USC University of Southern California

EE 105: Introduction to Electrical Engineering

Lecture 12

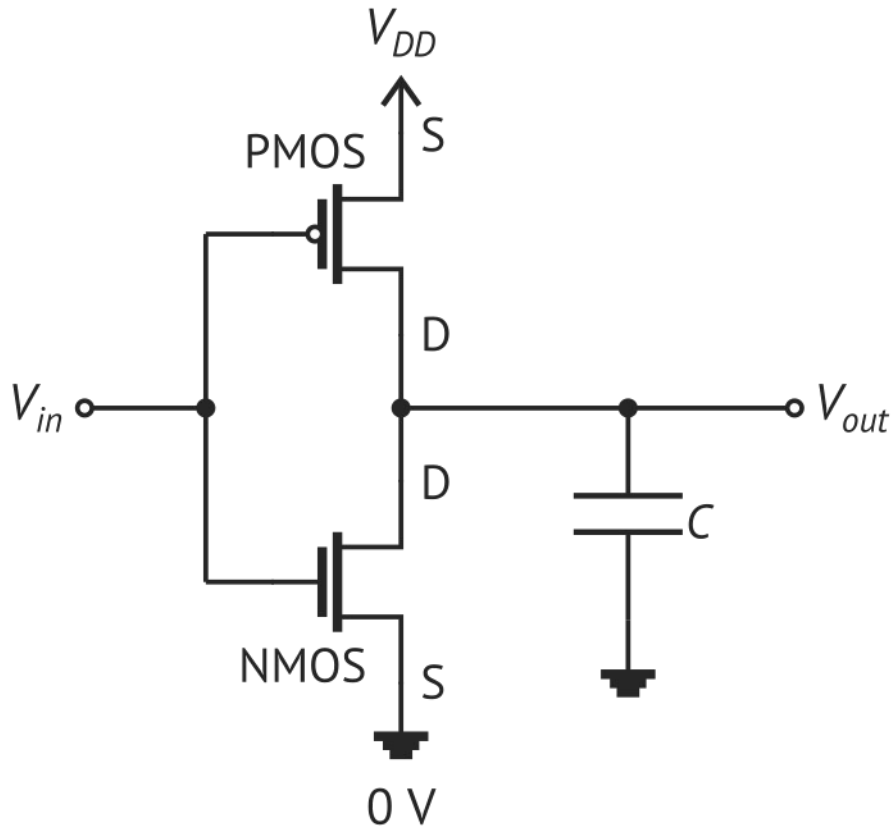
Optoelectronics

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CMOS (Complementary MOS) Inverter

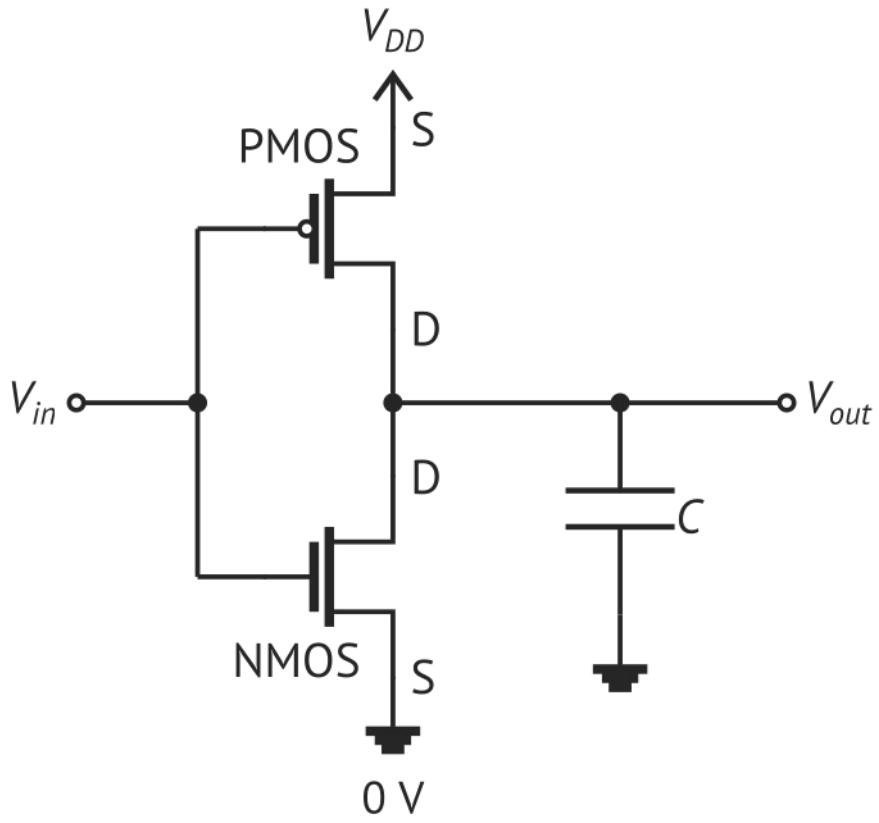
A PMOS pull-up and an NMOS pull-down share one input; their joined drains are the output.

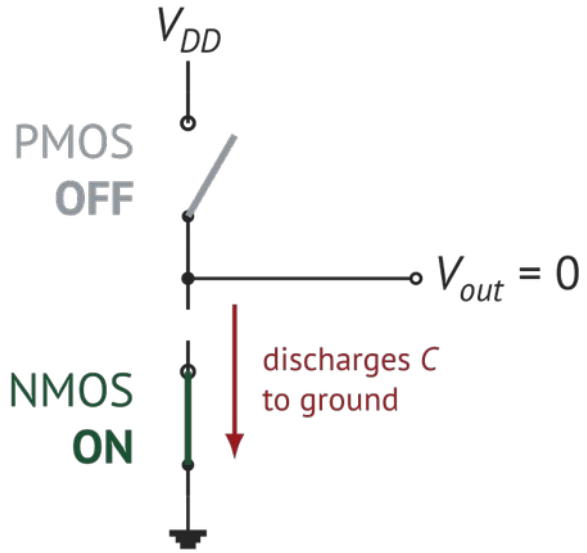


- **PMOS** on top: source at V_{DD}
- **NMOS** below: source at 0 V
- Gates joined: the input $\mathbf{V}_{in}$
- Drains joined: the output $\mathbf{V}_{out}$
- **C**: capacitance of the interconnect and of the next gates

CMOS (Complementary MOS) Inverter

Input high ($V_{in} = V_{DD}$): the NMOS is on, the PMOS is off, and the output falls to 0 V.





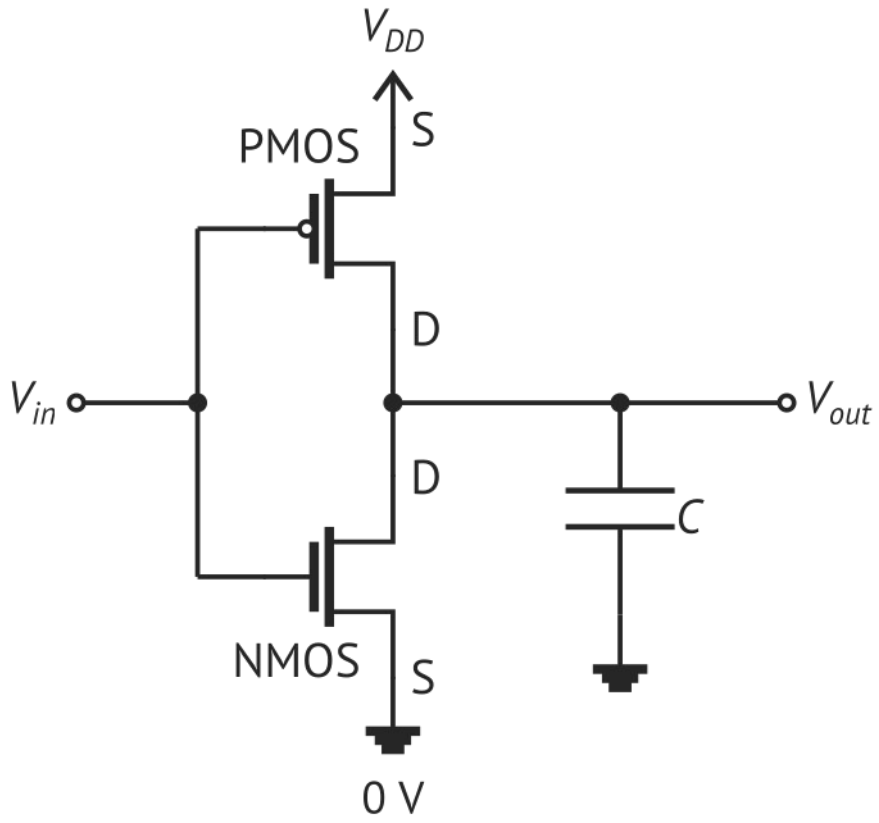
Truth table

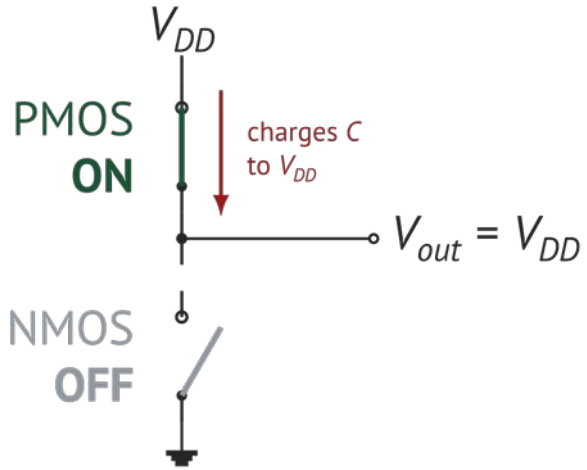
V_{in}	PMOS	NMOS	V_{out}
V_{DD}	off	on	**0 V**
0			?

NMOS: $V_{GS} = V_{DD} > V_{th}$, **on**. PMOS: $V_{GS} = 0$, **off**. Output pulled to ground.

CMOS (Complementary MOS) Inverter

Input low (V_{in} = 0): the PMOS is on, the NMOS is off, and the output rises to V_{DD}.





Truth table

V_{in}	PMOS	NMOS	V_{out}
V_{DD}	off	on	0 V
0	on	off	V_{DD}

PMOS: $V_{GS} = -V_{DD}$, **on**. NMOS: $V_{GS} = 0 < V_{th}$, **off**. Output pulled up to V_{DD}.

CMOS (Complementary MOS) Inverter

The output is the logical NOT of the input, and in either state no current flows from V_{DD} to ground.

Truth table (NOT gate)

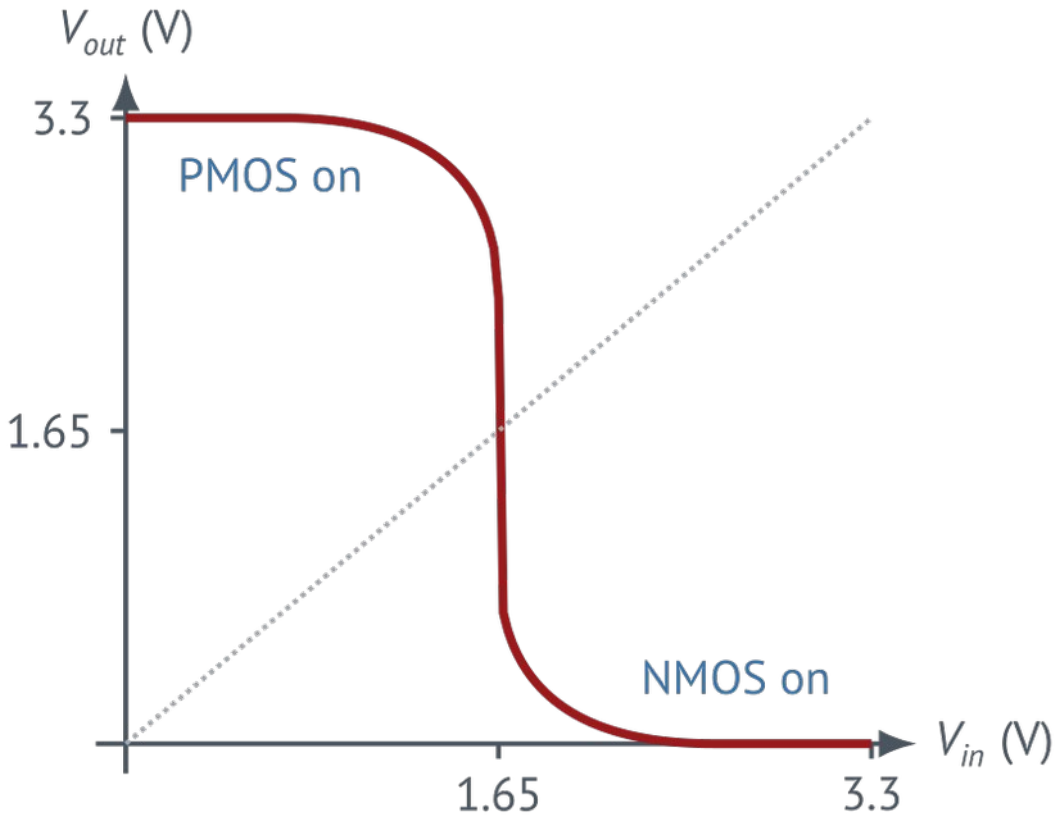
V_{in}	PMOS	NMOS	V_{out}
V_{DD}	off	on	0 V
0	on	off	V_{DD}

- One transistor is always **off**: no static current from V_{DD} to ground
- Power is used only when switching, to charge C

Dynamic power

$$P_{dyn} = C V_{DD}^2 f$$

Voltage transfer curve (V_{DD} = 3.3 V)



Qualitative discussion: n-MOSFET

As V_{DS} grows, the channel thins at the drain end until it pinches off and the current saturates.

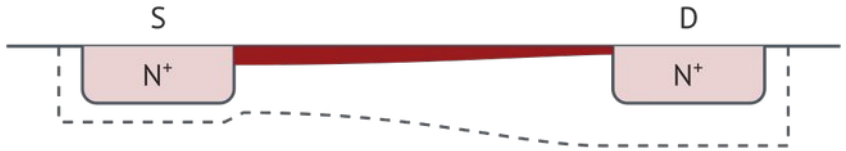
(a)



$V_{GS} > V_{th}$; $V_{DS} \approx 0$

I_D increases with V_{DS}

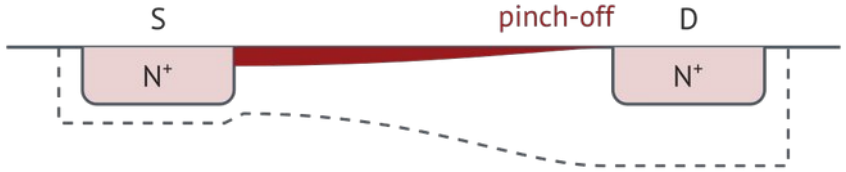
(b)



$V_{GS} > V_{th}$; V_{DS} small, > 0

I_D increases with V_{DS}, but the rate of increase decreases

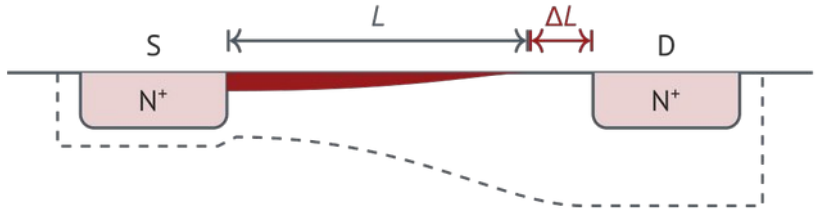
(c)



$V_{GS} > V_{th}$; V_{DS} at pinch-off

I_D reaches its saturation value $I_{D,sat}$; this V_{DS} is $V_{DS,sat}$

(d)



$V_{GS} > V_{th}$; $V_{DS} > V_{DS,sat}$

I_D does not increase further: the saturation region

Quantitative I_D-V_{DS} Relationships: "Square Law"

First attempt: the current rises with V_{DS} until pinch-off at $V_{DS,sat} = V_{GS} - V_{th}$, then stays flat.

$0 < V_{DS} < V_{DS,sat}$; $V_{GS} > V_{th}$

$$I_D = \mu_n C_{ox} \frac{W}{L} \left[(V_{GS} - V_{th}) V_{DS} - \frac{1}{2} V_{DS}^2 \right]$$

- I_D increases with V_{DS} until $\mathbf{V_{GS} - V_{DS} = V_{th}}$: the channel **pinches off** at the drain

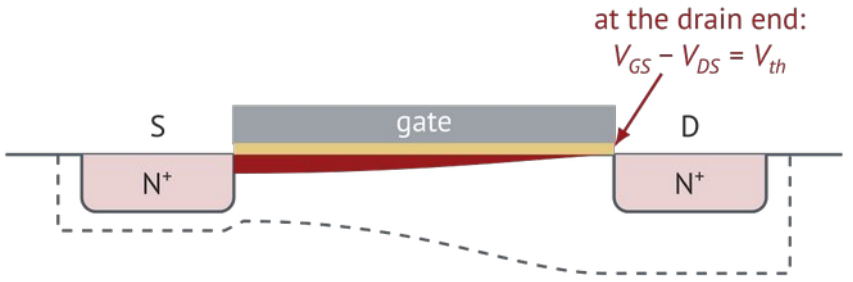
$V_{DS} \geq V_{DS,sat}$; $V_{GS} > V_{th}$

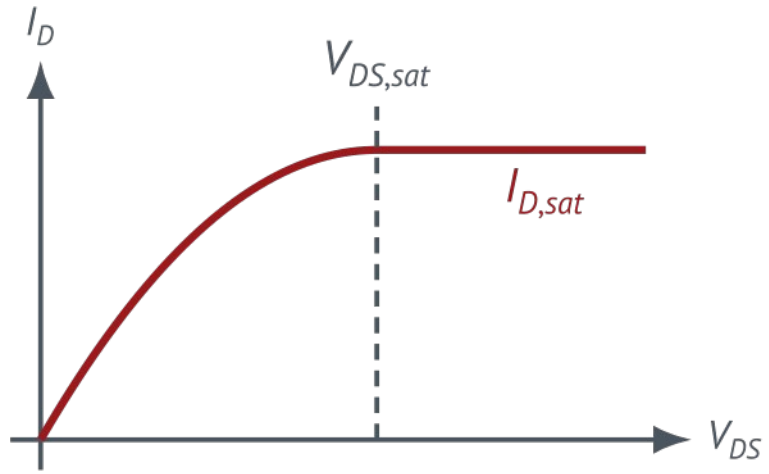
$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{th})^2$$

Oxide capacitance per unit area

$$C_{ox} = \varepsilon_{ox} / x_{ox}$$

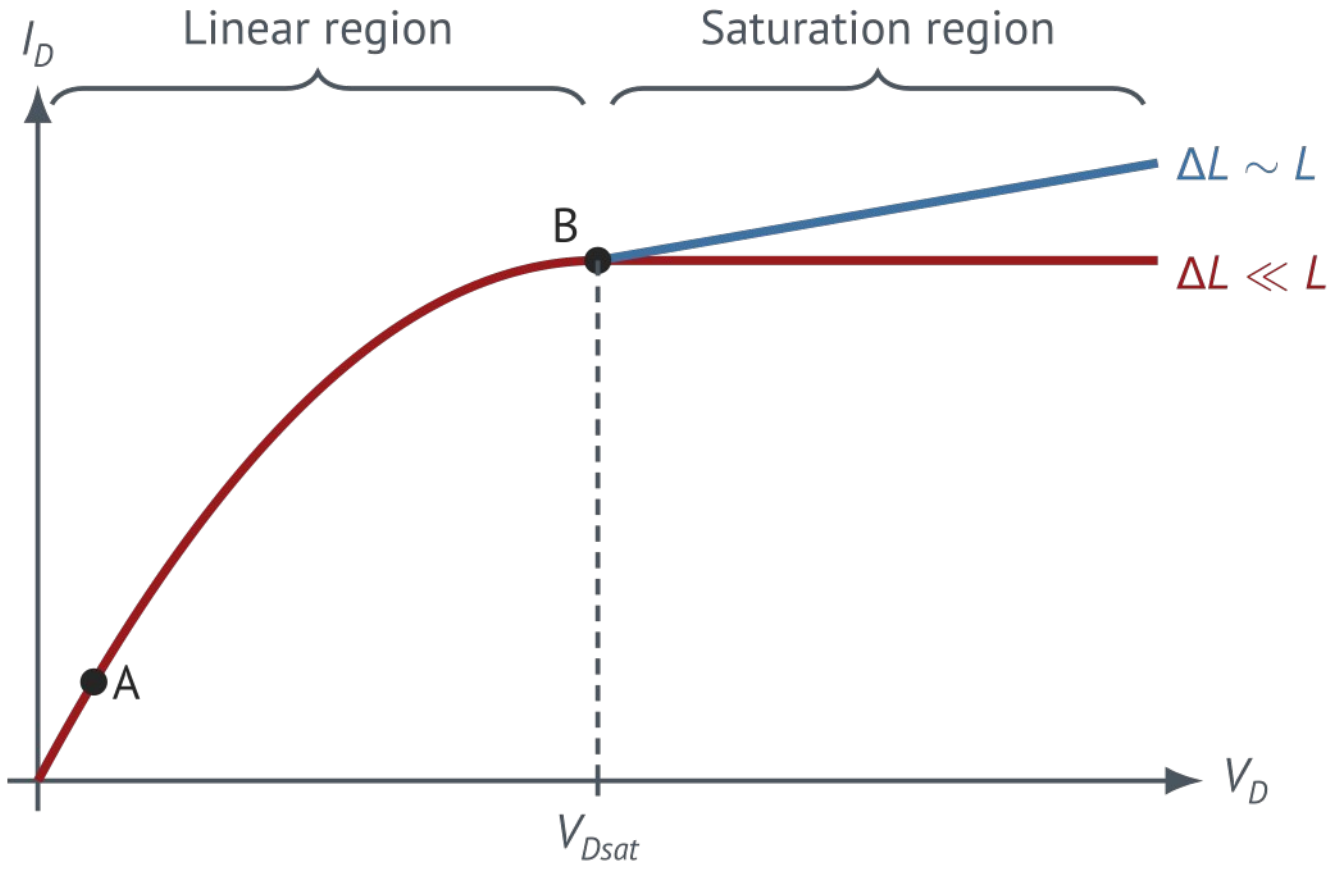
Pinch-off





I_D-V_{DS} characteristics for n-MOSFET

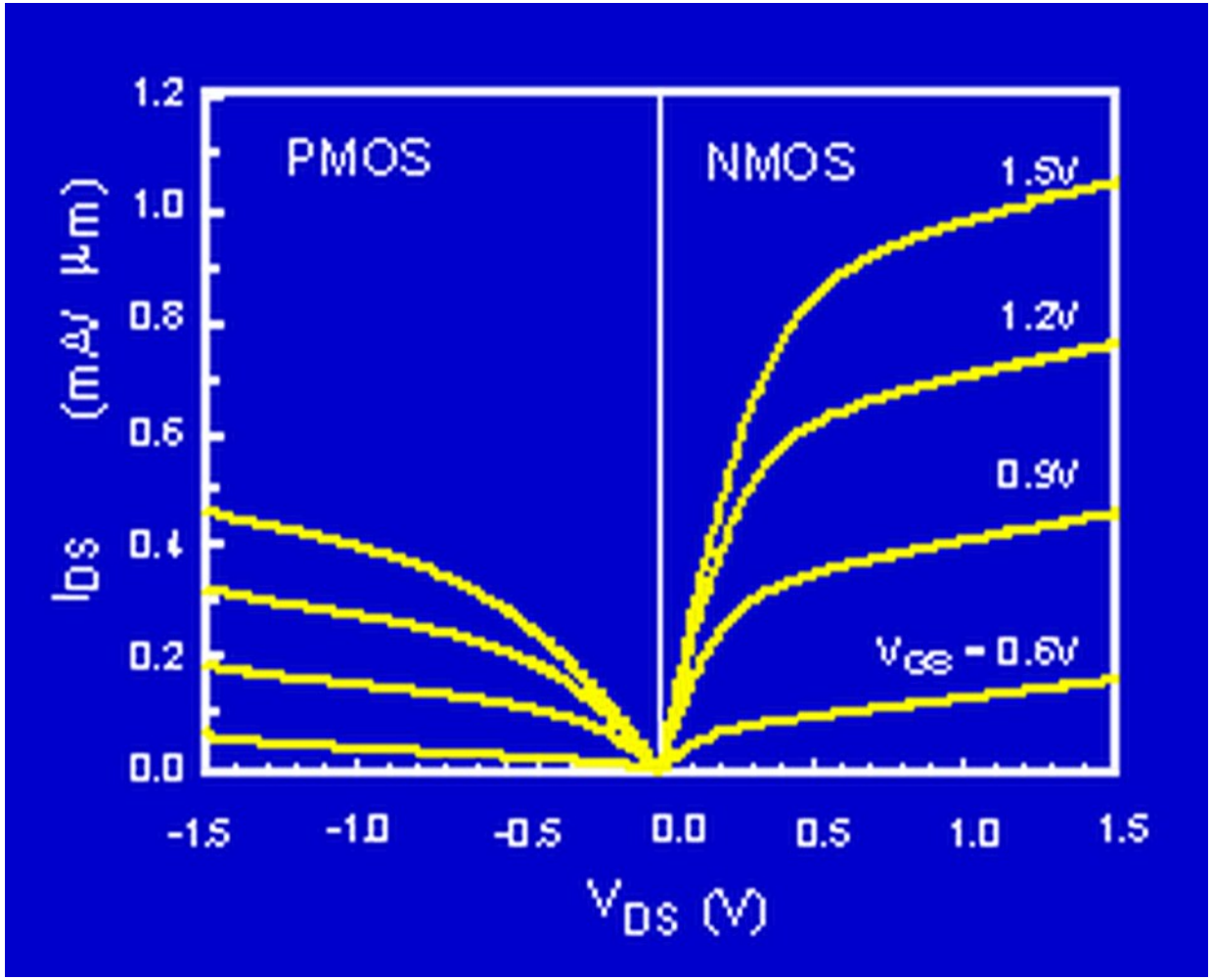
Linear region up to V_{Dsat}, then saturation: flat for a long channel, rising when ΔL is a large part of L.



- **A**: small V_{DS}; the channel acts as a resistor
- **B**: pinch-off at $V_{DS} = V_{Dsat}$
- **ΔL ≪ L** (long channel): the current stays flat
- **ΔL ∼ L** (short channel): it keeps rising, channel-length modulation

P-MOSFET and N-MOSFET IV Characteristics

The PMOS curves mirror the NMOS curves, but at the same gate drive they carry about half the current.



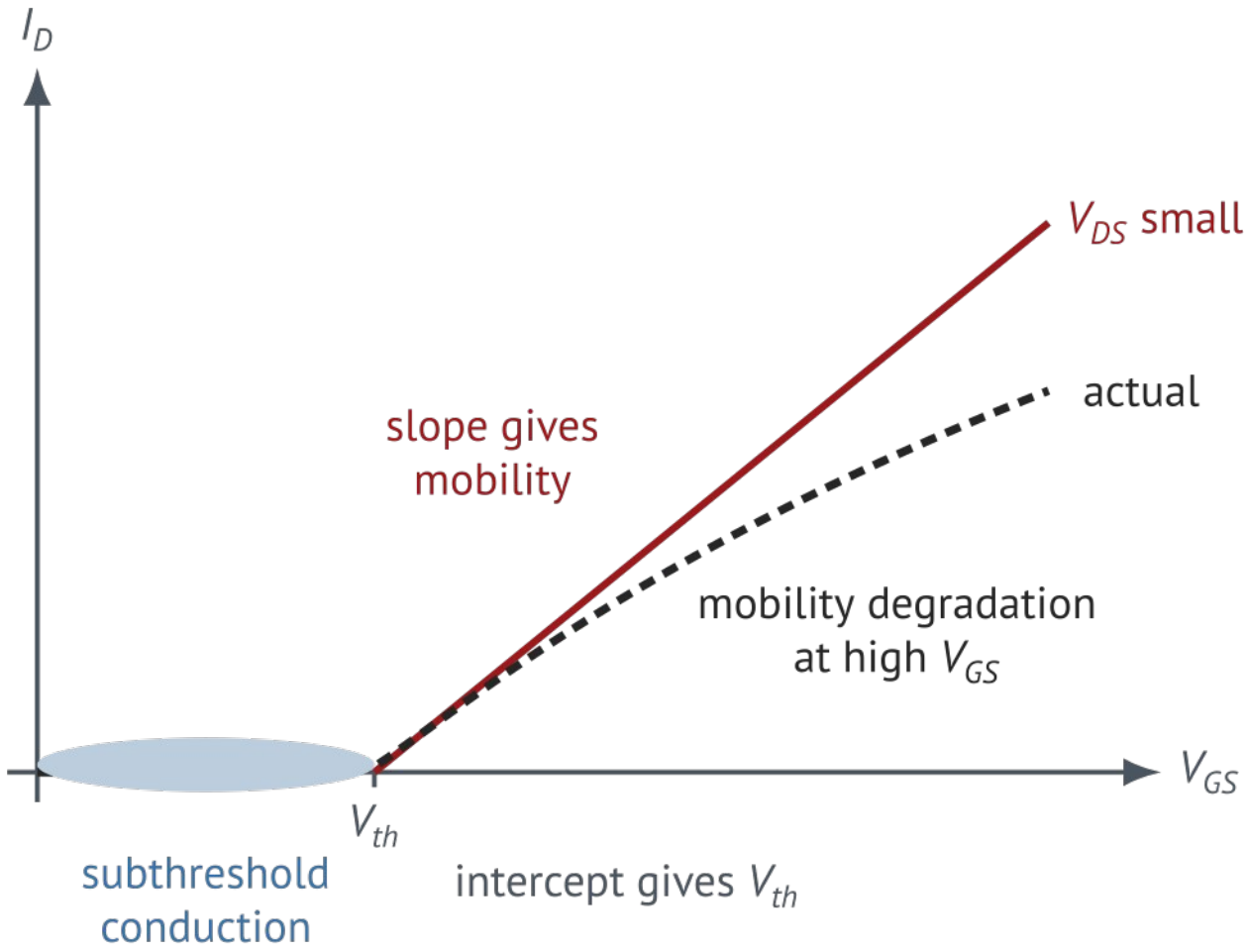
- PMOS: V_{DS} and V_{GS} negative; NMOS: positive
- Same shape: linear region, then saturation
- At the same $|V_{GS}|$, the PMOS current is **about half** as large

TRY IT

Why is the PMOS current about half as large?

Threshold and Subthreshold

At small V_{DS} the channel is a resistor: extrapolate the straight part to find V_{th}; its slope gives mobility.



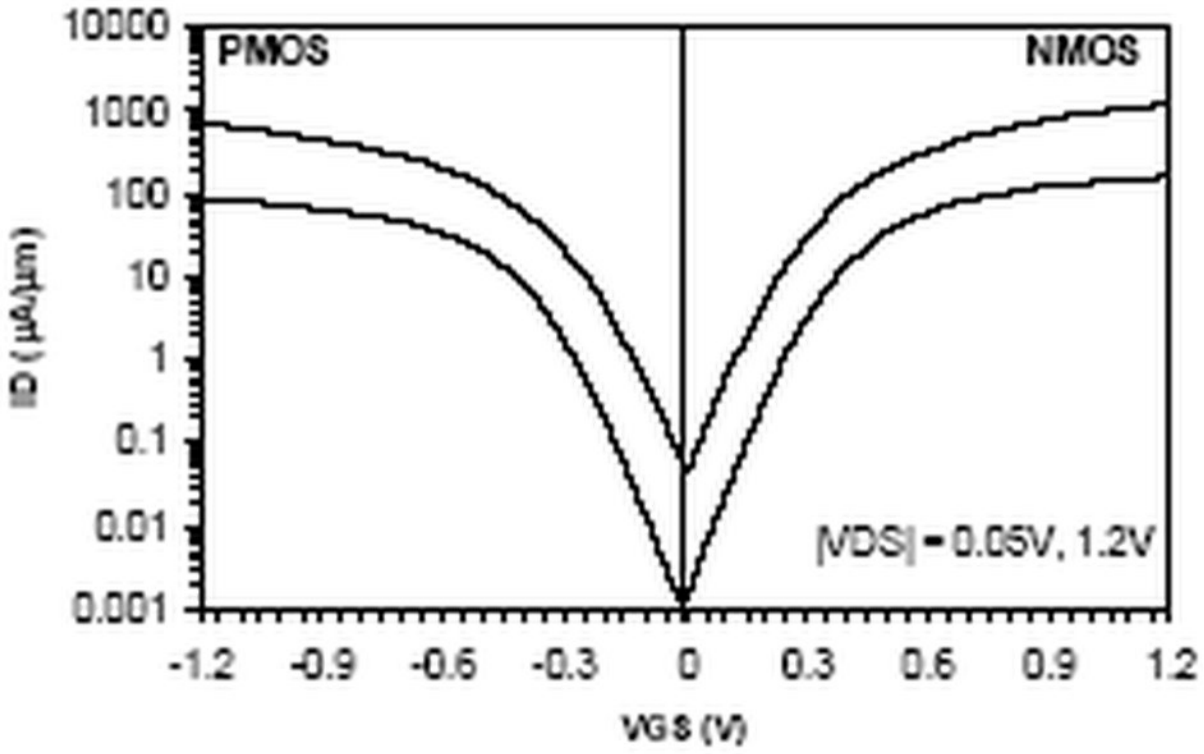
Linear region, small V_{DS}

$$I_D = \mu_{eff} C_{ox} \frac{W}{L} (V_{GS} - V_{th}) V_{DS} = \frac{V_{DS}}{R_{CH}}$$

- Straight line: intercept $\mathbf{V_{th}}$, slope ∝ **mobility**
- Above: the actual curve bends down (mobility degradation)
- Below V_{th}: small, but not zero

Subthreshold Current

Below threshold the current is small, not zero: it falls exponentially, one decade per 65 to 90 mV.



Intel 90 nm technology, gate length 45 nm (NMOS) and 50 nm (PMOS); $|V_{DS}|$ = 0.05 V and 1.2 V. T. Ghani et al., IEDM 2003.

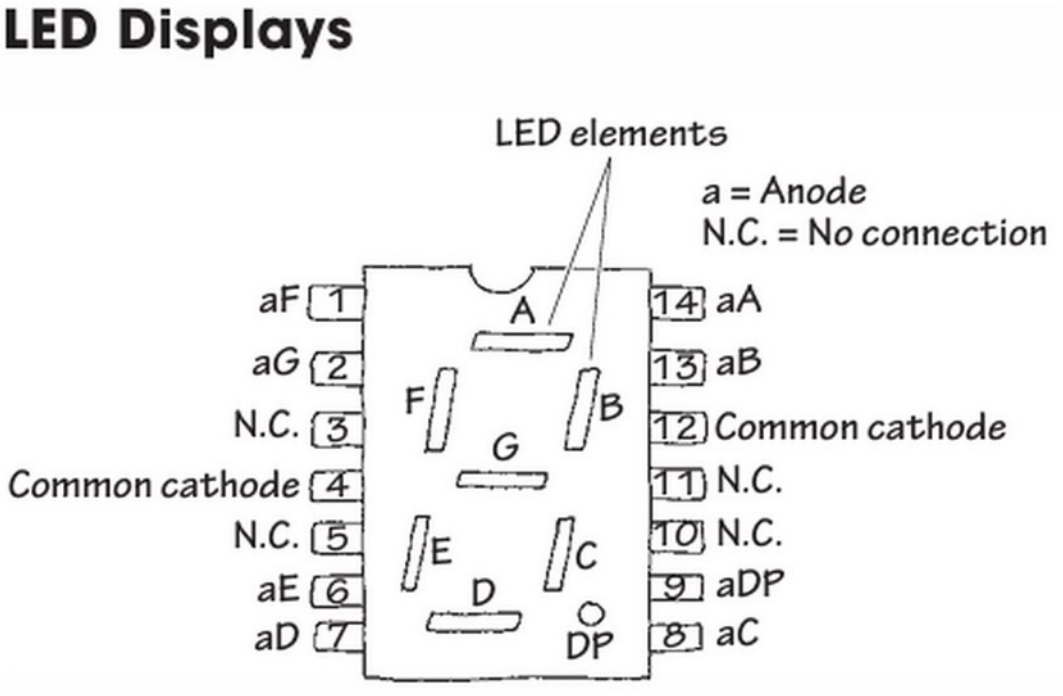
- The leakage that flows at $V_{GS} < V_{th}$ is the **subthreshold current**
- We assumed it was zero; in reality it is not
- The current at $V_{GS} = 0$ and $V_{DS} = V_{DD}$ is called $\mathbf{I}_{off}$

Subthreshold ($V_{GS} < V_{th}$)

$$I_D \approx I_0 \, e^{(V_{GS}-V_{th})/nV_T}$$

The seven-segment display

Each bar of a digit is its own LED; light the right segments and you write a number.



Common-cathode display: one anode pin per segment (a to g, DP).

LED: emits light (current in, light out)

Photodiode (PD): detects light (light in, current out)

- Seven segments a to g plus a decimal point, each one an LED
- All cathodes share a pin tied to ground
- Drive an anode high to light that segment

Writing "93"

9: a, b, c, d, f, g

3: a, b, c, d, g

11 LEDs on; e on the 9 and e, f on the 3 stay dark

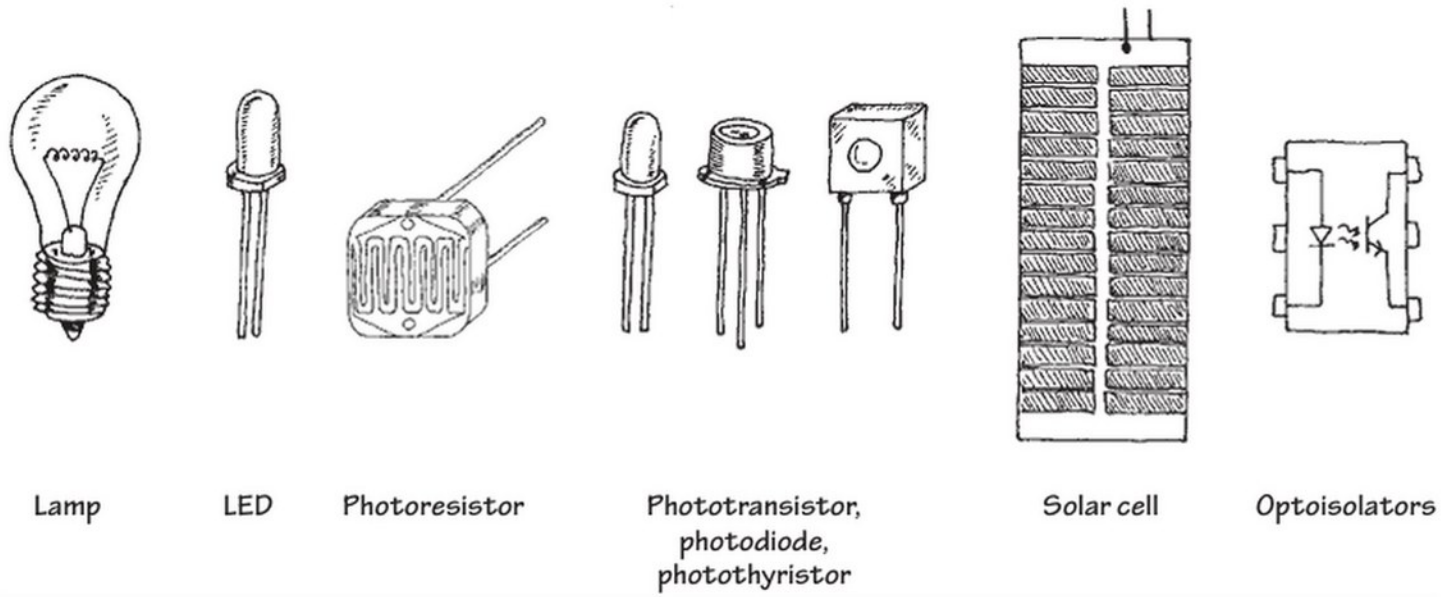


Video: printed OLED digits

youtube.com/watch?v=iYLOUAdQK78

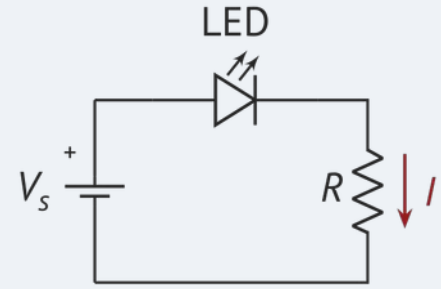
Light-based devices

Optoelectronic devices convert between light and current: some emit light, others detect it.



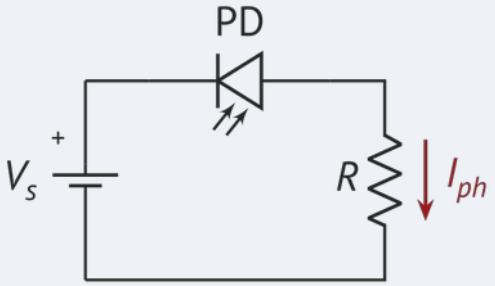
- **Emit light**: lamp (hot filament), LED
- **Detect light**: photoresistor, phototransistor, photodiode, solar cell
- **Optoisolator**: an LED and a detector sealed in one package

LED: forward bias



Current in, light out (arrows point out)

Photodiode: reverse bias



Light in, current out (arrows point in)

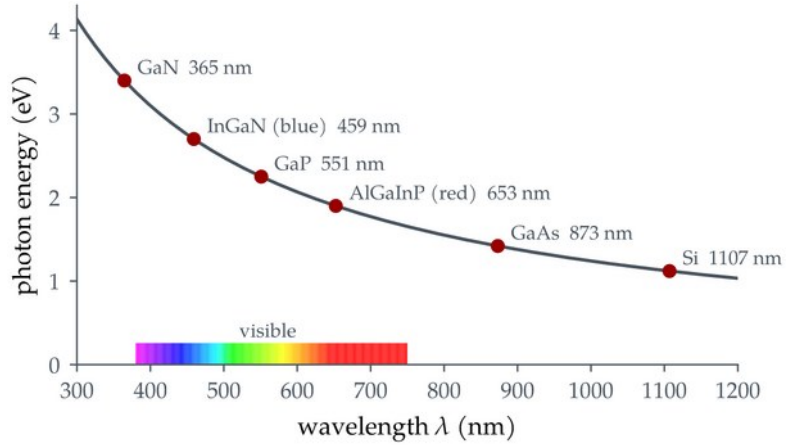
Artificially generating light

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Light comes from outer electrons changing energy level; an LED does this inside a semiconductor.

Band	Wavelength	Photon energy	Physical origin	Made by
Gamma rays	< 0.01 nm	> 124 keV	atomic nuclei	accelerators
X-rays	0.01 to 10 nm	124 eV to 124 keV	inner electrons	X-ray tubes
Ultraviolet	10 to 380 nm	3.3 to 124 eV	inner and outer electrons	lasers, arcs, lamps
Visible	**380 to 750 nm**	**1.65 to 3.3 eV**	**outer electrons**	**lasers, lamps, LEDs**
Infrared	750 nm to 1 mm	1.2 meV to 1.65 eV	molecular vibrations	hot bodies, LEDs
Microwaves, radio	> 1 mm	< 1.2 meV	electron and nuclear spin	electronic circuits

An LED is an outer-electron source: an electron drops across the band gap and leaves one photon with $E \approx E_g$.



Photon energy vs wavelength, with LED material band gaps.

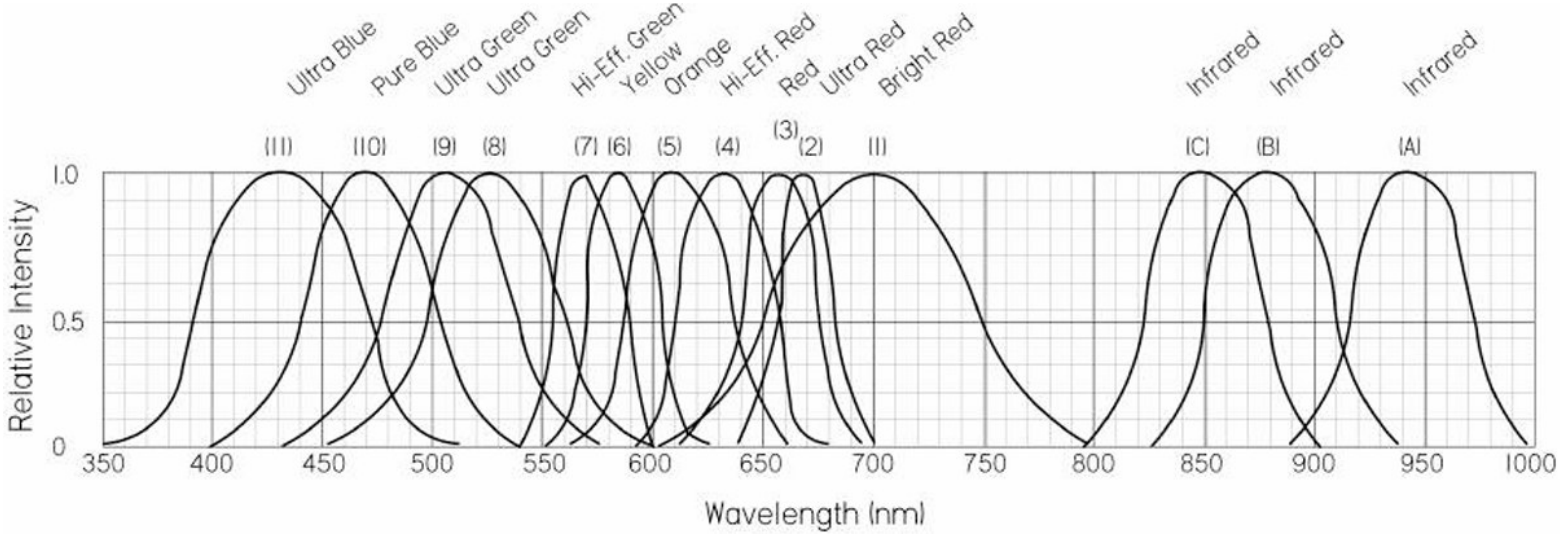
Photon energy

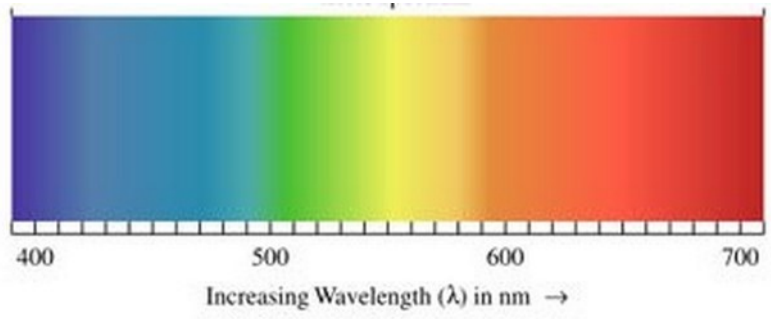
$$E = hf = \frac{hc}{\lambda}$$

$$E\,[\text{eV}] = \frac{1240}{\lambda\,[\text{nm}]}$$

LED emission spectra

Each LED emits a narrow band, 20 to 40 nm wide, around a peak wavelength set by its material.





- y axis: relative intensity (a.u.)
- x axis: wavelength; longer λ means lower photon energy

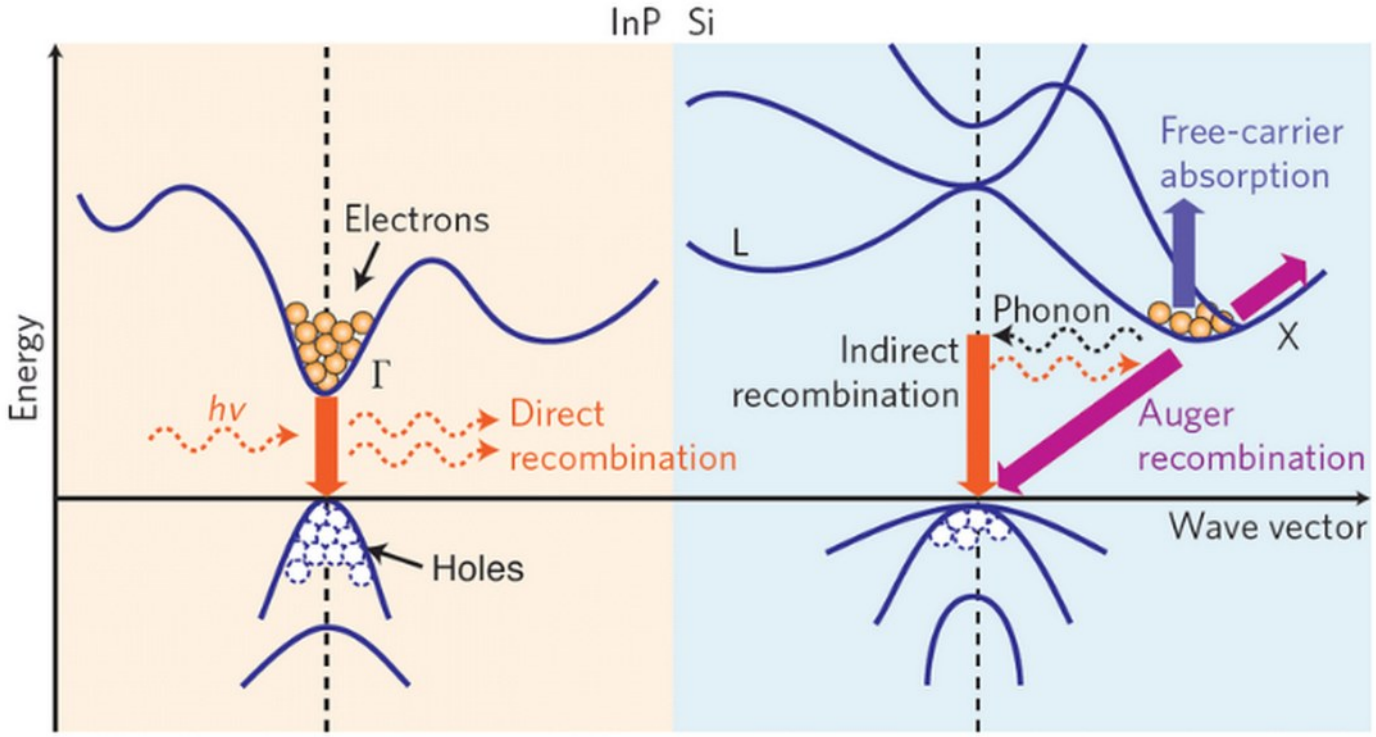
- One LED, one narrow peak
- Blue to red covers about 430 to 700 nm
- Infrared LEDs sit at 850 to 950 nm

Peak λ	Color	E (eV)
470 nm	blue	2.64
525 nm	green	2.36
630 nm	red	1.97
940 nm	infrared	1.32

$$E\,[\mathrm{eV}] = 1240/\lambda\,[\mathrm{nm}]$$

Direct vs indirect semiconductors

Only direct-gap semiconductors emit light efficiently; in silicon the energy ends up as heat.



Energy vs wave vector (crystal momentum) for InP (direct gap, left) and Si (indirect gap, right).

- **Direct gap**: conduction-band bottom right above the valence-band top; the electron drops straight down and emits a photon
- **Indirect gap**: the bottom sits at another momentum, so a phonon (lattice vibration) must take the difference
- That event is slow; the electron loses its energy as heat at a defect first

Direct (LED materials)

InP, GaAs, GaN; AlGaAs, InGaAs, InGaAsP

Indirect

Si, Ge, GaP, AlAs; silicon still detects light well

LEDs are made out of non-silicon semiconductors

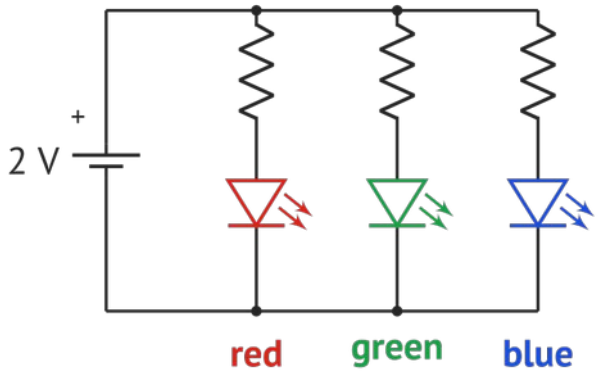
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LED color is set by the band gap of a III-V compound; higher photon energy needs more forward voltage.

Color	λ (nm)	Photon E (eV)	Semiconductor	V_F (V)
Infrared	> 760	< 1.63	GaAs, AlGaAs	< 1.9
Red	610 to 760	1.63 to 2.03	AlGaAs, GaAsP, AlGaInP, GaP	1.6 to 2.0
Orange	590 to 610	2.03 to 2.10	GaAsP, AlGaInP, GaP	2.0 to 2.1
Yellow	570 to 590	2.10 to 2.18	GaAsP, AlGaInP, GaP	2.1 to 2.2
Green	500 to 570	2.18 to 2.48	GaP, AlGaInP, AlGaP; InGaN/GaN	1.9 to 4.0
Blue	450 to 500	2.48 to 2.76	InGaN, ZnSe	2.5 to 3.7
Violet	400 to 450	2.76 to 3.10	InGaN	2.8 to 4.0
Ultraviolet	< 400	> 3.10	AlN, AlGaN, AlGaInN, diamond	3.1 to 4.4
White	broad		blue or UV chip + yellow phosphor	3 to 5

CHECKPOINT

Across 2 V, which LEDs light?



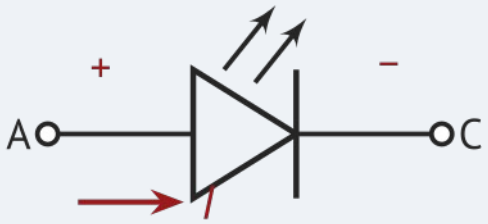
- Red (1.6 to 2.0 V): **lights**
- Blue (2.5 to 3.7 V): **stays dark**
- Green: GaP yes, InGaN no

$$qV_F \approx E_{\text{photon}} = \frac{hc}{\lambda}$$

LED symbols

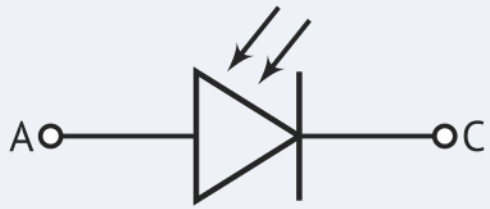
An LED is drawn as a diode with arrows pointing out; a photodiode's arrows point in.

LED



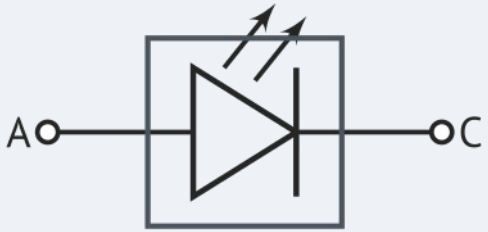
Light out; current flows A to C

Photodiode



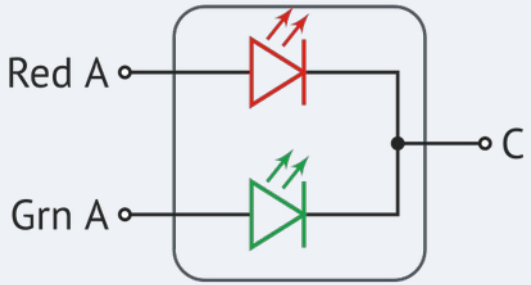
Light in; used in reverse bias

Blinking LED



An oscillator chip in the package

Bi-color LED



Red and green chips, common cathode

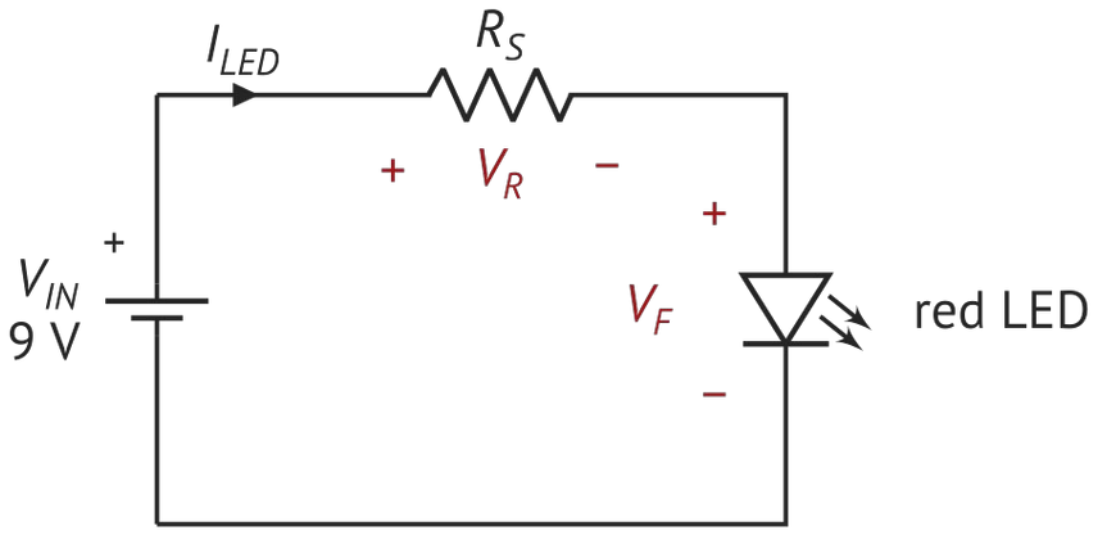
- **Anode (A)**: the + side; current enters here
- **Cathode (C)**: the – side, toward the bar
- On a real LED the anode is the longer lead
- Arrows out: emitter. Arrows in: detector
- A photodiode is the same diode, used in reverse

LED on when

$$V_A - V_C \geq V_F$$

LED driver circuit

A series resistor sets the LED current; never connect an LED straight across a voltage source.



EXAMPLE

A red LED has V_F = 1.8 V and should run at I_{LED} = 20 mA from a 9 V battery. Find R_S and the power rating it needs.

- V_F: LED forward voltage (data sheet)
- I_{LED}: LED forward current (sets brightness)
- R_S drops the rest: $V_R = V_{IN} - V_F$

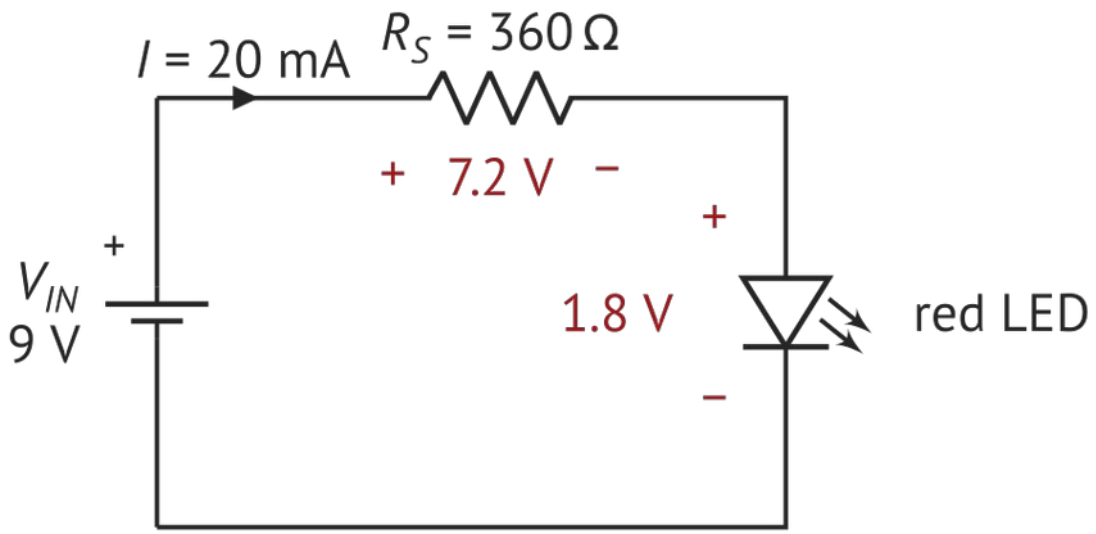
Design equation (KVL)

$$R_S = \frac{V_{IN} - V_F}{I_{LED}}$$

Without R_S, 9 V across a 1.8 V LED would drive an enormous current until the LED fails.

LED driver circuit: solution

KVL around the loop: the battery voltage splits into 1.8 V on the LED and 7.2 V on the resistor.



KVL around the loop

$$V_{IN} = V_F + I R_S$$

SOLUTION

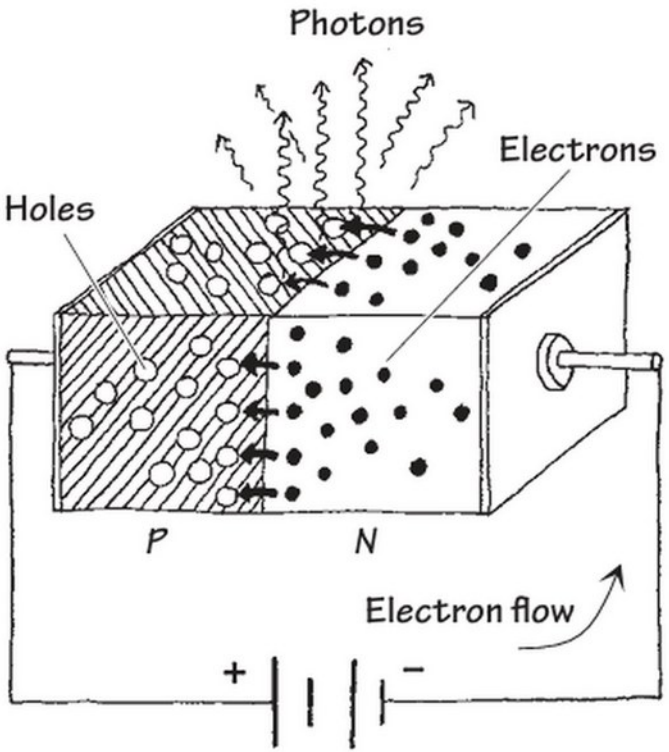
1. 9 V = 1.8 V + (20 mA) R_S, so 7.2 V = (20 mA) R_S
2. R_S = 7.2 V / 20 mA = **360 Ω**
3. $P_R = I^2 R_S$ = (20 mA)² × 360 Ω = **0.144 W**: use a 1/4 W resistor
4. P_{LED} = 1.8 V × 20 mA = **36 mW**; only 1.8/9 = 20 % of the battery power reaches the LED

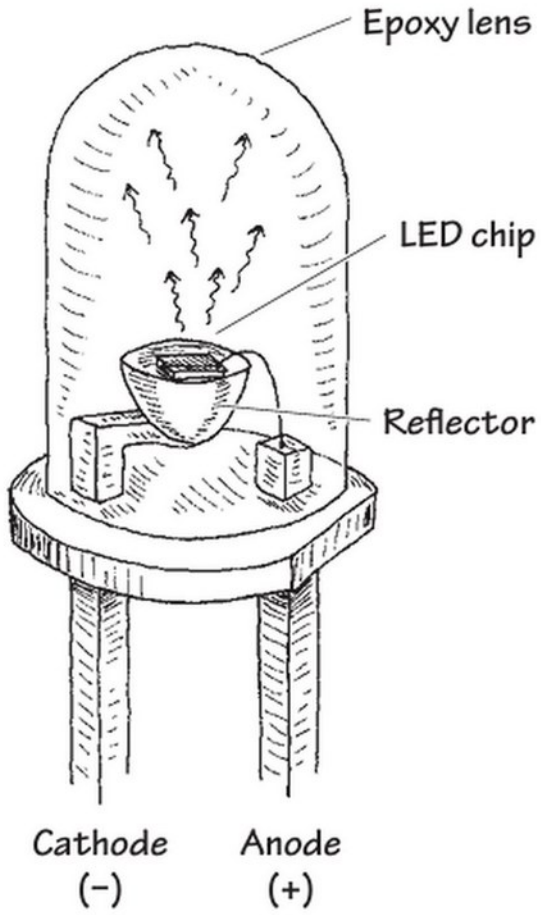
TRY IT

A 10 mA red LED (V_F = 2.0 V) runs from a 3.3 V Arduino pin. What R_S?

LED is a diode

An LED is a forward-biased pn junction: each electron that falls into a hole releases one photon.





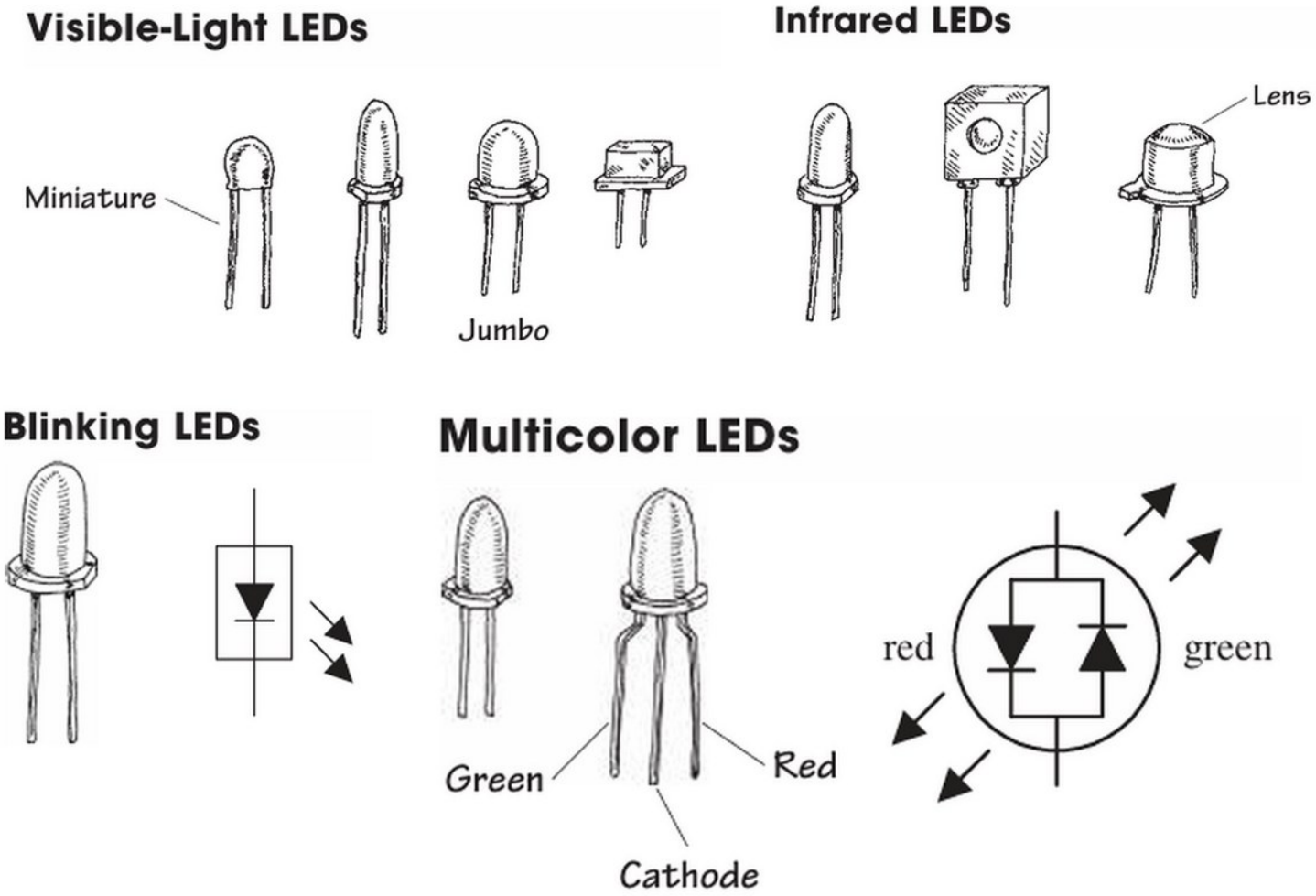
- Forward bias drives electrons from n and holes from p into the junction
- An electron drops into a hole and gives up about E_g as a photon
- The semiconductor chip is tiny: a reflector cup and an epoxy lens aim the light
- Leads: anode (+) is the longer one, cathode (–) the shorter

One recombination, one photon

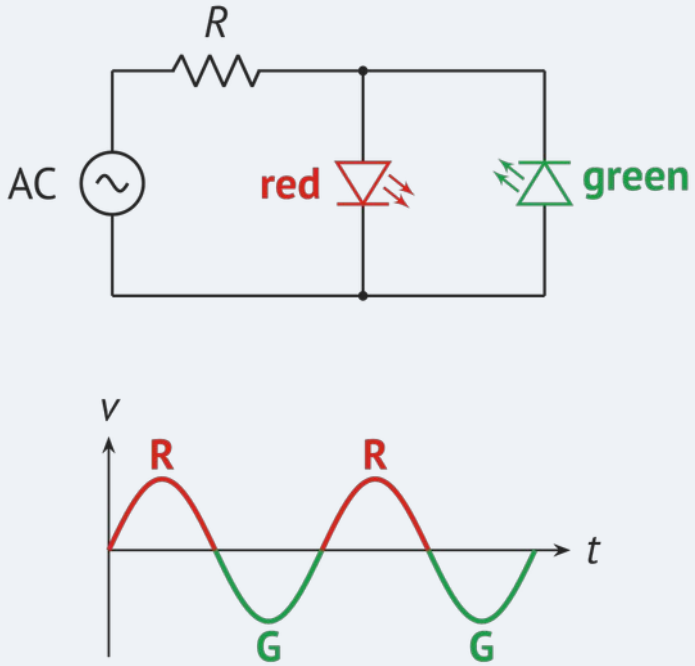
$$E_{\text{photon}} \approx E_g, \qquad \lambda \approx \frac{1240}{E_g\,[\text{eV}]}\ \text{nm}$$

LED packages

LEDs come in many packages; a two-lead bi-color LED glows red or green with the current's direction.



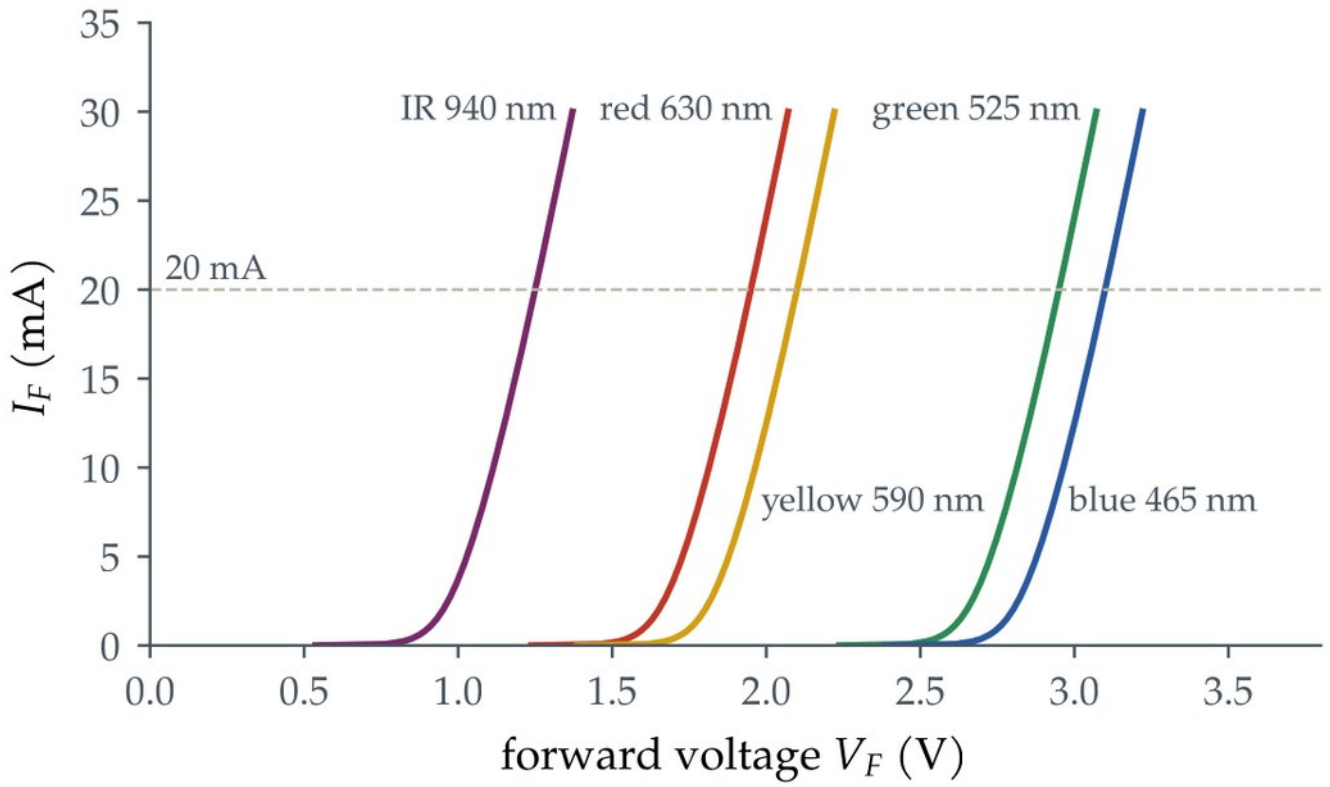
Two-lead bi-color LED on AC



- Positive half-cycle: red on
- Negative half-cycle: green on

IV characteristics for LEDs

Electrically an LED is a diode whose turn-on voltage grows with photon energy.



Representative LED I-V curves; the 20 mA line marks a typical operating point.

- Below turn-on almost no current; above it the current rises exponentially
- V_F at 20 mA: infrared ≈ 1.2 V, red 1.6 to 2.0 V, yellow ≈ 2.1 V, blue, green (InGaN) and white 2.5 to 3.5 V
- Anode: long lead; cathode: short lead and the flat notch

Diode equation and rule of thumb

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

$$qV_F \approx E_{\text{photon}}$$

Blue LED won the 2014 Nobel in Physics

Akasaki, Amano and Nakamura made efficient blue LEDs, which made bright, efficient white light possible.

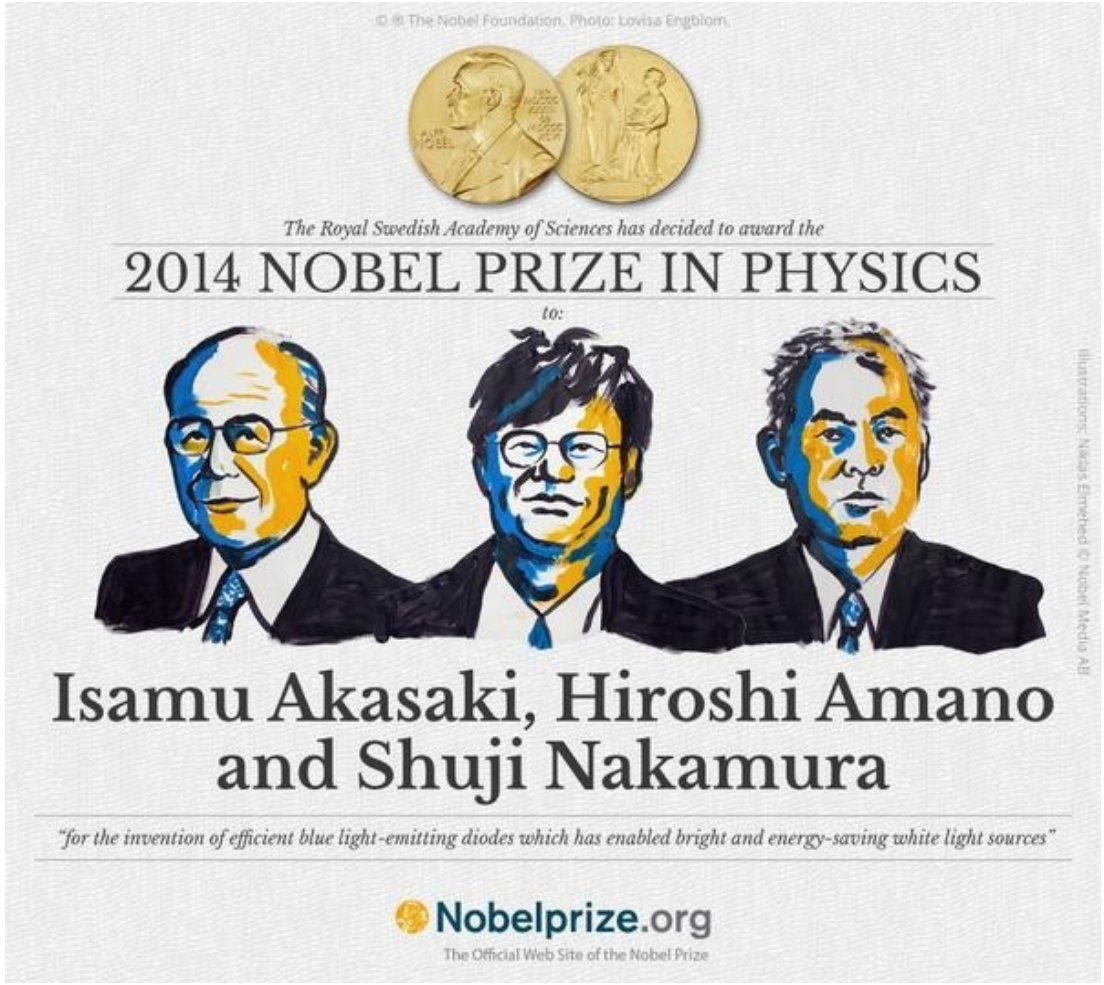


Illustration: Niklas Elmehed, © Nobel Media AB; nobelprize.org

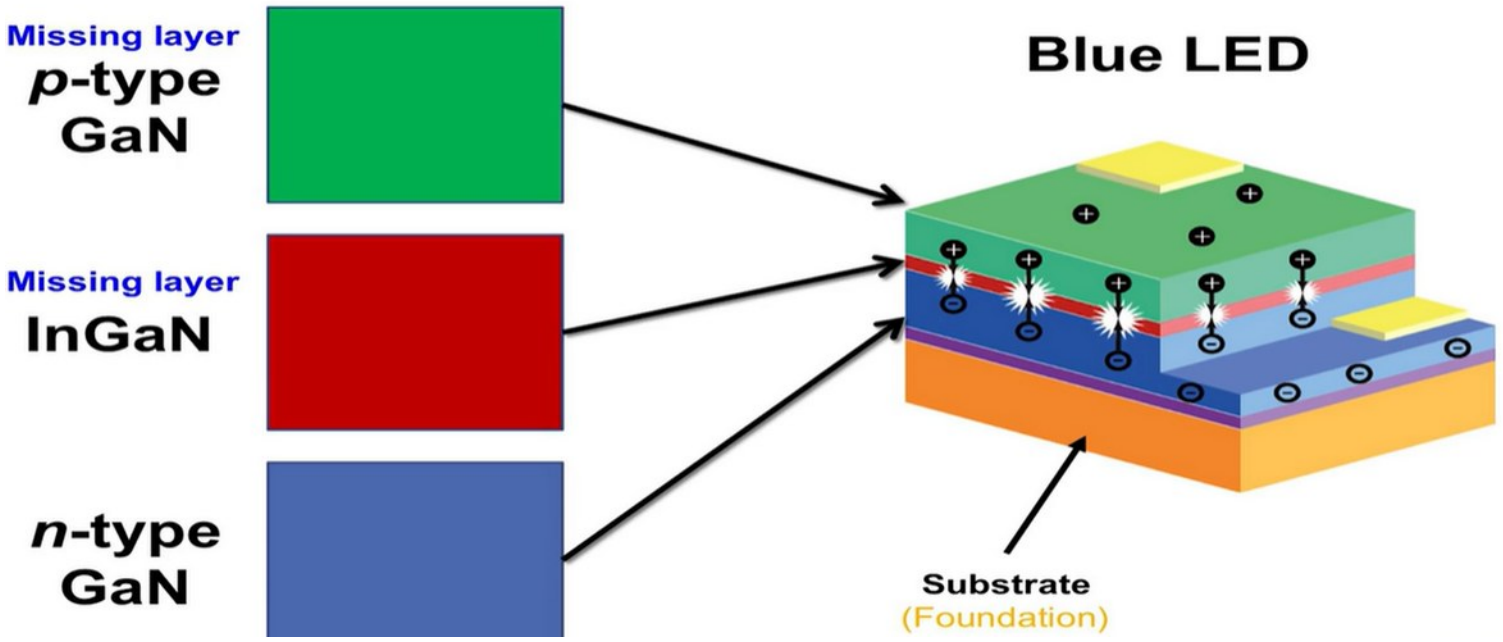
- Red and green LEDs existed since the 1960s; blue resisted for 30 years
- Two problems: growing good GaN crystals, and making p-type GaN
- With blue, LEDs span the spectrum: blue + phosphor gives white

"for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources"

Nobel citation, 2014

Steps to get the Blue LED

A blue LED needs three GaN-based layers; in the 1980s two of them could not be made.

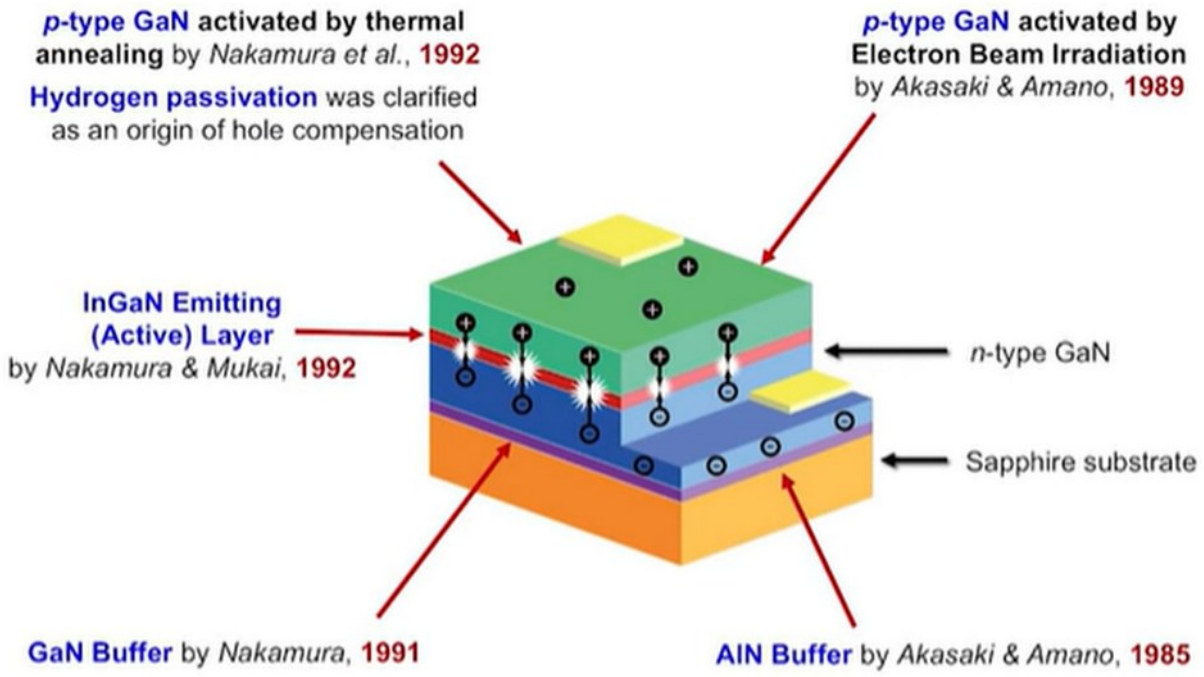


- **p-type GaN**: source of holes; **missing**
- **InGaN**: active layer that emits blue; **missing**
- **n-type GaN**: source of electrons; available

Nakamura ran crystal-growth experiments every day for about 1.5 years. The layers sit on a substrate, the foundation they are grown on.

InGaN LEDs

Each layer of the InGaN blue LED was its own breakthrough, between 1985 and 1992.

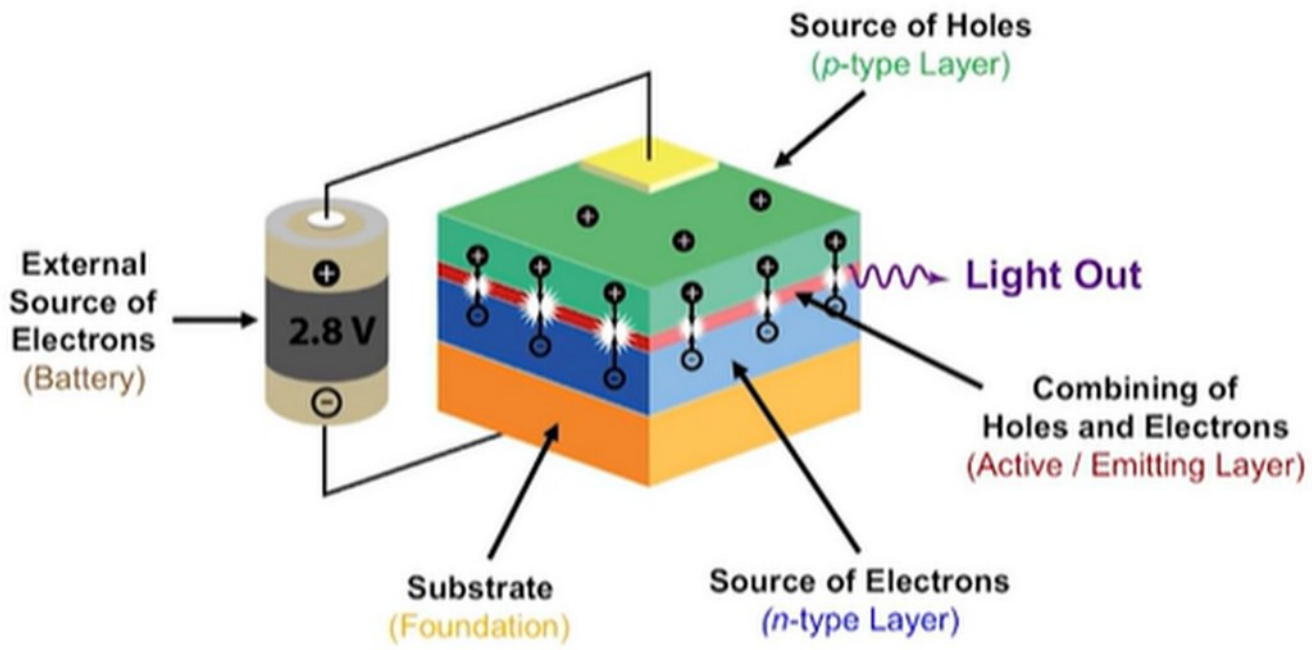


Year	Breakthrough	Who
1985	AlN buffer layer on sapphire	Akasaki, Amano
1989	p-type GaN by electron-beam irradiation	Akasaki, Amano
1991	GaN buffer layer	Nakamura
1992	p-type GaN by thermal annealing; hydrogen passivation explained	Nakamura et al.
1992	InGaN emitting (active) layer	Nakamura, Mukai

Layers bottom up: sapphire substrate, buffer, n-type GaN, InGaN active layer, p-type GaN.

LED colors: single color from one LED

The battery pushes electrons and holes into the active layer; its band gap sets the one color out.



- n-type layer: source of electrons
- p-type layer: source of holes
- They recombine in the thin active layer and emit light
- Photon energy ≈ active-layer E_g: one LED, one color

EXAMPLE

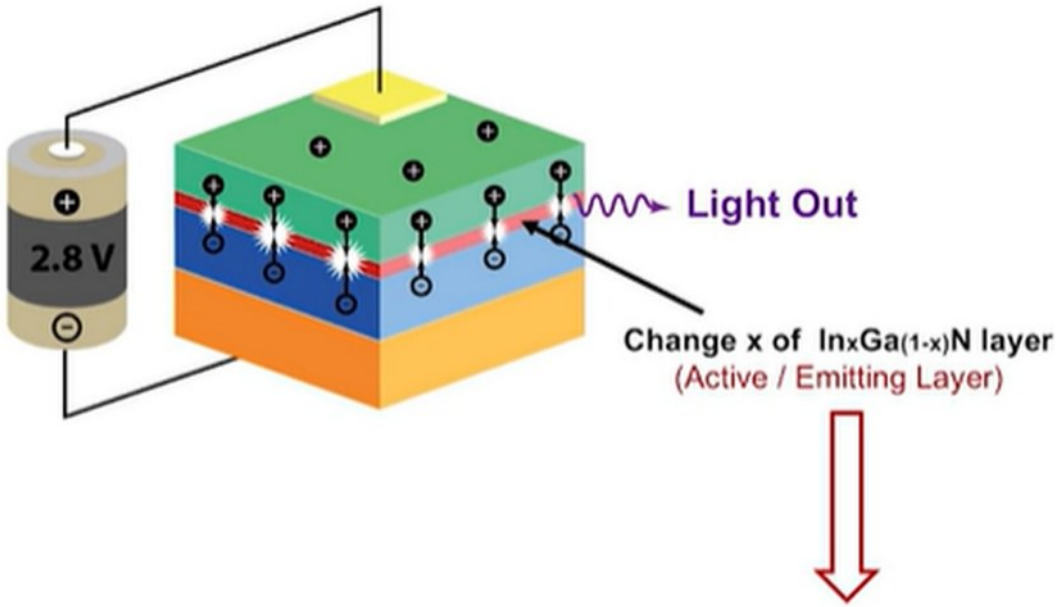
InGaN active layer, E_g = 2.7 eV: λ = 1240/2.7 = **459 nm**, blue. The 2.8 V battery supplies just over 2.7 eV per electron.

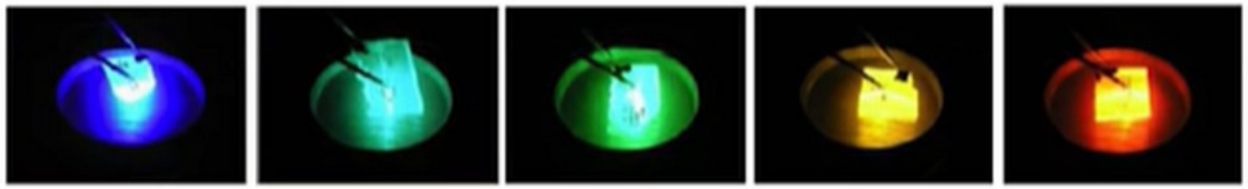
Color from band gap

$$\lambda\,[\mathrm{nm}] \approx \frac{1240}{E_g\,[\mathrm{eV}]}$$

Changing emission colors: can you change color?

Yes, when the chip is designed: more indium in InGaN shrinks the band gap and shifts the color toward red.





InGaN LEDs with increasing indium fraction x: blue, cyan, green, yellow, red.

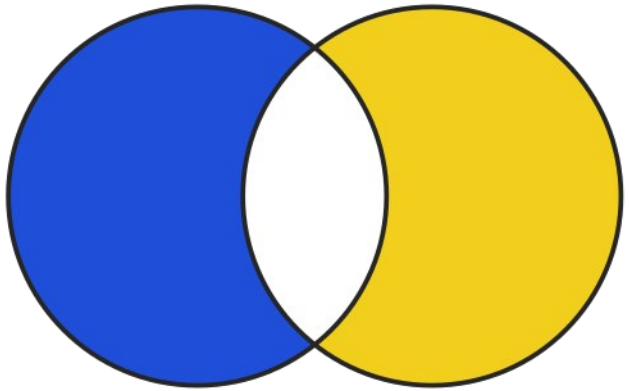
Target color	λ (nm)	E_g needed (eV)
GaN (x = 0)	365	3.40
violet	405	3.06
blue	460	2.70
green	525	2.36
yellow	590	2.10
red	630	1.97

- Band-gap engineering: pick x when the layer is grown
- A finished chip keeps its one color

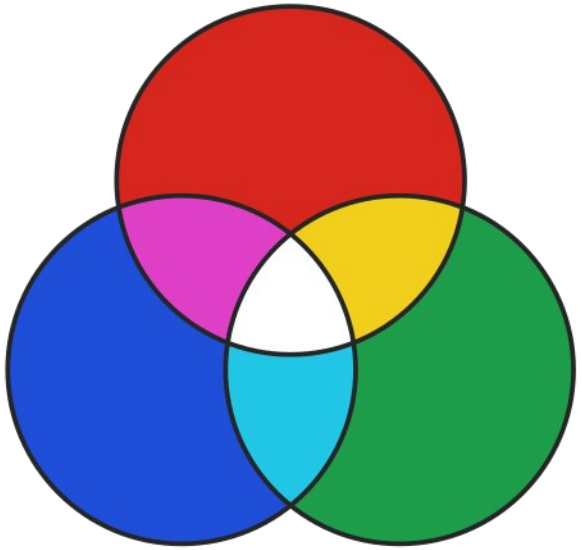
$$In_xGa_{1-x}N: \; x \uparrow \Rightarrow E_g \downarrow \Rightarrow \lambda \uparrow$$

How to get white light

One LED gives one color; white light needs colors combined, most simply blue plus yellow.



Blue + yellow
(easiest)



Blue + green + red
(highest quality)

Blue chip + yellow phosphor

A blue InGaN chip under a phosphor coat

The phosphor (YAG) turns part of the blue into broad yellow light

Most white LEDs, including ours

Red + green + blue chips

Three chips in one package

Best color quality; the mix can be tuned

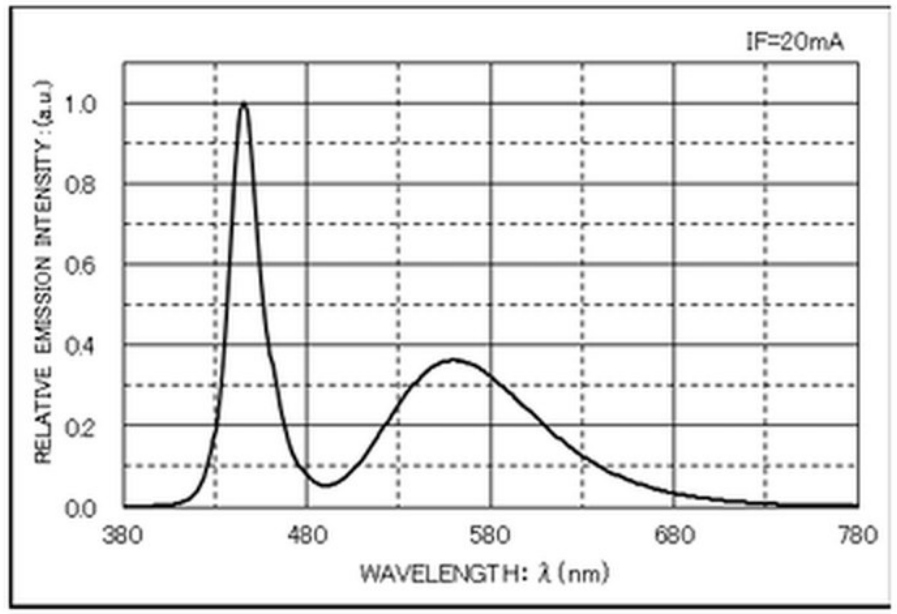
Three chips and drivers cost more

Colored light adds: overlapping beams mix toward white.

The LED in our demo board

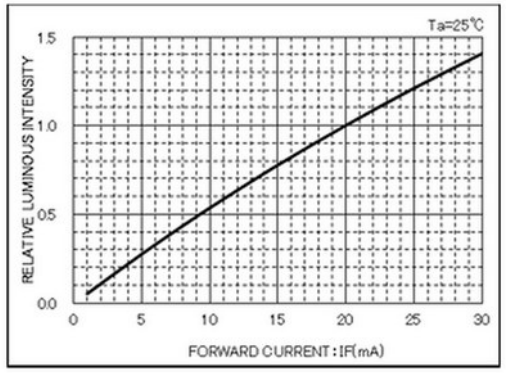
Our white LED: a blue peak near 450 nm, a broad phosphor band near 560 nm, and 1 mA at about 2.6 V.

Spectrum (I_F = 20 mA)



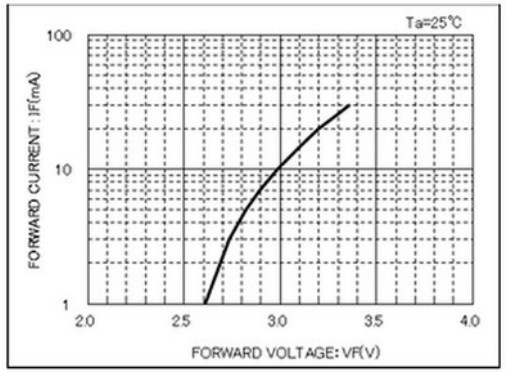
- Blue InGaN peak near 450 nm + phosphor band near 560 nm = white light

Light output vs current



- Nearly linear in current
- 1.0 at 20 mA

Current vs voltage (log scale)



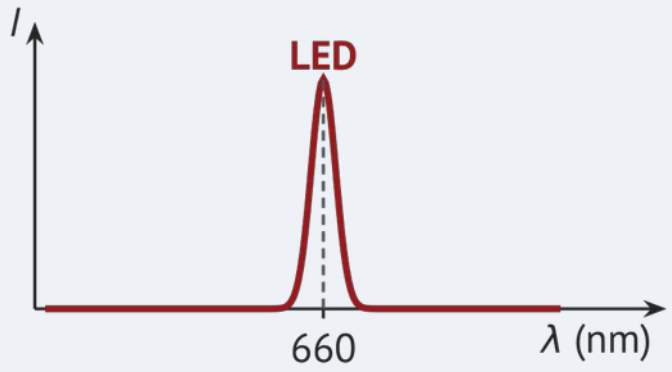
- 1 mA near 2.6 V
- 20 mA near 3.2 V

Data sheet: Rohm CSL0416WBCW1 (fscdn.rohm.com)

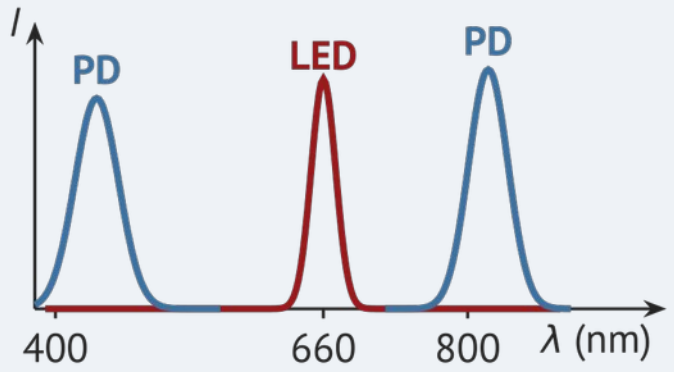
Matching the LED and the PD

A photodiode only sees light inside its spectral response, so pick it to match the LED's wavelength.

LED emits red light at 660 nm



This PD captures blue and near-infrared

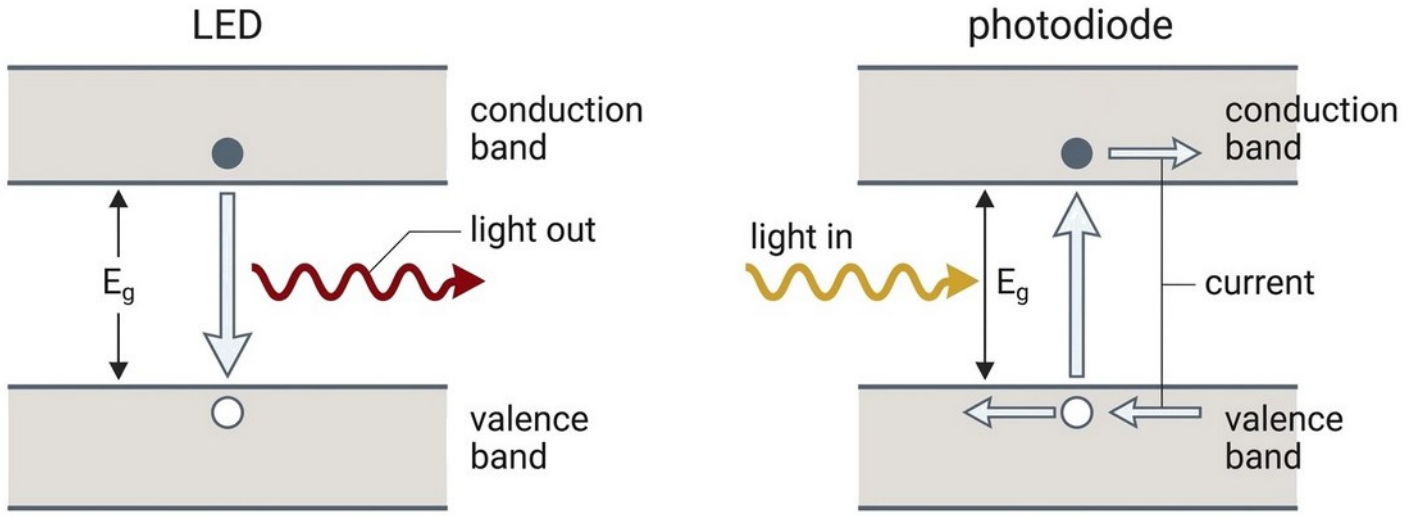


- The red light falls in the PD's dip: **the PD won't capture it**
- A detector's response comes from its band gap and any filter on its package
- Overlay the LED spectrum on the PD response before choosing parts

Our board: the photodiode's filter passes about 750 to 1050 nm, matched to 830 to 950 nm infrared LEDs. Visible light from the white LED barely registers.

How does a photodiode work

Run the LED backward: a photon with hν ≥ E_g lifts an electron into the conduction band.



One process, two directions: in an LED an electron falls and emits a photon; in a photodiode a photon lifts an electron and drives a current.

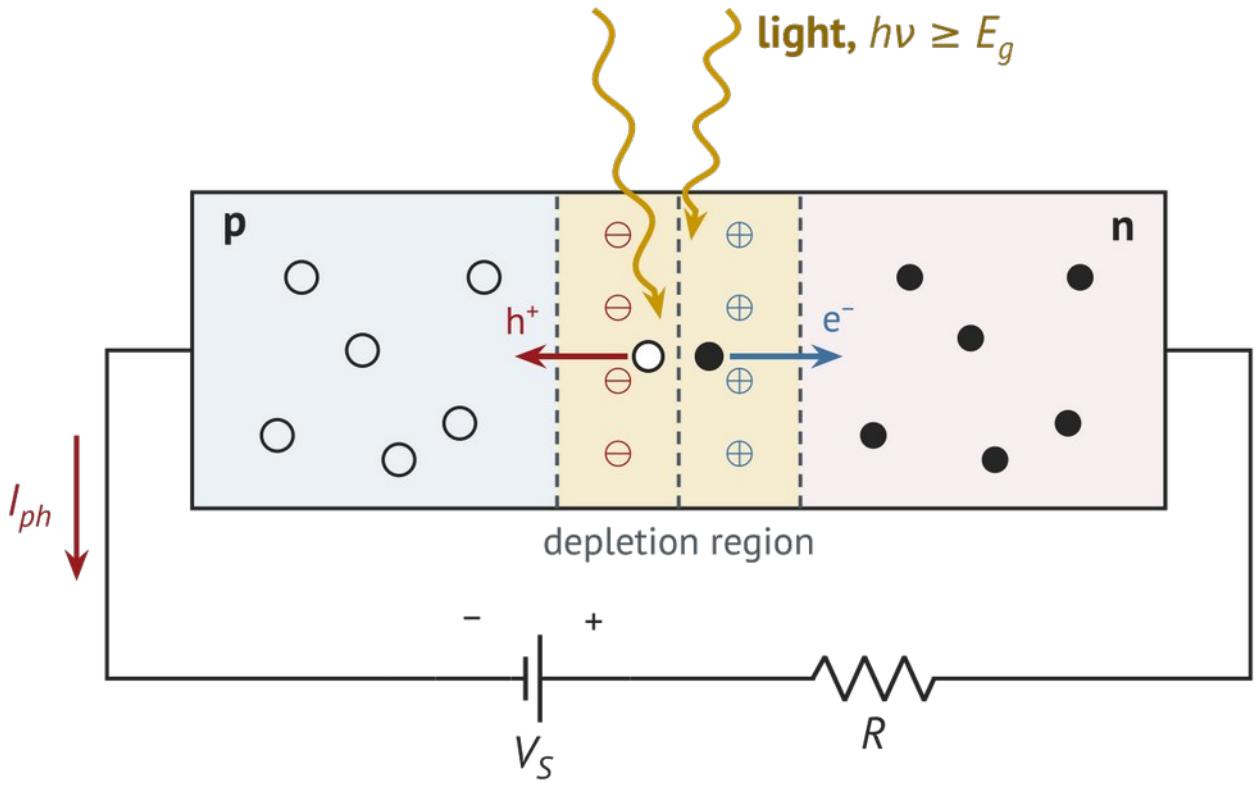
- A photon is absorbed and creates an **electron-hole pair**
- Only photons with hν ≥ E_g count; longer wavelengths pass through
- In plain silicon the pair recombines within microseconds
- At a pn junction the built-in field pulls the pair apart first (next slide)

Absorbed only if

$$h\nu \geq E_g \iff \lambda \leq \frac{1240}{E_g\,[\text{eV}]}\ \text{nm} \qquad \text{Si: } \lambda \leq 1107\ \text{nm}$$

How does a photodiode work: reverse bias

Reverse bias widens the depletion region; its field sweeps electrons to n and holes to p.



- Cathode (n) at the higher voltage: reverse bias
- The field separates the new pair: e^- to n, h^+ to p
- One absorbed photon, about one electron around the loop
- More light, more pairs, more current

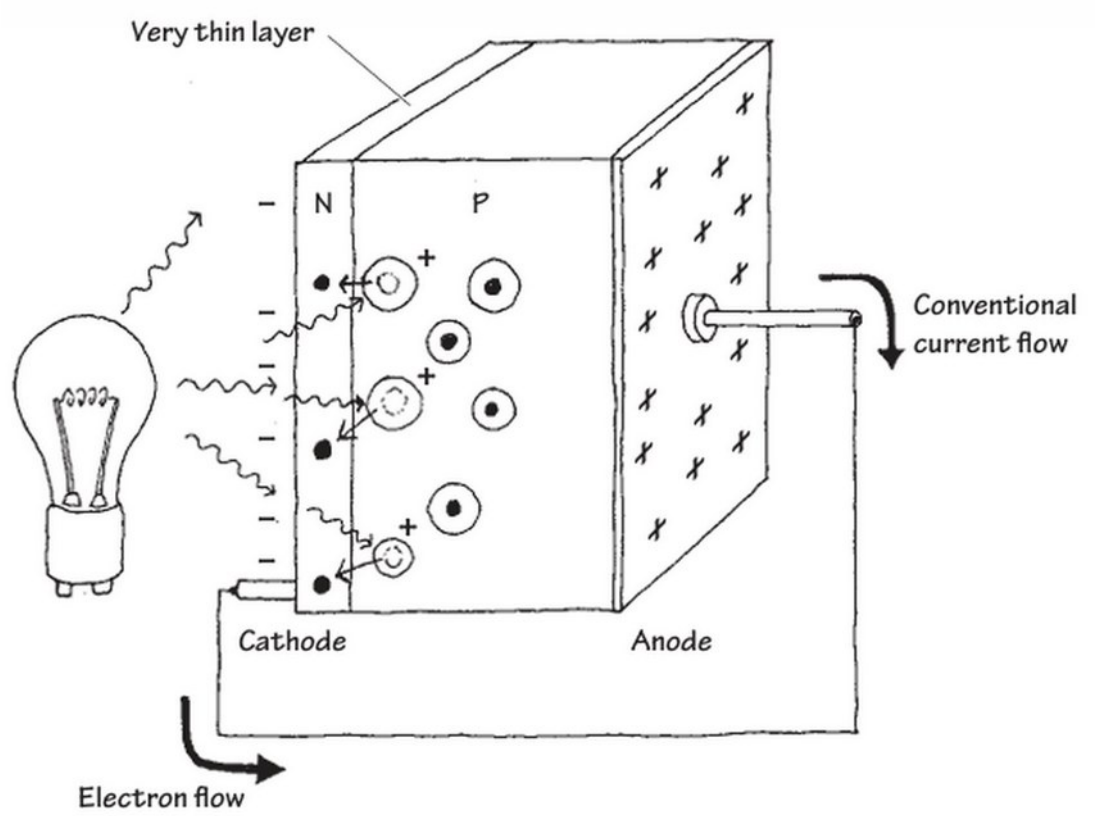
Inside the diode the photocurrent flows from cathode (n) to anode (p): the reverse direction.

Photocurrent into a voltage

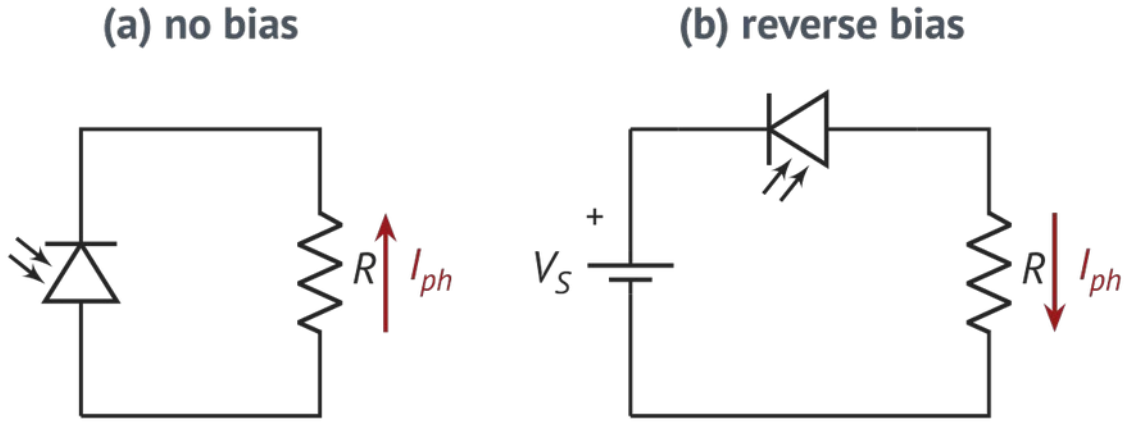
$$V_R = I_{ph} R \propto \text{light}$$

Photodiode

A photodiode is a pn junction with a very thin top layer, so light reaches the junction.



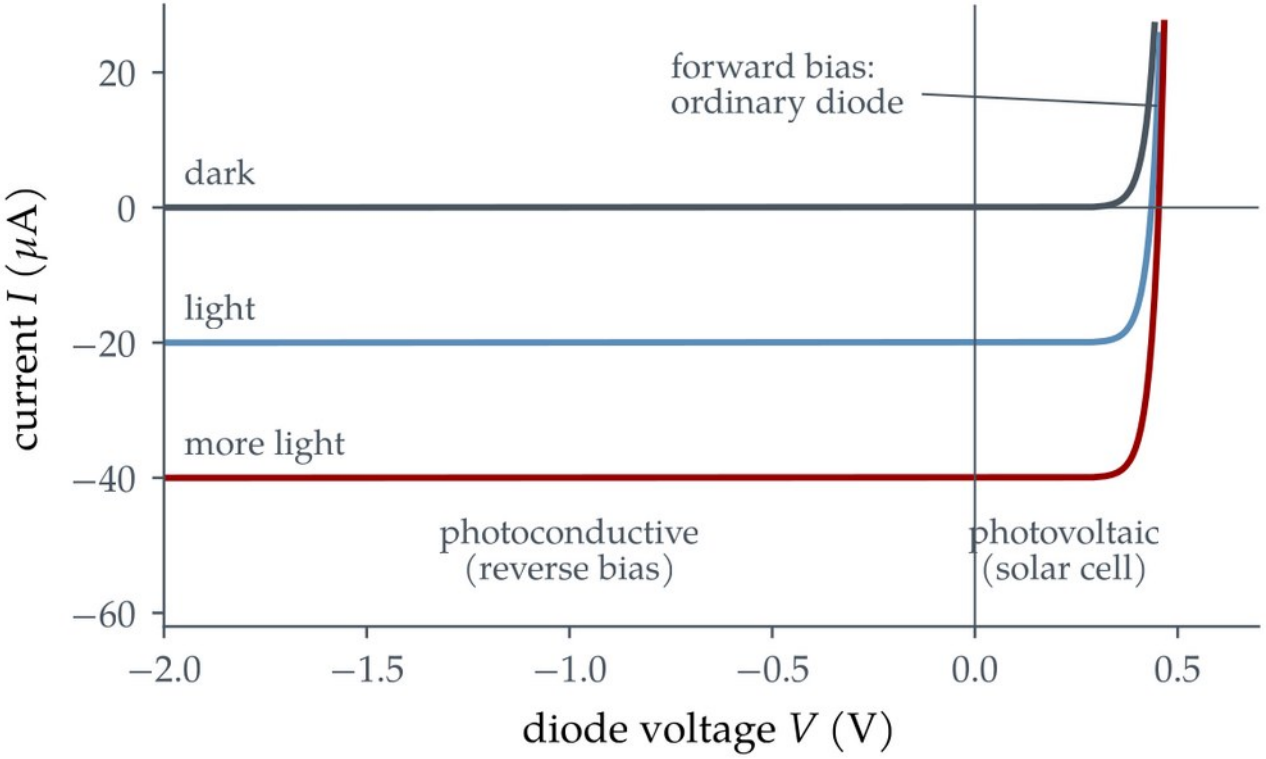
Light passes a very thin top layer and is absorbed at the junction.

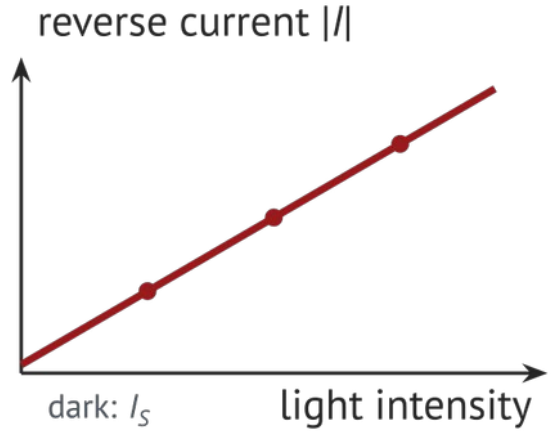


- **(a) No bias**: the PD drives R by itself, as a solar cell does
- **(b) Reverse bias**: current proportional to light; the sensing mode
- Photocurrent leaves the anode in both cases

IV of photodiode

Light shifts the diode curve down by the photocurrent, and the reverse current grows in step with light.





- Dark, light, more light: each step moves the curve down
- Reverse bias: flat current set by light. V > 0, I < 0: solar cell

Diode current with light

$$I = I_S\left(e^{V/nV_T} - 1\right) - I_{ph}$$

Photocurrent and responsivity

$$I_{ph} = \mathcal{R}P, \quad \mathcal{R} = \eta\frac{\lambda\,[\text{nm}]}{1240}\ \text{A/W}$$

The PD in our demo board

Our photodiode is a small silicon PIN diode, filtered to see near-infrared light only.

- **Vishay VEMD2023SLX01**: silicon PIN photodiode, side-looking surface-mount package
- **PIN**: a wide intrinsic (undoped) layer between p and n absorbs most photons inside the depleted zone
- Chip area 0.23 mm²; daylight-blocking filter: responds from about 750 to 1050 nm
- Reverse light current about 10 µA; viewing angle ±35°
- Used in the board's LED and photodiode pairs (Labs 3.2, 5.1)

[Data sheet: vishay.com/docs/83493/vemd2023slx01.pdf](vishay.com/docs/83493/vemd2023slx01.pdf)

VISHAY. www.vishay.com

VEMD2023SLX01
Vishay Semiconductors

Silicon PIN Photodiode



FEATURES
- Package type: surface mount
- Package form: side view
- Dimensions (L x W x H in mm): 2.3 x 2.55 x 2.3
- AEC-Q101 qualified
- High radiant sensitivity
- Daylight blocking filter matched with 830 nm to 950 nm IR emitters
- Fast response times
- Angle of half sensitivity: φ = ± 35°
- Package matched with IR emitter series VSMB2943SLX01
- Floor life: 4 weeks, MSL 2a, acc. J-STD-020
- Lead (Pb)-free reflow soldering
- Material categorization: For definitions of compliance please see www.vishay.com/doc?99912

RoHS COMPLIANT HALOGEN FREE GREEN

DESCRIPTION

VEMD2023SLX01 is a high speed and high sensitive PIN photodiode in a miniature side looking, surface mount package (SMD) with dome lens and daylight blocking filter. Filter is matched with IR emitters operating at wavelength of 830 nm to 950 nm. The photo sensitive area of the chip is 0.23 mm².

APPLICATIONS
- High speed photo detector
- Infrared remote control
- Infrared data transmission
- Photo interrupters
- IR touch panels

PRODUCT SUMMARY

COMPONENT	I_{ra} (µA)	φ (deg)	$\lambda_{0.5}$ (nm)
VEMD2023SLX01	10	± 35	750 to 1050

Note
- Test conditions see table "Basic Characteristics"

ORDERING INFORMATION

ORDERING CODE	PACKAGING	REMARKS	PACKAGE FORM
VEMD2023SLX01	Tape and reel	MOQ: 3000 pcs, 3000 pcs/reel	Side view

Note
- MOQ: minimum order quantity

ABSOLUTE MAXIMUM RATINGS (T_{amb} = 25 °C, unless otherwise specified)

PARAMETER	TEST CONDITION	SYMBOL	VALUE	UNIT
Reverse voltage		V_R	60	V
Power dissipation	$T_{amb} \leq 25$ °C	P_V	215	mW
Junction temperature		T_j	100	°C
Operating temperature range		T_{amb}	- 40 to + 100	°C
Storage temperature range		T_{stg}	- 40 to + 100	°C
Soldering temperature	Acc. reflow solder profile fig. 7	T_{sd}	260	°C
Thermal resistance junction/ambient	Acc. J-STD-051	R_{thJA}	250	K/W

PD characteristics

Data sheet curves: response from 750 to 1050 nm, dark current in nA, light current in µA.

Spectral sensitivity

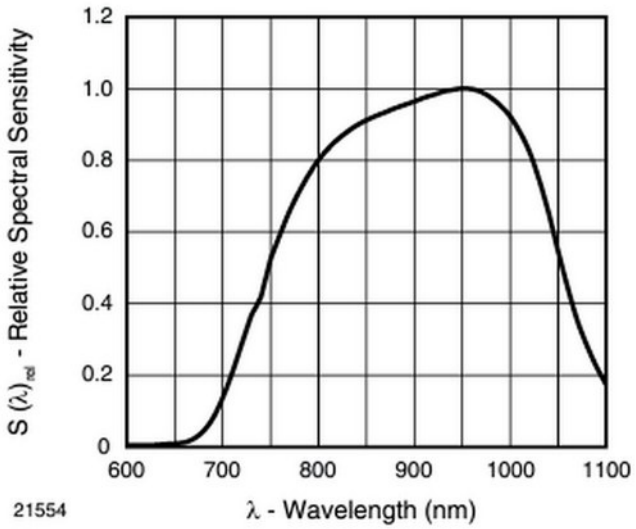


Fig. 5 - Relative Spectral Sensitivity vs. Wavelength

- Peak near 940 nm
- Filter blocks visible light; Si stops absorbing near 1100 nm

Dark current vs temperature

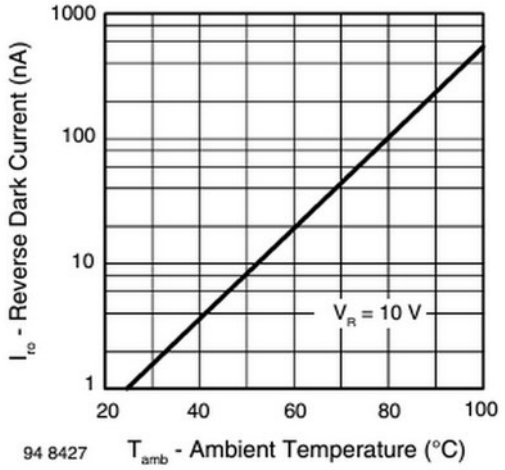


Fig. 1 - Reverse Dark Current vs. Ambient Temperature

- About 1 nA at 25 °C (V_R = 10 V)
- Rises about 10× per 25 °C

Light current vs irradiance

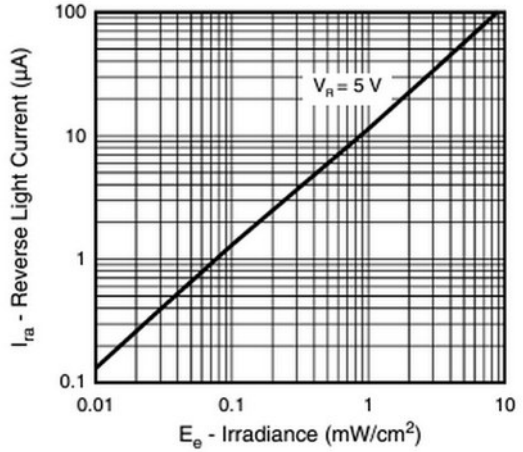
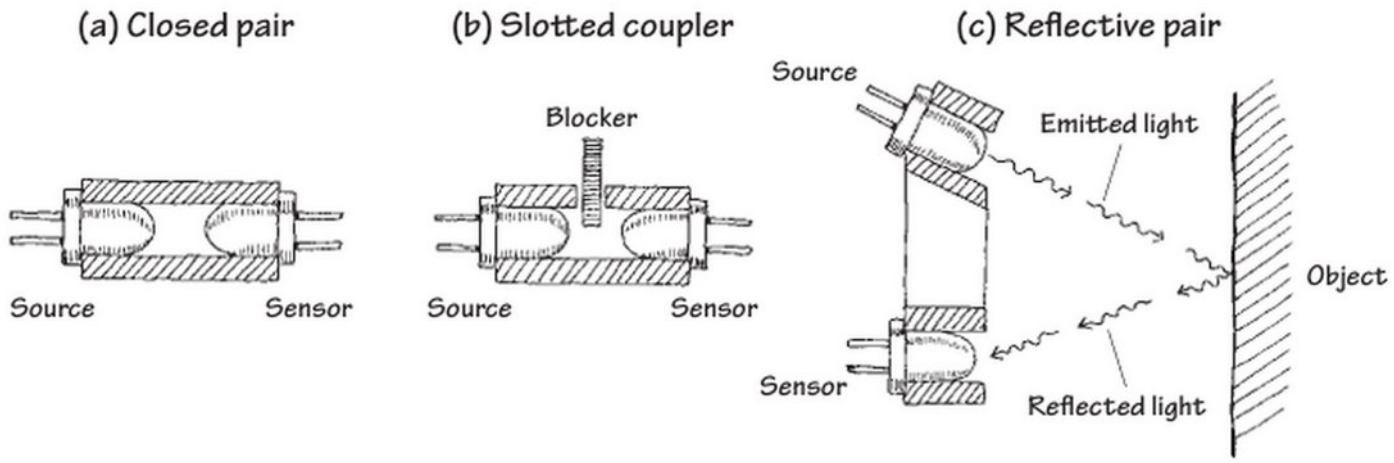


Fig. 3 - Reverse Light Current vs. Irradiance

- About 10 µA at 1 mW/cm² (V_R = 5 V)
- Straight line: current ∝ light

LED-PD combo

Pair an LED with a photodetector and light carries the signal: across a gap, a slot or off an object.



(a) Closed pair

LED and PD sealed in one package

Signal crosses with no wire

(b) Slotted coupler

A gap between LED and PD

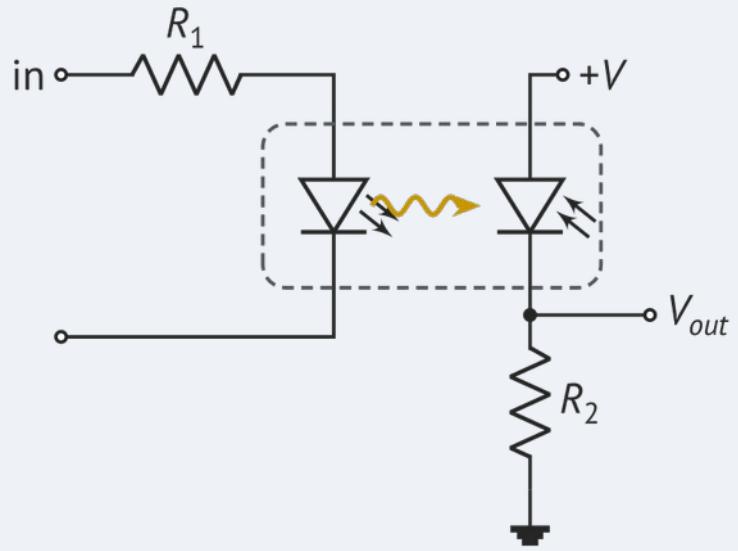
An object in the slot breaks the beam

(c) Reflective pair

Both aimed at an object

Reflected light reaches the sensor

Optoisolator: LED as source, PD as sensor



- Light is the only link between input and output
- V_{out} rises with the LED current