Lecture 8: Junctions with metals

- Metals as interconnects
  - Electromigration
- Schottky barrier Diodes
- Ohmic contacts
- Insulator-semiconductor junctions
- Interconnect technology
- Moore’s Law

Metals as conductors

- Metal serves three important roles in circuits:
  - As **interconnects** providing the pathways to pass electronic signals to and from a device.
  - As **Schottky barriers**, they provide junctions that can provide rectification, have built-in electric fields and have a variety of uses.
  - As **Ohmic contacts**, they allow electrons or holes to enter and leave semiconductors with little resistivity.
- Interconnects although obvious passive elements of a circuit are extremely important. The metal strips have to be able to carry adequate current and make good contacts with devices.
- Interconnects are deposited on interconnects and touch the active devices only through windows that are opened at selected point.

Metals as interconnects

- Aluminium is a commonly used interconnect material.
- It is a good conductor, with a resistivity of $2.6\times10^{-6}\Omega$-cm. The resistivity in thin-form can be up to a factor of 20 lower, allowing the thin interconnect film to carry very high current densities.
- High-speed devices work with high current densities ($\sim10^5$A/cm^2). At such current densities, a phenomenon known as electromigration occurs that is a major cause of breakdown in ICs.
- When electromigration occurs metal ions are forced to move downstream due to high electron current densities.
- The metal film will develop voids and hills at regions of curves and folks. The thinning will cause excess heating and failure.

Electromigration

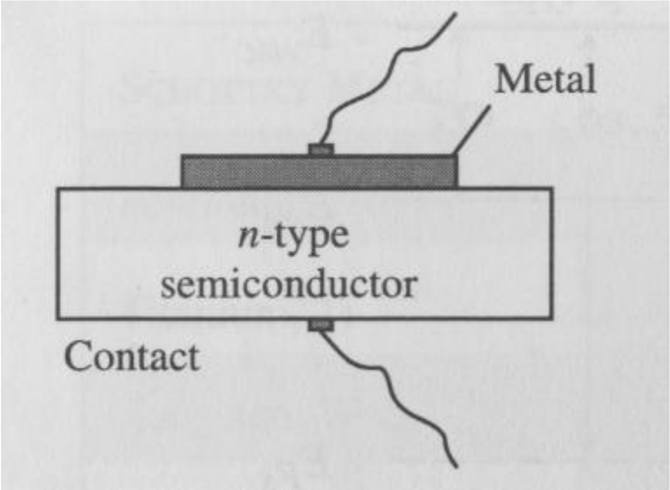
- Electromigration occurs mainly along the grain structure. Prevention of this phenomenon requires that the grain structure is controlled along the microcrystallites that form the metal lines.
- Larger grains have less surface area and therefore resist electromigration.
- Some allowing metals, such as copper, accumulate in the grain boundaries, locking the atoms there into place and preventing electromigration.
- Copper also prevents hillocking of Al films and thus prevents non-uniform thermal effects.
- Since 1998 scientists have been able to make interconnects from copper – delays in devices have been improved.

Resistivities of common metals

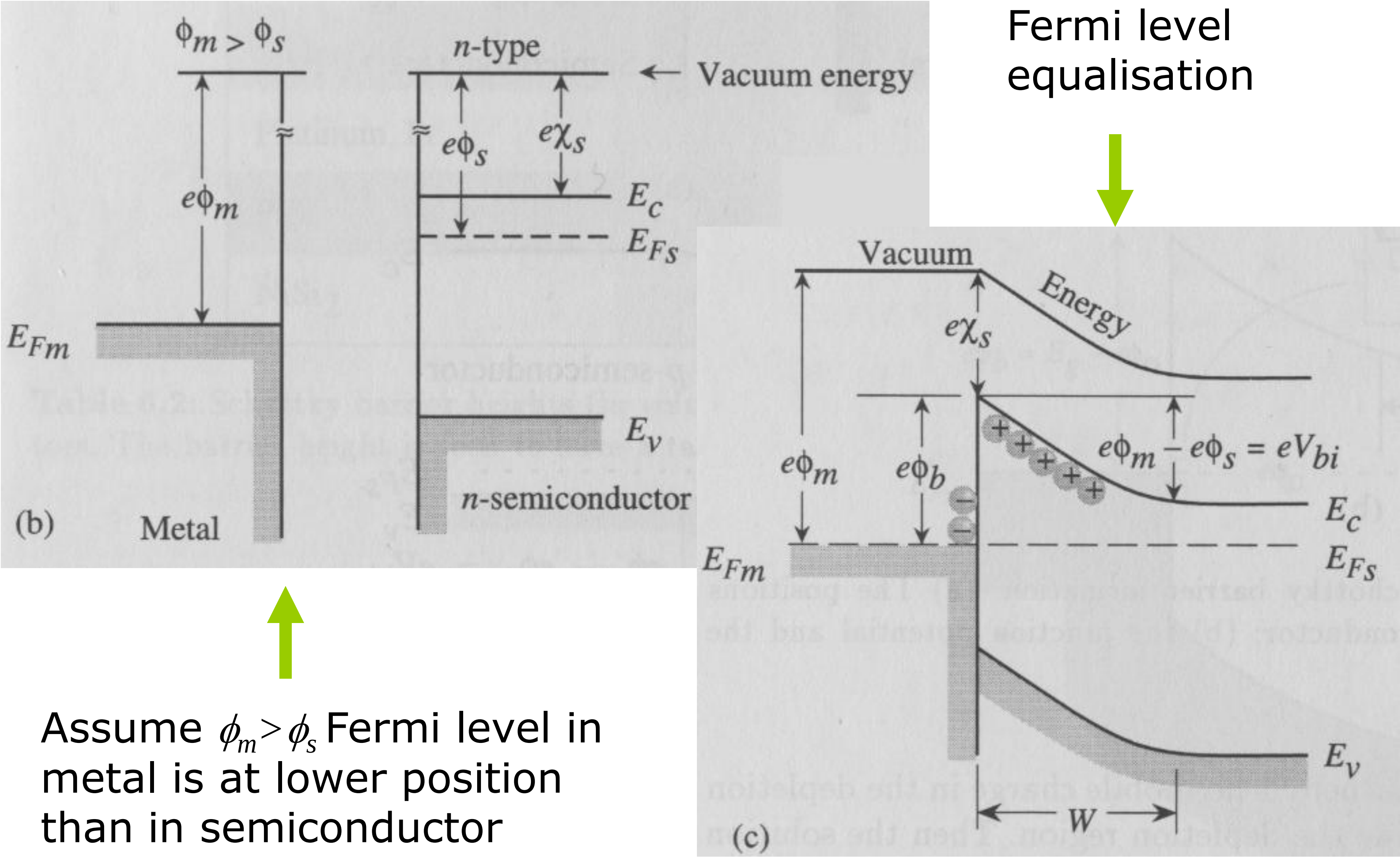
Material	Resistivity (μΩ-cm)
Aluminium (Al)	2.7
Titanium (Ti)	40.0
Tungsten (W)	5.6
Gold (Au)	2.44
Silver (Ag)	1.59
Copper (Cu)	1.77
Platinum (Pt)	10.0

Schottky barrier diode

- A strongly non-linear response can be obtained from a metal-semiconductor junction.
- The resulting Schottky barrier and diode are widely used in important applications.
- The Shottky diode has characteristics similar to those of a p-n junction diode except that for many applications it has a much faster response.



Schottky barrier diode



Fermi level equalisation

Assume $\phi_m > \phi_s$ Fermi level in metal is at lower position than in semiconductor

Schottky barrier diode

- To ensure the continuity of the vacuum layer, the Fermi level must move deeper into the bandgap of the semiconductor at the interface region.
- Since the metal side has an enormous electron density, the metal Fermi level or the band profile does not change when a small fraction of electrons are added or taken out.
- As the electrons move to the metal side, they leave behind positively charged dopants, and a dipole region is produced in the same way as for a *p-n* diode.
- In the ideal Schottky barrier, the height of the barrier at the semiconductor-metal junction, defined as the difference between the semiconductor conduction band at the junction and the metal Fermi level.

$$e\phi_b = e\phi_m - e\chi_s$$

Schottky barrier diode

- The electrons coming from the semiconductor into the metal face a barrier denoted by eV_{bi}.
- The potential is defined as the built-in potential of the diode:

$$eV_{bi} = e\phi_m - e\phi_s$$

- The height of the barrier can be altered by applying an external bias (as in the p-n junction).
- According to the discussion, a Schottky barrier height for n- or p-type semiconductors depends upon the metal and semiconductor properties.
- Experimentally the barrier height is *independent* of the metal employed. Qualitatively this can be understood in terms of a model based upon nonideal surfaces.
- The interface has a distribution of interface states that may arise from the presence of chemical defects or broken bonds.

Schottky Barrier: Current Flow

- Electrons can flow from the metal to the semiconductor and vice-versa.
- When external bias is applied, current flows in the device which occurs by the following mechanisms:
  - **Thermionic emission**: electrons with energy greater than the barrier height $e(V_{bi}-V)$ can overcome the barrier and pass across the junction. As the bias changes the barrier to be overcome by electrons changes and the electron current injected changes.
  - **Tunnelling**: electrons can tunnel through the barrier.
- The saturation current in the Schottky barrier is much higher than the p-n junction. This results in a turn-on voltage for a forward-bias conducting state at a very low bias, but also results in a high reverse current.

P-N vs Schottky Diode

p-n Diode	**Schottky Diode**
Reverse current due to minority carriers diffusing to the depletion layer → strong temperature dependence	Reverse current due to majority carriers that overcome the barrier → less temperature dependence
Forward current due to minority carrier injection from n- and p-sides	Forward current due to majority injection from the semiconductor
Forward bias needed to make the device conducting (the cut-in voltage) is large	The cut-in voltage is quite small
Switching speed controlled by recombination of minority charge carriers	Switching speed controlled by thermalisation of “hot” injected electrons across the barrier ~ps (majority carrier device).

Ohmic contacts

- In order for a device to be useful, a physical property of the device should respond in a controlled manner to an external response.
- In most devices the chosen physical property of the device is the current.
  - Has the advantage that changes in current flow can easily be detected and manipulated.
- For current flow to occur, electrons and holes must flow freely in and out of the semiconductor.
- A metal-semiconductor junction that does not provide a barrier to the flow of charge is required. Such a non-rectifying contact is termed an ohmic contact.

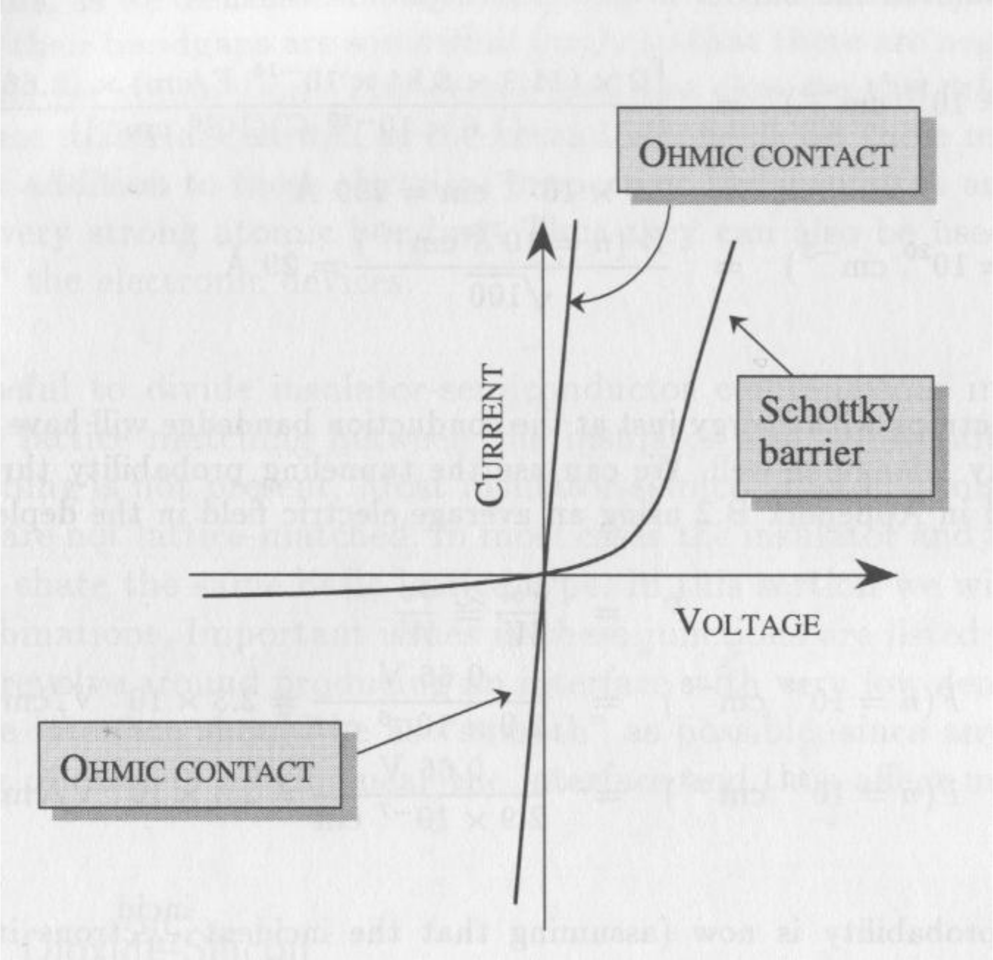
Ohmic contacts

- If near the interface region the semiconductor is heavily doped, the depletion width can be made extremely narrow.
- The electrons can now tunnel through the barrier with ease.
- The quality of an ohmic contact is usually defined through the resistance *R* of the contact over a certain area *A*.
- The normalised resistance is called the specific contact resistance r_c and is given by:

$$r_c = R \cdot A$$

- The resistance can be reduced by using a low Schottky barrier height and doping as heavily as possible.

Ohmic contacts



Insulator-Semiconductor Junctions

- There must be an isolation between an input and output signal of a device.
- The silicon dioxide-silicon junction is the most important junction in solid state physics.
  - Despite the severe mismatch between SiO_2 structure and Si structure, the interface quality is extremely high.
  - The ability to produce high quality interfaces is responsible for the remarkable success of metal-oxide-silicon (MOS) devices.
  - Due to low interface densities, there is very little trapping of electrons (holes) at the interface so that high speed phenomena can be predictably used.
  - No other semiconductor has a natural oxide producing a high-quality interface give Si a unique advantage in electronic devices.

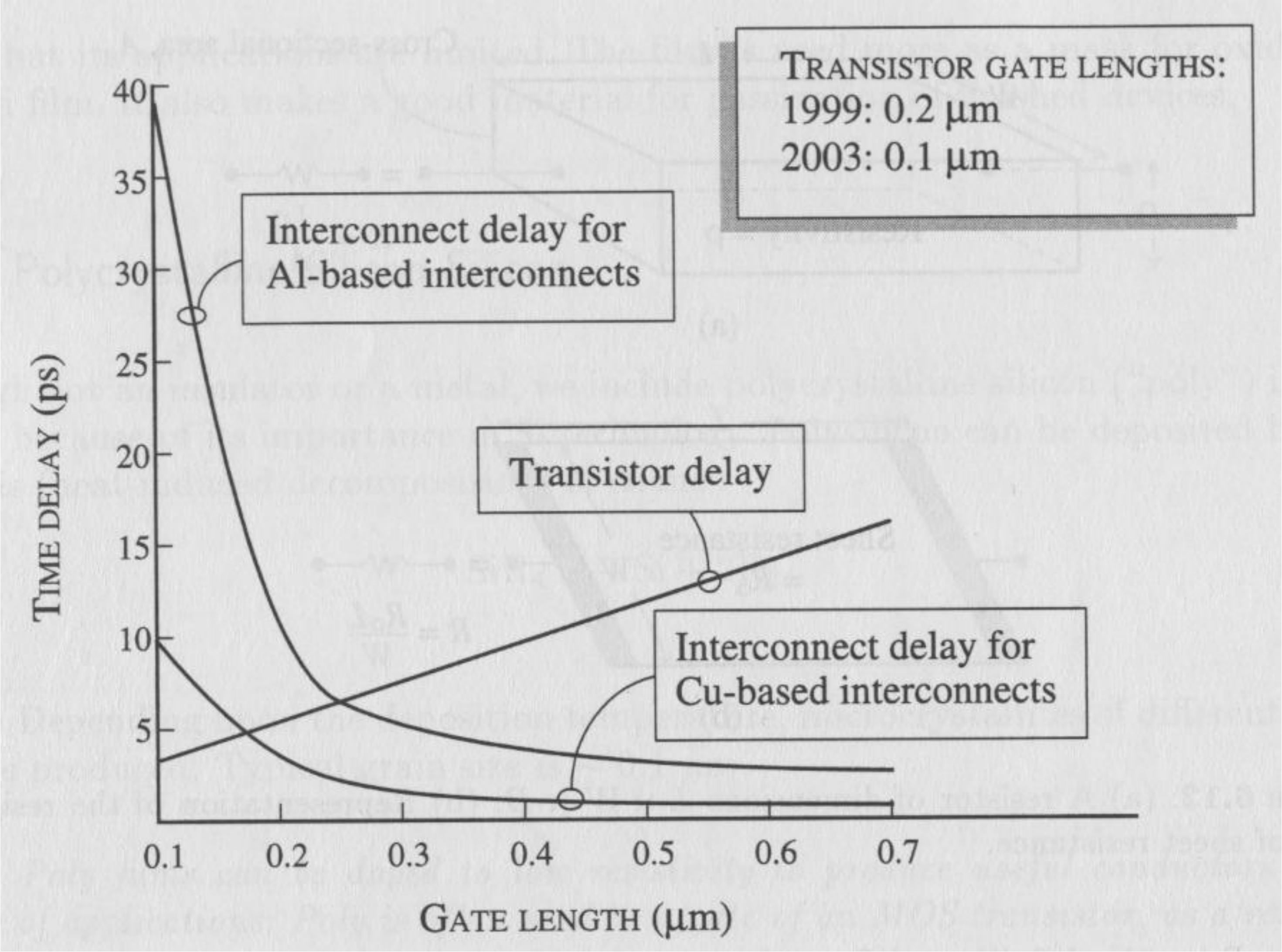
Interconnects

- Presently the most important metal used for interconnects is aluminium and the most important insulator in microelectronics technology is SiO_2.
- Aluminium has a reasonably high conductivity and can be deposited without problems.
- The key property of interconnects is the resistance associated with them and the maximum current density that can pass through without structural or electrical deterioration.
- The ability of an interconnect to withstand high current densities ($\sim 10^5 A/cm^2$) is an important requirement, since most microelectronic devices need high drive currents.

Interconnects

- As the density of devices on a chip becomes higher, the area of a typical interconnect has to become smaller.
- The RC delay time for signals to propagate from one device to another will increase.
- Semiconductor Industry Associates estimate that interconnect delay will become increasingly dominant and overtake device-switching delay.
- Copper (by virtue of its higher conductivity) is a material that has excellent potential.
- Copper technology has finally matured and in 1998 made it into products for the first time. IBM began offering high performance processors based on copper technology.

Interconnect delays

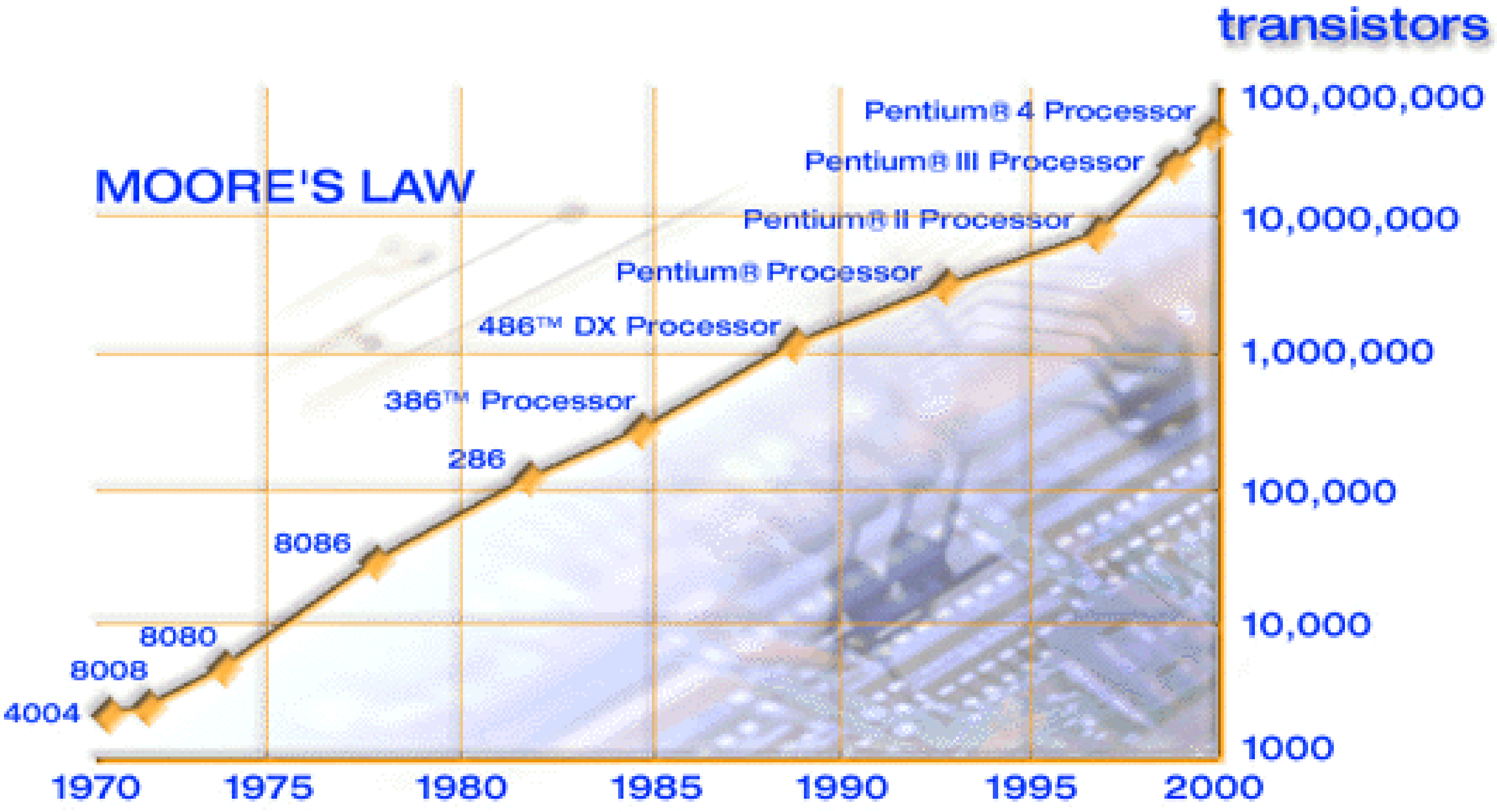


Moore’s Law

- “Gordon Moore made his famous observation in 1965, just four years after the first planar integrated circuit was discovered. The press called it "Moore's Law" and the name has stuck. In his original paper, Moore predicted that the number of transistors per integrated circuit would double every 18 months. He forecast that this trend would continue through 1975. Through Intel's technology, Moore's Law has been maintained for far longer, and still holds true as we enter the new century. The mission of Intel's technology development team is to continue to break down barriers to Moore's Law.”

  www.intel.com

Moore’s Law


MOORE'S LAW
transistors
100,000,000
10,000,000
1,000,000
100,000
10,000
1000
1970
1975
1980
1985
1990
1995
2000
4004
8008
8080
8086
286
386™ Processor
486™ DX Processor
Pentium® Processor
Pentium® II Processor
Pentium® III Processor
Pentium® 4 Processor

Intel processor timeline

	Year of introduction	Transistors
4004	1971	2,250
8008	1972	2,500
8080	1974	5,000
8086	1978	29,000
286	1982	120,000
386™ processor	1985	275,000
486™ DX processor	1989	1,180,000
Pentium® processor	1993	3,100,000
Pentium II processor	1997	7,500,000
Pentium III processor	1999	24,000,000
Pentium 4 processor	2000	42,000,000

Summary of Lecture 8

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