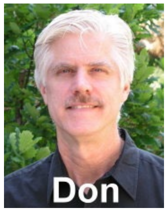
Course Hints

Good practices

- **Review** the slides before class
  - become familiar with material
- **Review** the lecture after class
  - what don't you understand
- Briefly **Study** the lab instructions
  - what components will you use
  - what instruments will you use
  - what measurements will you make

Electronics - PHYS 2371/2



Calendar of Topics Covered

Physics PHYS 2371/2372, Electronics for Scientists

Don Heiman and Hari Kumarakuru
Northeastern University, Fall 2020

Also see **Course Description** and **Syllabus**

This is a schedule of the topics covered, but it may be modified occasionally (09/24/2020).

Week #	Lectures	Weekly Topics (Chs.)	Homework (Ch-Problem)	Lab Experiments (always look for latest version)
III Sept 23-25	**Wed Lecture** Time-Dependent AC Circuits	The Oscilloscope (Ch-17) AC and Elements of Circuits (Ch-7/8) Circuit Analysis (LRC) (Ch-9/12) Resonance (Ch-10)	7-all, 8-3 12-all	**Worksheet-3**, **Worksheet-3 video** **RC data xls** ***Time-Dependent AC Circuits*** (R, RC, LRC)
IV Sept 30-Oct 2	**Wed Lecture** Semiconductor Devices	Solid State Devices (Ch-40) *p-n* Junction Diodes (Ch-41) Transistors/Circuits (Ch-42-45)	HW Handout	**Worksheet-4,** ***Say Hello (and Goodbye) to the Transistor***
V Oct 7-9	**Wed Lecture** Operational Amplifiers	Op-Amp Basics (Ch-28, 31) Basic Op-Amp Circuits (Ch-29)	28-1/3/4, 29-1/2/3/4	**Lab-5, *Op-Amps***
VI Oct 14	**Wednesday** Study for EXAM-1	**Study for EXAM-1** **Basics, AC Circuits, Semiconductors, Op-amps**		No Lab
VII Oct 19, 21-23 **MON/WED**	**MONDAY EXAM-I**	**Wed Lecture** Magnetoelectronics Magnetic induction/flux Transformers (Ch-11)	11-all	**Lab-6, *Build a Magnetometer***

TODAY

- ☐ **Semiconductors**
  Si, GaAs
  doping
  donors/acceptors
  mobility
- ☐ ***p-n* Junction**
  depletion region
  energy bandgap
- ☐ **Bipolar Junction Transistor**
  current amplification
  npn/pnp
  common emitter
  emitter follower
- ☐ **Preview Lab-4, Transistor**

R, C, L - Voltages/Currents

	R	C	L
$I(t)$ =	V(t)/R	$C\, dV(t)/dt$	$-1/L \int V(t)dt$
$V(t)$ =	I(t) R	$1/C \int I(t)dt$	$L\, dI(t)/dt$
Z =	**R**	$-i/\omega C$	$i\omega L$
X =	R	$1/\omega C$	ωL
Φ =	0	V lags I by 90° $\Phi = -\pi/2$	V leads I by 90° $\Phi = +\pi/2$

- C and L only change the flow of current
- C and L do not dissipate energy, they **store energy**
- C stores energy in **electric** field $\varepsilon_o E^2/2$
- L stores energy in **magnetic** field $B^2/2\mu_o$

X - Reactance Resists changes

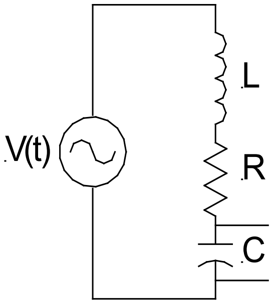
- **C - electric field resists extra charge**
- **L - magnetic field resists extra current**

Review LRC

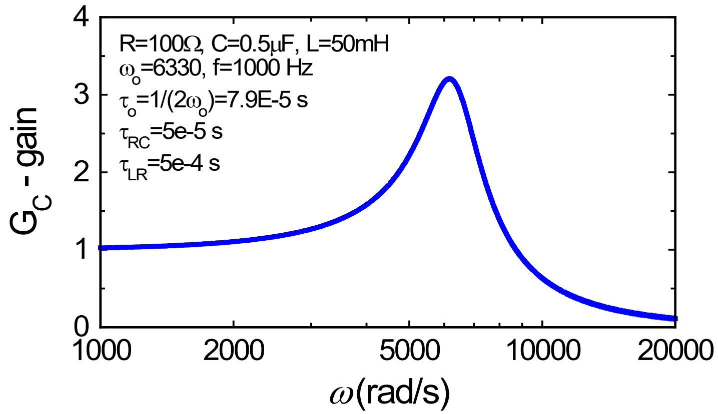
- **Time Constants**
  - $\tau_{RC} = RC, \quad \tau_{LR} = L/R$
- **LRC Circuit Gain– AC source**
  - **Voltage divider**

$$V_J = V_{in}\frac{Z_J}{Z_R + Z_L + Z_C}, \quad J = R, C, L$$

$$G_J \equiv \left|\frac{V_J}{V_{in}}\right| = \left|\frac{Z_J}{Z_R + Z_C + Z_L}\right|$$



$$G_C = \frac{1/\omega\tau_{RC}}{\sqrt{1 + [\omega\tau_{LR} - (1/\omega\tau_{RC})]^2}}$$



The resonance maximum in $G_C(\omega)$ occurs at ω_o when the denominator in the squared term is zero.

$$\omega_o = 1/\sqrt{LC}$$

- What is a **Semiconductor**
- What is a ***pn*-junction**
- How does a **diode** work
- How does a **transistor** work
- What is an **amplifier** circuit

Wolfgang Ernst Pauli
Nobel Prize in Physics – 1945

Pauli Exclusion Principle
No two electrons can occupy the same quantum state.

"***One should not work on semiconductors, that is a filthy mess; who knows if they really exist.***" 1931

Materials and Resistivity

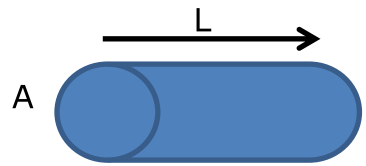
Classify materials according to how they conduct electricity - by their **Resistivity** (ρ)

Resistivity is a "material property" - independent of how much stuff you have

Material	Examples	Resistivity- ρ
Conductor (metal)	Cu, Al, Ag	$\rho \sim 10^{-6}$ Ωcm ~ μΩcm
Semiconductor	**Si, GaAs**	**$\sim 10^{-4} - 10^{4}$** Ωcm
Insulator	glass, ceramic	$> 10^{8}$ Ωcm

Resistance of semiconductor

$R = \rho\, L/A$



Example:
$L = 10\ \mu m$
$D = 0.1\ \mu m$

Silicon
$\rho = 1\ \Omega cm$ $\rho = 0.001\ \Omega cm$

$R = \rho\, L/A$
$= (\rho)(1E\text{-}3\ cm)/(\pi\ 1E\text{-}5^2\ cm^2)$

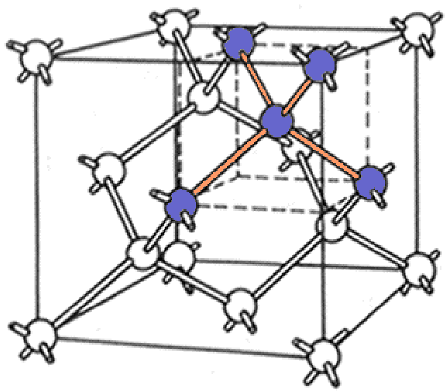
$R = 3\ M\Omega$ **$R = 3\ k\Omega$**

Types of Semiconductors

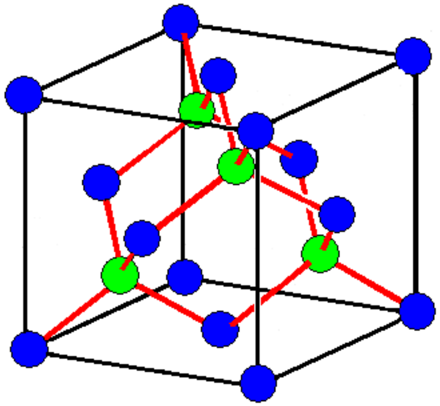
Periodic Table of Semiconductors

II	III	IV	V	VI
	B	C	N	O
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In	Sn	Sb	Te
Hg				

Si	IV	- all of our electronics
GaAs	III-V	- high frequency
AlGaAs	III-V	- red LED
InGaN	III-V	- blue LED
HgTe	II-VI	- IR detector



Silicon
"diamond structure"
but not carbon



GaAs
"zincblende structure"

Questions?

Group IV semiconductors

Group IV semiconductors

Si, Ge

- have 4 **valence** electrons
- tetrahedral coordination
- pairs of bonding (valence) electrons

Concept of Doping

Doping allows you to add **mobile** charges

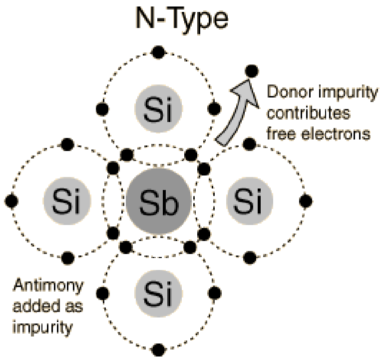
Doping - Add a small concentration of another type of atom (impurity)

Dope Si with an Sb atom

Substitute a Si atom with Sb

Replace the **4** valence electrons of Si (group-IV) with the **5** valence electrons of Sb (group-V)

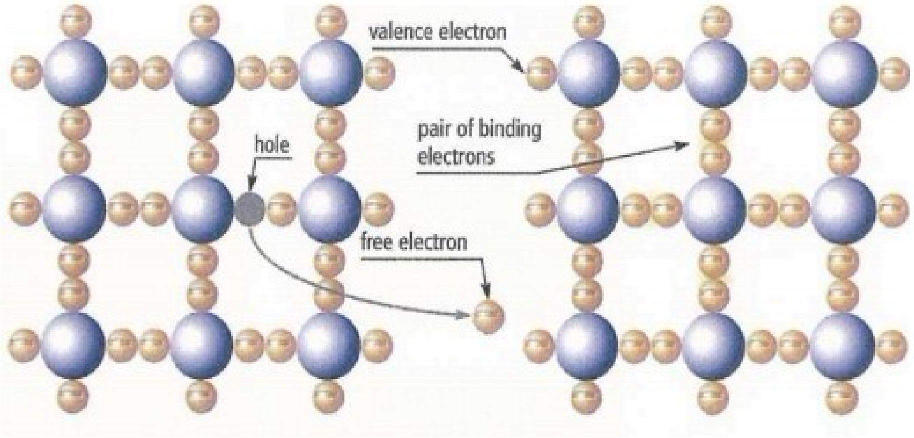
II	III	IV	V	VI
	B	C	N	O
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In	Sn	Sb	Te
Hg				



Concept of a Hole

Hole

- ➢ positive charge
- ➢ missing electron



Holes are Mobile (Itinerant)

Analogy to bubbles

A hole in a liquid is a bubble or simply missing liquid.

The bubble (hole) moves as liquid moves into the area that is left behind.

The basis for all semiconductor devices relies on the ability to make them with an excess **electrons** or **holes**.

Doping Electrons or Holes

Semiconductors are doped with impurities (other atoms)
to generate a density or concentration of free **carriers** (electrons or holes).

(1) Donor Impurity
Donates mobile electrons,
***n*-type** conductivity

(2) Acceptor Impurity
Donates mobile holes,
***p*-type** conductivity

Doping in Silicon

- *n*-type, **donor**, add group-V (P, As,Sb)
  - has one extra electron
- *p*-type, **acceptor**, add group-III (B,Al,Ga,In)
  - has one less electron
  - leaves a hole behind

II	III	IV	V	VI
	B	C	N	O
	Al	Si	P	S
Zn	Ga	Ge	As	Se
Cd	In	Sn	Sb	Te
Hg				

Note that doping leaves the semiconductor **neutral**

n-doping = electron plus positively charged atom
p-doping = hole plus a negatively charged atom

Use doping to make
pn-junction **diode**
or
transistors and FETs

Questions?

Semiconductor Properties

Resistivity – ρ

Conductivity – $\sigma = 1/\rho$

Carrier Density – n or p

Mobility – μ

Property	Designation	Units
Resistivity	ρ	Ωcm
Conductivity	$\sigma = 1/\rho$	1/Ωcm
Carrier (electron, hole)	n or p	#/cm^3
Mobility	μ	cm^2/Vs
relations	$\sigma = ne\mu$, $\rho=1/ne\mu$	

Example:
Phosphorus-Doped Silicon

$n = 10^{16}\ e/cm^3$ (1 in 10^6 atoms)
$\mu = 1450\ cm^2/Vs$

$\rho=1/ne\mu$
$=1/(10^{16} * 1.6\text{x}10^{-19} * 1450)$

$\rho = 0.4\ \Omega cm$

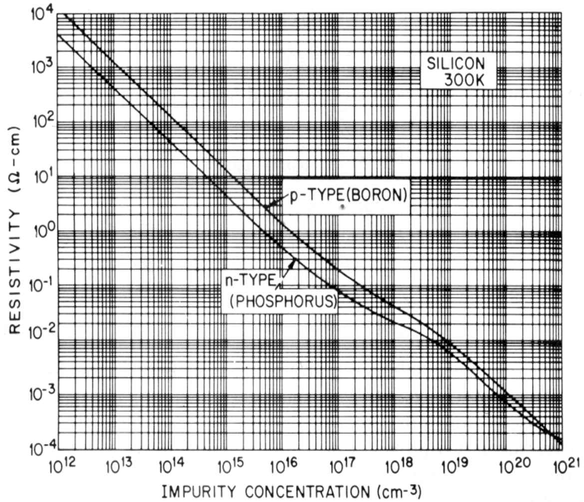
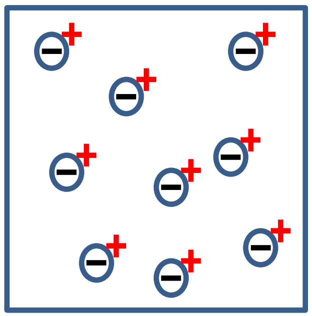


Fig. 21 Resistivity versus impurity concentration for silicon at 300 K. (After Beadle, Plummer, and Tsai, Ref. 38.)

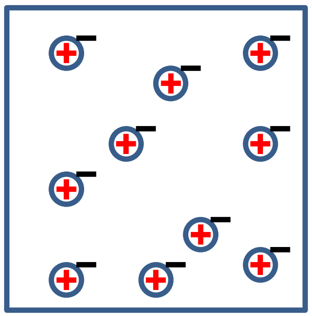
pn-junction (semiconductor diode)

p-type



mobile **+**
fixed **–**

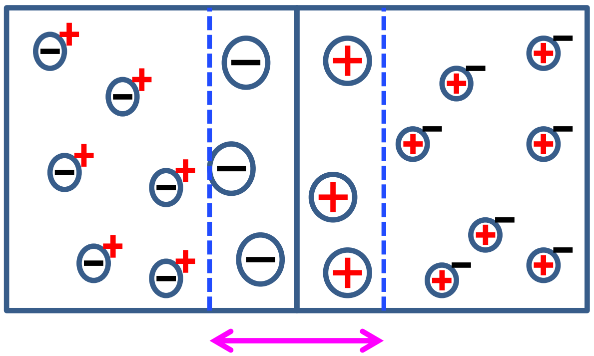
n-type



mobile **–**
fixed **+**

Combine mobile + and – charges

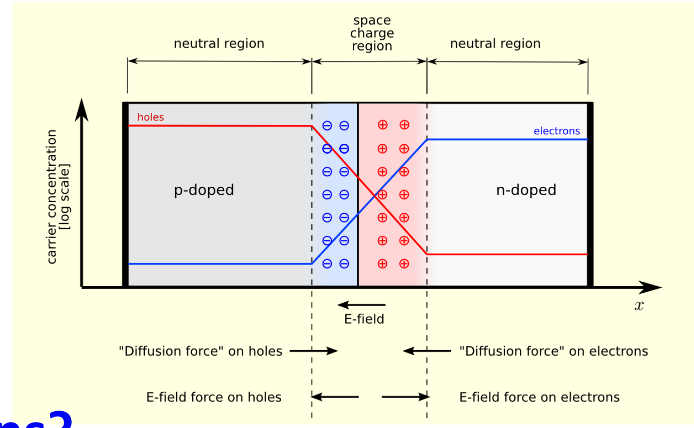
pn-junction



No carriers in the ***Depletion Region*** *= insulator*

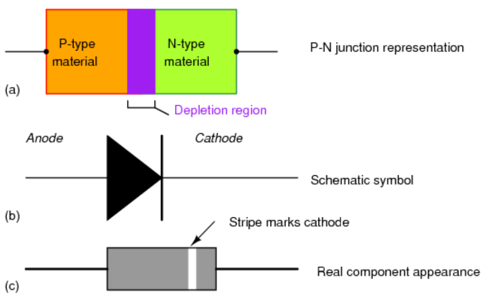
The depletion eventually stops as it builds up an ***electric field*** *that opposes the movement of charges.*

Depletion region has no mobile charges and makes an ***insulating barrier*** *that carriers cannot cross.*

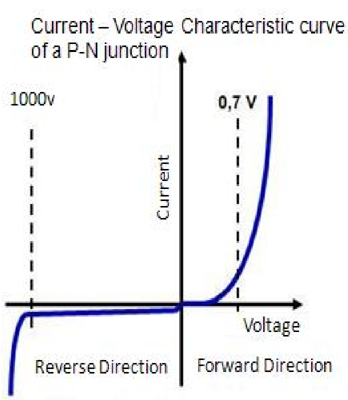


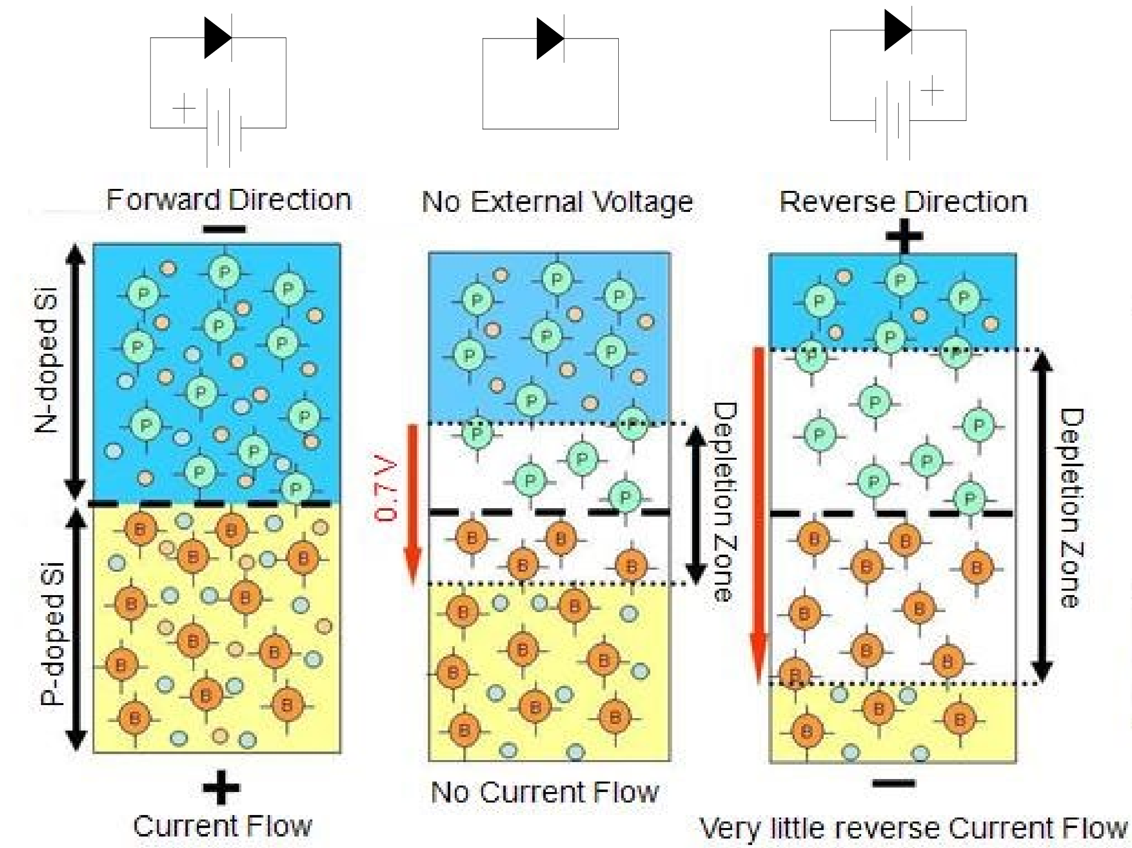
Questions?

Remarkable Diode Action



$$I = I_R\left(e^{qV/K_BT} - 1\right)$$





Forward Bias – depletion width reduces

Reverse Bias – depletion width increases

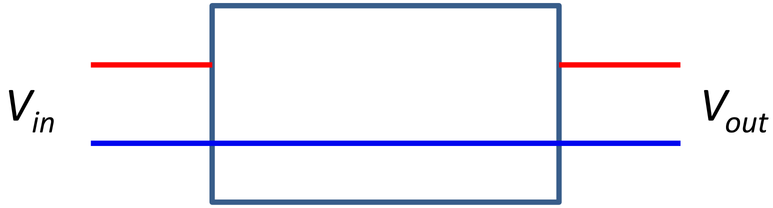
Questions?

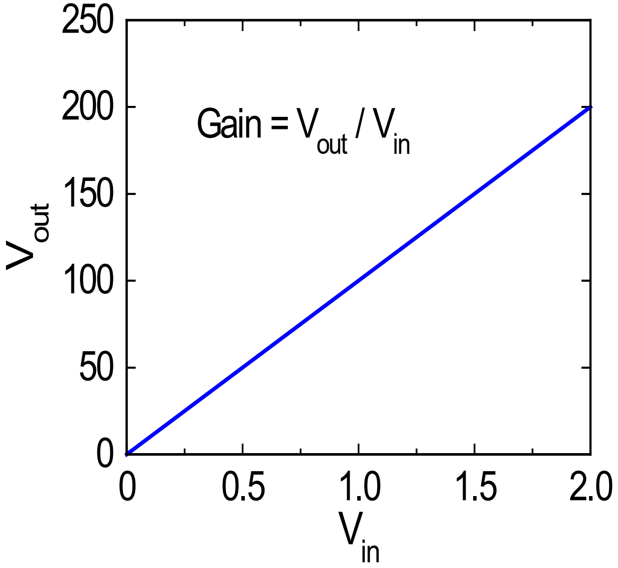
Amplifier (transistor)

Generic Amplifier

3-terminal device

V_{out} is a function of V_{in}





Invention of Transistor

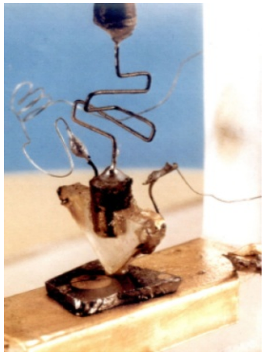
The transistor was invented at Bell Laboratory in 1947 by physicists John Bardeen, Walter Brattain, and William Shockley

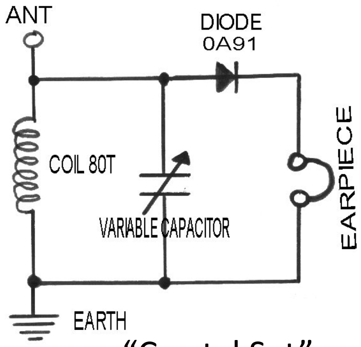
They probably built a **Crystal Set** radio receiver in their youth.
A crystal set is a radio receiver made using a piece of gemanium mineral.

Their **transistor** was very similar to the germanium *pn*-diode crystal set.

It is ironic that their Nobel Prize winning discovery
was probably influenced by their childhood experience.

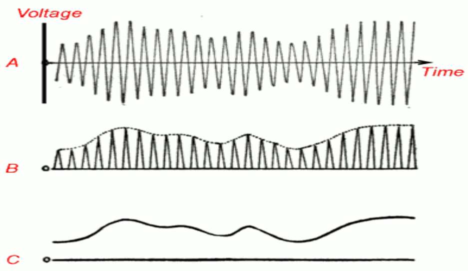
First Transistor





"Crystal Set"
note RLC circuit

Germanium Diode



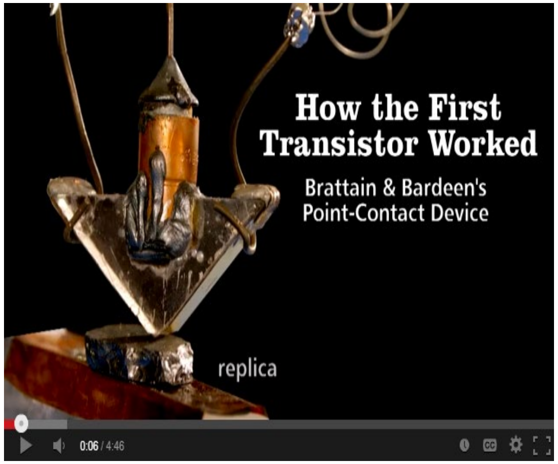
Rectify AM radio signal 540 to 1600 kHz,
then average voltage for audio frequencies

Transistor Videos

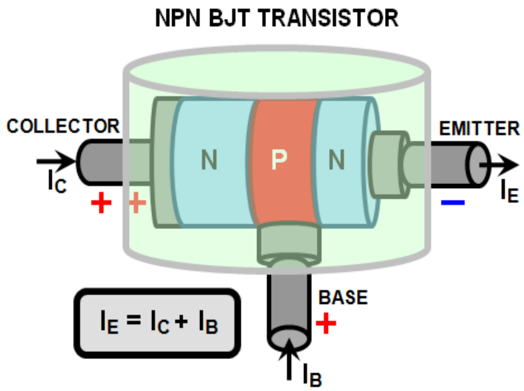
Invention of Transistor, 5 min
http://www.youtube.com/watch?v=RdYHljZi7ys&feature=related

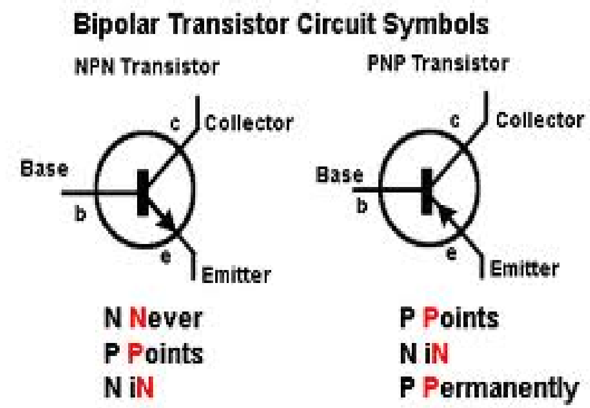
AT&T, Invention of Transistor, 11 min
http://www.youtube.com/watch?v=TIsr5R5zuOU

Transistor Introduction, 15 min (later)
http://www.youtube.com/watch?v=4QkRI1Ue208&feature=related

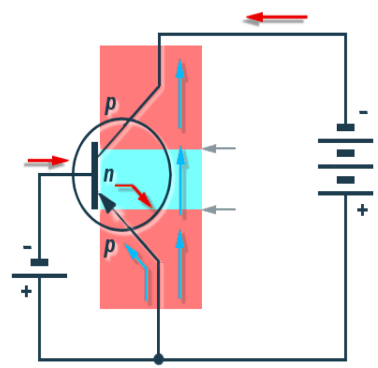


Bipolar Junction Transistor

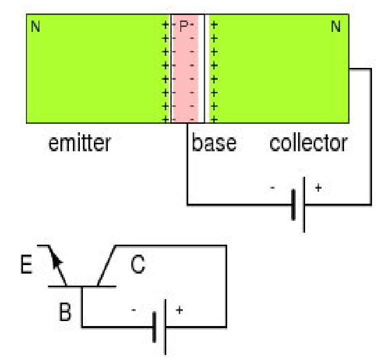




Small change in the base current, makes a large change in the collector current.



Voltage on the base, narrows or widens the depletion region, allowing more or less current to flow.



Transistor Basics

(not in text)

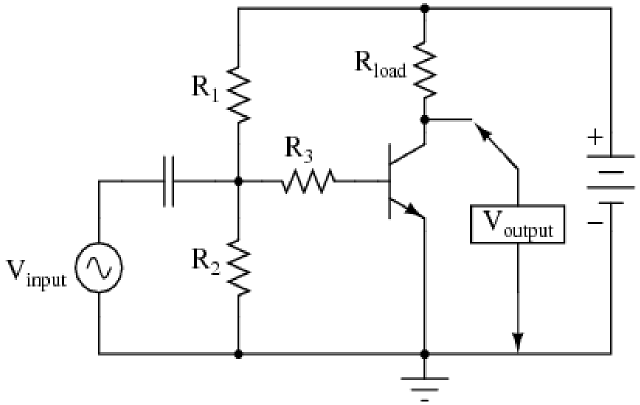
(1) Don't think of a transistor as a current amplifier
*– in practice, think of it as a device where the base voltage controls the transistor **resistance**.*

(2) In circuits
*– consider a transistor as a variable resistor in a **Voltage Divider**.*

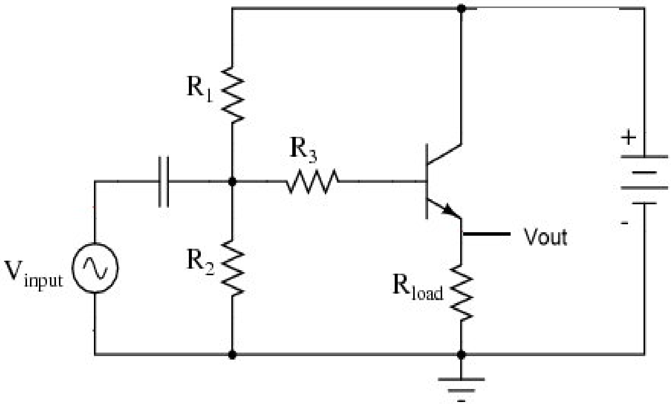
What is a transistor? How does a transistor work? Part 2
0-1:05, 4:15-7:08
http://www.youtube.com/watch?v=4QkRI1Ue208&feature=related

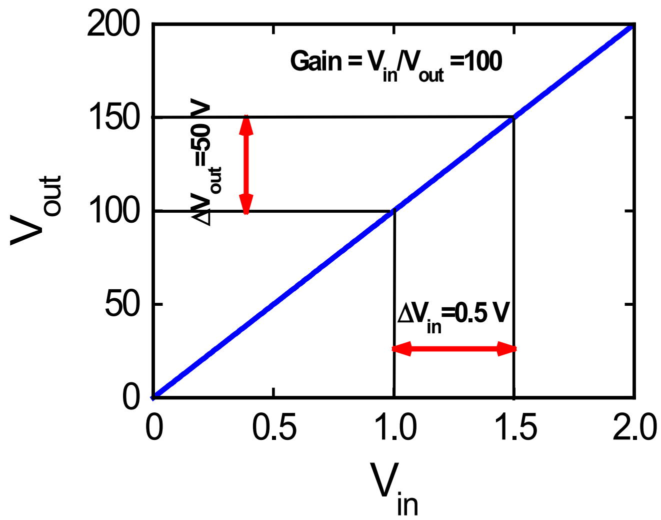
Transistor Circuits

Common Emitter



Emitter Follower





Linear Amplifier

A small modulated input voltage generates a large modulated output voltage.

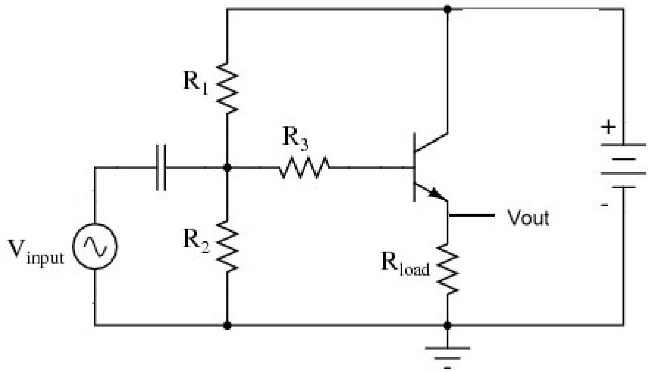
It replicates the time-varying input voltage, but increases it.

Emitter Follower Circuit
http://www.falstad.com/circuit/e-follower.html

Transistor Circuits

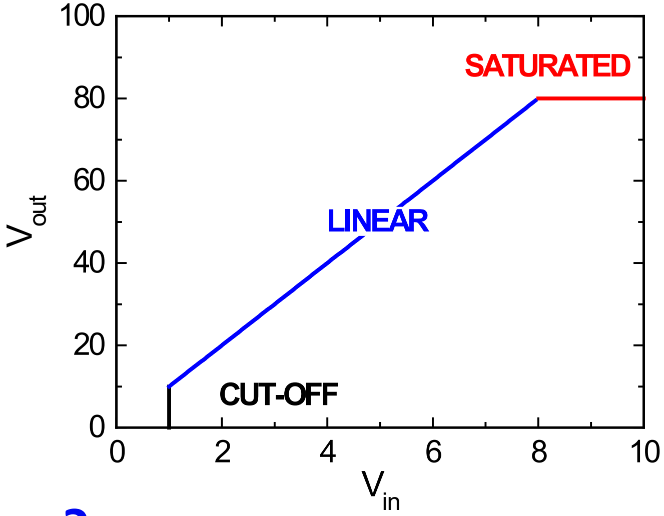
Transistor circuits can be designed as:

- a LINEAR AMPLIFIER
- a simple OFF/ON SWITCH



Three regions of output voltage
Cutoff, Linear, Saturated

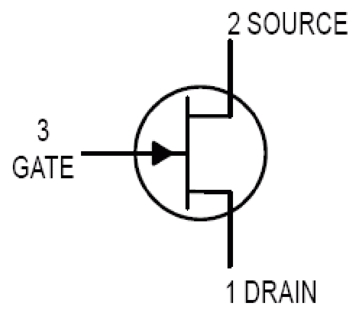
Cutoff	Linear	Saturated
low V_{in}	intermediate	high V_{in}
$R_T \rightarrow \infty$	V_{out}	$R_T \sim 0$
$V_{out} = 0$	**$V_{out}=G*V_{in}$**	**V_{out} high**



Questions?

Field Effect Transistor (FET)

Since transistors are used as resistors in a voltage divider, why not use a resistive device like an FET?



The basic principle of the field-effect transistor was first patented by Julius Edgar Lilienfeld in 1925.
(*predates the transistor by 32 years*)

FET is a simple 3-terminal device
(gate, source, drain)

The voltage on the gate controls the source-to-drain **resistance**

FET Advantages

- **very high gate resistance** (no gate current)
- have no threshold like a transistor
- are simply variable resistors
- very small size (high area density)

Field Effect Transistor (FET)

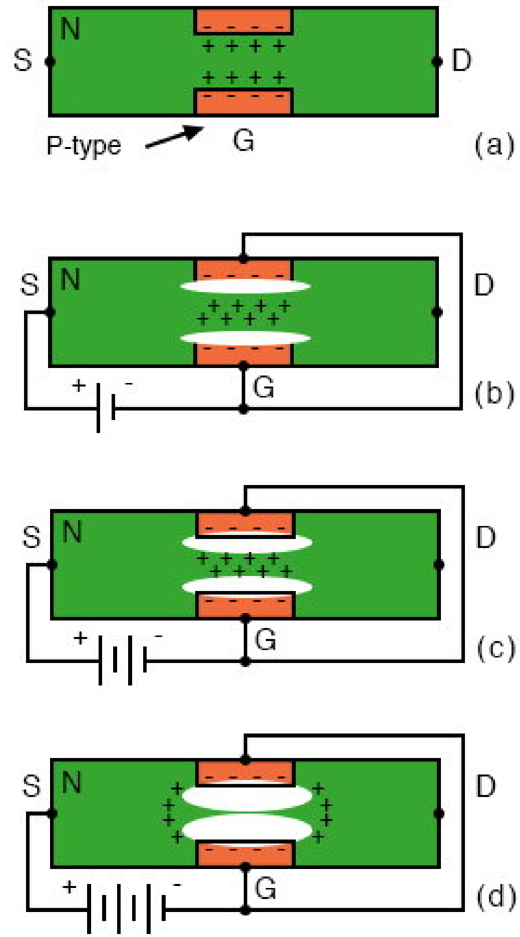
How do FETs work?

Resistance is controlled by an **electric field**

Voltage supplied to the gate depletes or induces carriers in a conducting region between the source and drain

Gate voltage controls R (or I)

Resistance is **R=ρL/A**
A = conducting region area
changing A → changes R



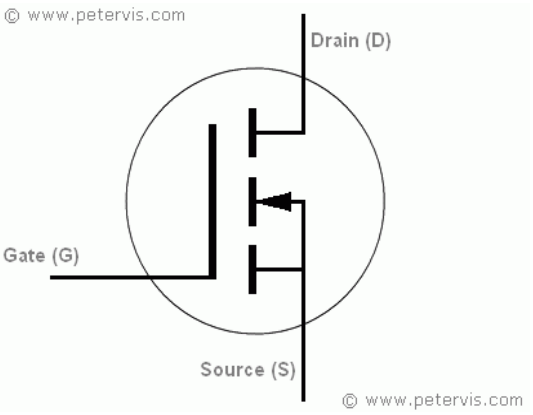
Questions?

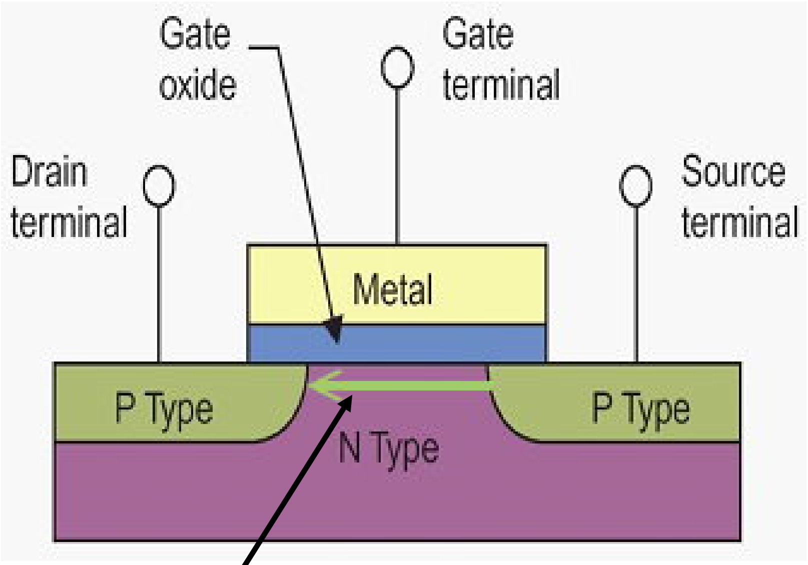
MOSFET

MOSFET

Metal **Oxide** Semiconductor FET

- Gate is **isolated** by an oxide barrier
- Most common transistor
- Better for IC (integrated circuits)





Electric field from the gate electrode creates a conducting **p-type inversion layer** in the n-type material that connects the p-type regions.

CMOS

CMOS

Complementary MOSFET

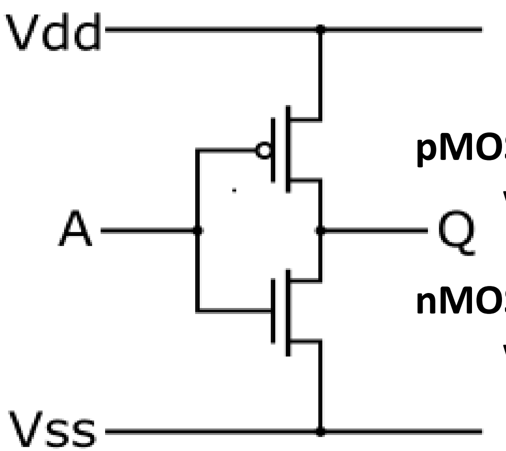
- Lower power
- Most **VLSI**
  (very large scale integration)

ADVANTAGE of CMOS

in voltage divider

One FET of the pair is always off

The series combination draws significant power only momentarily during switching between on and off states (80% of power in a chip). Consequently, CMOS devices have **much less waste** heat as other forms of logic, which normally have some standing current even when not changing state.



pMOS (top) turns on with **low** A voltage

nMOS (bottom) turns on with **high** A voltage

CMOS is the technology for most integrated circuits. CMOS technology is used in microprocessors, microcontrollers, static RAM, and other digital logic circuits.

Frank Wanlass patented CMOS in 1963.

Questions?

Lab Experiment – 4

Say Hello (and Goodbye) to the Transistor

Lab Hints

Good practices for lab experiments

- **Draw** circuit diagram in notebook
- **Arrange** protoboard to look like the diagram
  - make it look organized
- **Limit** the number of wires
- **PLOT**, plot, plot data
  - plot points **AS** you take data
- **ASK**, ask the TA
  - *"Does this plot look right?"*

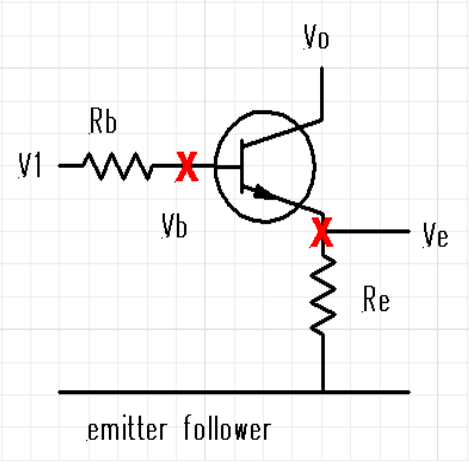
Worksheet-4, Say Hello (and Goodbye) to the Transistor Name:_______________

Physics PHYS 2371/2372, Electronics for Scientists

Don Heiman and Hari Kumarakuru, Northeastern University

II. Emitter-Follower Transistor Circuit

Here you will construct an "emitter follower" circuit to investigate the *linear regime* of a transistor. Set up the emitter follower circuit shown in the first figure on the next page. Use R_e = 100 Ω, R_b = 1 kΩ, and set V_o = +5 V.



1. Vary V_1 from 0 to 10 V while measuring V_b (base to ground) and V_e (emitter to ground) with DVMs, and use the oscilloscope to measure the DC voltage of V_1. Put V_1, V_b, V_e, values in a *table* and include columns for V_{be}, I_c (=I_e), I_b, and $\beta = I_c/I_b$.

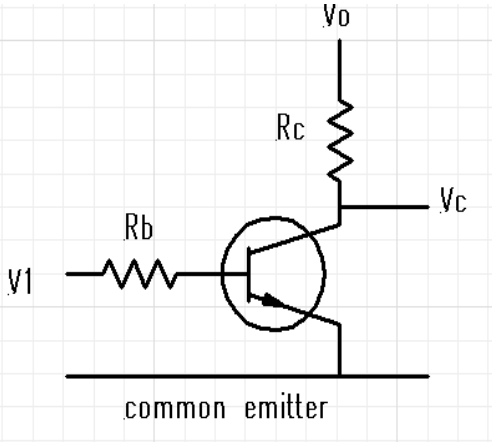
2. Plot V_e as a function of V_1 from 0 to 10 V and fill in data points to get a smooth curve.
In the plot, identify the 3 regions: cut-off, linear, and saturation. <u>Show plot to the TA</u>.

3. Plot I_c as a function of V_{be}. Compare to expected result and discuss.
What is the turn-on voltage?
V_{be}= ______________________
Does V_{be} change much with increasing I_C? _______________________

………

III. Common-Emitter Current Amplifier

Here you will construct a "common emitter" current amplifier. This circuit does not operate in the linear regime as in the previous circuit, but operates as an on/off switch. For example, it could be used to amplify low current TTL pulses (0 V off and +5 V on). Note that a TTL pulse must be greater than only +1.2 V to be considered "on."



Set up the common emitter circuit shown in the second figure.
Use R_c = 100 Ω, R_b = 1 kΩ, and set V_o = +5 V.

1. Vary the input V_1 from 0 to a few volts while measuring the output V_c.
Tabulate and plot V_c as a function of V_1. Show the plot to the TA.

2. Compute the effective resistance of the transistor (R_T) at 3 values of V_C, where V_C ~ 0 V, V_C ~ 1 to 4 V, and V_C ~ 5 V.

$R_T(V_C$~0) = ___________; $R_T(V_C$~1-4V) = ___________; $R_T(V_C$~5V) = ___________

………

Course Hints

Good practices

- **Review** the slides before class
  - become familiar with material
- **Review** the lecture after class
  - what don't you understand
- Briefly **Study** the lab instructions
  - what components will you use
  - what instruments will you use
  - what measurements will you make

окончание