

Fundamentals of Computer Systems

Transistors, Gates, and ICs

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Semiconductor

sem-i-con-duc-tor

noun

1. A substance, such as silicon or germanium, with electrical conductivity intermediate between that of an insulator and a conductor
2. A semiconductor device

Periodic Table of the Elements

The periodic table shows elements color-coded by groups. The following elements are circled in red: Boron (B), Carbon (C), Silicon (Si), Germanium (Ge), Arsenic (As), Antimony (Sb), and Tellurium (Te). Red arrows point from the letters 'B' and 'AS' above to the circled Boron and Arsenic elements, respectively.

1 IA H Hydrogen 1.008	2 IIA He Helium 4.003	3 IA Li Lithium 6.941	4 IIA Be Beryllium 9.012	5 IIIA B Boron 10.811	6 IVA C Carbon 12.011	7 VA N Nitrogen 14.007	8 VIA O Oxygen 15.999	9 VIIA F Fluorine 18.998	10 VIIIA Ne Neon 20.180	11 IA Na Sodium 22.990	12 IIA Mg Magnesium 24.305	13 IIIA Al Aluminum 26.982	14 IVA Si Silicon 28.086	15 VA P Phosphorus 30.974	16 VIA S Sulfur 32.065	17 VIIA Cl Chlorine 35.453	18 VIIIA Ar Argon 39.948	19 IA K Potassium 39.098	20 IIA Ca Calcium 40.078	21 IIIA Sc Scandium 44.956	22 IVA Ti Titanium 47.883	23 VA V Vanadium 50.942	24 VIA Cr Chromium 51.996	25 VIIA Mn Manganese 54.938	26 VIIIA Fe Iron 55.845	27 VIIIA Co Cobalt 58.933	28 VIIIA Ni Nickel 58.693	29 VIIIA Cu Copper 63.546	30 VIIIA Zn Zinc 65.38	31 IA Ga Gallium 69.723	32 IIA Ge Germanium 72.630	33 IIIA As Arsenic 74.922	34 IIIIA Se Selenium 78.96	35 IIIIA Br Bromine 79.904	36 IIIIA Kr Krypton 83.80	37 IA Rb Rubidium 85.468	38 IIA Sr Strontium 87.62	39 IIIA Y Yttrium 88.906	40 IIIIA Zr Zirconium 91.224	41 IIIIA Nb Niobium 92.906	42 IIIIA Mo Molybdenum 95.94	43 IIIIA Tc Technetium 98.906	44 IIIIA Ru Ruthenium 101.07	45 IIIIA Rh Rhodium 102.905	46 IIIIA Pd Palladium 106.42	47 IIIIA Ag Silver 107.868	48 IIIIA Cd Cadmium 112.411	49 IIIIA In Indium 114.818	50 IIIIA Sn Tin 118.710	51 IIIIA Sb Antimony 121.757	52 IIIIA Te Tellurium 127.6	53 IIIIA I Iodine 126.905	54 IIIIA Xe Xenon 131.29	55 IA Cs Cesium 132.905	56 IIA Ba Barium 137.327	57 IIIA La Lanthanum 138.905	58 IIIIA Ce Cerium 140.12	59 IIIIA Pr Praseodymium 140.908	60 IIIIA Nd Neodymium 144.24	61 IIIIA Pm Promethium 144.913	62 IIIIA Sm Samarium 150.36	63 IIIIA Eu Europium 151.964	64 IIIIA Gd Gadolinium 157.25	65 IIIIA Tb Terbium 158.925	66 IIIIA Dy Dysprosium 162.50	67 IIIIA Ho Holmium 164.930	68 IIIIA Er Erbium 167.255	69 IIIIA Tm Thulium 168.934	70 IIIIA Yb Ytterbium 173.054	71 IIIIA Lu Lutetium 174.967	72 IIIIA Ac Actinium 227.033	73 IIIIA Th Thorium 232.038	74 IIIIA Pa Protactinium 231.036	75 IIIIA U Uranium 238.029	76 IIIIA Np Neptunium 237.048	77 IIIIA Pu Plutonium 244.064	78 IIIIA Am Americium 243.061	79 IIIIA Cm Curium 247.070	80 IIIIA Bk Berkelium 247.070	81 IIIIA Cf Californium 251.08	82 IIIIA Es Einsteinium 252.083	83 IIIIA Fm Fermium 257.10	84 IIIIA Md Mendelevium 258.10	85 IIIIA No Nobelium 259.10	86 IIIIA Lr Lawrencium 260.10
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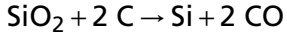
Legend:

- Alkali Metal
- Alkaline Earth
- Transition Metal
- Semimetal
- Nonmetal
- Basic Metal
- Halogen
- Noble Gas
- Lanthanide
- Actinide

Sand into Silicon



Silica a.k.a. SiO_2 a.k.a. Quartz

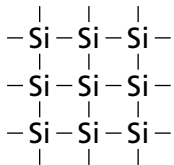


Elemental, amorphous silicon



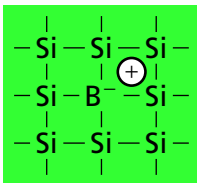
Monocrystalline
Silicon Ingot

Doping Silicon Makes It a Better Conductor



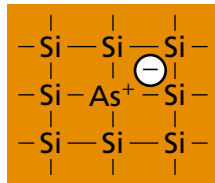
Undoped (pure)
silicon crystal

Not a good
conductor



p-type (doped)
silicon:

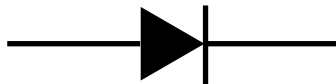
boron atom steals
a nearby electron



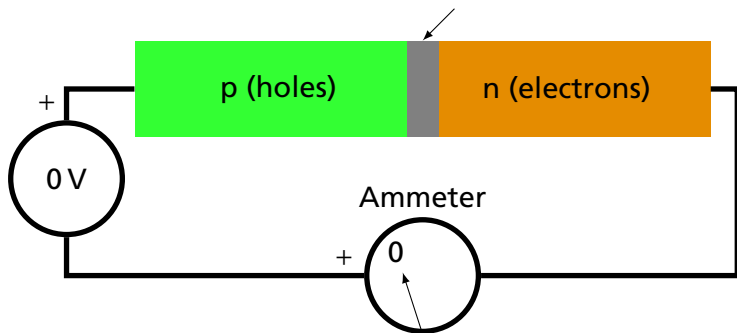
n-type (doped)
silicon:

arsenic's extra
electron jumps loose

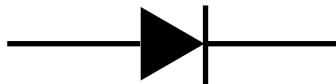
A PN Junction aka A Diode



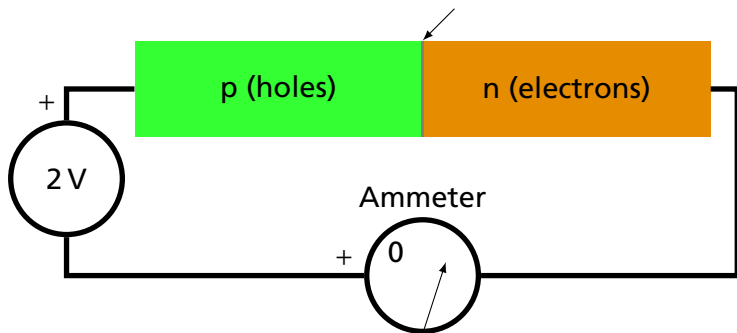
Depletion region



A PN Junction aka A Diode

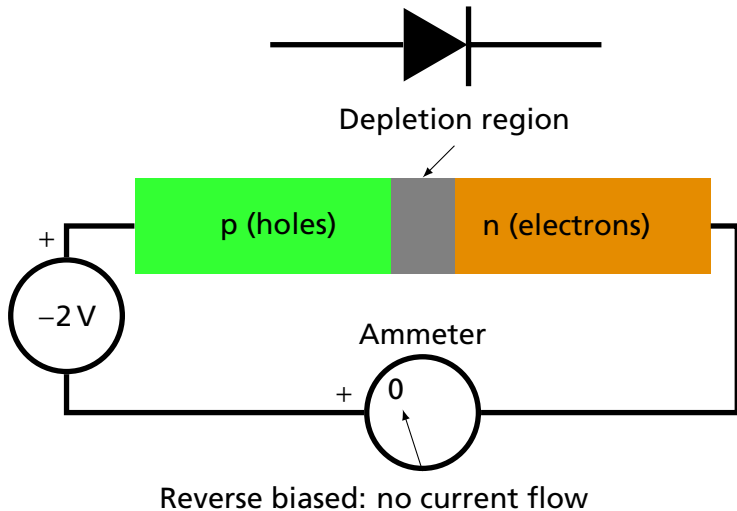


Depletion region

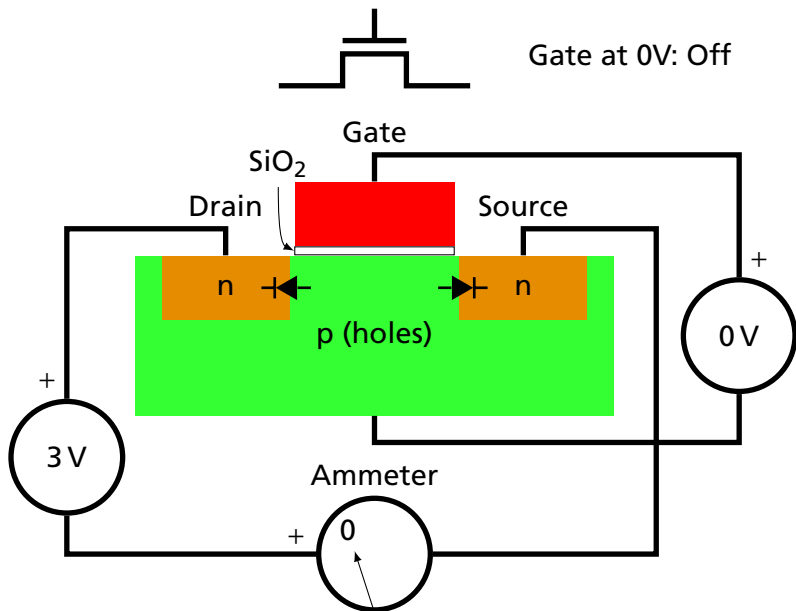


Forward biased: current flows

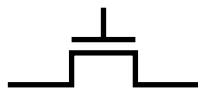
A PN Junction aka A Diode



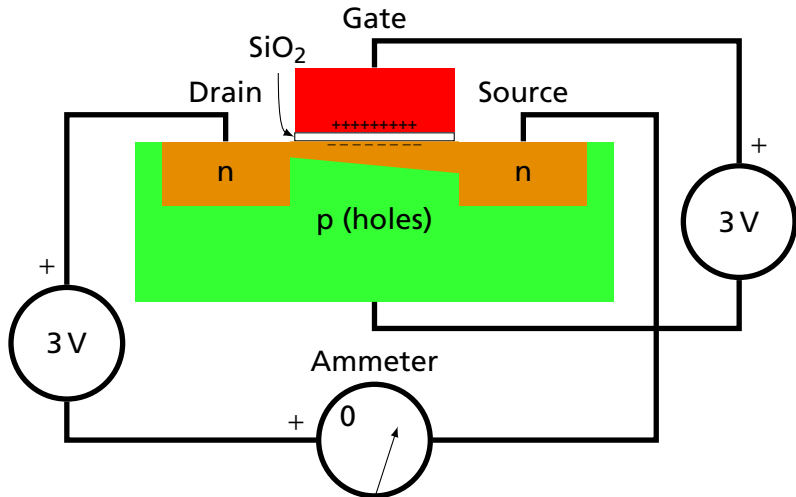
An N-Channel MOS Transistor



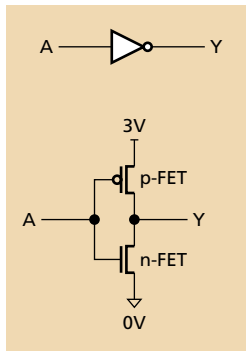
An N-Channel MOS Transistor



Gate positive: On



The CMOS Inverter

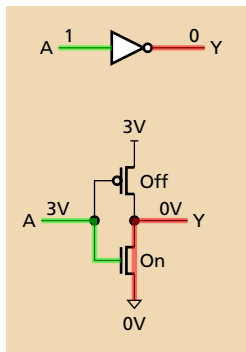


An inverter is built from two MOSFETs:

An n-FET connected to ground

A p-FET connected to the power supply

The CMOS Inverter



When the input is near the power supply voltage ("1"),

the p-FET is turned off;

the n-FET is turned on, connecting the output to ground ("0").

n-FETs are only good at passing 0's

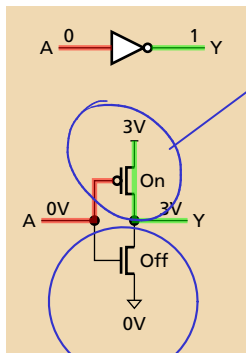
The CMOS Inverter

Pull up network
P FETs

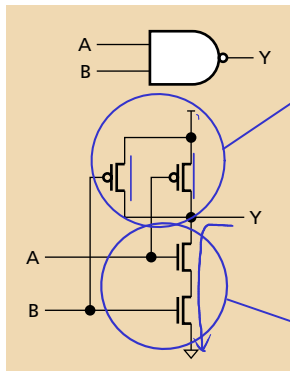
When the input is near ground ("0"),
the p-FET is turned on, connecting the
output to the power supply ("1");
the n-FET is turned off.

p-FETs are only good at passing 1's

Pull down network
N FETs



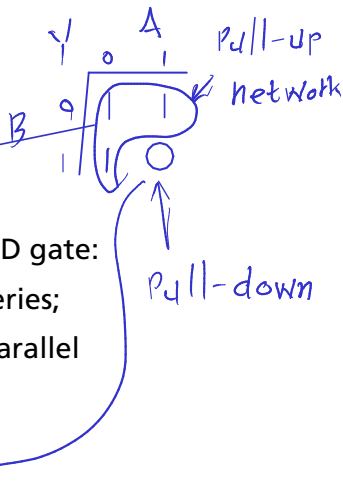
The CMOS NAND Gate



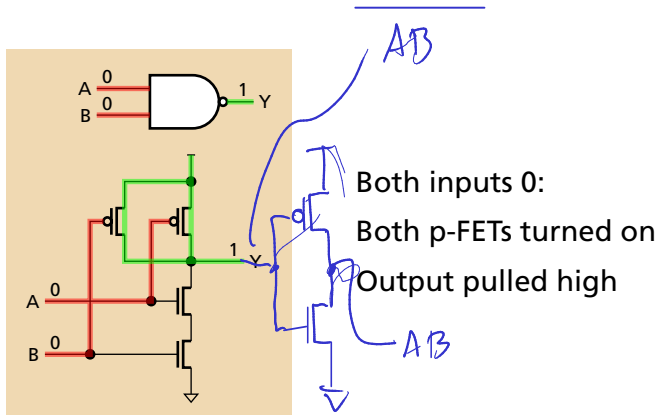
$$\bar{A} + \bar{B}$$

Two-input NAND gate:
two n-FETs in series;
two p-FETs in parallel

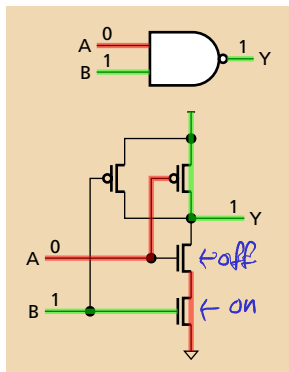
$$AB$$



The CMOS NAND Gate



The CMOS NAND Gate



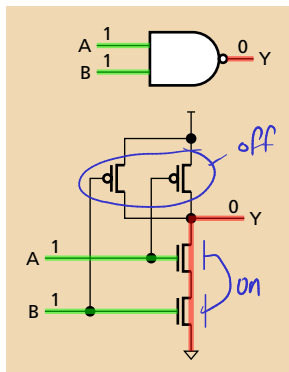
One input 1, the other 0:

One p-FET turned on

Output pulled high

One n-FET turned on, but does not control output

The CMOS NAND Gate



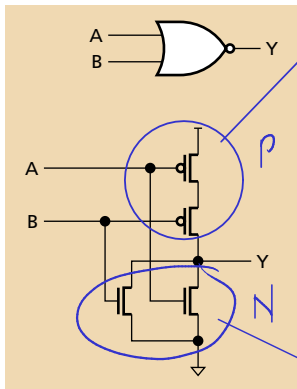
Both inputs 1:

Both n-FETs turned on

Output pulled low

Both p-FETs turned off

The CMOS NOR Gate



pull up network
on when $\bar{A} \bar{B}$

Two-input NOR gate:

two n-FETs in parallel;

two p-FETs in series.

Not as fast as the NAND gate
because n-FETs are faster than
p-FETs

$$\frac{\bar{A} \bar{B}}{A + B}$$

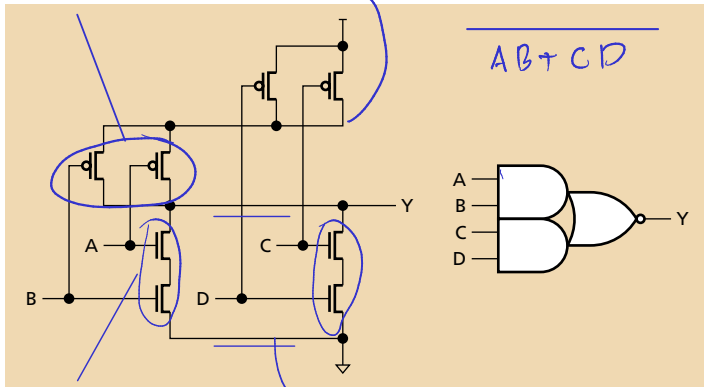
= 0 when $A + B$

$$\frac{\bar{A} \bar{B}}{A + B} = \text{NOR}$$

CMOS
NAND is GOD

A CMOS AND-OR-INVERT Gate

A parallel B (A+B) (C+D) series



$$AB + CD$$

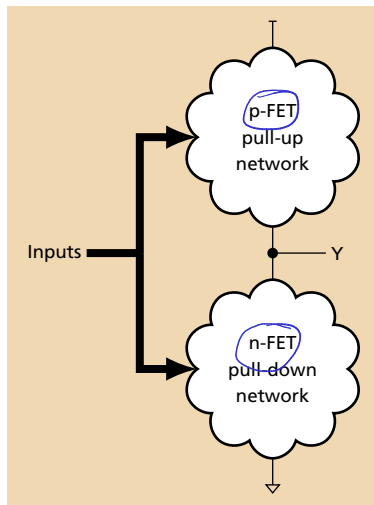
Pull up

↑ comp.

↓ Pull down

A series B "AB" parallel "CD"

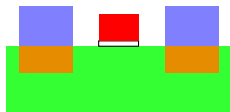
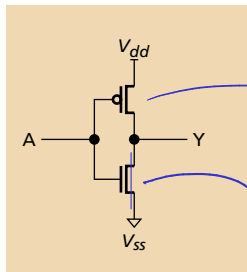
Static CMOS Gate Structure



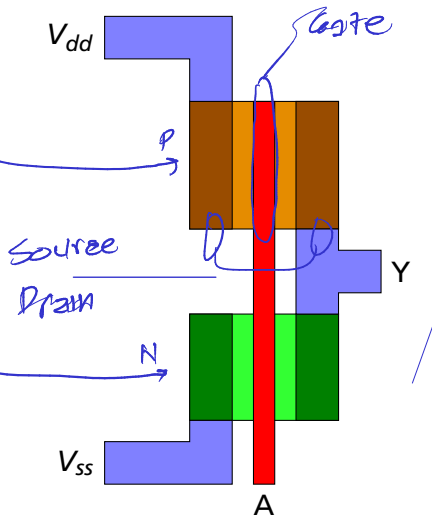
Pull-up and Pull-down networks must be complementary; exactly one should be connected for each input combination.

Series connection in one should be parallel in the other

CMOS Inverter Layout



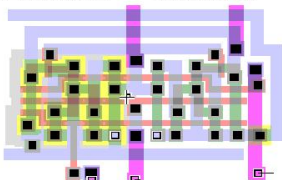
Cross Section Through
N-channel FET



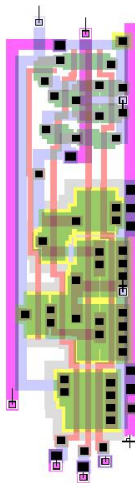
Top View

Full Adder Layouts

fa_ly_mini_jk size: 60 · 40 μ m (1.2 μ mCMOS)



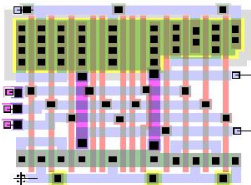
fa_ly_jtt size: 117 · 31 μ m (1.2 μ mCMOS)



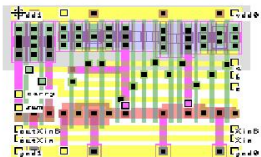
fa_ly_opt1 size: 63 · 50 μ m (1.2 μ mCMOS)

A
B
C

G

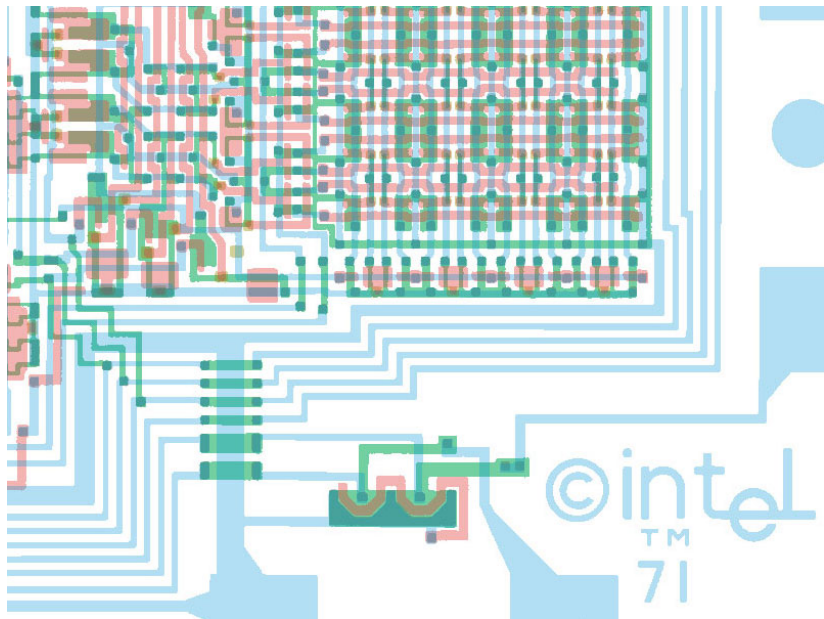


Fulladd L size: 37 · 26 μ m (0.5 μ mCMOS)



From <http://book.huihoo.com/design-of-vlsi-systems/>

Intel 4004 Masks



Intel 4004 Die Photograph

