To talk about “nano,” the electrical engineer almost always starts from transistor scaling, Moore’s law...
Let’s follow this somewhat traditional (boring) path for now. This course is about nanoELECTRONICS after all!

Moore’s Law

- Gordon E. Moore (born 1929), a co-founder of Intel
- Moore's Law is the **empirical observation** made **in 1965** that the number of transistors on an integrated circuit **for minimum component cost** doubles every 24 months (sometimes quoted as 18 months).
- Moore's law is **not** about just the density of transistors that **can** be achieved, but about the density of transistors at which the cost per transistor is the lowest.

What’s the driving force behind the scaling?

Transistor radio!

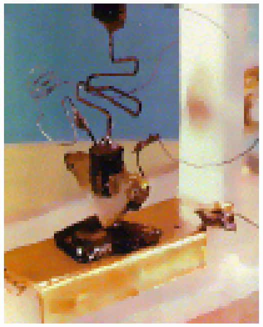
1965: $1/transistor

2006: 1 “microdolar”/transistor

Some History

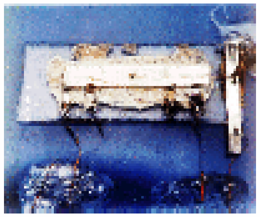
Invention of the transistor (BJT) 1947

Shockley, Bardeen, Brattain – Bell Labs



Single-transistor integrated circuit 1958

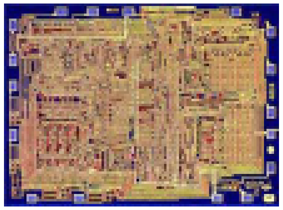
Jack Kilby – Texas Instruments



Invention of CMOS logic gates 1963

Wanlass & Sah – Fairchild Semiconductor

Moore's law 1965

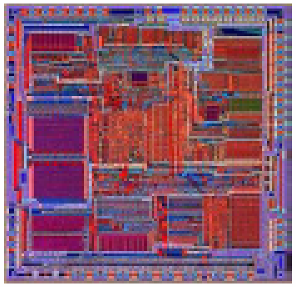


First microprocessor (Intel 4004) 1970

2,300 MOS transistors, 740 kHz clock frequency

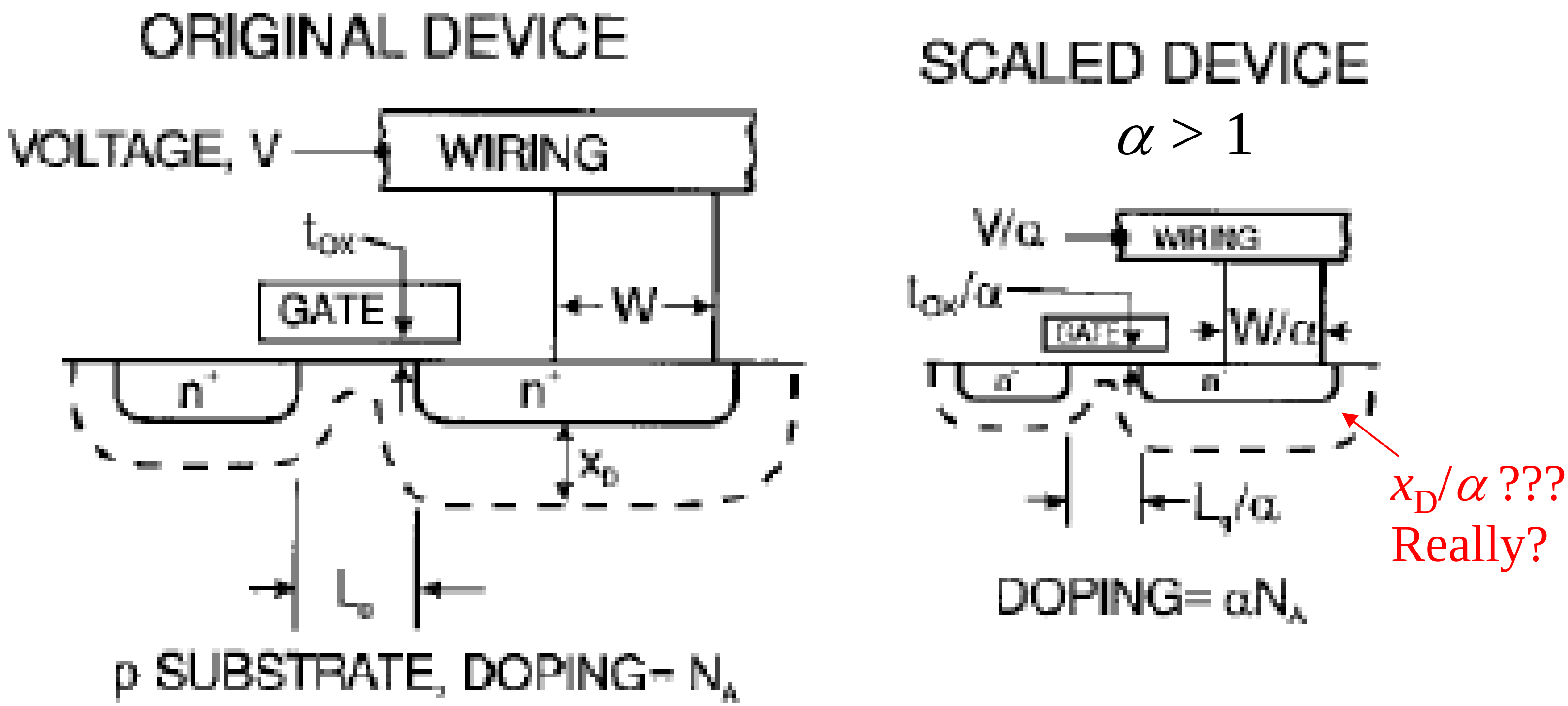
Very **L**arge **S**cale **I**ntegration 1978

Chips with more than ~20,000 devices



But the happy scaling days are long gone.
There are many issues with scaling… Among them, electrostatic control.
(We are not going to talk about all of them.)

Simple constant-field scaling: $V \rightarrow \alpha V$, $I \rightarrow \alpha I$



But the wafer is still "infinitely thick"...

L_g	t_{ox}
800 nm	18 nm
20 nm	0.45 nm

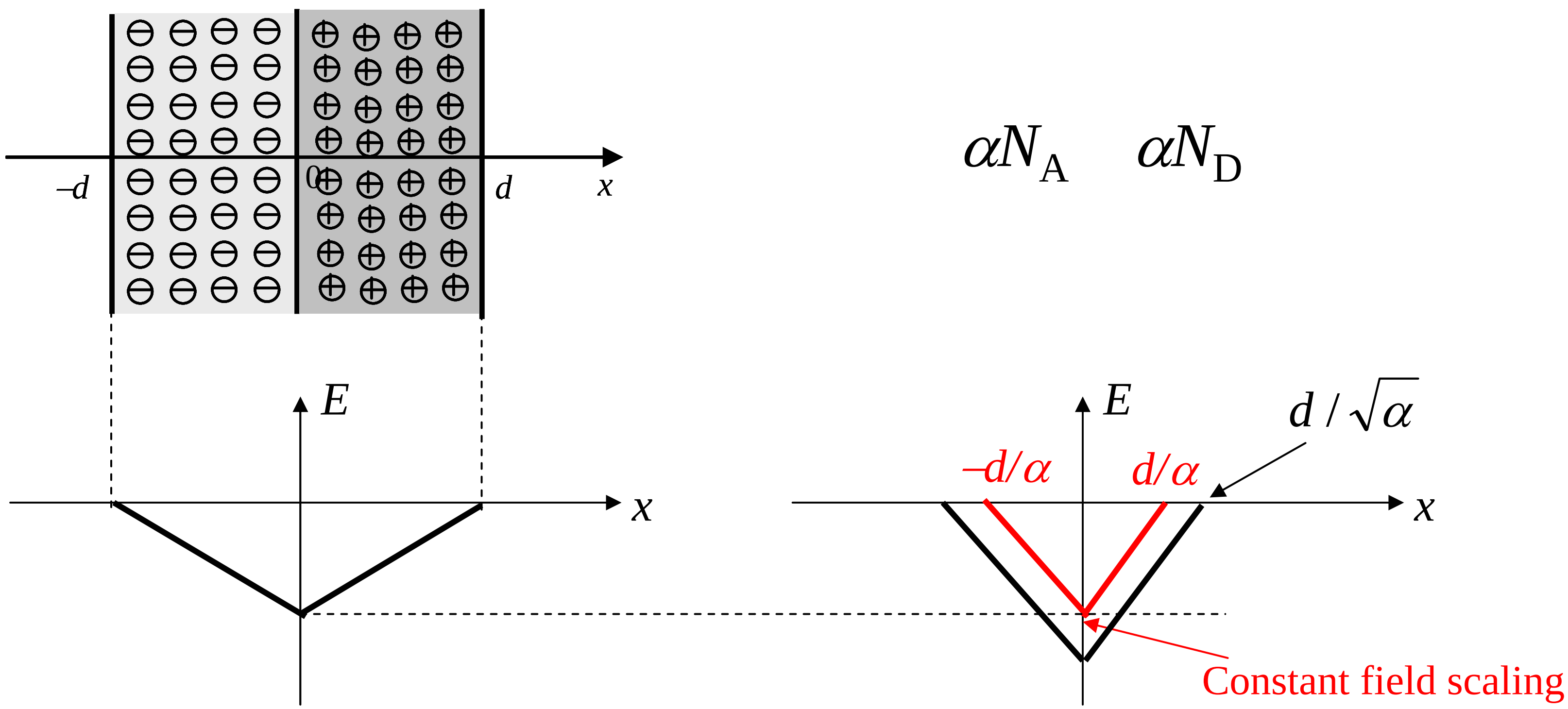
The Si-O bond length in SiO_2 is 0.16 nm

Thicker high-k dielectric can be used, but...

Consider a simple pn junction within the depletion approximation

Original

Scaled

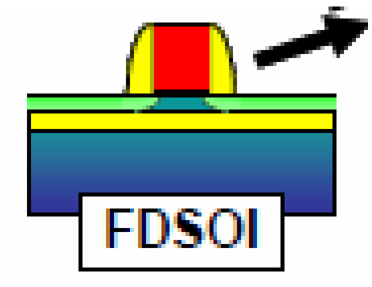


But the built-in voltage is largely determined by the band gap..., not much changed in the scaled junction

Think graphically about E, potential, and the band diagram

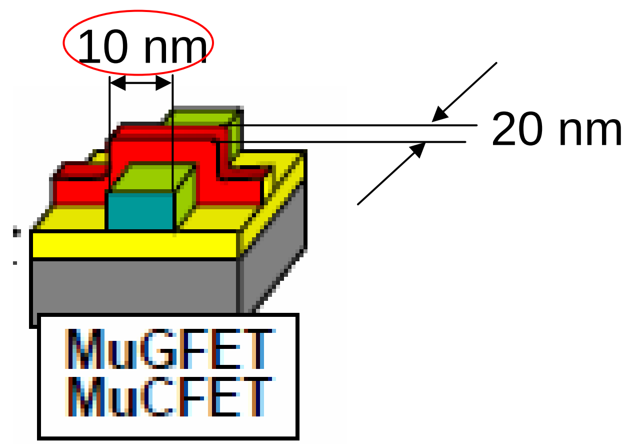
For good electrostatic control, we really need to get rid of the body (bulk)

Solutions (for now)



For L = 20 nm,
the Si needs to be
thinner than 5 nm.

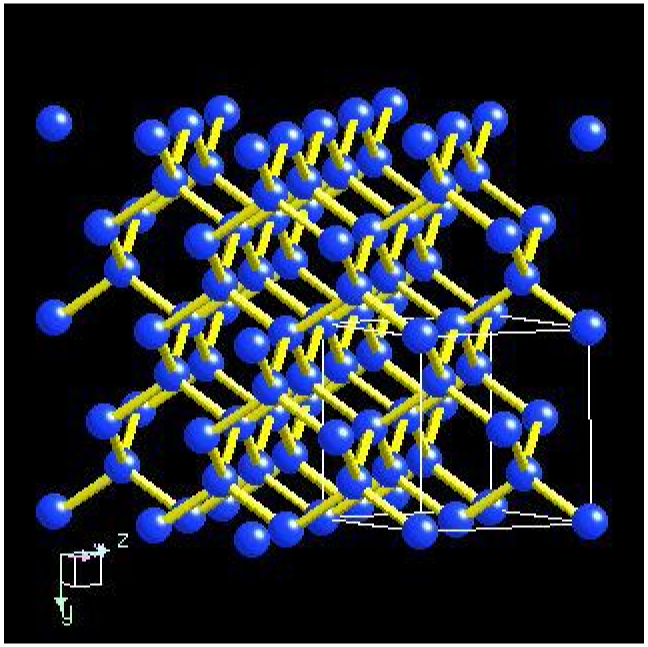
Ultra-thin body silicon-on-insulator

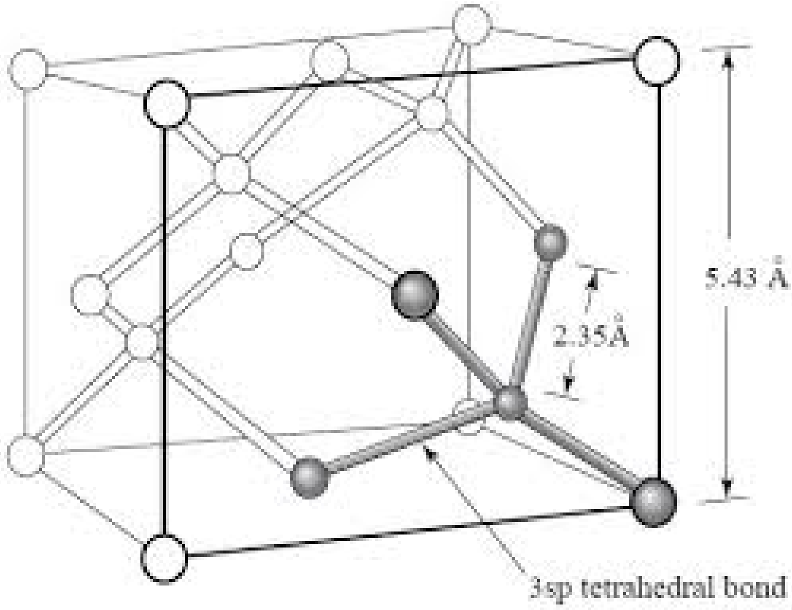


FinFET, 3D FET

Besides technical challenge,
anything wrong with making
the fin thinner?

Crystal structure of Si

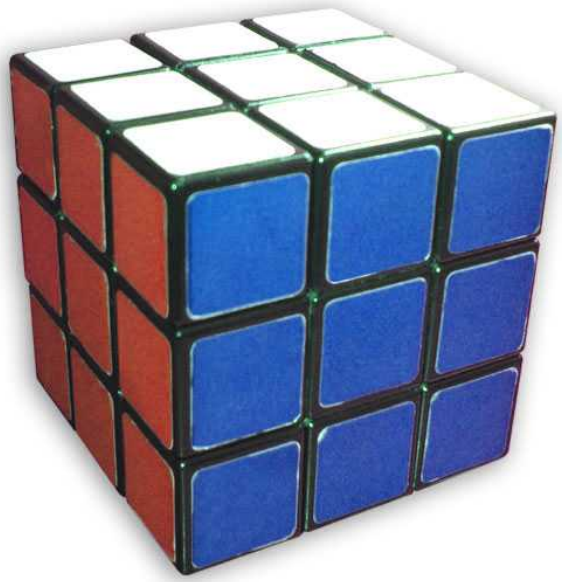




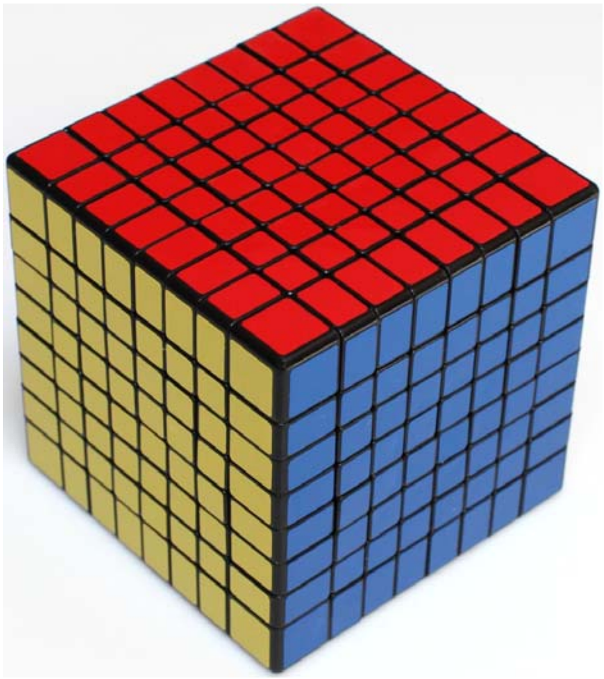
http://www.webelements.com/silicon/crystal_structure.html

http://onlineheavytheory.net/silicon.html

If several monolayers thin, is Si still the Si as we know it?



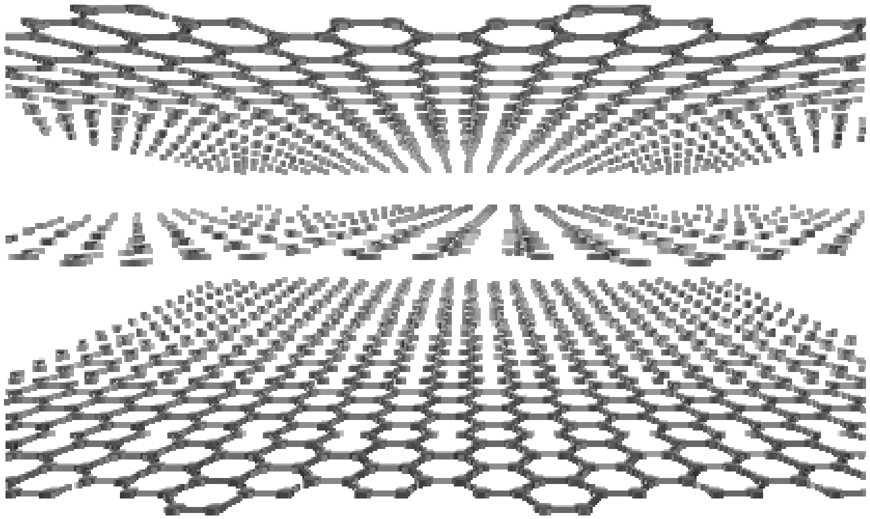
$$3^3 = 27$$
$$(3-2)^3 = 1$$



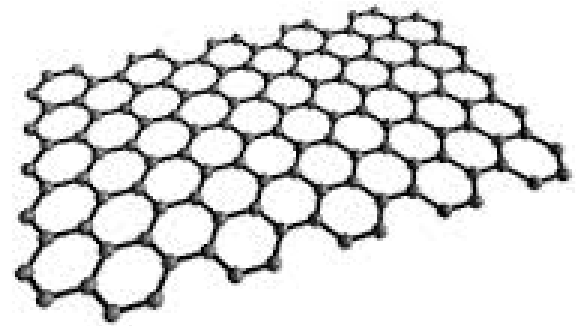
$$10^3 = 1000$$
$$(10-2)^3 = 512$$

Half of the small cubes are on the surface!

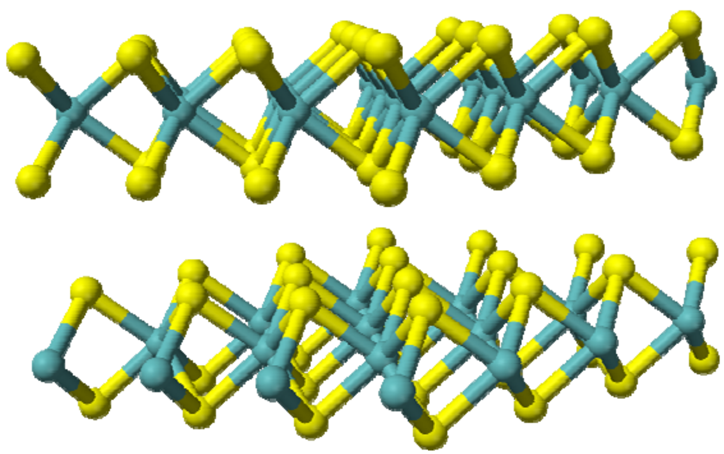
So we want things that are inherently low dimensional (2D or 1D)



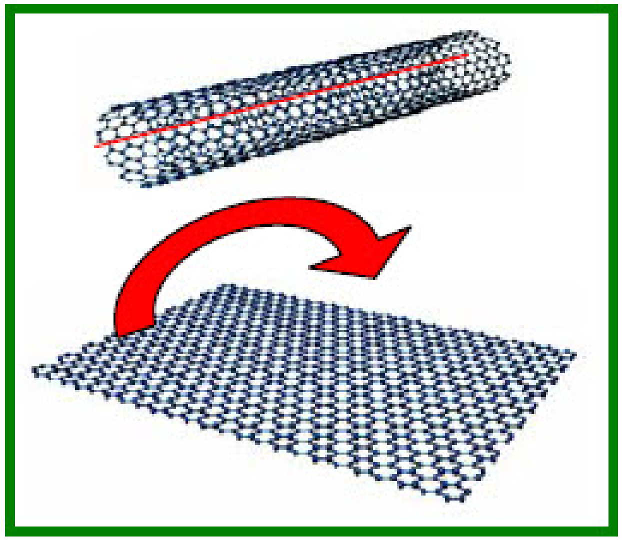
Graphite: 3D but layered (w/ van der Waals gaps)



Graphene: 2D



MoS_2



Carbon nanotube: (quasi-)1D

You've seen so far:

- Matter in the solid state is usually made of atoms in periodic arrays
- 3D and low dimensional (2D, 1D) materials
- There are reasons we want to make things small (one reason is scaling of microelectronics)
- When things are really small, a big fraction of atoms are on the surface
- When that happens, the thing may not be the thing as we know it
- Some materials are inherently low dimensional

We will talk about:

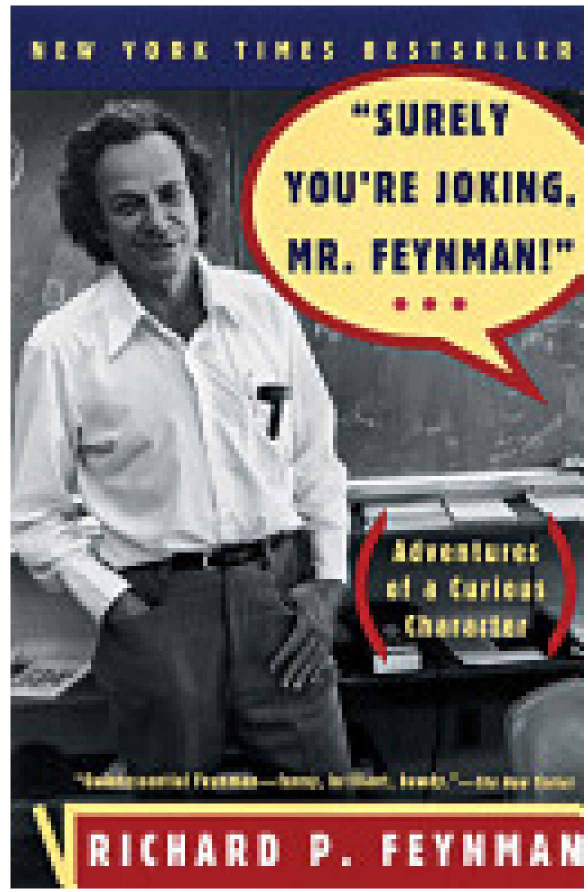
- How to handle things that are periodic
- The physics that rules the small world (in a different way than your typical physics professor would teach you)
- Low-dimensional things are conceptually simpler, easier to visualize. So we will start from 1D
- Then we go to 2D. Will use graphene as the platform, coz it's fascinating
- Will talk about many concepts in nanoelectronics on this platform
- Will go back to 1D: graphene → nanotubes
- We don't know what the "post-Si electronic material" (if any) would be. (This is our excuse to talk about more interesting things.)
- So this course is about the understanding of things.
- The understanding you get here will make it easy for you to understand future electronics

The above is a loosely defined "course description" of this course.

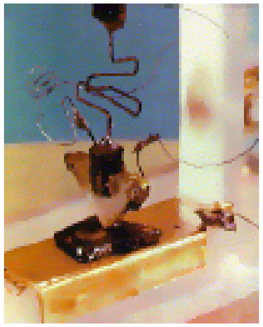
More Introduction before We Get to the Real Stuff

There are reasons to make things small. Microelectronics scaling is just one.

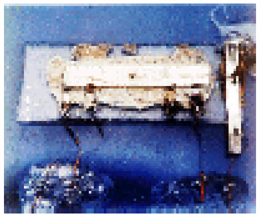
Let’s now look at things from a theoretical physicist’s “what nature allows us to do” kind of perspective.
(In contrast to the engineer’s “what we need to do”

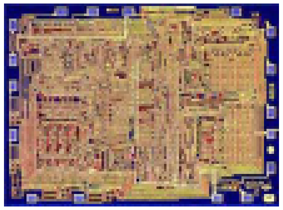


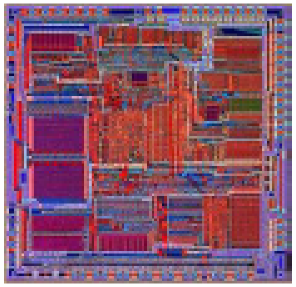
Some History



Invention of the transistor (BJT) Shockley, Bardeen, Brattain – Bell Labs	1947
Single-transistor integrated circuit Jack Kilby – Texas Instruments	1958
Feynman's speech	1959
Invention of CMOS logic gates Wanlass & Sah – Fairchild Semiconductor	1963
Moore's law	1965
First microprocessor (Intel 4004) 2,300 MOS transistors, 740 kHz clock frequency	1970
Very **L**arge **S**cale **I**ntegration Chips with more than ~20,000 devices	1978





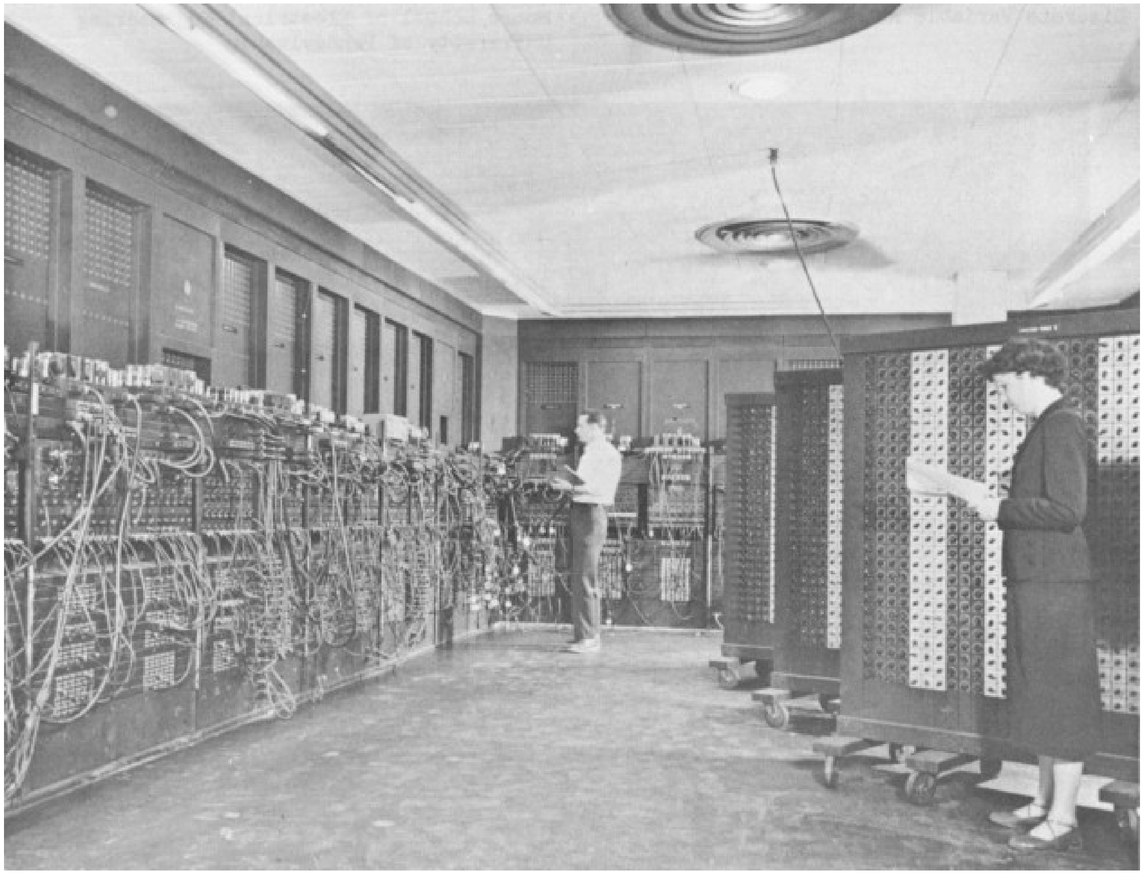


He talked about “miniaturization of the computer,” but what were computers like those days?

1950’s: the UNIVAC (Universal Automatic Computer)
In 1958, ***some*** ckts in UNIVAC II were “transistorized” (Wikipedia)

http://www.computer-history.info/Page4.dir/pages/Univac.dir/

ENIAC → EDVAC → ILLIAC, JOHNNIAC, and, of course, MANIAC...



Electronic Numerical Integrator and Calculator (ENIAC), 1945
To replace all the "computers", meaning the women who were employed to calculate the firing tables for the army's artillery guns.

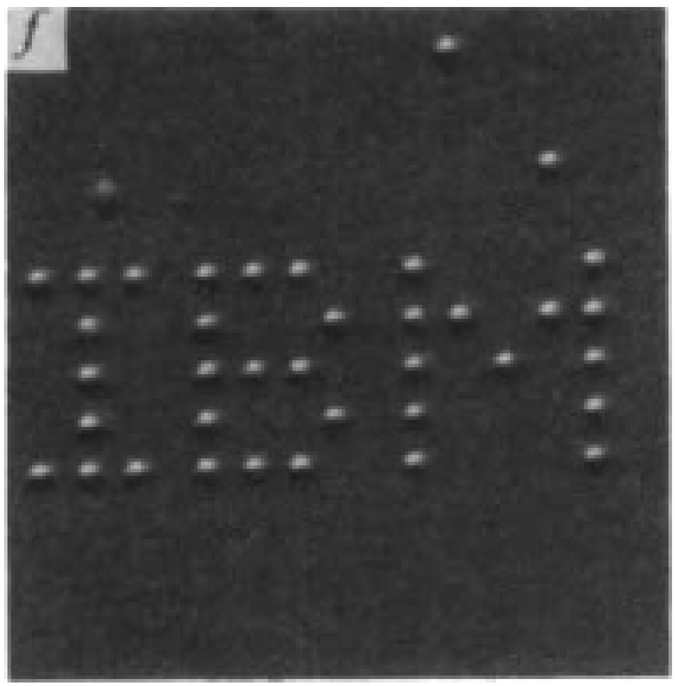
http://www.computersciencelab.com/ComputerHistory/HistoryPt4.htm

He called for "rearranging the atoms" and wanted better microscopes

Scanning tunneling microscope (STM)

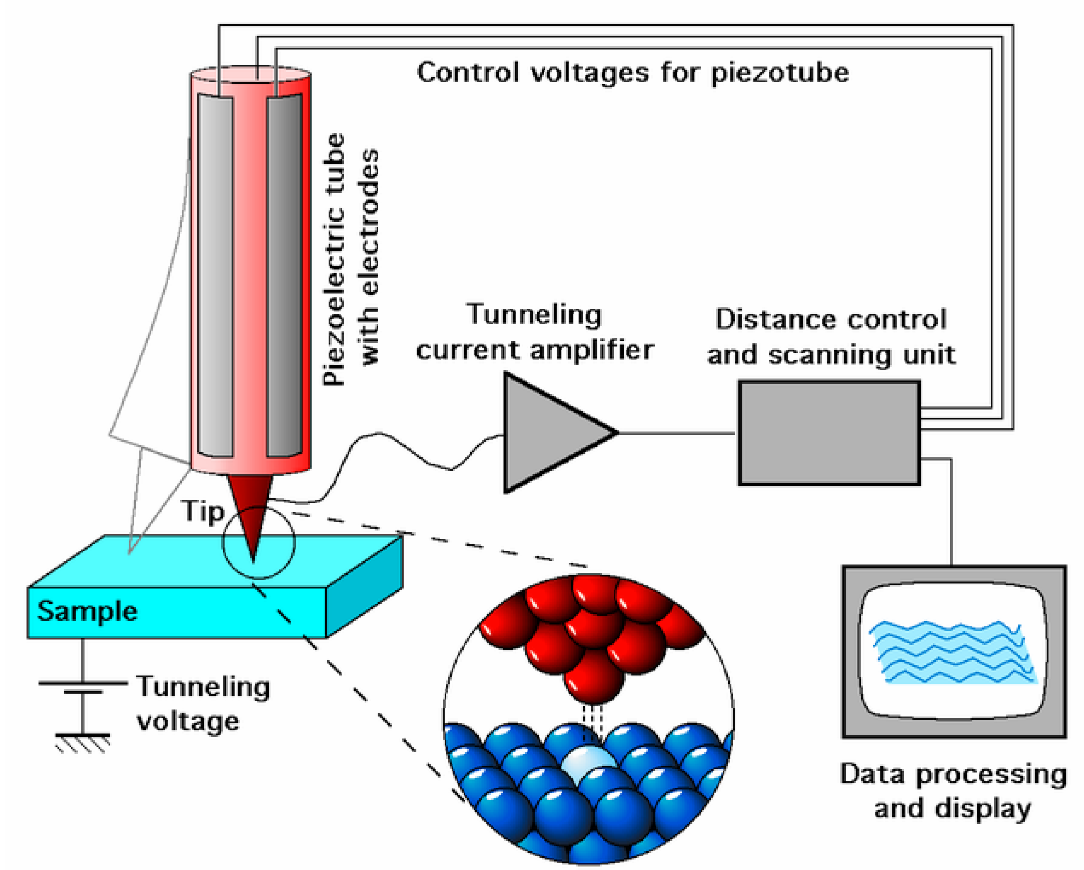
Developed in 1981

Won Nobel Prize in 1986



Xe atoms on Ni(110)

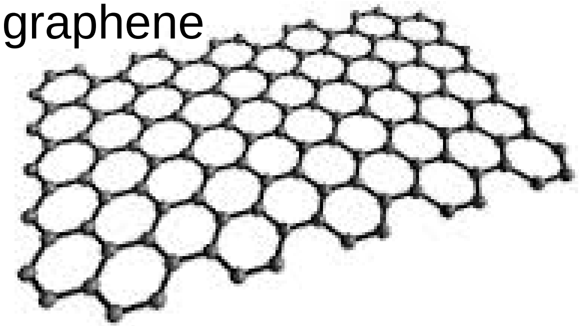
Eigler & Schweizer, Nature 344, 524 (1990)

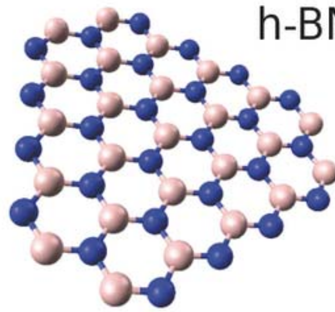


When he talked about better microscopes, he meant electron microscopes

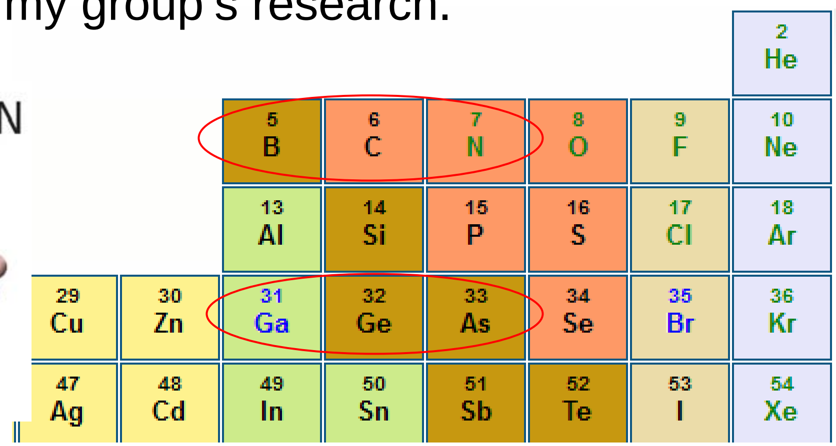
You can do chemistry by just looking at the atoms. Really?
Yes, we can now. Here's an example from my group's research.

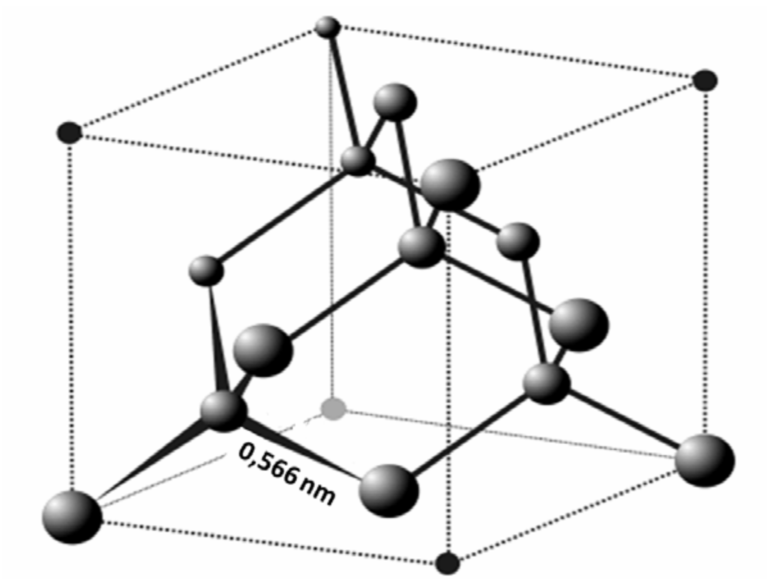
graphene



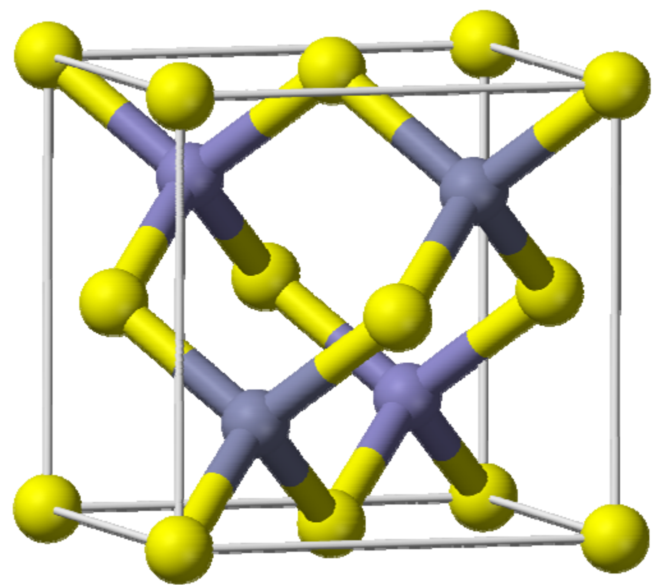


h-BN





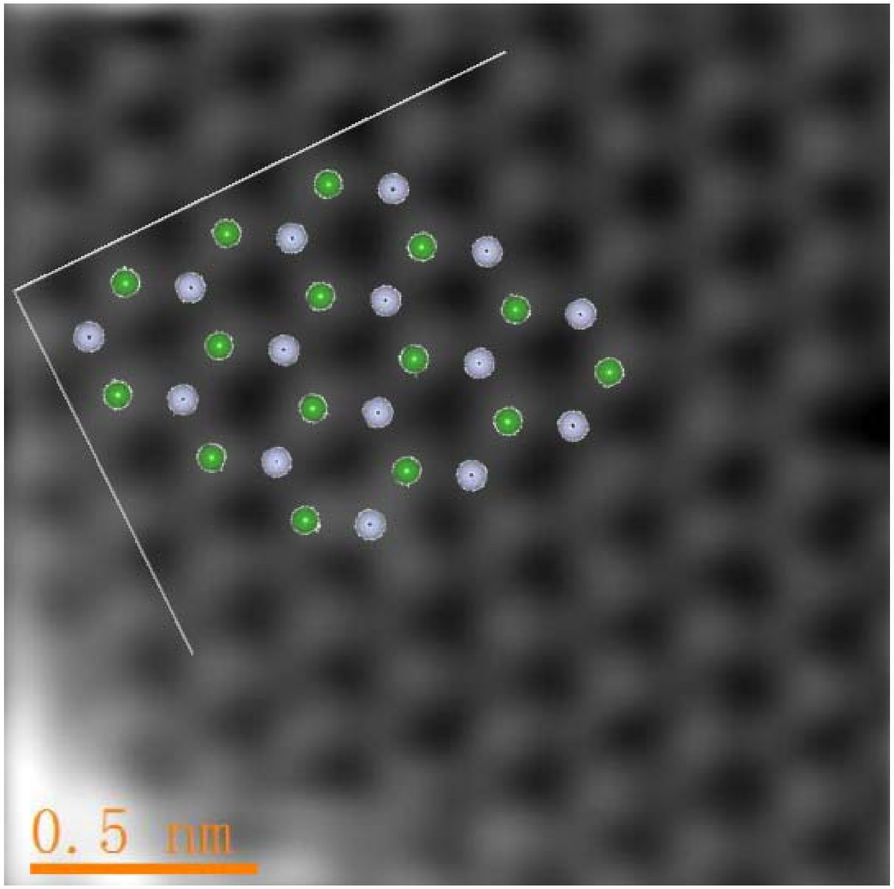
Ge



GaAs

Atomic resolution, Z-contrast scanning tunneling electron microscope @ ORNL

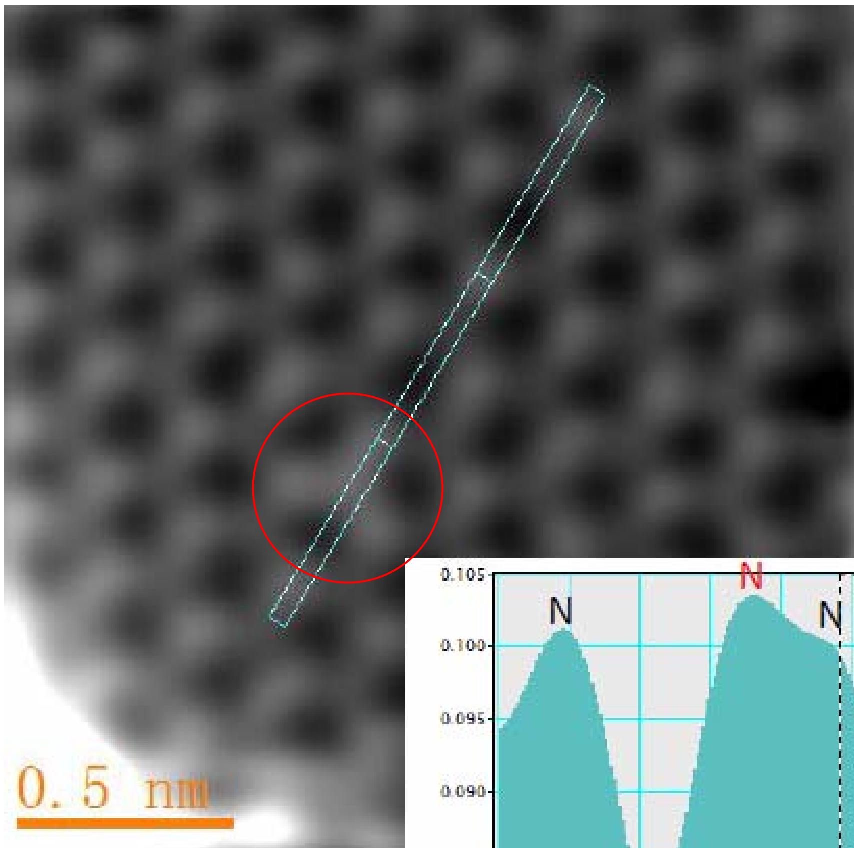
B: $Z = 5$, dimmer. N: $Z = 7$, brighter



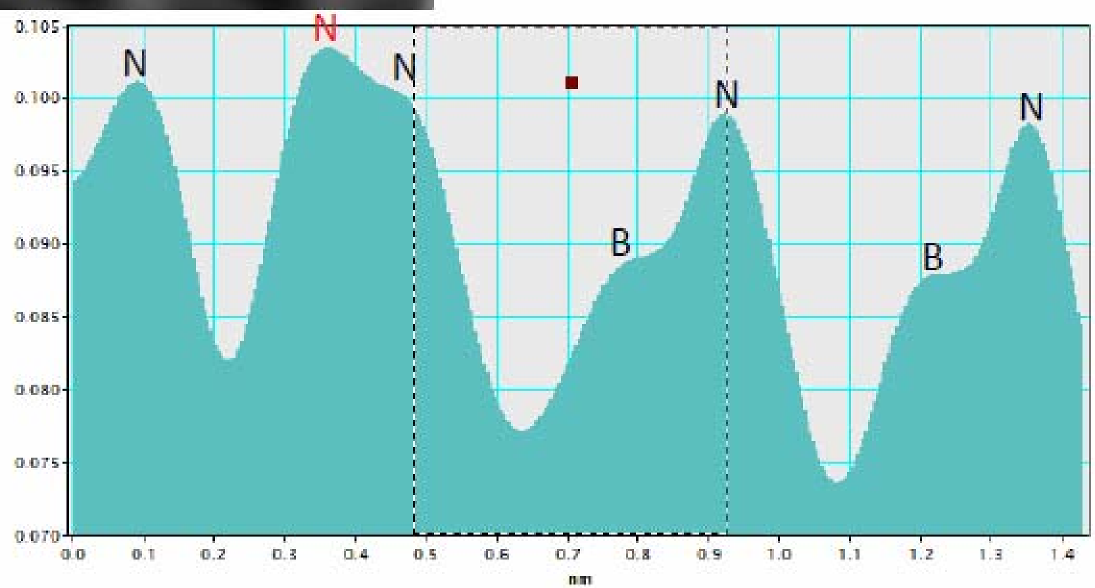
Images by Dr. Duscher's group (MSE Dept, UTK) and Dr. Chisholm's group (ORNL)

Nature’s Imperfections

First observation of antisites in h-BN

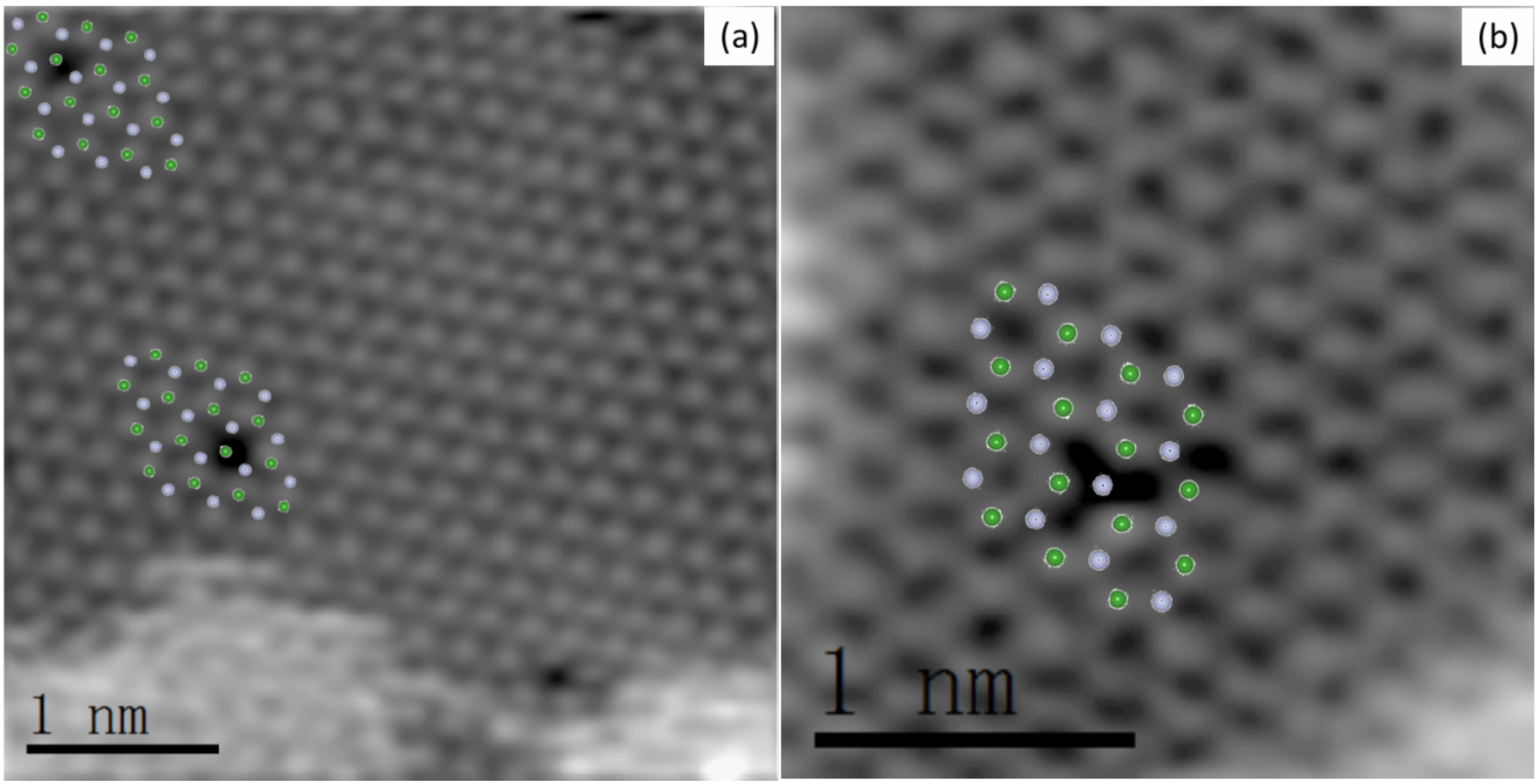


Anti site Defect in BN:
N substitution on B position



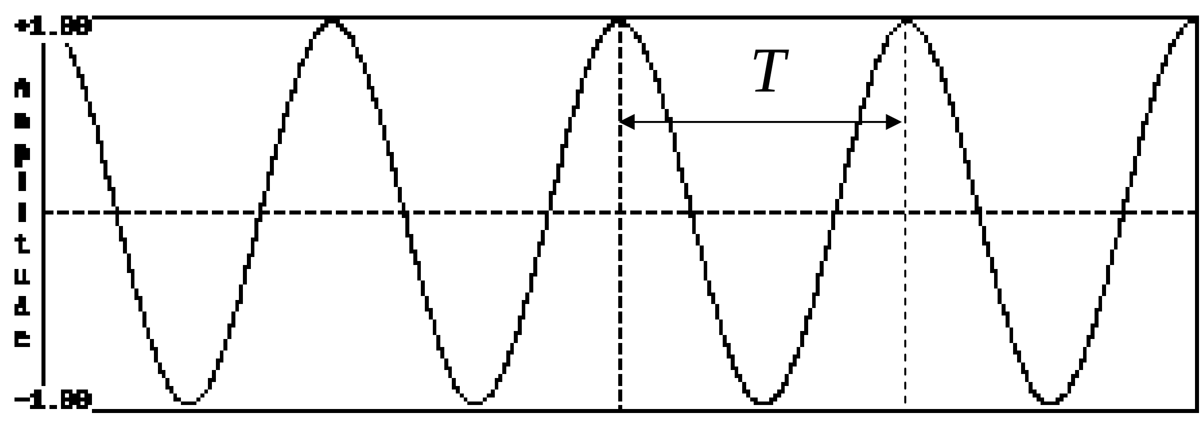
N vacancies

B vacancy



Well, so much for the introduction. Let’s get to the real stuff.

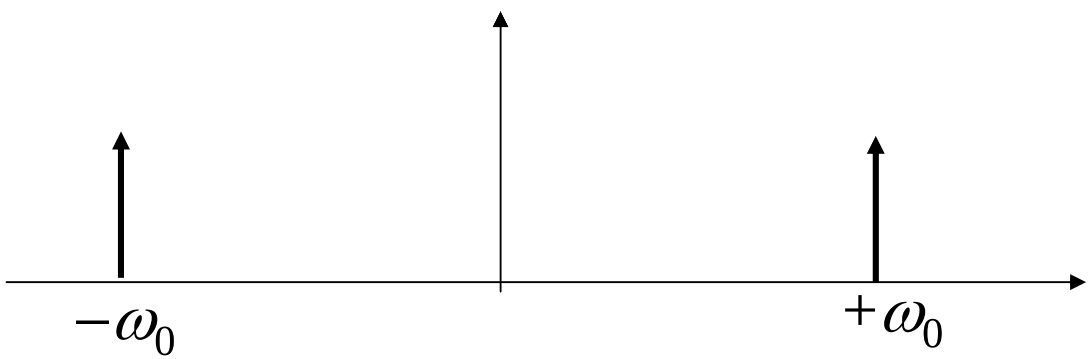
Periodic Things

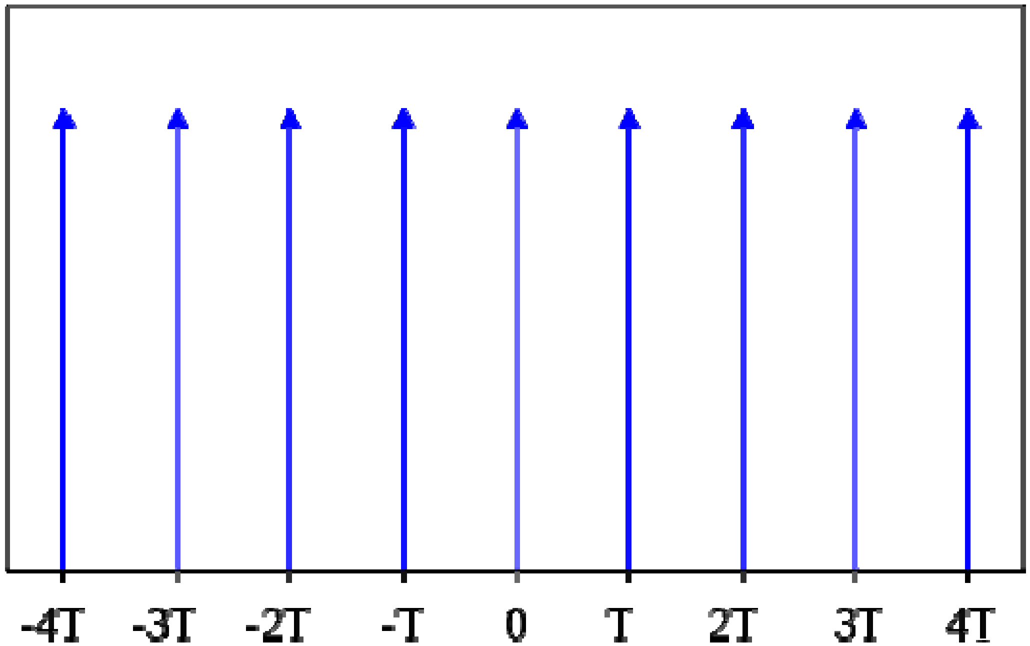


$y = \cos(\omega_0 t)$

$\omega_0 = 2\pi/T$

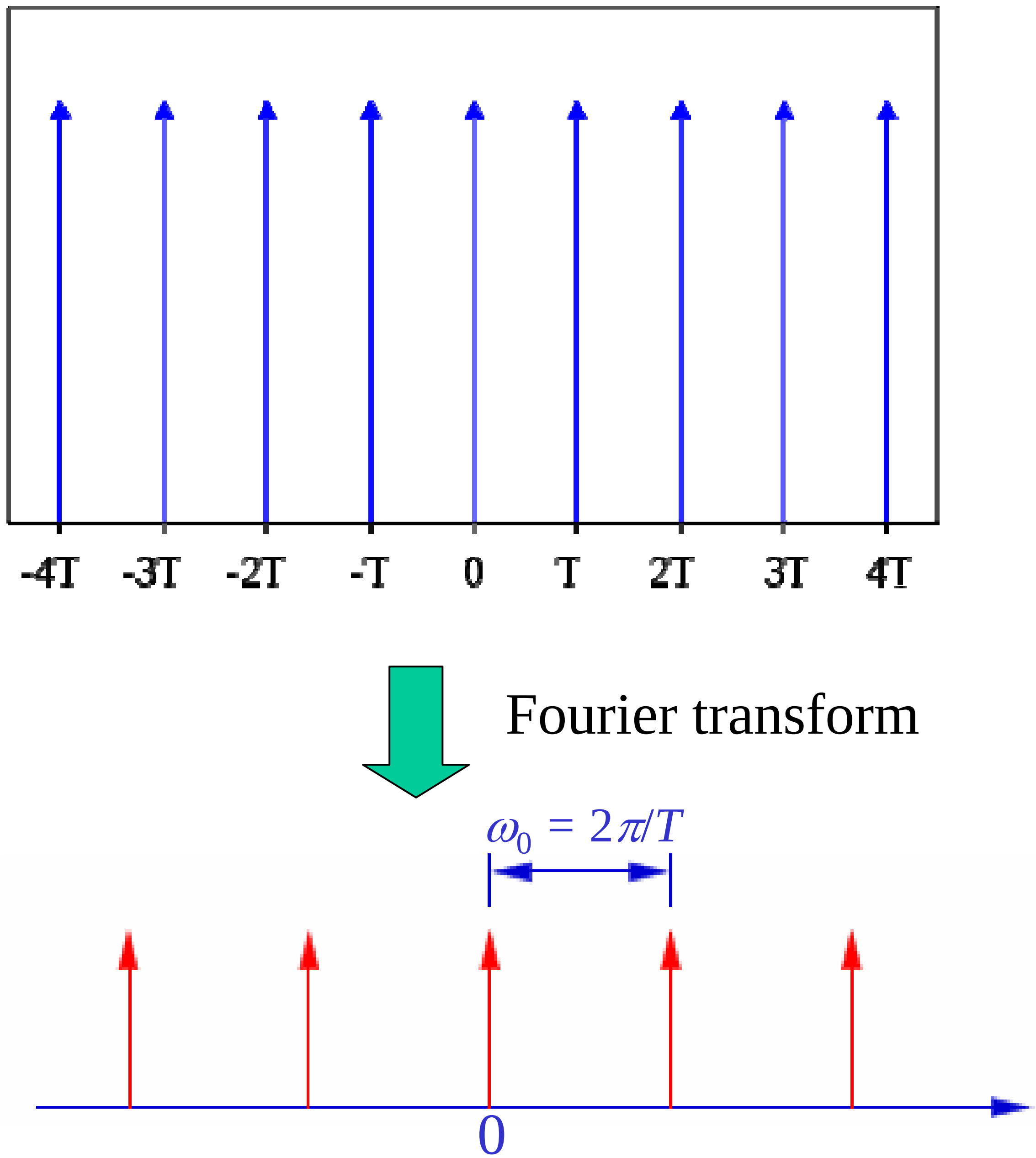
Fourier transform





Fourier transform

?


-4T -3T -2T -T 0 T 2T 3T 4T
Fourier transform
ω0 = 2π/T
0