

# Fundamentals of Computer Systems

Transistors, Gates, and ICs

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Summer 2016

# 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

1 IA TIA	2 IIA ZA	Periodic Table of the Elements																18 VIIIA 8A																																																																																																											
1 H Hydrogen 1.008	4 He Helium 4.003	13 B Boron 10.811	14 C Carbon 12.011	15 N Nitrogen 14.007	16 O Oxygen 15.999	17 F Fluorine 18.998	18 Ne Neon 20.180	3 Li Lithium 6.941	4 Be Beryllium 9.012	5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180	11 Na Sodium 22.990	12 Mg Magnesium 24.305	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948	19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.63	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80	37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.906	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.757	52 Te Tellurium 127.6	53 I Iodine 126.905	54 Xe Xenon 131.29	55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.384	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium 209	85 At Astatine 210	86 Rn Radon 222	87 Fr Francium 223	88 Ra Radium 226	89-103 Actinide Series	104 Rf Rutherfordium 261	105 Db Dubnium 262	106 Sg Seaborgium 263	107 Bh Bohrium 264	108 Hs Hassium 265	109 Mt Meitnerium 266	110 Ds Darmstadtium 267	111 Cn Copernicium 268	112 Uut Ununtrium 269	113 Uuq Ununquadium 270	114 Uup Ununpentium 271	115 Uuq Ununhexium 272	116 Uuo Ununseptium 273	117 Uus Ununseptium 274	118 Uuo Ununoctium 276	89 La Lanthanum 138.905	90 Ce Cerium 140.12	91 Pr Praseodymium 140.908	92 Nd Neodymium 144.24	93 Pm Promethium 144.913	94 Sm Samarium 150.36	95 Eu Europium 151.964	96 Gd Gadolinium 157.25	97 Tb Terbium 158.925	98 Dy Dysprosium 162.50	99 Ho Holmium 164.930	100 Er Erbium 167.255	101 Tm Thulium 168.934	102 Yb Ytterbium 173.054	103 Lu Lutetium 174.967	94 Ac Actinium 227	95 Th Thorium 232.038	96 Pa Protactinium 231.036	97 U Uranium 238.029	98 Np Neptunium 237.048	99 Pu Plutonium 244.064	100 Am Americium 243.061	101 Cm Curium 247.070	102 Bk Berkelium 247.070	103 Cf Californium 251.08	104 Es Einsteinium 252.083	105 Fm Fermium 257.10	106 Md Mendelevium 258.10	107 No Nobelium 259.10	108 Lr Lawrencium 260.10

Legend:

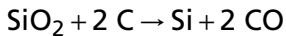
- Alkali Metal
- Alkaline Earth
- Transition Metal
- Semimetal
- Nonmetal
- Basic Metal
- Halogen
- Noble Gas
- Lanthanide
- Actinide

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# Sand into Silicon



Silica a.k.a.  $\text{SiO}_2$  a.k.a. Quartz

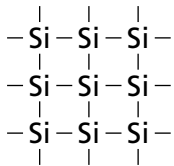


Elemental, amorphous silicon



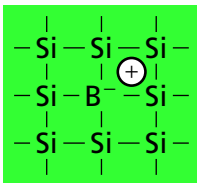
Monocrystalline  
Silicon Ingot

# Doping Silicon Makes It a Better Conductor



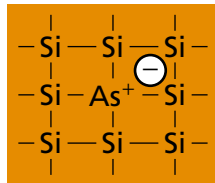
Undoped (pure)  
silicon crystal

Not a good  
conductor



p-type (doped)  
silicon:

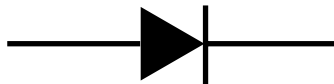
boron atom steals  
a nearby electron



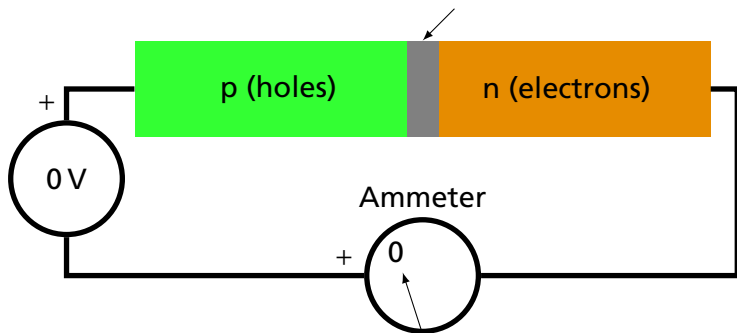
n-type (doped)  
silicon:

arsenic's extra  
electron jumps loose

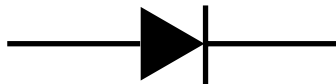
# A PN Junction aka A Diode



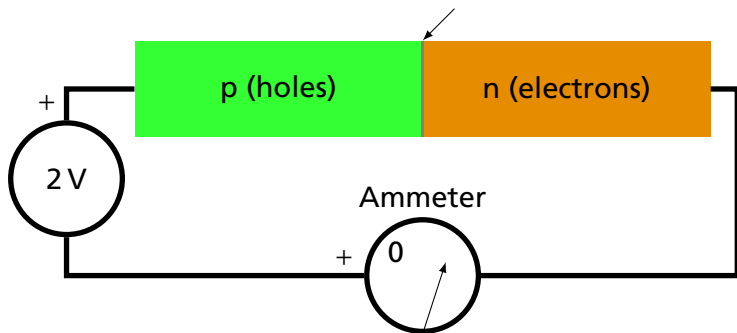
Depletion region



# A PN Junction aka A Diode

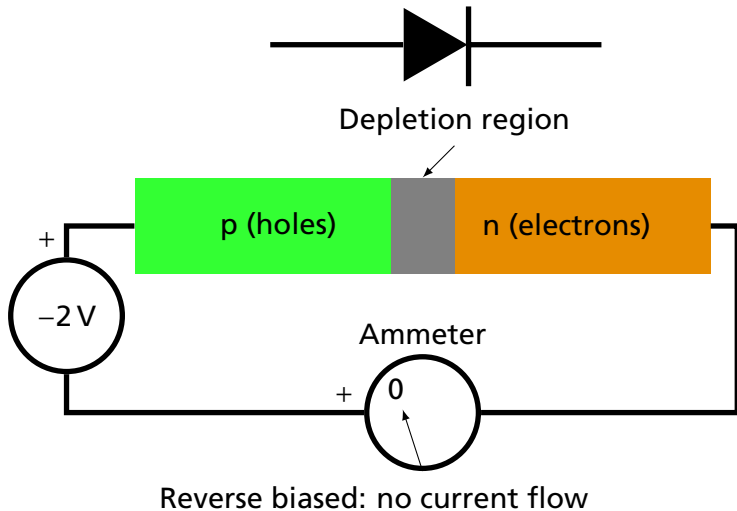


Depletion region

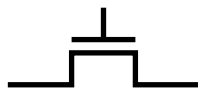


Forward biased: current flows

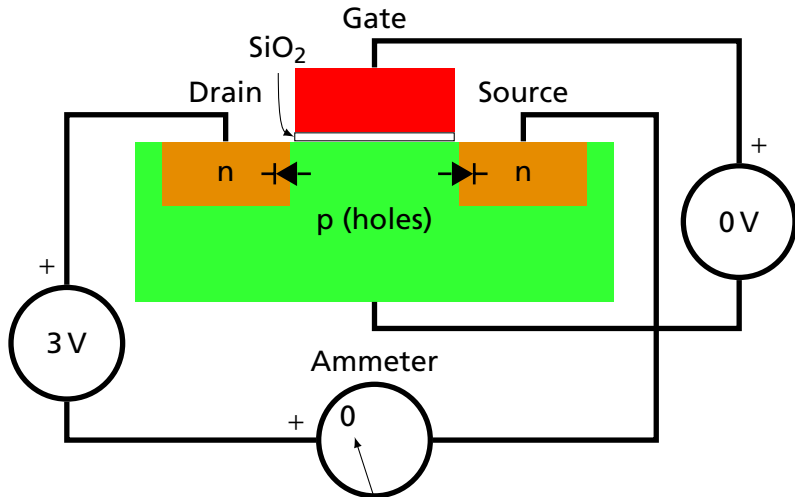
# A PN Junction aka A Diode



# An N-Channel MOS Transistor

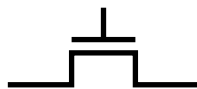


Gate at 0V: Off

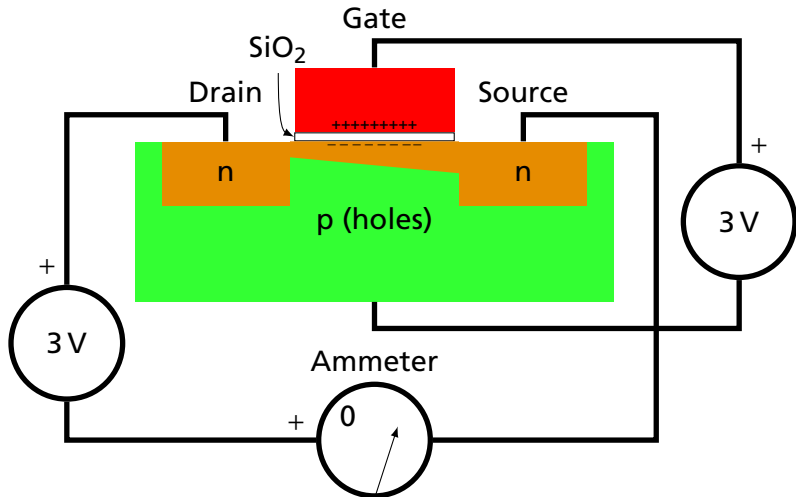




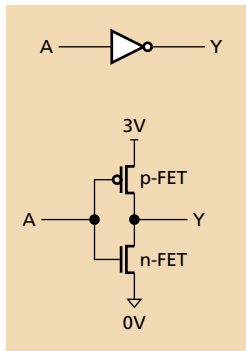
# An N-Channel MOS Transistor



Gate positive: On



# The CMOS Inverter

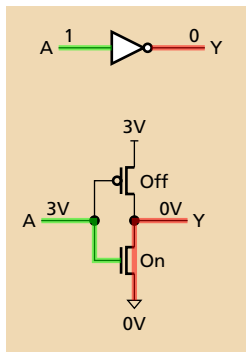


An inverter is built from two MOSFETs:

An n-FET connected to ground

A p-FET connected to the power supply

# The CMOS Inverter



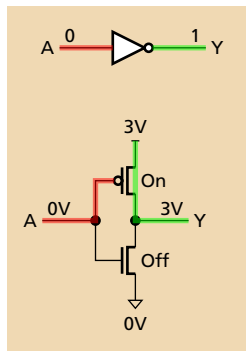
When the input is near the power supply voltage ("1"),

the p-FET is turned off;

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

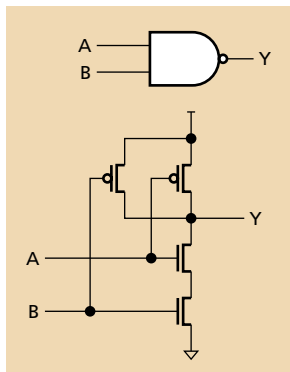
n-FETs are only good at passing 0's

# The CMOS Inverter



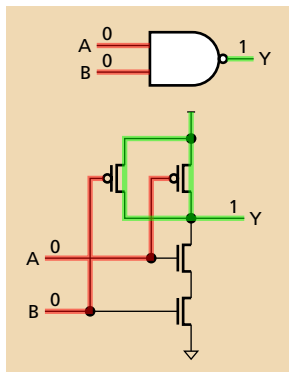
When the input is near ground ("0"), the p-FET is turned on, connecting the output to the power supply ("1"); the n-FET is turned off. p-FETs are only good at passing 1's

# The CMOS NAND Gate



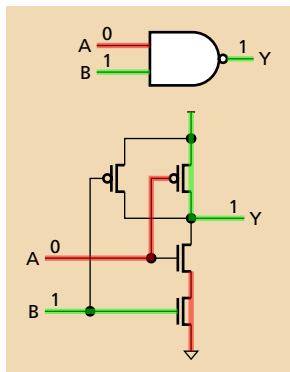
Two-input NAND gate:  
two n-FETs in series;  
two p-FETs in parallel

# The CMOS NAND Gate



Both inputs 0:  
Both p-FETs turned on  
Output pulled high

# The CMOS NAND Gate



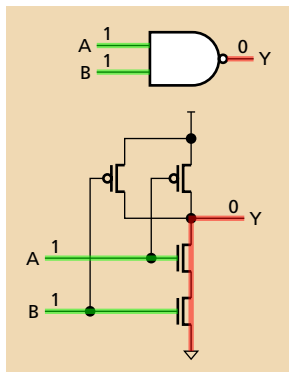
One input 1, the other 0:

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:

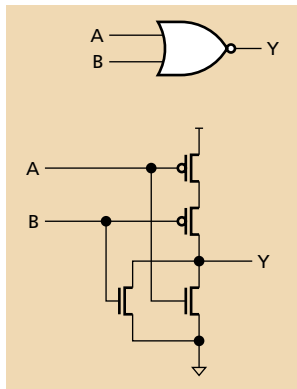
Both n-FETs turned on

Output pulled low

Both p-FETs turned off



# The CMOS NOR Gate



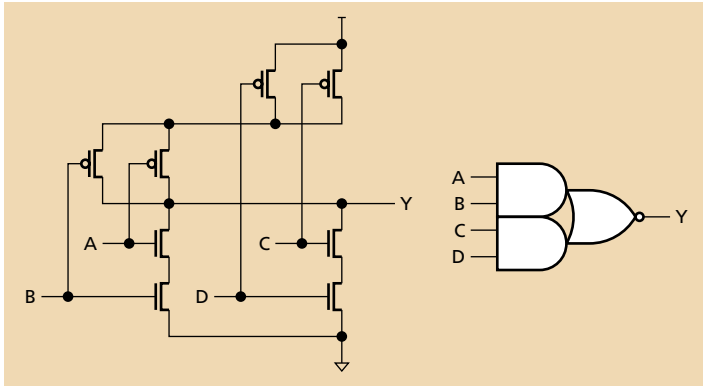
Two-input NOR gate:

two n-FETs in parallel;

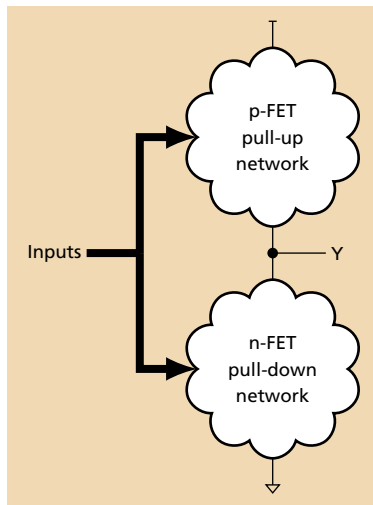
two p-FETs in series.

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

# A CMOS AND-OR-INVERT Gate



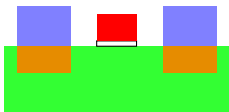
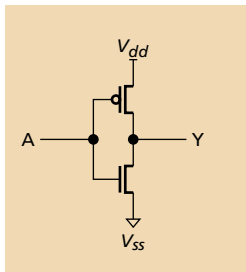
# Static CMOS Gate Structure



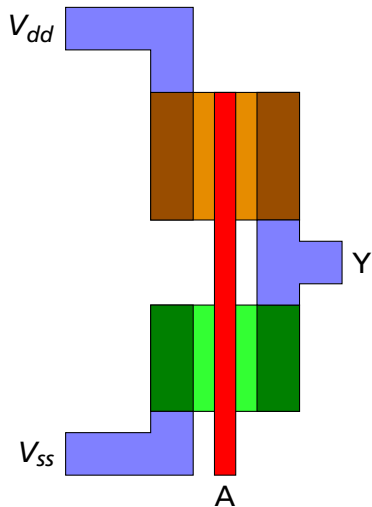
Pull-up and Pull-down networks must be complementary; exactly one should be connected for each input combination.

Series connection in one should be parallel in the other

# CMOS Inverter Layout



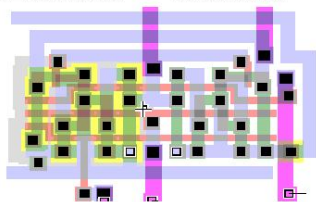
Cross Section Through  
N-channel FET



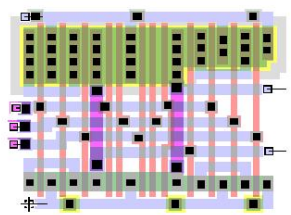
Top View

# Full Adder Layouts

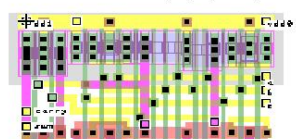
fa\_ly\_mini\_jk size: 60     · 40 $\mu$ m (1.2 $\mu$ mCMOS)



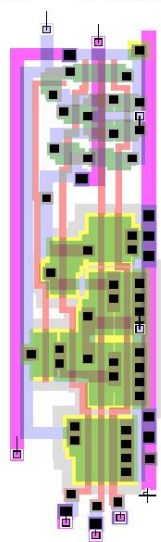
fa\_ly\_opt1 size: 63     · 50 $\mu$ m (1.2 $\mu$ mCMOS)



Fulladd.L size: 37     · 26  $\mu$ m (0.5 $\mu$ mCMOS)



fa\_ly\_itt size: 117     · 31  $\mu$ m (1.2 $\mu$ mCMOS)



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

# Intel 4004: The First Single-Chip Microprocessor

## Announcing a new era of integrated electronics



## A micro- programmable computer on a chip!

Intel introduces an integrated CMOS complete with a ROM for program memory, address and data registers, an accumulator and a single-chip random access memory. It's one of a family of four chips that comprise the Intel 4-bit micro-computer system - the first solution to bring you the power and flexibility of a dedicated general-purpose computer on one chip in as little as one drop of ink.

Intel's 4-bit system provides complete computing and control functions for test systems, data terminals, utility machines, measuring systems, control control systems and portable control systems.

The heart of any 4004 system is a Type 4004 CPU, which contains a complete set of 45 instructions, floating point and stack Type 4002 ROM, for program storage, and data memory Type 4001 RAM, for data storage. When you require rapid turn-around or need only a few systems, Intel's erasable and re-programmable ROM, Type 4003, may be substituted for the Type 4002 mask-programmed ROM.

Intel's 4-bit system is easily interfaced with switches, key boards, displays, teleprinters, printers, modems, A/D converters and other popular peripherals.

The 4004 family is now in stock at Intel's Santa Clara headquarters and at our regional headquarters in Europe and Japan. In the U.S., call your local Intel representative for technical information and literature. In Europe, contact Intel at Avenue Louise 214, B-1050 Brussels, Belgium. Phone 32(2)27 4004. In Japan, contact Intel Japan, Ltd., Parkside Plaza Bldg., 8th F., 2-2-1, Shinjyuku, Shinjyuku-ku, Tokyo 102. Phone 81(3)432-4101.

Intel Corporation now produces micro-computers, microprocessors and microperipherals at 3065 Avenida Arroyo, San Jose, Costa Rica. Phone 506(2) 228-7000.

intel  
delivers.

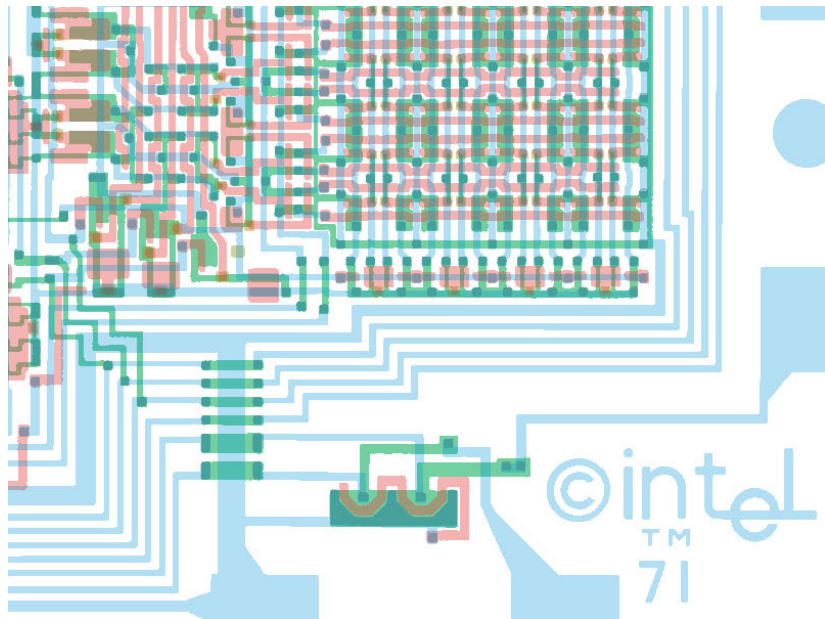
4001: 256-byte ROM + 4-bit IO port

4002: 40-byte RAM

4003: 10-bit shift register

4004: 740 kHz 4-bit CPU w/ 45 instructions (2300 transistors)

# Intel 4004 Masks



# Intel 4004 Die Photograph

