The Incredible Shrinking Transistor: How Much Smaller?

This is an outline of the lecture. See instructor for access to the entire lecture.

You will need to be on the internet to see many of the images.

The Computer Revolution and the Chip

We all know that computers and related technology have changed profoundly the way that we live.

Information (for better or worse) is easy to obtain.

Seems most everything is automated.

Communications are instantaneous over most of the world.

Consumer and entertainment electronics are sophisticated and cheap.

Life-saving technology (e.g., medical) is commonly available.

What's behind all of this?

Miniaturization of electronics is at the heart

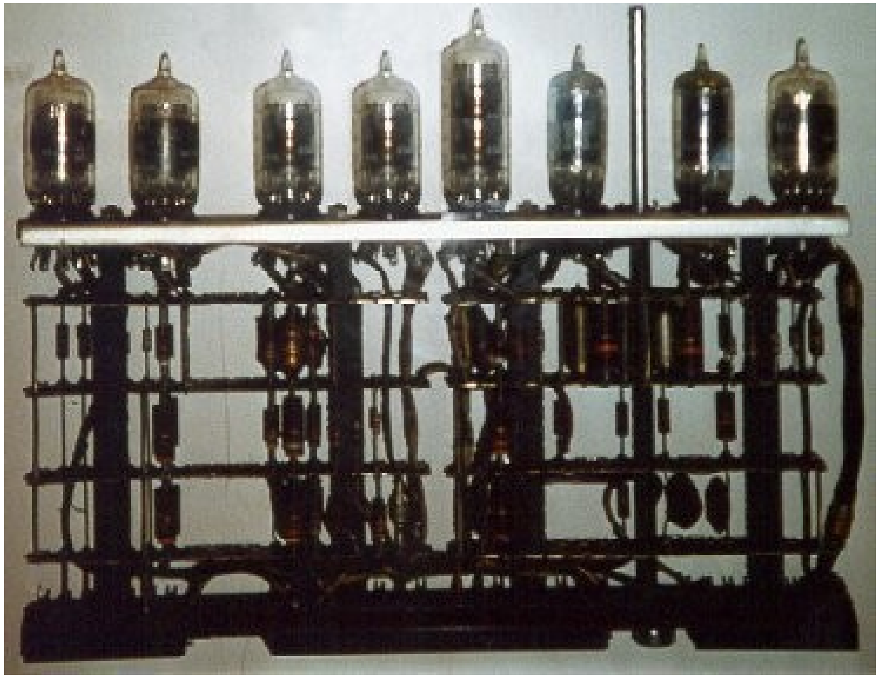
Vacuum Tubes (valves)

Transistors

Integrated Circuits (chips)

Vacuum Tubes

Still used in some specialized applications



Part of an IBM 701– one of the first scientific computers. 4000 tubes. 1950s. Taken from

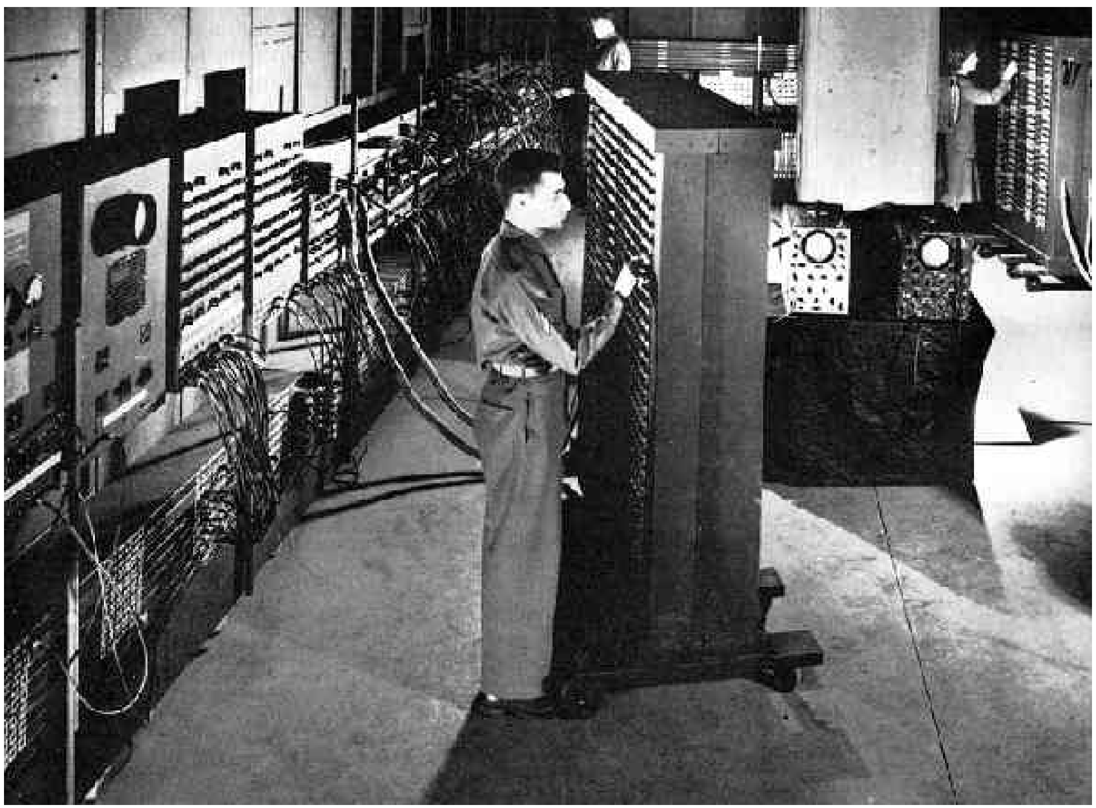
http://mason.gmu.edu/~montecin/vacuum_tube.html

Vacuum Tube Computer:

ENIAC

Images from

http://www.tcf.ua.edu/AZ/ITHistoryOutline.htm



First High-Speed, General Purpose Computer Using Vacuum Tubes: Electronic Numerical Integrator and Computer (ENIAC)

Discrete Transistors

Still used when high power is needed

Can see lots of them in consumer electronics

Transistor Photos and History

http://www.porticus.org/bell/belllabs_transistor.html

Bardeen, Brattain, Shockley
December 1947

http://www.rpi.edu/~schubert/Educational%20resources/1947%20First%20point%20contact%20transistor-3.jpg

Integrated Circuits

Smaller, Cheaper, Faster

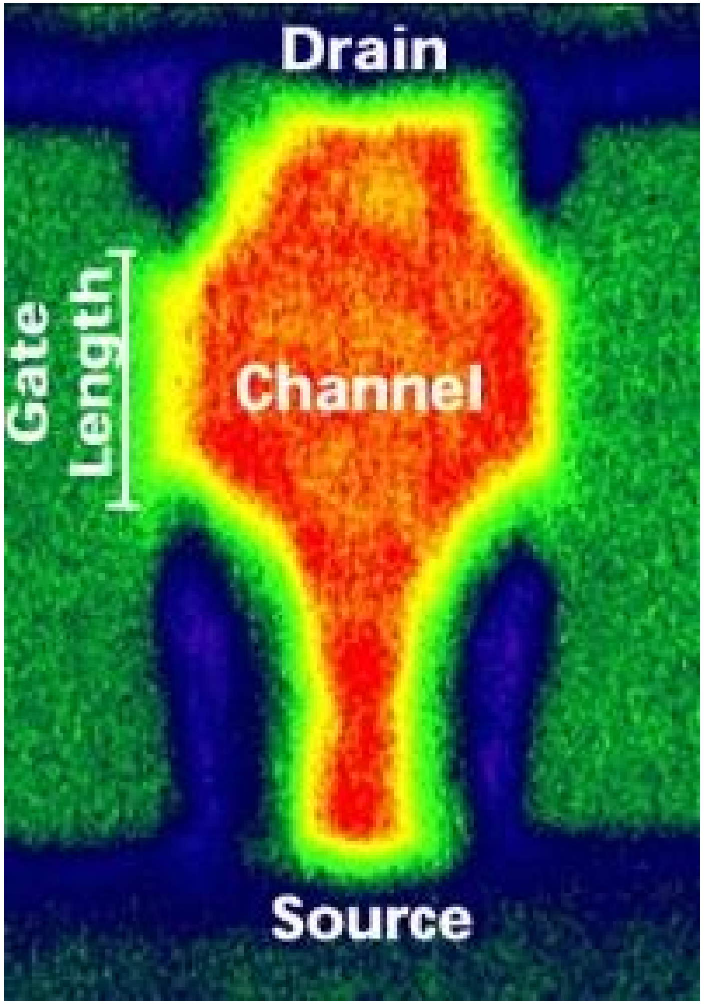
Basis of most electronic devices now

1960s: handful of components

Pentium 4: 42,000,000 transistors
plus lots of other parts

Sense of Scale

How small is it?

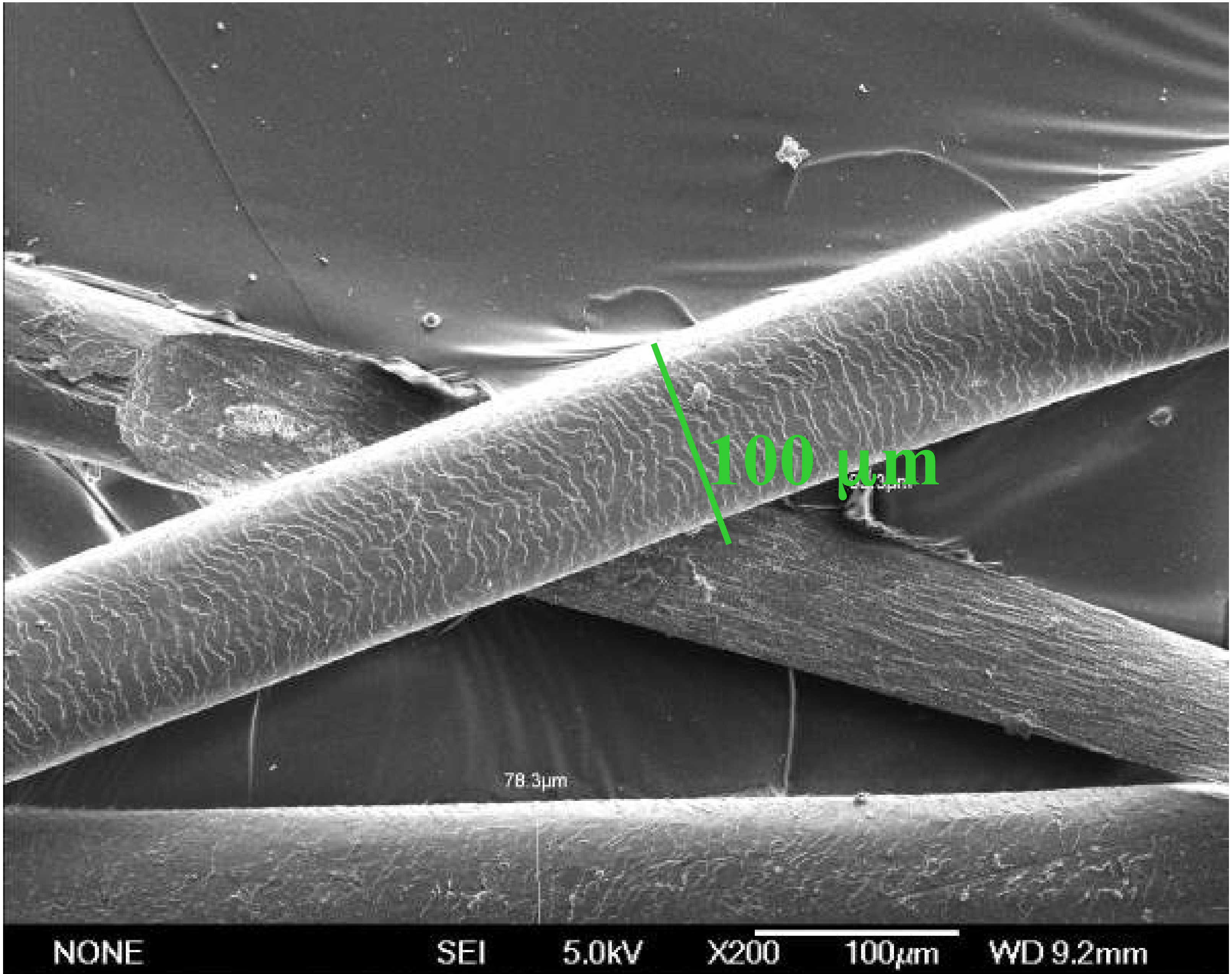


Transistor with 50 nm structures.

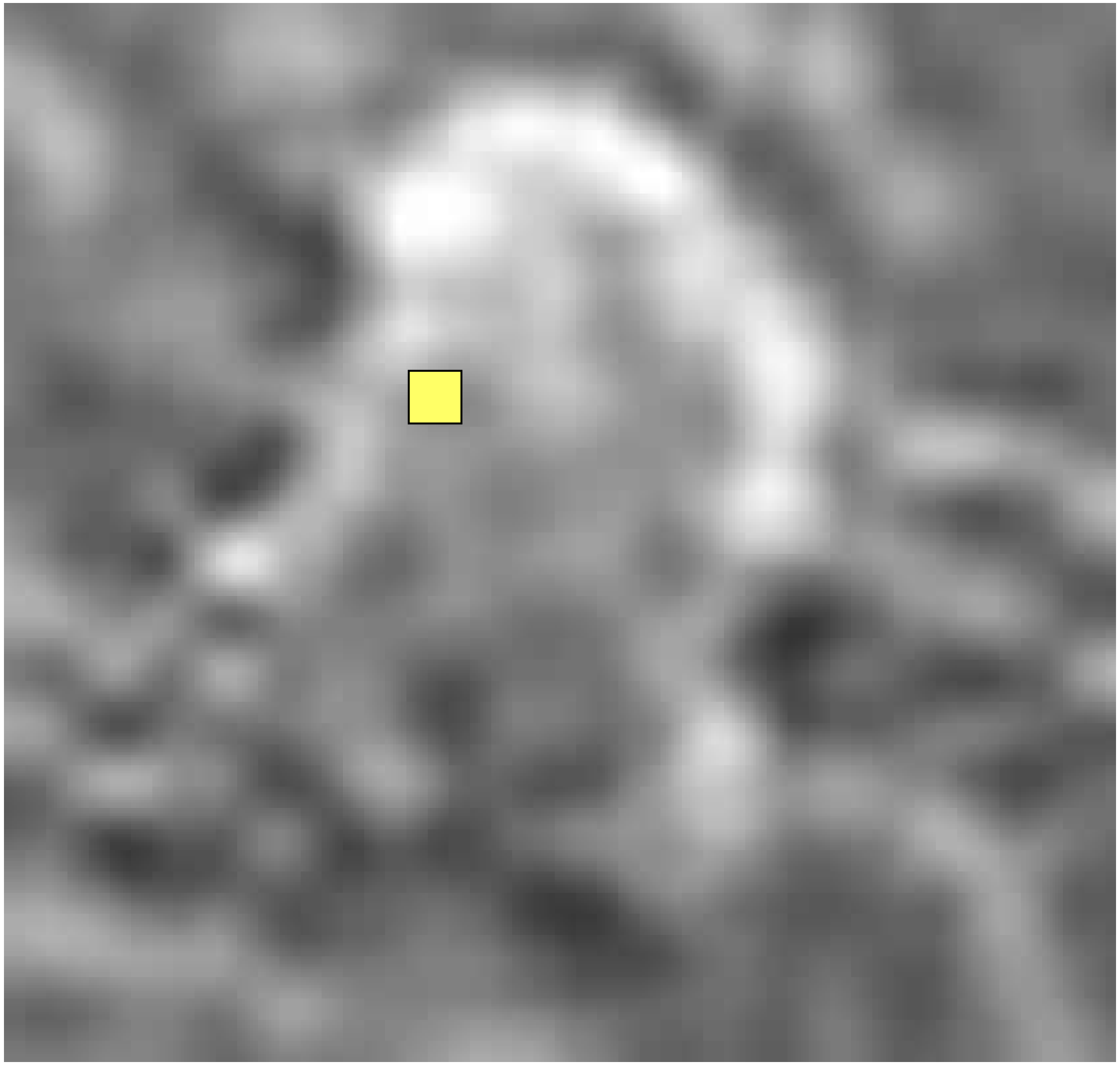
Smaller prototypes exist now.

http://www.bell-labs.com/news/1999/november/15/1.html.

Human hair (from the electron microscope lab at Victoria U)

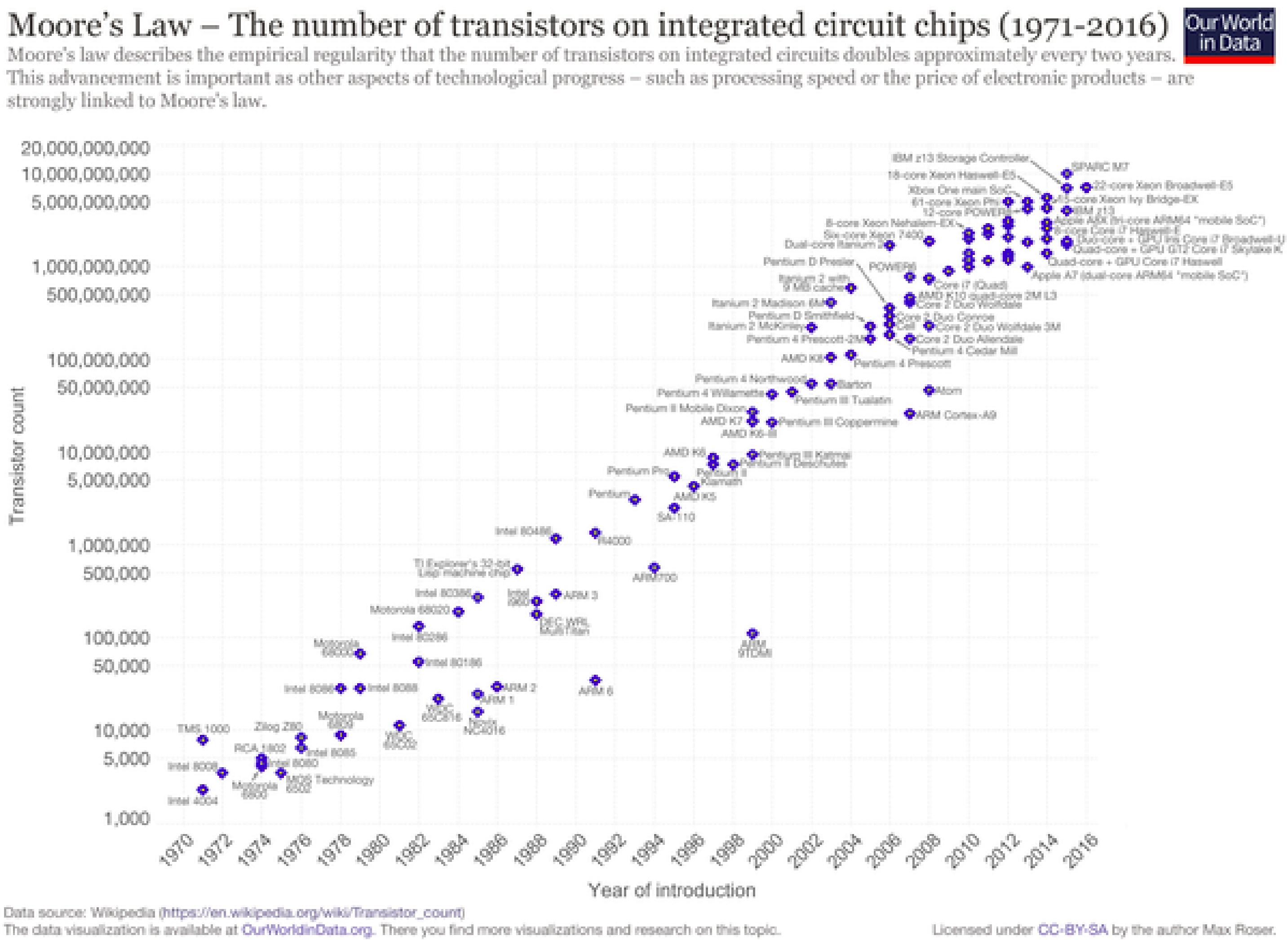


The yellow square is roughly the size of a chip transistor (order of magnitude)



Moore's Law:

Number of transistors on a chip doubles every two years.



https://upload.wikimedia.org/wikipedia/en/9/9d/Moore%27s_Law_Transistor_Count_1971-2016.png

How can we make something that small?

Want to understand the basic idea behind the technology

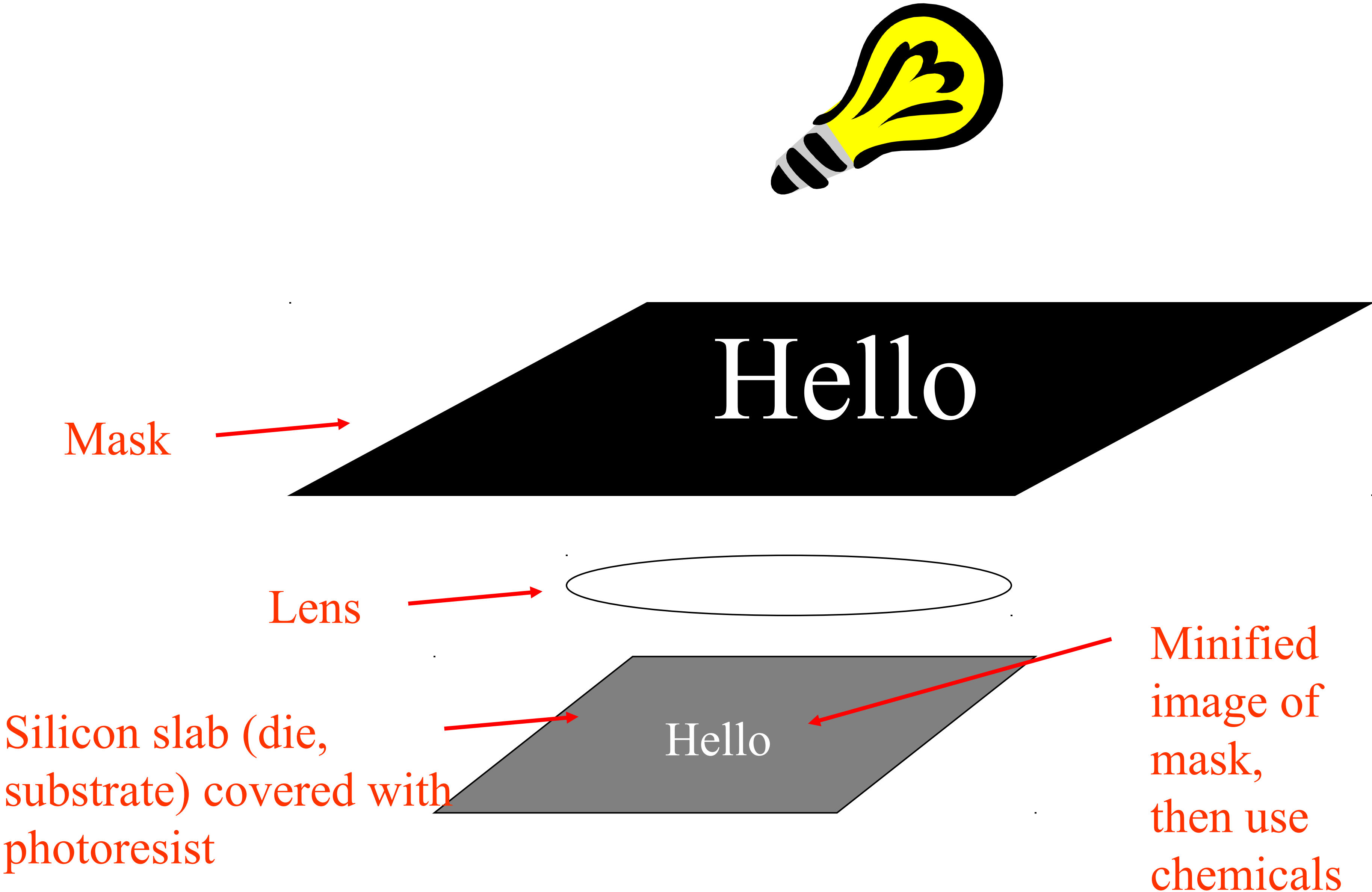
Want to know whether miniaturization is likely to continue

Picture Perfect: Making a microscopic transistor
Basic idea is *lithography*

Simplified Schematic of how lithography works

Photoresist (burns away under light followed by chemicals)

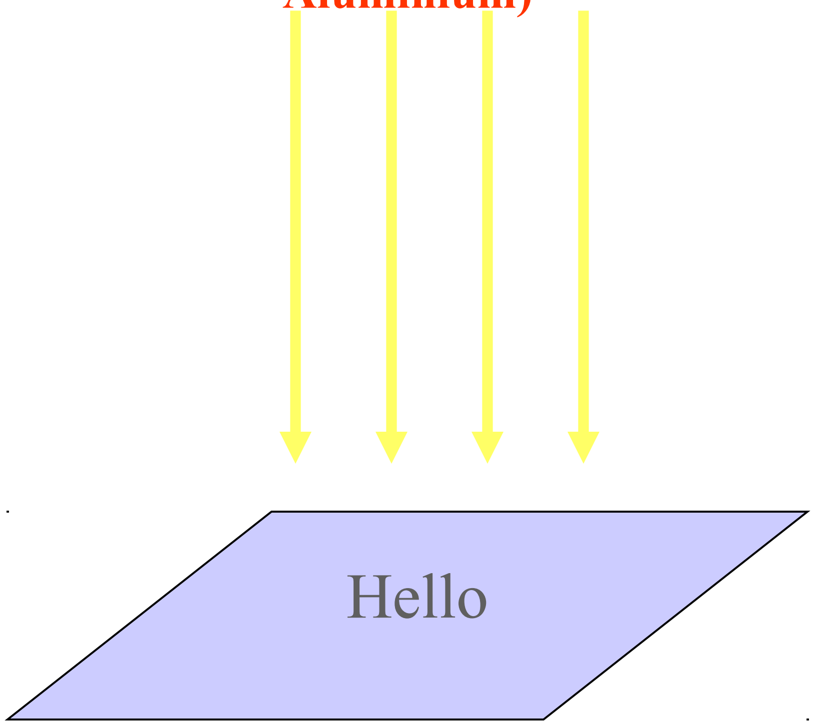
Simplified Lithography



Simplified Lithography

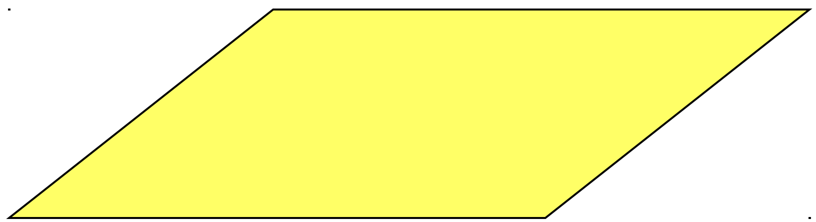
Metal

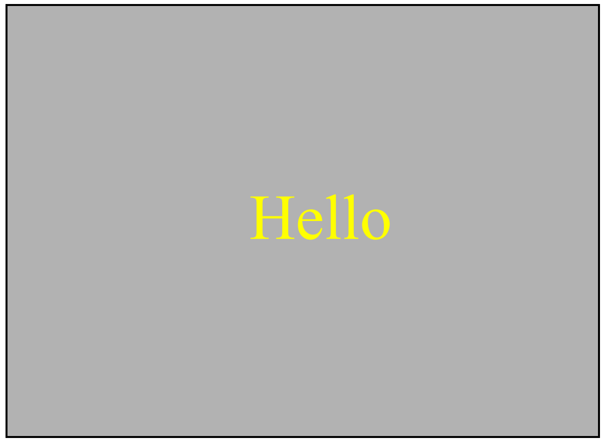
(perhaps Aluminium)



Simplified Lithography

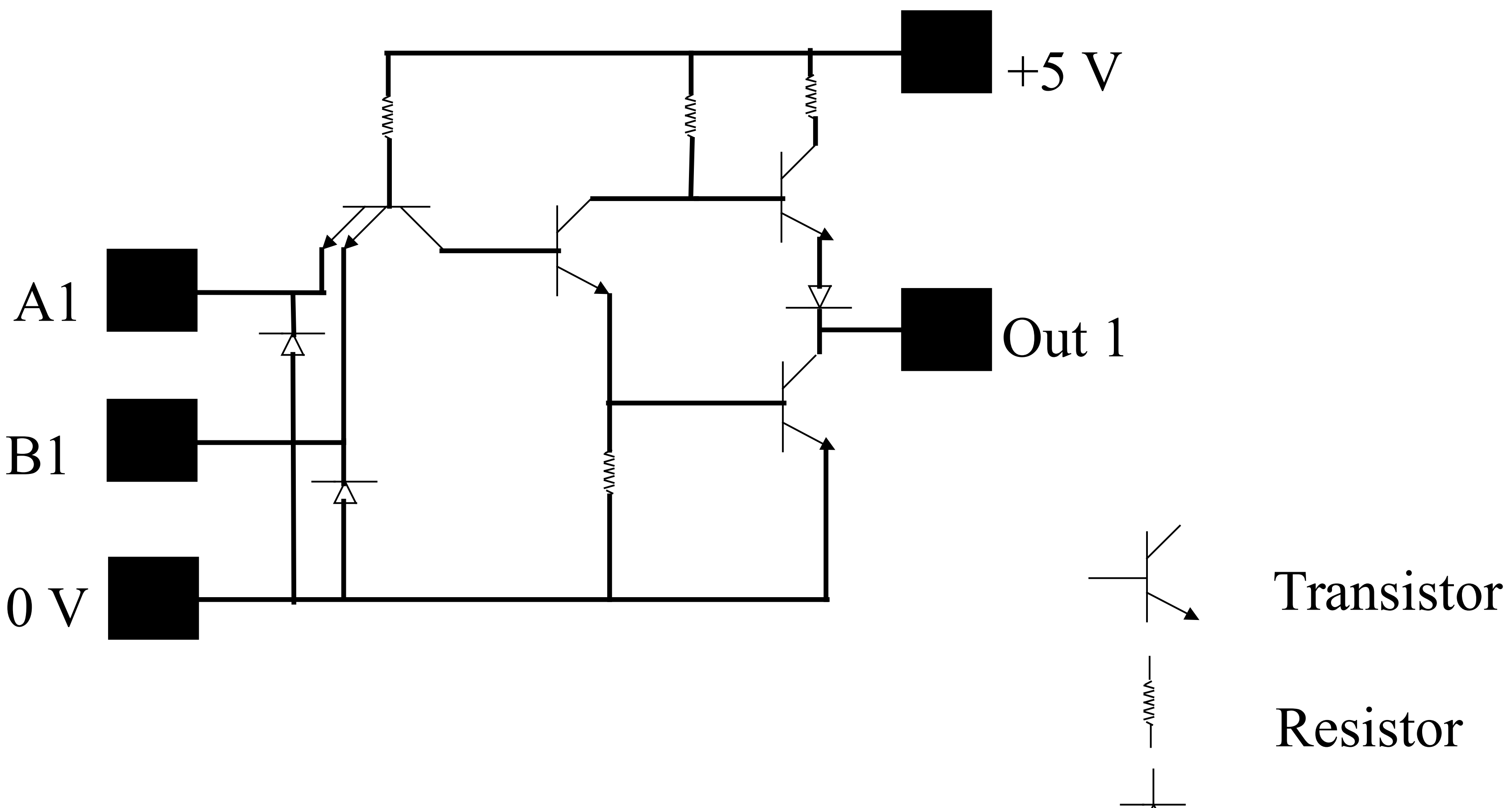
Burn away photoresist with chemicals or plasma



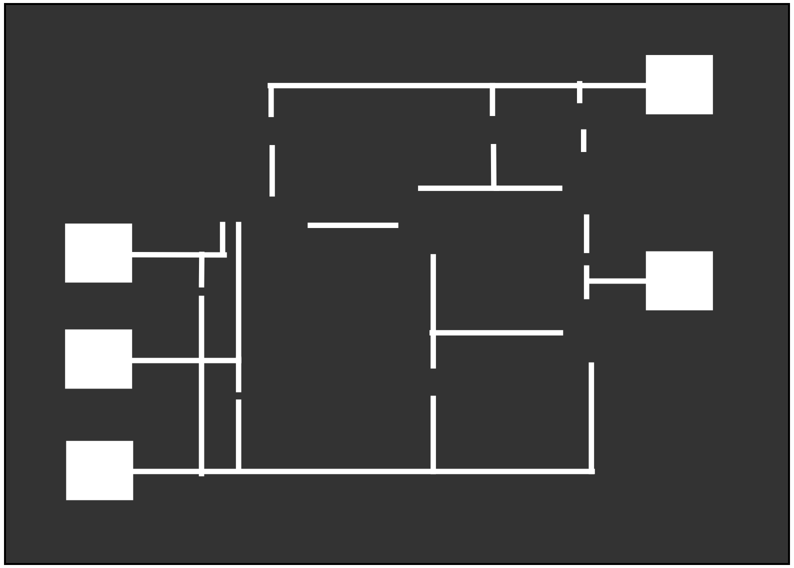


Miniaturized Metal “hello” on Silicon substrate

Circuit diagram

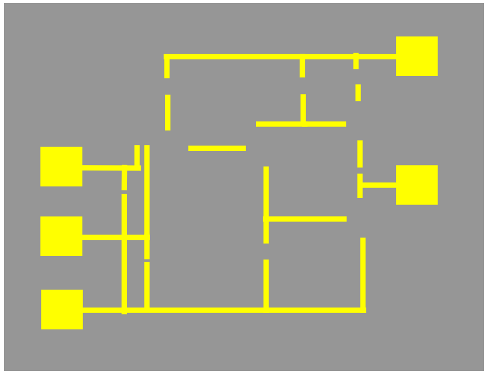


Simplified Lithography

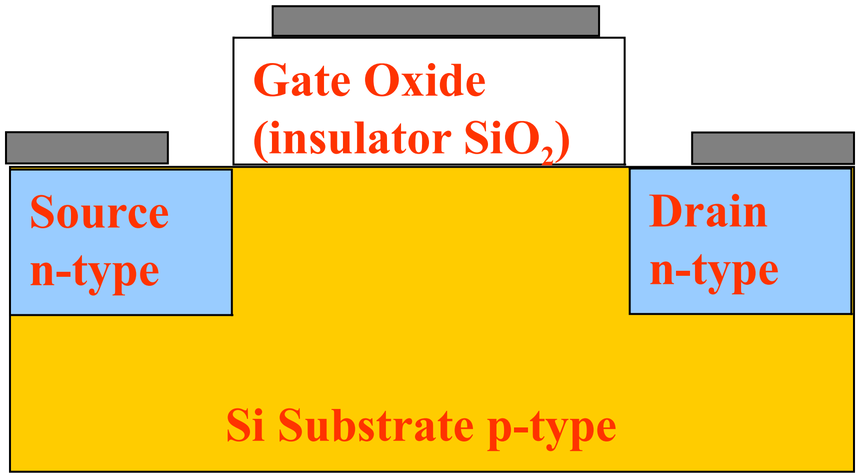


Wire mask

Miniaturized Wires on
Silicon Substrate



Schematic cross section of transistor device in an IC



Constructed with multiple layers, multiple uses of lithography

Current chips 9 –13 layers typical

Can Moore's Law Continue?

Certainly not forever!

Can't make transistors smaller than an atom.

Can't make signals go faster than the speed of light.

There are various other limits imposed by physics.

Example: Thermodynamic limits on the amount of energy that has to be associated with flipping a one to a zero.

But the fundamental limits are a ways off – can probably get more doublings in performance.

Already running into limitations of the standard technology.

I. Running into limitations in manufacturing devices much smaller than the current generation.

II. Even if you can manufacture smaller devices, they may not work as expected.

We will now look at examples of both of these problems and some possible ways to advance.

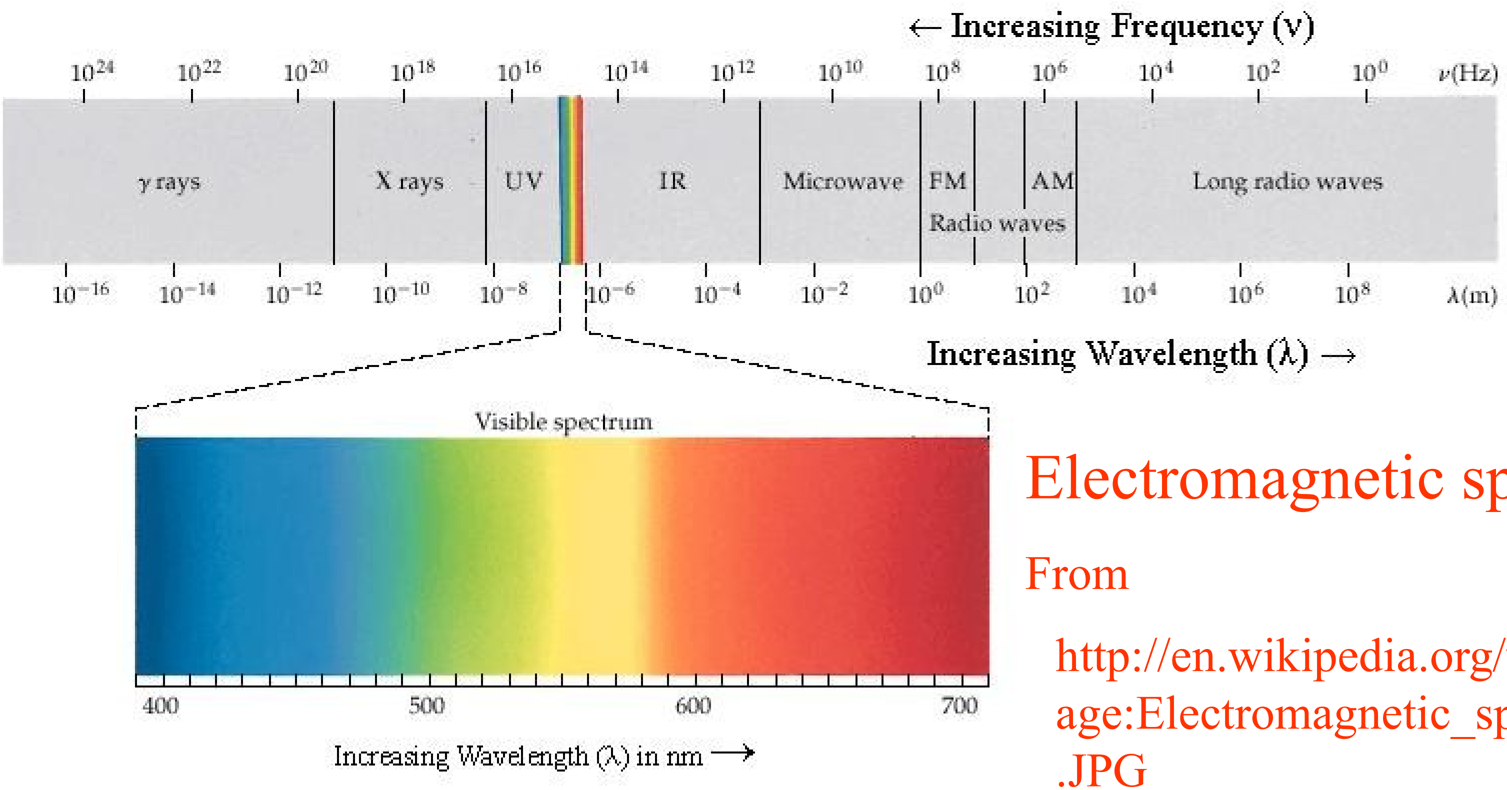
I. Limits on making things smaller

Recall our discussion of lithography.

Essentially want an image of a wire or an area to become part of a transistor.

Shining a light through a hole that’s too small produces interference instead of a sharp shadow.

Size limit of features in the image is approximately the wavelength of the light



Electromagnetic spectrum

From

http://en.wikipedia.org/wiki/Image:Electromagnetic_spectrum.JPG

Devices are already much smaller than wavelength of visible light.

Using ultraviolet and increasingly extreme ultraviolet. Plans for 13 nm.

Would need to use x-rays to get much smaller geometries.

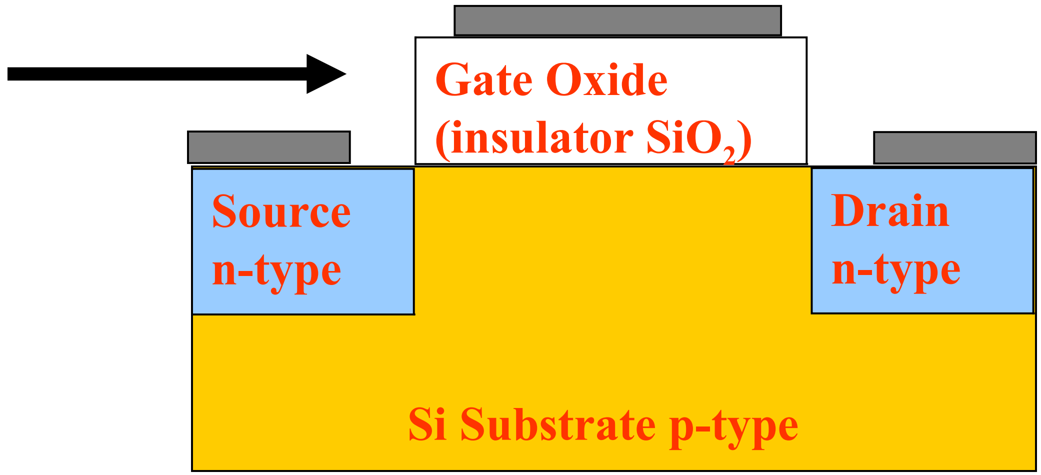
- Optical devices like lenses would have to be further developed.
- Expensive and difficult.

II. Unexpected Behavior

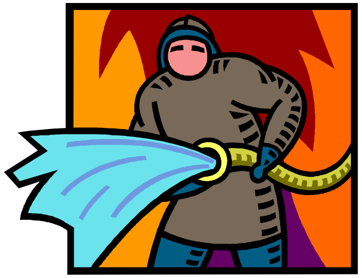
Electrons can "tunnel" through insulating portions of the device that are too thin.

Quantum mechanical effect that cannot be understood in terms of classical physics.

Gate Oxide is a place where tunneling can occur



Can reduce this effect by user higher power to turn on/off transistor



Too hot to handle!

Decreasing size requires higher power for devices to be reliable.

Heating of chips is already a problem.

You’ve seen the heat sinks!

Reduction to too small could melt the chips!!!

Various approaches to reduce the heating, but these involve major changes to chip technology and would be expensive.

Sleep transistors: Bias off when not in use.

Further reading: FinFETs, High-K Gate Oxides, Copper Traces.

New Technologies

Conventional chip technology may be approaching its limits.

Time for fundamentally new technologies?

Examples

Recently reported single electron molecular transistors.

Made one at a time with atomic force microscopes and carbon nanotubes.

Not suitable for lithographic techniques.

Optical logic devices use light instead of electricity.

Further reading: quantum computing, non-metallic magnets, organic conductors.

Summary

Much of the tech advance and economic growth of the past 50 years has been fueled by rapid increases in the performance of electronics.

Described by Moore's Law: number of transistors on an IC doubles every two years. Has held since 1960s.

Performance gains cannot continue forever: laws of physics put limits on performance.

More doublings possible.

Currently technology – the CMOS circuit made with lithography – will probably reach its limits much sooner, perhaps in next few years.

Even if performance gains continue, may occur at a slower rate.

Will need lots of innovative new physics, chemistry, and engineering to continue the growth in performance.

In-class exercises

1. Photoresist is

a. Material that has a resistance that depends on light

b. Material that can be burned away by light and chemicals.

c. Material that blocks light

2. Why is it now necessary to use ultraviolet light in lithography? ANSWER: THE FEATURES ARE TOO SMALL FOR LIGHT WITH VISIBLE WAVELENGTHS

3. Maximum number transistors are on a chip now?

a. Thousands

b. Millions

c. Billions