Lecture 2

VE 311 Analog Circuits

Xuyang Lu

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上海交通大學
SHANGHAI JIAO TONG UNIVERSITY

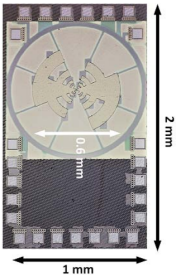
Recap of Last Lecture

- Logistics
- Analog Circuits
- Moore's Law

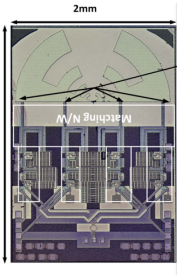
To Be Covered In This Lecture

- Scaling
- Review of 215 (Thevenin)
- Semiconductor Basics

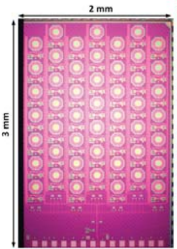
RF, mm-Wave, and THz chips



Imaging



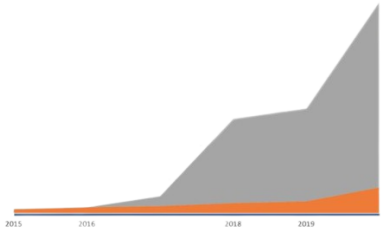
Communication



Biomedical

- Now we can interact with higher and higher frequencies.
- What my lab explores.

Apple A-series As an Example

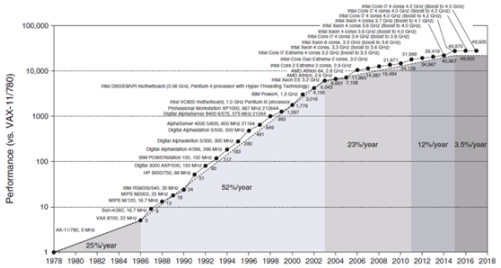


Alternative Processing Power (A9-A14)

- 16 core NPU (11 TOPS)
- ML accelerators
- GPU and Rendering
- Facial recognition
- Speech recognition
- Augmented reality

- Emergence of dedicated AI accelerator ASICs are 10× more efficient than CPU.
- Historically CPU doubles every 24 mos., it's now down to 30%
- We're now seeing 100%+ processing power improvements for SoC

CPU Performance Trends



Performance of CPU over the years (Source: HENNESSY,2017)

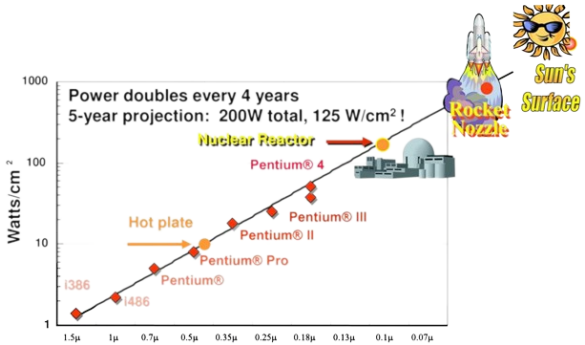
- Dennard scaling in CPU has come to an end.
- Now transistors can interact with 100 GHz, why the clock is still 4 GHz?

Dennard Scaling

Transistor properties	dennardian	post dennard
Quantity	s^2	s^2
Frequency	s^2	s^2
Capacitance	$1/s^2$	$1/s$
V_{dd}^2	$1/s$	1
power $= V_{dd}^2 \cdot F \cdot C \cdot Q$	1	s^2

- As the size of the transistors shrunk, and the voltage was reduced, circuits could operate at higher frequencies at the same power.
- Dennard scaling ignored the leakage current, saturation velocity, and threshold voltage, which establish a baseline of power per transistor.

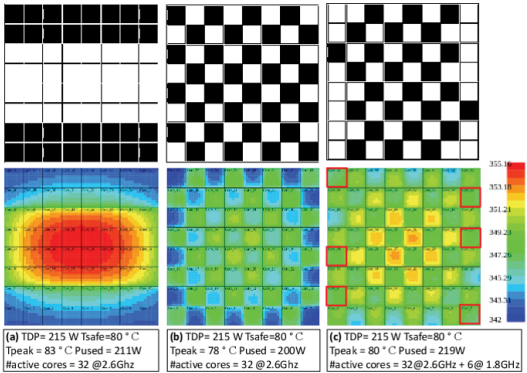
CPU Performance Trends



Source: Fred Pollack

- Power density increases exponentially.

Dark Silicon



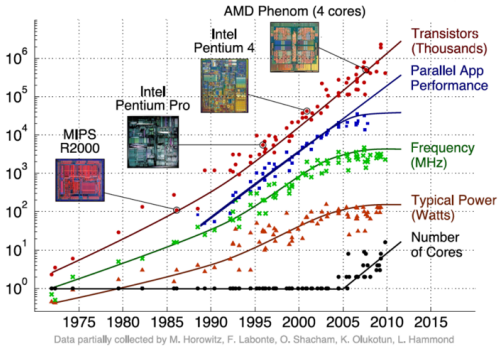
Heat map of multi-core processors

Solutions:

- Thermal management
- Power management
- Multi-thread mapping
- Degree of-parallelism
- Frequency/Supply (Dim)

In a 10 nm process, dark silicon can be 50% 80%

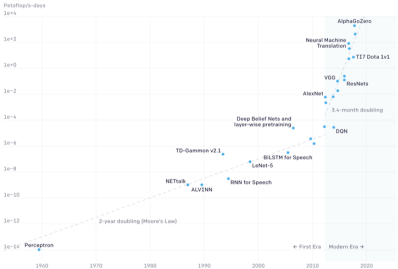
Power and Performance



Performance of CPU over the years

- These created a "Power Wall" that has limited practical processor frequency to around 4 GHz since 2006.
- Improvement from multi-core and accelerators, but not frequency.

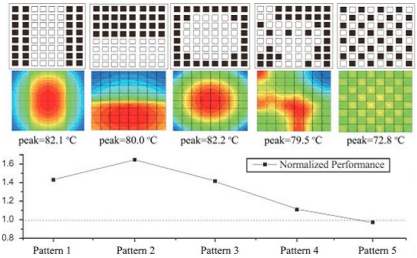
Ever-increasing Need



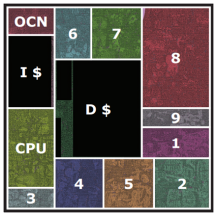
Requirement of computational power over algorithms

- The development of AI algorithms requires increasing computational power.

Area versus Power



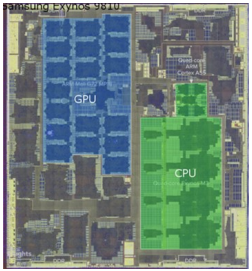
Heatmaps



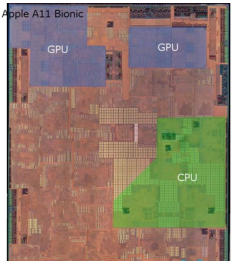
ASIC Cores

- Because of dark silicon, power instead of area is the biggest challenge.
- In RISC, many power are wasted for reconfigurability, such as instruction fetching.

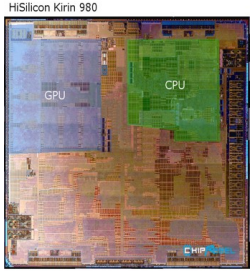
RF, mm-Wave, and THz chips



Samsung 9810



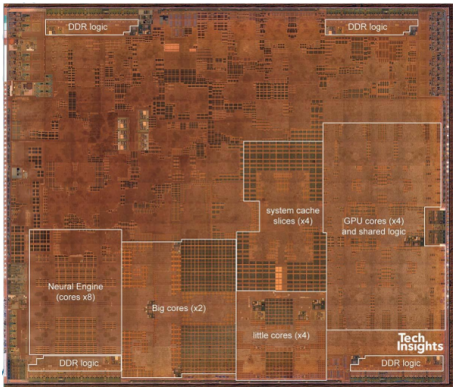
Apple A11 Bionic



Kirin 980

- Integration of CPU, GPU, and XPU on the same die is possible.

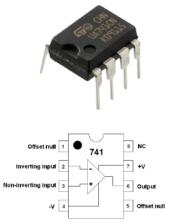
State of the Art SOCs

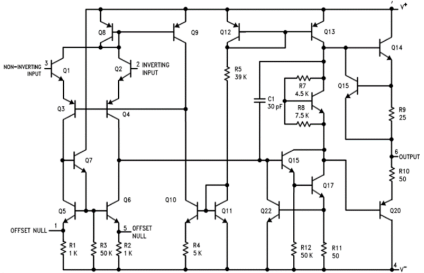


- 2x Large CPUs
- 4x Small CPUs
- GPUs
- Neural processing unit (NPU)
- Lots of memory
- DDR memory interfaces

Course Outcome

Understanding





Innovation

- You are only bounded by your imagination.
- Welcome to our lab's weekly group meeting.
- Propose project ideas and seek guidance.
- Take upper-level courses.

Active vs Passive Components

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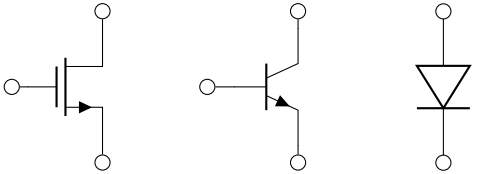
Active Components



MOSFET BJT Diode

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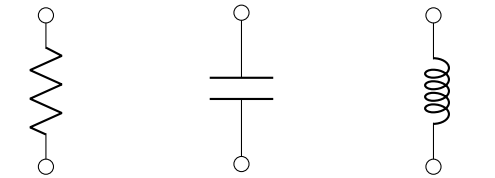
Passive Components



Resistor Capacitor Inductor

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Linear vs Nonlinear Circuit

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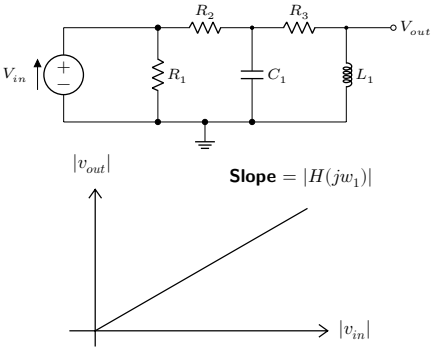
Linear Circuit



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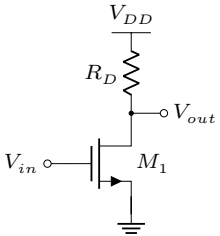
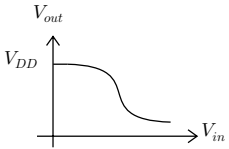
Nonlinear Circuit





Analog vs Digital

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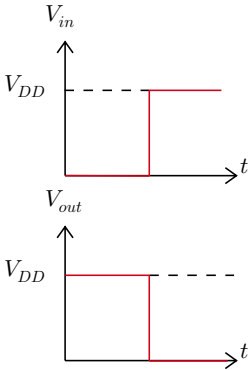
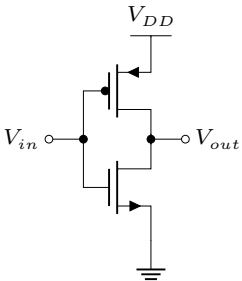
Digital





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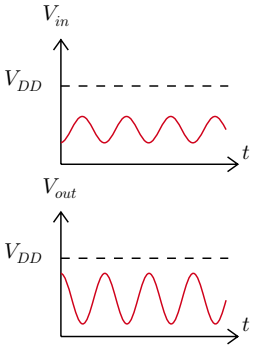
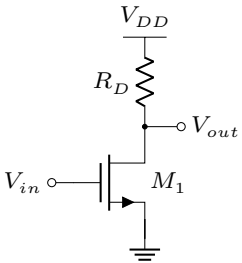
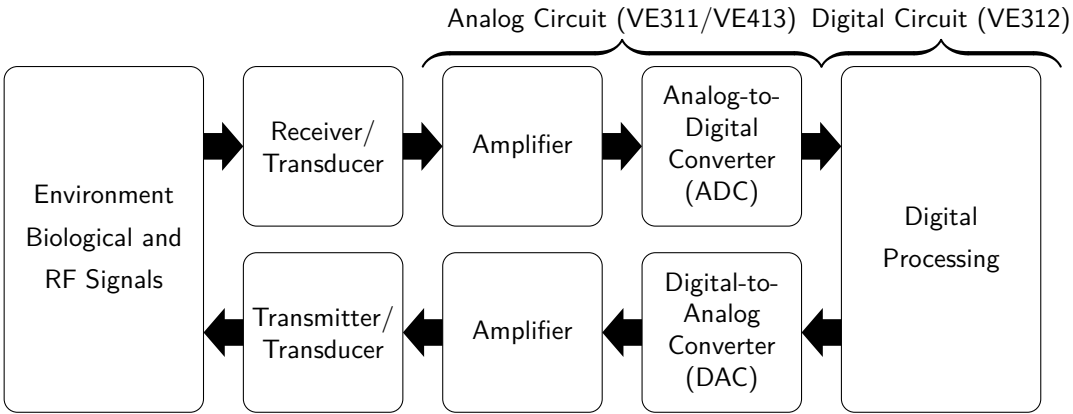
Analog

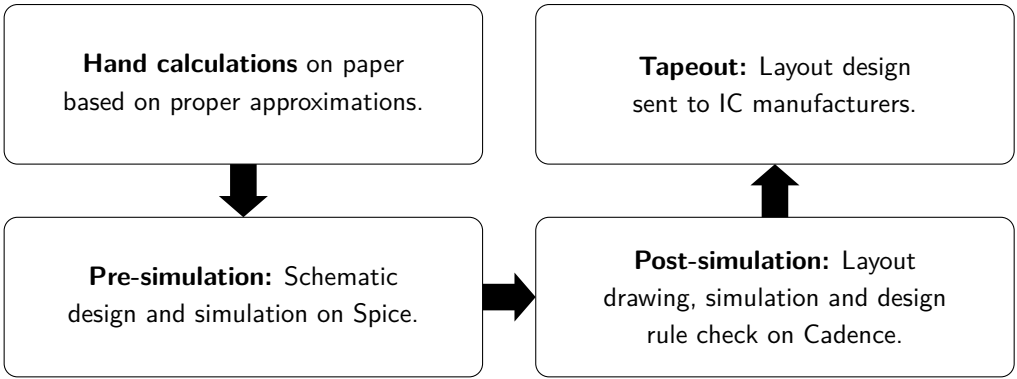




Analog Circuit in IC

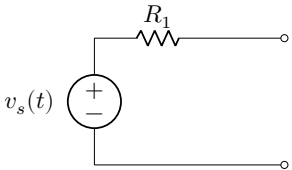


IC Design Process

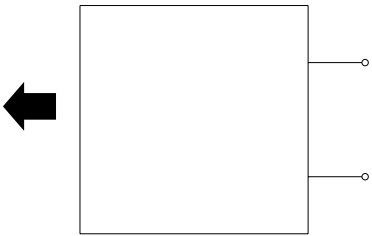


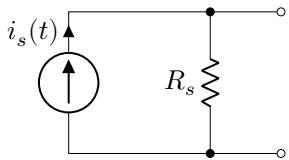
Thevenin and Norton Equivalents

Reading Sedra and Smith, Section 1.1



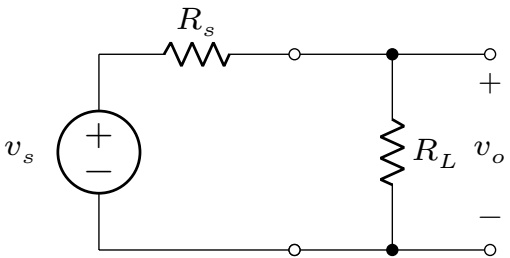
Thevenin Equivalent





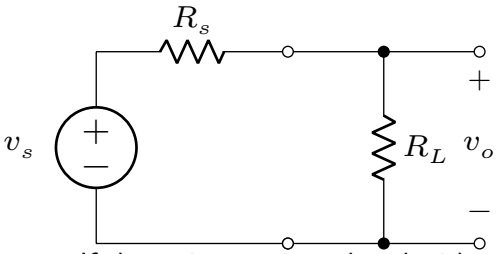
Norton Equivalent

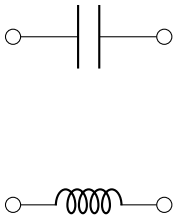
Thevenin and Norton Equivalents



- What is the voltage at the output?
- We should know Thevenin and Norton Equivalents of a network.

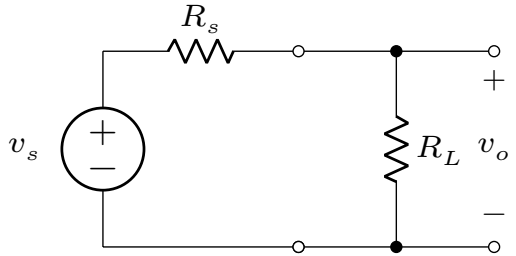
Thevenin and Norton Equivalents





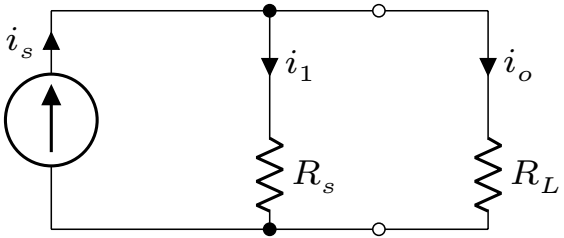
- If the resistance is replaced with an impedance, the same principle shall hold.

Thevenin and Norton Equivalents



- Do we want larger or smaller R_s to get the largest output voltage?

Thevenin and Norton Equivalents

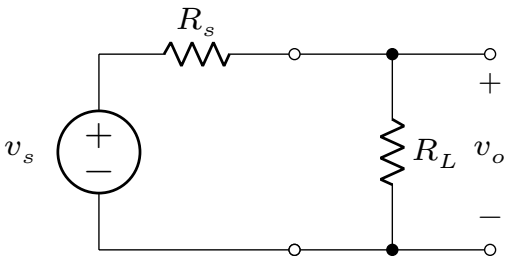


Norton Equivalents

$$i_o = i_s \frac{R_s}{R_L + R_s}$$

- From a current perspective, do we want large or small R_s?

Thevenin and Norton Equivalents



- What is the condition for maximum power transfer to the load?
- Why is it important?

Power Calculation

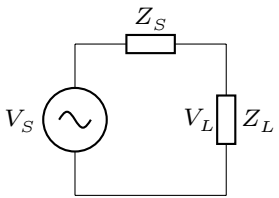
Why is power $\frac{1}{2}\operatorname{Re}\{\mathrm{VI}^*\}$

$$s(t) = v(t) \cdot i(t) = V_M \cdot \cos(\omega t + \phi_V) \cdot I_M \cdot \cos(\omega t + \phi_I) \tag{1}$$

$$= \frac{V_M I_M}{2} \cdot [\cos(\phi_V - \phi_I) + \cos(2\omega t + \phi_V + \phi_I)] \tag{2}$$

So the average power is nothing more than the non-time varying component. Therefore, we create the complex power notion $S = P + jQ$

Maximum Power Transfer



What is the power delivered to the load?

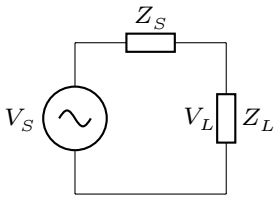
- source impedance

$$Z_s = R_s + jX_s \tag{3}$$

- load impedance

$$Z_L = R_L + jX_L \tag{4}$$

Maximum Power Transfer



$$P = \frac{1}{2} V_L^2 \operatorname{Re}\left(\frac{1}{Z_L}\right) = \frac{1}{2} V_S^2 \left|\frac{Z_L}{Z_S + Z_L}\right|^2 \operatorname{Re}\left(\frac{1}{Z_L}\right) \tag{5}$$

$$P = \frac{1}{2} V_S^2 \frac{R_L}{\left(R_S + R_L\right)^2 + \left(X_S + X_L\right)^2} \tag{6}$$

- power delivered to load as function of circuit parameters

Maximum Power Transfer

$$P = \frac{1}{2} V_S^2 \frac{R_L}{(R_S + R_L)^2 + (X_S + X_L)^2} \tag{7}$$

- To find the maximum, we can take partial derivative and set them to be zeros
- We can do $\frac{\partial P}{\partial R_L} = 0$ and $\frac{\partial P}{\partial X_L} = 0$

$$\begin{cases} R_S^2 - R_L^2 + (X_L + X_S)^2 = 0 \\ X_L (X_L + X_S) = 0 \end{cases} \tag{8}$$

$$\begin{cases} R_S = R_L \\ X_L = -X_S \end{cases} \tag{9}$$

Maximum Power Transfer

$$P = \frac{1}{2} V_S^2 \frac{R_L}{(R_S + R_L)^2 + (X_S + X_L)^2} \tag{10}$$

- Now we plug it back into the equation

$$P = \frac{V_S^2}{8 R_S} \tag{11}$$

- It represents the highest power that can be extracted from the source.

Finding Thevenin Equivalent Voltage

To find V_{TH}

- Open circuit output terminals
- Find V_{OC}

$$V_{TH} = V_{OC} \tag{12}$$

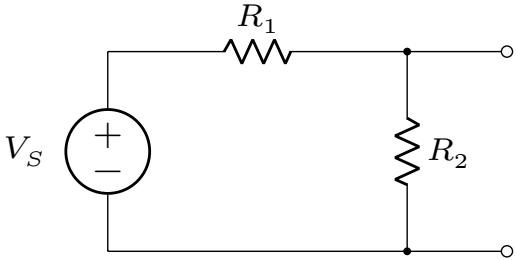
Finding Thevenin Equivalent Resistance

To find R_{TH}

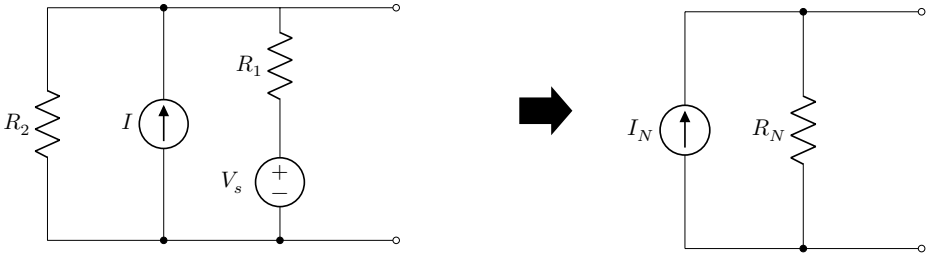
- Zero out independent sources
- Current sources are replaced with an open circuit and voltage sources are replaced with a short circuit.
- Determine the equivalent resistance seen through the port by applying a test source (V_T or I_T)

$$R_{TH} = V_T/I_T \tag{13}$$

Finding Thevenin Equivalent

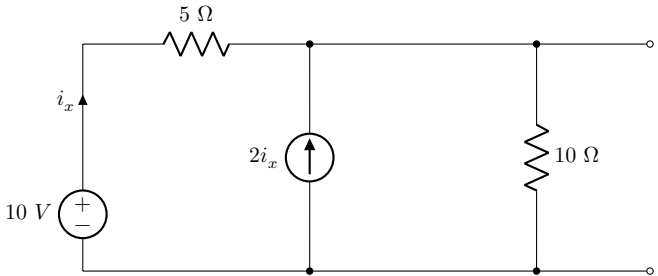


Practice: Finding Norton Equivalent

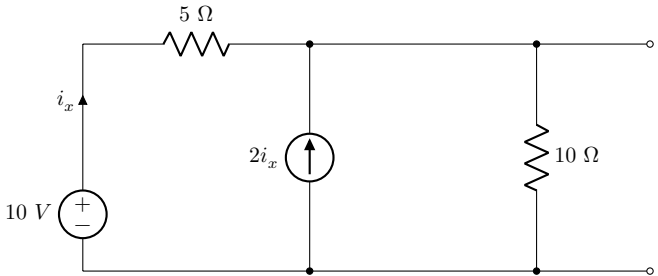


- Make sure you know this by heart, practice Thevenin model as well.

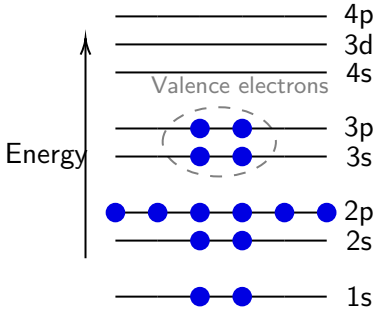
Thevenin Voltage of Dependent Sources



Thevenin Resistance of Dependent Sources

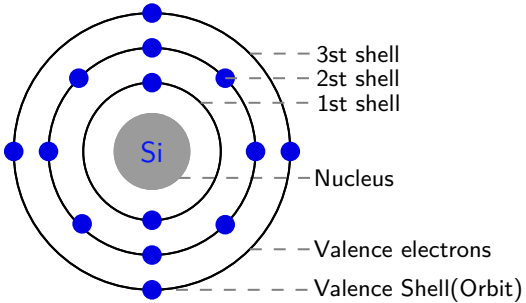


Semiconductor Physics



- Pauli exclusion principle requires that each electron must have a distinct energy state defined by a unique set of quantum numbers.

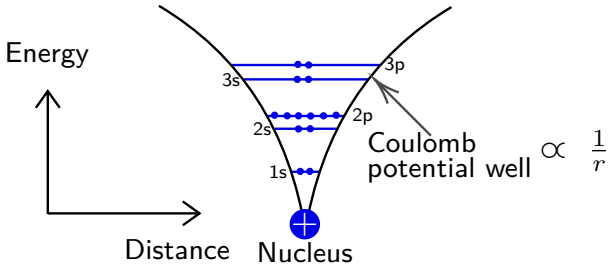
Semiconductor Physics

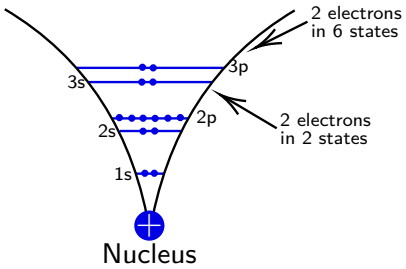


- Silicon has its inner shell (1s, 2s and 2p orbitals) totally filled with electrons.
- It's outer shell has 2 valence electrons in 3s orbital and 2 valence electrons in 3p orbital.

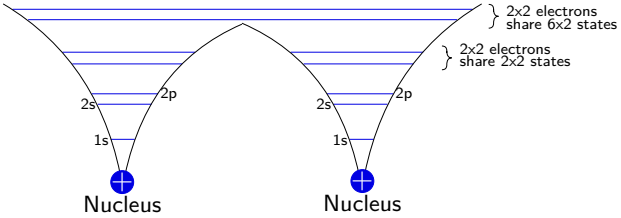
Semiconductor Physics

- When two silicon atoms are far away from each other, there is no interaction.





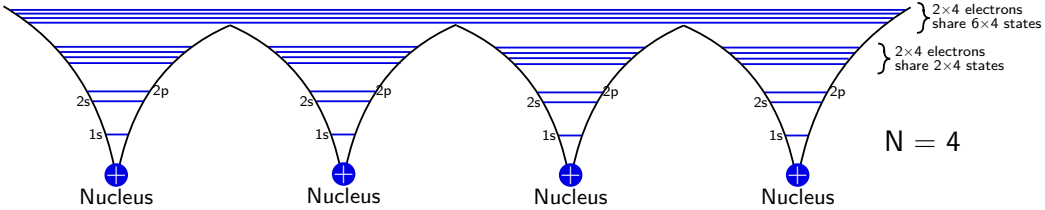
Semiconductor Physics



When two silicon atoms are close enough to each other:

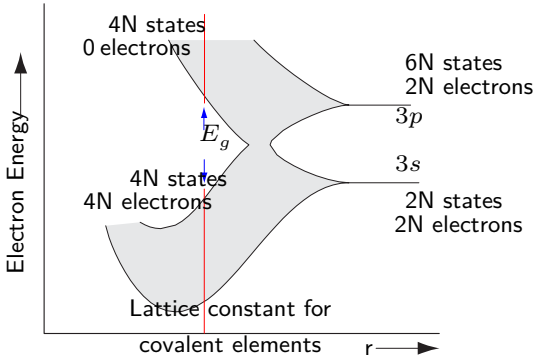
- Wavefunctions overlap and potential wells are influenced by neighboring nucleus
- The valence electrons become delocalized (e.g. through tunneling).
- Each state splits into N substates, where N is number of atoms.

Semiconductor Physics



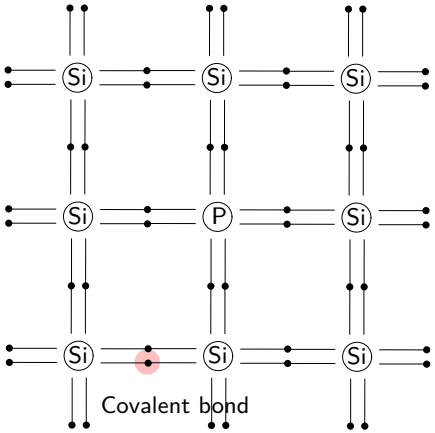
- Discrete states grow into bands when N is large.

Semiconductor Physics

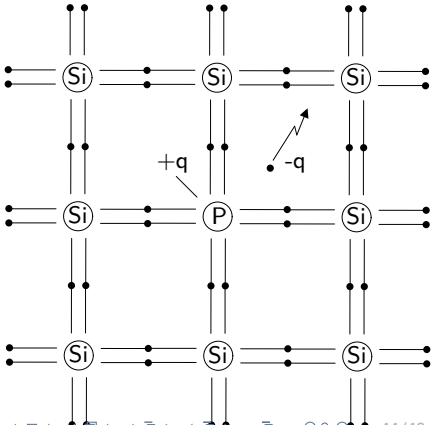


- the band gap energy (1.12 eV) is relatively small
- electrons with sufficient thermal energy can jump from valence band to conduction band

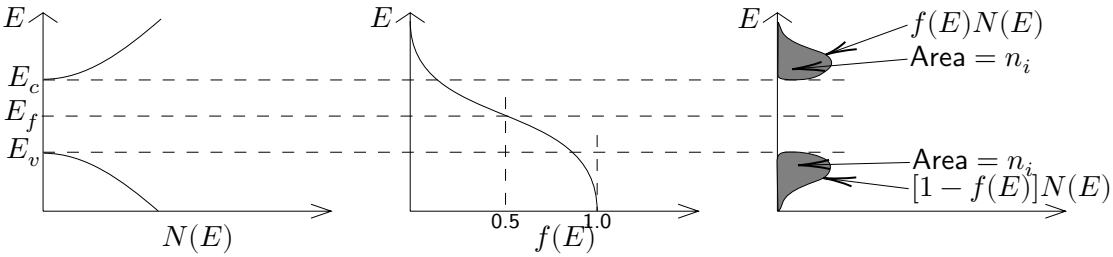
Intrinsic Si



Electrons with sufficient thermal energy can jump from valence band to conduction band.



Intrinsic Si

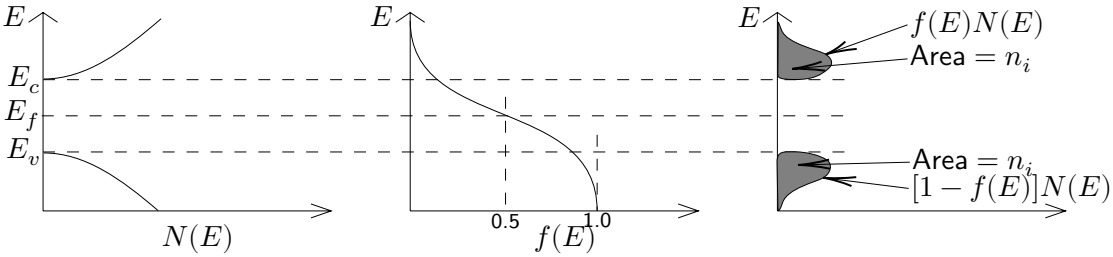


Density of States$/(\mathrm{cm}^3 * \mathrm{J})$

Fermi-Dirac Distribution

$$f(E) = \frac{1}{\exp(\frac{E - E_f}{k\mathrm{T}}) + 1} \quad (14)$$

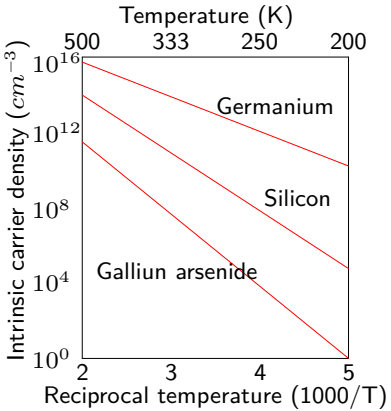
Intrinsic Si



$$n = \int_{E_c}^{\infty} f(E)N(E)dE = n_i \qquad (15)$$

$$p = \int_{-\infty}^{E_v} [1 - f(E)]N(E)dE = n_i \qquad (16)$$

Intrinsic Si



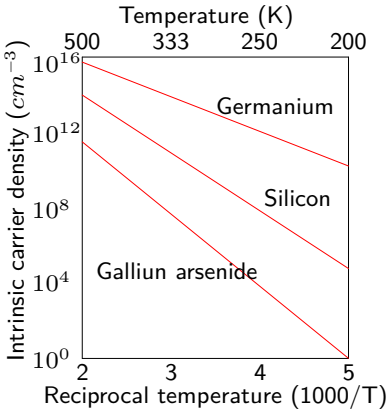
$$np = n_i^2 = \mathrm{BT}^3 \exp(-\frac{E_G}{k\mathrm{T}}) \quad (17)$$

k (Boltzmann's Constant)

$$= 1.38 \times 10^{-23}\ \mathrm{J/K} = 8.62 \times 10^{-5}\ e\mathrm{V/K} \quad (18)$$

	B (K^{-3}·cm^{-6})	E_G (eV)
Si	1.08 $\times 10^{31}$	1.12
Ge	2.31 $\times 10^{30}$	0.66
GaAs	1.27 $\times 10^{29}$	1.42

Intrinsic Si



At 300K

$$n_i^2 = (1.08 \cdot 10^{31}) \cdot 300^3 \cdot e^{\frac{-1.12}{(8.62 \cdot 10^{-5}) \cdot 300}}$$

$$= 4.52 \times 10^{19} (1/\mathrm{cm}^6) \quad (19)$$

$$n_i = 6.73 \times 10^9 (1/\mathrm{cm}^3) \approx 10^{10} (1/\mathrm{cm}^3) \quad (20)$$