

# ECE 231 course notes: technical material by topic

Semiconductor Physics and Devices, textbook Neamen 4th edition – the technical content of every lesson at <https://lessons.ihsan.cc/ece231/>, merged across the overview and lab lessons and organised by topic rather than by lesson. This lesson uses  $kT = 0.025852$  eV at 300 K and the formula sheet's  $n_i = 10^{10} \text{ cm}^{-3}$ ; the official problem-set solutions use 0.0259 eV and  $n_i = 1.5 \times 10^{10} \text{ cm}^{-3}$ , so some 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. Smaller lattice spacing means greater wavefunction overlap and a *wider* gap; dilating the lattice narrows it.

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

ON THE FORMULA SHEET

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

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 ( $m_n^* = 0.067 m_0$ , mobility about  $8500 \text{ cm}^2/\text{V}\cdot\text{s}$ ) suits high-frequency devices where silicon ( $m_n^* \approx 1.08 m_0$ , about  $1350 \text{ cm}^2/\text{V}\cdot\text{s}$ ) does not.

### 1.1 Worked example

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

## 1.2 Short practice

PS1 -- Q2 · INTRO · OFFICIAL SOLUTION AGREES

$2 \times 10^{16} \text{ cm}^{-3}$  boron atoms are added to silicon as a substitutional impurity, uniformly distributed. What is the distance between boron atoms?

ANSWER

Modelling the volume per dopant,  $1/N_B$ , as a cube of edge  $d$ :  $d = (1/2 \times 10^{16})^{1/3} = 3.68 \times 10^{-6} \text{ cm} \approx 37 \text{ nm}$  – about 136 silicon lattice spacings, one boron per 2.5 million silicon atoms.

## How many carriers, and how doping sets the number

Neamen 4.

Carrier density is **density of states times Fermi function**:

ON THE FORMULA SHEET

$$f(E) = \frac{1}{1 + \exp\left(\frac{E - E_F}{kT}\right)}$$

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, each scaling as  $T^{3/2}$ ); 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. The **intrinsic Fermi level** sits off midgap by the carriers' mass asymmetry:

$$E_{Fi} - E_{\text{midgap}} = \frac{3}{4} kT \ln\left(\frac{m_p^*}{m_n^*}\right), \quad p_0 = n_i \exp\left(\frac{E_{Fi} - E_F}{kT}\right)$$

Doping moves  $E_F$ , not  $E_g$ . Donors (group V) sit  $\sim 0.03$  eV below  $E_c$ , acceptors (group III)  $\sim 0.05$  eV above  $E_v$ , both essentially all ionised at 300 K. With both present only the difference counts (the compensated formula  $n_0 = \frac{N_d - N_a}{2} + \sqrt{\left(\frac{N_d - N_a}{2}\right)^2 + n_i^2}$  covers every regime), and when  $N_d - N_a \gg n_i$  simply  $n_0 = N_d - N_a$ . Every  $kT$  of Fermi-level movement is a factor of  $e$  in  $n_0$ , since  $n_0 \propto \exp(-(E_c - E_F)/kT)$ .

**Which atoms, how much, and where it breaks.** Boron, aluminium and gallium are acceptors in Si; phosphorus, arsenic and antimony are donors. A group IV atom in a III-V crystal is **amphoteric**: Sn on a Ga site in GaAs gives up an electron and acts as a donor. Practical doping runs about  $10^{16}$ – $10^{18}$   $\text{cm}^{-3}$  against  $n_i \approx 10^{10}$   $\text{cm}^{-3}$  in Si at room temperature, and  $E_{Fi}$  sits at midgap only when  $m_p^* \approx m_n^*$ .

- **Compensation** comes from charge neutrality,  $n_0 + N_a = p_0 + N_d$  (all ionised).  $N_d = N_a$  gives  $n_0 = p_0$ , as in intrinsic material;  $|N_d - N_a| \gg n_i$  gives  $n_0 = N_d - N_a$  and  $p_0 = n_i^2/n_0$ .
- **Temperature** sets three regimes. At low  $T$  the dopants are only partly ionised (**freeze-out**); across the **extrinsic** plateau  $n_0 \approx N_d$  (roughly 100–500 K for  $N_d = 5 \times 10^{15}$   $\text{cm}^{-3}$  in Si); once  $n_i$  exceeds  $N_d$  the sample turns **intrinsic**.
- **Degenerate** doping puts  $E_F$  within about  $3kT$  of  $E_c$  or  $E_v$ , and the Maxwell-Boltzmann form above stops holding; in Si that starts near  $10^{19}$   $\text{cm}^{-3}$  carriers.
- At equilibrium  $E_F$  is **flat in position**: join two materials and carriers flow until their Fermi levels line up, which is where a junction's built-in voltage comes from (section 4).

## 2.1 Worked example

PS1 -- Q11 · CORE · OFFICIAL SOLUTION AGREES

The electron concentration in silicon at  $T = 300\text{ K}$  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  $2.5 \times 10^9$  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  $kT = 0.0259\text{ eV}$ .

## 2.2 Short practice

PS2 -- Q3 · CORE · AI-WORKED

Silicon at 300 K is doped with  $N_d = 6 \times 10^{15}\text{ cm}^{-3}$ , all ionised. (a) Find  $E_c - E_F$ . (b) How many more donors must be added to move  $E_F$  a distance  $kT$  closer to  $E_c$ ?

ANSWER

(a)  $n_0 = N_d$  (the  $n_i^2/N_d$  correction is  $1.7 \times 10^4$ , negligible):  $E_c - E_F = 0.025852 \ln(2.8 \times 10^{19}/6 \times 10^{15}) = 0.2184\text{ eV}$ . (b) A  $kT$  shift needs  $N'_d = eN_d = 1.63 \times 10^{16}\text{ cm}^{-3}$ , an addition of  $1.03 \times 10^{16}\text{ cm}^{-3}$ .

# 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:

ON THE FORMULA SHEET

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

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. With both mechanisms present the electron current is

$$J_n = e\mu_n n \mathcal{E} + eD_n \frac{\partial n}{\partial x}$$

## 3.1 Excess carriers and lifetime

Light or injection adds pairs:  $n = n_0 + \delta n$ ,  $p = p_0 + \delta p$ , and  $np \neq n_i^2$ . Generation makes electrons and holes together ( $g'_n = g'_p$ , so  $\delta n = \delta p$ ), and they recombine together at  $R'_n = R'_p = \alpha_r np$ . Thermal generation balances recombination only at equilibrium:

$$\frac{dn(t)}{dt} = \alpha_r n_i^2 - \alpha_r n(t)p(t)$$

Under **low injection** ( $\delta n \ll$  the majority density) in p-type material this linearises to  $d(\delta n)/dt = -\alpha_r p_0 \delta n$ , so the excess decays exponentially with the **minority-carrier lifetime**:

$$\delta n(t) = \delta n(0)e^{-t/\tau_{n0}}$$

$$\tau_{n0} = \frac{1}{\alpha_r p_0}, \quad R' = \frac{\delta n}{\tau_{n0}} \text{ (p-type);} \quad \tau_{p0} = \frac{1}{\alpha_r n_0}, \quad R' = \frac{\delta p}{\tau_{p0}} \text{ (n-type)}$$

The minority lifetime is set by the *majority* density: the more partners there are, the sooner a minority carrier finds one. Recombination through traps follows Shockley-Read-Hall, where  $n'$  and  $p'$  are set by the trap level:

ON THE FORMULA SHEET

$$R = \frac{np - n_i^2}{\tau_{p0}(n + n') + \tau_{n0}(p + p')}$$

For a trap near midgap ( $E_T \approx E_{Fi}$ , so  $n' \approx p' \approx n_i$ ) in p-type material under low injection,  $p \approx p_0 \gg n$ ,  $n_i$  and  $np - n_i^2 \approx p_0 \delta n$ , so the denominator is  $\tau_{n0}p_0$  and the general rate reduces to  $R = \delta n/\tau_{n0}$ , the same form as above; n-type gives  $R = \delta p/\tau_{p0}$ . Only the minority lifetime survives.

## LECTURE EXAMPLE · CORE · FROM THE MODULE 3 SLIDES

Si with  $N_a = 10^{16} \text{ cm}^{-3}$  and  $n_i = 10^{10} \text{ cm}^{-3}$ ; light raises  $p$  by 10%.

## WORKED SOLUTION

$\delta p = \delta n = 10^{15} \text{ cm}^{-3}$ , while  $n_0 = n_i^2/p_0 = 10^4 \text{ cm}^{-3}$ . So  $n$  goes from  $10^4$  to about  $10^{15} \text{ cm}^{-3}$ , eleven orders of magnitude, while  $p$  moves 10%. Injection is a minority-carrier event.

### 3.2 Continuity and ambipolar transport

Carriers in a slice change by what flows in, what is generated and what recombines:

$$\frac{\partial n}{\partial t} = \frac{1}{e} \frac{\partial J_n}{\partial x} + g' - \frac{\delta n}{\tau_n}$$

Substituting  $J_n$  for a homogeneous sample gives one equation in the excess *minority* carrier. That is the **ambipolar** result, and it holds under four assumptions: low injection, the minority carrier's  $D$  and  $\mu$ , a constant minority lifetime, and equal generation of both carriers (charge neutrality):

$$\begin{aligned} \text{p-type: } \frac{\partial \delta n}{\partial t} &= D_n \frac{\partial^2 \delta n}{\partial x^2} + \mu_n \mathcal{E} \frac{\partial \delta n}{\partial x} + g' - \frac{\delta n}{\tau_{n0}} \\ \text{n-type: } \frac{\partial \delta p}{\partial t} &= D_p \frac{\partial^2 \delta p}{\partial x^2} - \mu_p \mathcal{E} \frac{\partial \delta p}{\partial x} + g' - \frac{\delta p}{\tau_{p0}} \end{aligned}$$

Three special cases cover most problems:

## ON THE FORMULA SHEET

$$\delta n(t) = Ae^{-t/\tau} \quad (g' = 0), \quad \delta n(t) = g'\tau \left(1 - e^{-t/\tau}\right) \quad (\delta n(0) = 0)$$

$$\delta n(x) = Ae^{-x/L} + Be^{x/L}, \quad L^2 = D\tau$$

the last in steady state with no field and  $g' = 0$ ;  $L$  is the **diffusion length**, how far a minority carrier gets before it recombines.

### 3.3 Quasi-Fermi levels

$E_F$  is defined only at equilibrium. Away from it each carrier gets its own level, written so the equilibrium forms carry over:

$$n_0 + \delta n = n_i \exp\left(\frac{E_{Fn} - E_{Fi}}{kT}\right), \quad p_0 + \delta p = n_i \exp\left(\frac{E_{Fi} - E_{Fp}}{kT}\right)$$

## LECTURE EXAMPLE · CORE · AI-WORKED

$n_0 = 10^{15} \text{ cm}^{-3}$  ( $p_0 = 10^5 \text{ cm}^{-3}$ ,  $n_i = 10^{10} \text{ cm}^{-3}$ ); light gives  $\delta n = \delta p = 10^{13} \text{ cm}^{-3}$ .

## WORKED SOLUTION

$E_{Fn} - E_{Fi} = 0.025852 \ln(1.01 \times 10^{15}/10^{10}) = 0.2979 \text{ eV}$ , barely above the equilibrium  $E_F - E_{Fi} = 0.2976 \text{ eV}$ . But  $p \approx 10^{13} \text{ cm}^{-3}$ , so  $E_{Fi} - E_{Fp} = 0.025852 \ln(10^{13}/10^{10}) = 0.1786 \text{ eV}$ : the hole level drops from 0.2976 eV above  $E_{Fi}$  to 0.1786 eV below it. The majority level hardly moves; the minority level moves a long way.

### 3.4 Measuring them: Hall effect and Haynes-Shockley

Lab 2 theory, in the course notation ( $e$  for the manual's  $q$ ).

**Hall effect (majority carriers).** Current  $I_x$  flows along a slab of width  $W$  and thickness  $d$  in a field  $B_z$ . The force  $\mathbf{F} = q \mathbf{v} \times \mathbf{B}$  pushes carriers to one side until the field they build balances it,  $e\mathcal{E}_y = ev_x B_z$ . Holes and electrons are pushed to the *same* side, because reversing the charge also reverses the drift direction, so the polarity of the Hall voltage  $V_H$  gives the type. With  $v_x = I_x/(epWd)$  and  $\mathcal{E}_y = V_H/W_p$ , where  $W_p$  is the spacing of the Hall contacts:

$$p = \left| \frac{I_x B_z}{e\mathcal{E}_y W d} \right| \quad (n \text{ the same form}), \quad \mu_p = \left| \frac{I_x}{ep\mathcal{E}_x W d} \right| = \frac{v_d}{\mathcal{E}_x}$$

where  $\mathcal{E}_x$  is the applied field, measured between two contacts along the current.

**Haynes-Shockley (minority carriers).** A forward-biased rectifying contact injects a short pulse of minority carriers; a reverse-biased one a distance  $d$  downstream collects it. Under low injection (in p-type Si with  $p_p = 10^{15}$ ,  $n_p \approx 10^5 \text{ cm}^{-3}$ , so  $\delta n \ll p_p$ ) the pulse obeys the p-type ambipolar equation: its peak **drifts** at  $\mu\mathcal{E}$ , it **spreads** into a widening Gaussian by diffusion, and its area **shrinks** by recombination. The transit time gives the minority mobility, and Einstein gives  $D$  (with  $kT/e \approx 25 \text{ mV}$  at room temperature):

$$t_0 = \frac{d}{v} = \frac{d}{\mu\mathcal{E}} \Rightarrow \mu = \frac{d}{\mathcal{E}t_0}, \quad \Gamma_e = -D_e \frac{dn}{dx}, \quad D_e = \mu \frac{kT}{e}$$

In a p-type sample the minority electrons drift against  $\mathcal{E}$ , so the field polarity is the reverse of an n-type setup.

## 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

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

Read off the band diagram, the barrier is the gap minus how far  $E_F$  sits from each band edge on its own side, which ties  $V_{bi}$  to  $E_g$ :

$$eV_{bi} = E_g - (E_c - E_F)_n - (E_F - E_v)_p \Rightarrow V_{bi} = \frac{E_g}{e} - \frac{kT}{e} \ln \left( \frac{N_c N_v}{N_a N_d} \right)$$

using  $n_i^2 = N_c N_v e^{-E_g/kT}$ . A wider gap gives a larger barrier at the same doping.

**Electrostatics, in order.** With  $E_F$  flat across the junction, work out  $V_{bi}$ , then integrate charge to field, then field to potential. Poisson's equation links them,  $d\mathcal{E}/dx = \rho/\epsilon_s = -d^2\phi/dx^2$ , with  $\mathcal{E}(-x_p) = \mathcal{E}(x_n) = 0$  and  $\phi(-x_p) = 0$ ,  $\phi(x_n) = V_{bi}$ :

$$\mathcal{E} = -\frac{eN_a}{\epsilon_s}(x + x_p) \quad (-x_p \leq x \leq 0), \quad \mathcal{E} = -\frac{eN_d}{\epsilon_s}(x_n - x) \quad (0 \leq x \leq x_n)$$

$$\phi = \frac{eN_a}{2\epsilon_s}(x + x_p)^2 \quad (\text{p side}), \quad \phi = \frac{eN_d}{\epsilon_s} \left( xx_n - \frac{x^2}{2} \right) + \frac{eN_a}{2\epsilon_s} x_p^2 \quad (\text{n side})$$

The field is a triangle peaking at the junction,  $|\mathcal{E}_{max}| = eN_a x_p / \epsilon_s = eN_d x_n / \epsilon_s$ , and the potential is two parabolas. Matching them gives the widths:

$$x_n = \sqrt{\frac{2\epsilon_s V_{bi}}{e} \frac{N_a}{N_d} \frac{1}{N_a + N_d}}, \quad x_p = \sqrt{\frac{2\epsilon_s V_{bi}}{e} \frac{N_d}{N_a} \frac{1}{N_a + N_d}}, \quad W = \sqrt{\frac{2\epsilon_s V_{bi}}{e} \frac{N_a + N_d}{N_a N_d}}$$

Under an applied bias  $V_a$ , replace  $V_{bi}$  with  $V_{bi} - V_a$ : forward bias narrows the region, reverse bias widens it.

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  $\alpha$ , and  $\beta = \alpha / (1 - \alpha)$ : at  $\alpha = 0.99$ ,  $\beta = 99$ ; at  $\alpha = 0.995$ ,  $\beta = 199$ . A thin, lightly doped base raises the transport factor; a heavily doped emitter against the lighter base raises the injection efficiency.

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.

### 6.1 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  $\alpha$  toward one, and  $\beta = \alpha / (1 - \alpha)$  converts that into large gain.

# Lab instrumentation and measurement

Instrument and measurement principles from Lab 1 – not lab procedure or logistics.

**Resistors.** A four-band resistor's value and tolerance band:

ON THE FORMULA SHEET

$$R = (10 d_1 + d_2) \times 10^m \Omega, \quad R_{\min} = R(1 - \frac{t}{100}), \quad R_{\max} = R(1 + \frac{t}{100})$$

Digit colours: black 0, brown 1, red 2, orange 3, yellow 4, green 5, blue 6, violet 7, grey 8, white 9; the same colours as a multiplier give that power of ten, gold 0.1, silver 0.01; tolerance brown 1%, red 2%, gold 5%, silver 10%. A decade box gives the same nominal-vs-actual gap: one dial per decade, each step its own resistor with its own tolerance, and a box set to zero is not zero ohms – measure it at the setting used.

## 7.1 Worked example

Yellow, violet, red, gold: digits 4 and 7, multiplier  $10^2$ , so  $R = 4700 \Omega$ ; gold promises the real part is within 5% of that.

ANSWER

$$R_{\min} = 4700(0.95) = 4465 \Omega, \quad R_{\max} = 4700(1.05) = 4935 \Omega.$$

**Measuring resistance.** In 2-wire mode the lead resistance sits inside what is sensed; in 4-wire mode a separate sense pair carries no current, so lead resistance drops nothing.

ANSWER

A  $10 \Omega$  part with  $0.3 \Omega$  in each lead reads  $10.6 \Omega$  2-wire (6% high) and  $10 \Omega$  4-wire. Rule: 4-wire for small resistances, 2-wire for everything else.

**DC supply.** Each output holds either the set voltage (CV) or the current limit (CC), whichever the load makes true:

ON THE FORMULA SHEET

$$R_{\text{load}} > \frac{V_{\text{set}}}{I_{\text{limit}}} \Rightarrow \text{CV}, \quad I = \frac{V_{\text{set}}}{R_{\text{load}}}; \quad R_{\text{load}} < \frac{V_{\text{set}}}{I_{\text{limit}}} \Rightarrow \text{CC}, \quad V = I_{\text{limit}} R_{\text{load}}$$

## 7.2 Short practice

5 V across a  $470\ \Omega$  resistor, current limit 50 mA. What does the ammeter read, and what mode is the supply in? Now replace the resistor with  $10\ \Omega$ .

ANSWER

$470\ \Omega > 5\text{V}/50\text{mA} = 100\ \Omega$ : CV,  $I = 5/470 = 10.6\ \text{mA}$ . With  $10\ \Omega < 100\ \Omega$ : CC,  $I = 50\ \text{mA}$  and  $V_R = 50\text{mA} \times 10\ \Omega = 0.5\ \text{V}$ .

**Meter placement and range.** A voltmeter goes in parallel (nearly open,  $10\ \text{M}\Omega$  or more), an ammeter in series (nearly a short); a current function placed across a source is a short across the source. A range reads to 120% of its face value and shows OVLD above that; the last digit is about a millionth of the range, so the smallest range the reading fits in gives the most digits.

**Sinusoids.** The generator makes

ON THE FORMULA SHEET

$$v(t) = V_{\text{off}} + V_p \sin(2\pi ft), \quad V_{pp} = 2V_p, \quad T = \frac{1}{f}, \quad V_{\text{rms}} = \sqrt{V_{\text{off}}^2 + \frac{V_p^2}{2}}$$

and for no offset  $V_{\text{rms}} = V_p/\sqrt{2} \approx 0.707 V_p$ . On the scope, a screen  $10 \times 8$  divisions gives peak height  $V_p/(\text{V/div})$  divisions, one period  $T/(\text{s/div})$  divisions wide, and  $10(\text{s/div})f$  cycles on screen.

## 7.3 Worked example

A 2 V peak, 1 kHz sine with no offset, read at 1 V/div and  $500\ \mu\text{s/div}$ .

ANSWER

$V_{pp} = 4\ \text{V}$ ,  $V_{\text{rms}} = 1.41\ \text{V}$ ,  $T = 1\ \text{ms}$ ; on screen, 2 divisions tall and 5 cycles wide.

**Generator loading.** The generator has a real  $50\ \Omega$  in series with its output; its display reports the voltage that would appear across the load it was told to expect. Set to  $50\ \Omega$  and driving a true  $50\ \Omega$  load, the display is correct; driving a  $1\ \text{M}\Omega$  input instead (which halves nothing) delivers twice the displayed amplitude. Setting the load to High Z fixes the display for a high-impedance load such as a scope.

Sections 1--6: lesson source `src/ece231_course_overview.jsx` (`ece231-course-overview`); ECE 231 outlines, Problem Sets 1--2 and PS1 solutions; Module 3 slides (2026-09-23, annotated 2026-10-02), Tutorial 3 and the course formula sheet; Lab 2 manual v1.1, theory sections 2.1 and 3.1. Section 7: lesson source `src/ece231_lab1_instruments.jsx` (`ece231-lab1-instruments`), instrument and measurement content only.