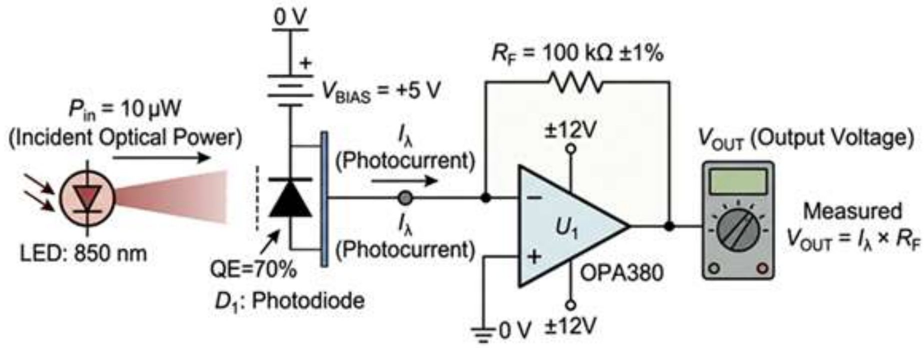
Tutorial 3

Exercise 1: Responsivity and Quantum Efficiency

1.

$$R = \frac{0.70 \cdot (1.602 \times 10^{-19}) \cdot (850 \times 10^{-9})}{(6.626 \times 10^{-34}) \cdot (3 \times 10^{8})} \approx 0.48 \text{ A/W}$$

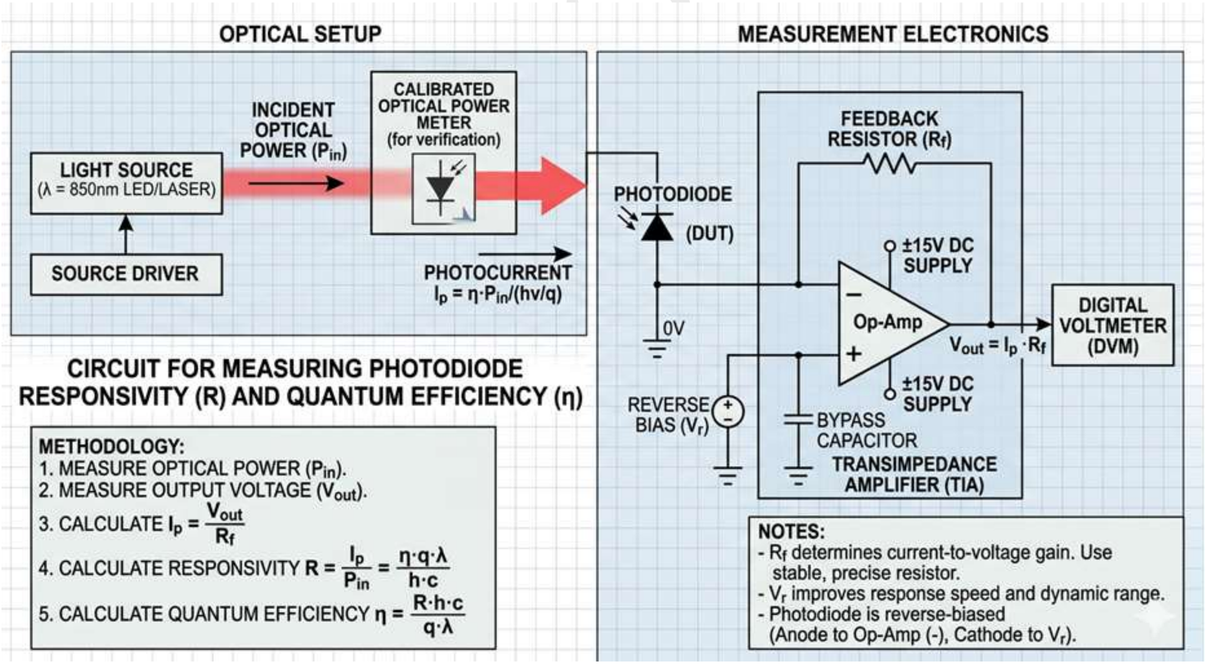
2.



Given λ =850nm, QE=70% Calculate $R = \frac{0.70 \times 850}{1242} \approx 0.48$ A/W

P_{in}=10μW, I_λ = 10μW × 0.48 A/W = 4.8 μA

V_{OUT} = 4.8μA× 100kΩ = 0.48 V



METHODOLOGY:
1. MEASURE OPTICAL POWER (P_{in}).
2. MEASURE OUTPUT VOLTAGE (V_{out}).
3. CALCULATE $I_p = \frac{V_{out}}{R_f}$
4. CALCULATE RESPONSIVITY $R = \frac{I_p}{P_{in}} = \frac{\eta \cdot q \cdot \lambda}{h \cdot c}$
5. CALCULATE QUANTUM EFFICIENCY $\eta = \frac{R \cdot h \cdot c}{q \cdot \lambda}$

NOTES:
- R_f determines current-to-voltage gain. Use stable, precise resistor.
- V_r improves response speed and dynamic range.
- Photodiode is reverse-biased (Anode to Op-Amp (-), Cathode to V_r).

3. Quantum efficiency is limited by how many incident photons actually create collected electron-hole pairs. To increase from 70% to 85%, you can focus on these physical improvements:

Anti-Reflection (AR) Coating: Apply or optimize a thin-film AR coating on the photodiode surface. This reduces the number of photons reflected away, allowing more to enter the semiconductor material.

Increase Depletion Width: Use a **PIN photodiode** structure instead of a standard PN junction. The intrinsic (i) layer increases the volume where photons can be absorbed and converted into current before they recombine.

Material Quality & Passivation: Improve the purity of the semiconductor to reduce "recombination centers" (defects). Surface passivation also prevents charge carriers from being lost at the material's edges.

Back-Surface Reflection: For thin diodes, add a reflective layer on the back so photons that pass through the material the first time are reflected back into the active region for a second chance at absorption

Exercise 2: Photoconductors and Gain

1.
$$G = \frac{10,000\ \text{ns}}{100\ \text{ns}} = 100$$

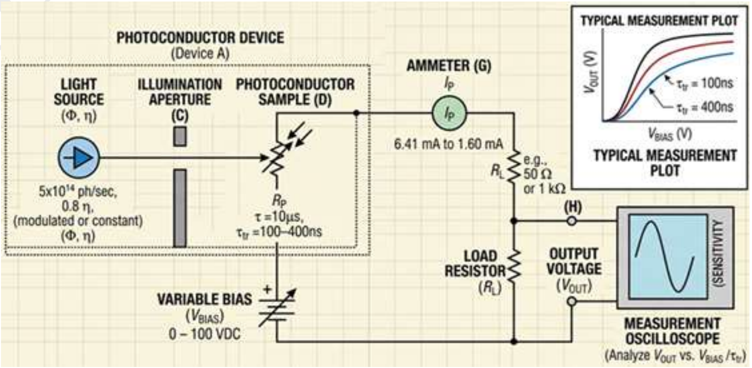
2. Photoconductors are unique because they can have a photoconductive gain (G) greater than 1, meaning one photon can result in many electrons flowing through the circuit. Photoconductive Gain (G) is the ratio of carrier lifetime (τ) to the transit time (τ_{tr}).

2.
$$I_p = (1.602 \times 10^{-19}) \cdot 0.80 \cdot (5 \times 10^{14}) \cdot 100 \ = 6.408 \times 10^{-3}\ \text{A} = 6.41\ \text{mA}$$

3.
$$G_{new} = \frac{10,000\ \text{ns}}{400\ \text{ns}} = 25$$
$$I_{total} = (1.602 \times 10^{-19}) \cdot 0.80 \cdot (5 \times 10^{14}) \cdot 25 = 1.602\ \text{mA}$$

The sensitivity significantly **decreases**. By increasing the transit time by a factor of 4, the output current dropped from $6.41mA$ to $1.6mA$ to transit time τ_{tr}. This suggests that sensitivity is inversely proportional to transit time; slower devices are less sensitive.

4.

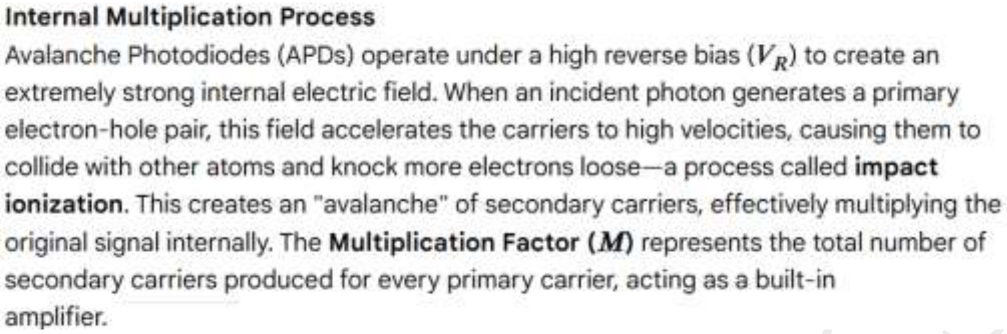


https://www.analog.com/en/resources/technical-articles/stabilize-transimpedance-amplifier-circuit-design.html

Exercise 3: Avalanche Photodiodes (APD)

1. $$M = \frac{1}{1-(\frac{95}{100})^3} = \frac{1}{1-0.857} \approx 7$$

2.

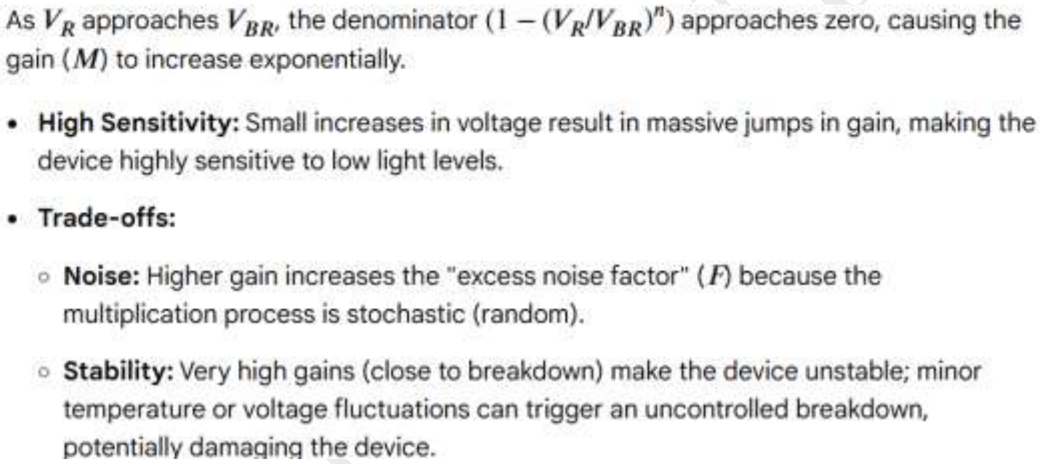


Internal Multiplication Process

Avalanche Photodiodes (APDs) operate under a high reverse bias (V_R) to create an extremely strong internal electric field. When an incident photon generates a primary electron-hole pair, this field accelerates the carriers to high velocities, causing them to collide with other atoms and knock more electrons loose—a process called **impact ionization**. This creates an "avalanche" of secondary carriers, effectively multiplying the original signal internally. The **Multiplication Factor (M)** represents the total number of secondary carriers produced for every primary carrier, acting as a built-in amplifier.

3. $$\textbf{Reciprocal (Gain } M\textbf{):}\ \frac{1}{0.058808} \approx \mathbf{17.00}$$

4.



As V_R approaches V_{BR}, the denominator $(1-(V_R/V_{BR})^n)$ approaches zero, causing the gain (M) to increase exponentially.

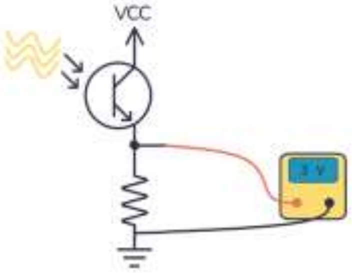
- **High Sensitivity:** Small increases in voltage result in massive jumps in gain, making the device highly sensitive to low light levels.
- **Trade-offs:**
  - **Noise:** Higher gain increases the "excess noise factor" (F) because the multiplication process is stochastic (random).
  - **Stability:** Very high gains (close to breakdown) make the device unstable; minor temperature or voltage fluctuations can trigger an uncontrolled breakdown, potentially damaging the device.

Exercise 4: Phototransistors

1. $$I_C \approx \beta \cdot I_\lambda = 150 \times 2 \times 10^{-6} = 300\mu A$$

2. $$I_{dark} = \mathbf{8\mu A}$$

3.



Exercise 5: Smart Streetlight Sensor

1. Calculate the Primary Responsivity (R)

Before transistor amplification, we find the responsivity of the base-collector junction acting as a photodiode.

$$R = \frac{\eta \cdot \lambda \, (\text{in } \mu m)}{1.24} = \frac{0.65 \cdot 0.60}{1.24} \approx 0.3145 \text{ A/W}$$

2. Calculate the Base Photocurrent ($I\lambda$)

This is the current generated by the incident light before the transistor's gain is applied.

$$I_\lambda = R \cdot P_{in} = 0.3145 \text{ A/W} \cdot 10 \times 10^{-6} \text{ W} = 3.145\mu A$$

3. Calculate the Total Collector Current (IC)

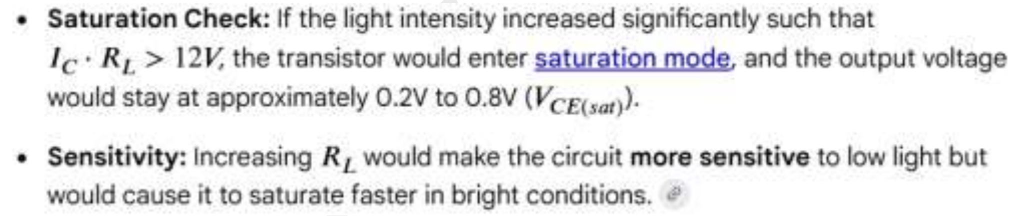
Apply the transistor's current gain (β) to the base current and include the leakage dark current.

$$I_C = (\beta \cdot I_\lambda) + I_{dark} = (120 \cdot 3.145\mu A) + 0.05\mu A = 377.4\mu A + 0.05\mu A = 377.45\mu A$$

4. Calculate the Final Output Voltage ($Vout$)

In a standard common-emitter configuration, the output voltage is measured at the collector. As light increases, IC increases, causing a larger voltage drop across RL

$$V_{out} = V_{CC} - (I_C \cdot R_L) = 12V - (377.45 \times 10^{-6} \text{ A} \cdot 10{,}000\Omega) = 12V - 3.7745V = 8.2255V$$



- **Saturation Check:** If the light intensity increased significantly such that $I_C \cdot R_L > 12V$, the transistor would enter saturation mode, and the output voltage would stay at approximately 0.2V to 0.8V ($V_{CE(sat)}$).
- **Sensitivity:** Increasing R_L would make the circuit **more sensitive** to low light but would cause it to saturate faster in bright conditions.

5.