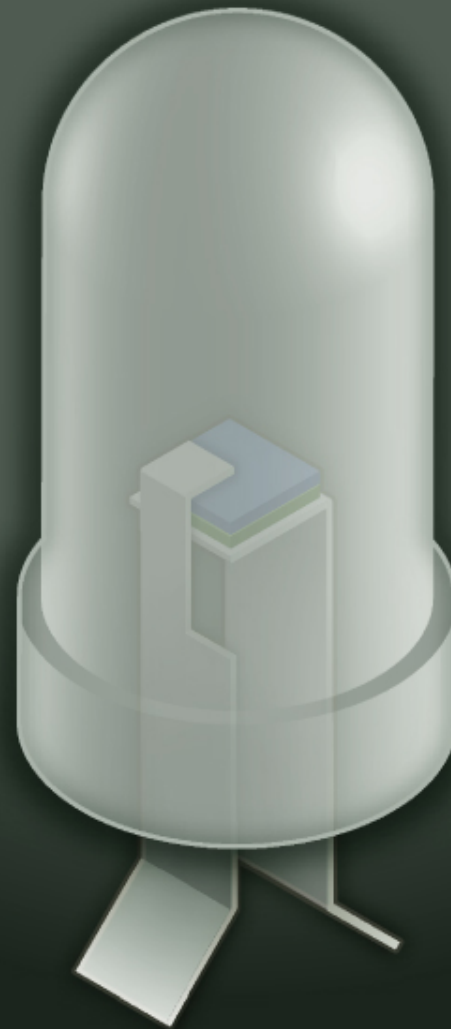
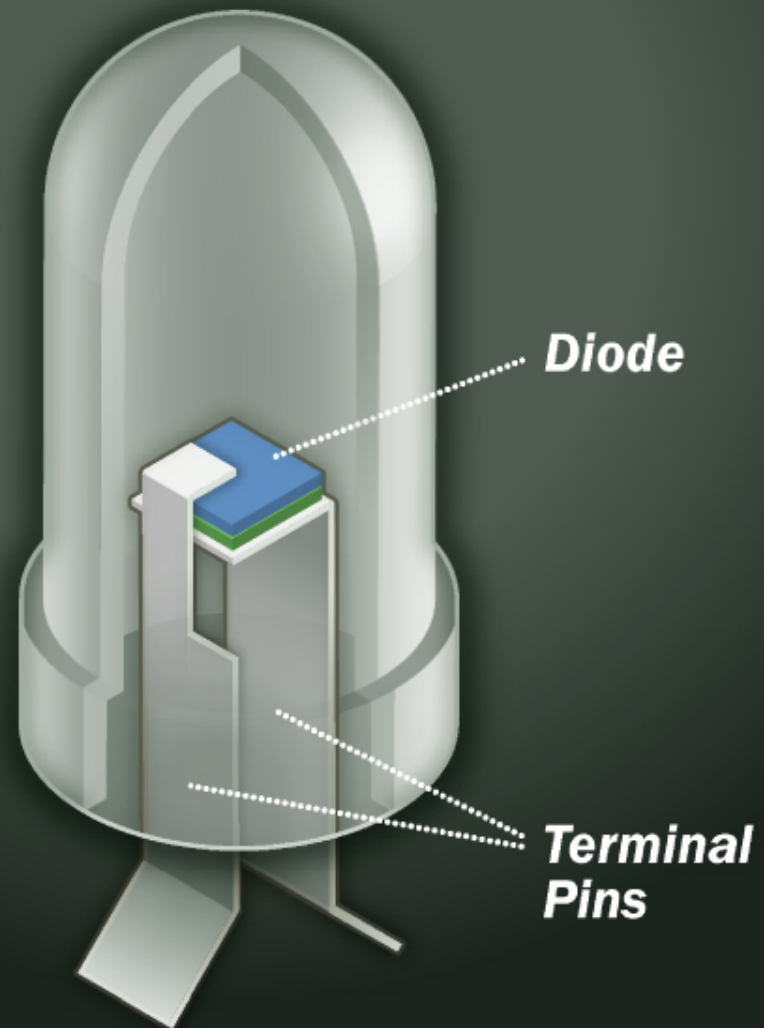


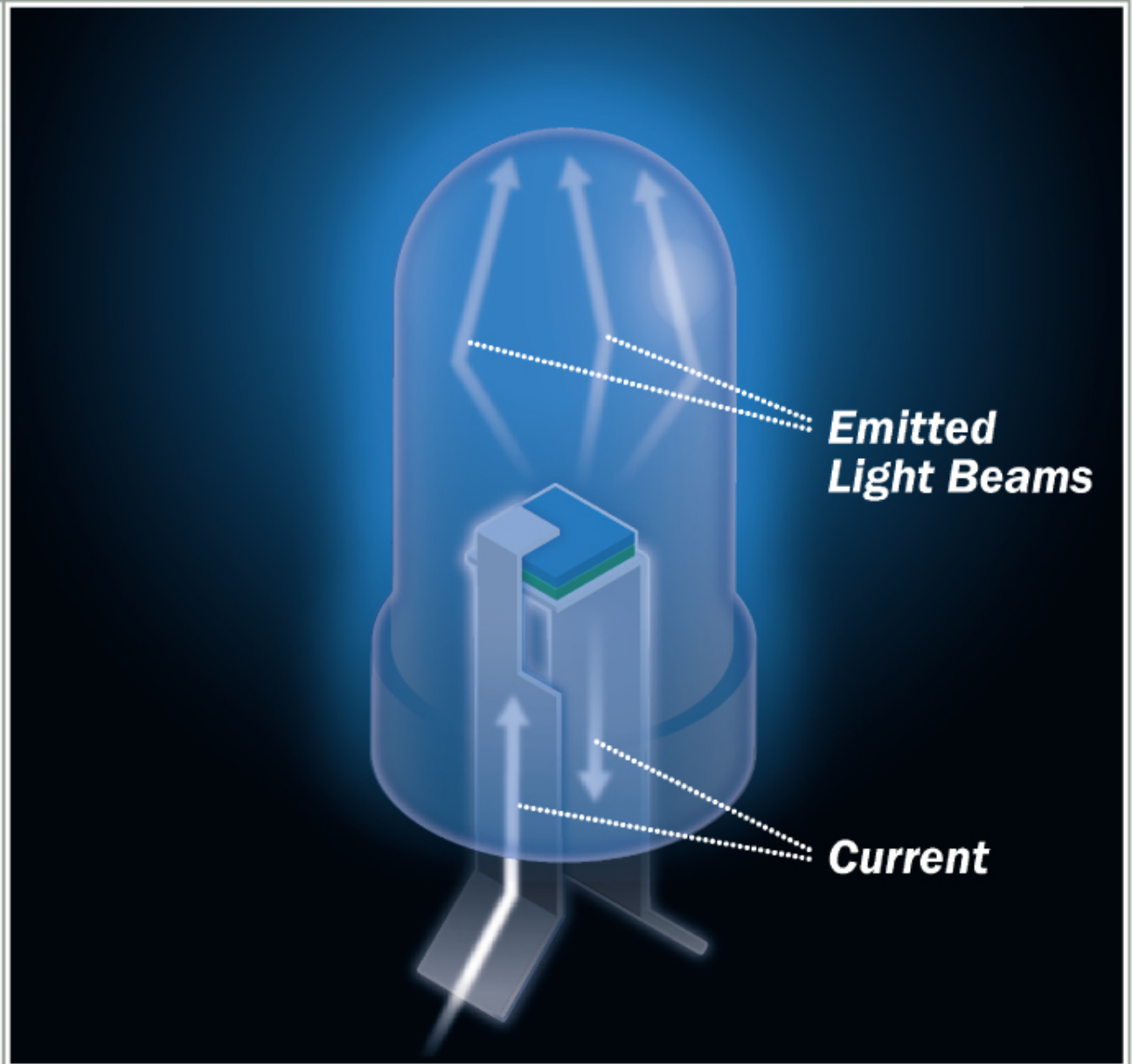
## Light Emitting Diodes (LEDs)



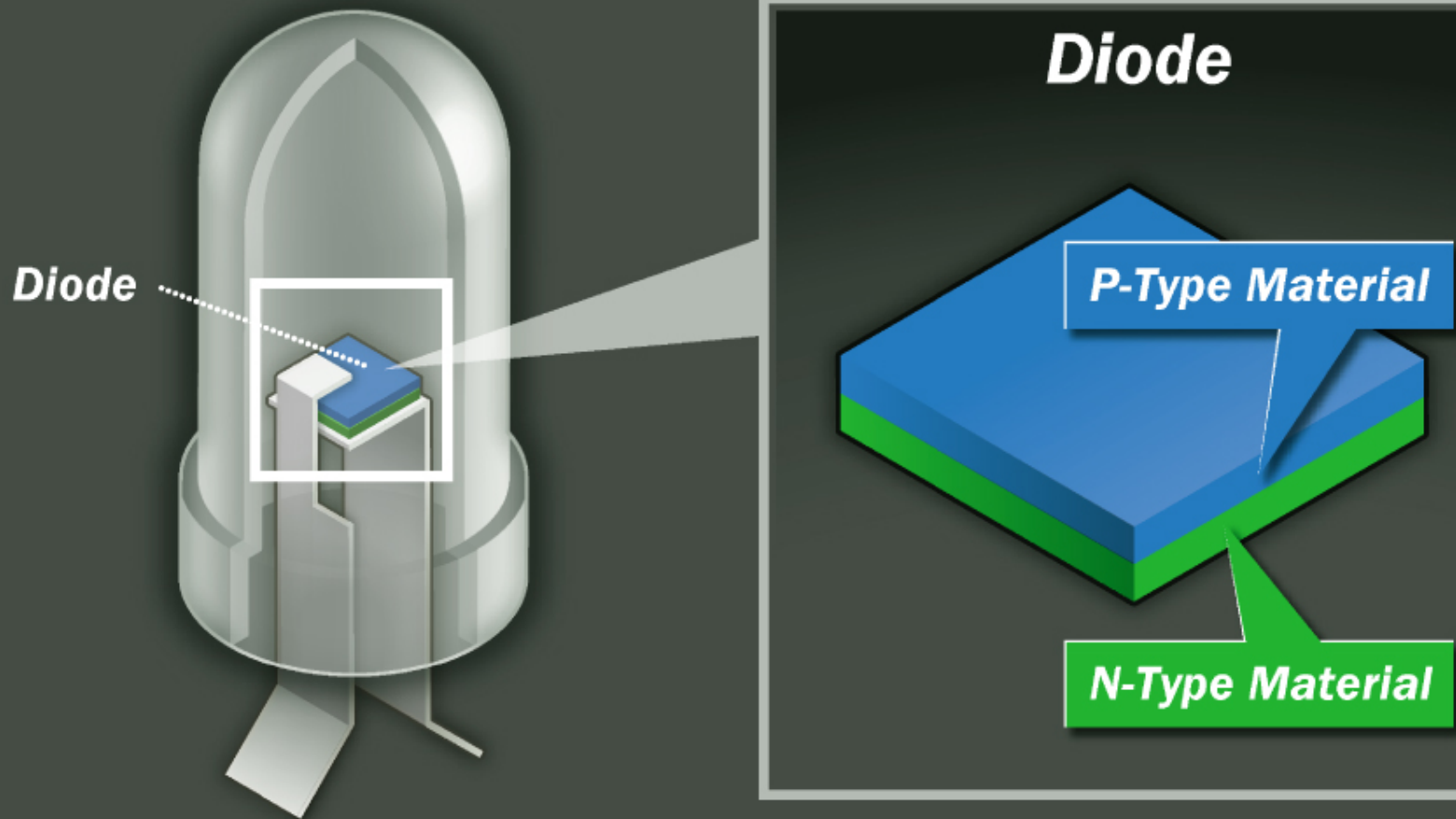
## Light Emitting Diodes (LEDs)



## Light Emitting Diodes (LEDs)

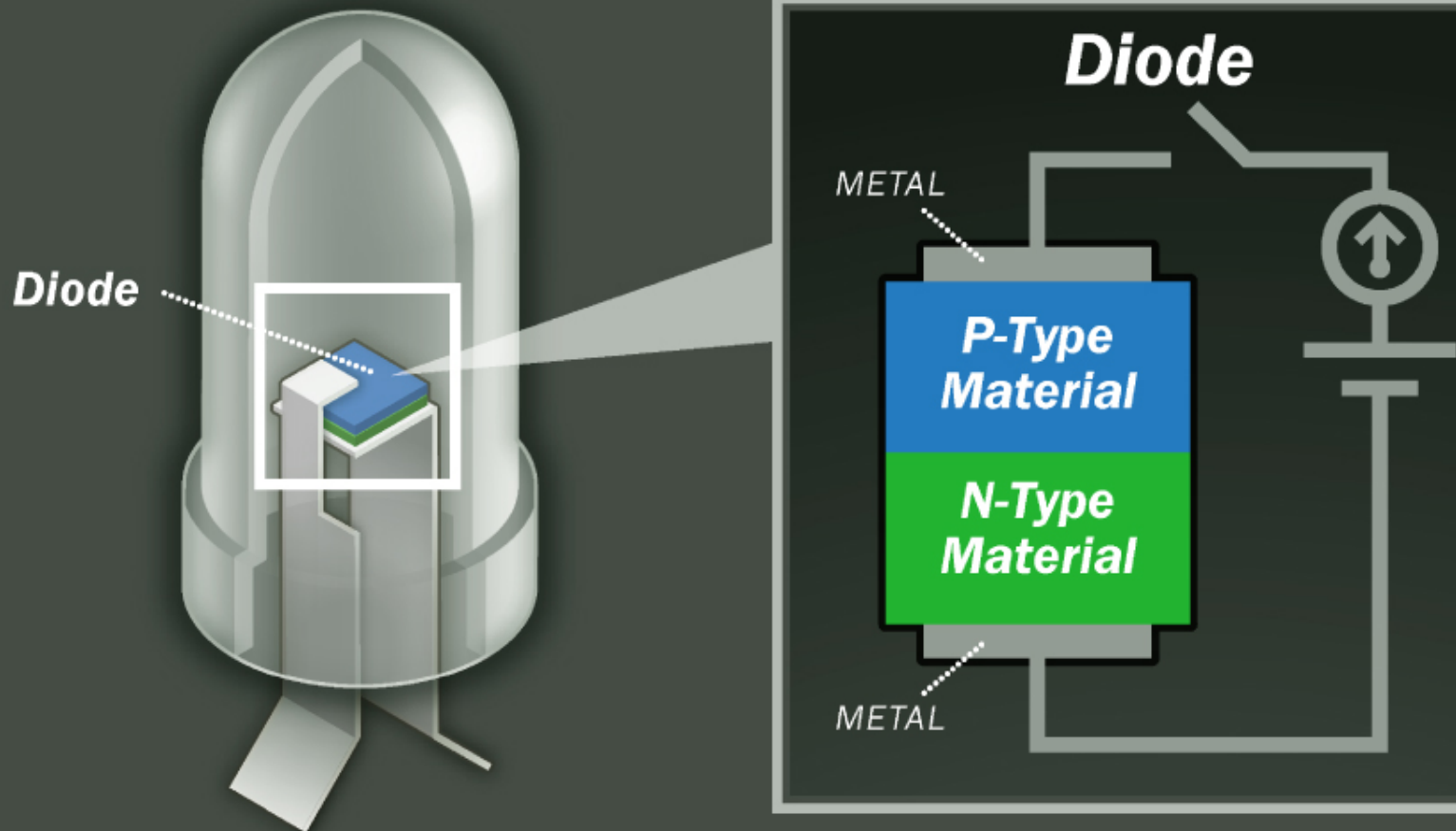


A **Diode** Is the Simplest Kind of Semiconductor Device



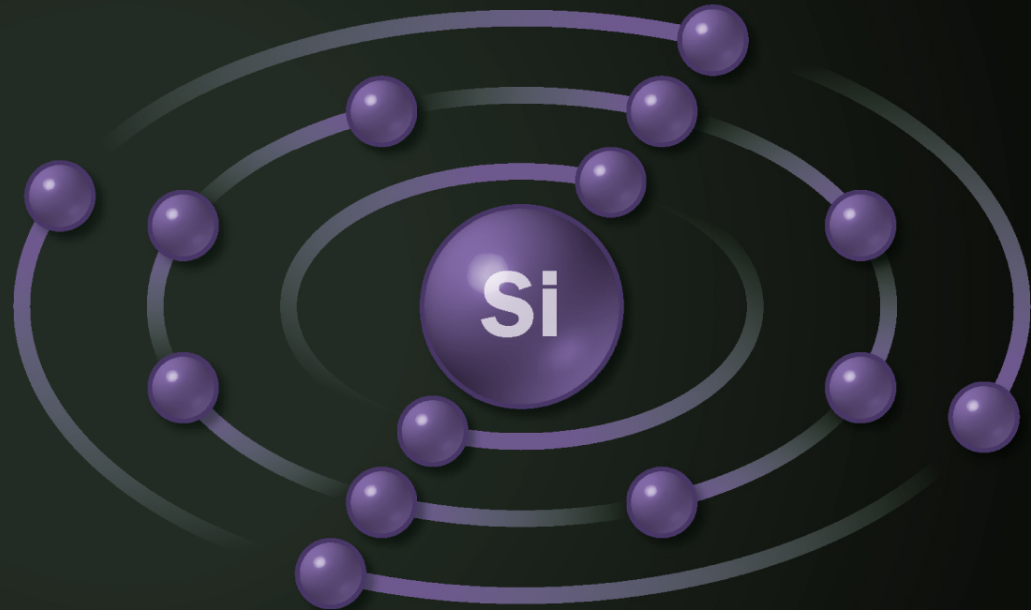


## A **Diode** Is the Simplest Kind of Semiconductor Device



# Silicon Is Commonly Used to Make Semiconductors

## GROUP IV

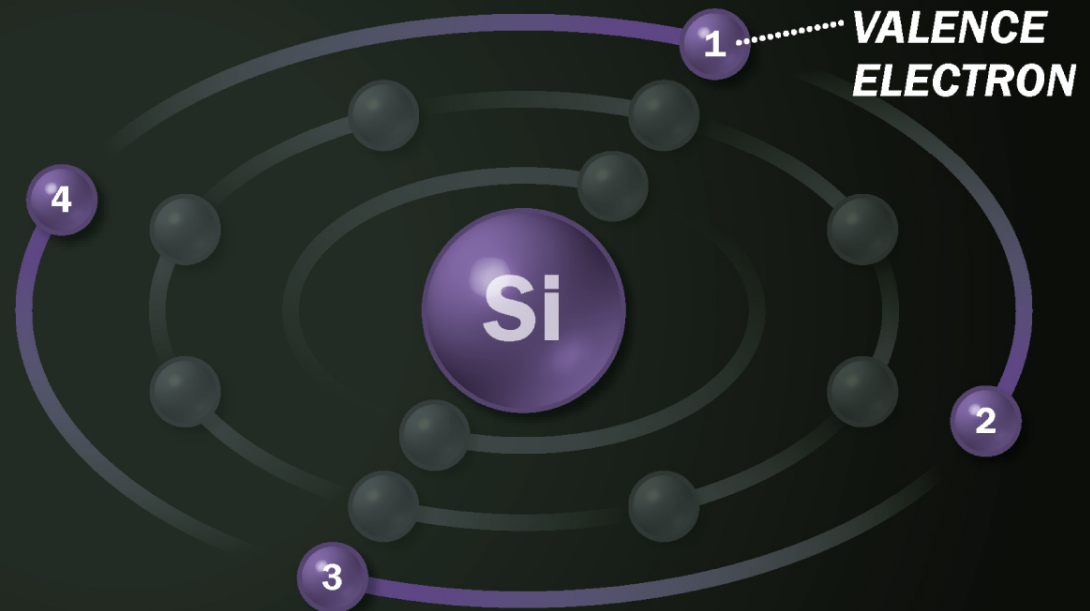


# Silicon Is Commonly Used to Make Semiconductors

## GROUP IV



***4 valence electrons  
participate in  
covalent bonds.***

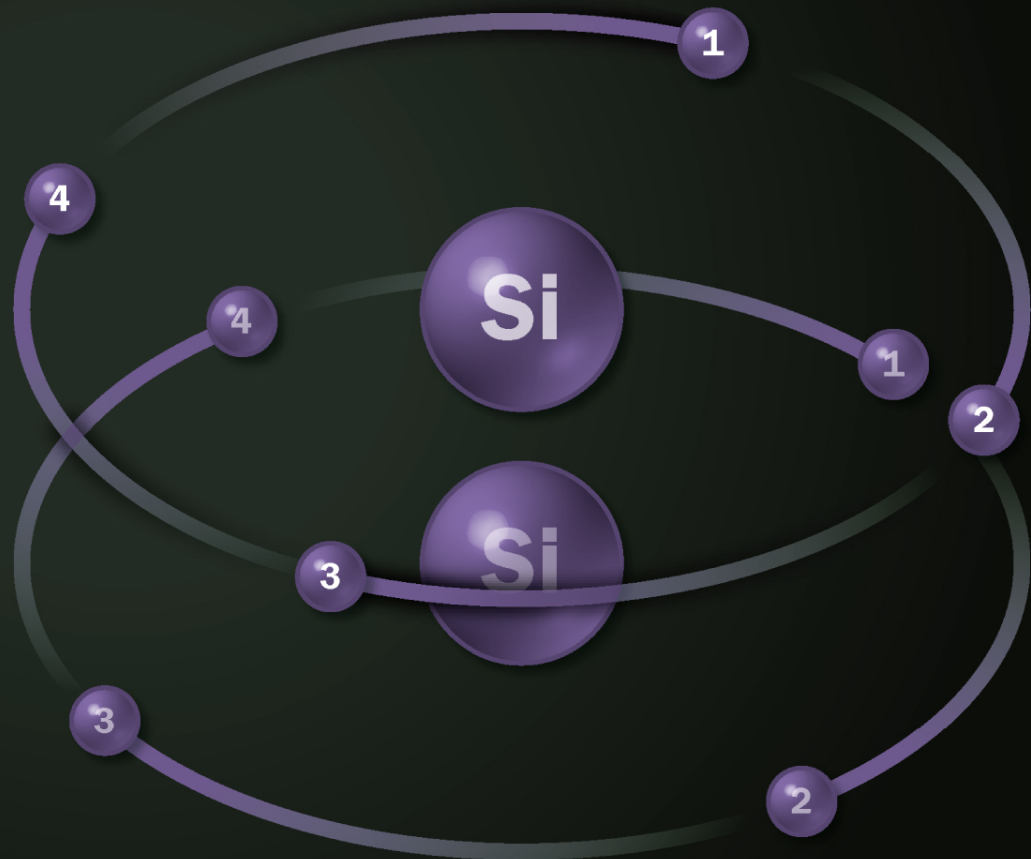


# Silicon Is Commonly Used to Make Semiconductors

## GROUP IV



*Two silicon atoms form perfect covalent bonds because each has four electrons in its outer orbital.*

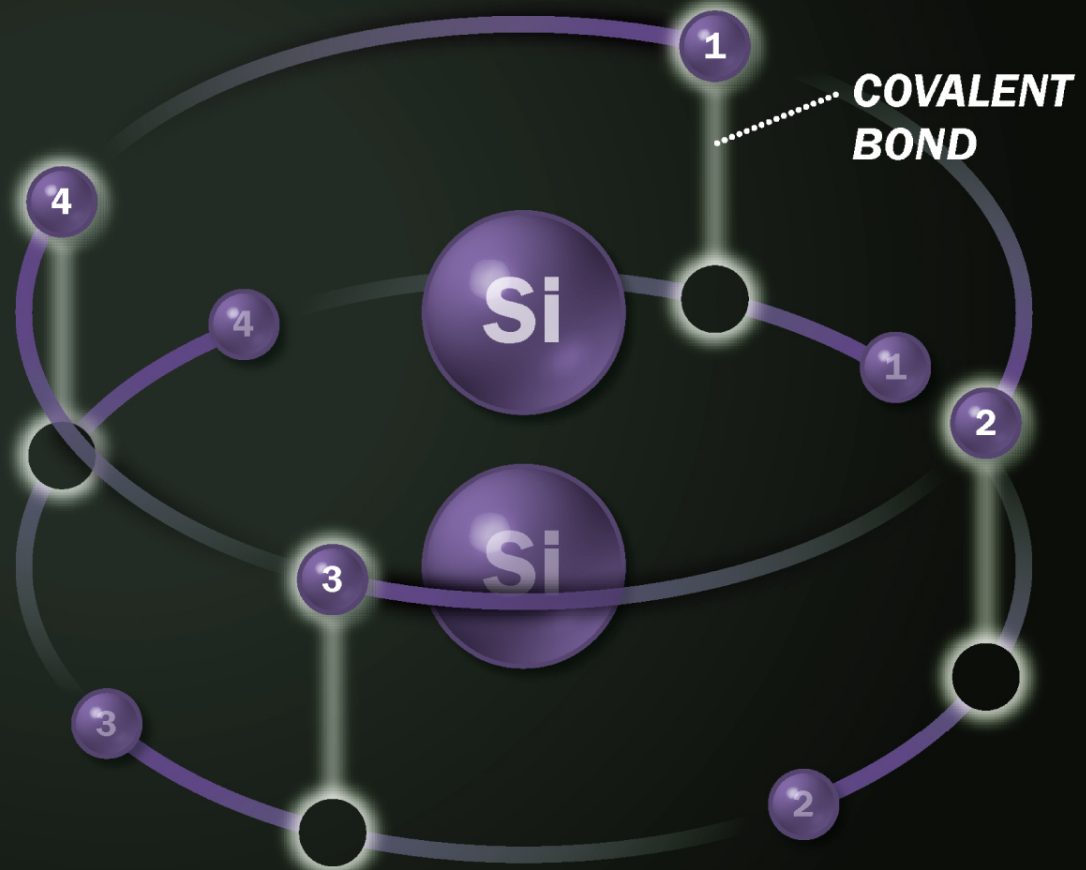


# Silicon Is Commonly Used to Make Semiconductors

## GROUP IV



*Two silicon atoms form perfect covalent bonds because each has four electrons in its outer orbital.*

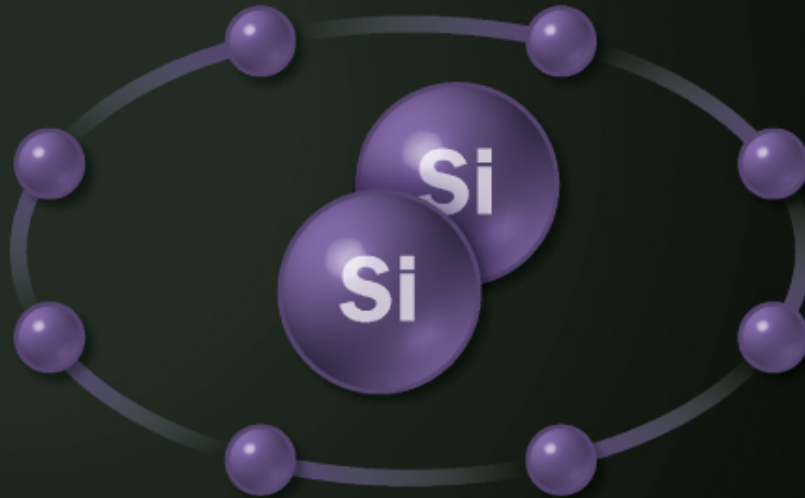


# Silicon Is Commonly Used to Make Semiconductors

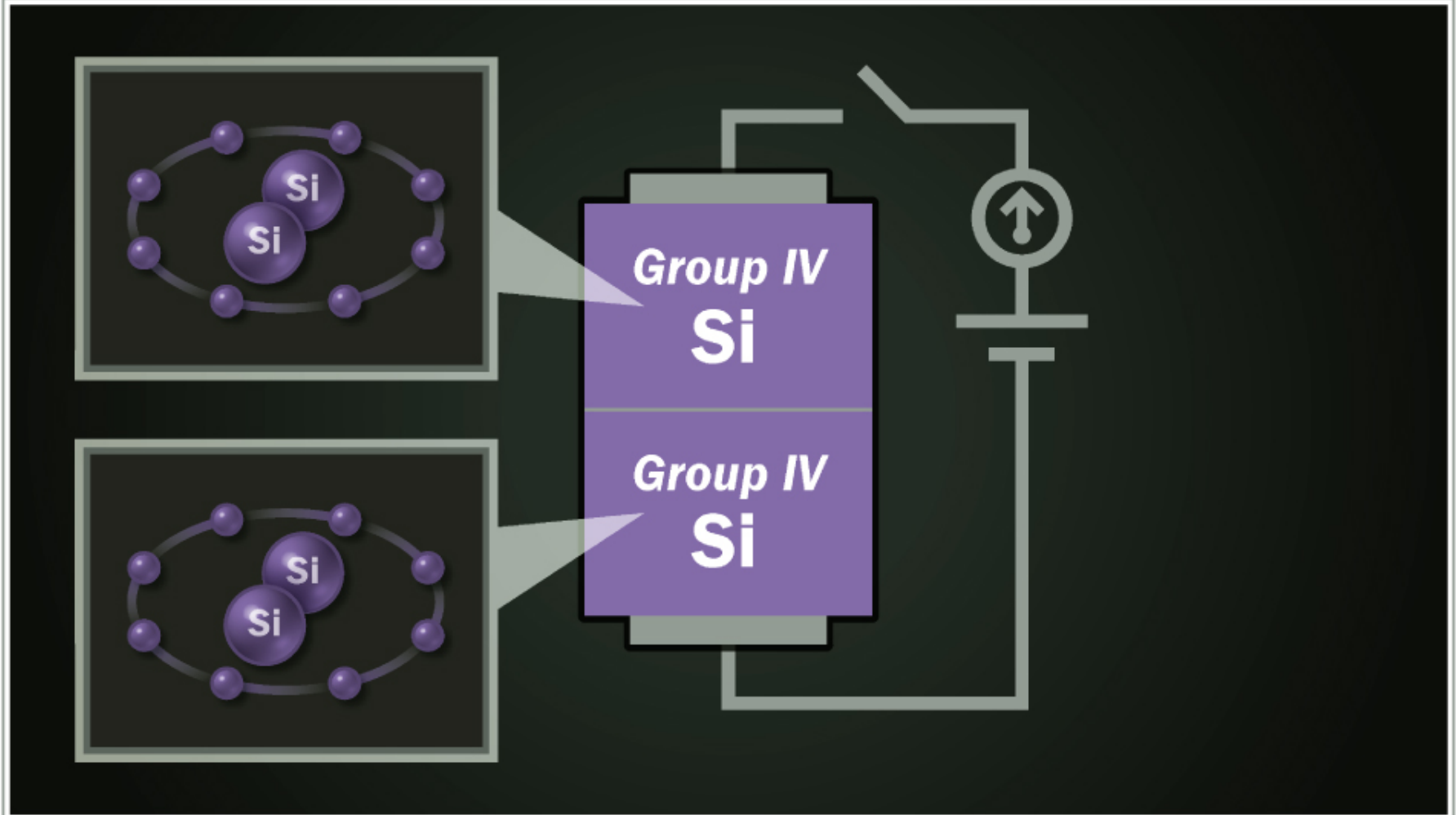
## GROUP IV



*Two silicon atoms form covalent bonds since each has four electrons in its outer orbital.*



# Ordinary Semiconductor "Diode" (Before Doping)



# Periodic Table of Elements

GROUP I A																GROUP VIII A																
1	H															He																
HYDROGEN																HELIUM																
3	4															5	6	7	8	9	10											
Li	Be															B	C	N	O	F	Ne											
LITHIUM	BERYLLIUM															BORON	CARBON	NITROGEN	OXYGEN	FLUORINE	NEON											
11	12											GROUP VIII B				GROUP I B		GROUP II B		13	14	15	16	17	18							
Na	Mg																			Al	Si	P	S	Cl	Ar							
SODIUM	MAGNESIUM																			ALUMINUM	SILICON	PHOSPHORUS	SULPHUR	CHLORINE	ARGON							
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36															
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr															
POTASSIUM	CALCIUM	SCANDIUM	TITANIUM	VANADIUM	CHROMIUM	MANGANESE	IRON	COBALT	NICKEL	COPPER	ZINC	GALLIUM	GERMANIUM	ARSENIC	SELENIUM	BROMINE	KRYPTON															
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54															
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe															
RUBIDIUM	STRONTIUM	YTTORIUM	ZIRCONIUM	NIOBIUM	MOLYBDENUM	TECHNETIUM	RUTHENIUM	RHODIUM	PALLADIUM	SILVER	CADMIUM	INDIUM	TIN	ANTIMONY	TELLURIUM	IODINE	XENON															
55	56	57-71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86															
Cs	Ba	La-Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn															
CAESIUM	BARIUM	LANTHANIDE	HAFNIUM	TANTALUM	TUNGSTEN	RHENIUM	OSMIUM	IRIDIUM	PLATINUM	GOLD	MERCURY	THALLIUM	LEAD	BISMUTH	POLONIUM	ASTATINE	RADON															
87	88	89-103	104	105	106	107	108	109	110	111	112		114																			
Fr	Ra	Ac-Lr	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub		Uuq																			
FRANCIUM	RADIUM	ACTINIDE	RUTHERFORDIUM	DUBNIUM	SEABORGIUM	BOHRNIUM	HASSIUM	MEITNERIUM	UNUNBIUM	UNUNTRIUM	UNUNQUADRIUM		UNUNQUADIUM																			
																		57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
																		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
																		LANTHANUM	CERIUM	PRASEODYMIUM	NEODYMIUM	PRIMETHIUM	SAMARIUM	EUROPIUM	GADOLINIUM	TERBIUM	DYSPROSIUM	HOLEMIUM	ERBIUM	THULIUM	YTTERIUM	LUTETIUM
																		89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
																		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
																		ACTINIUM	THORIUM	PROTACTINIUM	URANIUM	NEPTUNIUM	PLUTONIUM	AMERICIUM	CURIUM	BERKELIUM	CALIFORNIUM	EHSTENIUM	FERMIUM	MENDELEVIUM	NOBELIUM	LAWRENCIUM



# Periodic Table of Elements

GROUP I		GROUP II <sup>A</sup>		GROUP III		GROUP IV		GROUP V		GROUP VI		GROUP VII		GROUP VIII <sup>A</sup>																			
1 <b>H</b> HYDROGEN	3 <b>Li</b> LITHIUM	4 <b>Be</b> BERYLLIUM	12 <b>Mg</b> MAGNESIUM	20 <b>Ca</b> CALCIUM	30 <b>Zn</b> ZINC	38 <b>Sr</b> STRONTIUM	48 <b>Cd</b> CADMIUM	80 <b>Hg</b> MERCURY	5 <b>B</b> BORON	13 <b>Al</b> ALUMINUM	31 <b>Ga</b> GALLIUM	49 <b>In</b> INDIUM	81 <b>Tl</b> THALLIUM	6 <b>C</b> CARBON	14 <b>Si</b> SILICON	32 <b>Ge</b> GERMANIUM	50 <b>Sn</b> TIN	82 <b>Pb</b> LEAD	7 <b>N</b> NITROGEN	15 <b>P</b> PHOSPHORUS	33 <b>As</b> ARSENIC	51 <b>Sb</b> ANTIMONY	83 <b>Bi</b> BISMUTH	8 <b>O</b> OXYGEN	16 <b>S</b> SULPHUR	34 <b>Se</b> SELENIUM	52 <b>Te</b> TELLURIUM	84 <b>Po</b> POLONIUM	9 <b>F</b> FLOURINE	17 <b>Cl</b> CHLORINE	35 <b>Br</b> BROMINE	53 <b>I</b> IODINE	85 <b>At</b> ASTATINE

# Doping Is Used to Change the Electrical Properties of a Semiconductor

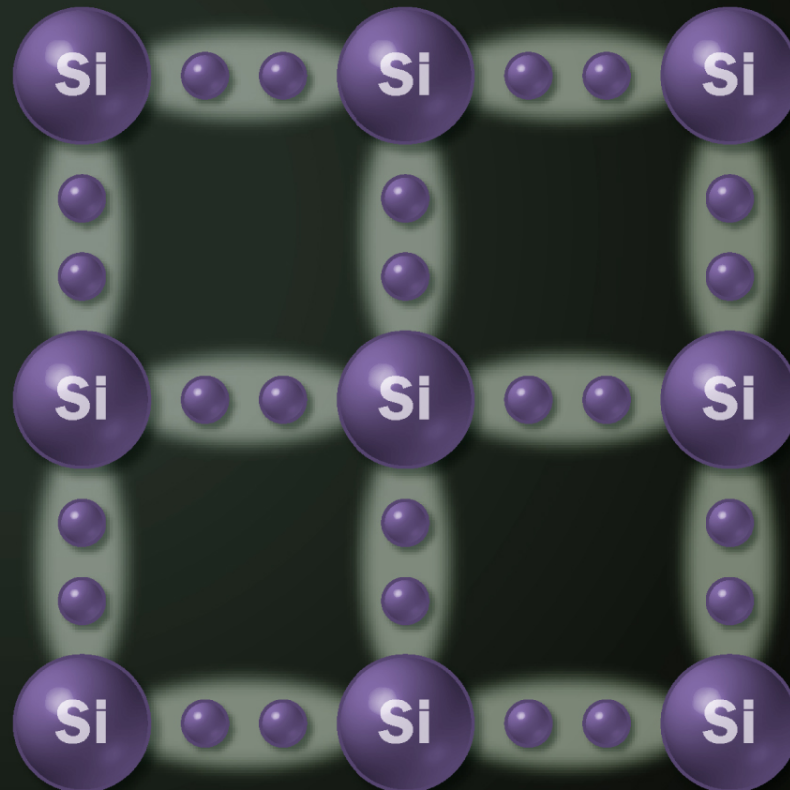
## N-TYPE DOPING

14

**Si**

Silicon

**Group IV  
Semiconductor**  
*Example: Silicon*



SILICON CRYSTAL LATTICE

# Doping Is Used to Change the Electrical Properties of a Semiconductor

## N-TYPE DOPING

14

**Si**

Silicon

**Group IV  
Semiconductor**  
Example: Silicon

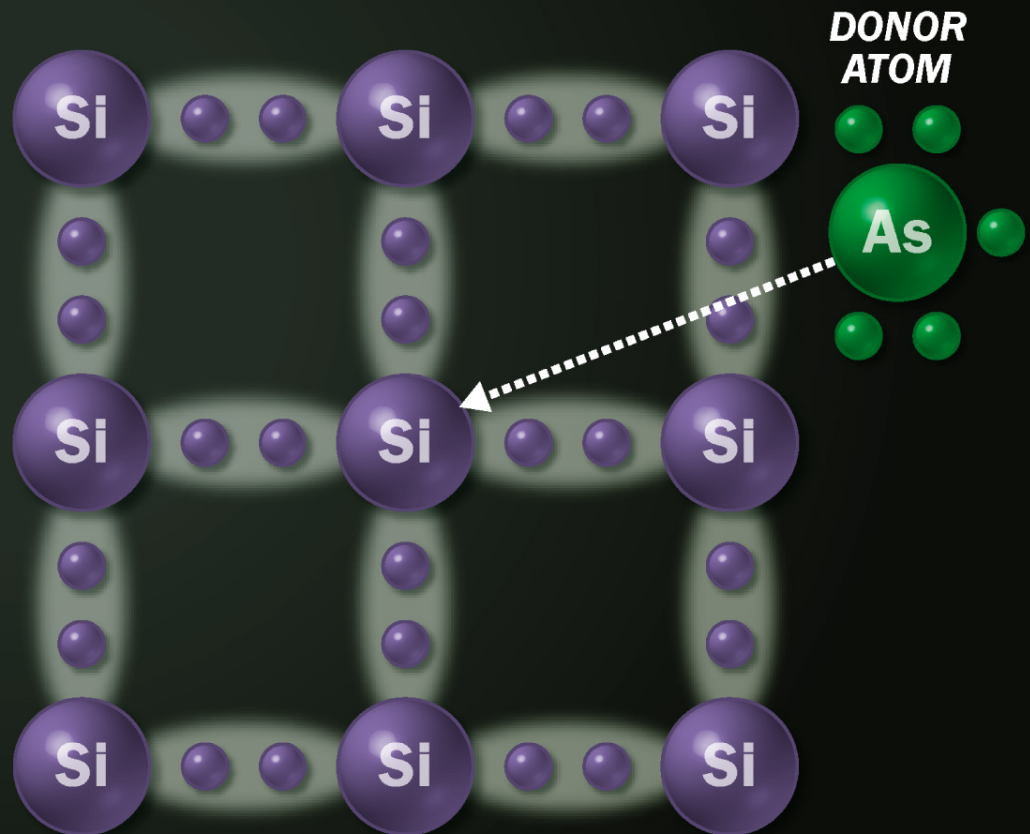
ADD:

33

**As**

Arsenic

**Group V  
Dopant Element**  
Example: Arsenic



# Doping Is Used to Change the Electrical Properties of a Semiconductor

## N-TYPE DOPING

14

**Si**

Silicon

**Group IV  
Semiconductor**  
Example: Silicon

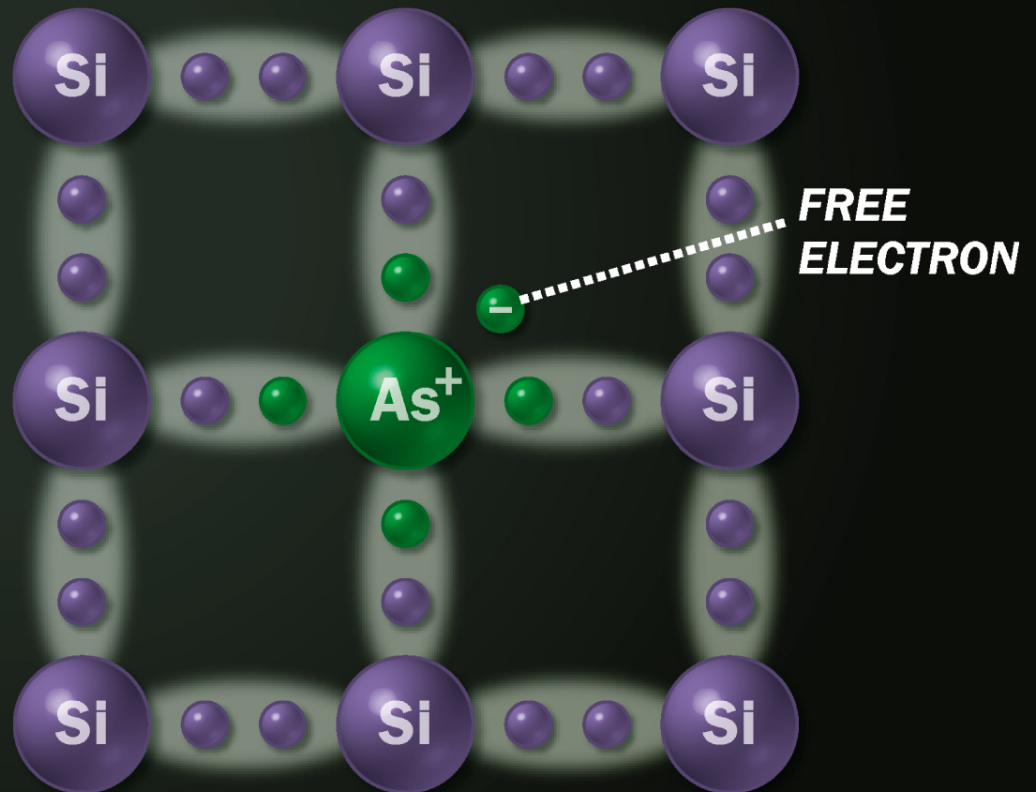
ADD:

33

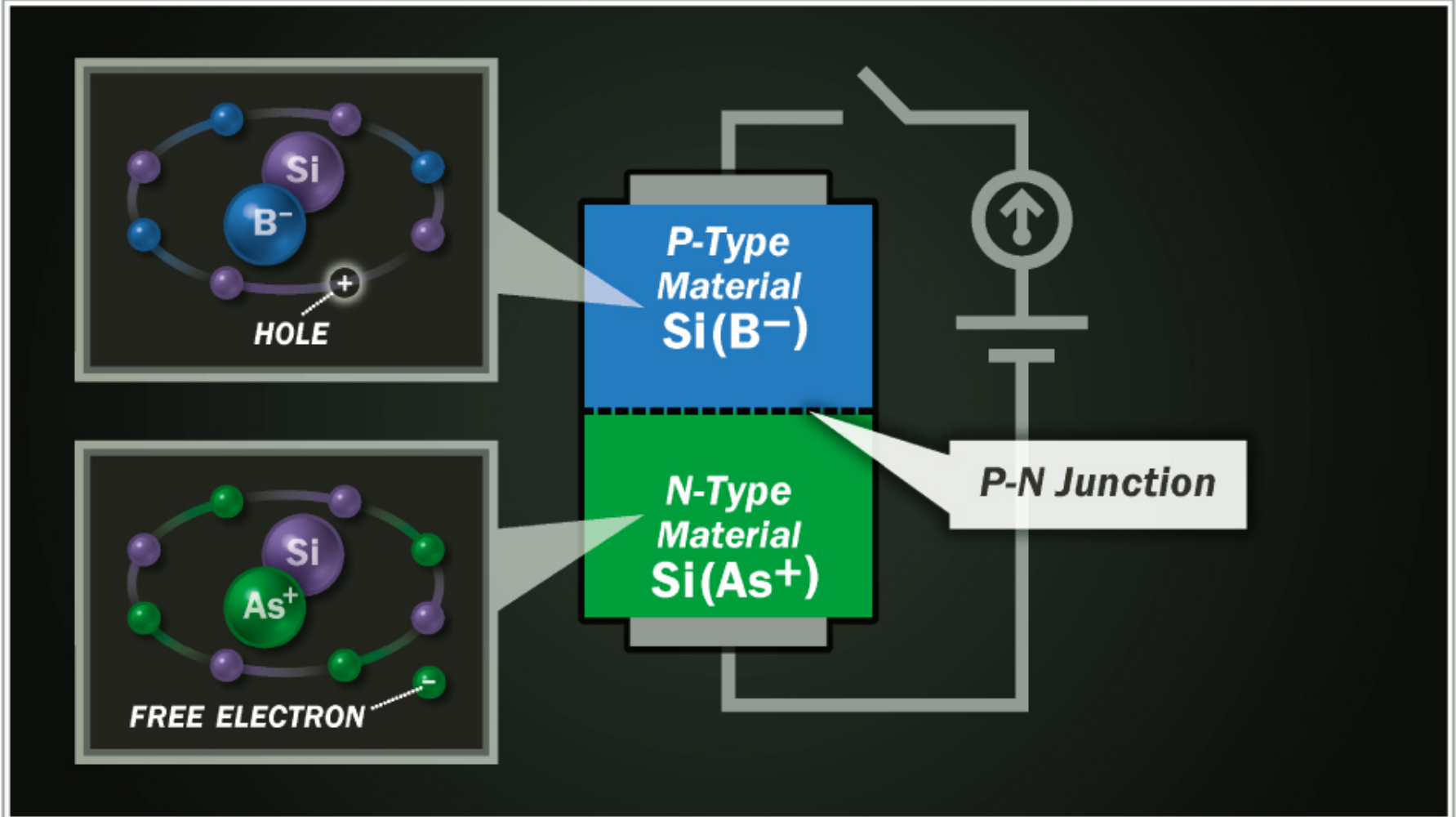
**As**

Arsenic

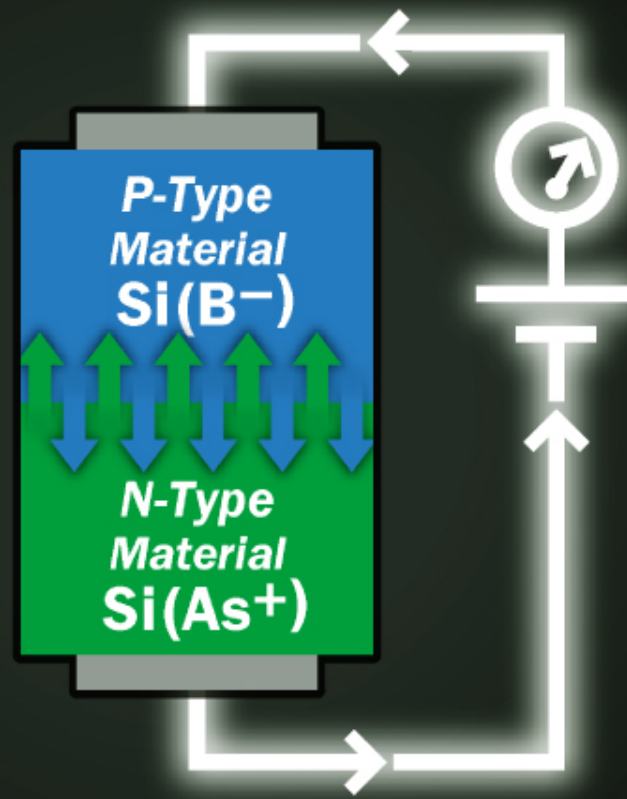
**Group V  
Dopant Element**  
Example: Arsenic



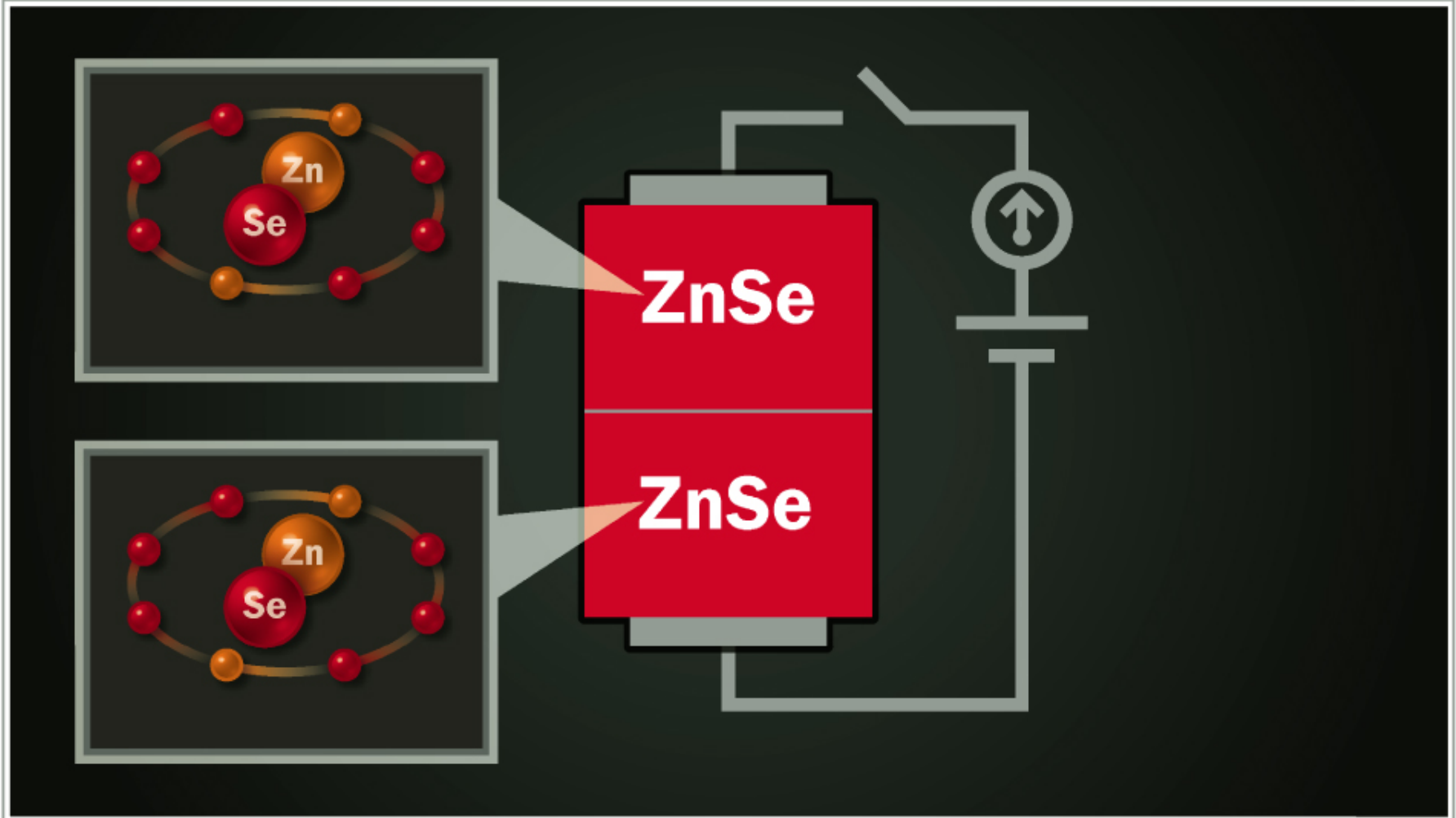
## Example of an Ordinary Semiconductor Diode (Doping)



## Example of an Ordinary Semiconductor Diode

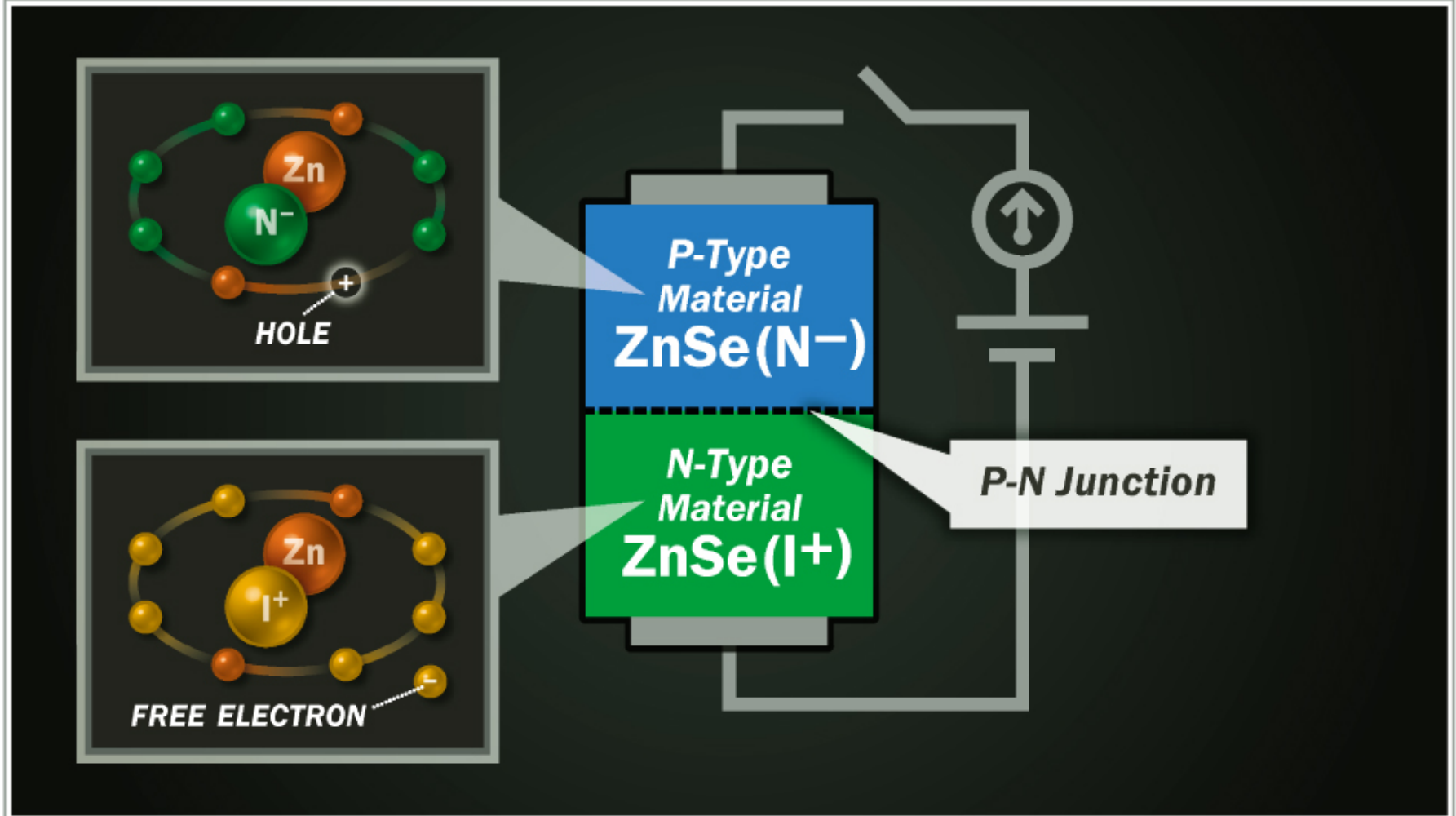


# Wide Band-Gap Semiconductor Diode (Before Doping)



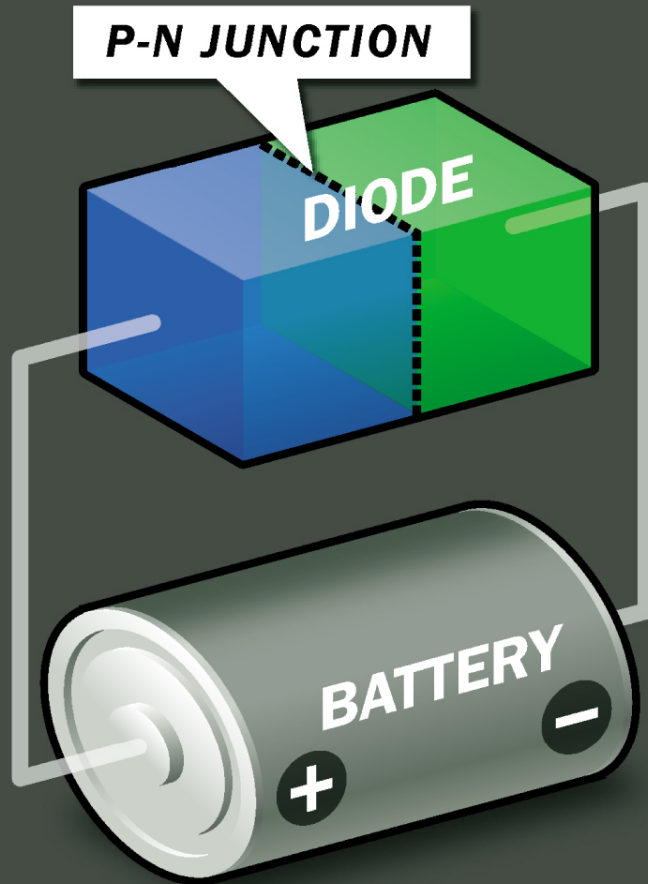


# Wide Band-Gap Semiconductor Diode (Doping)

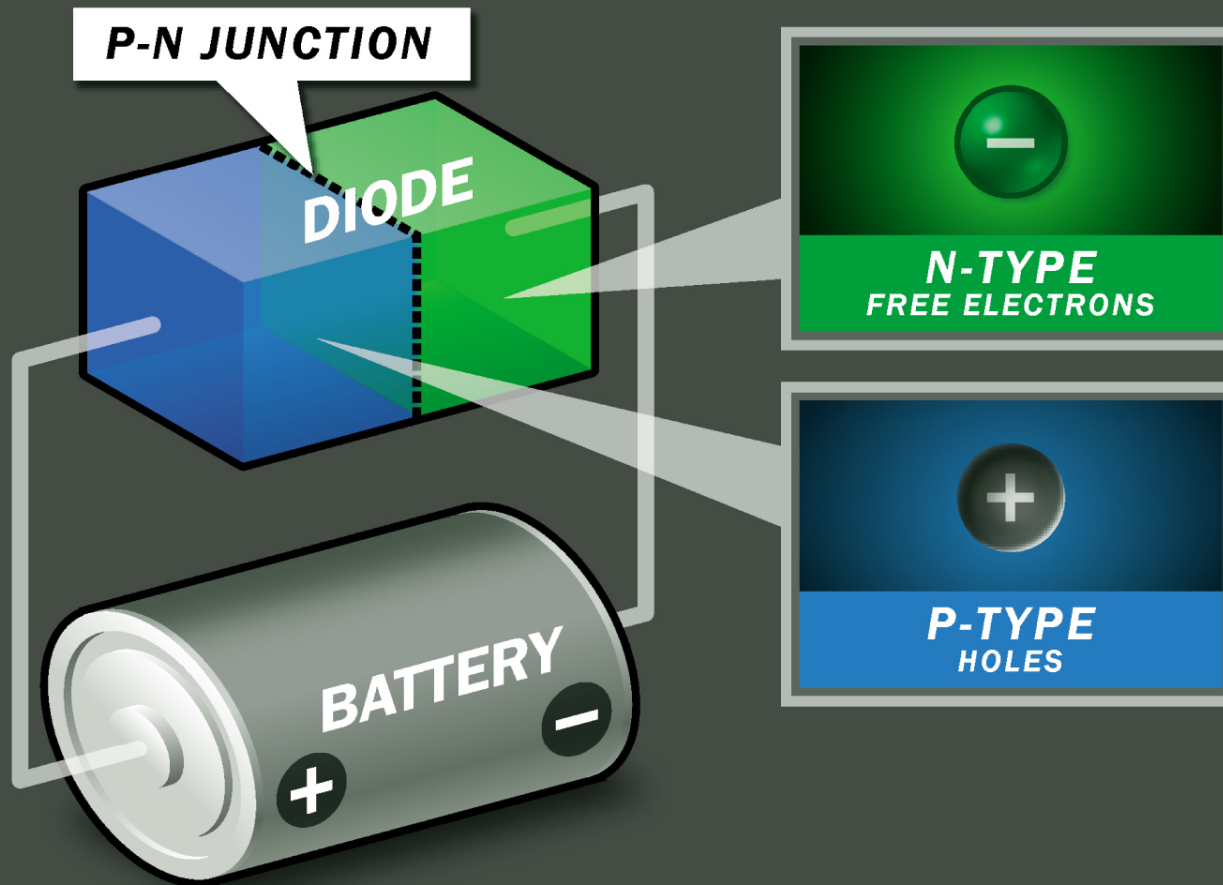




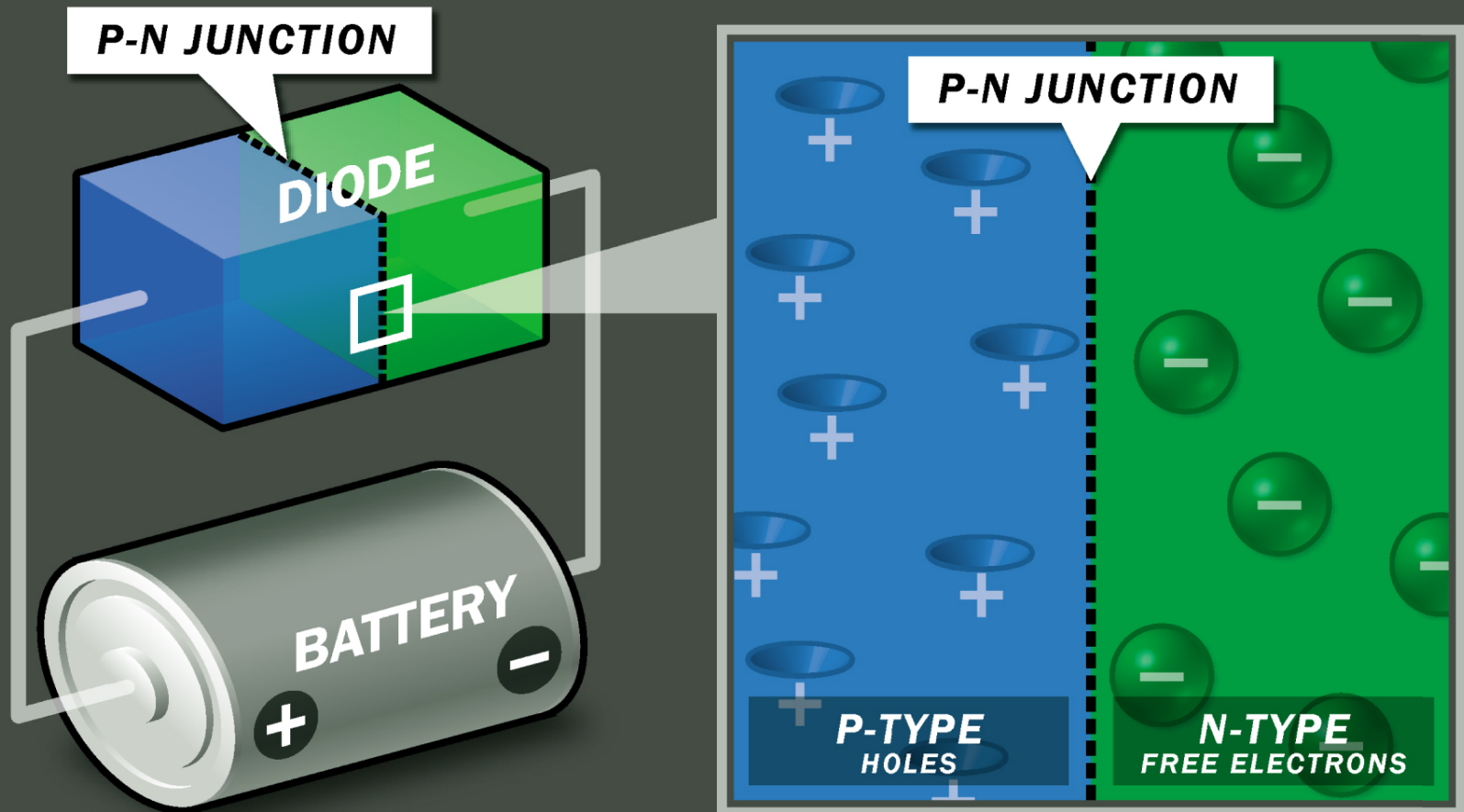
# The P-N Junction and Light Emission



# The P-N Junction and Light Emission

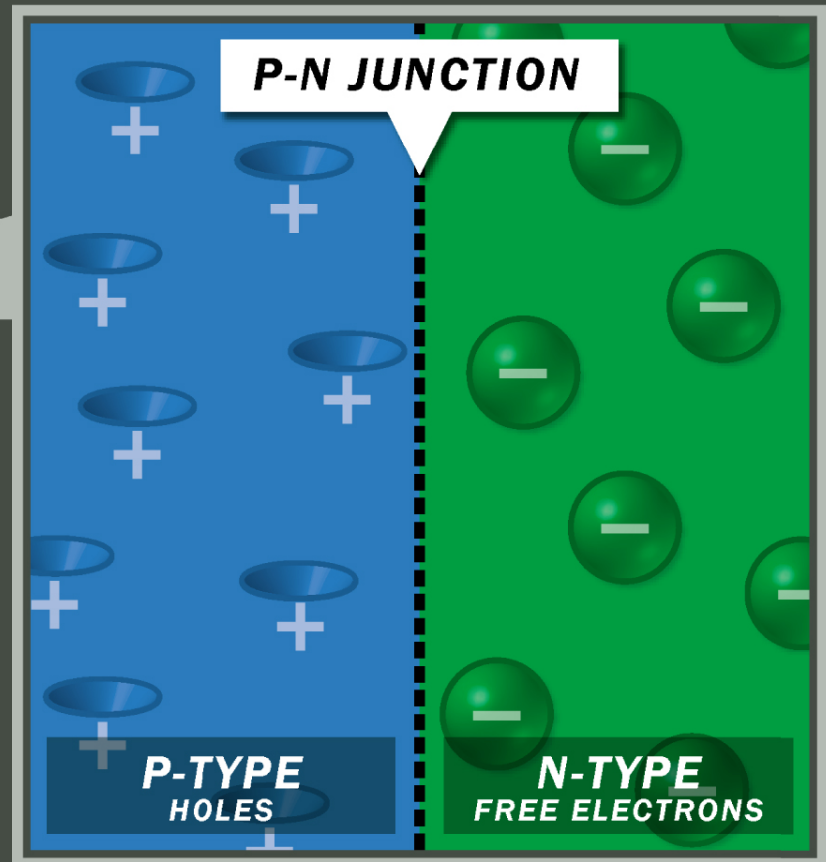
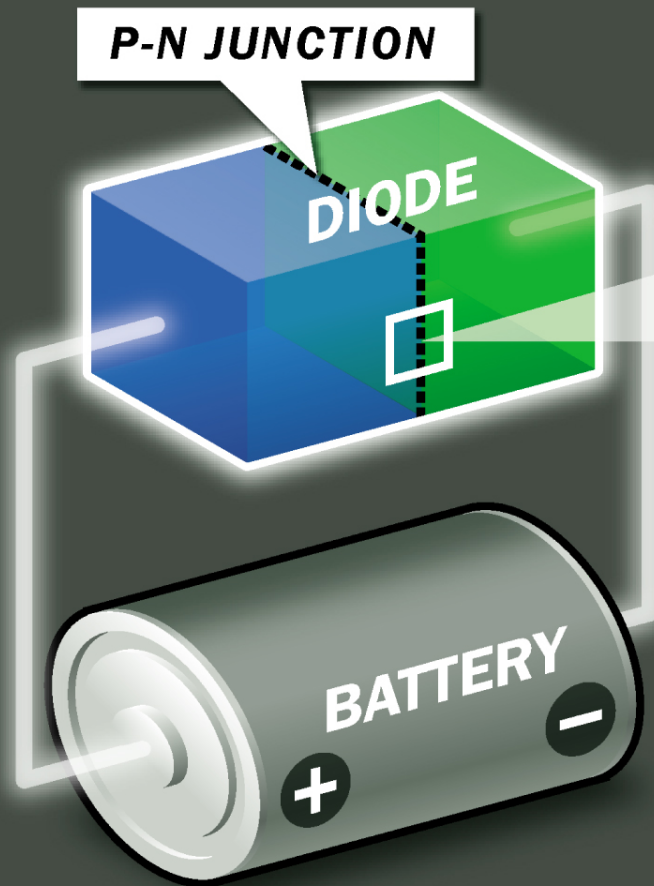


# The P-N Junction and Light Emission



# The P-N Junction and Light Emission

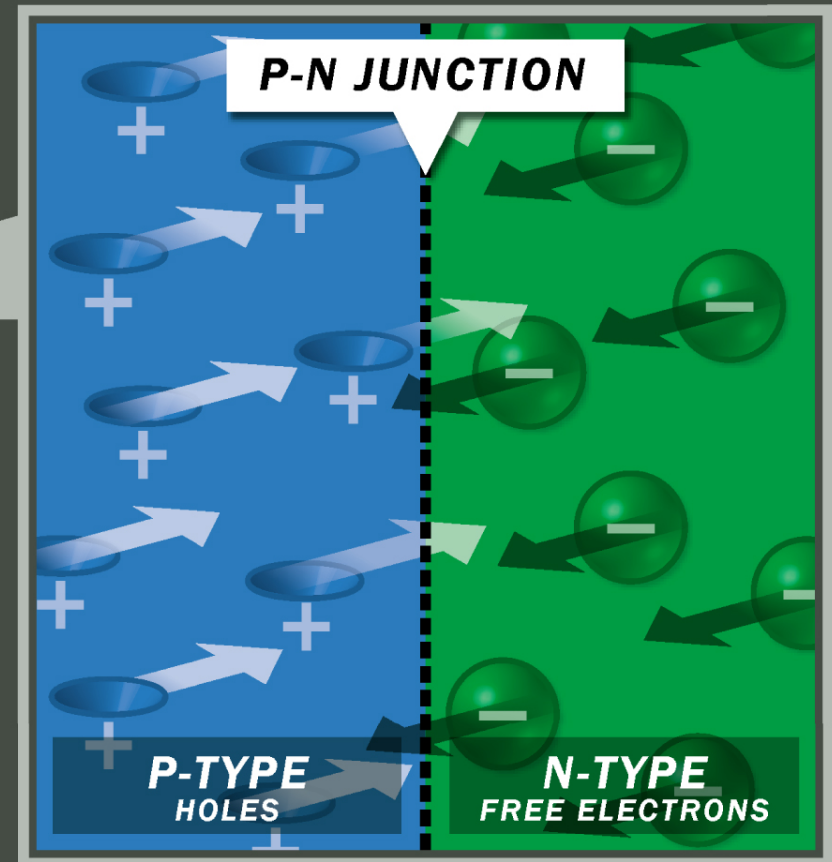
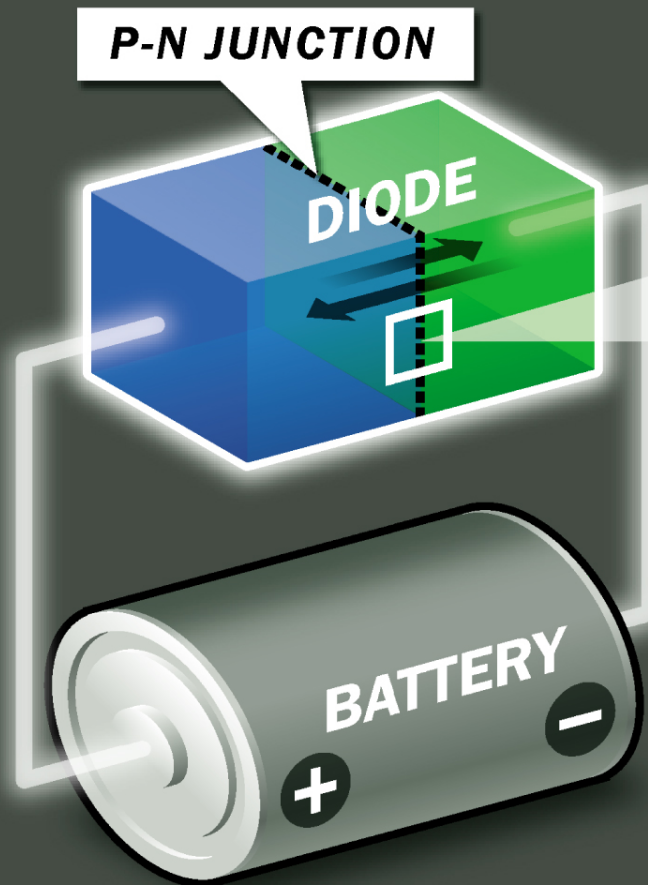
*Current flows from battery.*



# The P-N Junction and Light Emission

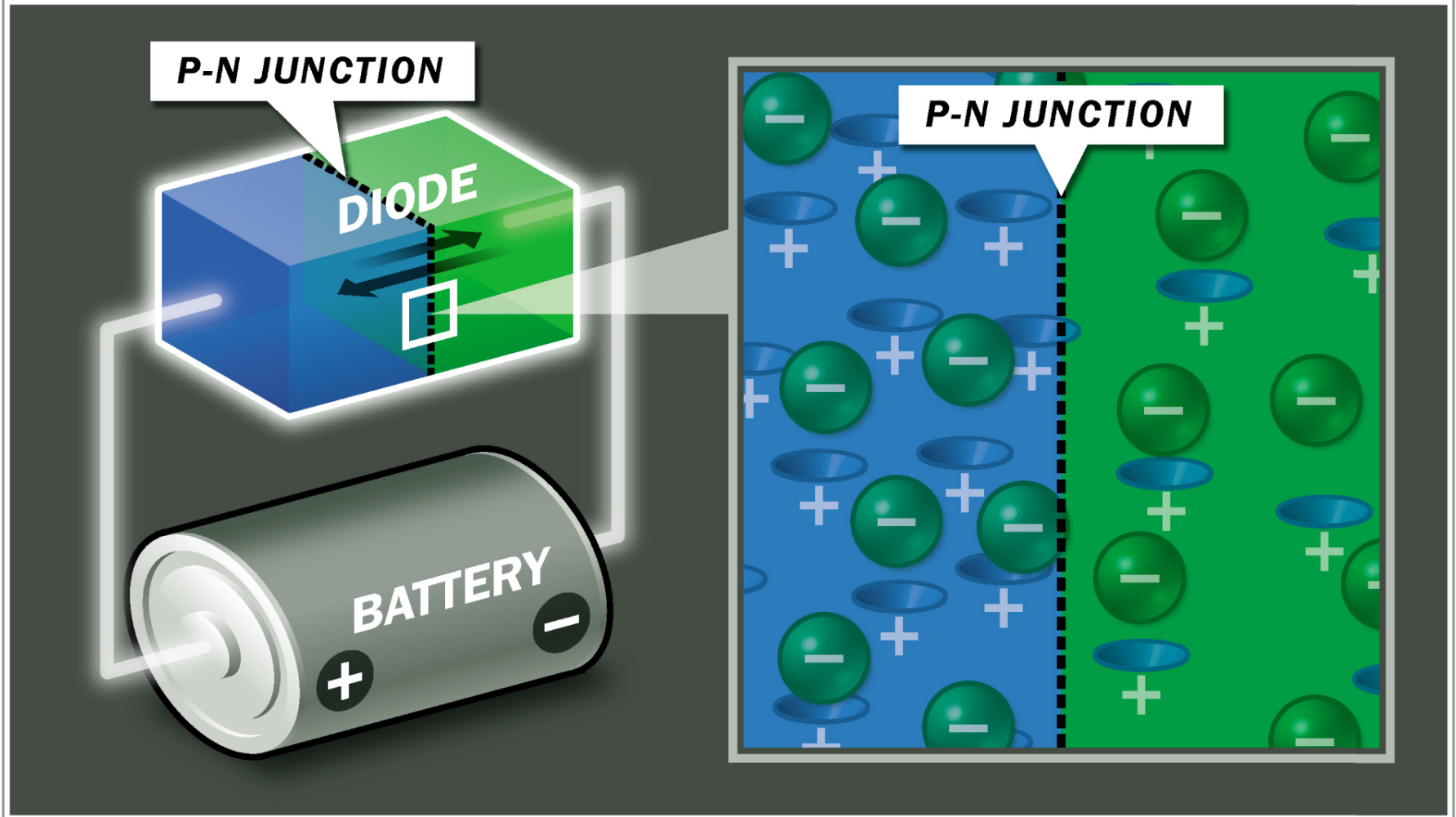
**HOLES** move toward **FREE ELECTRONS**  
across P-N Junction.

**FREE ELECTRONS** move toward **HOLES**  
across P-N Junction.



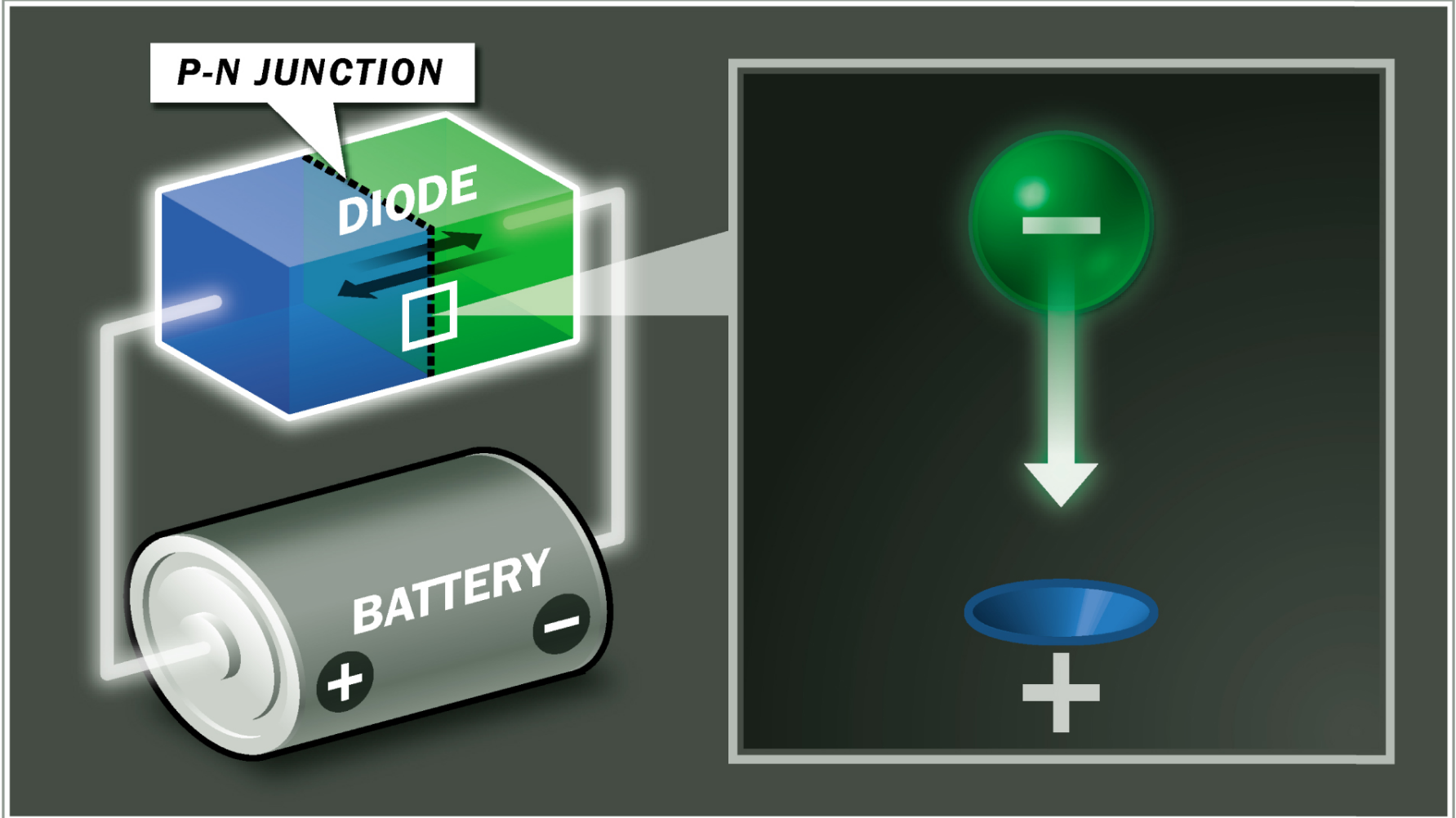
# The P-N Junction and Light Emission

*HOLES* exist at a lower energy orbital than  
*FREE ELECTRONS*.



# The P-N Junction and Light Emission

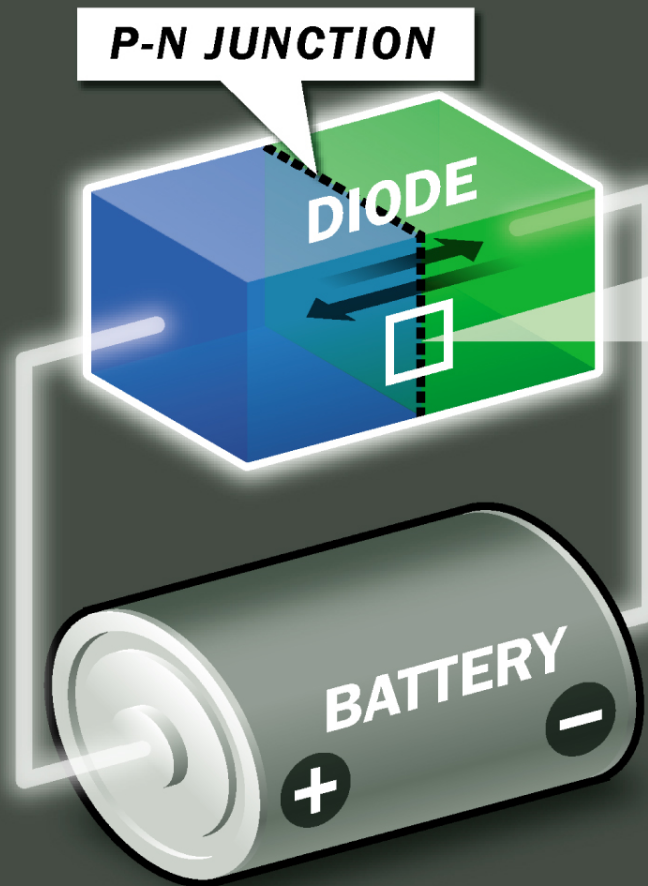
When a **FREE ELECTRON** “falls into a **HOLE**”,  
it loses energy, which is emitted as a light photon.





## The P-N Junction and Light Emission

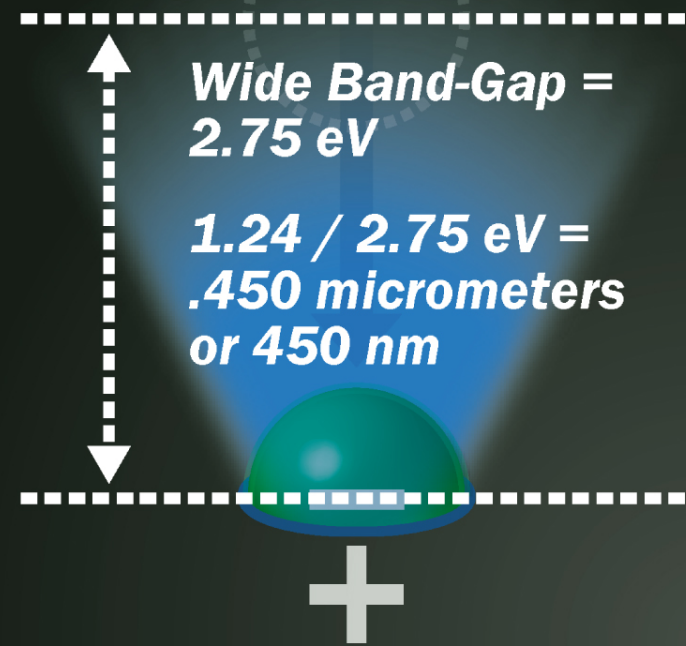
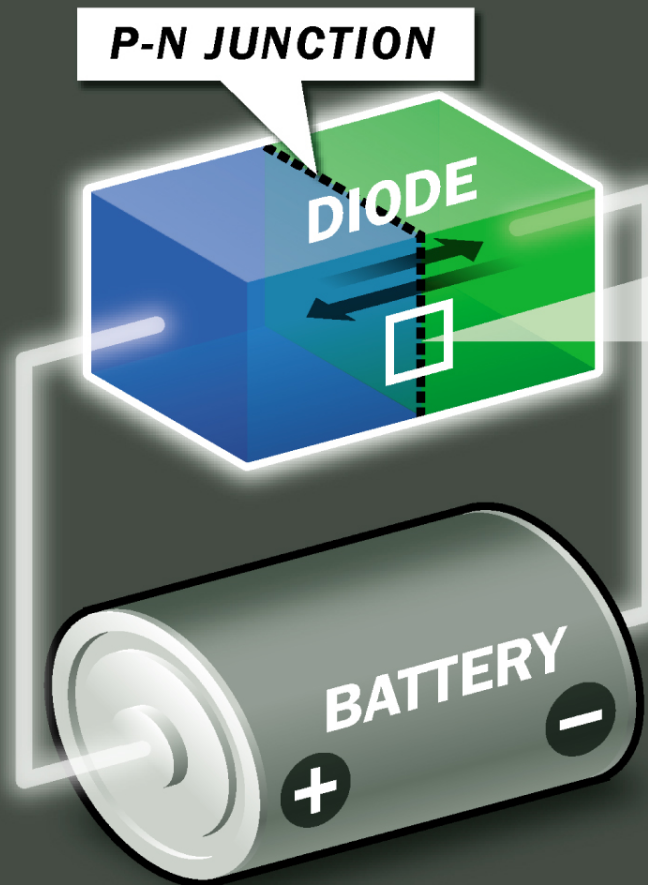
*A greater energy drop (bigger “fall”) releases a  
higher-energy photon which is characterized by  
a higher frequency.*



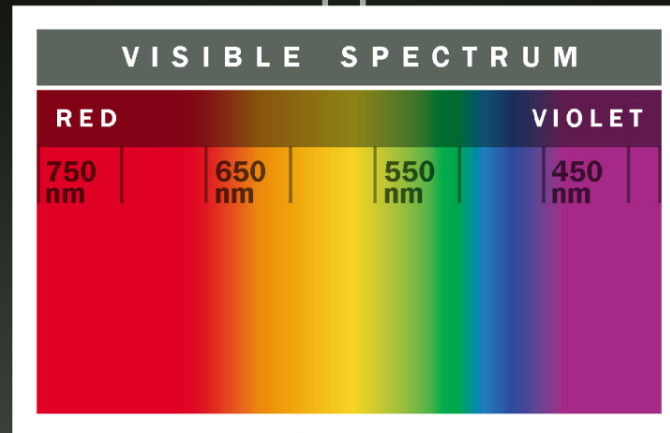


## The P-N Junction and Light Emission

*A greater energy drop (bigger “fall”) releases a higher-energy photon which is characterized by a higher frequency.*



# The Light Spectrum and Visible Light



INFRARED

VISIBLE

ULTRAVIOLET

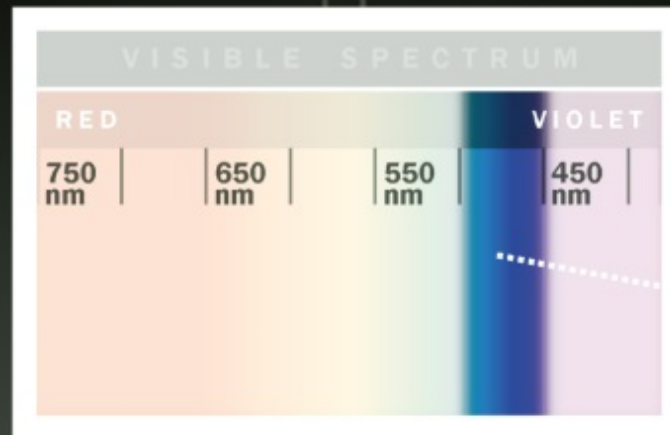
LOW ENERGY

HIGH ENERGY

LOW FREQUENCY

HIGH FREQUENCY

# The Light Spectrum and Visible Light



**Blue Light:**  
**450 nm – 495 nm**  
**2.76 eV – 2.51 eV**

INFRARED

VISIBLE

ULTRAVIOLET

LOW ENERGY

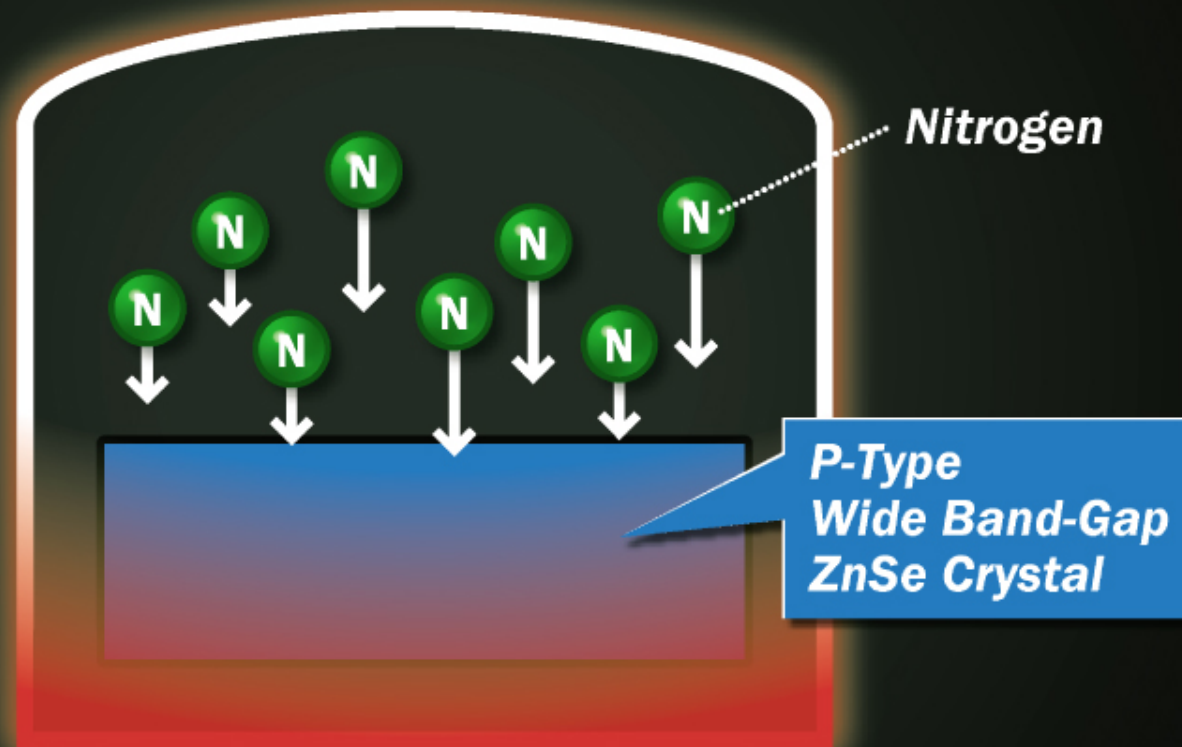
HIGH ENERGY

LOW FREQUENCY

HIGH FREQUENCY

## ***Doping Methods:***

Diffusion or Implantation into an Existing Wide Band-Gap Crystal



## **Doping Methods:**

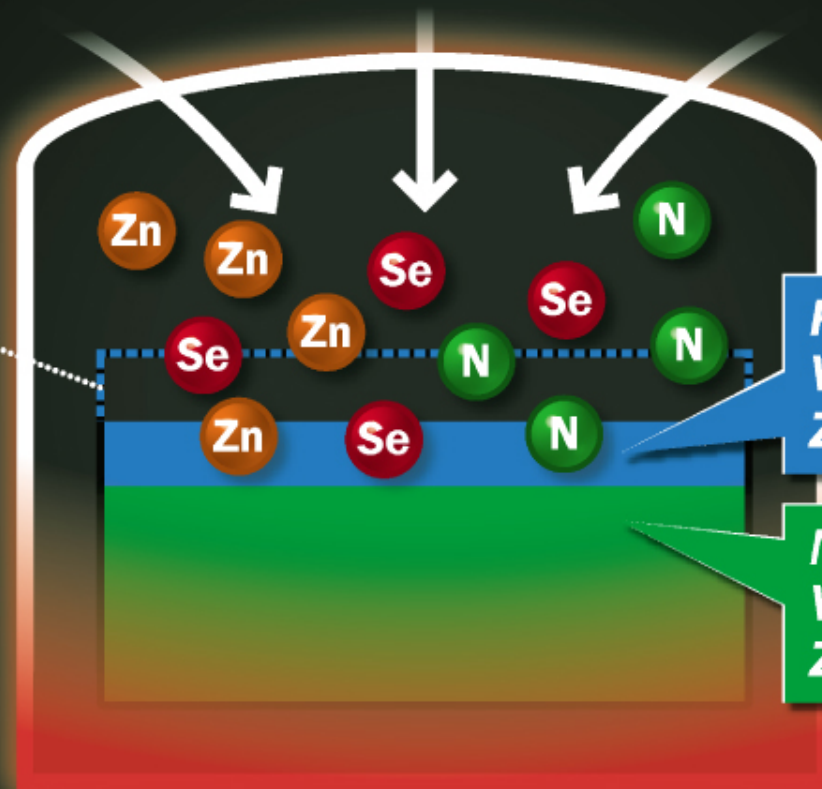
Growth (MOCVD)

**Zinc-Containing Gas    Selenium-Containing Gas    Nitrogen-Containing Gas**

**Epitaxial  
Layer**

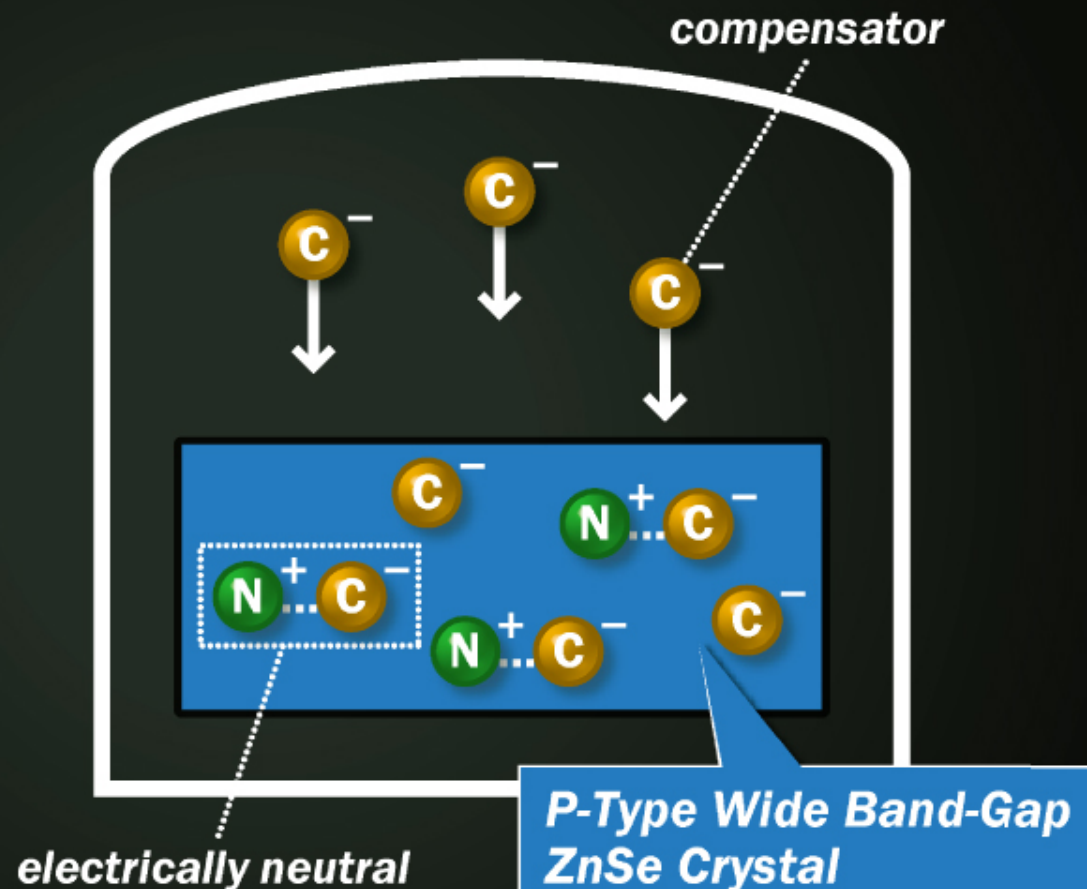
**P-Type  
Wide Band-Gap  
ZnSe Crystal**

**N-Type  
Wide Band-Gap  
ZnSe Crystal**



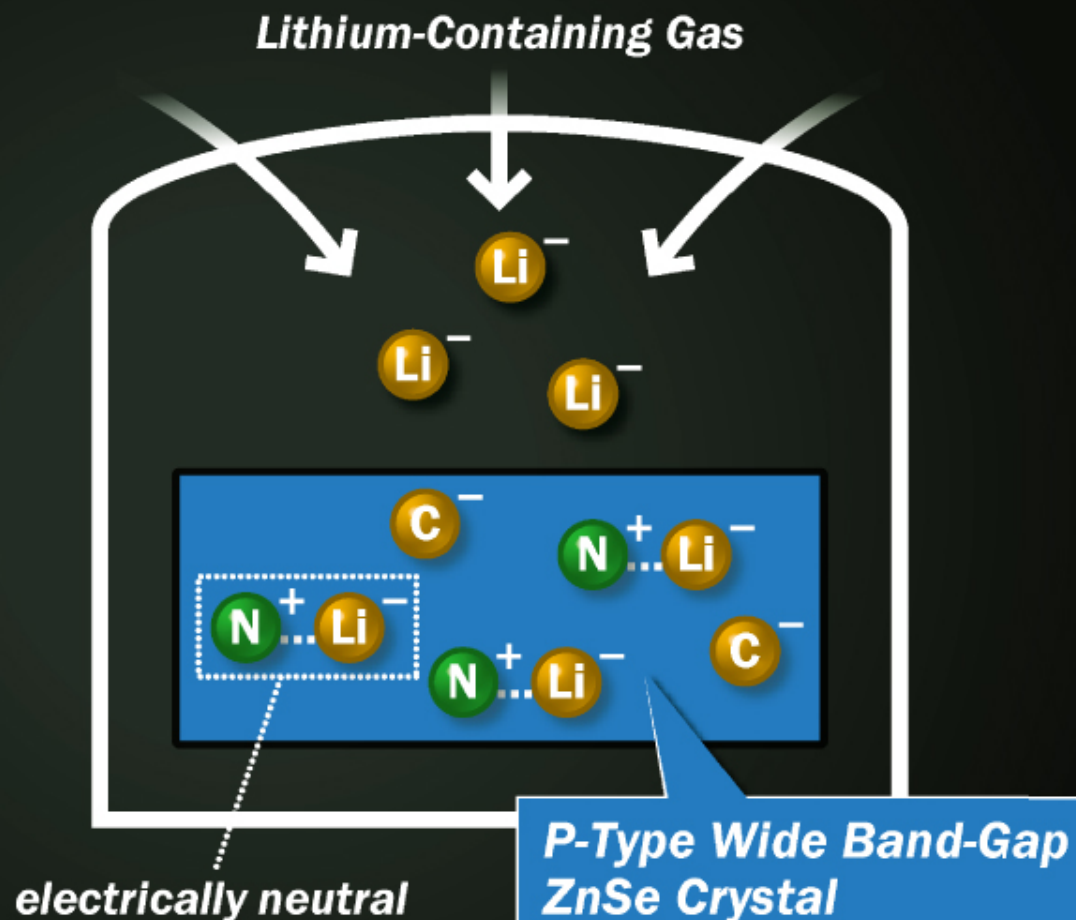
## **The Problem** According to Dr. Neumark

*Compensator  
impurities neutralize  
the dopant.*



## **The Solution** According to Dr. Neumark — Part 1

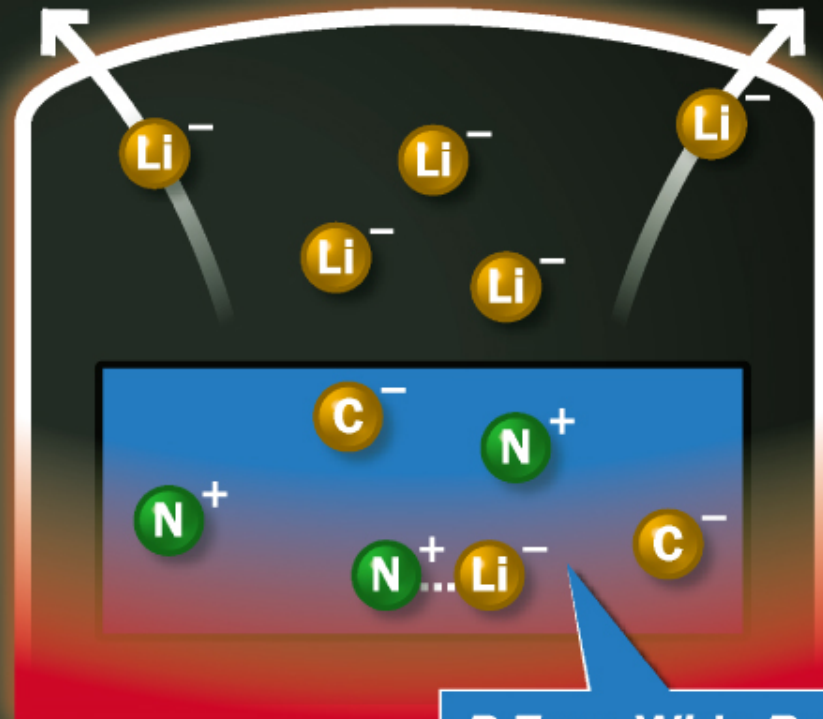
**Add lithium**  
(**'618 Patent**)  
**or hydrogen**  
(**'499 Patent**)  
**to P-type**  
**crystal material.**





## **The Solution** According to Dr. Neumark — Part 2

*Heat to  
remove lithium.*



*P-Type Wide Band-Gap  
ZnSe Crystal*