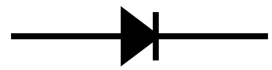
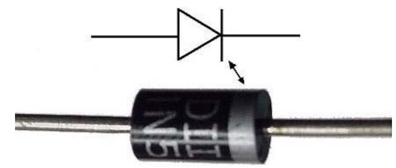
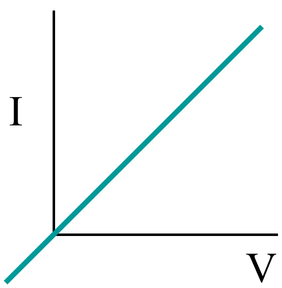
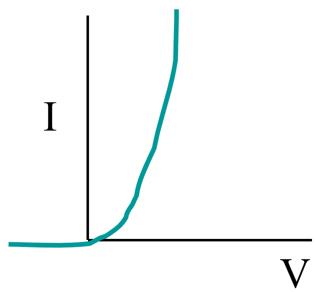
Diodes

- Diodes are essentially one-way current gates
- Symbolized by: 
- Current vs. voltage graphs:

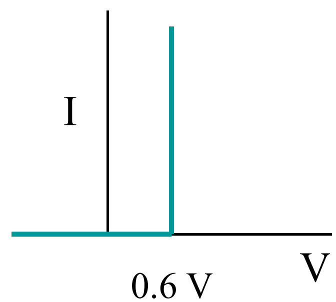




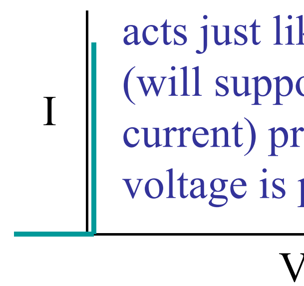
plain resistor



diode

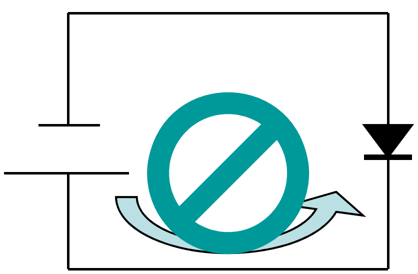


idealized diode

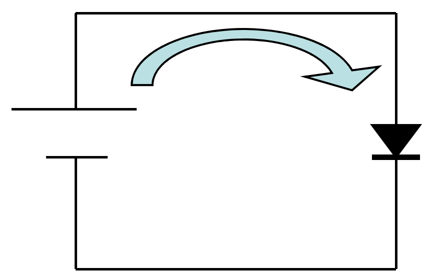


acts just like a wire (will support arbitrary current) provided that voltage is positive

WAY idealized diode



no current flows

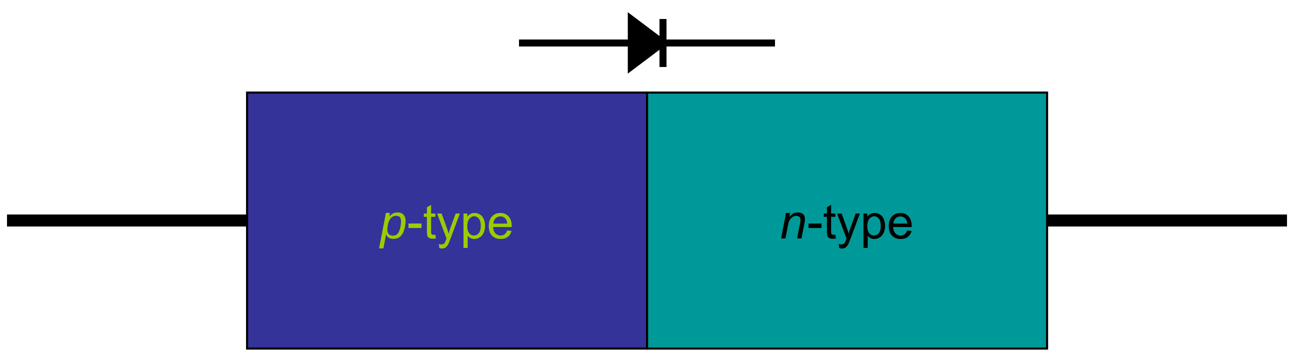


current flows

the direction the arrow points in the diode symbol is the direction that current *will* flow

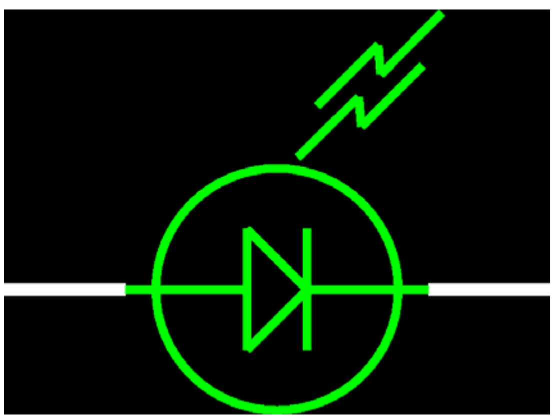
Diode Makeup

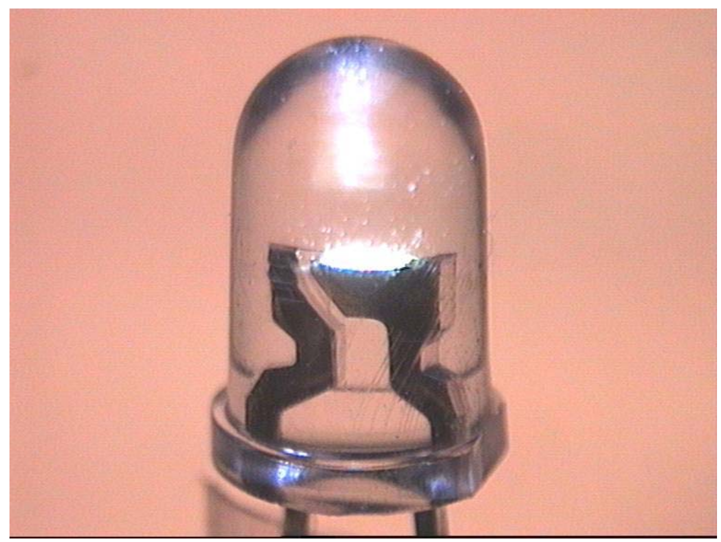
- Diodes are made of semiconductors (usually silicon)
- Essentially a stack of *p*-doped and *n*-doped silicon to form a *p-n junction*
  - doping means deliberate impurities that contribute extra electrons (*n*-doped) or “holes” for electrons (p-doped)
- Transistors are *n-p-n* ir *p-n-p* arrangements of semiconductors



LEDs: Light-Emitting Diodes

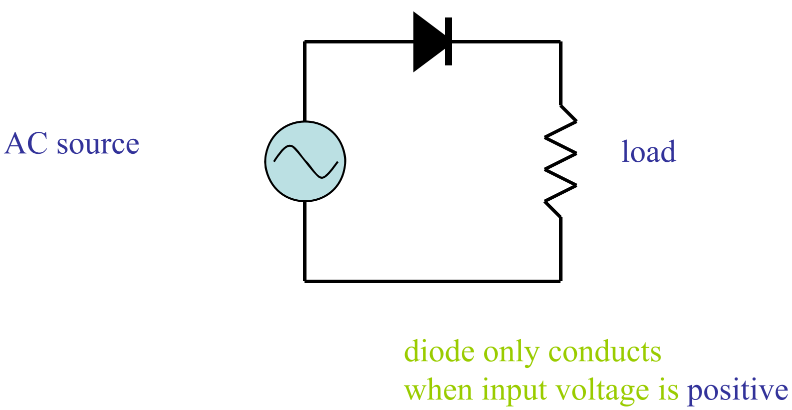
- Main difference is material is more exotic than silicon used in ordinary diodes/transistors
  - typically 2-volt drop instead of 0.6 V drop
- When electron flows through LED, loses energy by emitting a photon of light rather than vibrating lattice (heat)
- Anything with an LED cares about the battery orientation (it's still a diode, after all)
- LED efficiency is 30% (compare to incandescent bulb at 10%)

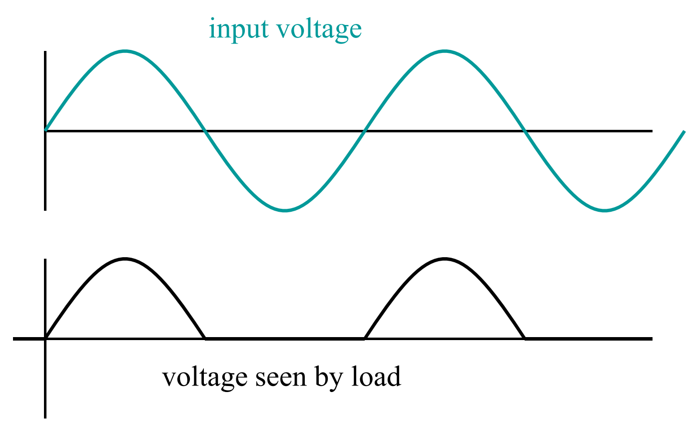




Getting DC back out of AC

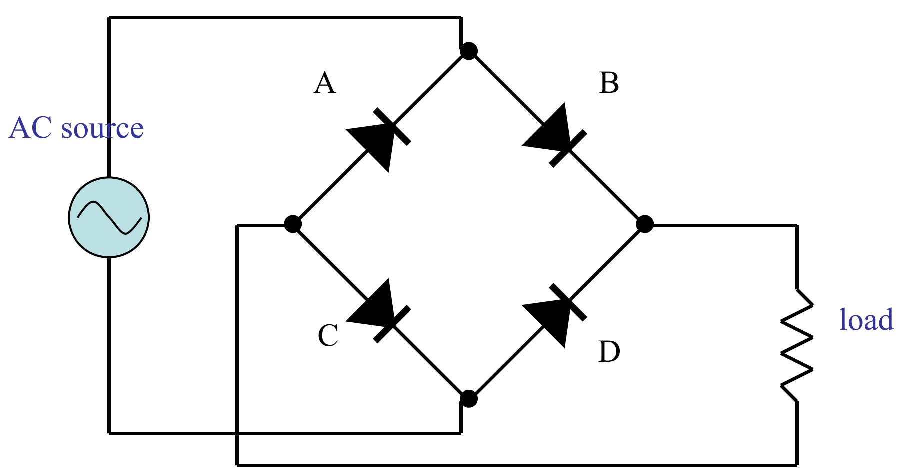
- AC provides a means for us to distribute electrical power, but most devices actually *want* DC
  - bulbs, toasters, heaters, fans don't care: plug straight in
  - sophisticated devices care because they have diodes and transistors that require a certain polarity
    - rather than oscillating polarity derived from AC
    - this is why battery orientation matters in most electronics
- Use diodes to "rectify" AC signal
- Simplest rectifier uses one diode:

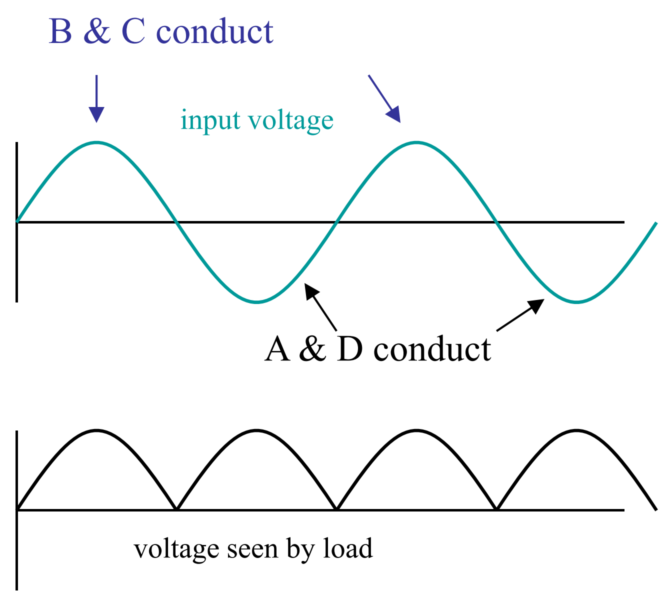




Doing Better: Full-wave Diode Bridge

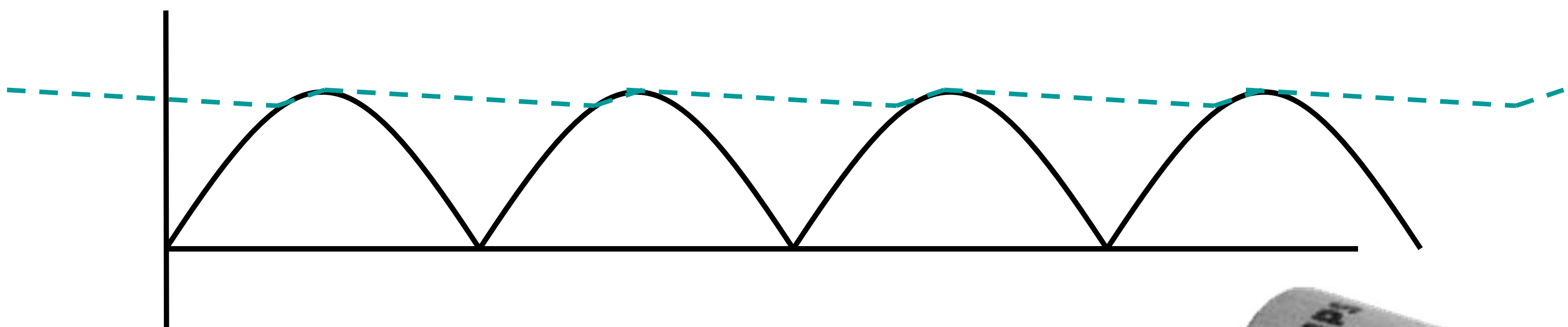
- The diode in the rectifying circuit simply prevented the negative swing of voltage from conducting
  - but this wastes half the available cycle
  - also very irregular (bumpy): far from a "good" DC source
- By using four diodes, you can recover the negative swing:

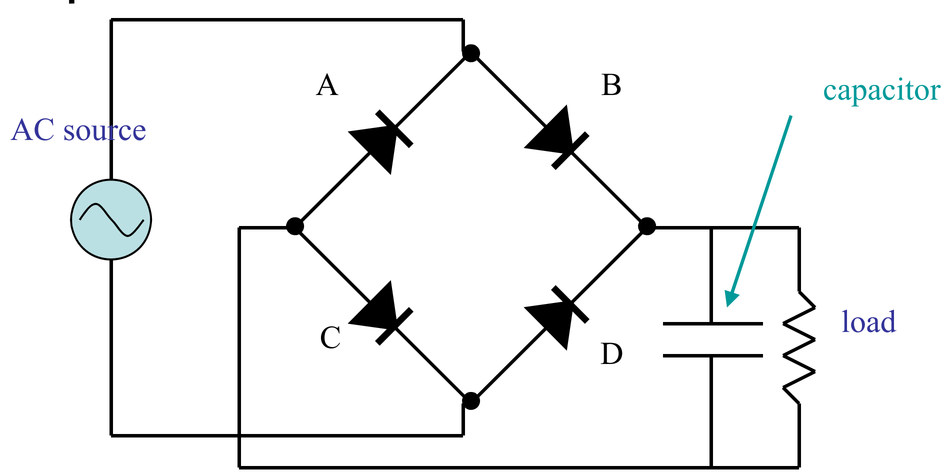


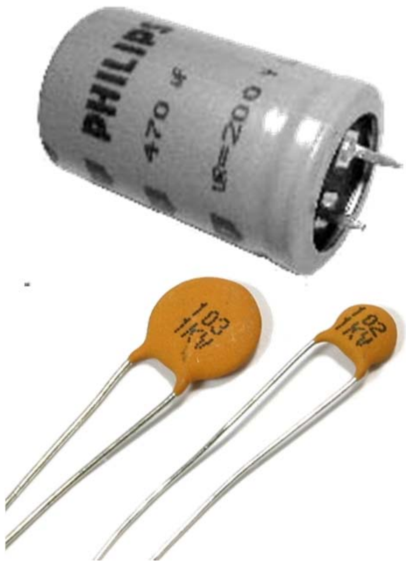


Smoothing out the Bumps

- Still a bumpy ride, but we can smooth this out with a capacitor
  - capacitors have capacity for storing charge
  - acts like a reservoir to supply current during low spots
  - voltage regulator smoothes out remaining ripple







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LETTERS

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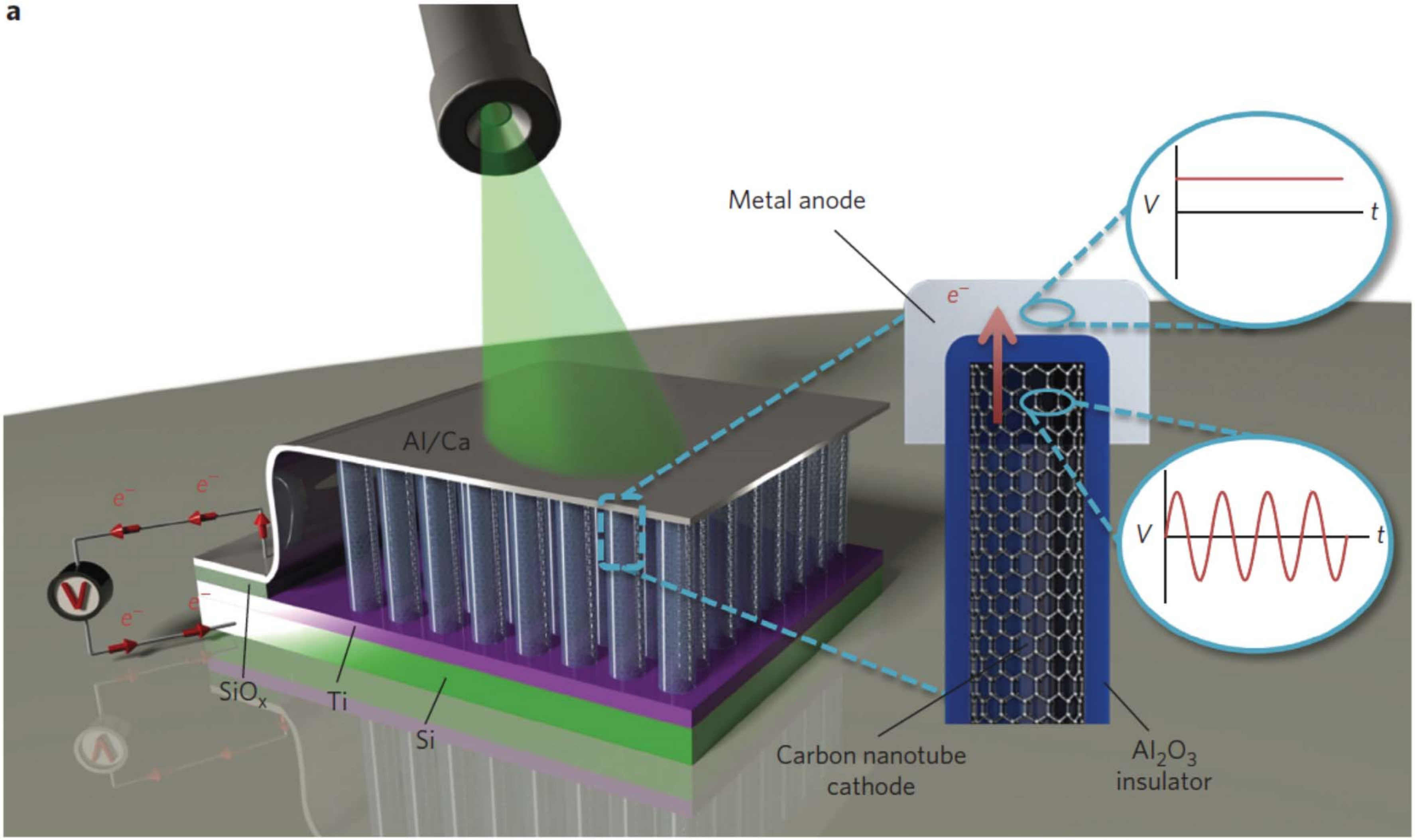
A carbon nanotube optical rectenna

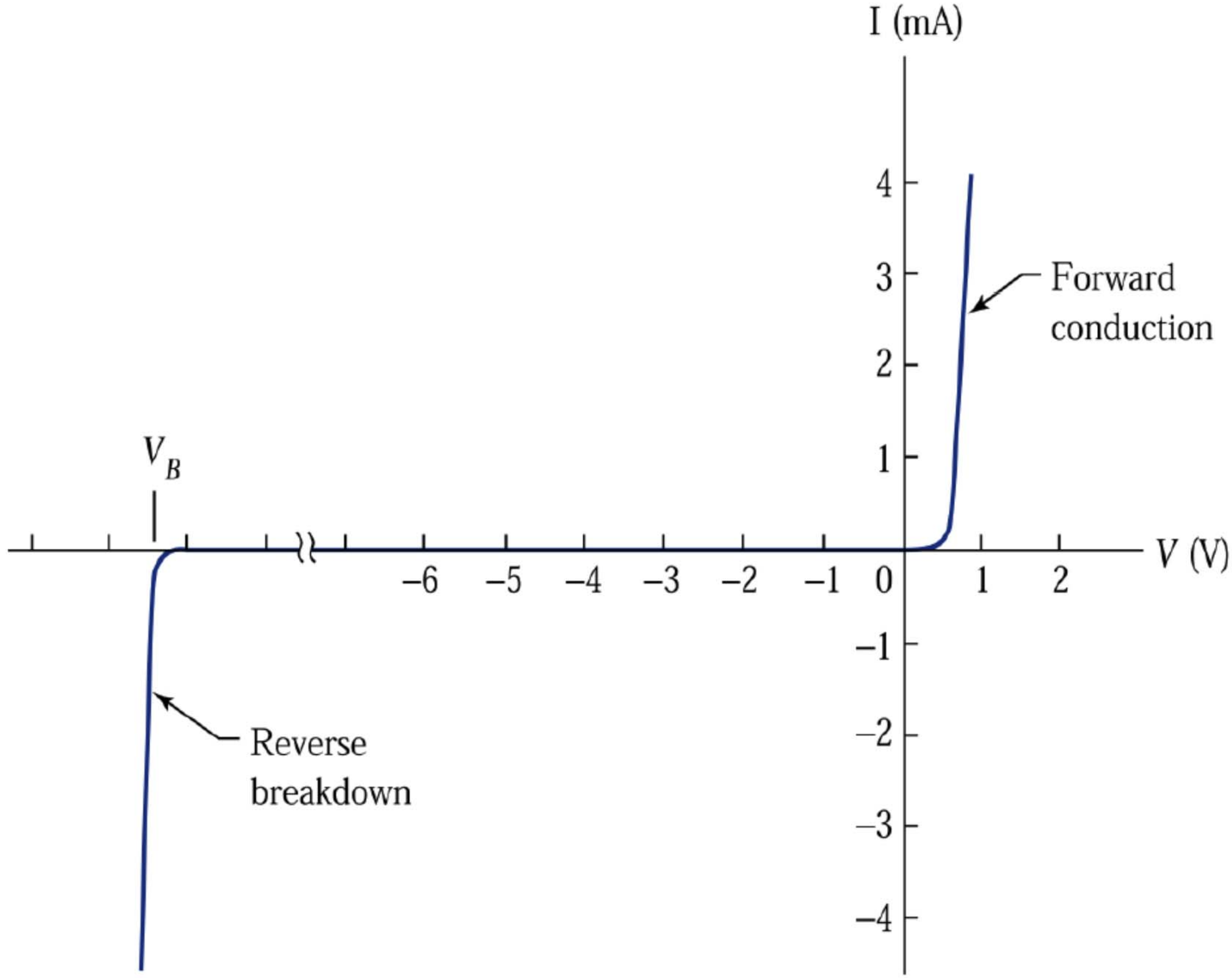
Asha Sharma[1,2†], Virendra Singh[1†], Thomas L. Bougher[1†] and Baratunde A. Cola[1,3*]

An optical rectenna—a device that directly converts free-propagating electromagnetic waves at optical frequencies to direct current—was first proposed over 40 years ago[1], yet this concept has not been demonstrated experimentally due to fabrication challenges at the nanoscale[2,3]. Realizing an optical rectenna requires that an antenna be coupled to a diode that operates on the order of 1 PHz (switching speed on the order of 1 fs). Diodes operating at these frequencies are feasible if their capacitance is on the order of a few attofarads[3,4], but they remain extremely difficult to fabricate and to reliably couple to a nanoscale antenna[2]. Here we demonstrate an optical rectenna by engineering metal–insulator–metal tunnel diodes, with a junction capacitance of ~2 aF, at the tip of vertically aligned multiwalled carbon nanotubes (~10 nm in diameter), which act as the antenna[5,6]. Upon irradiation with visible and infrared light, we measure a d.c. open-circuit voltage and a short-circuit current that appear to be due to a rectification process (we account for a very small but quantifiable contribution from thermal effects). In contrast to recent reports

a

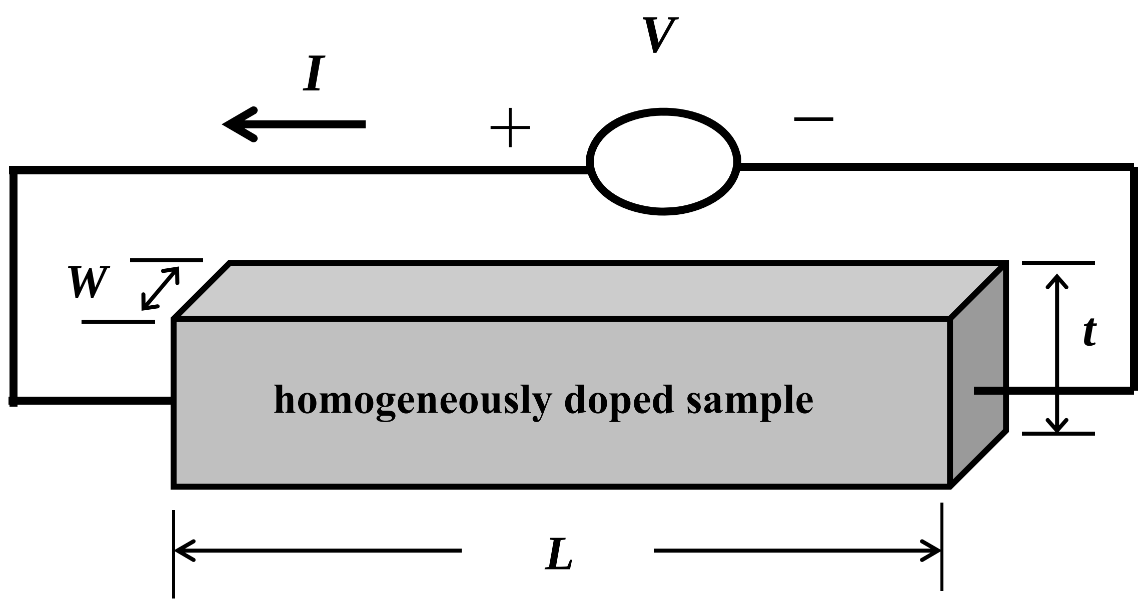

Metal anode
e⁻
V
t
Al/Ca
e⁻
V
t
SiOx
Ti
Si
Carbon nanotube cathode
Al2O3 insulator

I-V curve of a diode


I (mA)
4
3
2
1
−1
−2
−3
−4
Forward
conduction
Reverse
breakdown
V_B
−6
−5
−4
−3
−2
−1
0
1
2
V (V)

Drifting

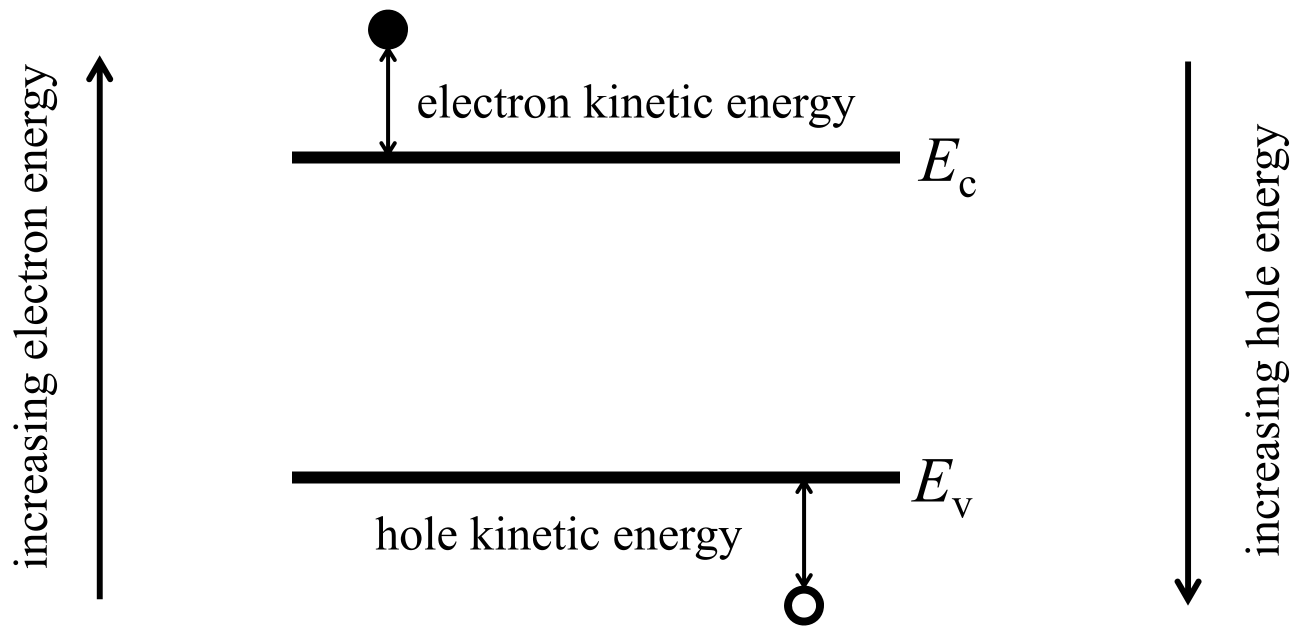
Electrical Resistance



Resistance $$\boxed{R \equiv \frac{V}{I} = \rho \frac{L}{Wt}}$$ **(Unit: ohms)**

where ρ is the resistivity

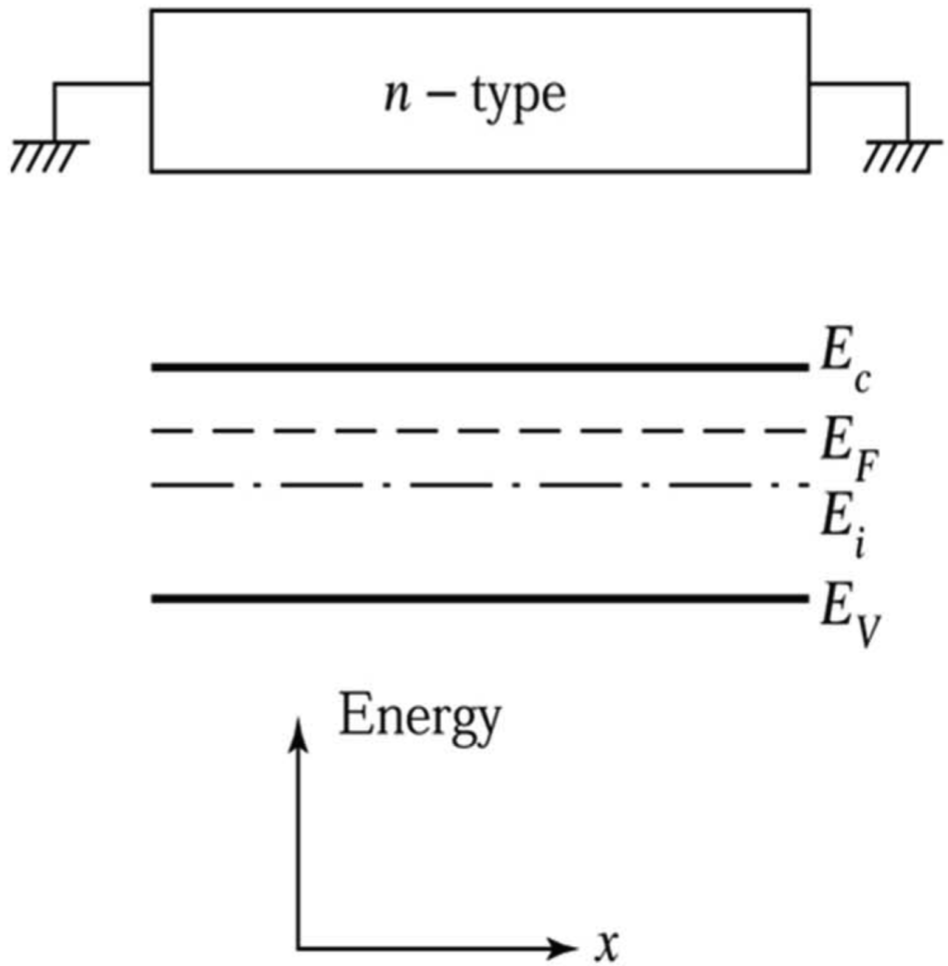
Potential *vs.* Kinetic Energy



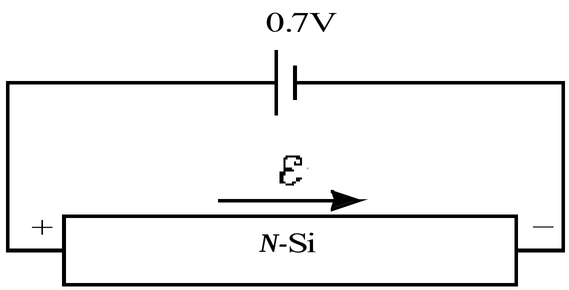
***E_c* represents the electron potential energy:**

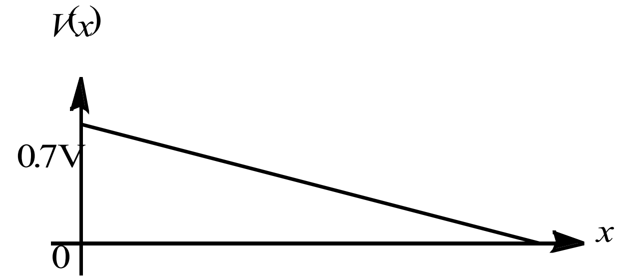
$$\text{P.E.} = E_c - E_{\text{reference}}$$

Under thermal equilibrium



Electrostatic Potential, V



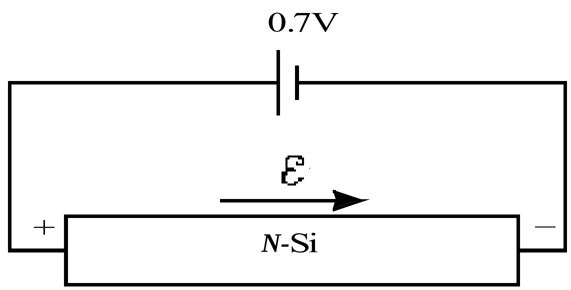


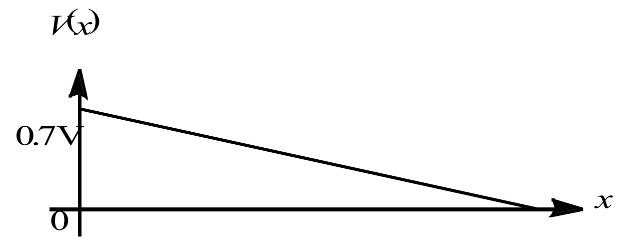
- The potential energy of a particle with charge -q is related to the electrostatic potential $V(x)$:

$$\text{P.E.} = -qV$$

$$V = \frac{1}{q}(E_{\text{reference}} - E_{\text{c}})$$

Electric Field, $\mathcal{E}$

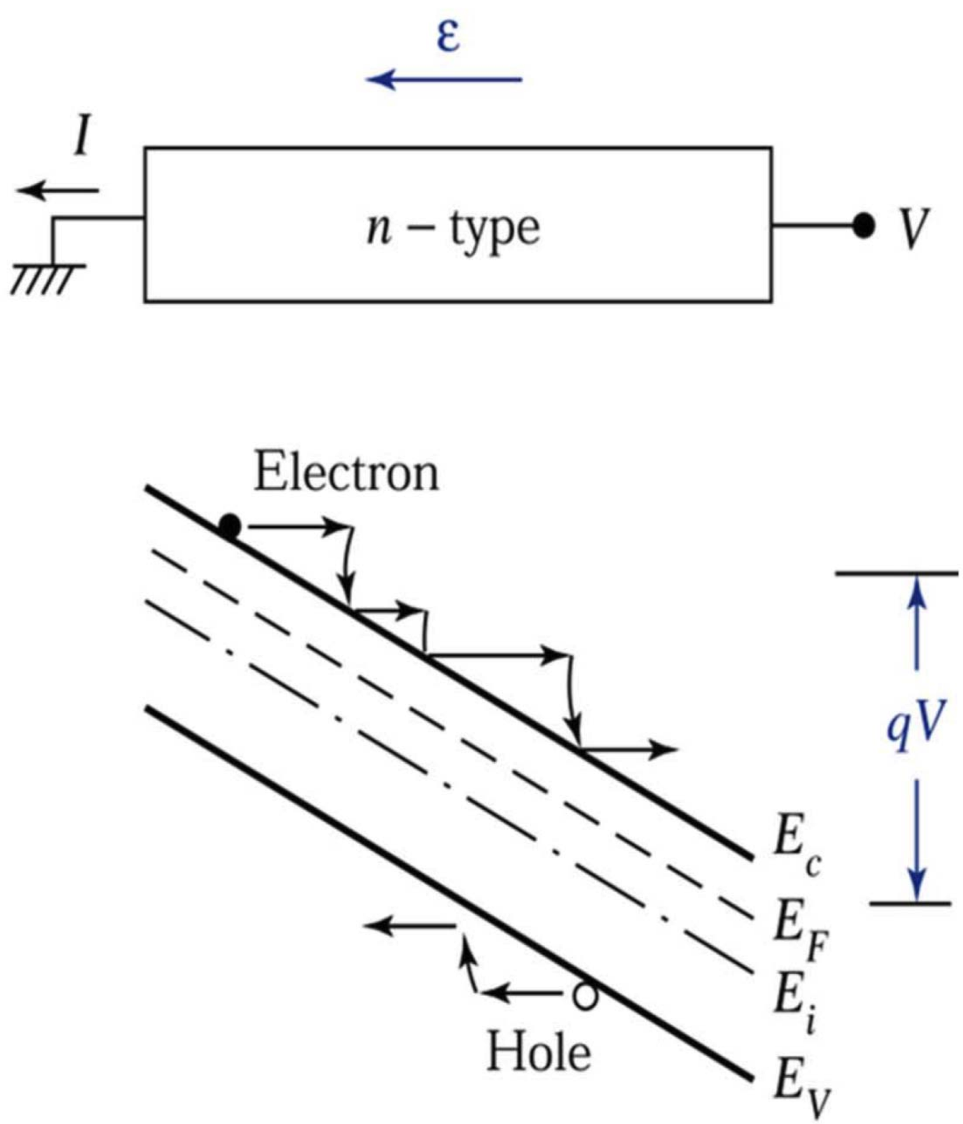




$$\mathcal{E} = -\frac{dV}{dx} = \frac{1}{q}\frac{dE_c}{dx}$$

- Variation of E_c with position is called ***"band bending."***

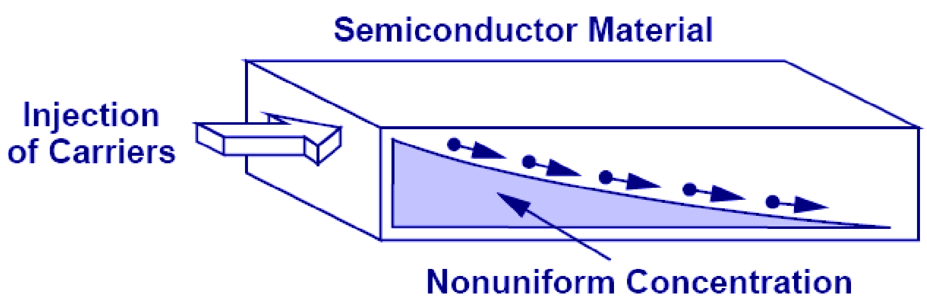
Under a biasing condition



Diffusion

Carrier Diffusion

- Due to thermally induced random motion, mobile particles tend to move from a region of high concentration to a region of low concentration.
  - Analogy: ink droplet in water
- Current flow due to mobile charge diffusion is proportional to the carrier <u>concentration gradient</u>.
  - The proportionality constant is the ***diffusion constant***.



$$J_p = -qD_p \frac{dp}{dx}$$

<u>Notation</u>:
$D_p \equiv$ hole diffusion constant (cm^2/s)
$D_n \equiv$ electron diffusion constant (cm^2/s)

Diffusion Current

- Diffusion current within a semiconductor consists of hole and electron components:

$$J_{p,diff} = -qD_p \frac{dp}{dx} \qquad J_{n,diff} = qD_n \frac{dn}{dx}$$

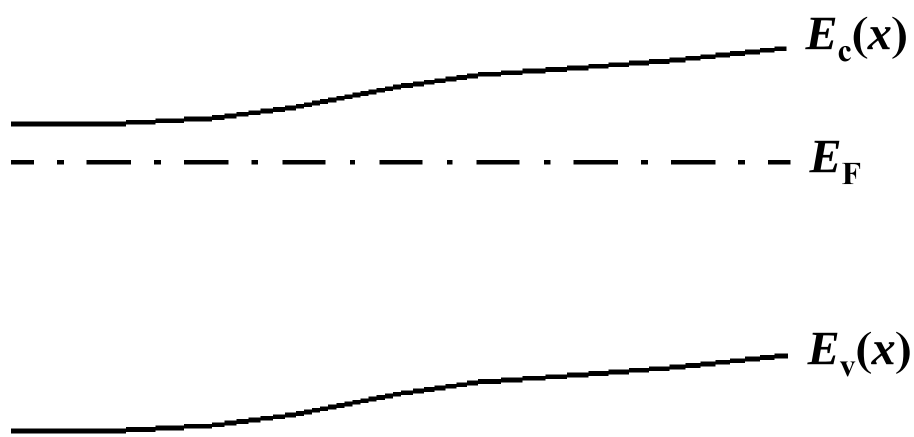
$$J_{tot,diff} = q(D_n \frac{dn}{dx} - D_p \frac{dp}{dx})$$

- The total current flowing in a semiconductor is the sum of drift current and diffusion current:

$$\boxed{J_{tot} = J_{p,drift} + J_{n,drift} + J_{p,diff} + J_{n,diff}}$$

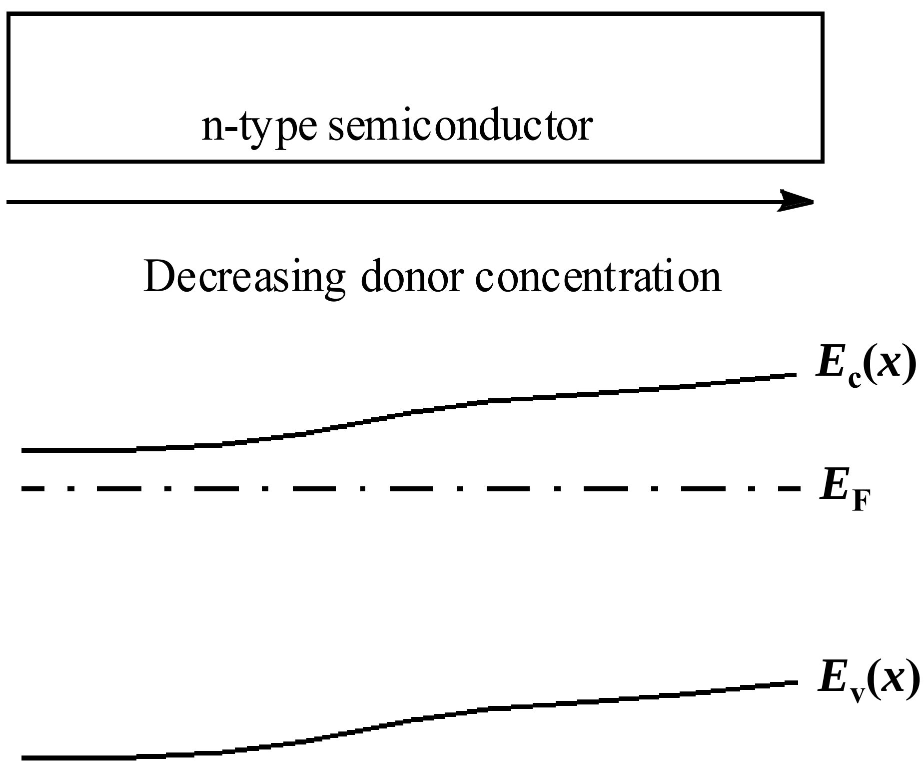
Non-Uniformly-Doped Semiconductor

- The position of E_F relative to the band edges is determined by the carrier concentrations, which is determined by the net dopant concentration.
- **In equilibrium E_F is constant**; therefore, the band-edge energies vary with position in a non-uniformly doped semiconductor:



Built-In Electric Field due to $n(x)$, $p(x)$

Consider a piece of a non-uniformly doped semiconductor:



$$n = N_c e^{-(E_c - E_F)/kT}$$

$$\frac{dn}{dx} = -\frac{N_c}{kT} e^{-(E_c - E_F)/kT} \frac{dE_c}{dx}$$

$$= -\frac{n}{kT}\frac{dE_c}{dx}$$

$$= -\frac{n}{kT} q\mathcal{E}$$

Quasi-Neutrality Approximation

- If the dopant concentration profile varies gradually with position, then the majority-carrier concentration distribution does not differ much from the dopant concentration distribution.

$$N_\mathrm{D}(x) + p(x) = N_\mathrm{A}(x) + n(x)$$

  – n-type material: $n(x) \cong N_\mathrm{D}(x) - N_\mathrm{A}(x)$

  – p-type material: $p(x) \cong N_\mathrm{A}(x) - N_\mathrm{D}(x)$

$\rightarrow\ \mathcal{E} = -\dfrac{kT}{q}\left(\dfrac{1}{n}\right)\dfrac{dn}{dx} = -\dfrac{kT}{q}\left(\dfrac{1}{N_\mathrm{D}}\right)\dfrac{dN_\mathrm{D}}{dx}$ in n-type material