

ECE 231 at a glance: course page and the seven units

The key-points printable for <https://lessons.ihsan.cc/ece231/ece231-course-overview/> – Semiconductor Physics and Devices, instructor William S. Wong, textbook Neamen 4th edition.

ECE 231 at a glance

Who teaches it, when it meets, and what every mark is worth.

Taught by **William S. Wong** (DC 3712, wswong@uwaterloo.ca). Lectures Mondays and Fridays 2:30–3:50 PM, PSE 4043, Sep 9–Dec 8; tutorials Thursdays 4:30–5:20 PM, PSE 4043; labs every other week, Mondays 8:30–11:20 AM, E2 3347 (section 203). Textbook: D. Neamen, *Semiconductor Physics and Devices*, 4th edition.

THE ASSESSMENT

COMPONENT	WHEN	WEIGHT
Labs (5, L1–L5)	weeks 3, 5, 7, 9, 11	20%
Quizzes (2)	Oct 8, Nov 26	10%
Midterm	Oct 27, 9:00 AM	20%
Final exam	TBA, during exam period	50%

A late lab report loses credit; a missed exam or quiz with no declared absence is worth zero. This lesson uses $kT = 0.025852$ eV at 300 K; the official solutions use 0.0259 eV, so some of their last digits differ.

Why a solid has a bandgap

Neamen 1 and 3.

Close-packed atoms split each level into N closely spaced levels forming a **band**; below a critical separation a **bandgap** E_g opens between bands. Silicon's gap is 1.12 eV, diamond's 5.5 eV – only silicon conducts at room temperature, since thermal excitation across E_g falls off exponentially with gap size. The vacancy left behind, the **hole**, is a positive carrier; thermal generation always makes carriers in pairs.

A carrier's response to a field is its **effective mass**:

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$$\frac{1}{m^*} = \frac{1}{\hbar^2} \frac{d^2 E}{dk^2}$$

Near a band edge $E(k) = C_1 k^2$ and $m^* = \hbar^2 / (2C_1)$: a sharply curved band gives a light carrier – why GaAs ($m_n^* = 0.067 m_0$) suits high-frequency devices where silicon ($m_n^* \approx 1.08 m_0$) does not.

2.1 Worked example (Problem Set 1)

PS1 -- Q5 · CORE · OFFICIAL SOLUTION AGREES

Two semiconductors have parabolic conduction-band minima at the origin. Curve A reaches $E = 0.05$ eV and curve B reaches $E = 0.5$ eV, both at $k = \pm 0.08 \text{ \AA}^{-1}$. Find m_A^* and m_B^* in units of m_0 .

WORKED SOLUTION

One point off each curve fixes C_1 . Converting units: $k = 0.08 \text{ \AA}^{-1} = 8.0 \times 10^8 \text{ m}^{-1}$, $k^2 = 6.4 \times 10^{17} \text{ m}^{-2}$, $\hbar = 1.054 \times 10^{-34} \text{ J}\cdot\text{s}$. Curve A at $E = 0.05$ eV:

$$C_{1,A} = \frac{0.05 \times 1.60 \times 10^{-19}}{6.4 \times 10^{17}} = 1.25 \times 10^{-38} \text{ J} \cdot \text{m}^2,$$

$$m_A^* = \frac{\hbar^2}{2C_{1,A}} = \frac{1.112 \times 10^{-68}}{2.50 \times 10^{-38}} = 4.45 \times 10^{-31} \text{ kg} = 0.49 m_0.$$

Curve B reaches ten times the energy at the same k , so C_1 is ten times larger and the mass ten times smaller: $m_B^* = 4.45 \times 10^{-32} \text{ kg} = 0.049 m_0$.

Answer: $m_A^* = 0.49 m_0$, $m_B^* = 0.049 m_0$.

How many carriers, and how doping sets the number

Neamen 4.

Carrier density is **density of states** times **Fermi function**, integrated over energy; in the Maxwell-Boltzmann tail ($E_c - E_F \gg kT$) that collapses to:

ON THE FORMULA SHEET

$$n_0 = N_c \exp\left(\frac{-(E_c - E_F)}{kT}\right), \quad p_0 = N_v \exp\left(\frac{-(E_F - E_v)}{kT}\right)$$

where N_c, N_v are the effective densities of states (material and temperature only); how the sample was made enters only through E_F . Multiplying the two cancels E_F : $n_0 p_0 = N_c N_v \exp(-E_g/kT) = n_i^2$, the **mass-action law** – fixed by material and temperature alone, never by doping, so only the majority carrier need be found directly.

Doping moves E_F , not E_g . Donors (group V) sit ~ 0.03 eV below E_c , acceptors (group III) ~ 0.05 eV above E_v , both essentially all ionised at 300 K. With both present, only the difference counts, and when $N_d - N_a \gg n_i$ simply $n_0 = N_d - N_a$.

3.1 Worked example

PS1 -- Q11 · CORE · OFFICIAL SOLUTION AGREES

The electron concentration in silicon at $T = 300$ K is $n_0 = 2 \times 10^5 \text{ cm}^{-3}$. (a) Position of the Fermi level relative to E_v . (b) Find p_0 . (c) n-type or p-type?

WORKED SOLUTION

(a)

$$E_c - E_F = kT \ln\left(\frac{N_c}{n_0}\right) = (0.025852) \ln(1.4 \times 10^{14}) = 0.842 \text{ eV},$$

so $E_F - E_v = E_g - 0.842 = 1.12 - 0.842 = 0.278 \text{ eV}$.

(b) $p_0 = n_i^2/n_0 = (1 \times 10^{10})^2/2 \times 10^5 = 5 \times 10^{14} \text{ cm}^{-3}$.

(c) Holes outnumber electrons by 2.5×10^9 and E_F sits well below midgap: **p-type**.

Answers: (a) 0.278 eV above E_v · (b) $5 \times 10^{14} \text{ cm}^{-3}$ · (c) p-type.

Official solution: $E_c - E_F = 0.8436 \text{ eV}$, $E_F - E_v = 0.2764 \text{ eV}$, $p_0 = 2.414 \times 10^{14} \text{ cm}^{-3}$, p-type – from the hole side, $p_0 = N_v \exp(-(E_F - E_v)/kT)$, and $kT = 0.0259 \text{ eV}$.

What moves carriers, and what happens away from equilibrium

Neamen 5 and 6.

Every current is **drift**, driven by a field, or **diffusion**, driven by a concentration gradient, or both:

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$$v_{dn} = -\mu_n \mathcal{E}, \quad \mu_n = \frac{e\tau_n}{m_n^*}, \quad J_{drift} = e(\mu_n n + \mu_p p)\mathcal{E} = \sigma \mathcal{E}, \quad \frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{e}$$

The **Einstein relation** links mobility and diffusion via the same scattering: phonons worsen mobility with temperature ($\mu \propto T^{-3/2}$), ionized impurities improve it ($\mu \propto T^{3/2}/N_I$), and mobility peaks where the two cross. Away from equilibrium each carrier gets its own **quasi-Fermi level**; the **continuity equation** plus a recombination **lifetime** tracks how the excess population decays.

Why a junction passes current one way

Neamen 7 and 8.

Diffusion uncovers fixed dopant charge, building a field that cancels it at equilibrium (the **depletion approximation**: no mobile carriers inside, neutral outside; $x_p N_a = x_n N_d$ puts most of the width on the lightly doped side):

ON THE FORMULA SHEET

$$V_{bi} = \frac{kT}{e} \ln\left(\frac{N_a N_d}{n_i^2}\right), \quad |\mathcal{E}_{max}| = \frac{2(V_{bi} - V_a)}{W}$$

The minority-carrier diffusion equation gives the **ideal diode equation**; forward bias raises injected current exponentially, reverse bias saturates it at $-J_s$:

$$J = J_s \left(\exp\left(\frac{eV_a}{kT}\right) - 1 \right)$$

Controlling a channel you never touch

Neamen 9 and 10.

Work-function mismatch at a metal-semiconductor contact leaves a barrier: a rectifying **Schottky contact**, or an **ohmic contact** if the surface is doped heavily enough to tunnel through it. Over an oxide, no steady gate current flows; sweeping the gate on p-type gives **accumulation**, **depletion**, then **inversion** (an n-type surface layer) past the **threshold voltage** V_T .

With n-type source/drain either side of the gate, the inversion layer connects them above V_T : a gate-controlled resistor (**triode**) at small V_{DS} , until $V_{DS} = V_{GS} - V_T$ pinches it off at the drain and the current flattens (**saturation**).

Current gain, and junctions that trade with light

Neamen 12 and 14.

In an npn BJT, forward bias on the emitter-base junction injects electrons into the base; the base is thinner than a diffusion length, so most cross before recombining and reach the collector. Two fractions close to one – **base transport factor** and **emitter injection efficiency** – multiply to give α , and $\beta = \alpha / (1 - \alpha)$: at $\alpha = 0.99$, $\beta = 99$; at $\alpha = 0.995$, $\beta = 199$.

Run the same junction with photons: absorption in the depletion region creates a pair the field separates – **photodetector** (reverse biased) or **solar cell** (unbiased). Forward biased, carriers recombine; a **direct-gap** material like GaAs emits light efficiently (**LED**), silicon's indirect gap makes it a poor emitter.

7.1 Check yourself

Why is the base made thin and lightly doped, and the emitter heavily doped?

ANSWER

A thin base raises the base transport factor (carriers cross before recombining); a heavily doped emitter against a lightly doped base raises the injection efficiency (negligible back-injection). Both push α toward one, and $\beta = \alpha / (1 - \alpha)$ converts that into large gain.