QE3. Nanoelectronics

- Nanoelectronic devices: quantum dots, nanowires
- graphene and 2D nanomaterials

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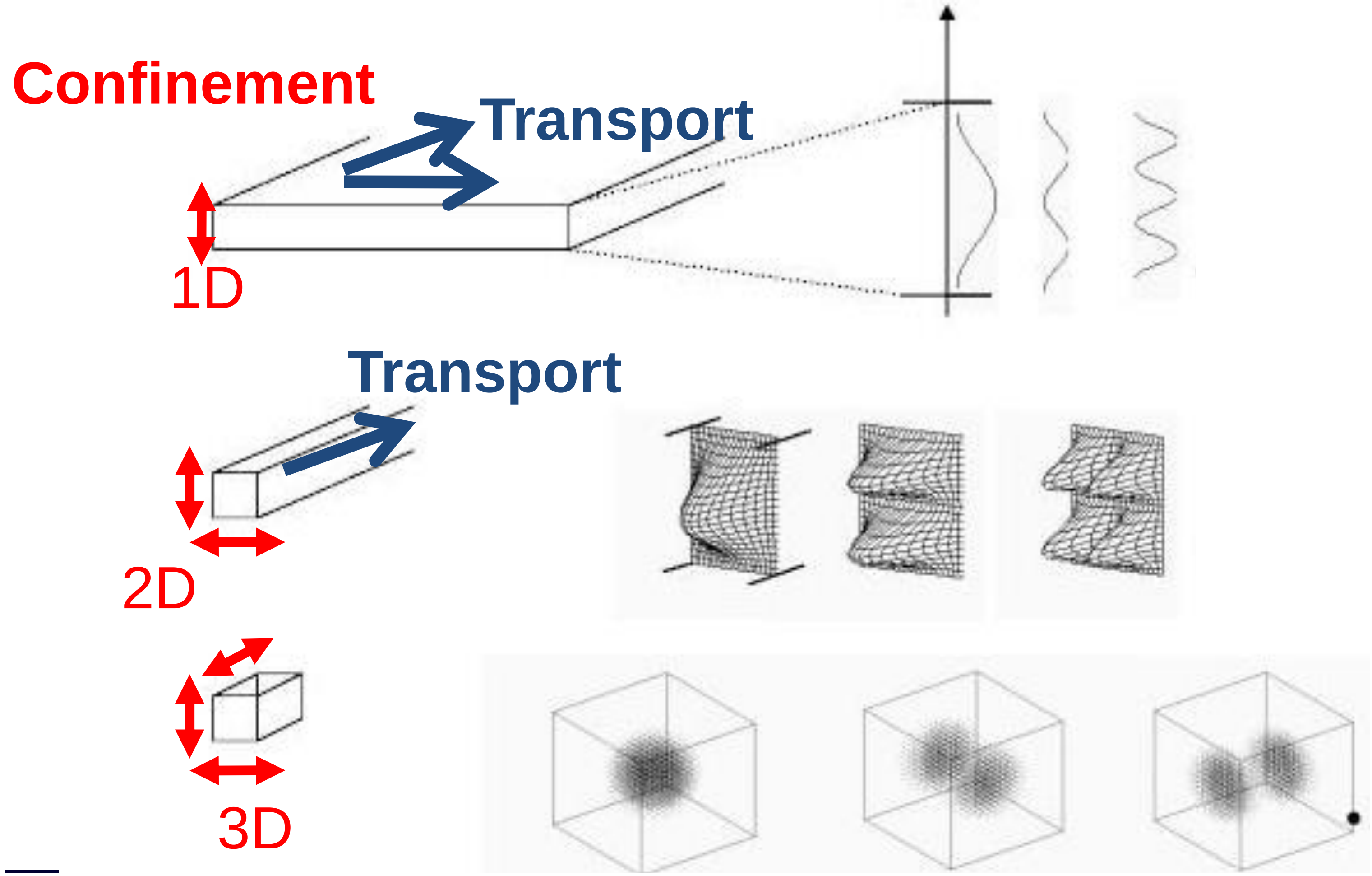
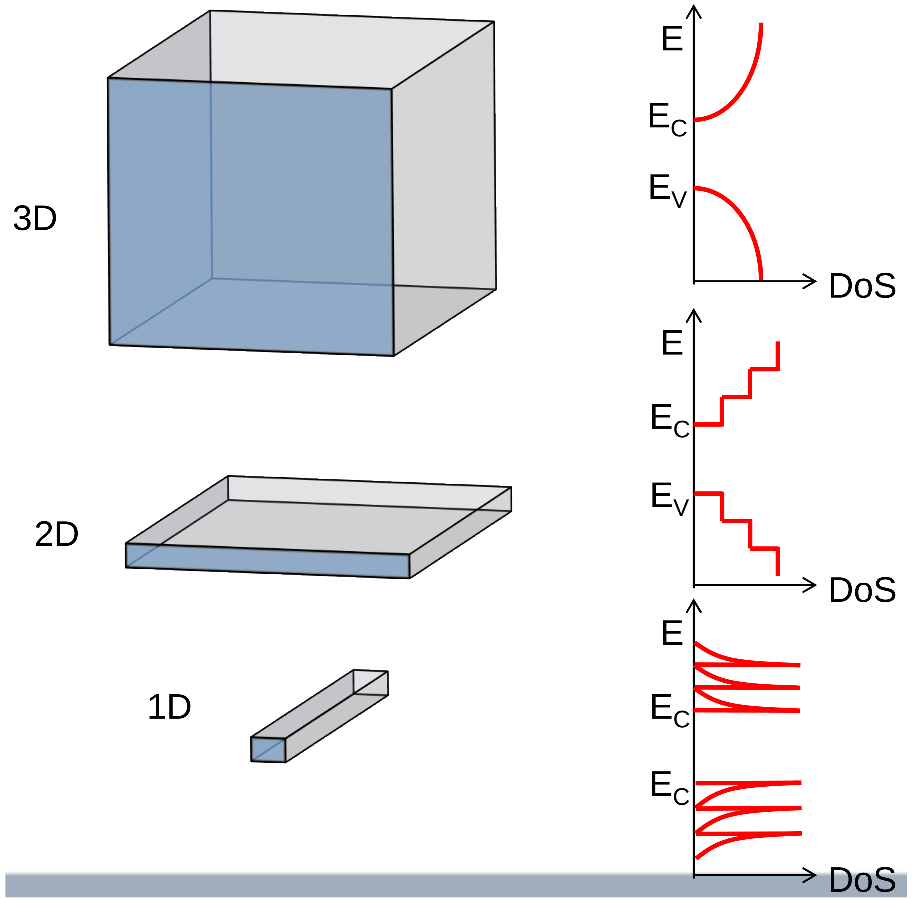
NATIONAL CENTRE FOR SCIENTIFIC RESEARCH "DEMOKRITOS"

Confinement effects: wavefunctions



Confinement effects: DoS



Energy Subbands

In a “large” silicon crystal electrons can move in the three directions of space. In a nanowire with a very small section, the electrons can only move along the length of the wire (*x*-direction) and form standing waves along the directions perpendicular to this motion. The electrons forming these standing waves have discrete energy values. Assuming a nanowire with rectangular cross-section (height=t_{si}, width=W_{si}), solving the 2D particle-in a box problem using Schrödinger’s equation yields the energy values:

$$E_{nynz} = \frac{\hbar^2}{2m_y^*}\left(\frac{\pi n_y}{t_{si}}\right)^2 + \frac{\hbar^2}{2m_z^*}\left(\frac{\pi n_z}{W_{si}}\right)^2$$

where n_y=1, 2, 3…, n_z=1, 2, 3… and where is the effective mass of electrons in the crystal i^{th}-direction of confinement. Adding to the values of the energy of the electron in the direction of motion along the nanowire,

$$E_x = \frac{\hbar k_x^2}{2m_x^*}$$

where k_x is the momentum of the electron in the *x*-direction, one finds out that the permitted energy levels for the electrons form a series of continuums within the conduction band, called “energy subbands”. Each subband has its own minimum energy value, , and the lowest energy subband is located at an energy

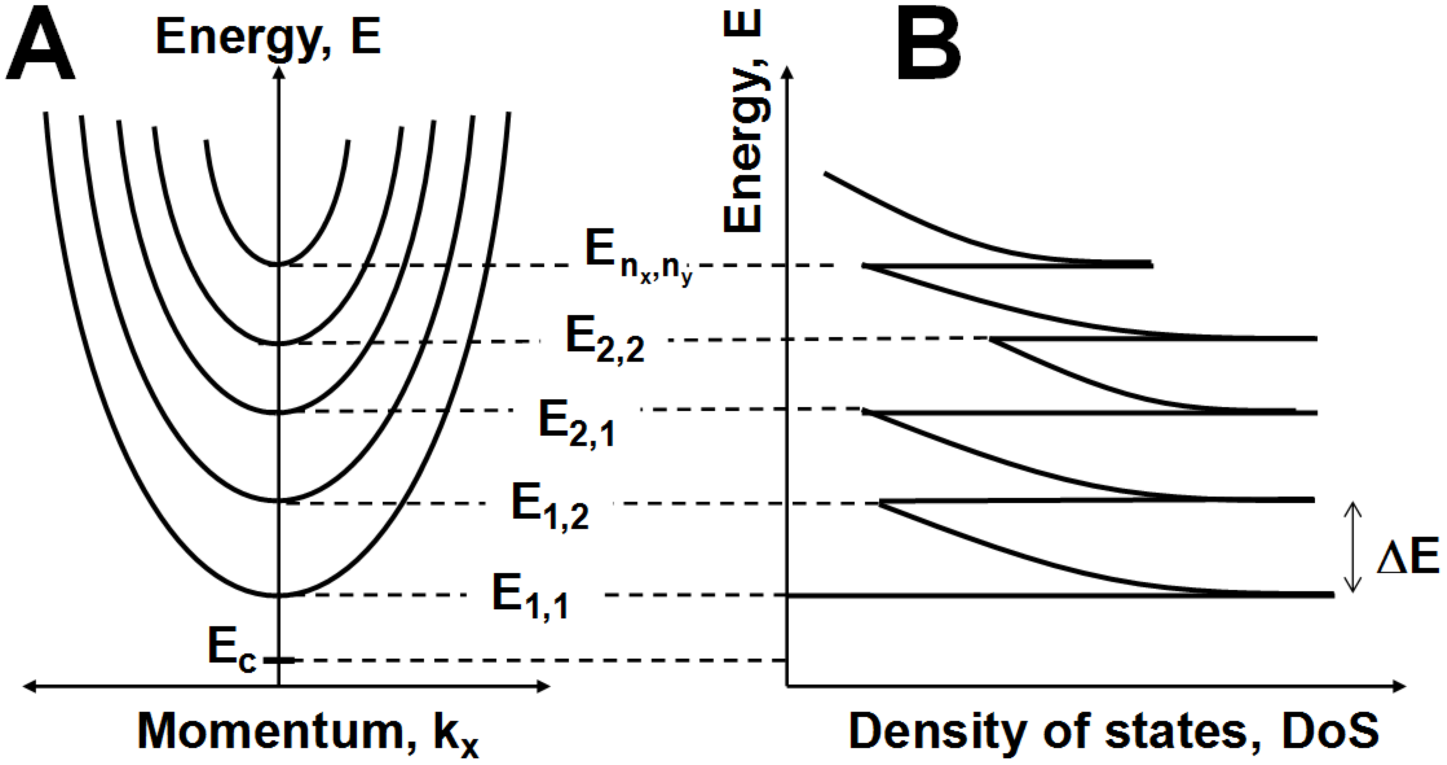
$$\frac{\hbar^2}{2m_y^*}\left(\frac{\pi}{t_{si}}\right)^2 + \frac{\hbar^2}{2m_z^*}\left(\frac{\pi}{W_{si}}\right)^2$$

above the 3D conduction band minimum. The density of states, ρ, in each subband is infinite at each ”resonance” energy level E_{nynz}, and it drops as a function of the square root of energy above these levels:

$$\rho = \frac{dn}{dE} = \frac{1}{\pi}\sqrt{\frac{2m}{\hbar^2}}\sqrt{E - E_{nynz}}$$

where *n* is the electron concentration.

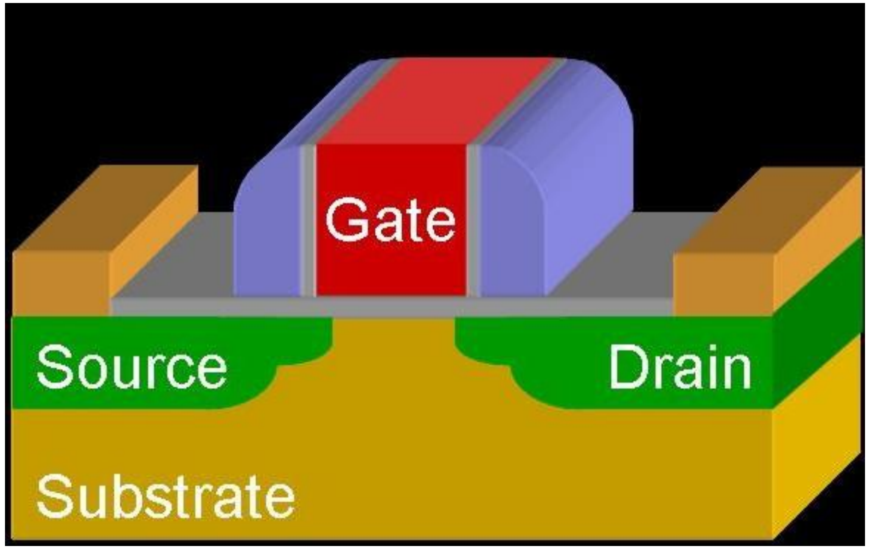
Energy subbands and Density of states

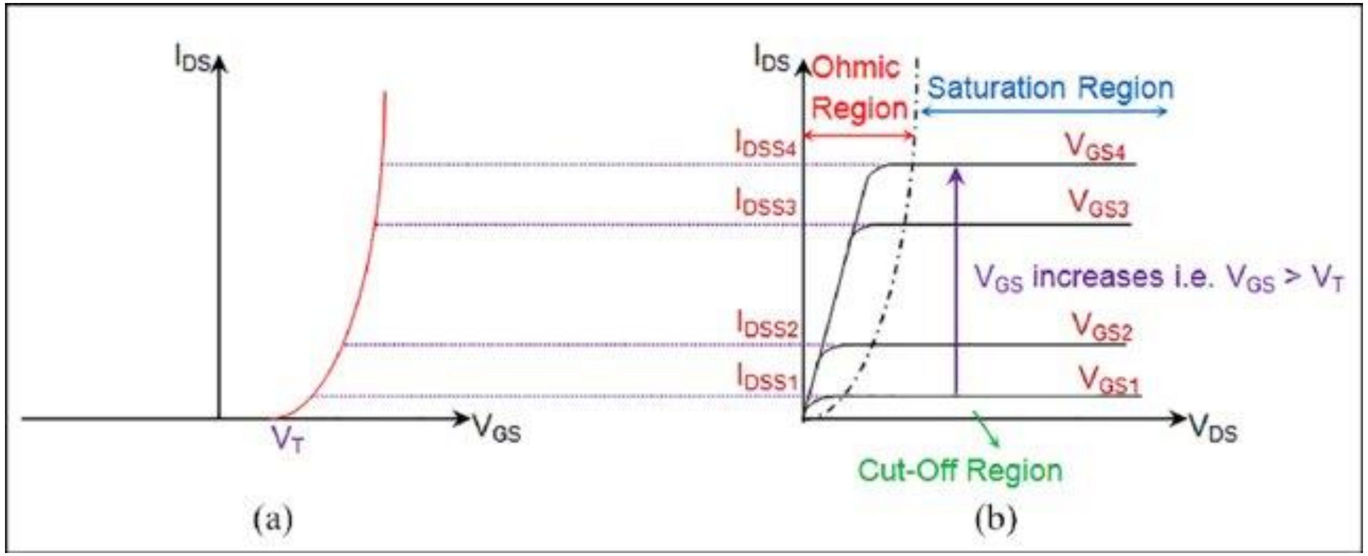


Energy vs. electron momentum in the transport direction x. Five subbands are shown in this example.

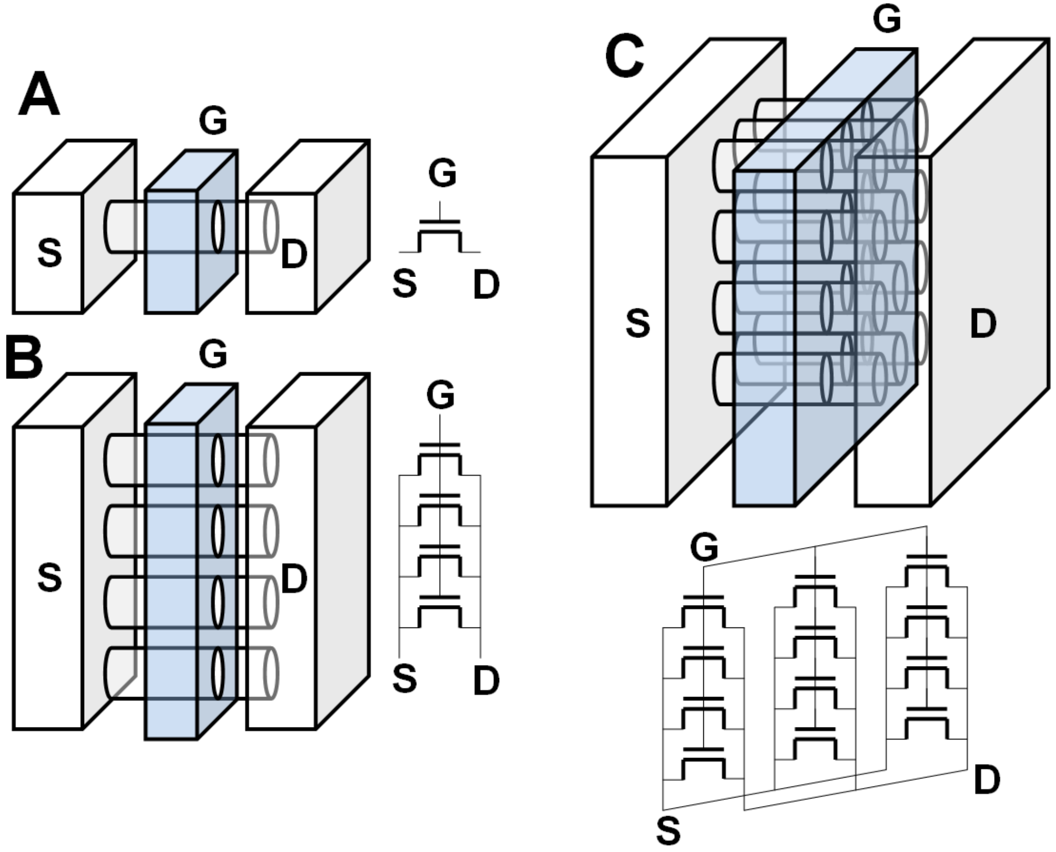
Density of states vs. energy. DE is the energy separation between the two first subbands with energies E1,1 and E1,2

MOSFET (planar)





Horizontal nanowire transistors

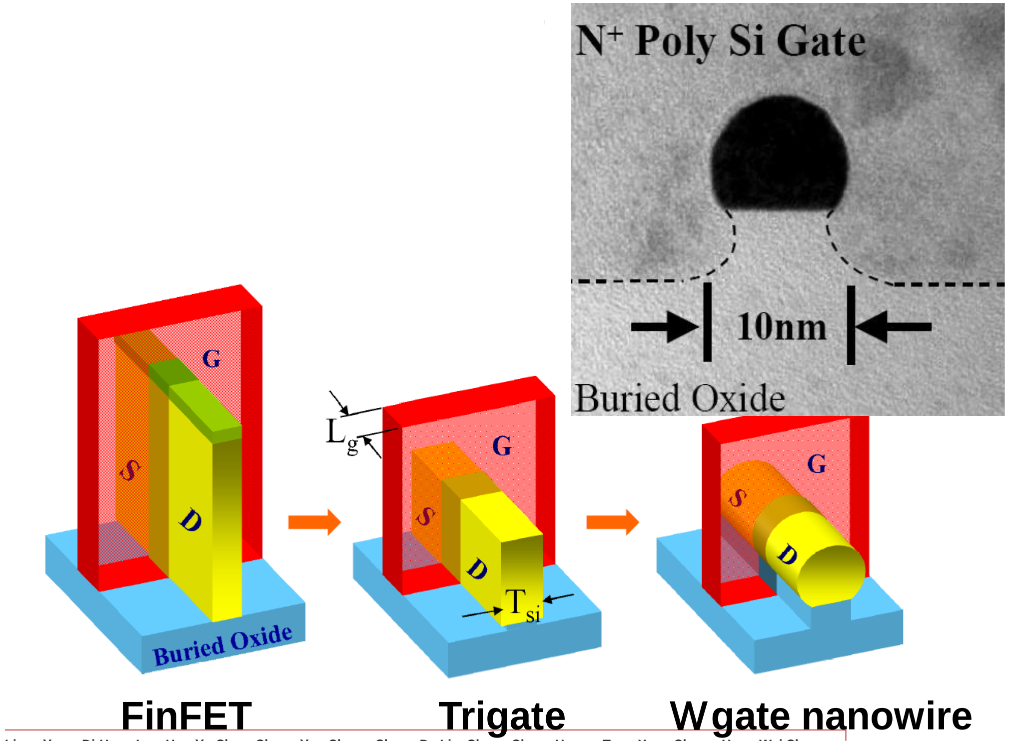


A: Single transistor.

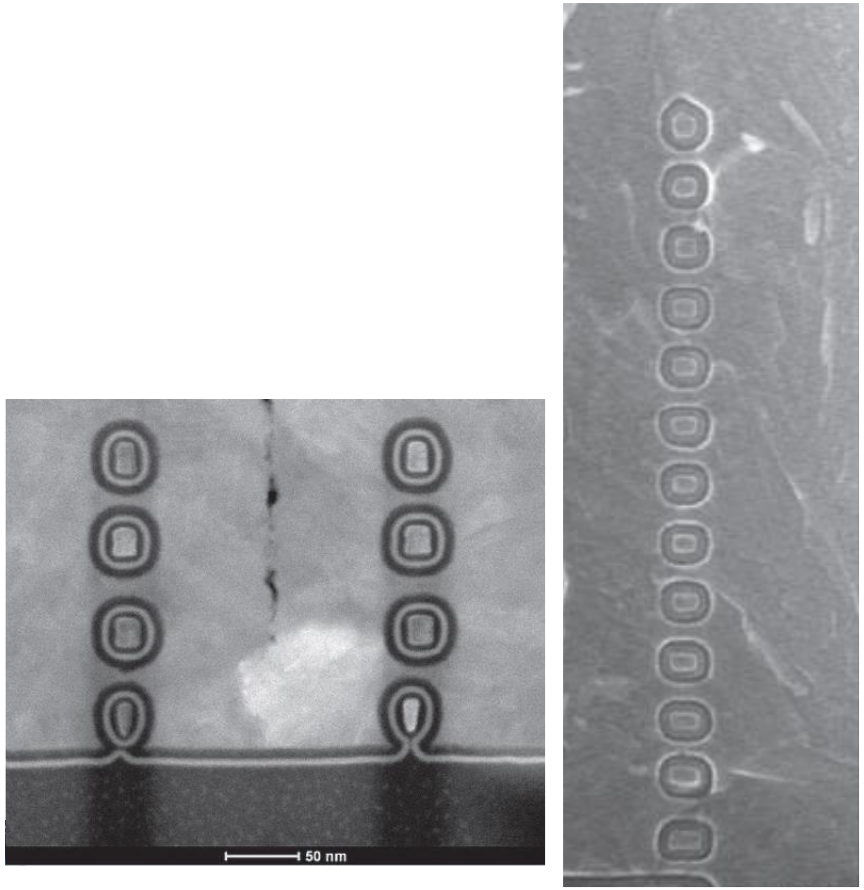
B: Four transistors in parallel occupying the footprint of a single transistor.

C: Twelve transistors in parallel occupying the footprint of four transistors.

Horizontal nanowire transistors

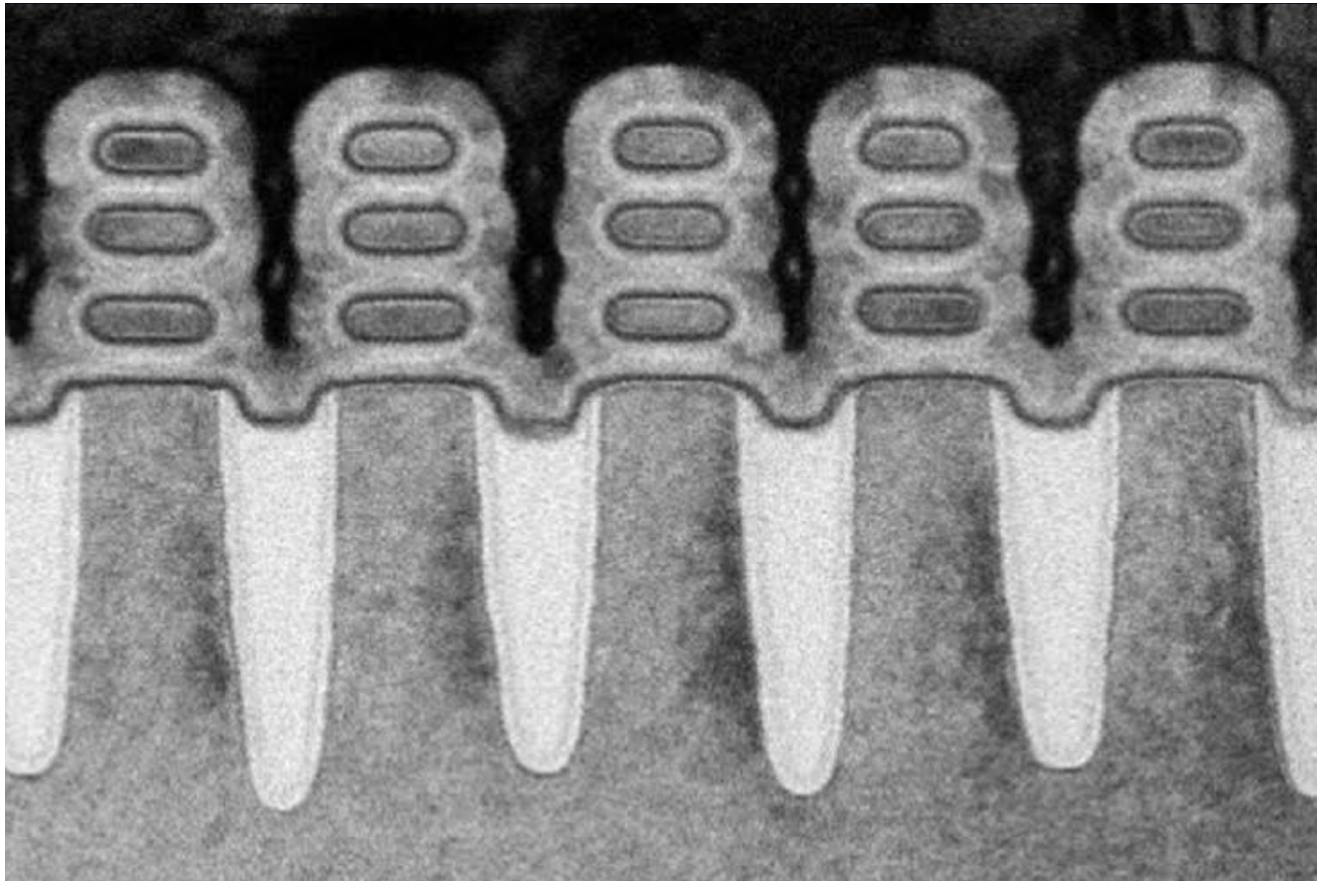


Single NW FET



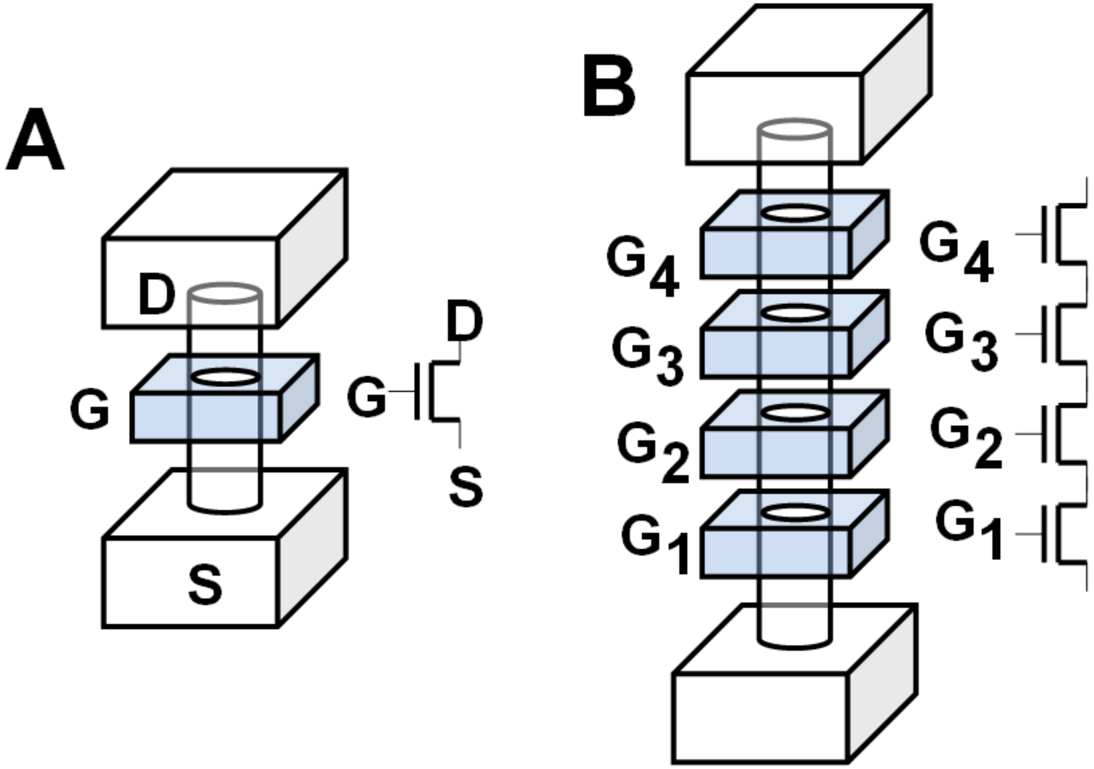
Stacked GAA NW FET

Stacked GAA nanowire transistors



IBM Claims 5nm Nanosheet Breakthrough

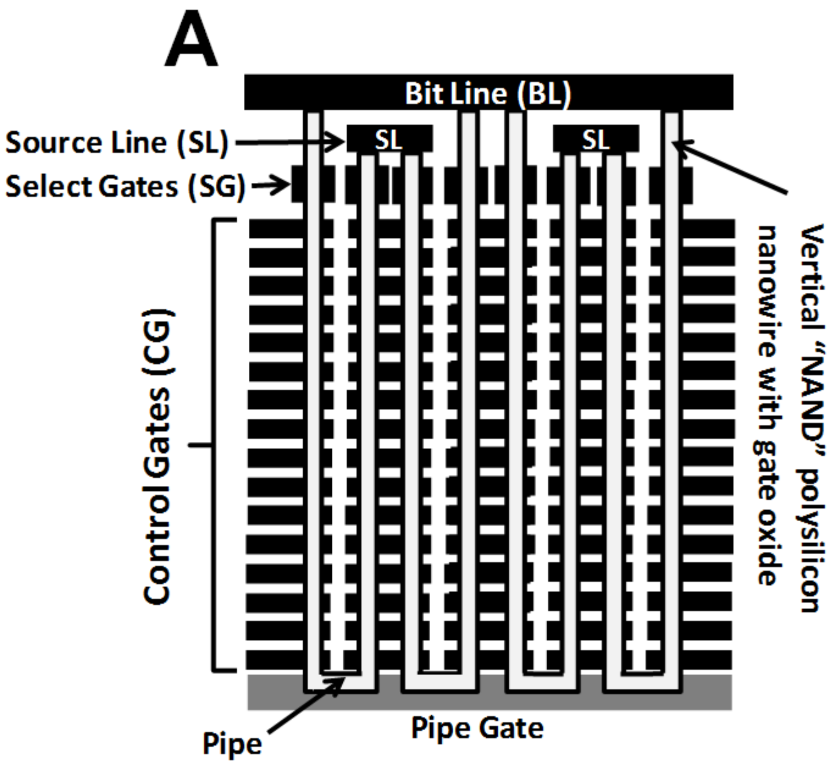
Vertical nanowire transistors



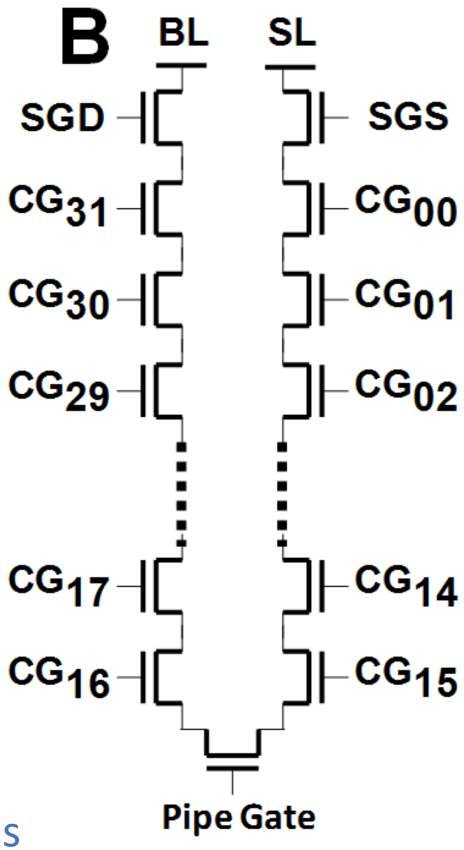
A: Single transistor.

B: Four transistors in series forming a NAND-type gate.

Vertical nanowire flash memory

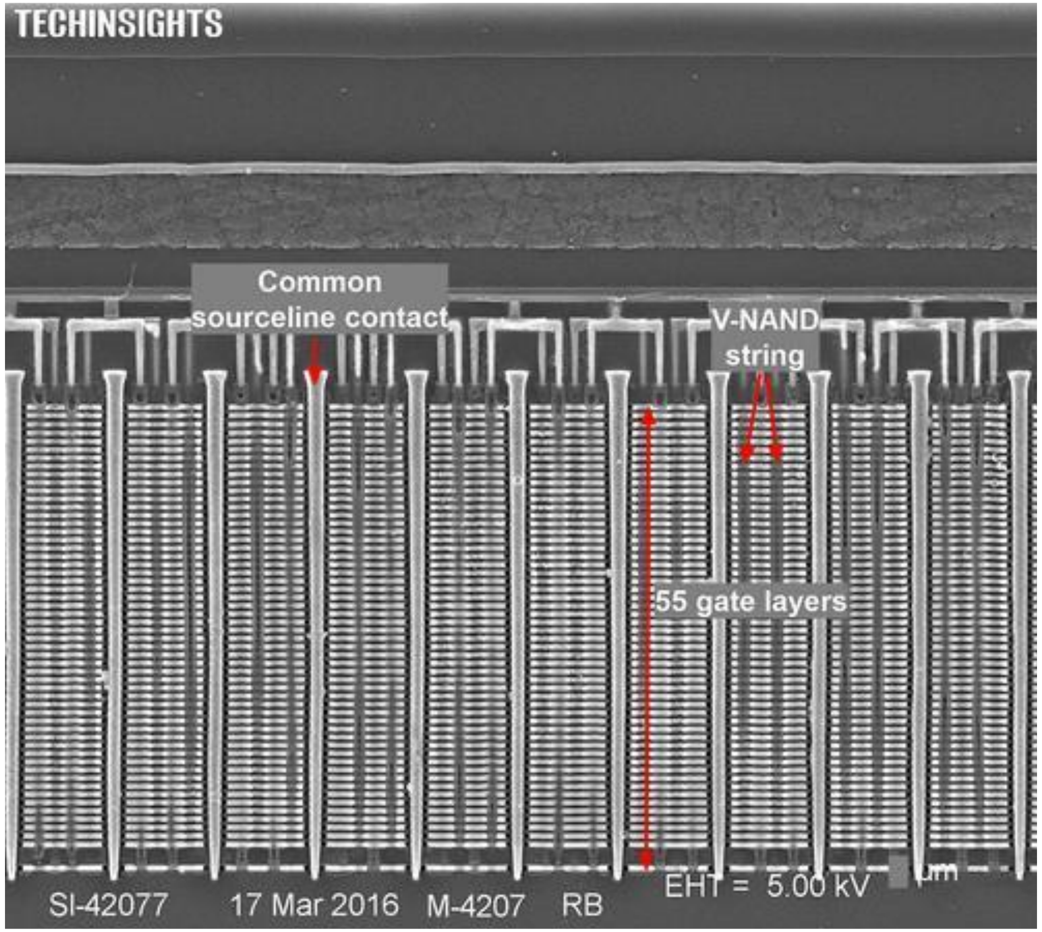


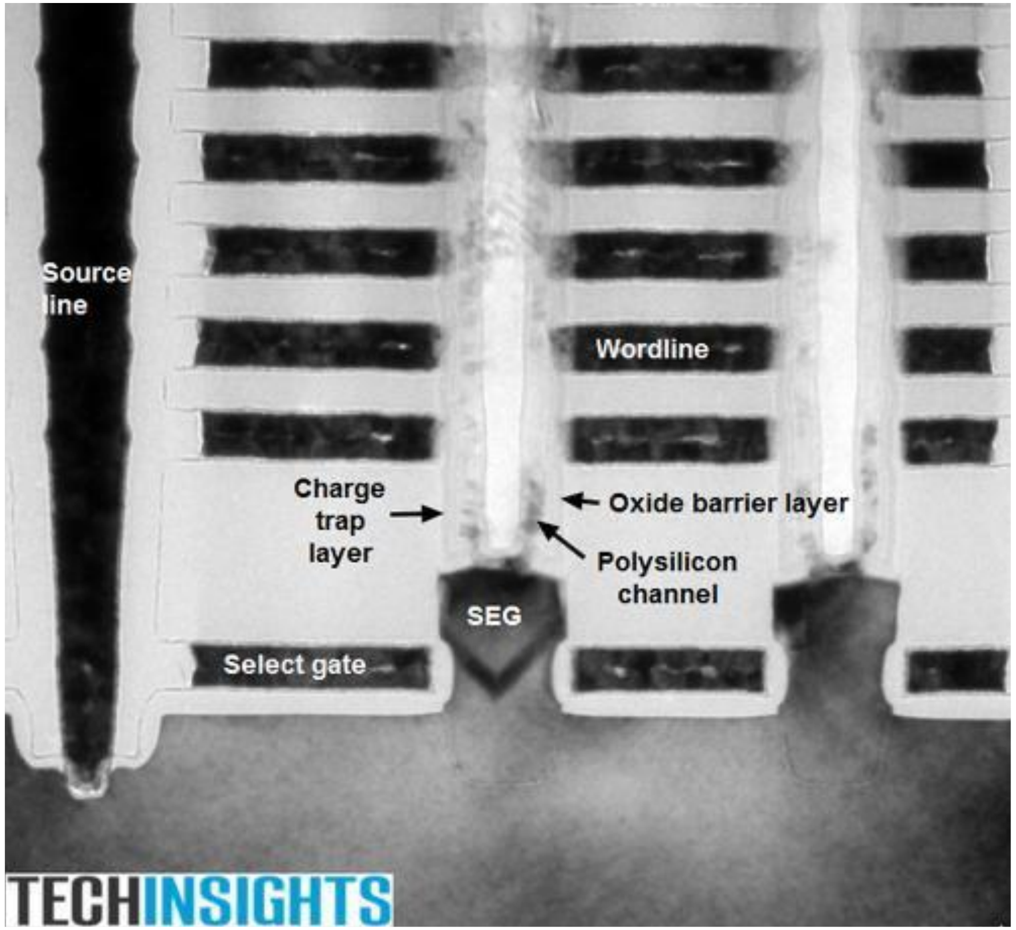
A: Cross section of the device showing multiple control gates (32 in series). The pipe gate allows to place 32 transistors in series using only 16 control gate layers.



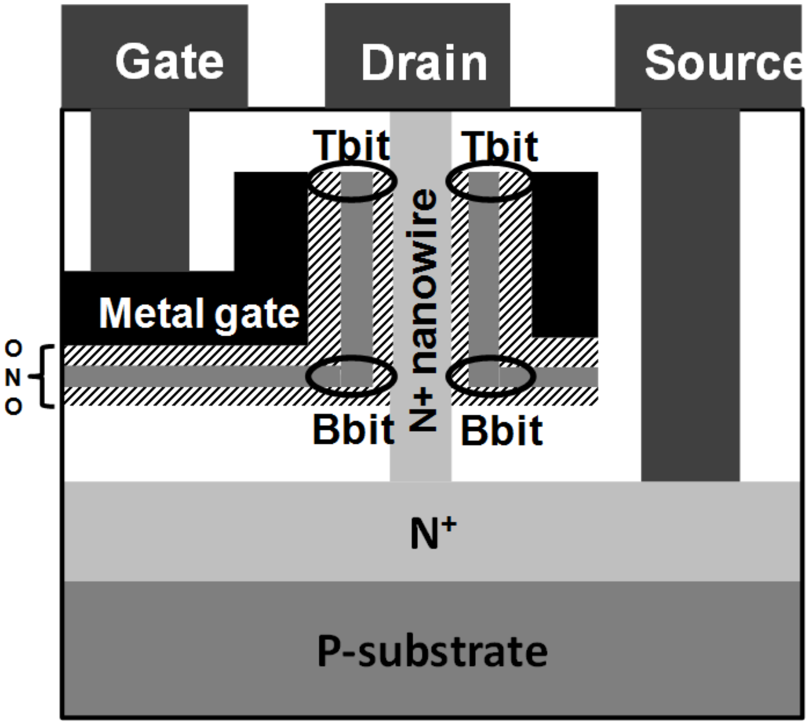
B: Equivalent circuit.

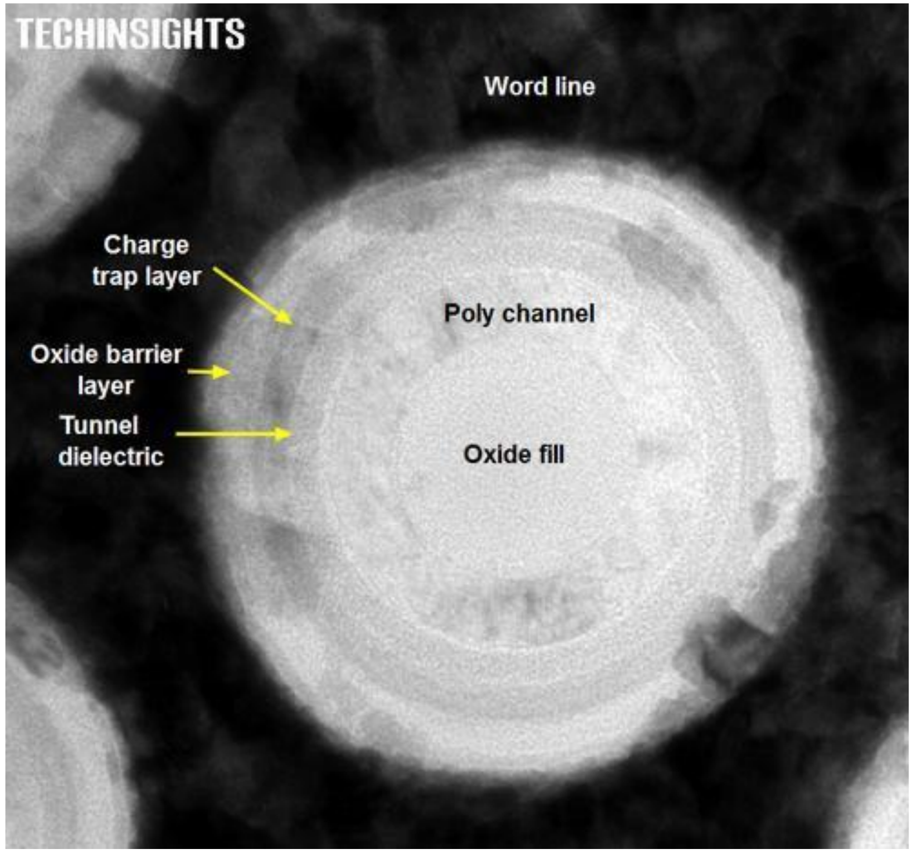
Samsung’s vertical NAND flash memory



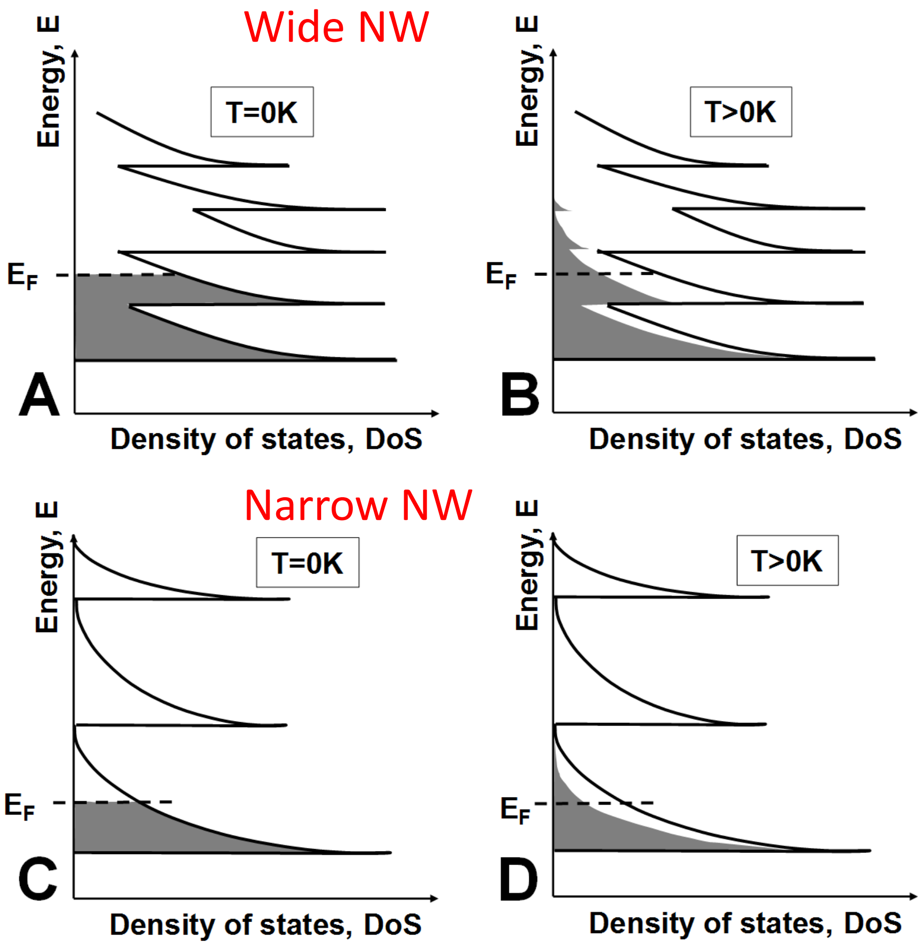


Samsung’s vertical NAND flash memory





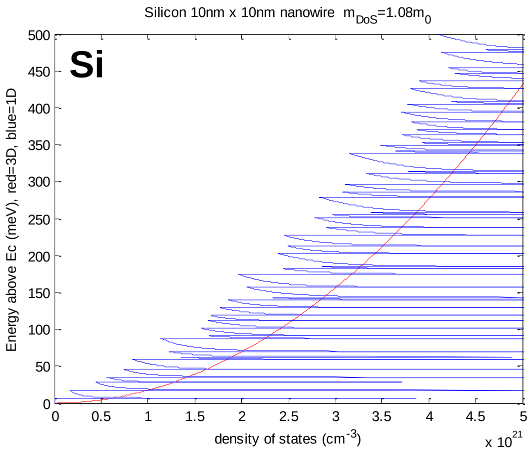
Density of states & Fermi-Dirac Function

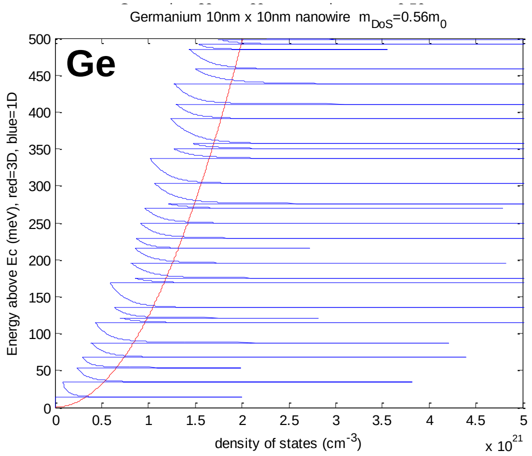


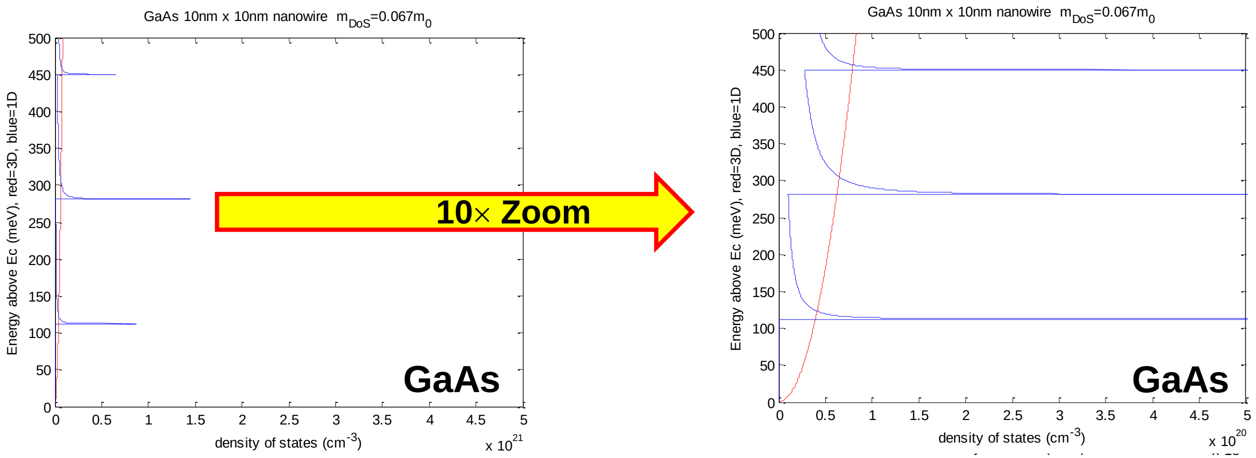
Density of states in nanowires with a larger (A,B) or smaller (C,D) cross section, and at T=0K or T>0K. The energy separation between subbands is larger in the nanowire with the smaller cross section. In the wider nanowire (A,B) we choose the Fermi Level such that part of the second subband is filled with electrons (in grey color) at T=0K. At T>0K, thermal energy electrons spreads electrons over the first four subbands.

In the narrower nanowire (C,D), we choose the Fermi Level such that part of the first subband is filled with electrons at T=0K. The energy separation between subbands is large enough for the electrons to remain confined to the first subband at T>0K.

DoS in Si, Ge, GaAs nanowires with square cross section of 10nm × 10nm

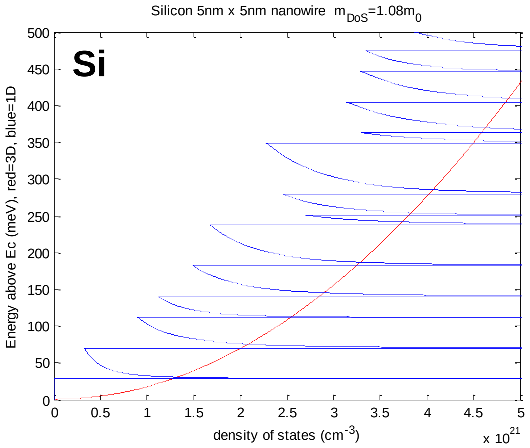

Silicon 10nm x 10nm nanowire $m_{DoS}=1.08m_0$

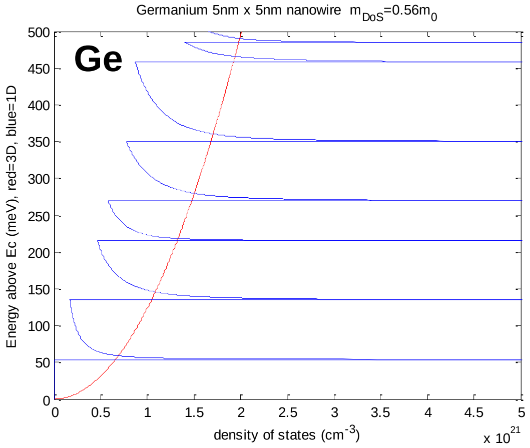

Germanium 10nm x 10nm nanowire $m_{DoS}=0.56m_0$

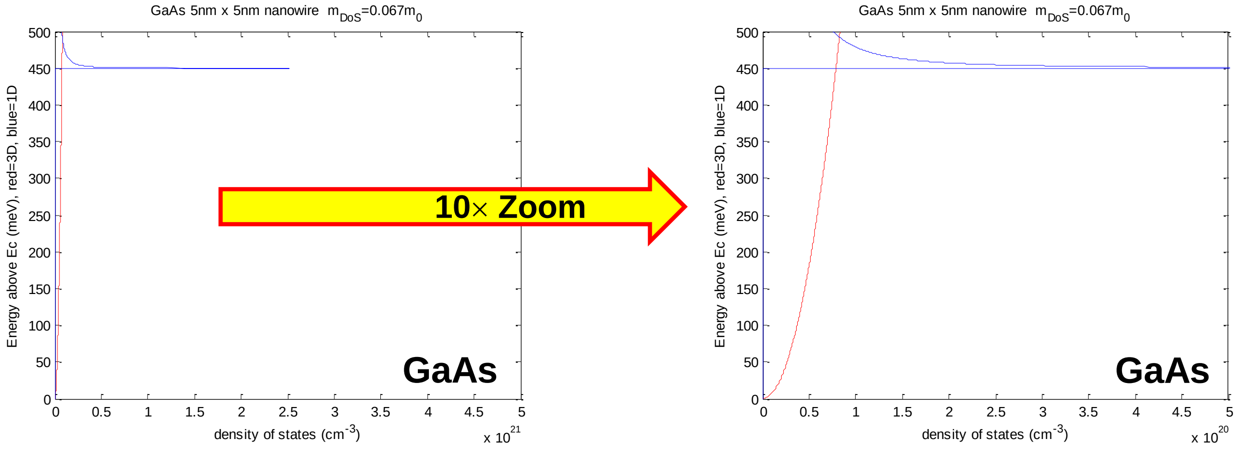

GaAs 10nm x 10nm nanowire $m_{DoS}=0.067m_0$

GaAs 10nm x 10nm nanowire $m_{DoS}=0.067m_0$

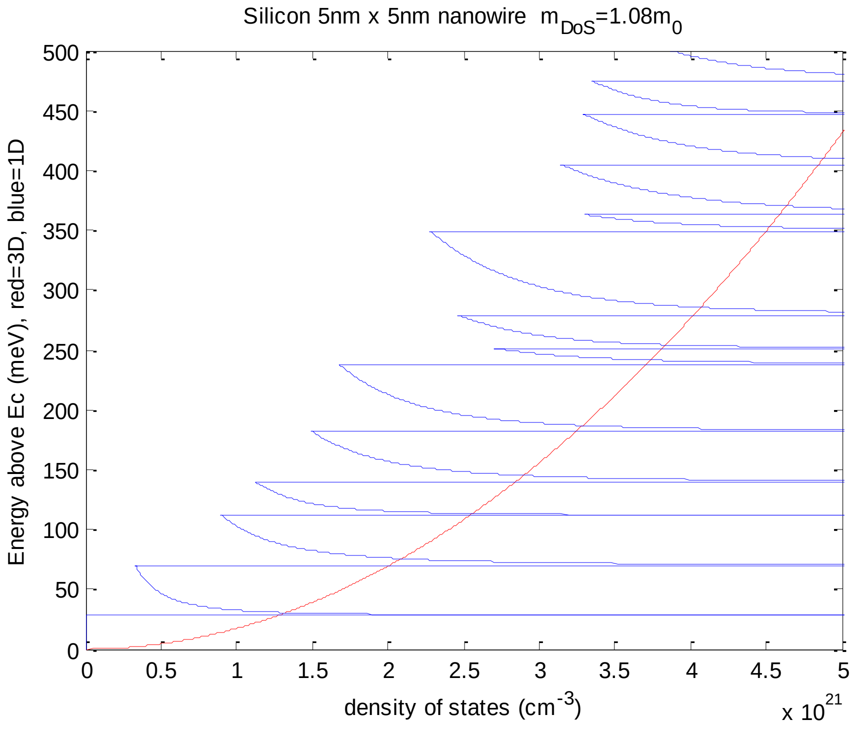
DoS in Si, Ge, GaAs nanowires with square cross section of 5nm × 5nm

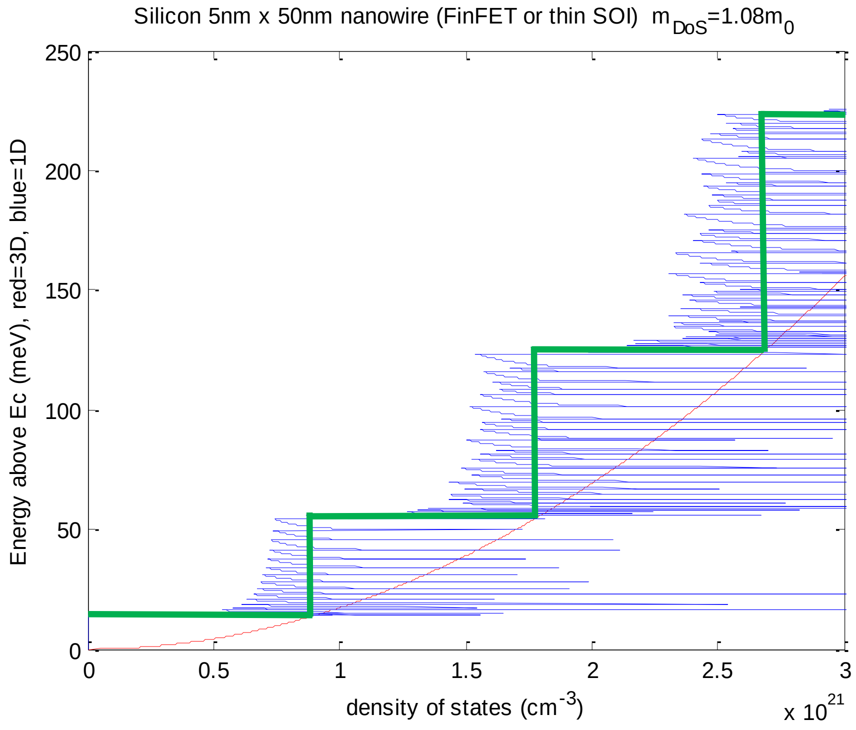




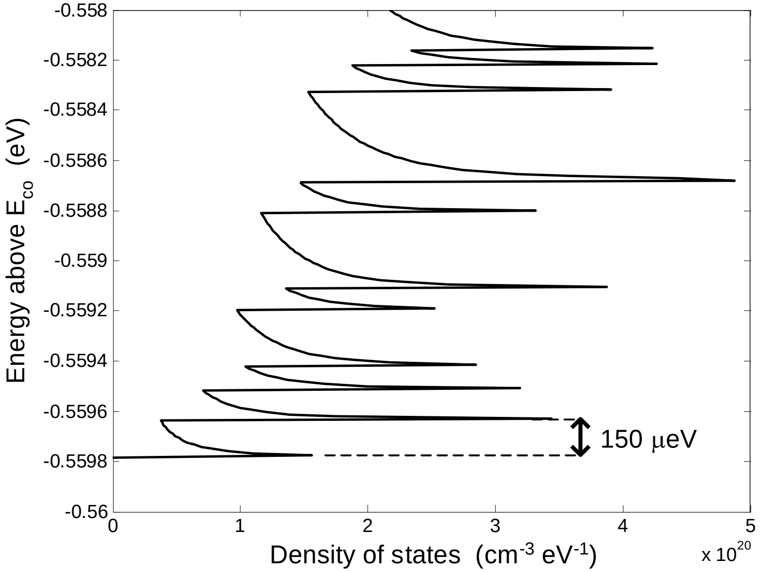


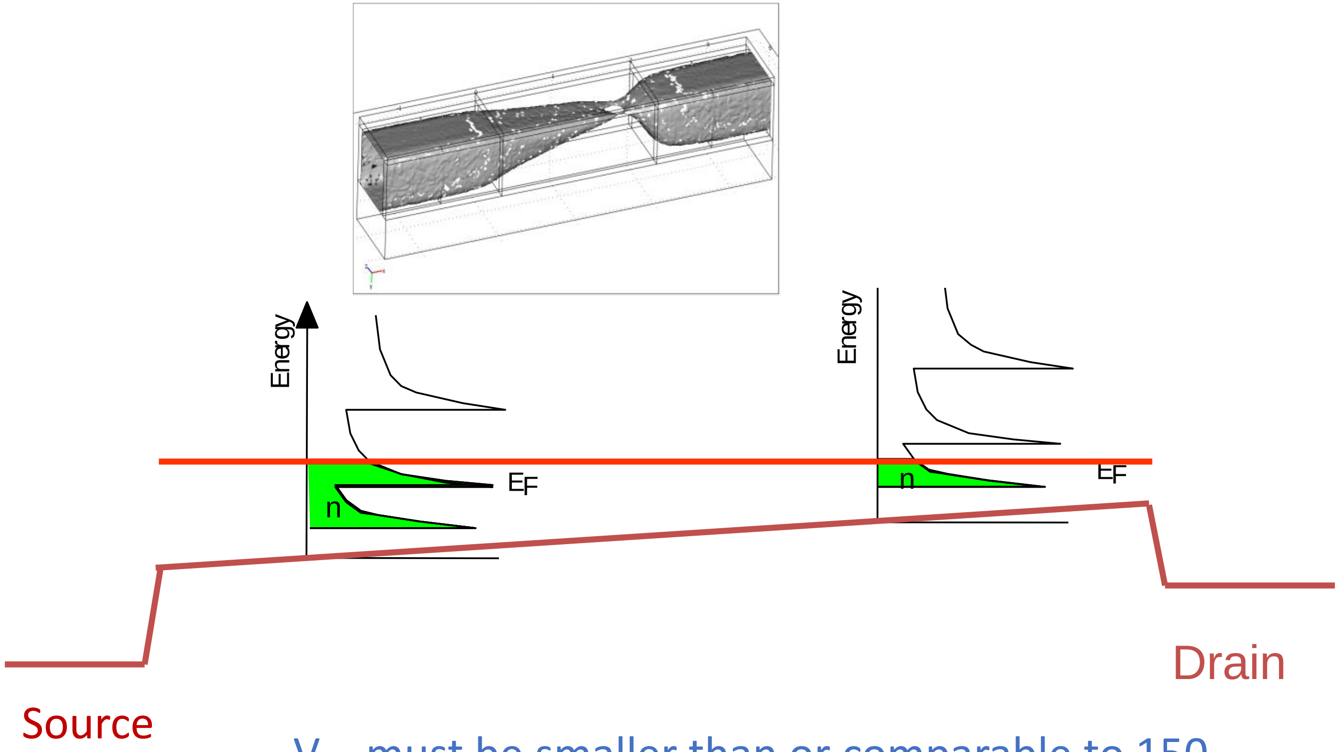
DoS in Si nanowires with cross sections of 5nm x 5nm and 5nm x 50nm





Subband Current Measurements

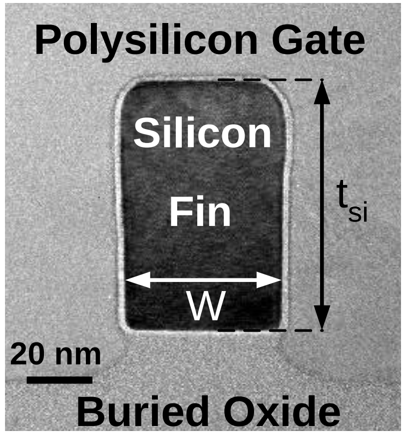


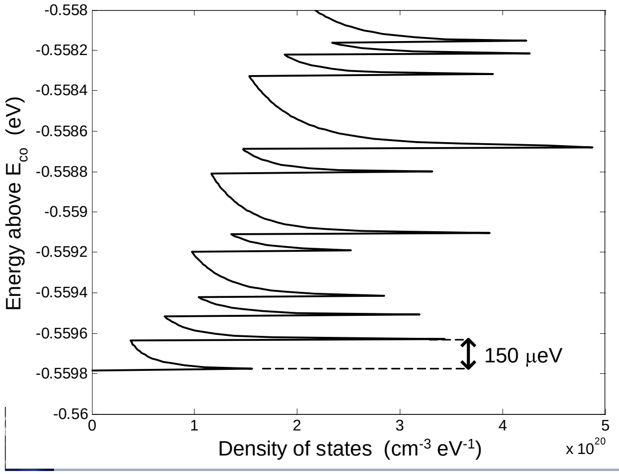


kT must be smaller than or comparable to 150 meV to resolve current in different subbands.

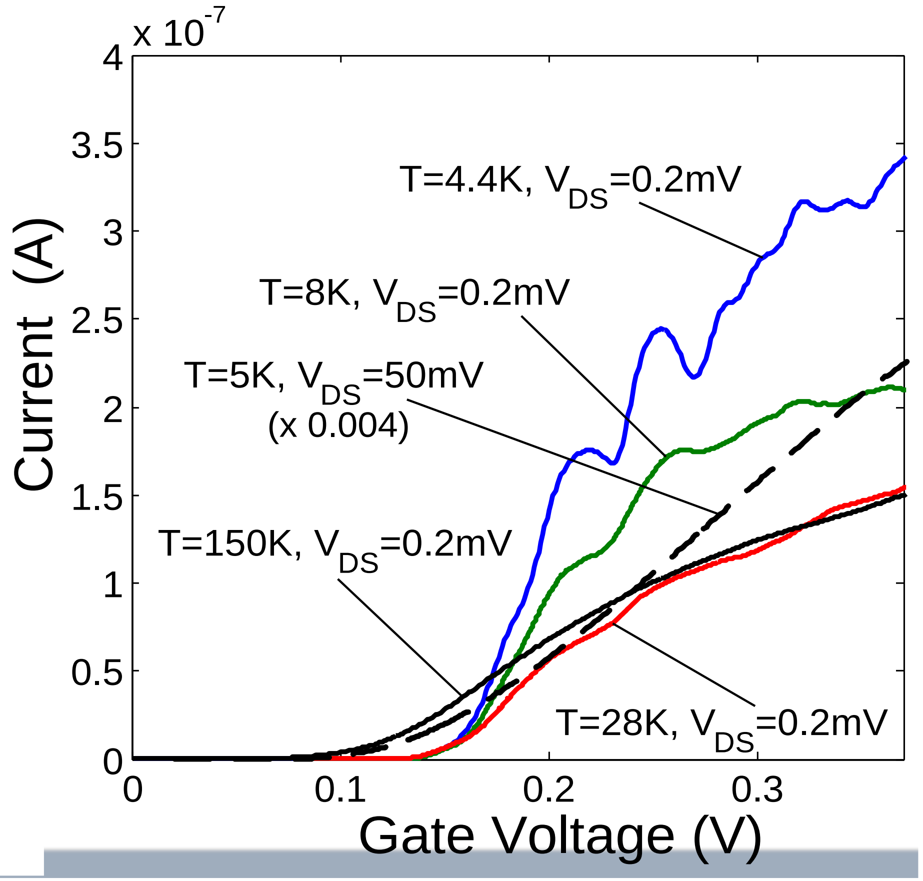
V_{DS} must be smaller than or comparable to 150 mV to resolve current in different subbands.

Nanoscale Quantum Phenomena





At low temperature



The End

THANK YOU

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Lesson	Kassap	Hanson
1		Chap.4, 9.1, 9.2, 9.3.1
2		
3		