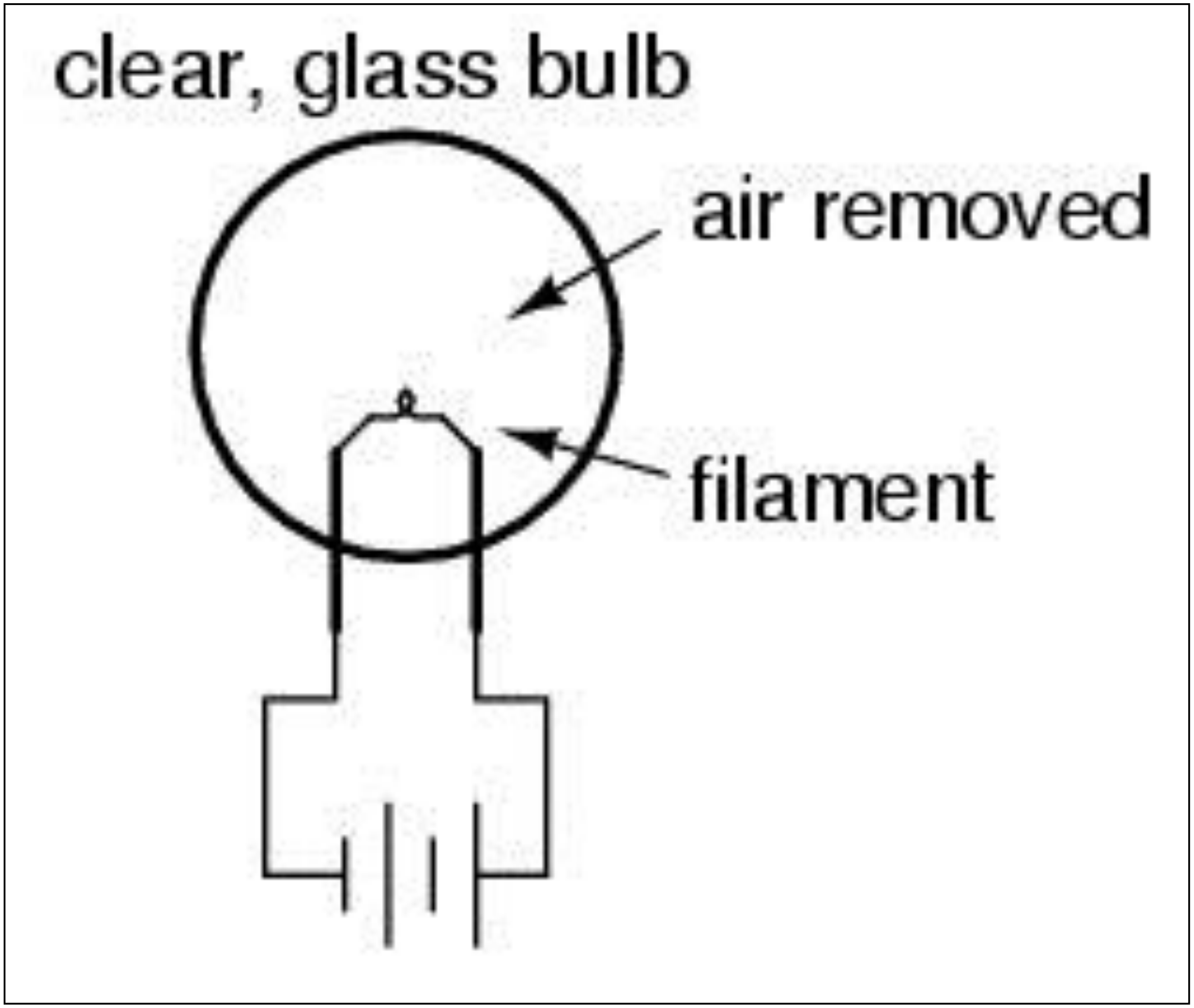
Sierra College **CIE-01**
Jim Weir **530.272.2203**
jweir43@gmail.com
www.rstengineering.com/sierra

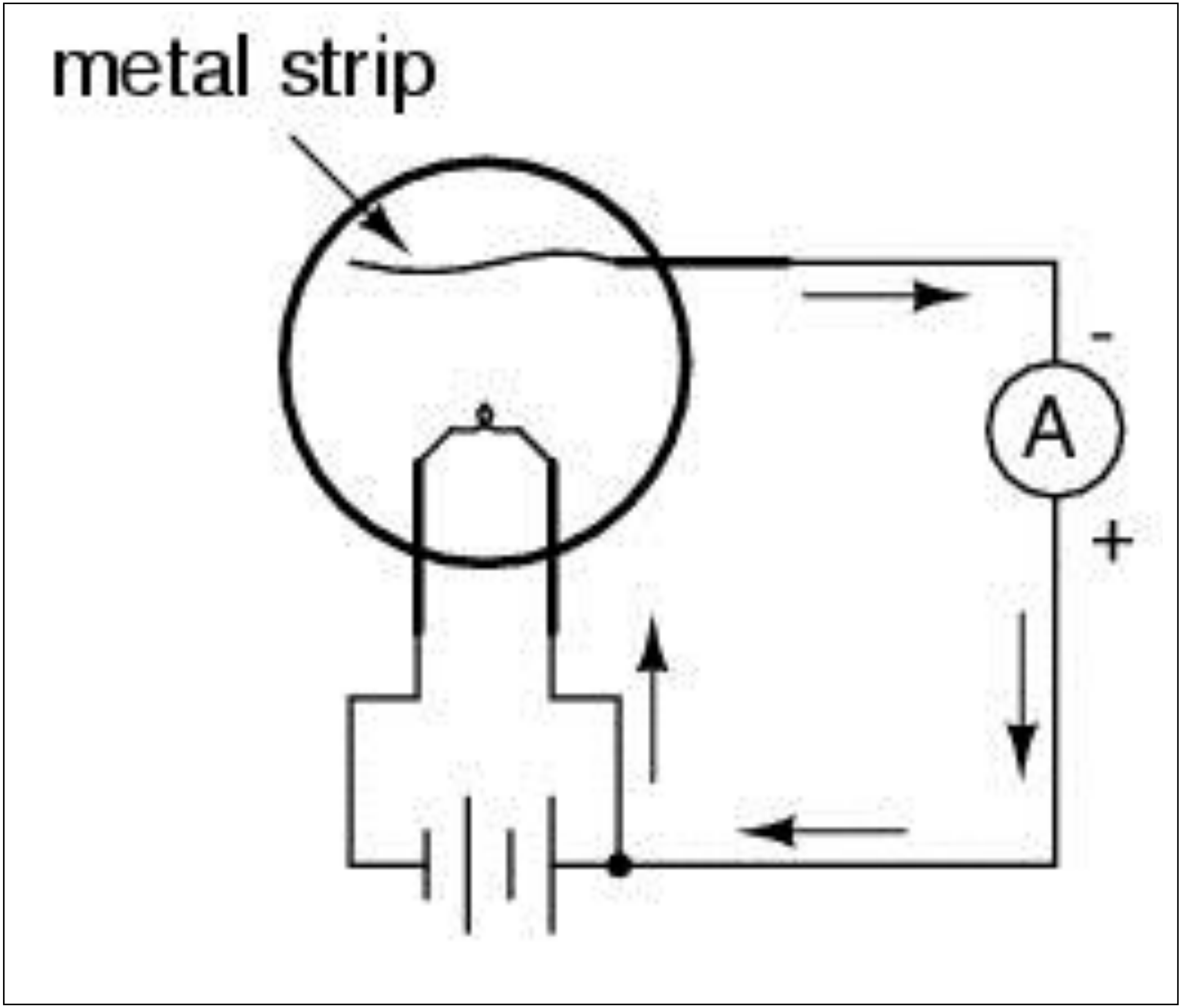
Lesson 06

Vacuum Tubes
Elementary Semiconductors
Diodes

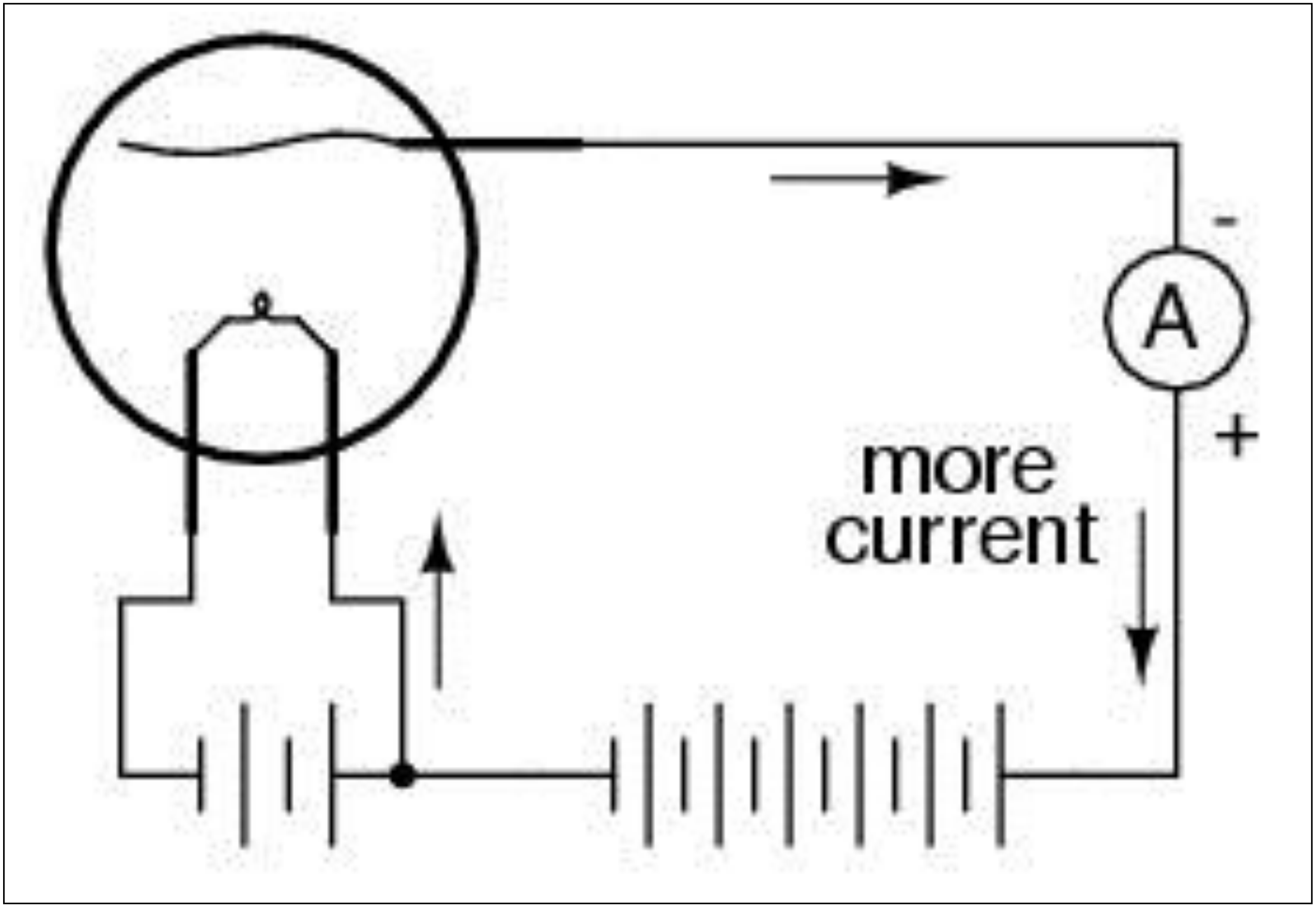
Vacuum Tubes: In 1879, Edison had made great strides in perfecting his electric light bulb design. However, he was curious why the inside of the glass envelope around the filament darkened over time. He theorized (correctly) that the carbon on the sewing thread that he was using as a filament was being "boiled off" of the thread and condensing on the relatively cool glass surface.



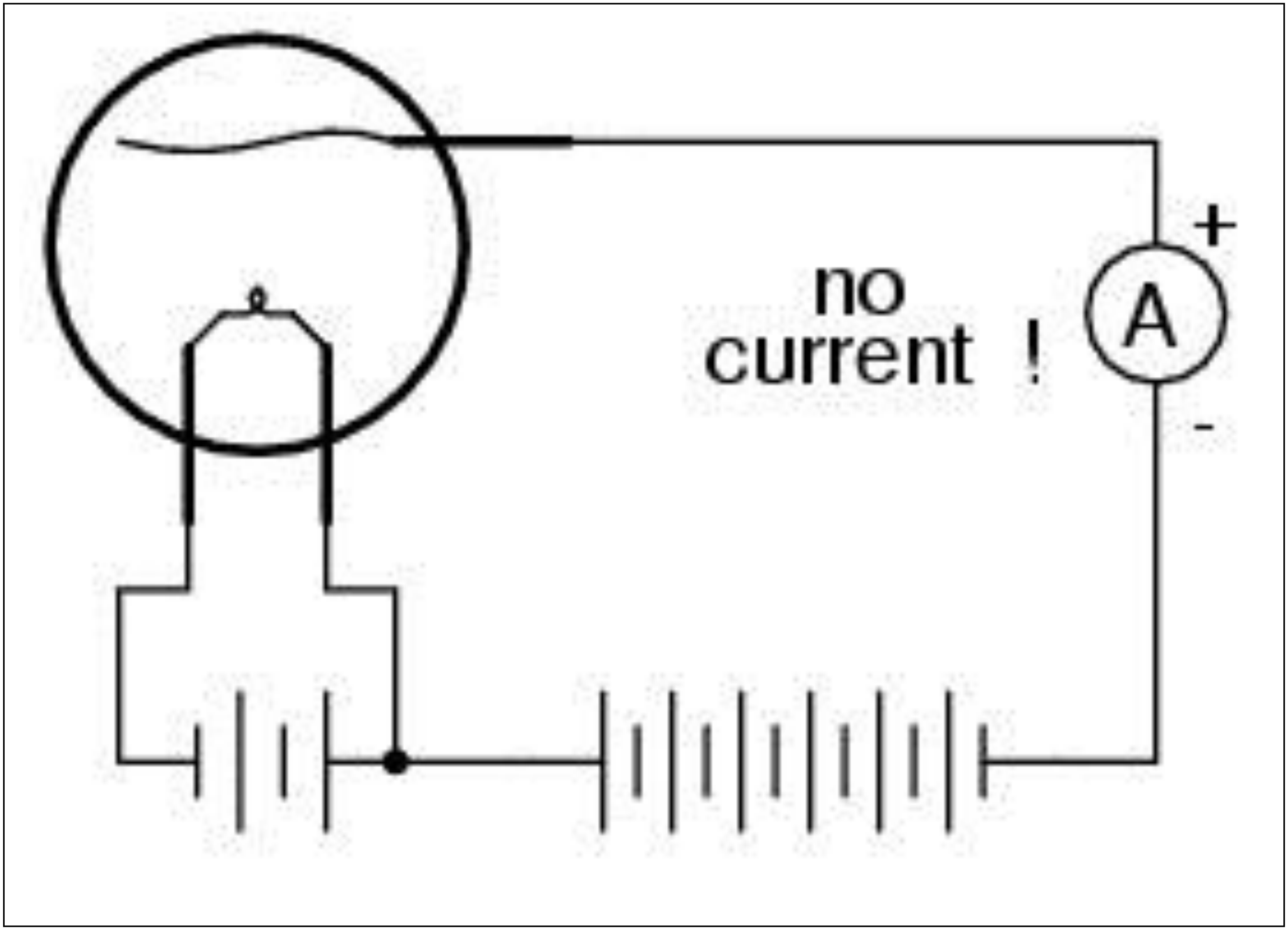
In 1883, in an attempt to suck the carbon onto another surface, Edison experimented with putting a metal strip or plate inside the light bulb to see if he could coax the carbon into plating out on the metal instead of the glass. When he hooked an ammeter up between the filament and the metal strip (let's start calling it the "plate") he noticed that there was a current flowing.



In an attempt to suck more current (and perhaps catch those pesky carbon atoms in the process), he hooked a bigger battery up between filament and plate. While he certainly achieved his result of getting more current flow, he failed to attract any of the carbon onto the plate and thus considered the experiment a failure.



In the process, he noted that when he reversed the big battery, there was NO current flow. He noted this result and simply wrote the effect down as having no practical use. He had invented the vacuum tube and tossed the results into a dusty notebook on the shelf, then went back to working on the original problem of the glass darkening.



In 1904, John Fleming (England) re-discovered the "Edison effect" and the vacuum tube (what the Brits call a "valve"). His "diode" (from the Greek *di*=two *ode*=element, or a two element device) helped the newly invented "radio" science to press forward.

A diode has a single function in life. It allows electricity to flow in one direction and does not let it flow in the opposite direction. This definition is true no matter whether you are talking about vacuum tubes or semiconductors.

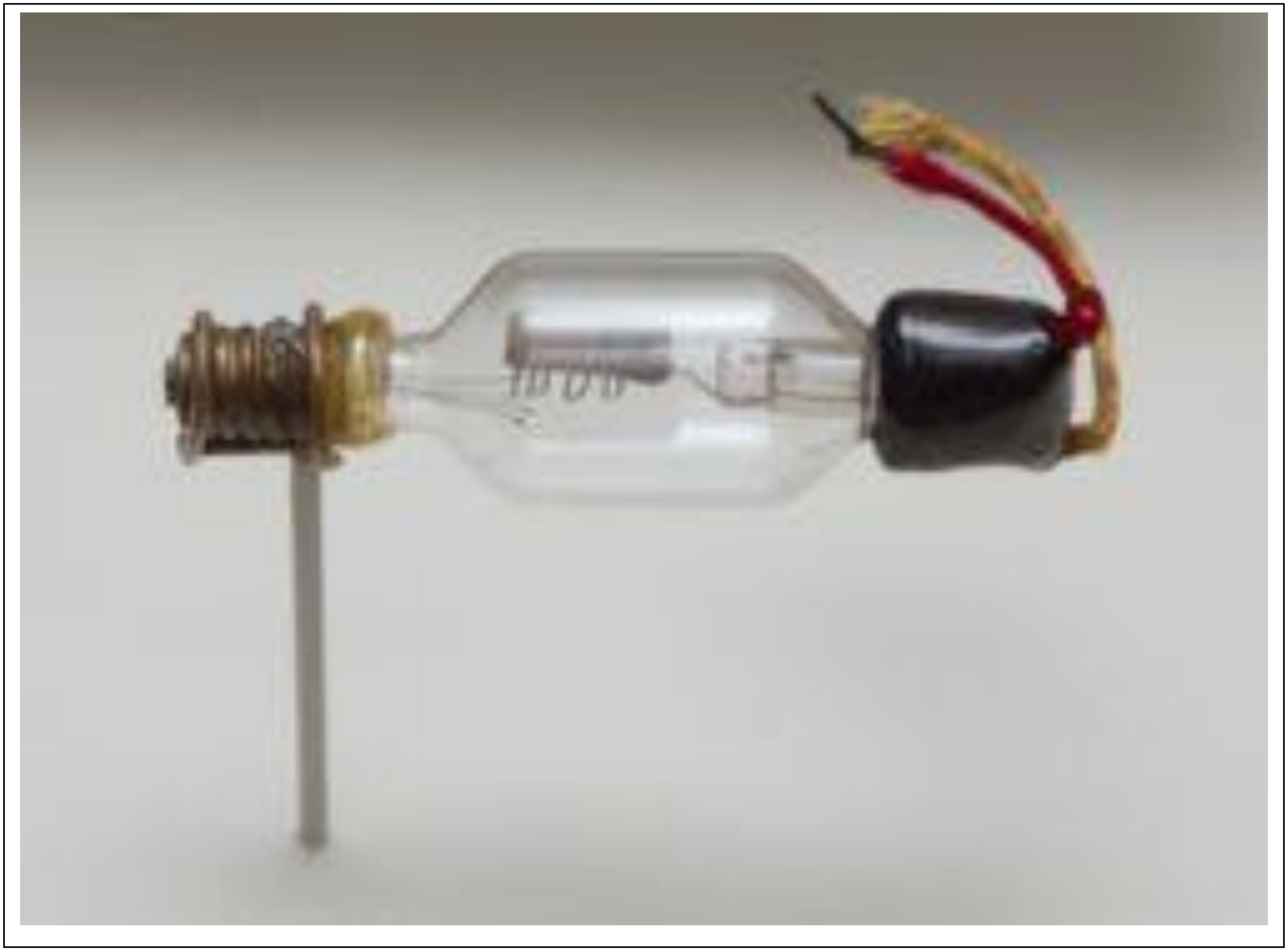
Note that our understanding of a "valve" is probably more an accurate description of what a tube does than a "tube". A "tube" is a round thingy without much more to describe it -- inner tube, a subway system, chemistry test tube, and the like. Valve is much more specific.

A picture of one of the first Fleming valves. Inventions aren't always pretty (as we shall soon see).

In 1906, Lee de Forest noticed that if he put a metal screen around the filament and between the filament and the plate that he could control a large amount of plate current change with a minute amount of current on the screen, which he called a "grid".

When you can control a large quantity of current or voltage at one point with a small quantity of current or voltage at another point, you have *AMPLIFICATION*.

De Forest called this invention the "Audion" but we know it today as a triode (Greek *tri*=three) or a three-element tube (filament or heater, grid, plate).



Later inventors added more grids for different reasons and we would up with tetrodes (4 elements), pentodes (5 elements), hexodes (6 elements), and heptodes (7 elements).

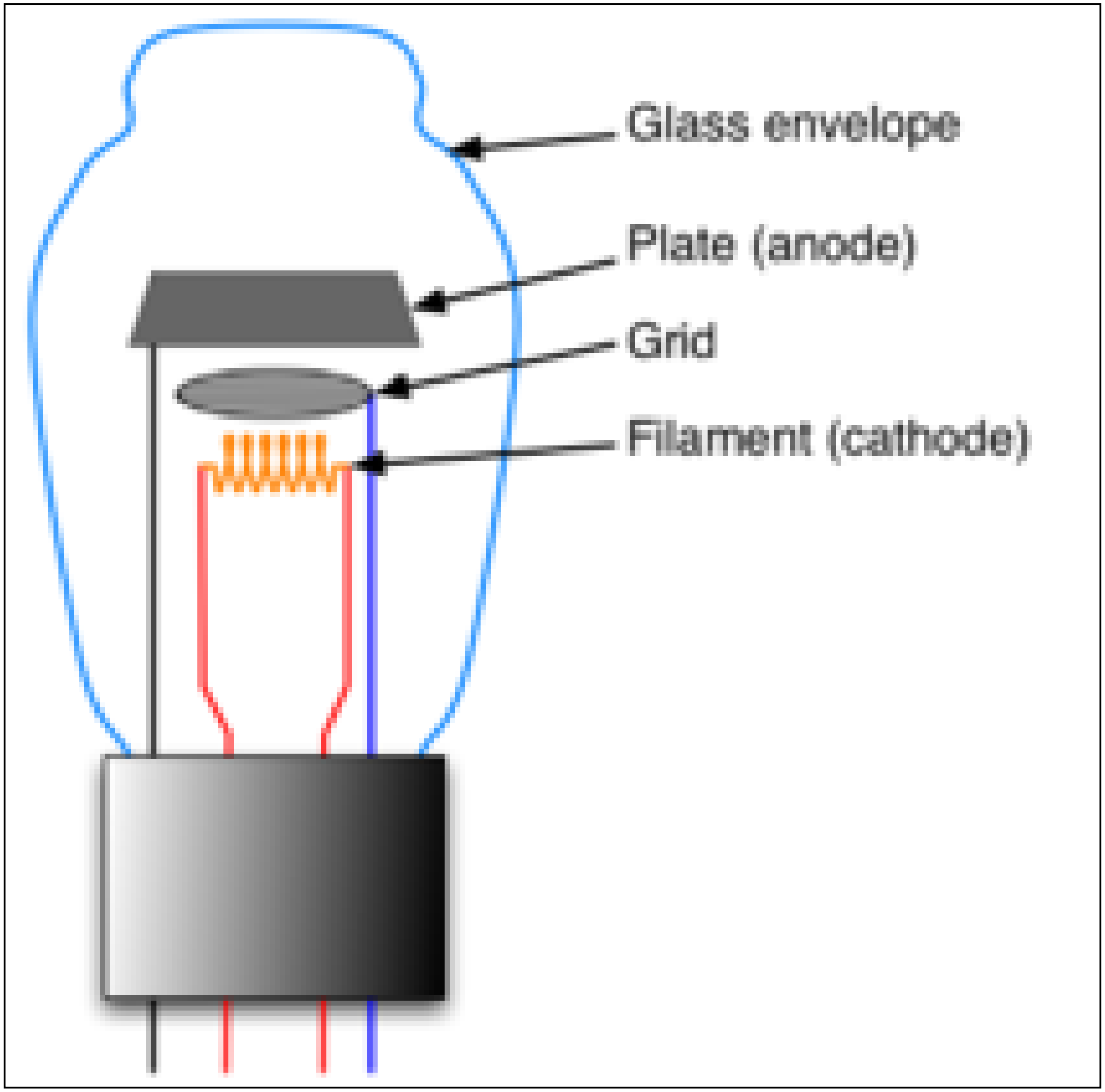
Here is how a vacuum tube works: The filament emits electrons by means of "thermionic emission", which means that when the filament gets hot, it "boils off" electrons. This electron-boil creates a "space charge" of electrons around the filament, or cathode.

If a relatively high positive voltage (say, above 20 volts or so up to a few hundred volts) is applied to the plate relative to the cathode, the electrons will be attracted to the plate … the higher the voltage, the more the electrons will be attracted up to a point called "saturation" where all the electrons that can be emitted are consumed by the plate.

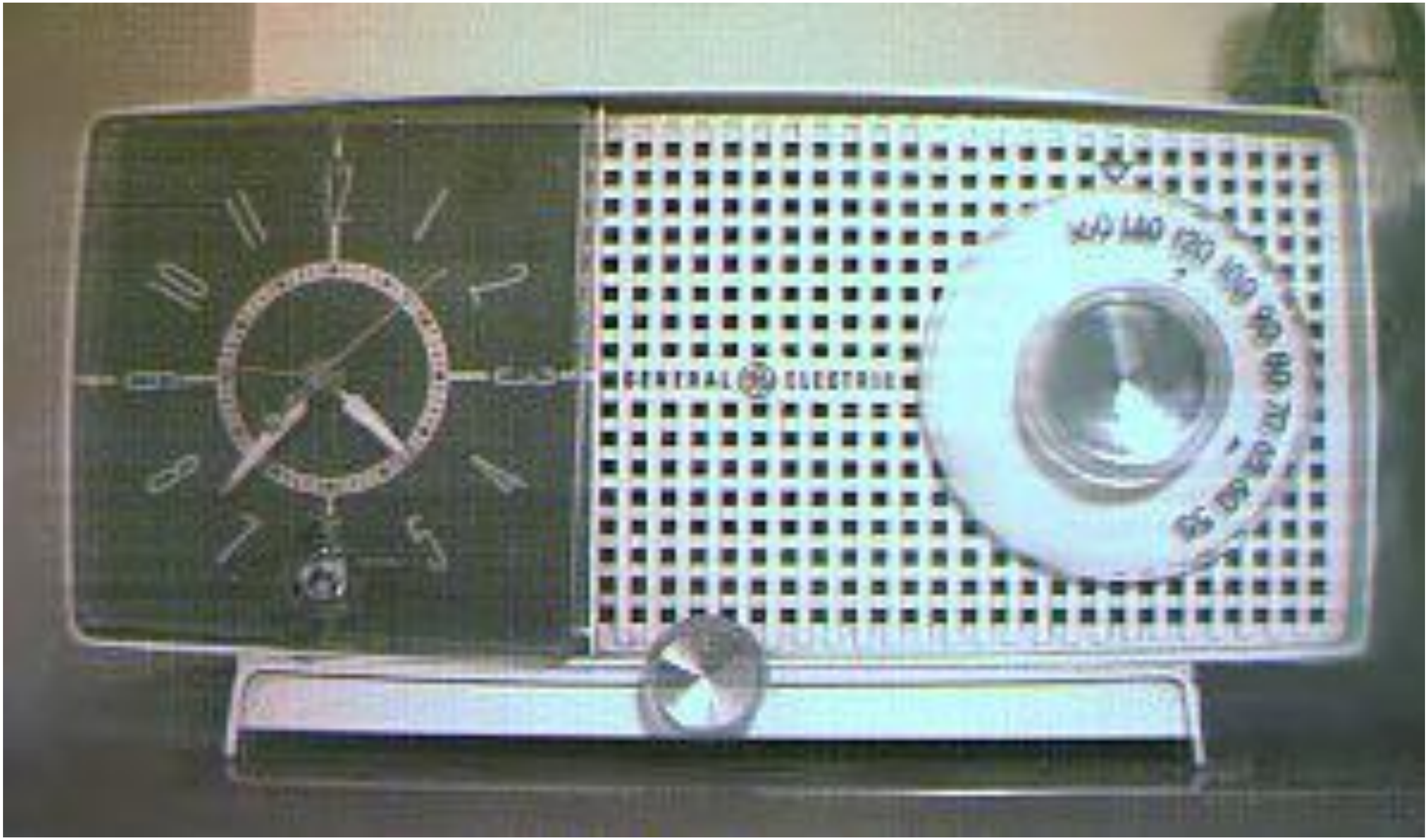
The addition of a grid (fine wire mesh) between the cathode and the plate allowed almost the same number of electrons to flow between the cathode and the plate until a negative voltage was applied to the grid. That negative voltage repelled the electrons and if the voltage was sufficiently negative, ALL the electrons were repelled, a condition known as cutoff.

Thus, a small amount of voltage (usually less than 10 volts in a small receiving tube) could cut off several hundred volts on the plate, and thus we have amplification. Now we have something more like a faucet valve.

And, once we have amplification, and if we can control how and where the large plate signal is fed back to the control grid, we can have the current in the tube "chasing it's tail" and in the process (depending on how fast you made it chase the tail) you have an "oscillator", or producer of radio waves. After this, all things are possible in electronics.



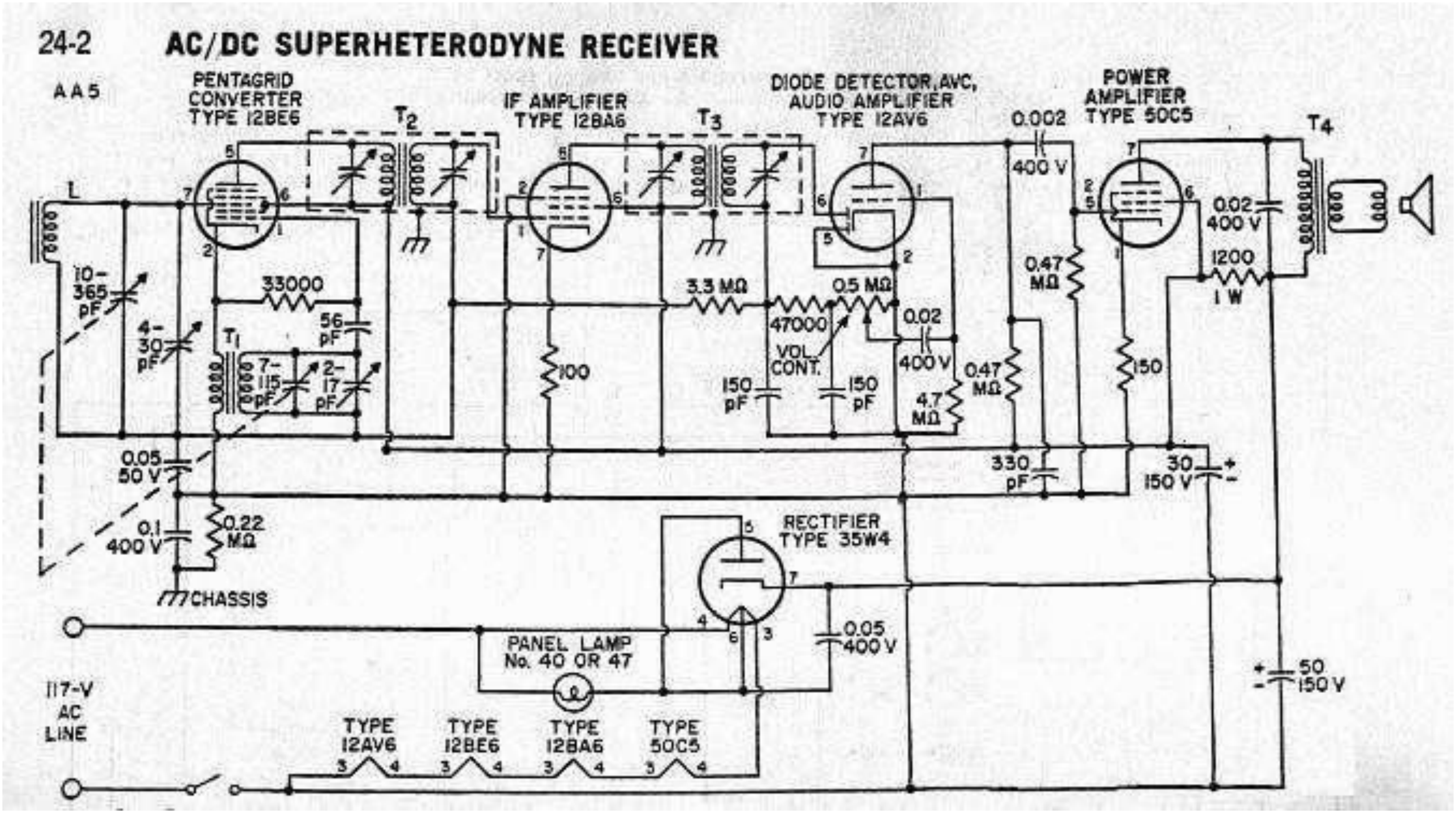
Here is a photograph of what is called the "all american 5", so called because millions of them were made with exactly the same tube lineup, circuit, and components. You could make them for peanuts and sell them for real money. The one shown here woke me up every day of my life from 5th grade through high school.



Here is a schematic of one of those old turkeys.

A few items of interest. One, note that the filament voltages (50+35+(12*3) equals a particularly interesting voltage. What is it?

Second, note that the AC line is directly connected to the radio without going through a voltage reducing power transformer. This was particularly interesting to a pre-teenage boy who loved messing around inside of radios … until I got my hands across the power line one day.



Third, note (going from left to right) a 7-element heptode converter, a pentode IF amplifier, a triode-dual diode detector, a pentode power amplifier, and a diode rectifier.

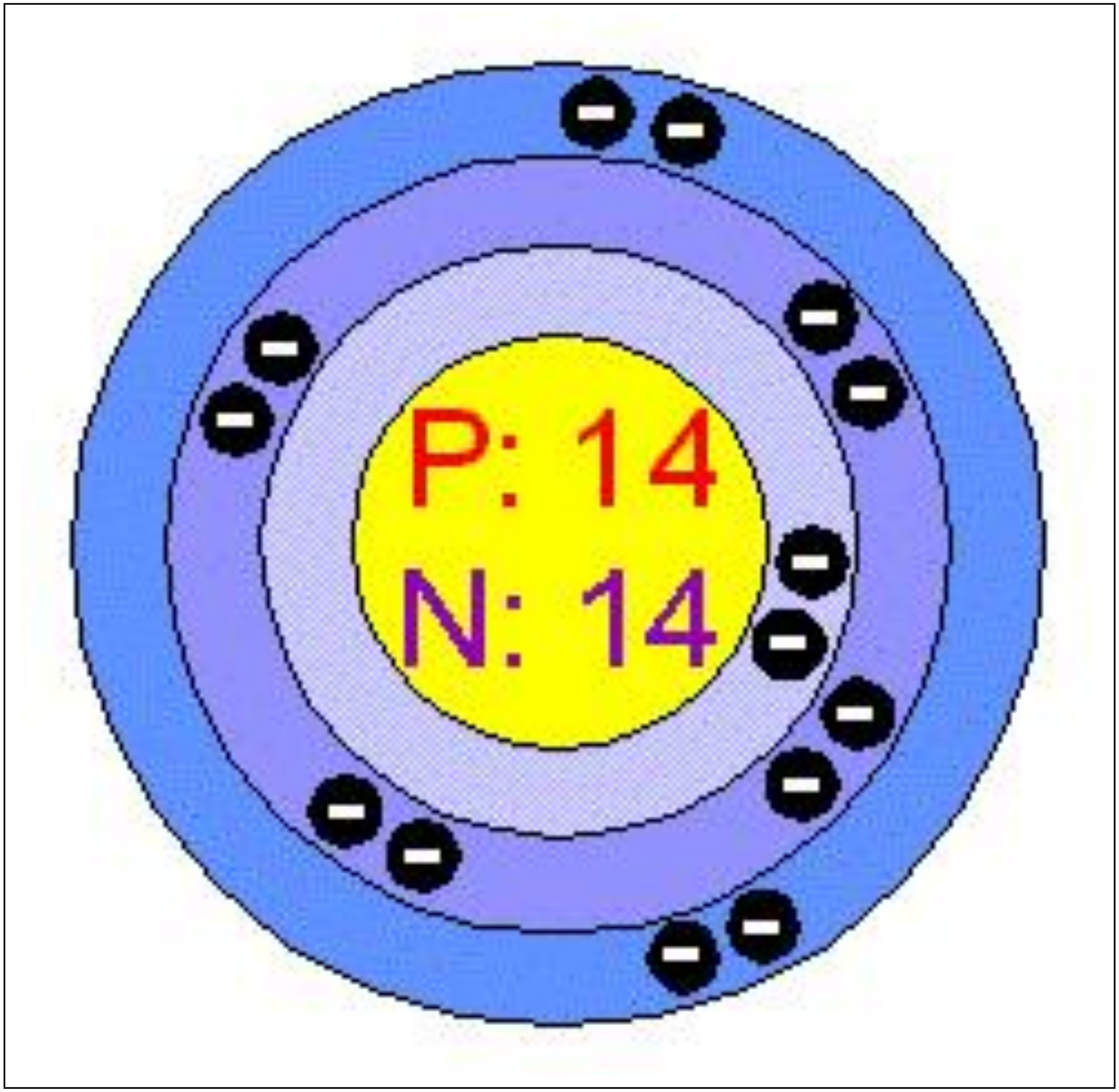
The last gasp of the power-hungry vacuum tube was the Nuvistor. Introduced in 1959, it was intended to compete with transistors. Less than a decade later, the Nuvistor was quietly laid to rest in favor of the power-sipping transistor.

There is argument, even to this day, about whether or not music amplifiers "sound better" when built with vacuum tubes. Here you see a guitar amplifier built with vacuum tubes that will sell for upwards of $5000, while you can put together a solid-state "transistor" version with roughly the same specifications for less than a tenth of that price.

Semiconductors: We have a pretty good concept of what conductors are. These are things that transmit electrons from one circuit to another fairly well. All metals, carbon, and a few of the rare earths come to mind. Insulators have a similar understanding … glass, ceramics, dry wood, air, and plastics are some that we have seen.

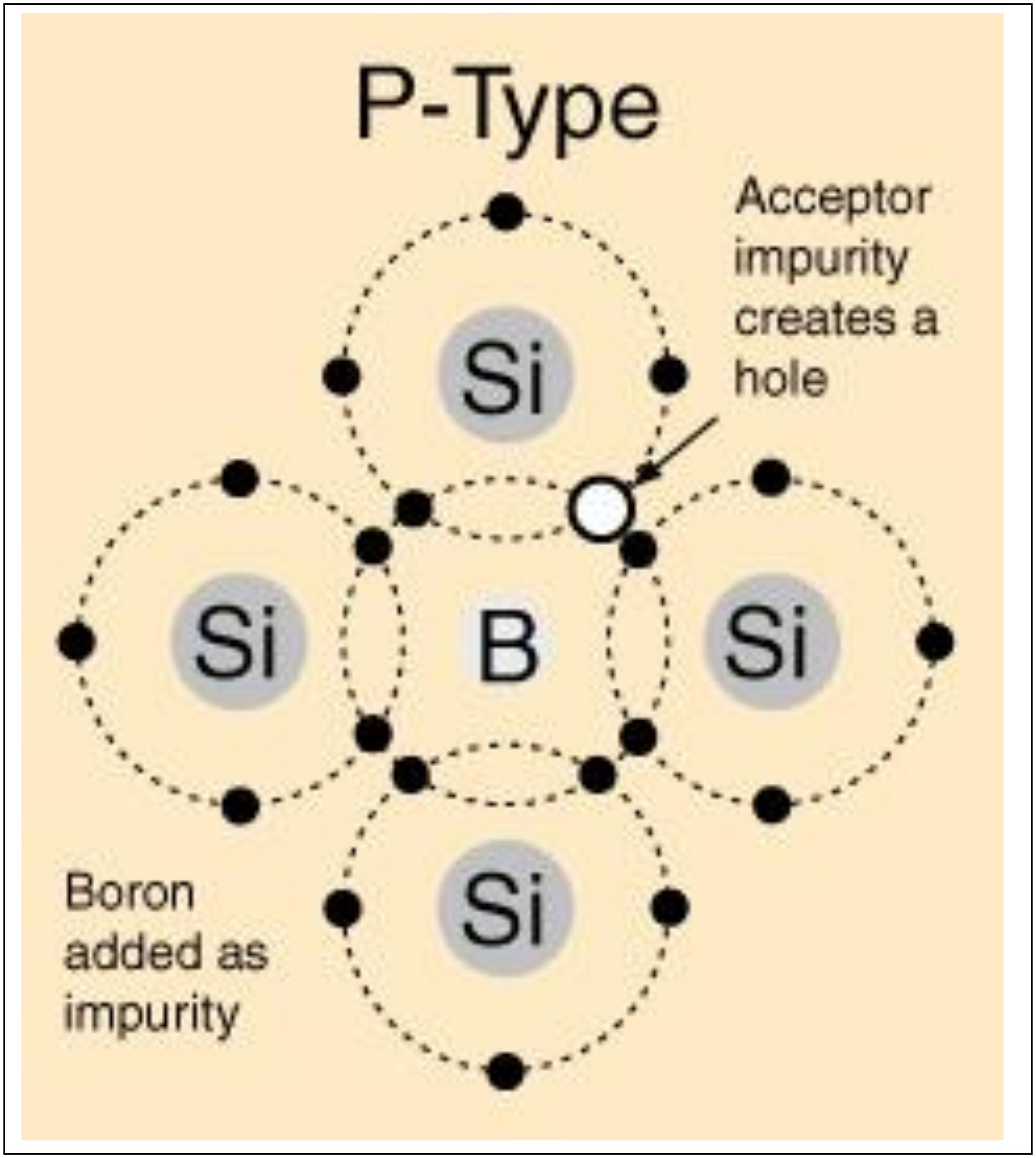
But what is a semiconductor? I can tell you what it is NOT. It is NOT pure silicon. Pure silicon is nearly the best insulator known to man. In researching this week's lesson, I cannot tell you how many hits I got proclaiming that silicon and germanium are semiconductors. They are NOT.

Look at the atomic structure of silicon. See those four electrons out in the valence band? Those four electrons share quite nicely with their next door neighbor atom to form a very stable 8-electron conduction band with no electrons deficient or left over to cause conduction. Not only do they form a very nice shell-full atom, but this structure lends itself very well to forming nice crystals. The other three members of this 4th column of the periodic table contains carbon (diamond), germanium (which forms sort of nice crystals), and tin, which doesn't form crystals at all.



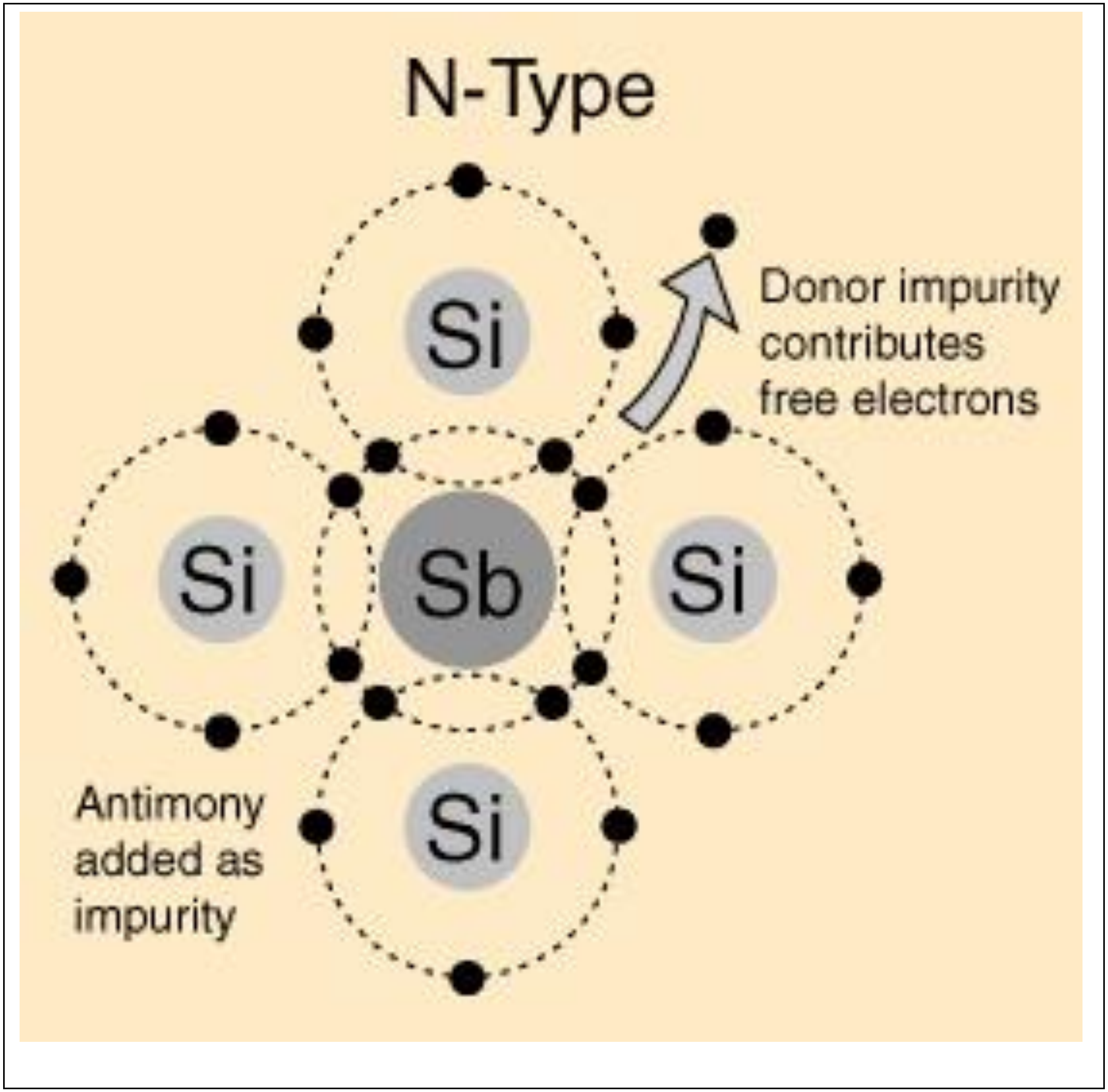
Now if you toss in a smattering of impurities of a certain kind (smattering is about one atom in every million atoms of silicon) then you can transform the silicon insulator into a doped silicon semiconductor -- not a good insulator, not a good conductor, but a material that has some very interesting uses.

What are the certain kinds of impurities? If we toss in some elements from column 3 of the periodic table (such as boron, aluminum, gallium, or indium) then we make a semiconductor that can acce***P***t electrons and is called a ***P**-type* semiconductor. The impurity is called an acce***P***tor.



On the other hand, if we "dope" (or toss in) some elements from column 5 of the periodic table (such as phosphorus, arsenic, or antimony), then we make a semiconductor that can ***D***o***N***ate electrons and is called an ***N***-type semiconductor. The impurity is called a ***D***onor.

So far, all we've learned how to make with semiconductors is a very expensive form of resistor.

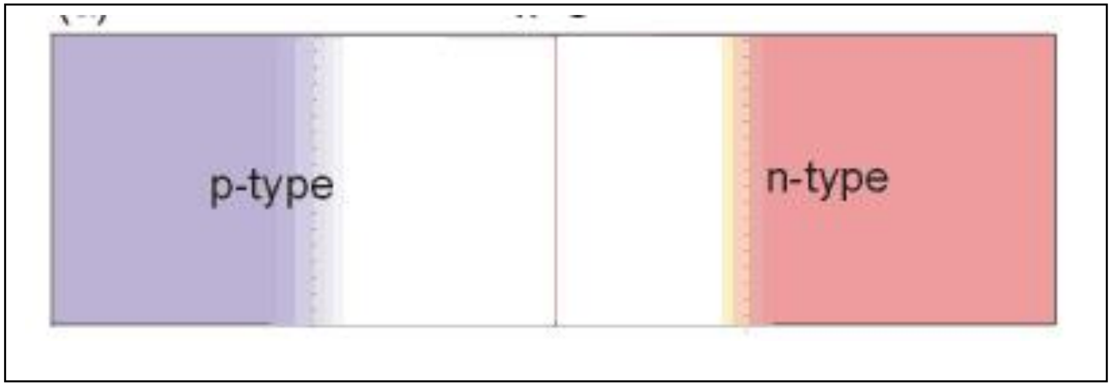


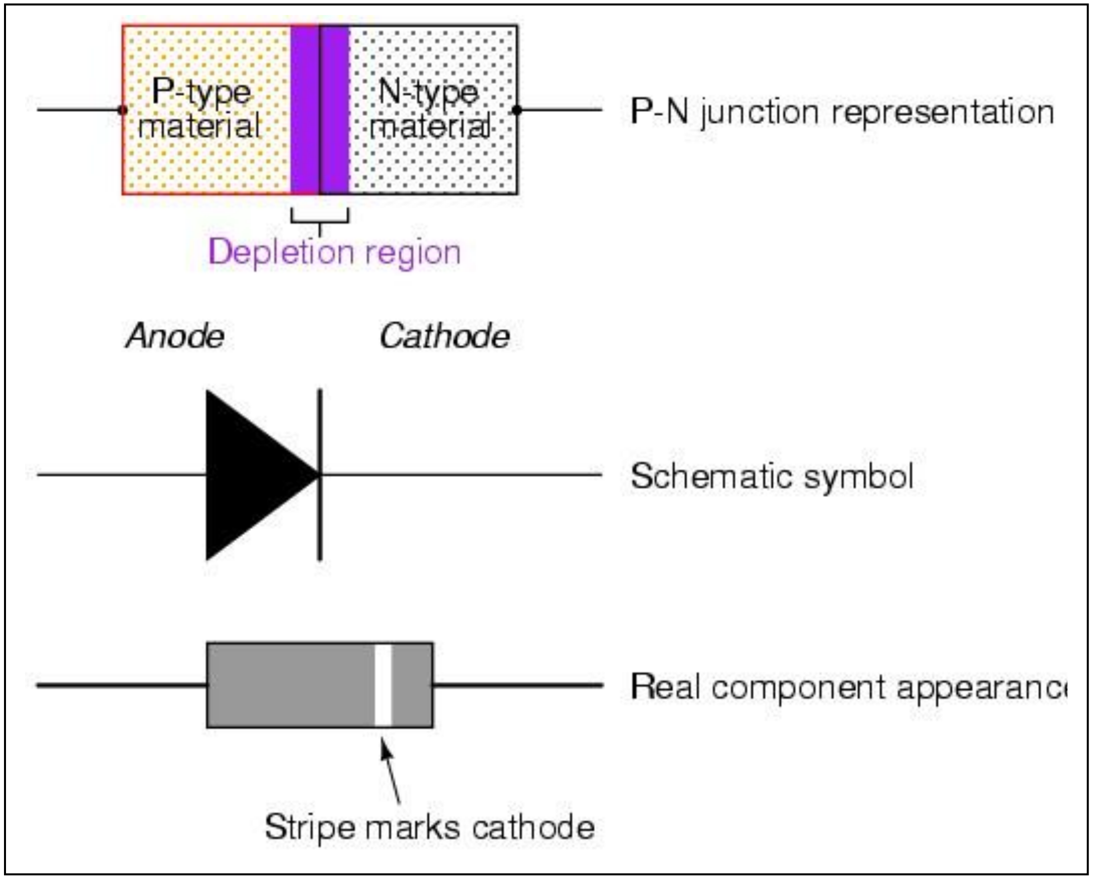
Diodes: We saw in the vacuum tube section how hot filaments and metal plates can make a device that passes current only in one direction, and we called this tube a diode. A very long time ago we found out how to make semiconductor material into a diode.

We could start with either N or P type material, it really doesn't make a difference. Suppose we have a flat piece of P type material that looks something like a hockey puck and the size of a grain of salt split into a thousand pieces. Now we take that hockey puck and expose just one side of the puck to some donor atoms, generally at some elevated temperature in an oven. Let's put in twice as many donor atoms as there are acceptor atoms and wait for just a few seconds, then take the hockey puck out of the oven. What do we have? In the n-type material, the donor atoms have so far overwhelmed the acceptor atoms that we have true n-type material. In the area where the donor atoms hadn't yet penetrated the crystal, we still have p-type material. Right in the middle we have a tiny, millimicroscopic area where the N and the P materials have fought to a standstill and we are back to pure ("intrinsic") material. This intrinsic area is called the "depletion region".

If you would like to get more into the physics of this operation, I'd suggest a good reading of Britney Spears Guide To Semiconductor Physics at http://britneyspears.ac/lasers.htm

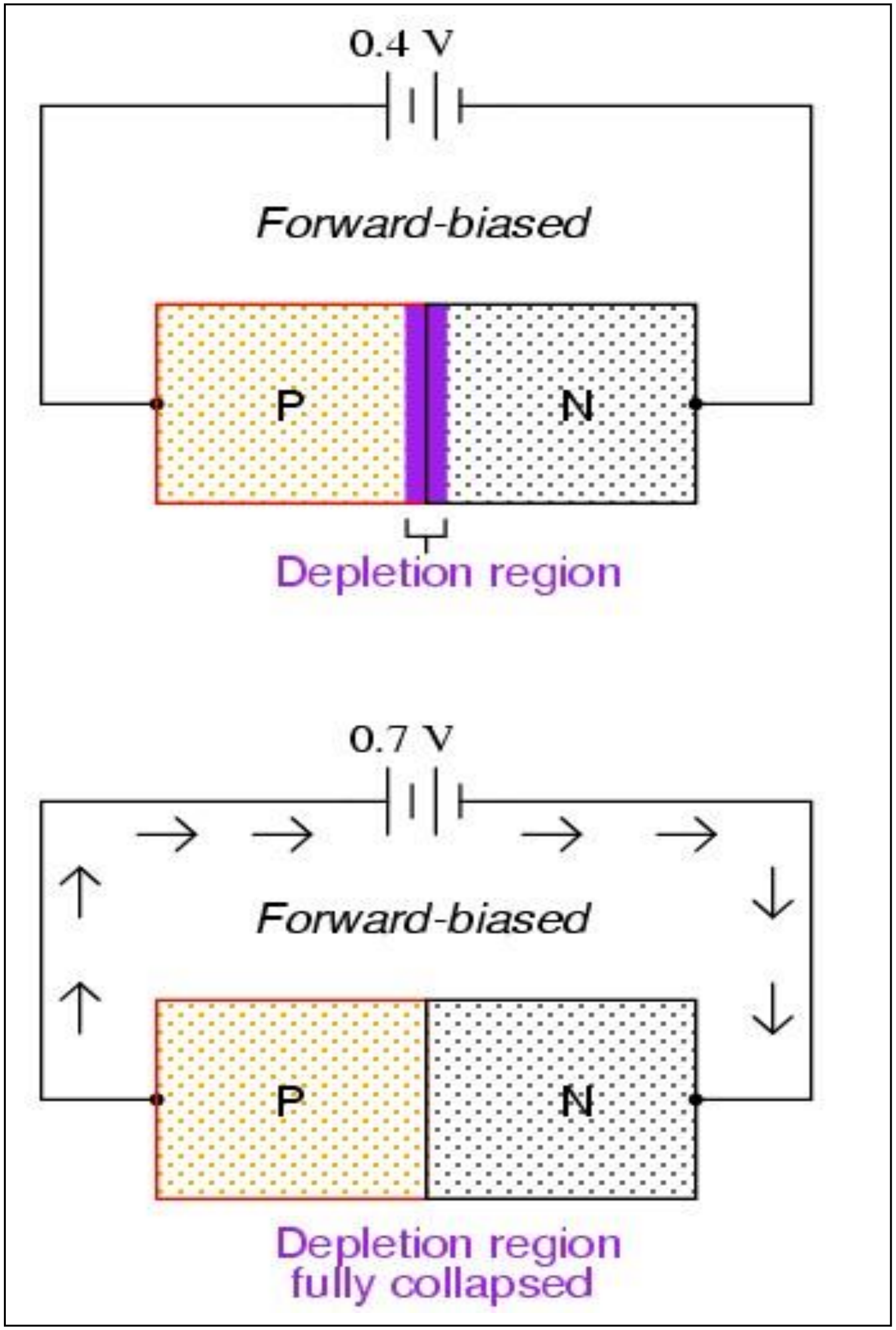
Now remember, intrinsic silicon is an INSULATOR, so for the time being, the diode is simply p material on one side, n material on the other side, and separated by an insulator. (Speaking of which, what do we call two conductors separated by an insulator?)





Let's put leads onto the p and n ends of our little sandwich and connect a power supply to the device, positive to the p side and negative to the n side. What happens?

At about 0.4 volts, the depletion region starts becoming narrow enough that electrons (and holes) that have enough energy can "jump" across the barrier. At about 0.7 of a volt, nobody has to do any jumping at all…the barrier is fairly well completely gone and electron-hole current may proceed virtually without limit.

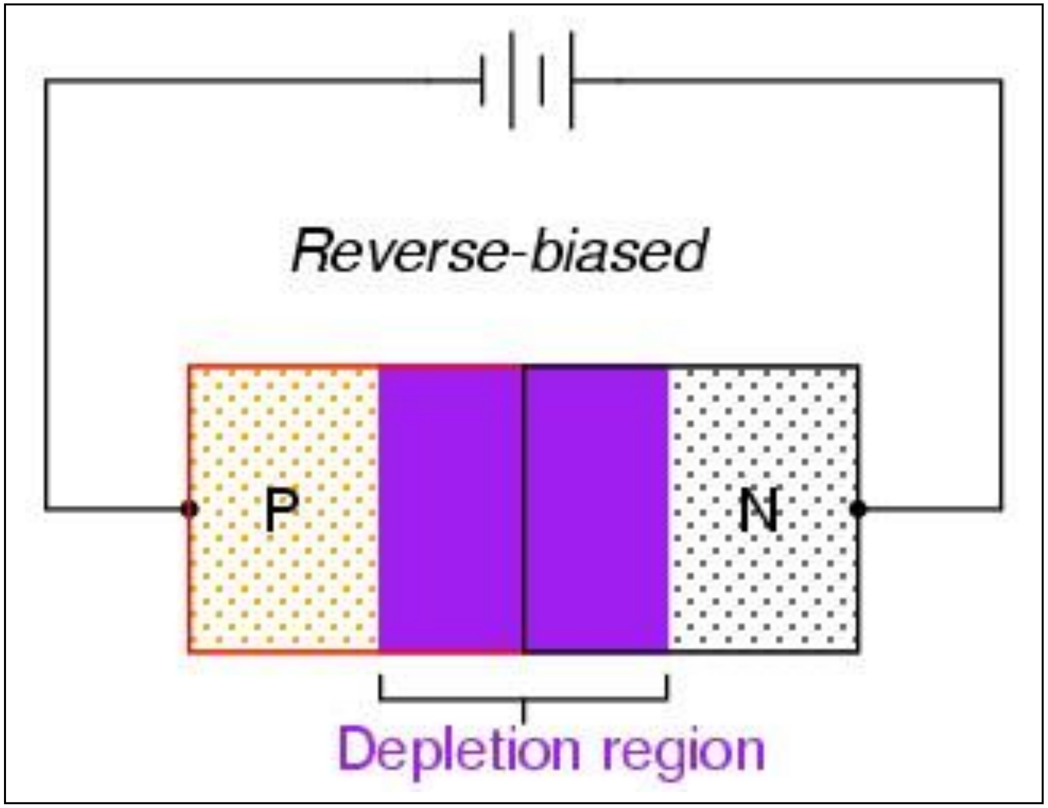


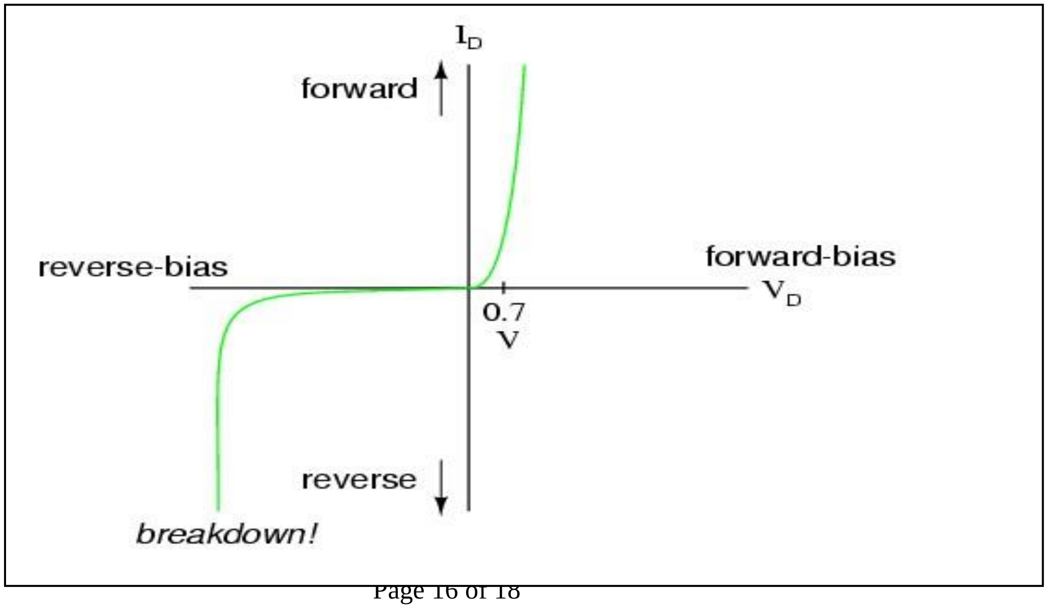
What happens if we reverse the battery? The depletion region just gets wider and wider the more voltage we apply. Two things of note here:

1. That means that the conductive regions (p and n) are being moved further apart with a larger and larger insulator being inserted between them. What does this make?

2. Note the graph to the right. At some relatively high reverse voltage, the current RAPIDLY increases and there is a constant voltage maintained across the diode. This "breakdown" causes the diode to act as a ***voltage regulator*** at the breakdown voltage and by doping the diode carefully, we can make this breakdown occur anywhere from about 2 volts to a thousand volts with reasonable accuracy.

While we won't go into the semiconductor physics of what is happening, we commonly call this the ZENER effect (after Clarence Zener of Bell Labs).





Let's briefly summarize the various types and uses of diodes:

1. Switching diodes -- garden variety of small signal diode used to pass current in one direction and block it in the other. Generally limited to a few milliamperes.

2. Rectifier diodes -- used in power supplies to convert AC power to DC power. Ratings from an ampere or so to thousands of amperes. Shown here –➔➔ 35,000 volt 55 amp rectifier >

3. Zener diodes -- used to regulate voltage. Used in ***reverse biased*** configuration.

4. Light emitting diodes -- diodes that have been specially constructed and doped to emit light when forward biased.

5. Varactors or varicaps -- diodes that use the reverse bias phenomenon of depletion region growth to make electrically variable capacitors. Used for tuning radio circuits.

6. Tunnel diodes -- obsolete device once used as RF oscillators, amplifiers, and fast switching diodes.

7. Schottky diodes -- can be made from a semiconductor material and a metal contact that acts as a microscopic doping agent.

8. Catswhisker diodes -- found in early "crystal set" radios in the middle 1900s that used galena (lead sulphide) as the semiconductor. A form of catswhisker could be made from a Gillette blue blade razor blade and a sharpened wire or safety pin, used by WWII soldiers in the so-called "foxhole radio".

9. Photodiodes -- all diodes are photodiodes to some extent, in that light will cause the separation of neutral atoms into ions, holes, and electrons and thus provide an electric current. Most diodes have some sort of optical barrier to prevent this effect from being noticeable.

10. Gunn diodes -- are used as microwave oscillators and amplifiers.


REG. U.S. PAT. OFF
MADE IN
U.S.A.
Gillette
KNOWN THE
WORLD OVER
PATENT NUMBERS
OTHER PATS PENDING
Gillette