Photovoltaics: Plugging in the Sun

Every hour of every day, enough energy from the Sun reaches Earth to meet the entire planet's energy needs for an entire year

6.4×10^{17} kJ/hour

Compare with the 1.7×10^{12} kJ/mole of H_2 consumed in a fusion reactor

The U.S. currently taps less than 0.5% of our electrical energy needs via solar power

A change in this percentage could provide the answer to the pending energy shortage

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In a way, all energy on Earth could be considered as “solar power”

It is the energy of the Sun which allows plants to grow and keeps the planet a suitable temperature for life

Fossil fuels are the ancient remains of that life, and provide most of the energy used on Earth

This is a means of *indirectly* converting solar energy into electrical energy

But it’s not a rapid process – it takes billions of years to replace the fossil fuel stockpile

What people mean by “solar power” is a method of tapping into the Sun’s radiant energy directly

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Photovoltaic cells (or solar cells) are electrochemical cells which convert radiant energy into electrical energy **without** an intermediate such as fuel

Such cells already exist – if you're using a scientific calculator, chances are really good that it's solar powered

It takes only one or two PV cells to power a calculator

If more energy is needed, multiple PV cells can be connected together in an array

Such PV arrays are already commonly used to power satellites, traffic signals, safety lighting, etc.

How do they work?

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How do they work?

To understand that, we need to understand something about the way metals behave

PV cells are made from a class of materials called **semiconductors**

Semiconductors are materials which *partially* resemble metals in their properties

Metals are defined as being good conductors of electricity

That is, an electron put in to one end of a piece of metal will travel freely to the other end

Why?

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Why?

One way of picturing the bonding in metals is a model called the **“electron sea model”**

In this model, we imagine solid metals as an array of positive nuclei fixed in space

These nuclei are surrounded by their valence electrons

But those outermost electrons are only loosely bound

When lots of nuclei and lots of valence electrons are gathered together, the valence electrons are free to move from one nucleus to another

Thus, the electrons can be pictured as a liquid negative charge, traveling throughout the material

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Semiconductors work *almost* the same way

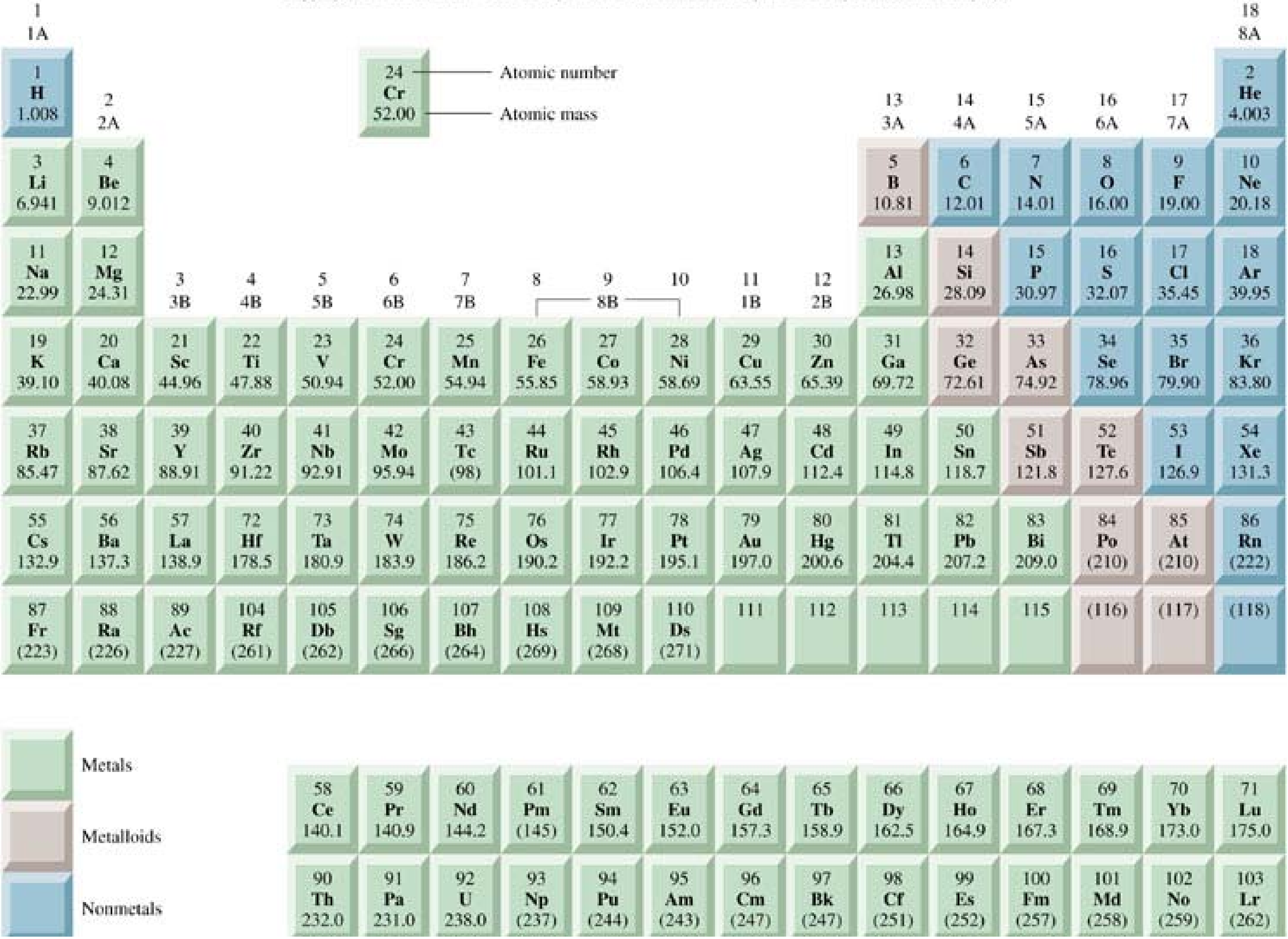
But in semiconductors, the valence electrons are more tightly bound than in metals

As a result, they do not “flow” completely freely

Energy needs to be put in in order for the valence electrons to move

So: conductors have freely moving electrons, nonconductors have strongly bound electrons, and **semi**conductors are normally nonconductive, but can be made to conduct if energy is supplied

One of the first semiconductors discovered and one of the first applied to PV cells is silicon. Si, AN 14

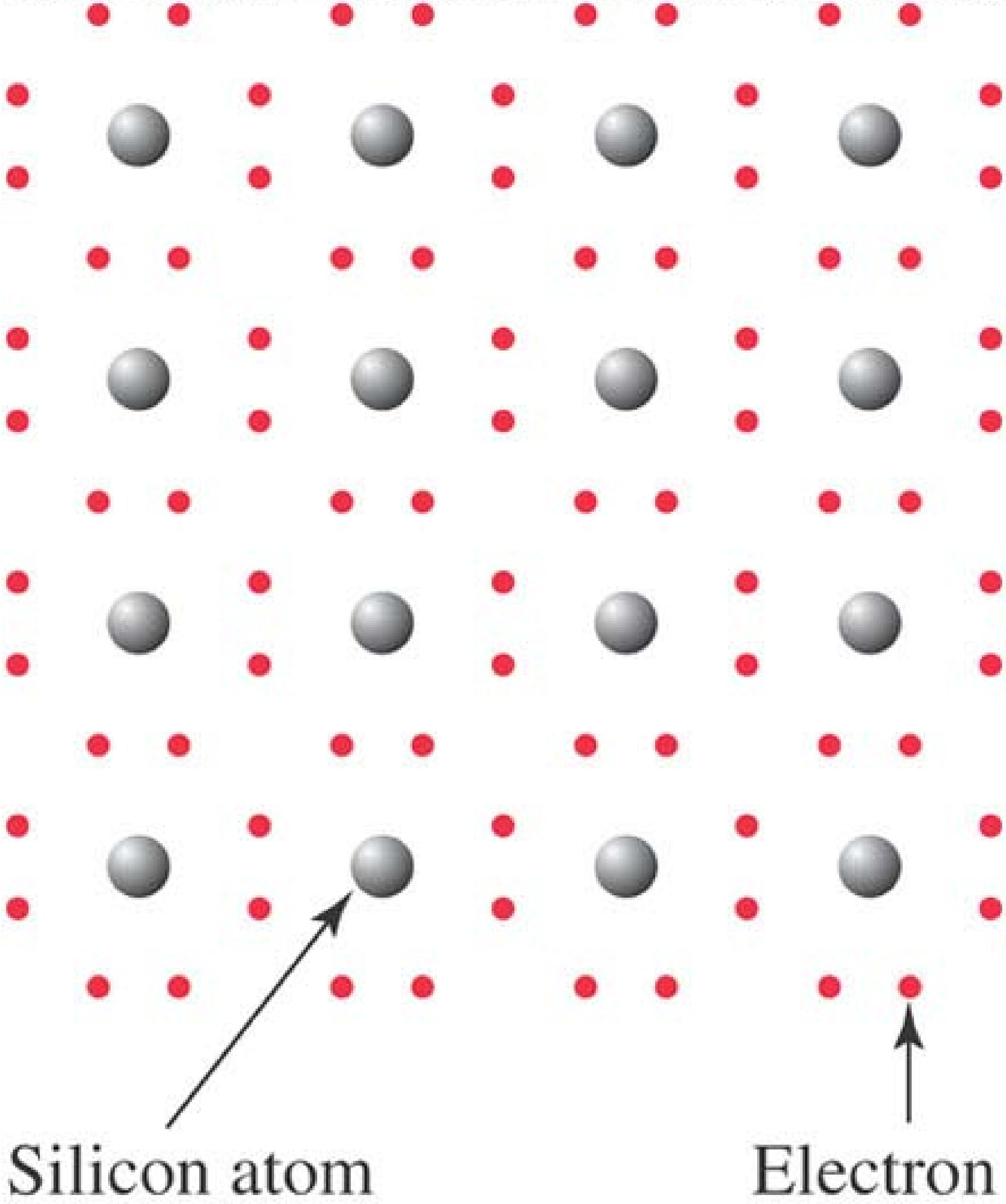


24 — Atomic number
Cr
52.00 — Atomic mass

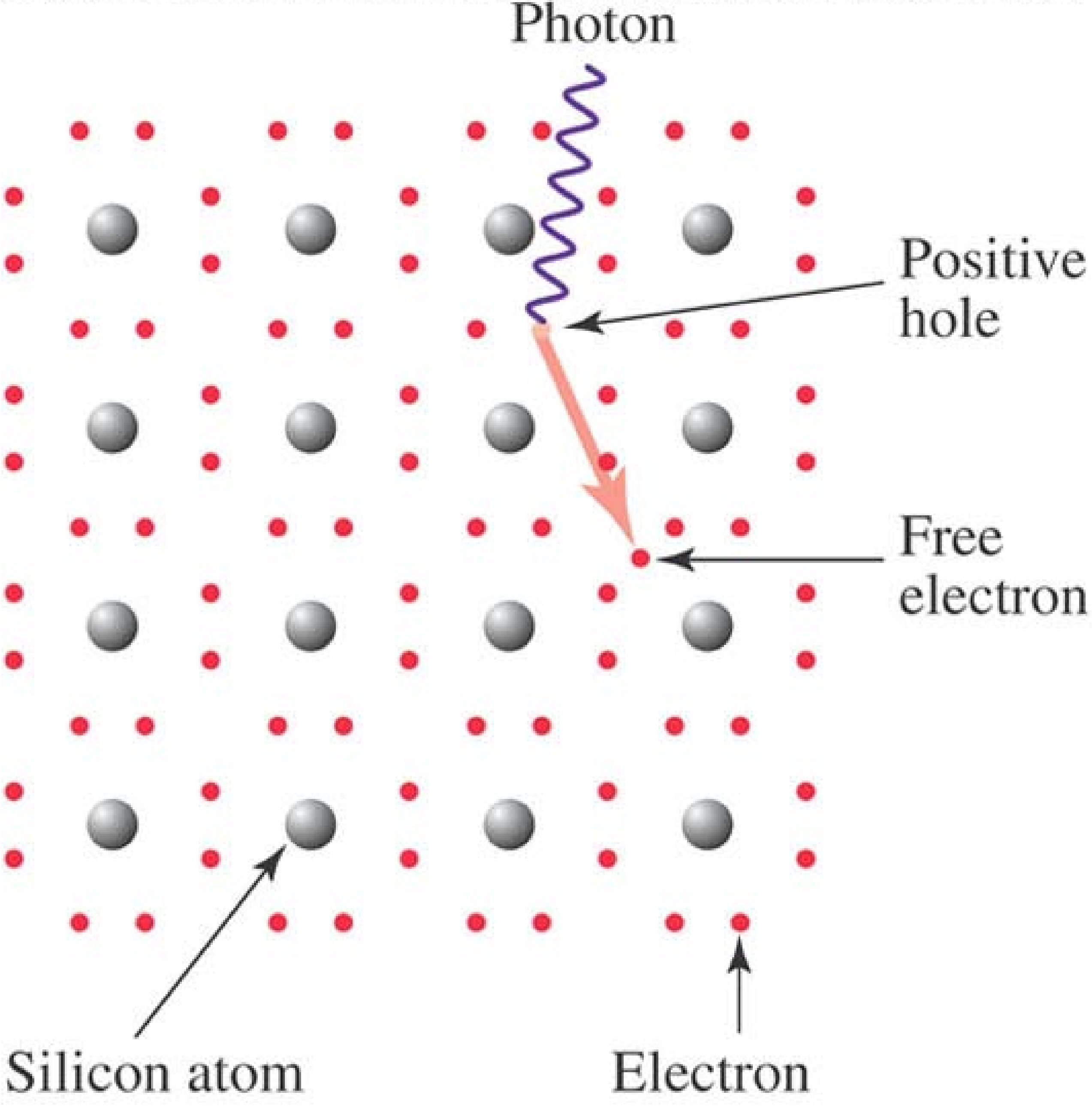
1 1A	2 2A	3 3B	4 4B	5 5B	6 6B	7 7B	8	9 8B	10	11 1B	12 2B	13 3A	14 4A	15 5A	16 6A	17 7A	18 8A
1 **H** 1.008																	2 **He** 4.003
3 **Li** 6.941	4 **Be** 9.012											5 **B** 10.81	6 **C** 12.01	7 **N** 14.01	8 **O** 16.00	9 **F** 19.00	10 **Ne** 20.18
11 **Na** 22.99	12 **Mg** 24.31											13 **Al** 26.98	14 **Si** 28.09	15 **P** 30.97	16 **S** 32.07	17 **Cl** 35.45	18 **Ar** 39.95
19 **K** 39.10	20 **Ca** 40.08	21 **Sc** 44.96	22 **Ti** 47.88	23 **V** 50.94	24 **Cr** 52.00	25 **Mn** 54.94	26 **Fe** 55.85	27 **Co** 58.93	28 **Ni** 58.69	29 **Cu** 63.55	30 **Zn** 65.39	31 **Ga** 69.72	32 **Ge** 72.61	33 **As** 74.92	34 **Se** 78.96	35 **Br** 79.90	36 **Kr** 83.80
37 **Rb** 85.47	38 **Sr** 87.62	39 **Y** 88.91	40 **Zr** 91.22	41 **Nb** 92.91	42 **Mo** 95.94	43 **Tc** (98)	44 **Ru** 101.1	45 **Rh** 102.9	46 **Pd** 106.4	47 **Ag** 107.9	48 **Cd** 112.4	49 **In** 114.8	50 **Sn** 118.7	51 **Sb** 121.8	52 **Te** 127.6	53 **I** 126.9	54 **Xe** 131.3
55 **Cs** 132.9	56 **Ba** 137.3	57 **La** 138.9	72 **Hf** 178.5	73 **Ta** 180.9	74 **W** 183.9	75 **Re** 186.2	76 **Os** 190.2	77 **Ir** 192.2	78 **Pt** 195.1	79 **Au** 197.0	80 **Hg** 200.6	81 **Tl** 204.4	82 **Pb** 207.2	83 **Bi** 209.0	84 **Po** (210)	85 **At** (210)	86 **Rn** (222)
87 **Fr** (223)	88 **Ra** (226)	89 **Ac** (227)	104 **Rf** (261)	105 **Db** (262)	106 **Sg** (266)	107 **Bh** (264)	108 **Hs** (269)	109 **Mt** (268)	110 **Ds** (271)	111	112	113	114	115	(116)	(117)	(118)

58 **Ce** 140.1	59 **Pr** 140.9	60 **Nd** 144.2	61 **Pm** (145)	62 **Sm** 150.4	63 **Eu** 152.0	64 **Gd** 157.3	65 **Tb** 158.9	66 **Dy** 162.5	67 **Ho** 164.9	68 **Er** 167.3	69 **Tm** 168.9	70 **Yb** 173.0	71 **Lu** 175.0
90 **Th** 232.0	91 **Pa** 231.0	92 **U** 238.0	93 **Np** (237)	94 **Pu** (244)	95 **Am** (243)	96 **Cm** (247)	97 **Bk** (247)	98 **Cf** (251)	99 **Es** (252)	100 **Fm** (257)	101 **Md** (258)	102 **No** (259)	103 **Lr** (262)

🟩 Metals
▨ Metalloids
🟦 Nonmetals



(a)



(b)

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Energy needs to be put in in order for the valence electrons to move - How much energy?

The energy required for a mole of electrons of Si to be freed up to move is 108 kJ/mole

That corresponds to $1.8x10^{-19}$ J/electron

In a PV cell, that energy comes from light…

… and that $1.8x10^{-19}$ J/electron corresponds to light with a wavelength of 1100 nm ($E=h\nu$, $\lambda=c/\nu$)

Visible light corresponds to wavelengths from 400-750 nm

So visible light is **shorter** wavelength, and has **more** energy

Visible light has enough energy to free an electron in Si!

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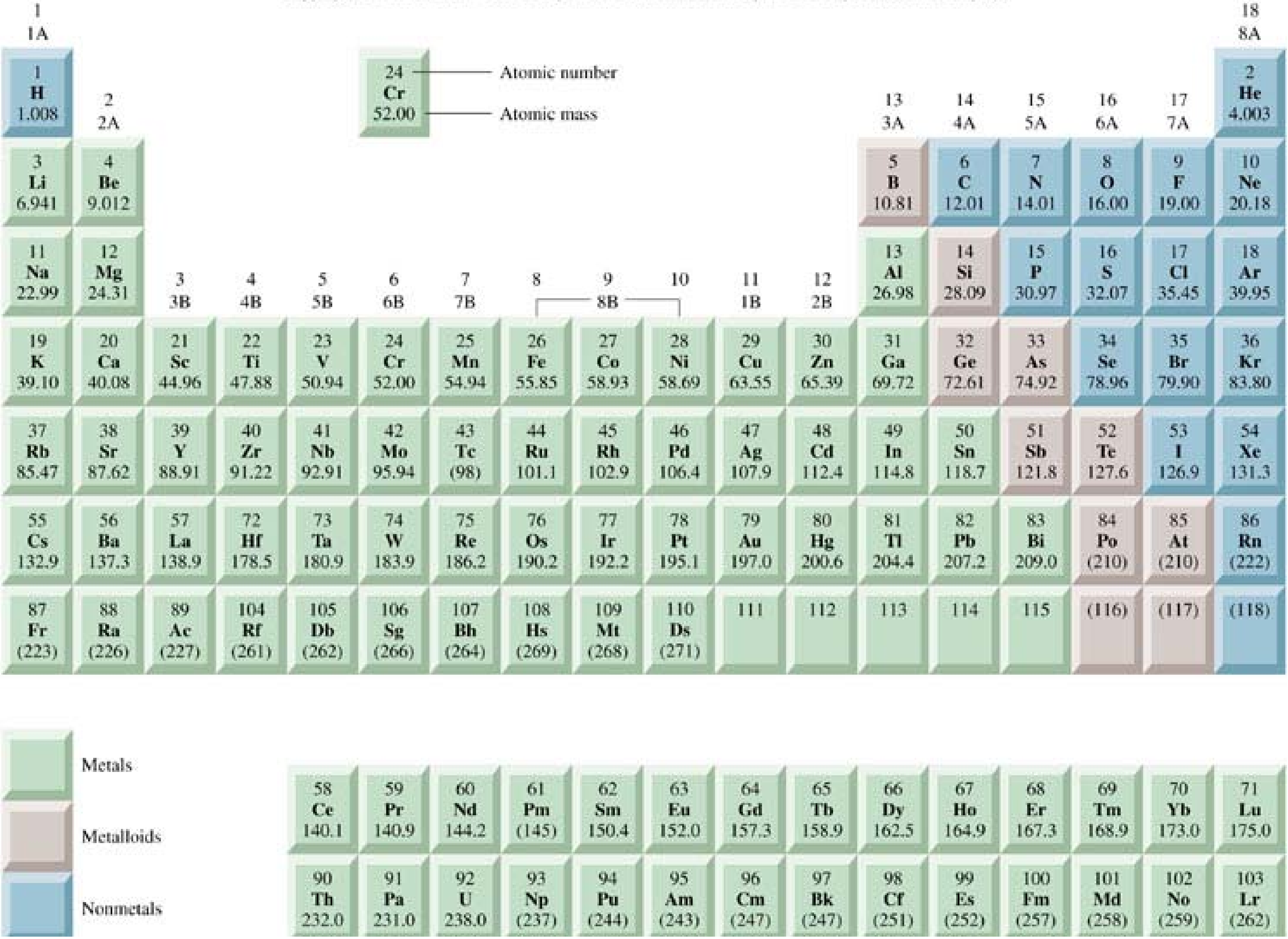
Visible light has enough energy to free an electron in Si!

Nonetheless, this process is not efficient enough to provide reliable solar power

We’d like a way to make the material *more* conductive than standard silicon

One way that this can be accomplished is using a process called **doping**, where small amounts of other elements are added to pure silicon

Typically, we use about 1 ppm gallium (Ga) or arsenic (As) for this



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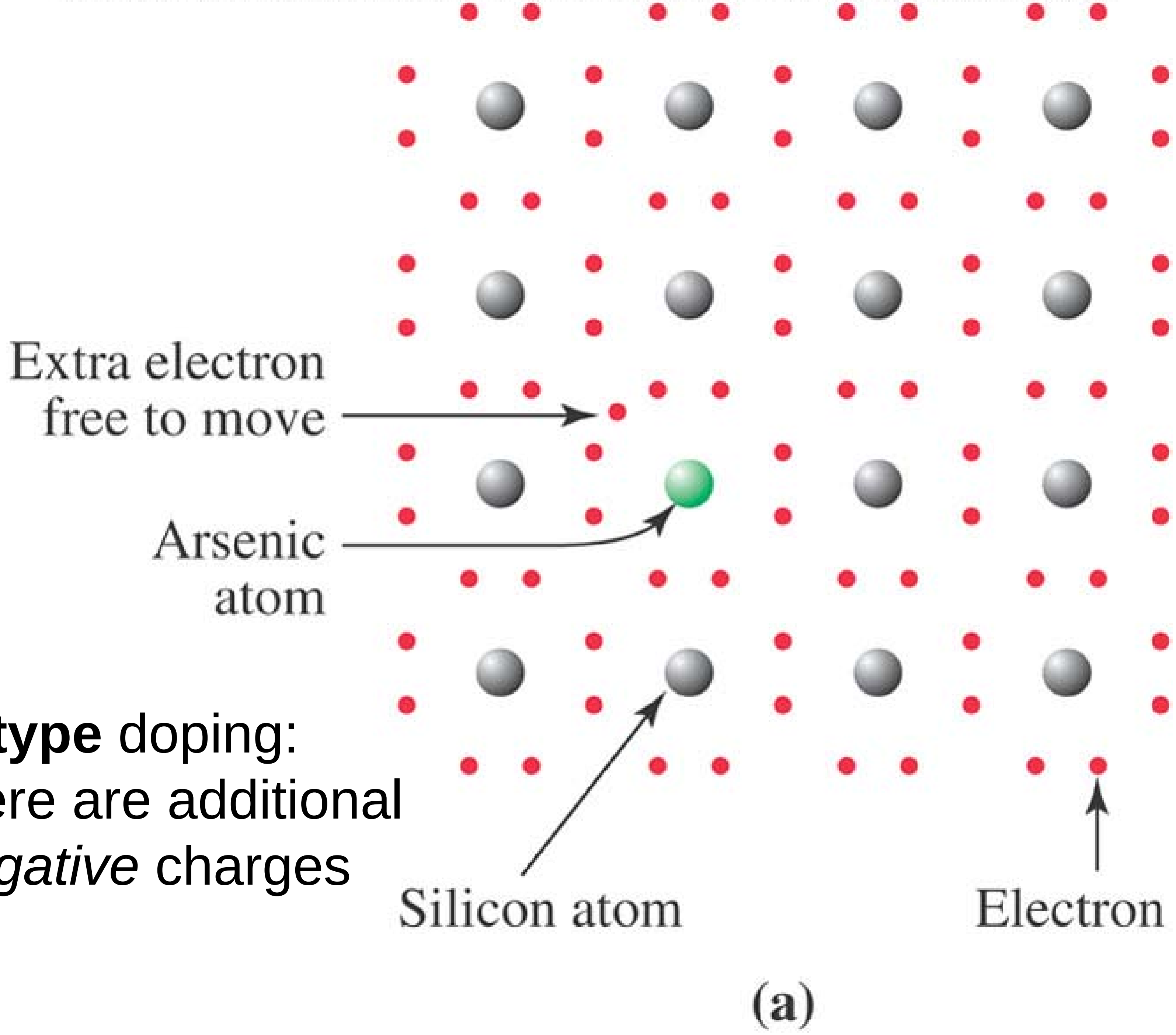
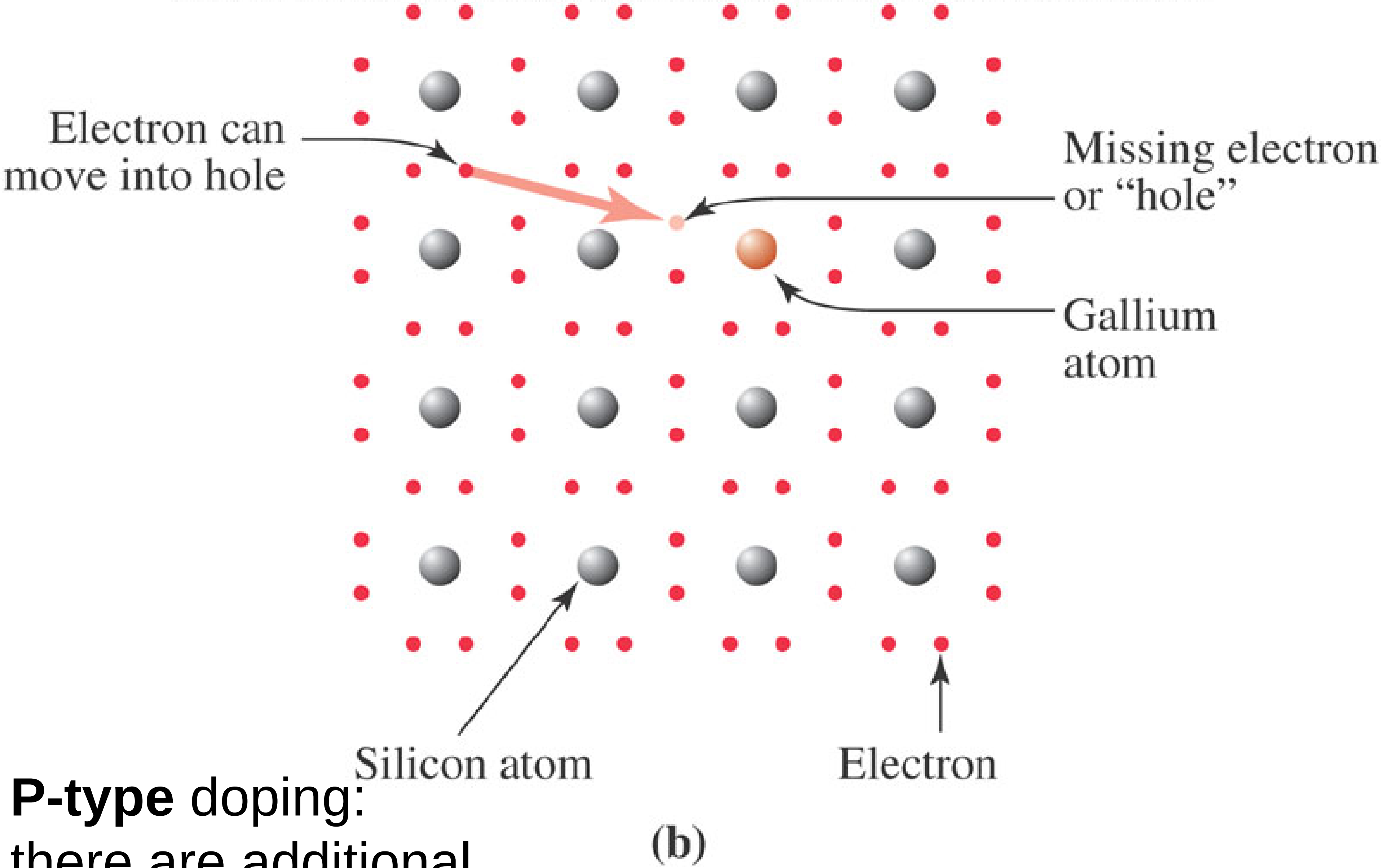


N-type doping:
there are additional
negative charges



P-type doping:
there are additional
positive charges

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Either kind of doping means that it requires less energy to induce conduction

This means that longer wavelengths of light can do the job

This means that **more** of the Sun's rays can be harnessed

How do we harness this to provide predictable current?

We sandwich layers of n-type semiconductors together with p-type semiconductors, forming **p-n junctions**

Photovoltaics: Plugging in the Sun

We sandwich layers of n-type semiconductors together with p-type semiconductors, forming **p-n junctions**

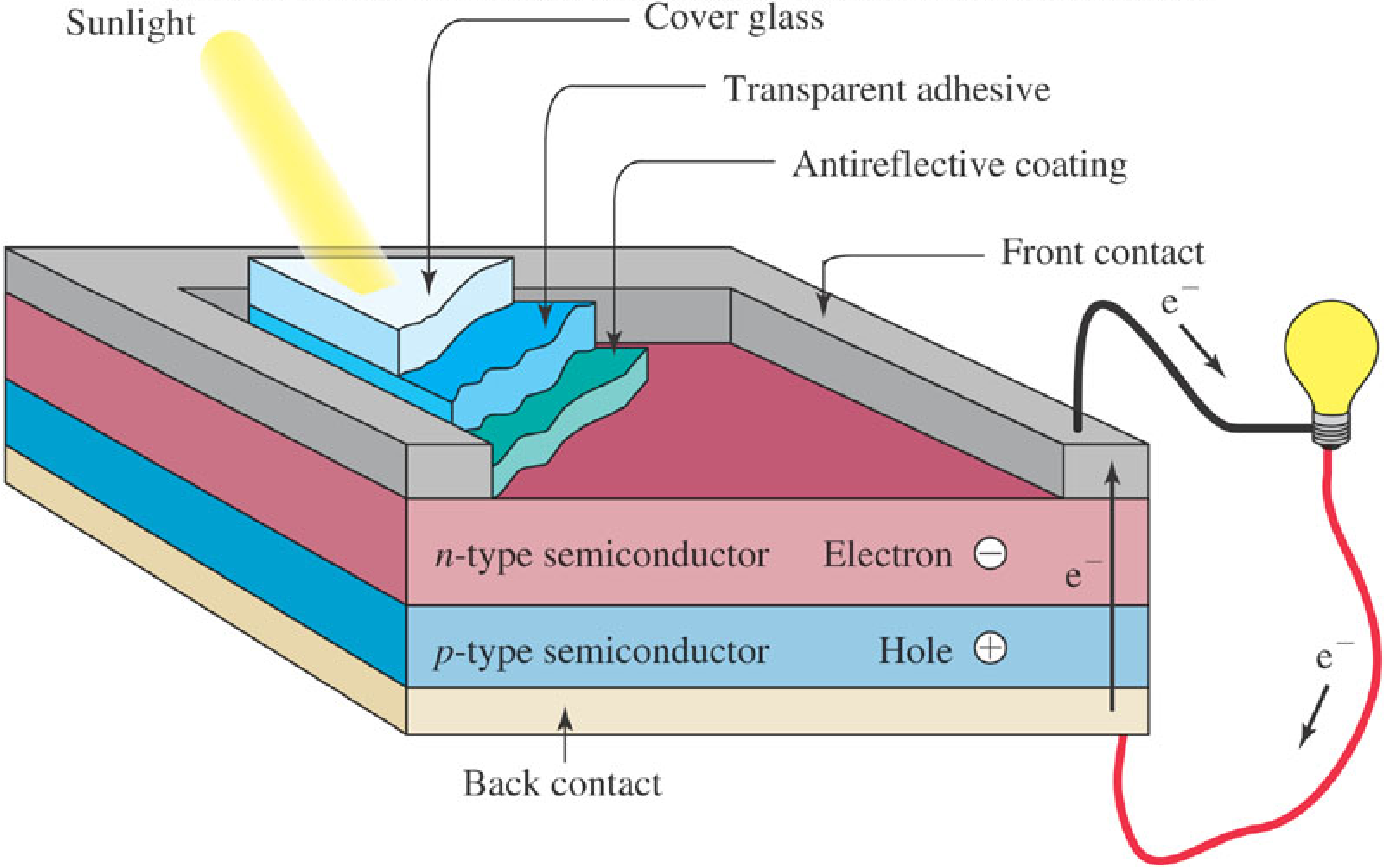
Electrons from the n-type layer diffuse into the positive holes in the p-type layer

This produces a **voltage** across the junction

As light shines on the junction, *electrons move*, and the current flows

Just as important as the reduced energy for conduction is the fact that the junction provides a **direction** of the flow, and this can be tapped as in any other electrochemical cell

As long as the cell is exposed to light, current will flow


Sunlight
Cover glass
Transparent adhesive
Antireflective coating
Front contact
e⁻
n-type semiconductor
Electron ⊖
e⁻
p-type semiconductor
Hole ⊕
e⁻
Back contact

Photovoltaics: Obstacles

So why isn’t solar power providing ALL of our electrical needs?

Much like the hydrogen fuel cell, the silicon needed for PV cells is in short supply

Silicon itself is plentiful – **sand** is SiO_2, and essentially infinite

But pure Si is quite rare, and the purification process is expensive

PV cells require 99.999% pure silicon

Photovoltaics: Obstacles

So why isn’t solar power providing ALL of our electrical needs?

The process of converting radiant energy is also somewhat inefficient

In principle, 31% of the Sun’s energy to which the PV cell is sensitive could be converted into electricity

But some of the radiant energy is reflected or absorbed by the rest of the cell

Modern PV cells have efficiencies up to 15%

- Compared to ~4% in the 1950s
- Compared to the 63% maximum efficiency of a conventional power plant

Photovoltaics: New Directions

Scientists are also searching for new compounds to replace silicon

Much of the effort has been put into using germanium – the element between gallium and arsenic, with the same number of valence electrons as silicon

New options include 50/50 compounds whose number of valence electrons *average* the same as Si or Ge

GaAs, InAs, CdSe, CdTe

Some exciting developments have occurred with mixtures of indium, gallium and nitrogen which have greater maximum efficiency and are able to access more of the Sun’s emitted wavelengths

Photovoltaics: New Directions

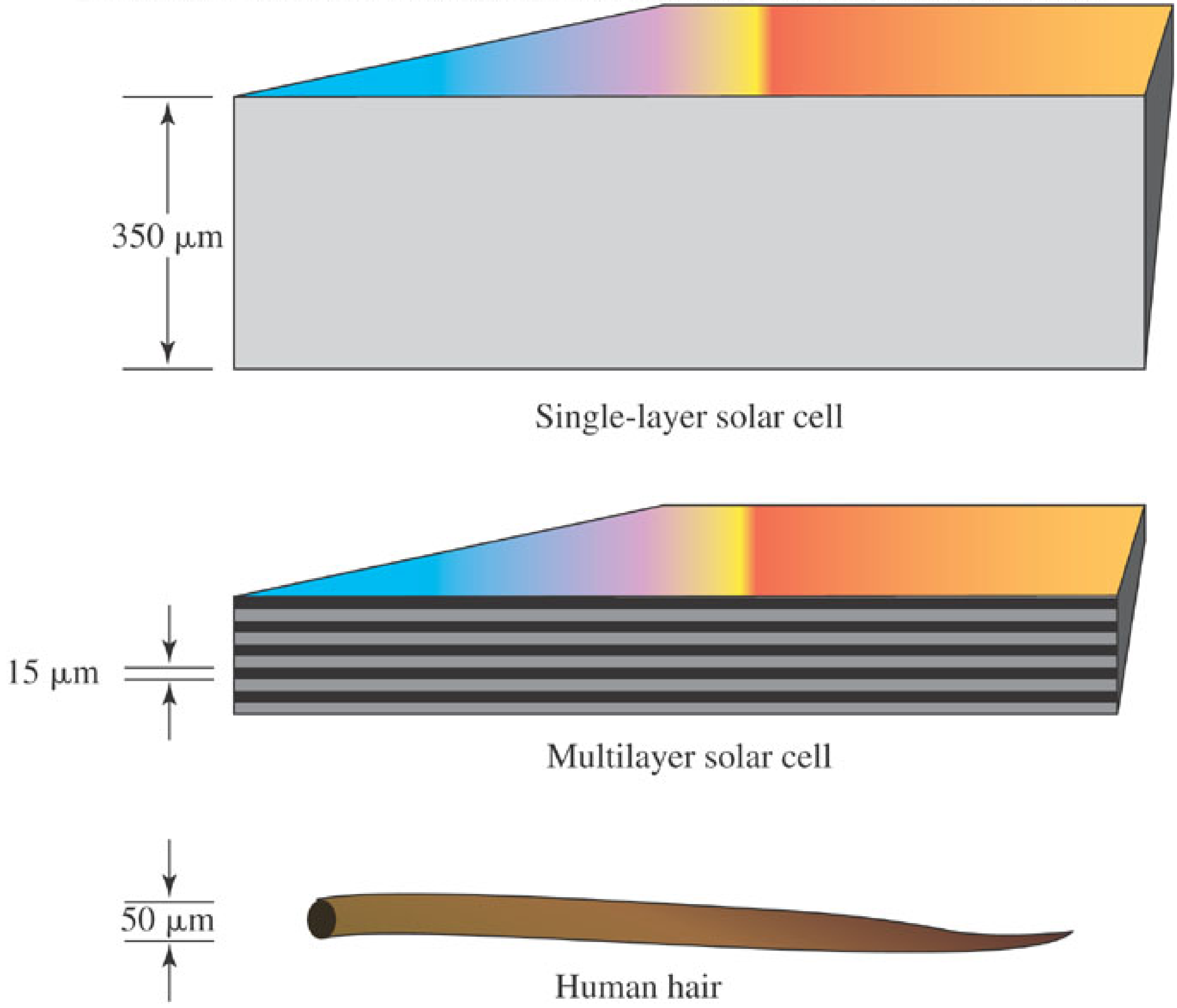
Another direction of research is in changing the *form* of the silicon

Non-crystalline silicon is more efficient at absorbing photons

This allows the absorbing material to be made much thinner

Similar research is going on into producing much thinner individual *layers* within the cell, meaning electrons have shorter distances to travel to the p-n junctions and efficiency can be higher

Lower-grade silicon can be used for these new applications


350 μm
Single-layer solar cell
15 μm
Multilayer solar cell
50 μm
Human hair

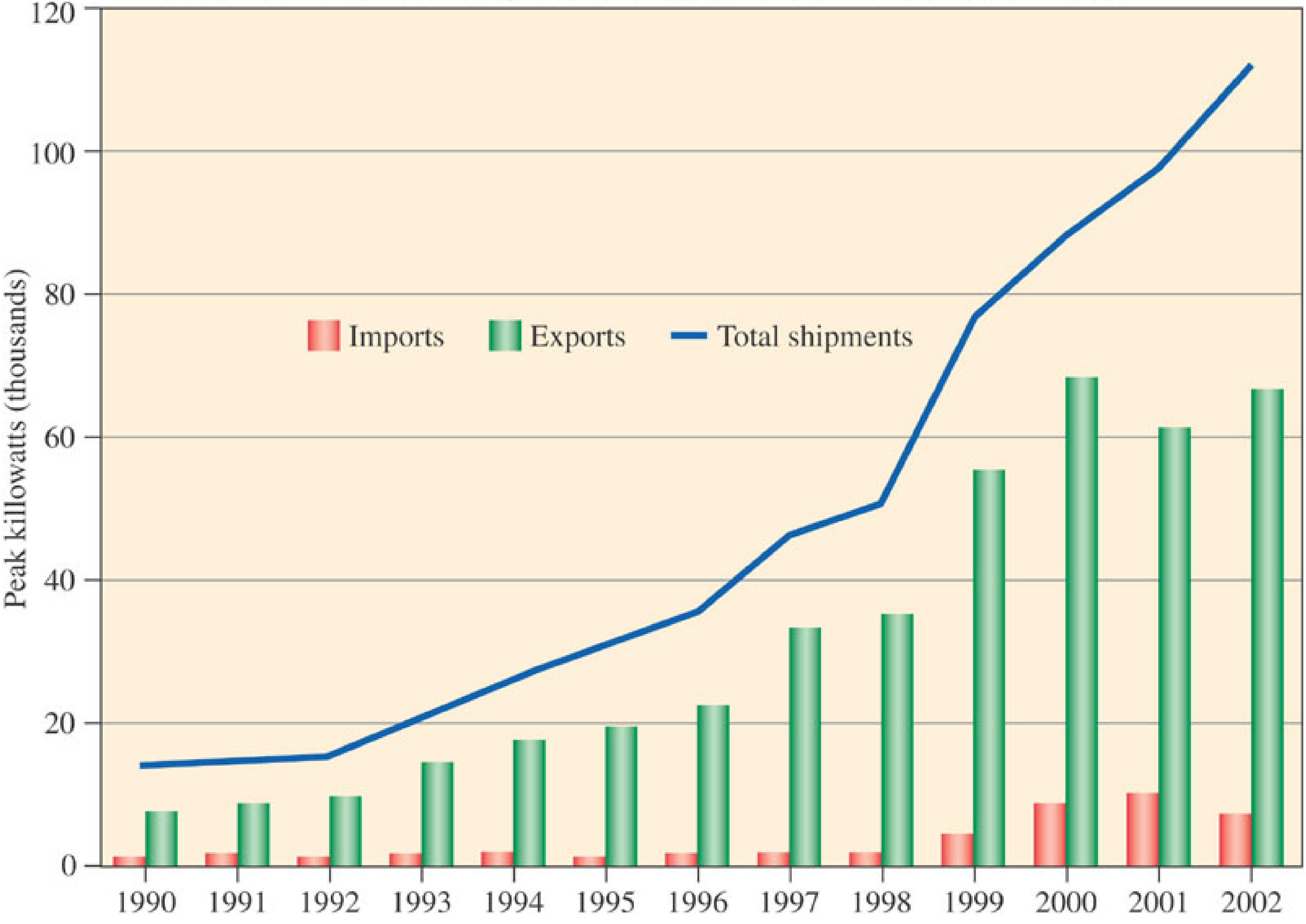
Photovoltaics: The Future

Like many other technologies we’ve discussed, the price of PV cells is decreasing at the same time that fossil fuels become more expensive

- In 1974, PV electricity cost $3 per kilowatt-hour
- In 2003, the price was approximately 25 cents
- The Solel solar plant in California’s Mojave Desert operates at 10 cents per kW/hr

A 200 MW plant could operate on 1 square mile

It is estimated that the entire electrical needs of the U.S. could be met by a solar plant the size of New Jersey



120
100
80
60
40
20
0
Peak killowatts (thousands)
Imports
Exports
Total shipments
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002

Photovoltaics: The Future

In the U.S., the Million Solar Roofs program has pledged to install 1 million residential PV systems by 2010

Grew out of California statutes to encourage solar power

Initially confined to CA, but has since expanded

Couples PV electrical power with **solar thermal** systems designed to heat air and water directly

By partnering with local businesses, they have made the technologies much more affordable to interested consumers

Photovoltaics: The Future

The most explosive growth in solar power is in regions inaccessible to “traditional” power

PV systems require very little wiring, and are nearly maintenance-free

Alaska, Colombia, the Dominican Republic, Mexico, Sri Lanka, South Africa, China, India

And Indonesia, where 70% of homes are off the power line grid

Photovoltaics: The Future

Solar powered cars have been designed and driven

Both the U.S. and Australia have long distance road races for solar vehicles

Solar powered bikes, boats and planes have been successfully tested

For these races, PV cells are coupled with traditional (and non-traditional) storage batteries

A reminder of the fact that solar power is only available when the sun is shining

But by diverting extra power during daylight into recharging batteries, solar power has the potential to provide much of the energy shortfall