Mini-Review Nanosystem

SINGLE-ELECTRON TRANSISTOR AND QUANTUM DOTS MADE FROM A CADMIUM SELENIDE NANOCRYSTAL

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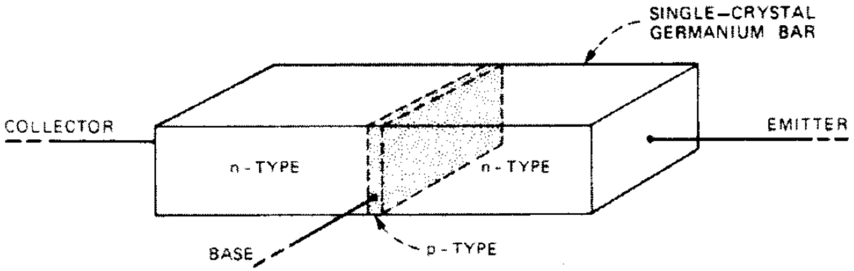
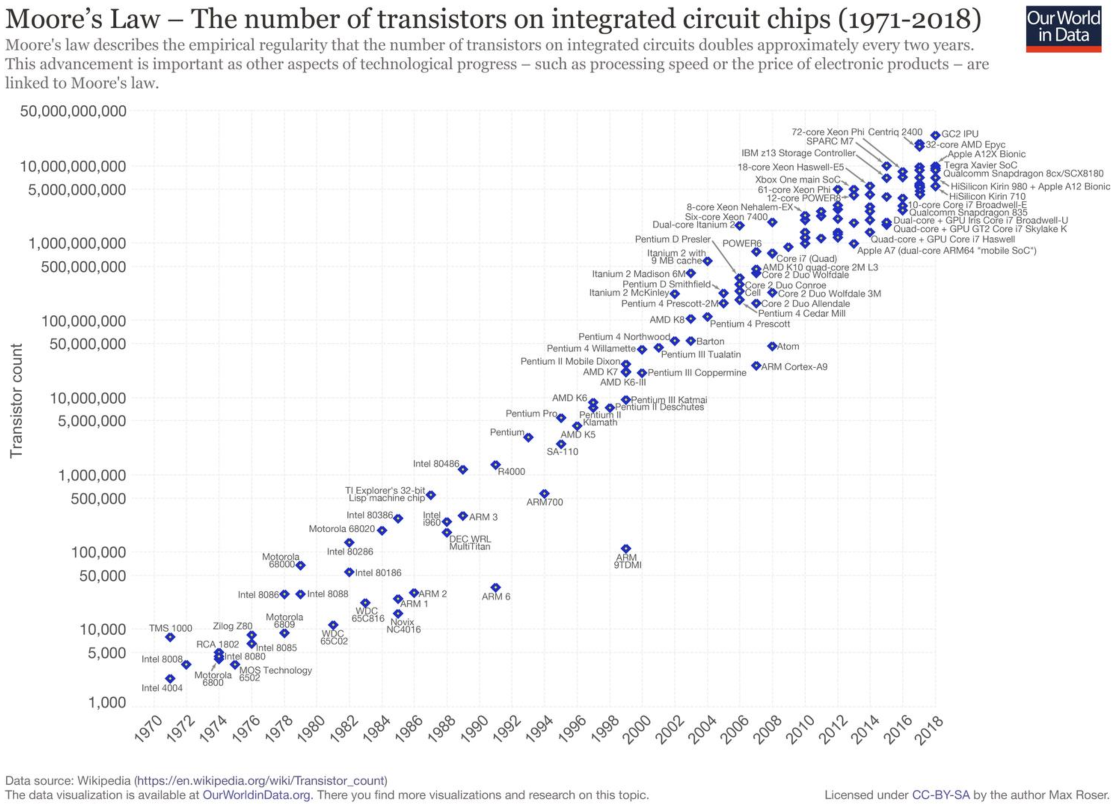
11/11/2023

INTRODUCTION



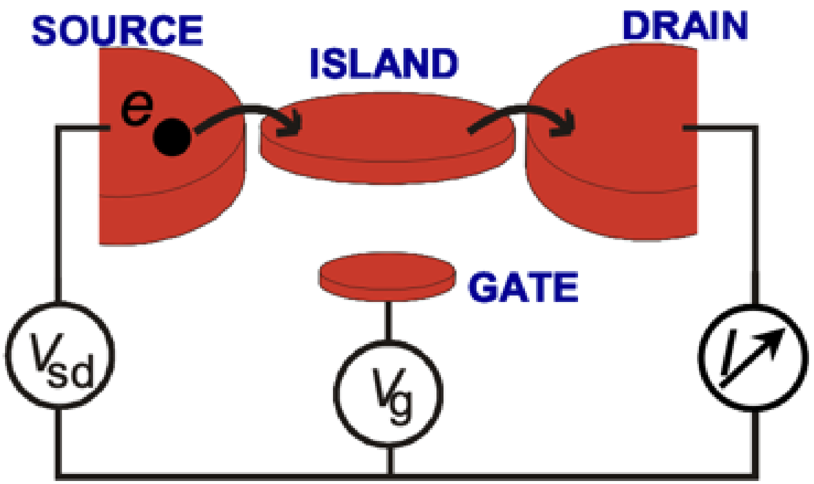
- First junction transistor [1]

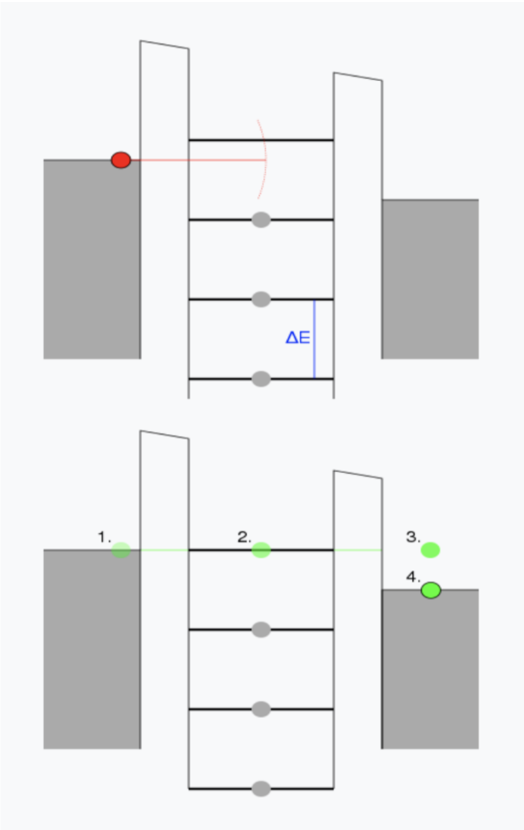


[1] *A hystory of the invention of the transistor and where it will lead us,William F. Brinkman et al, 1997*

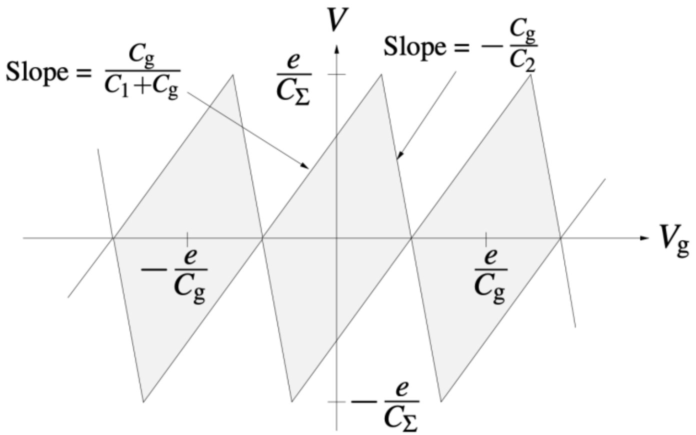
Single electron transistor

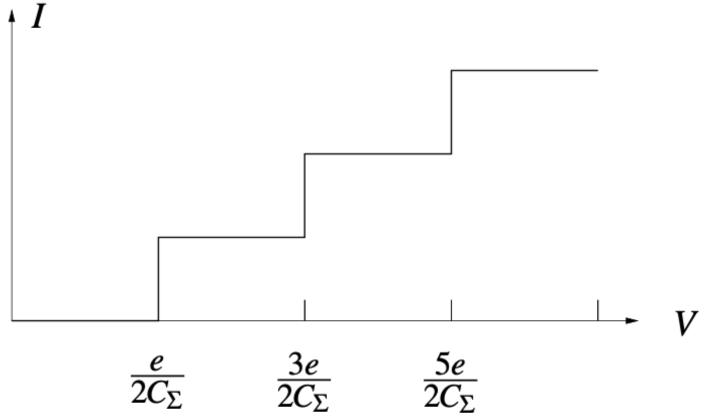
- Quantum dots
- Tunneling effect
- Blocked and passing state





Coulomb blocade



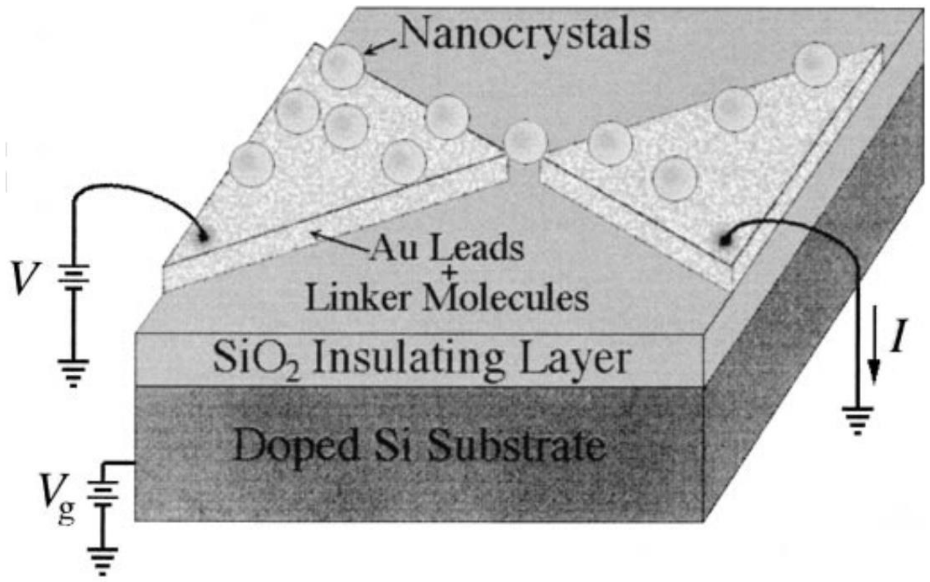


- Coulomb energy $E_c = e^2/ 2C$
- Stability diagram for the SET
- Stable conditions (i.e. no current flow) are only present for values of *V* and *Vg* within the shaded regions
- Coulomb staircase

$$k_B T \ll E_c$$

[2] *Single-Electron Devices and Their Applications, KONSTANTIN K. LIKHAREV 1999*

cadmium selenide nanocrystal

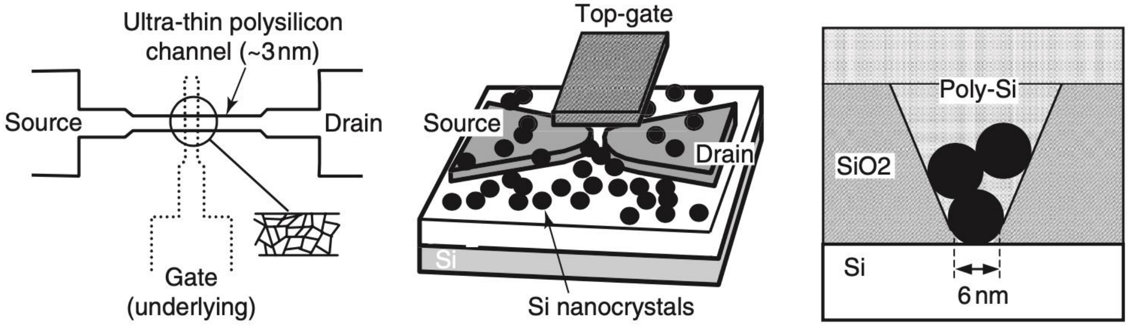


single-electron transistor made from a cadmium selenide nanocrystal [3]

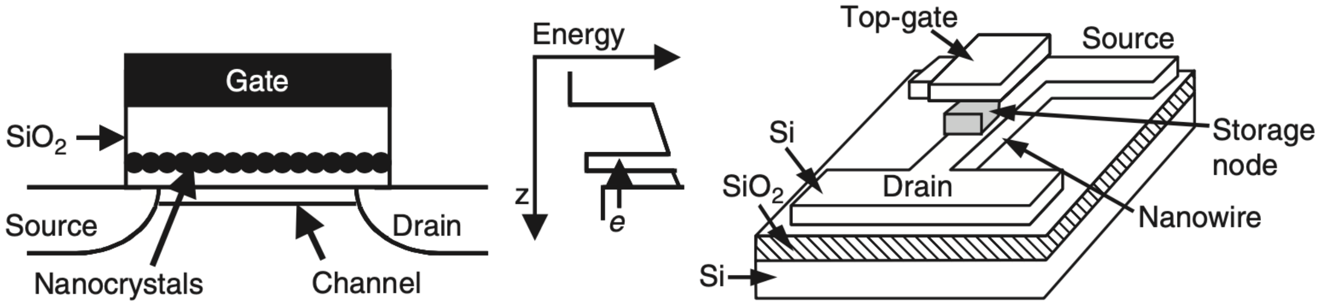
- number of charge carriers can tuned
- Suitable Bandgap
- Variable size
- Optical properties

[3] A single-electron transistor made from a cadmium selenide nanocrystal, David L. Klein, Richard Roth, Andrew K. L. Lim, A. Paul Alivisatos & Paul L. McEuen

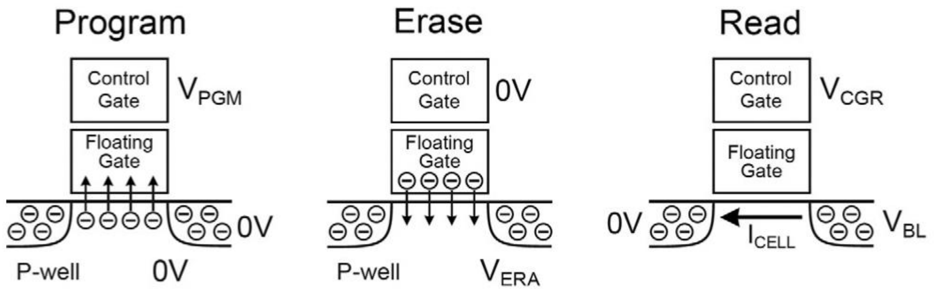
Semiconductor Quantum Dots for memory
The model



Single-electron transistors using silicon nanocrystals [4]



Nanosilicon memory cells [5]

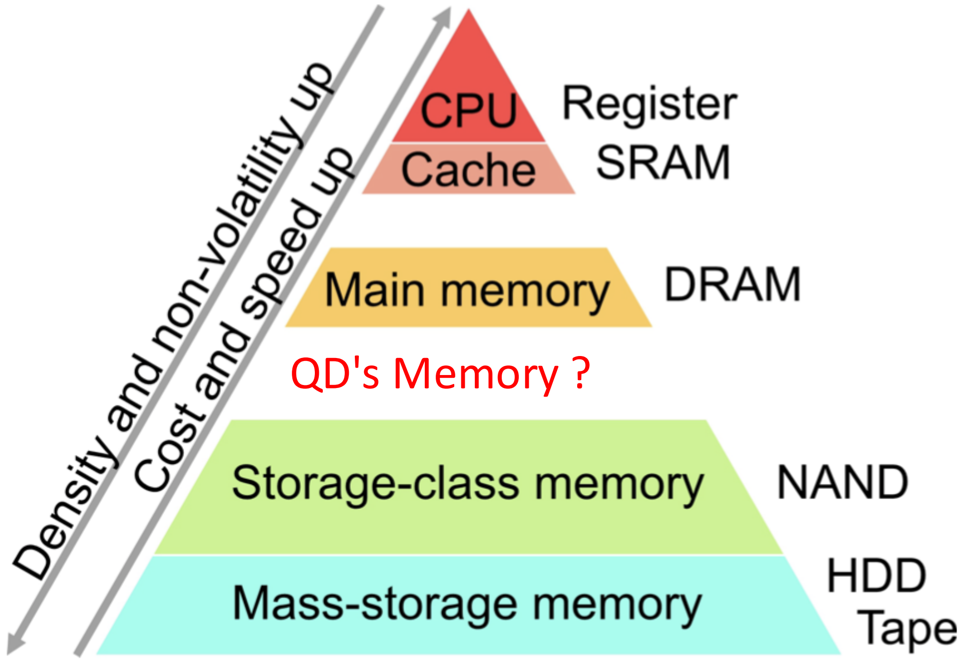


NAND flash memory cells

[4] K.Yano,T.Ishii,T.Sano,T.Hashimoto,T.Kobayashi,F.MuraiandK.Seki,*Appl.Phys.Lett.***67**, 828 (1995)
[5]K. Yano, T. Ishii, T. Sano, T. Mine, F. Murai, T. Hashimoto, T. Kobayashi, T. Kure and K. Seki, *Proc. IEEE* **87**, 633 (1999)

Semiconductor Quantum Dots for memory comparaison and challenge

- Good scalability small cell size 2-20nm
- power consumption - 0.35 V
- Price
- The write-erase times are ≈10μs
- Data retention – 10^5s≈1month
  \> volatile memory



Semiconductor Quantum Dots for memory [6]

materials	ON/OFF ratio	memory window (V)	retention time (s)	mobility ($cm^2 V^{-1} s^{-1}$)	multilevel	optical modulation
polysilicon dot	-	0.16	5	-	4	no
Si nanocrystal	10^3	4.5	2×10^4	-	2	no
Si QD	10^7	1.8	10^5	-	2	no
Fe_2O_3 QD	10^7	1.3	10^5	-	2	no
InAs QD	10^3	6.2	-	-	2	no
$CsPbBr_3$ QD	1.86×10^5	16.47	10^3	0.24	6	yes
carbon QD	10^4	15.2	7×10^6	-	5	yes
graphene QD	10^5	80	-	-	2	no
graphene QD	10^6	25.5	200	1.25×10^{-4}	2	yes
rGOQD QD	10	6.83	-	5.005	2	no
CdSe QD	10^2	5.8		-	2	yes
CdSe QD	10^5	-	10^4	0.21	2	yes
CdSe QD	10^4	18	500	-	2	no
ZnSe/ZnS QD	-	149	4.1×10^4	-	2	no
CdSe/ZnS QD	-	3.3	10^4	-	6	yes
CdSe/ZnS QD	10	23	5×10^3	0.01	2	no
CdSe/ZnS QD	10^4	68.5	10^4	-	2	no
CdSe/ZnS QD	6.9×10^4	73	10^4	-	7	yes
CdSe/ZnS QD	10^4	58	10^4	0.08	2	no

[6] Semiconductor Quantum Dots for Memories and Neuromorphic Computing Systems Ziyu Lv,§ Yan Wang,§ Jingrui Chen, Junjie Wang, Ye Zhou, and Su-Ting Han**

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Representative Parameters of the QD-Based RRAM Devices [6]

QD materials	device structure	V_{SET} (V)	V_{RESET} (V)	ON/OFF ratio	cycles	retention time
CdSe QD	Al/CdSe/ITO	−2.5	2.3	100	-	6000 s
	ITO/In_2O_3/CdSe/Al	−1	2	10^3	10^5	4000 s
	Ag/PMSSQ/CdSe: PMSSQ/PMSSQ/ITO	3.3	−4.9	10^4	-	10^4 s
	ITO/CdSe/Al/CdSe/Al	−0.45	2	10^4	10^5	4000 s
	Al/CdSe/Al/CdSe/ITO	2	−1	10^4	10^5	3000 s
CdSe-ZnS QD	Ti/CdSe-ZnS/Ti-TiOx/CdSe-ZnS/ITO	1	−2	100	10^5	1500 s
	Al/LiF/CdSe-ZnS: poly N-vinylcarbazole (PVK): TPBi/ITO/Glass/ITO/CdSe-ZnS: PVK/Al	1.45	-	3×10^3	-	-
	Al/CdSe-ZnS/AlOx/CdSe-ZnS/ITO	0.6	−2	10^3	2×10^5	2×10^4 s
	Ag/PMSSQ2/PMSSQ: CdSe-ZnS/PMSSQ1/ITO	−0.7	4.5	10^4	-	1×10^4 s
	azurin/CdSe-ZnS/Au	2	0.5	10^3	50	-
CdS-PbS QD	ITO/CdS-PbS: PMMA/Al	−2.1	-	10^5	-	14400 s
CdSe-ZnSe QD	Al/CdSe-ZnS: carbon nanotubes/ITO	1.1	−2.6	10^4	-	several days

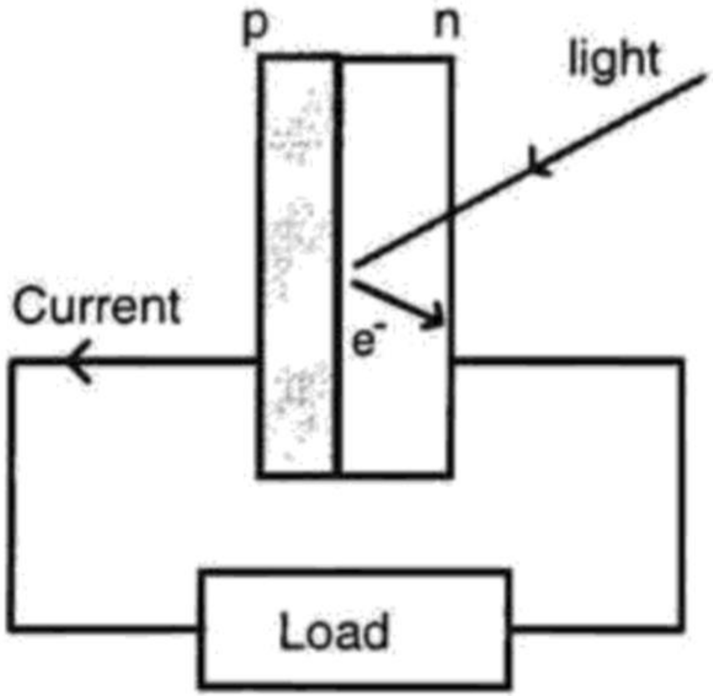
[6] Semiconductor Quantum Dots for Memories and Neuromorphic Computing Systems Ziyu Lv,§ Yan Wang,§ Jingrui Chen, Junjie Wang, Ye Zhou, and Su-Ting Han**

Quantum dots-sensitized solar cells

Nowadays :

- Storage system
- Conversion Efficiency
- Cost

- New generation ?



[7] *The physics of solar cells, Jenny Nelson 2003*

Comparative photovoltaic performance of CdSe QDs-sensitized solar cells

Photoanode structure and sensitizer	J_{SC} (mA cm^{-2})	V_{OC} (V)	FF	η (%)	Remarks
TiO_2 nanosheets (NSs) photoanode with high (001)-exposed facets (CdS/CdSe-sensitized)	15.07	0.58	0.51	4.42	Superior pore size, specific surface area, porosity, and electron transport properties
Cu_2S mesh CE sandwiched between two TiO_2 porous photoanodes (CdS/CdSe-sensitized) + concentrating photovoltage (CPV) concept	32.297	0.629	0.408	8.28	Photothermal effect accelerates polysulphide conversion reactions, very high J_{SC}
TiO_2 polydisperse mesoporous spheres (PMSs) and NPs hybrid photoanodes (CdS/CdSe co-sensitized)-bi layer film	14.06	0.608	0.55	4.70	Increased QDs loading and scattering effect, reduced RCM, structural advantages of PMSs and nanocrystals
ZnO/SnO_2 hierarchical NSs-based microflowers (ZS-MF) composite photoanode (CdS/CdSe co-sensitized)	14.3	0.607	0.572	4.98	Better light scattering and higher loading of QDs
3D-ordered macroporous (3DOM) TiO_2 films photoanode (CdSe-sensitized)	10.36	0.64	0.55	3.60	Large specific surface area and high QD loading, better transport and lesser recombination (RCM)

[8] Quantum dots-sensitized solar cells: a review on strategic developments, SUNDAR SINGH1,* , ZISHAN H KHAN2, MOHD BILAL KHAN2, PRAMOD KUMAR3 and PRAGATI KUMAR4

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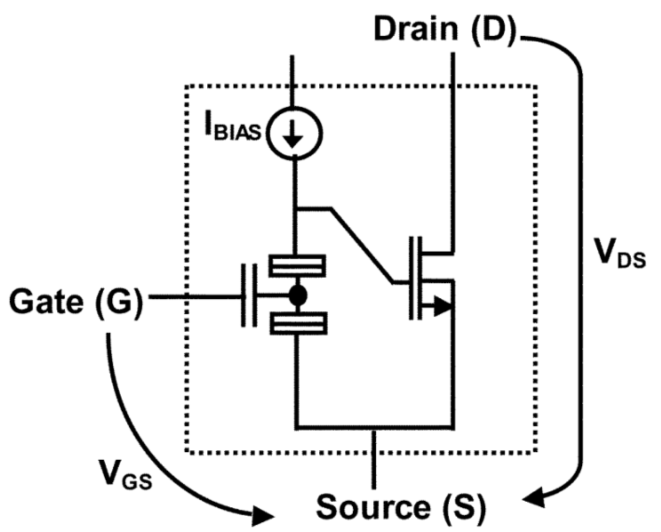
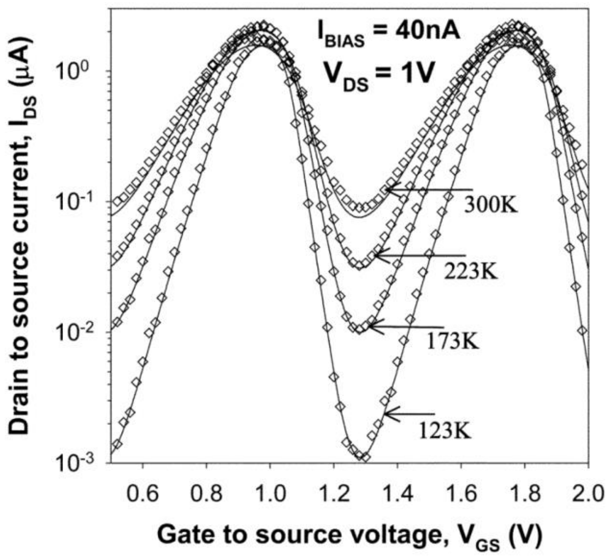
Hybrid CMOS-SET

Background charges

Room temperature $T_{max} < e^2/(40kC_{\Sigma})$



Schematic of the SETMOS device [9]



characteristics predicted by SMARTSPICE (solid line) at different temperatures [9]

[9] Analytical Modeling of Single Electron Transistor for Hybrid CMOS-SET Analog IC Design, Santanu Mahapatra et al

Other Applications

- high-sensitivity electrometer
- Single electron spectroscopy - Light-emitting diodes made from cadmium selenide nanocrystals
- Infrared detection
- voltage or current-controlled logic circuits
- programmable transistors
- Many more

Limits

- Temperature dependancy
- Background charges
- Precision and uniformity of the structure
- Power consumption/dissipation
- Fluctuations of the operation voltage
- Heavy-metal quantum dot semiconductors can be cytotoxic

Thank you for your attention

Annexe

- [1] *A hystory of the invention of the transistor and where it will lead us, William F. Brinkman et al, 1997*
- *[2] Single-Electron Devices and Their Applications, KONSTANTIN K. LIKHAREV 1999*
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