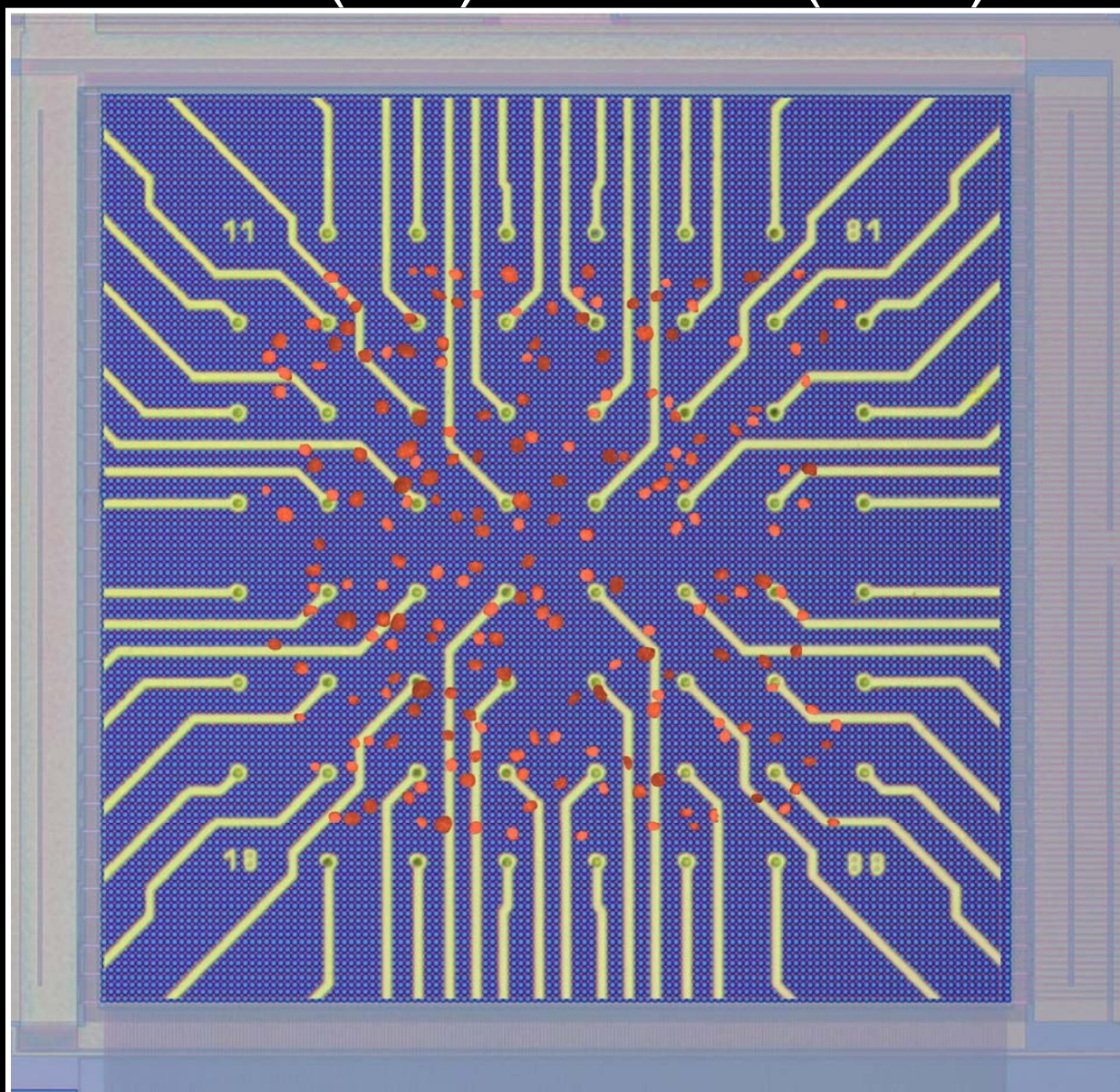
complex wiring

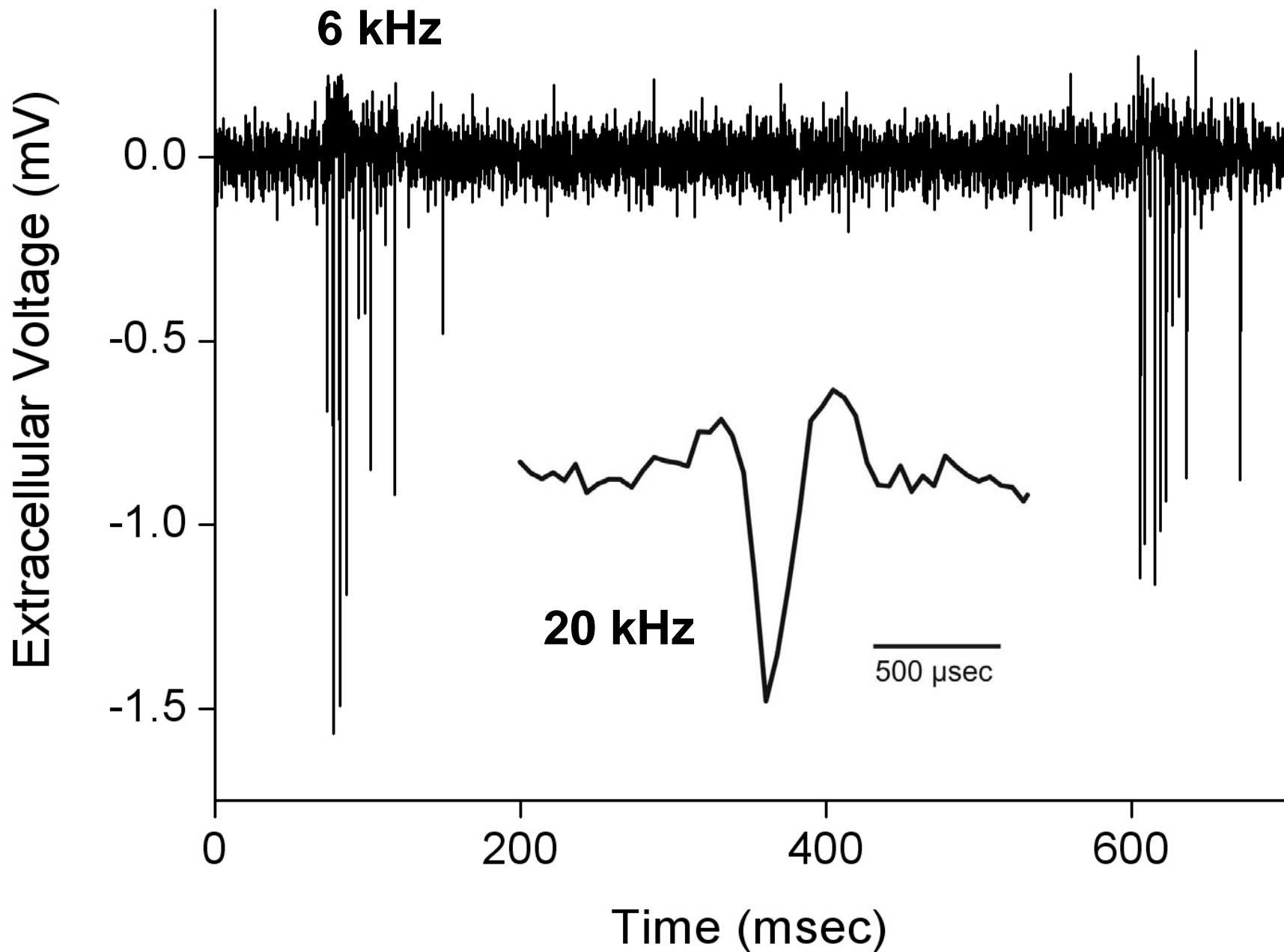
nerve cells

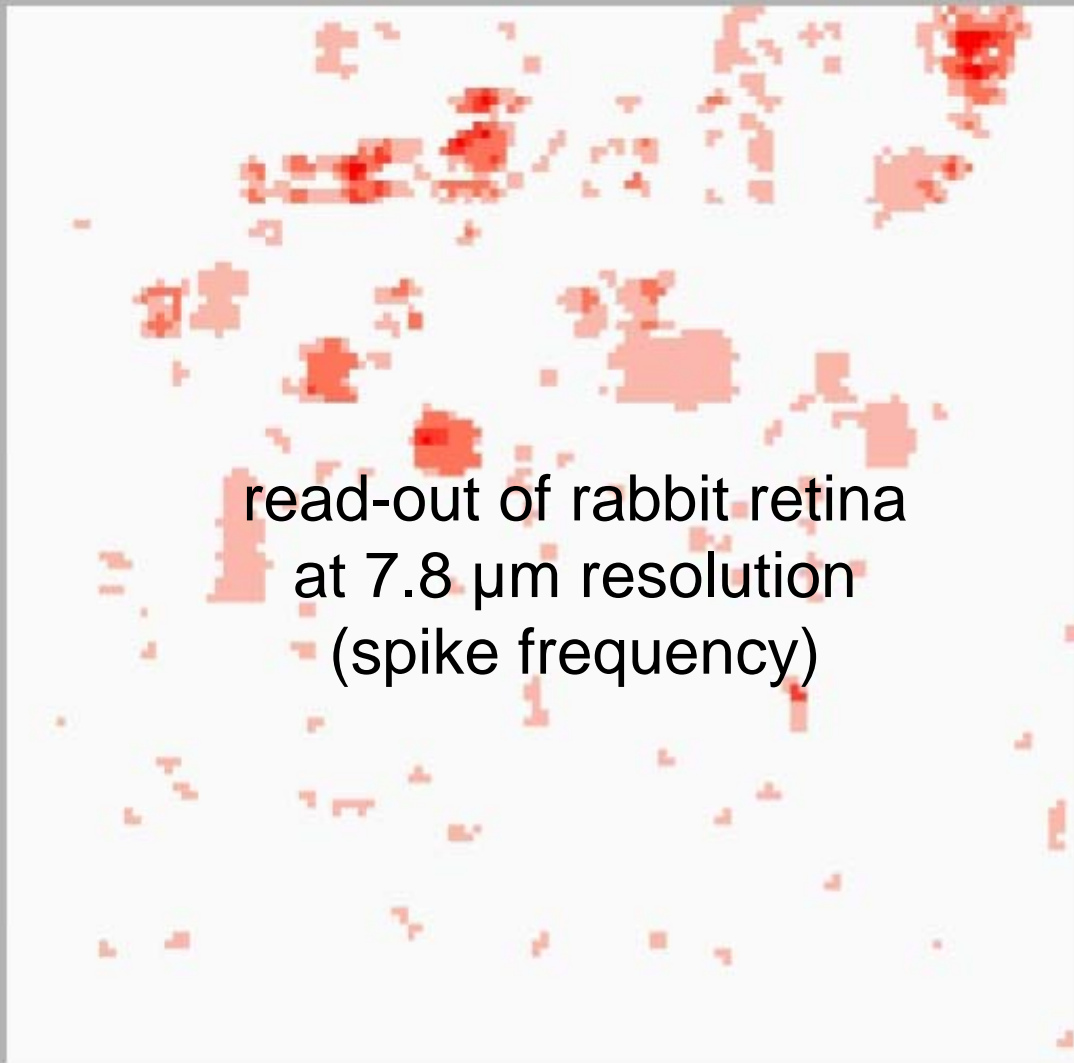
silicon

retina (red) on MTA (blue)

16384  
/mm<sup>2</sup>







read-out of rabbit retina  
at 7.8  $\mu\text{m}$  resolution  
(spike frequency)



**650ms**

electrolyte

**Microscopic structure of  
tissue/chip contact ?**

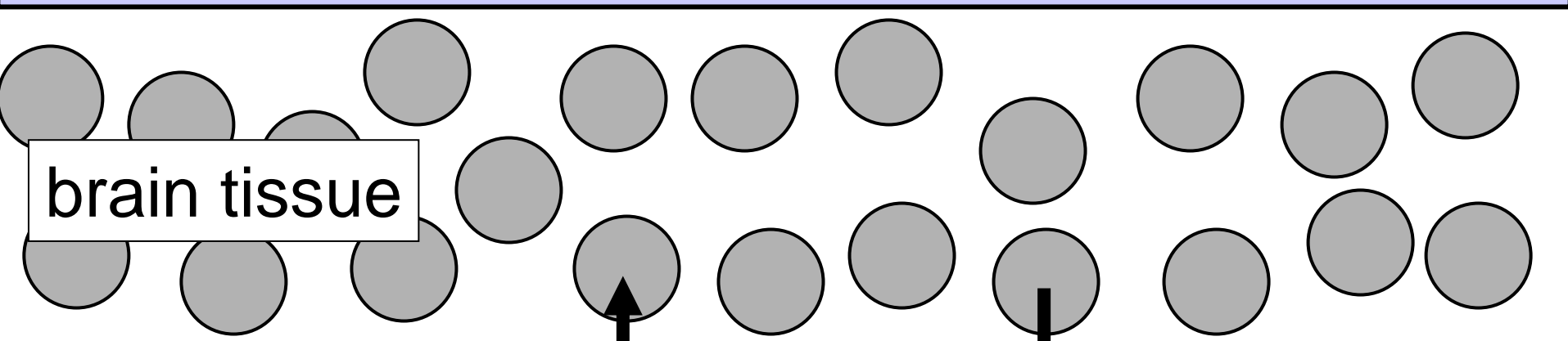
brain tissue

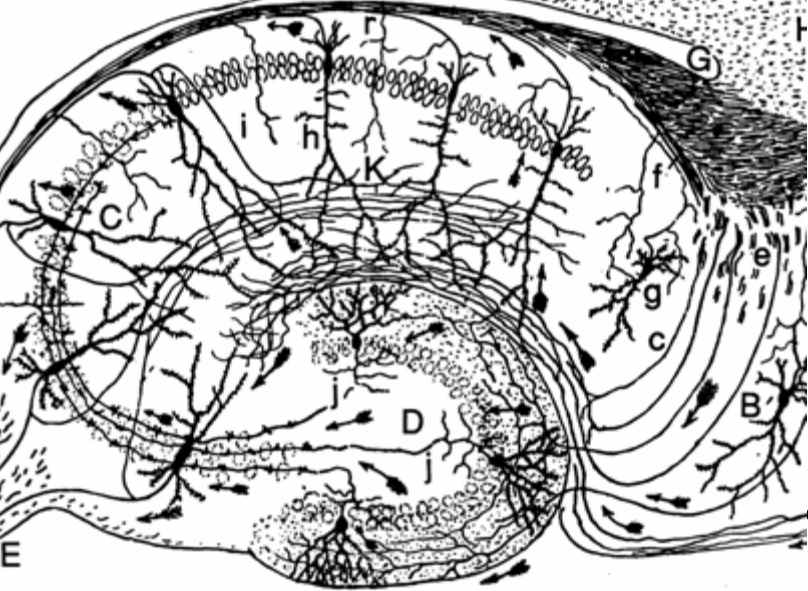
capacitors

transistors

silicon

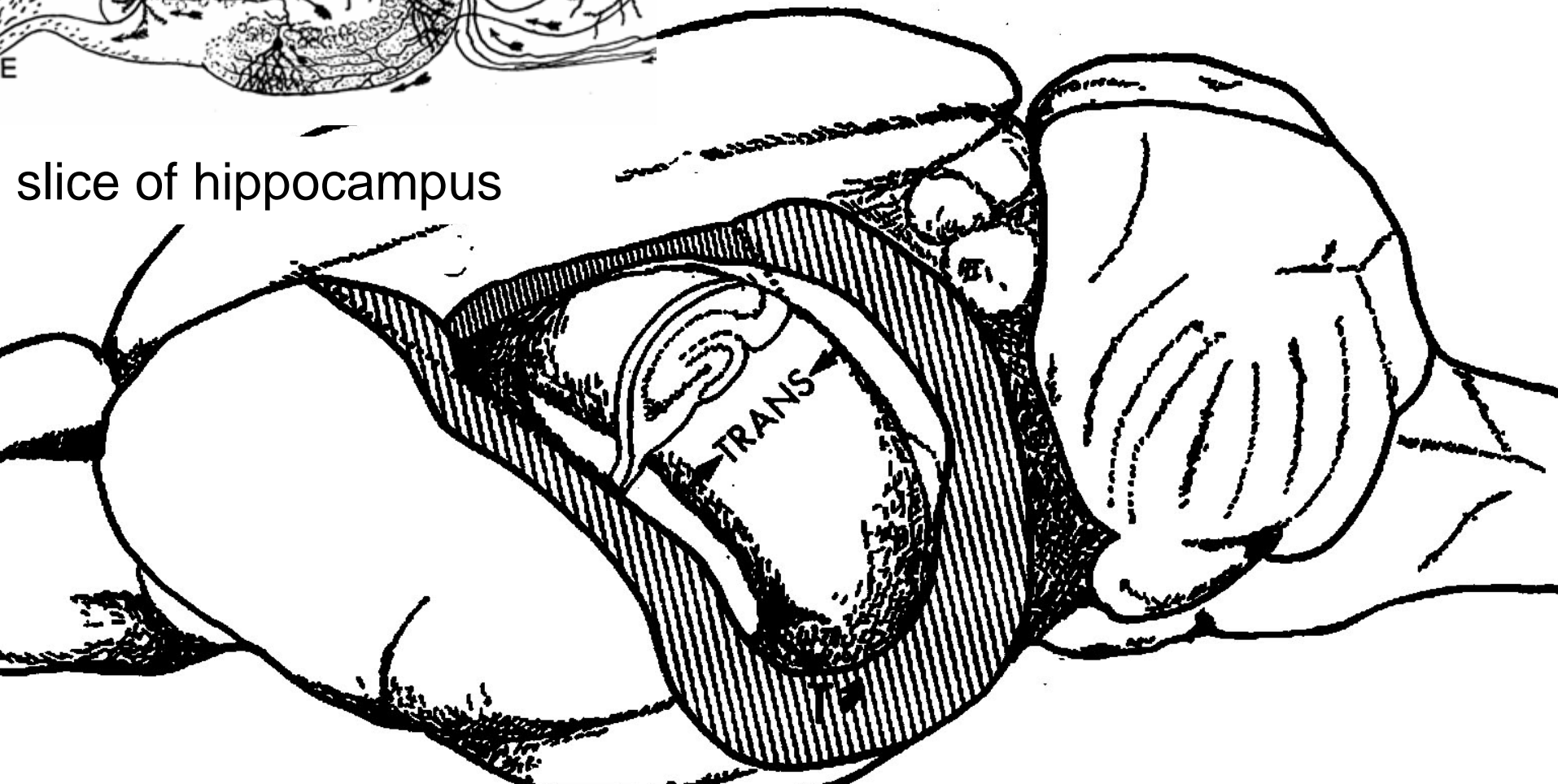
**Interfacing on a mean-field level !**

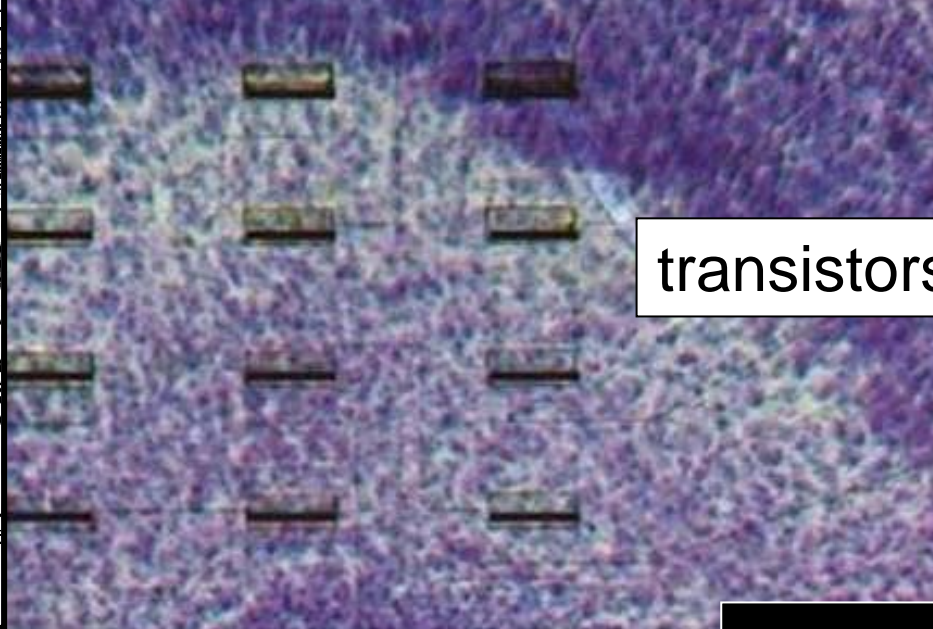
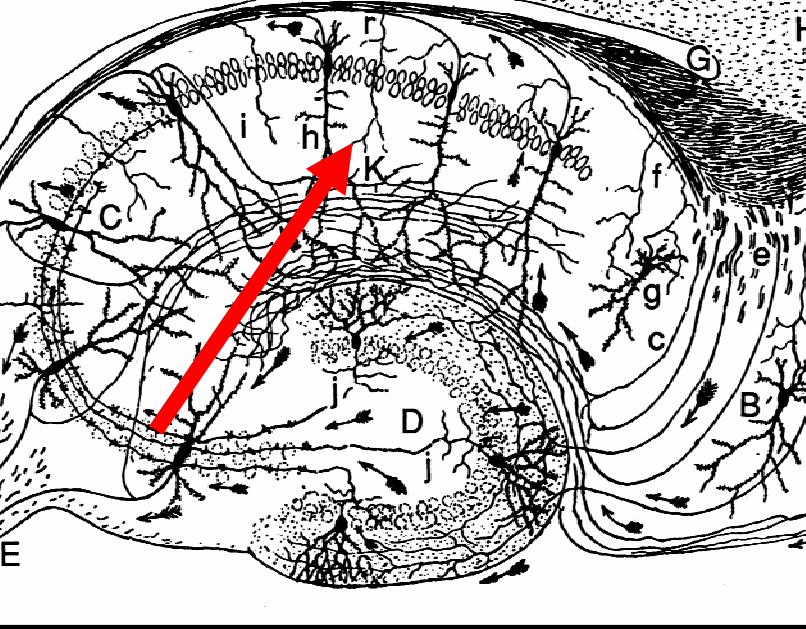




rat brain

slice of hippocampus

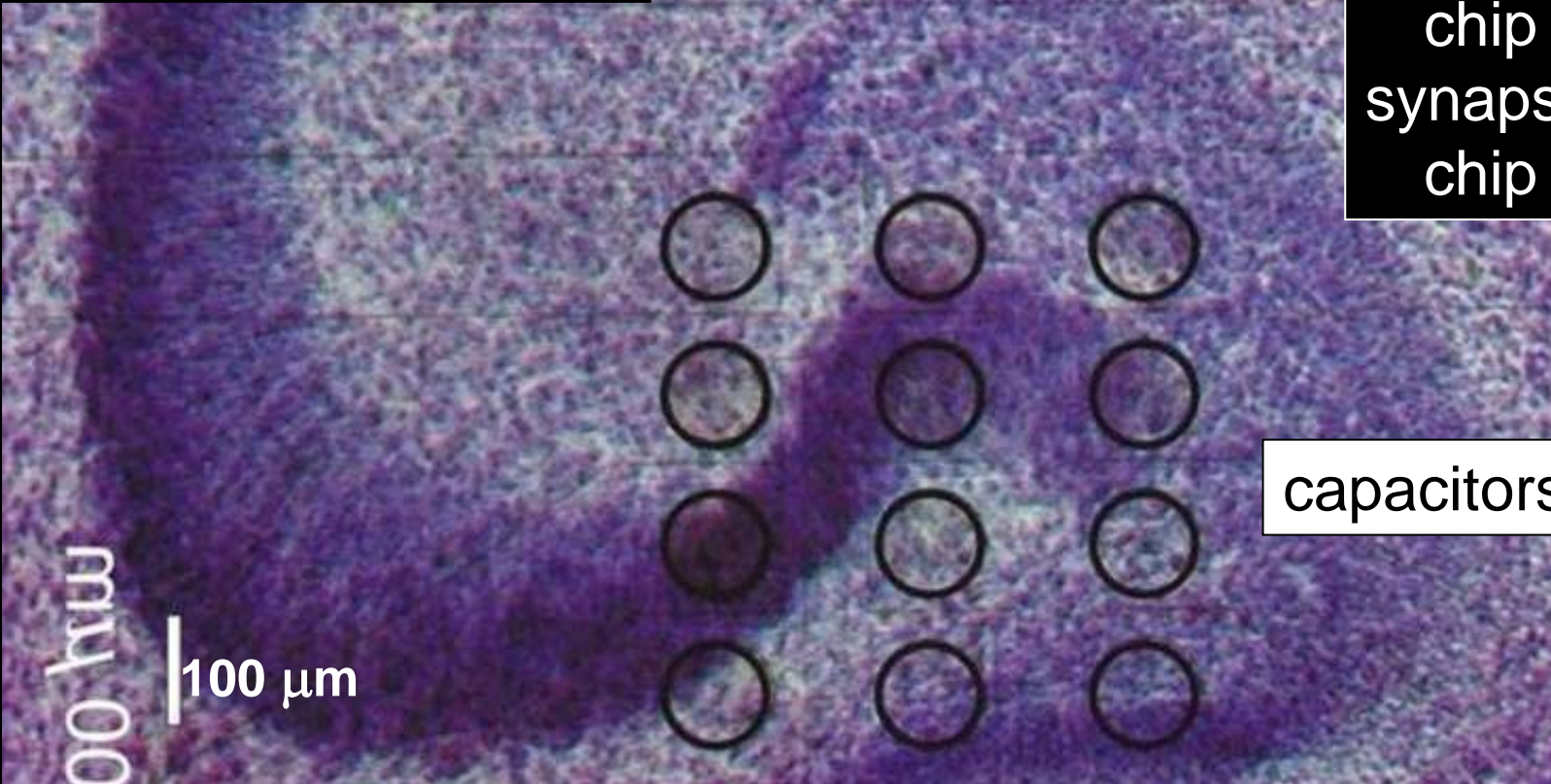




transistors

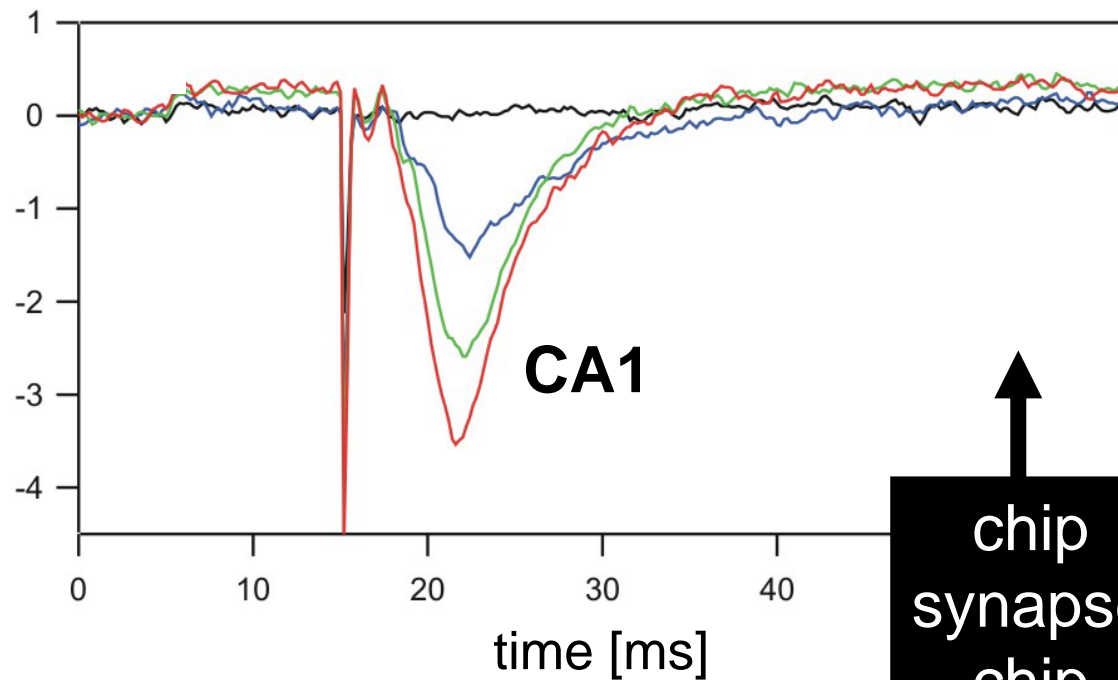
chip  
synapse  
chip

capacitors

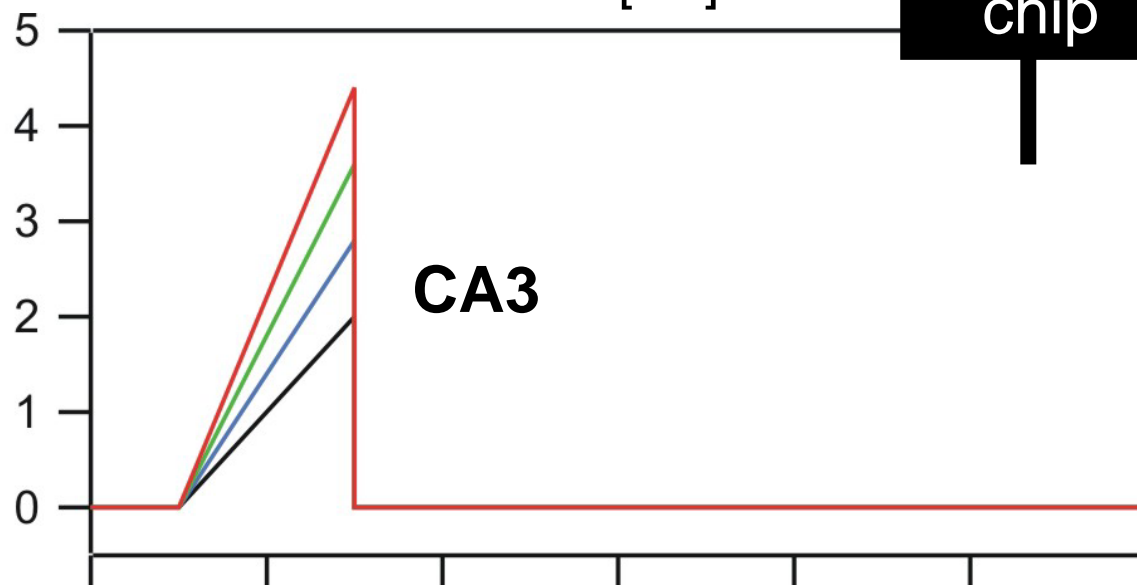


100 μm

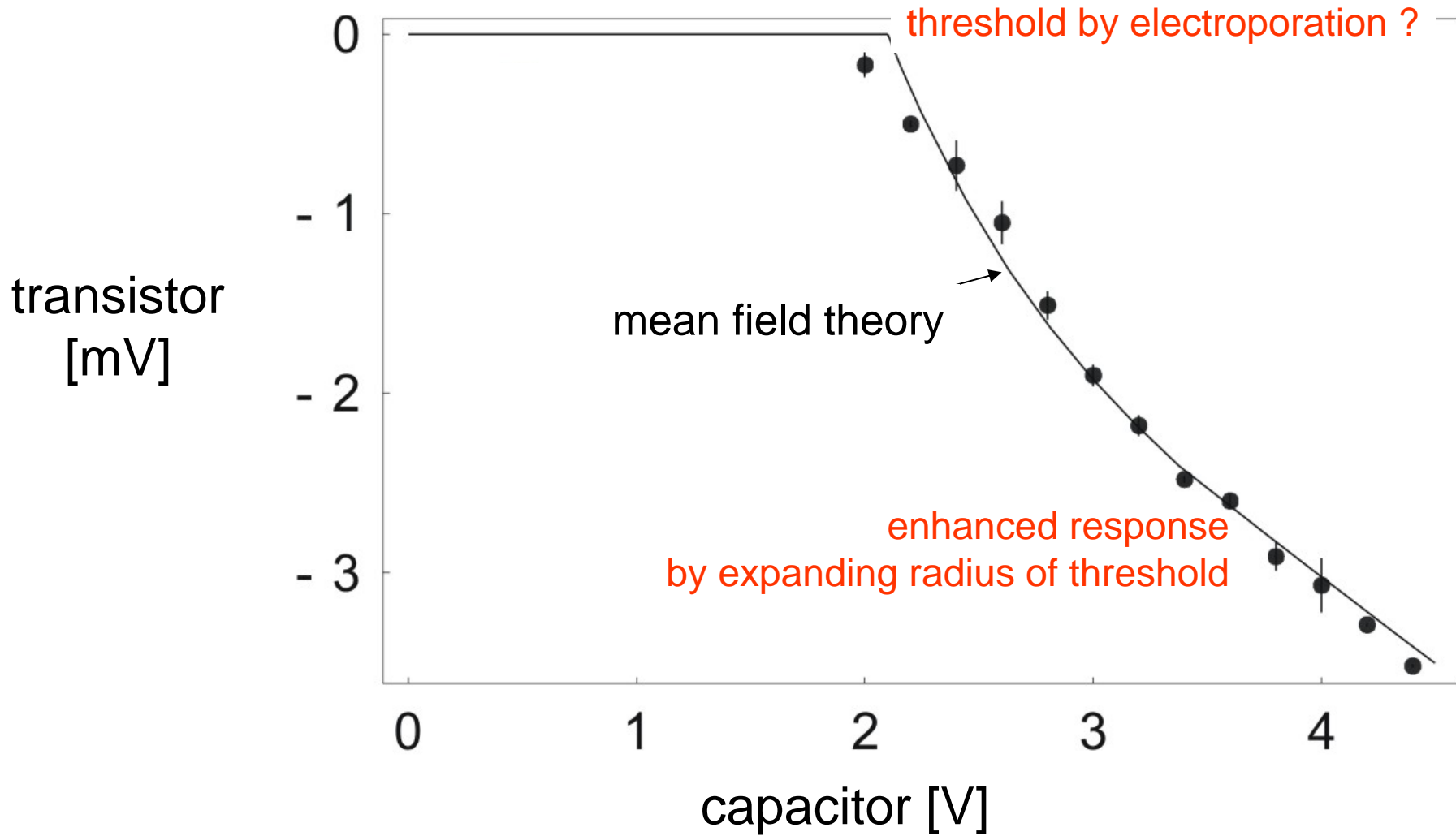
transistor  
record [mV]



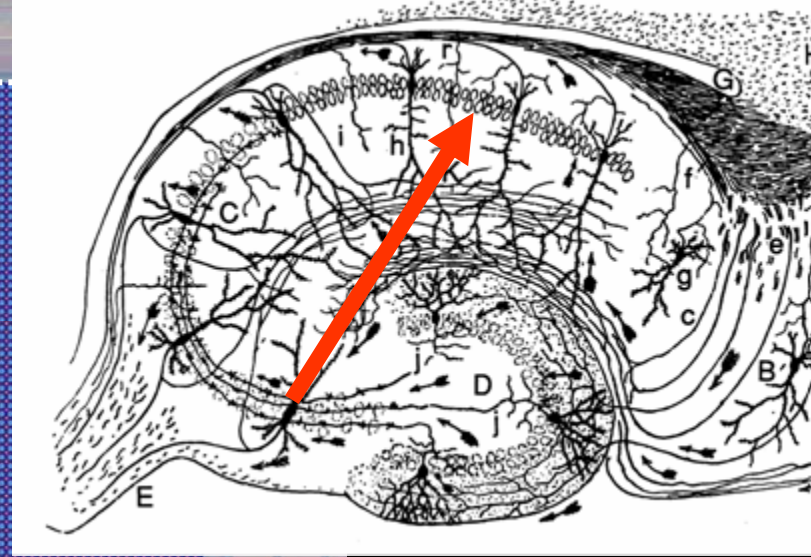
capacitor  
stimulus [V]



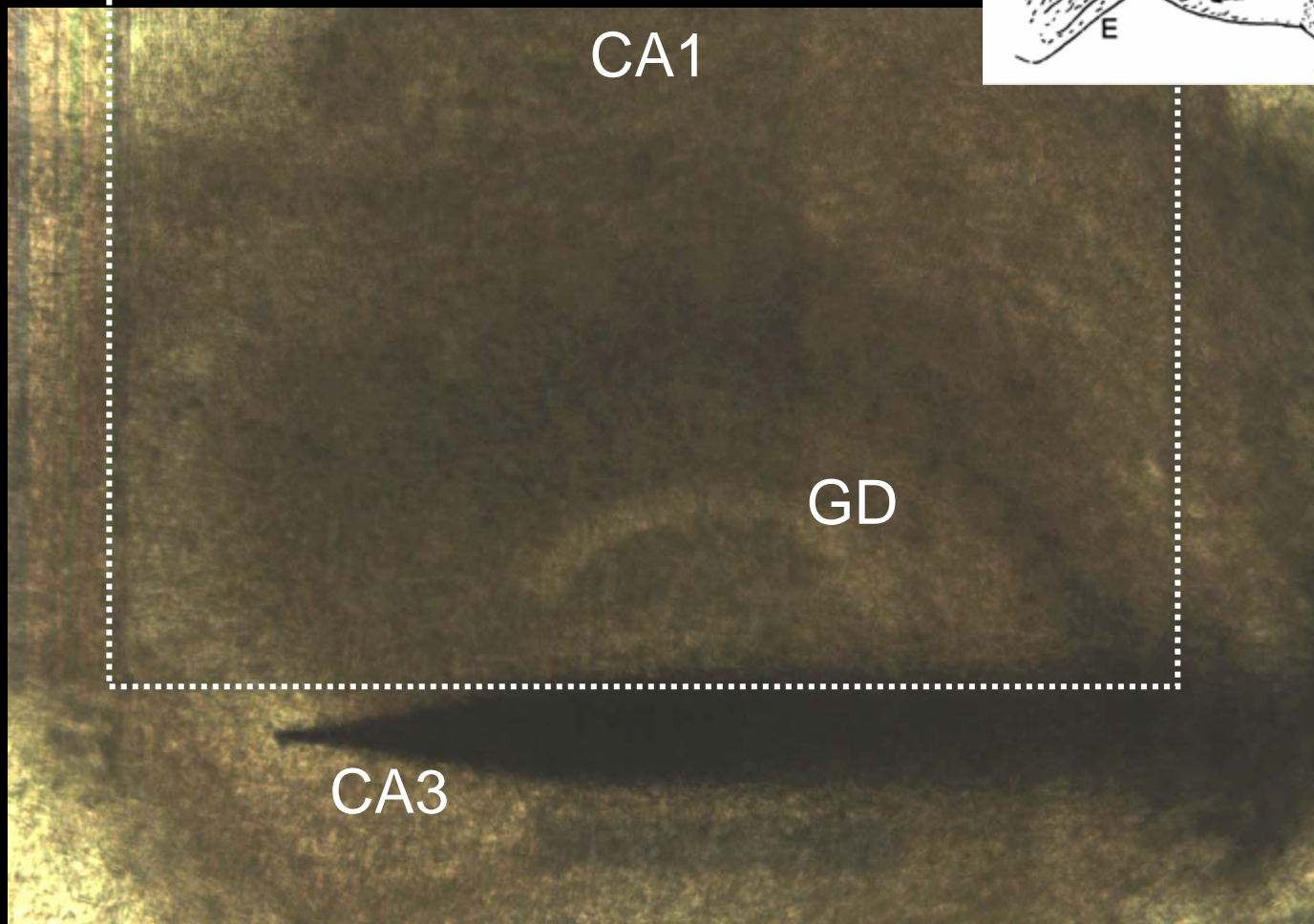
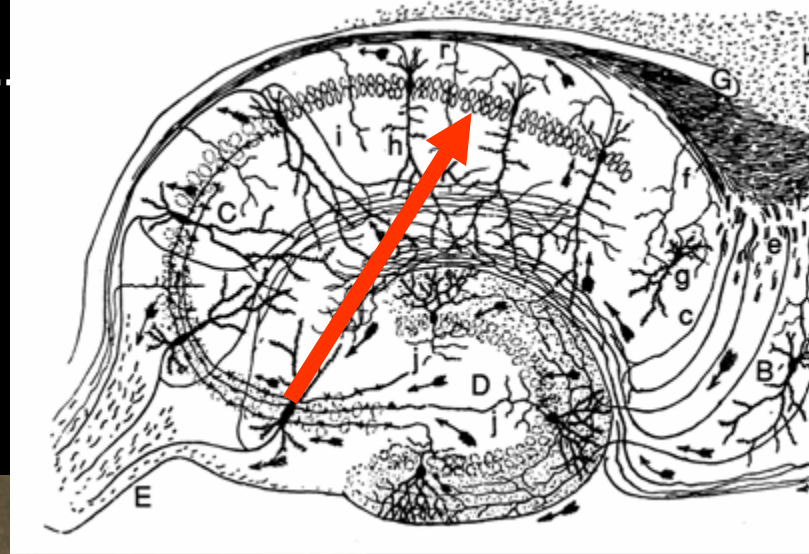
# stimulus response relation



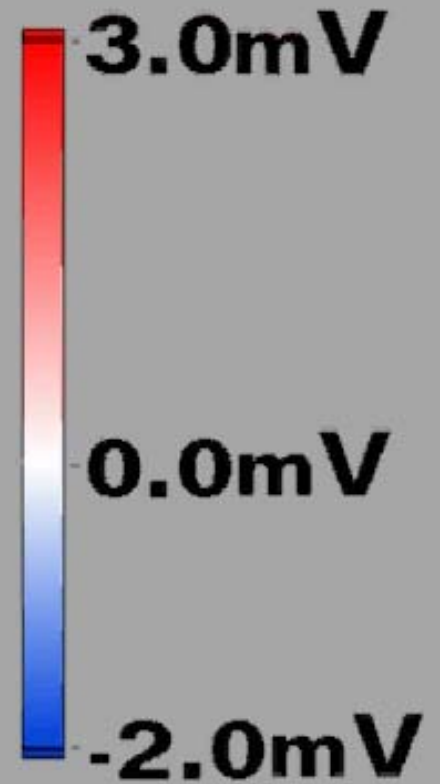
16384 transistors/mm<sup>2</sup>



hippocampus slice  
on transistor array

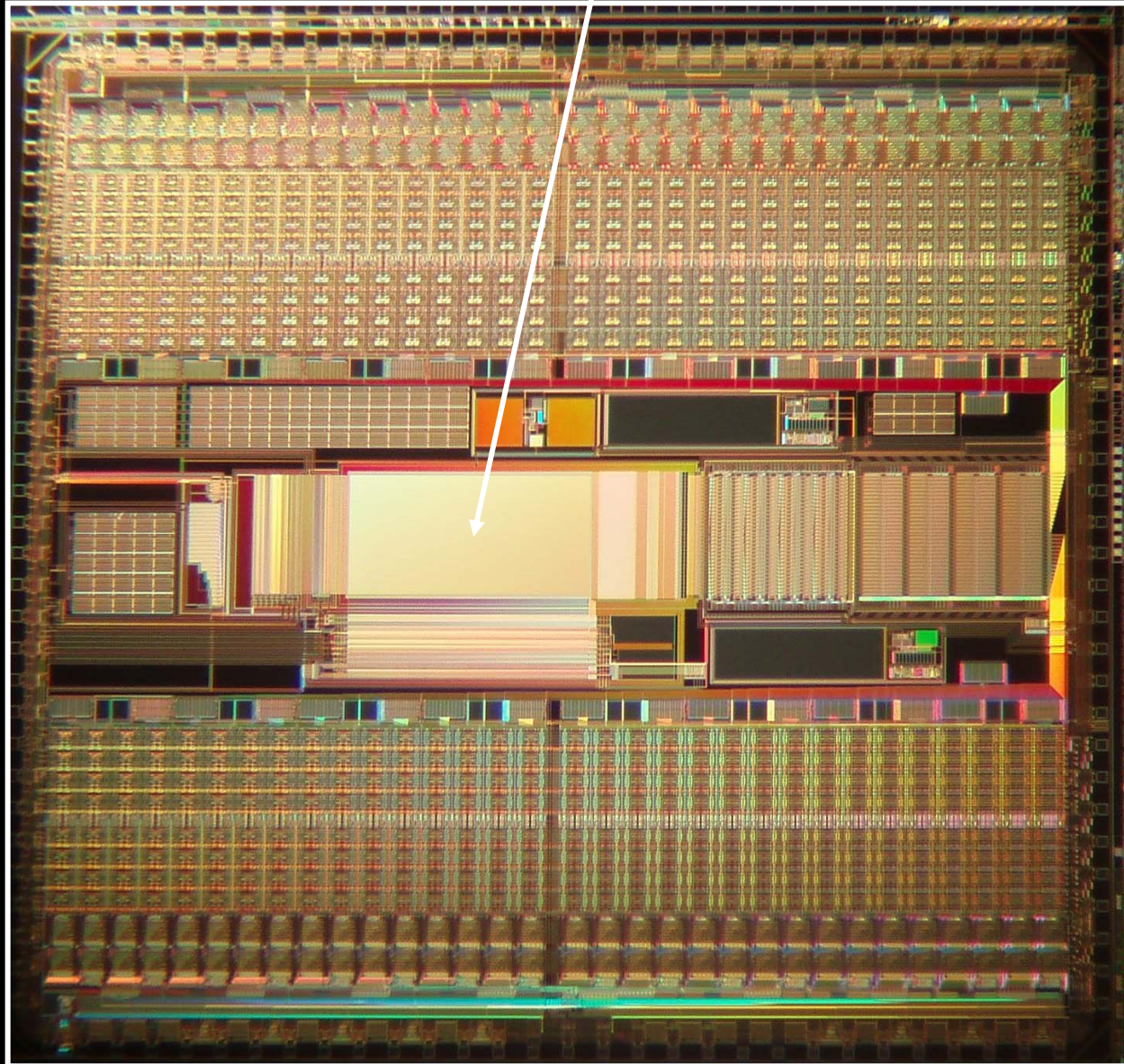


read-out of brain slice  
at 7.8  $\mu\text{m}$  resolution  
(extracellular field potential)



**-0.94ms**

32000 two-way contacts

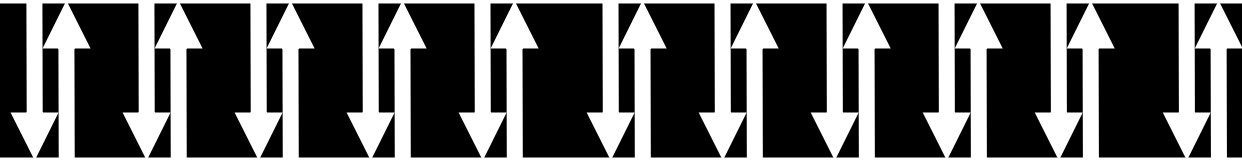


# Outline

1. Cell-Silicon Contact
2. Ions & Electrons
3. Nerve Cells on Silicon
4. Neuronal Networks on Chip
5. Brain Tissue on Chip

# Conclusion

ion channel, nerve cell, brain tissue

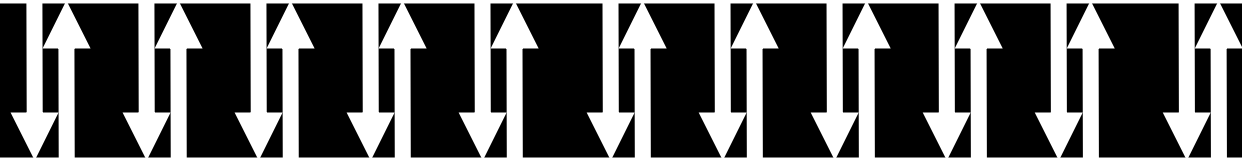


capacitor, transistor, CMOS chip



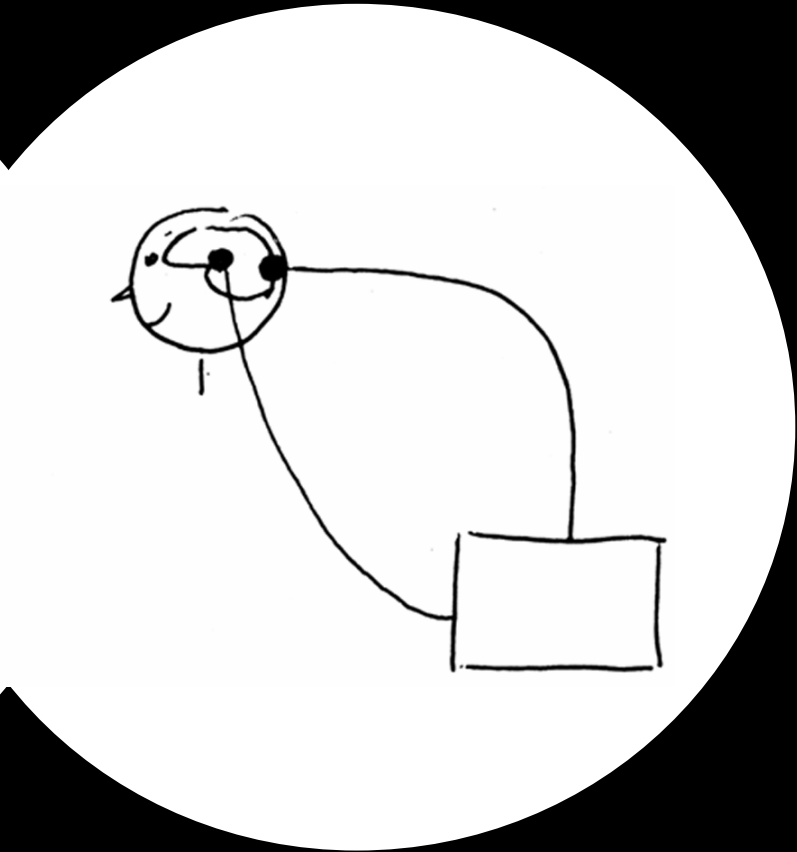
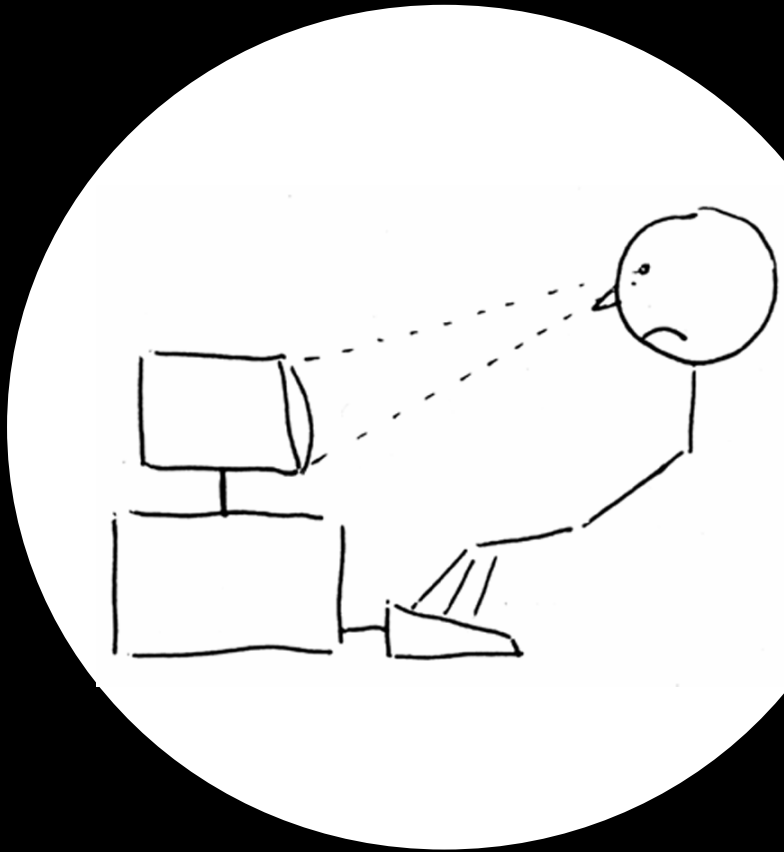
# Conclusion

thinking brain tissue



computing microprocessor





Raimund Gleixner  
Moritz Völker  
Frank Wallrapp  
Markus Schmidtner  
Ingmar Schön

Günther Zeck  
Matthias Merz  
Alexander Kaul  
Ralf Zeitler  
Janosch Lichtenberger  
Michael Hutzler  
Christoph Hermann

Max Planck Society  
DFG SFB 563  
EU IST (NaChip)

Armin Lambacher

Naweed Syed (Calgary)  
Günther Zeck (Martinsried)  
Roland Thewes (Infineon)