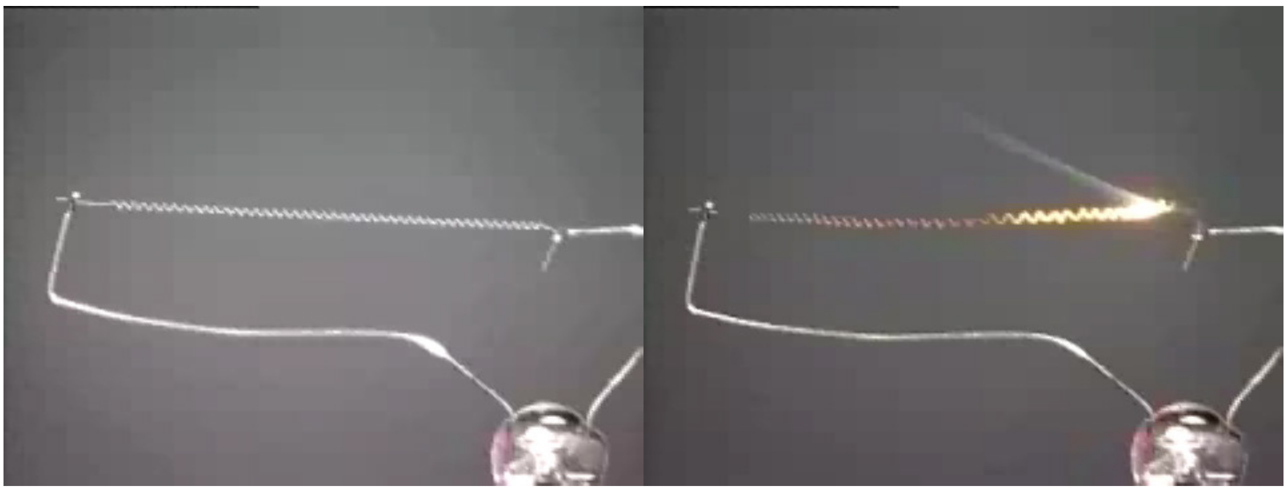
http://invsee.eas.asu.edu/nmodules/lightbulbmod/burnout.html

Why does a light bulb burn out?

A tungsten filament is drawn to a very uniform diameter when it is manufactured. As a result, when a light bulb is first turned on the filament emits light relatively evenly along the length of the filament. Explore the failure of a filament using the following movie which shows an accelerated view of a filament failing. Notice how the light emitted from the filament changes intensity and location with time.



Why does the filament get bright at one point before it fails ?

Standard electrical outlets in the United States provide 110 volt (V) electricity. For an incandescent light bulb, the electric current (i) used to heat the filament is determined by the electrical resistance (R) of the filament according to Ohm's Law:

$$\mathrm{V} = i\, R$$

Electric power (P) is the rate of conversion of electrical energy to another form, such as heat. For a resistor, such as a tungsten light bulb filament, the power may be expressed as:

$$\mathrm{P} = i^2 R = \mathrm{V}^2/R.$$

The voltage drop across the filament is essentially constant. As a result, when R varies, so does i. In particular, R can vary locally with the cross-sectional area of the filament:

$$R = \rho\ (l/s),$$

where ρ is the specific resistance of tungsten (ohms), l is the length of a filament region (cm) and s is the cross-sectional area of the filament region locally (cm^2).

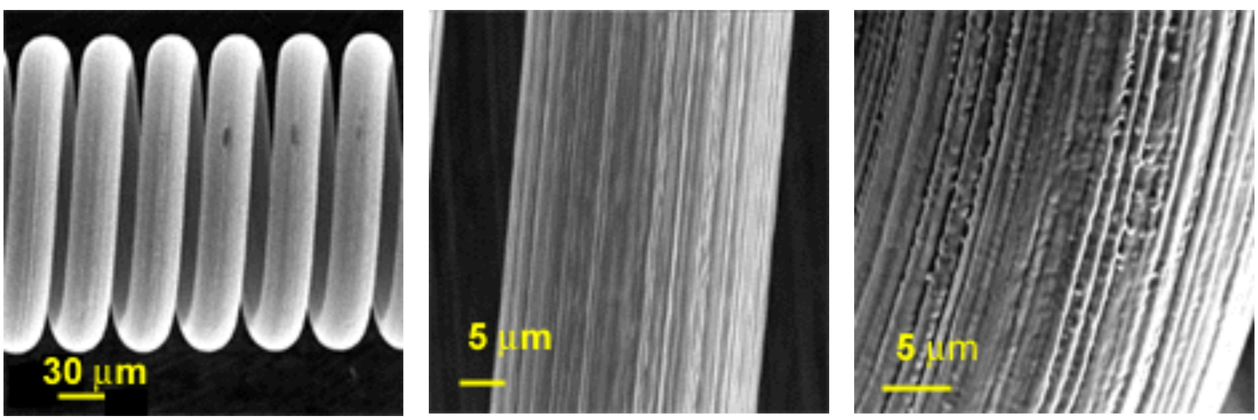
If the cross-sectional area of the filament changes with time to vary along its length, the current passing through each part of the filament will remain constant. Although if the overall resistance varies, so will i. The resistance of each section will be inversely proportional to s.

Suppose a filament has three regions (1, 2, and 3) with different values of s and, consequently, R. Then $V = iR_1 + iR_2 + iR_3$ and the total power dissipated as a function of filament region is given by:

$$P = i^2 R_1 + i^2 R_2 + i^2 R_3 = i^2 \rho_1(l_1/s_1) + i^2 \rho_2(l_2/s_2) + i^2 \rho_3(l_3/s_3)$$

A Closer Look:

Tungsten is obtained as mining ore powder, which is sintered and shaped into feedstock to manufacture the filaments. The tungsten is drawn through diamond extruding molds at a high temperature to yield very long, thin filament wire. The wire is then wound into spirals and double spirals to allow the filament to more efficiently maintain the high temperatures needed. The spiral shape minimizes the convective cooling of the filament by the inert gas in the bulb.

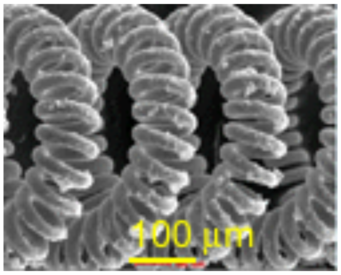


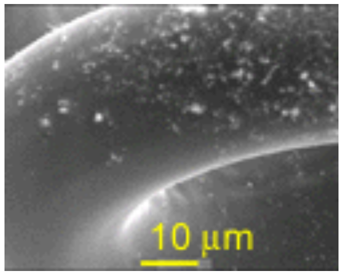
The above Scanning Electron Microscope (SEM) pictures show a new filament, its highly uniform thickness, and the characteristic axial marks left from the extrusion process.

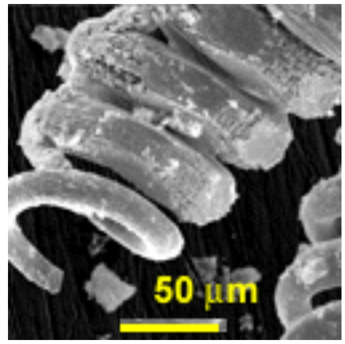
Although tungsten is the most temperature resistant filament material known, it is highly reactive when hot. Light bulbs are filled with an inert gas such as nitrogen or argon to avoid the filament reacting with air. Exposing the hot filament to even the smallest amount of air causes the tungsten to oxidize to tungsten trioxide (WO_3):

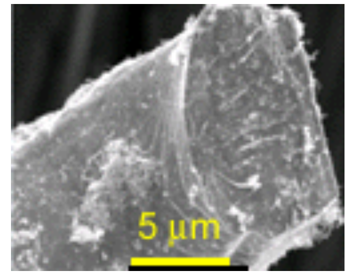
$$2W + 3O_2(g) \text{ ----> } 2WO_3$$

The oxide forms a gas which solidifies as smoke particles in the atmosphere in the light bulb when the filament is white hot. The Scanning Electron Microscope pictures below show a filament which failed after a slow air leak.









The first two pictures show the filament away from where it failed. Note the white WO_3 smoke particles that have settled back on the smooth surface. The extrusion marks have been etched away by oxygen. The next two pictures show the failed region of the filament and the failure surface, respectively.

Why is this region more sensitive to failure? What can you say about the region where it failed?

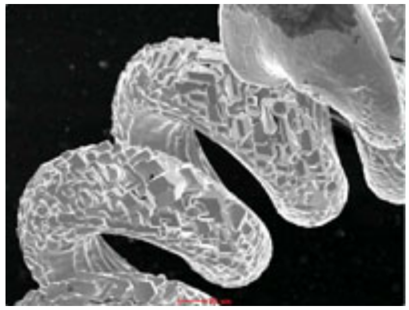
Even when the light bulb is perfectly sealed from air it still “burns out,” but not as fast. Tungsten directly vaporizes from the filament surface while at the extremely high temperatures tungsten filaments operate at. The pressure of tungsten vapor over a filament is 10^{-4} Torr at 2757°C.

$$W(\text{solid}) + \text{heat} \text{ -----> } W(\text{gas})$$

As the trace of tungsten vapor leaves the surface by sublimation, the cool argon/nitrogen gas around the filament causes the vapor to solidify as smoke, which slowly settles on the glass bulb giving it that irregular gray tint as it ages. Filaments fail by brittle fracture when they become too weak from thinning.

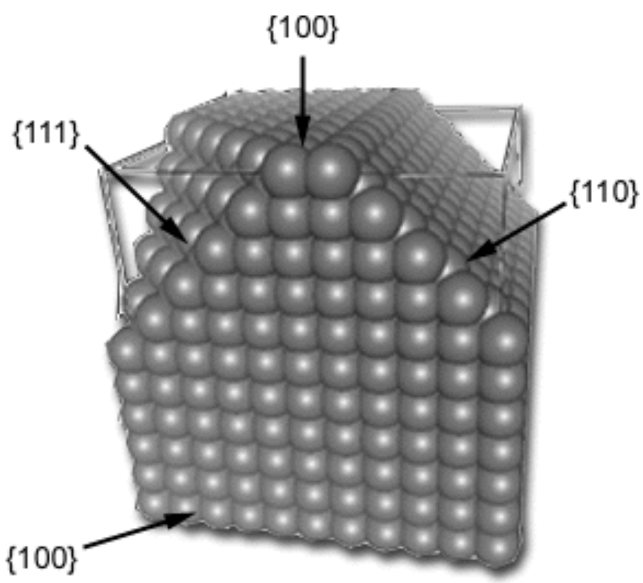
Atomic View:

The scanning electron microscopy image below shows how an old filament has aged.

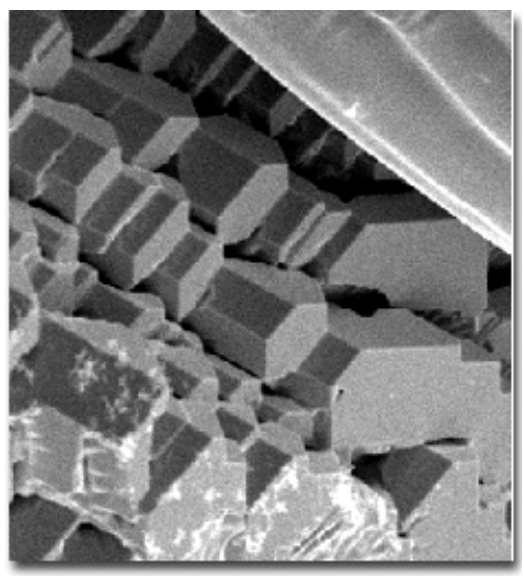


Its surface has been etched away by sublimation revealing beautiful tungsten single crystal shapes and a smoother region with distinct lines etched in the surface. Grain boundaries (poorly packed regions between well packed single crystal regions) are weaker, more reactive areas, where filaments often fail.

The next image shows how the shape of the exposed filament crystals can be related to the atomic-level packing of their tungsten atoms. The atomic packing arrangements of the basic planes seen in the images of the filament crystals are shown.

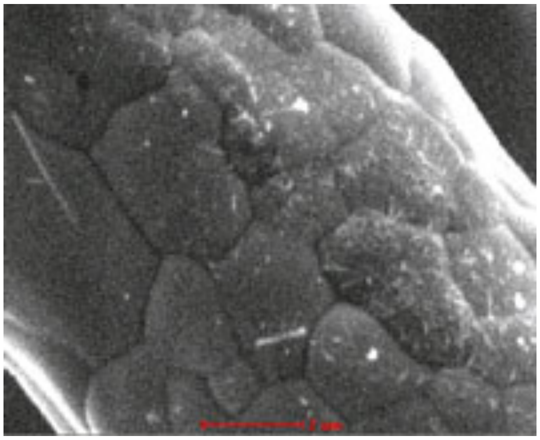


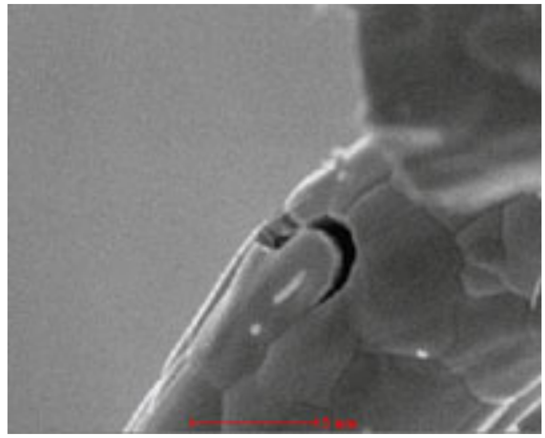
An atomic level model (top) showing the {100}, {110} and {111} faces, of a body centered cubic tungsten crystal.



These faces are apparent in the SEM image of a tungsten filament.

The following two scanning electron microscope images show filaments that have not yet been extensively eroded. The grain boundaries between the single crystal regions in the filament appear as depressed lines on the surface in the images. The atoms across these boundaries are more weakly bound together. Hence, these areas erode more quickly, as seen in these depressed surface regions. They are also physically much weaker and fracture more easily, as seen by the grain boundary fracture in the right image.





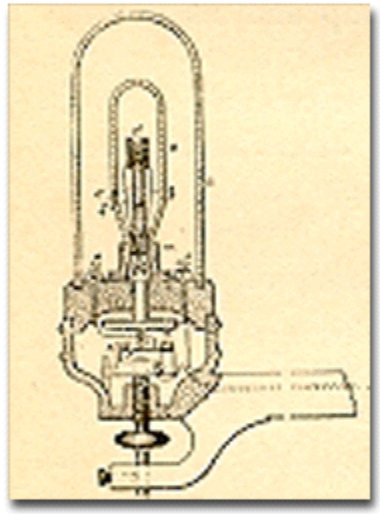
The atomic arrangement of atoms can affect the strength and corrosion resistance of materials, like light bulb filaments. Filament grain boundaries erode faster, becoming thinner and hotter, which in-turn accelerates the thinning process. A thinning grain boundary region becomes too weak to support the filament, eventually fracturing at the grain boundary.

http://invsee.eas.asu.edu/nmodules/lightbulbmod/history.html

History of the Incandescent Light

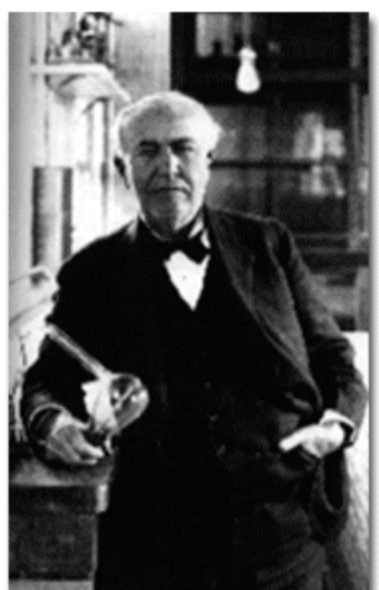
The invention of the incandescent light bulb has a history spanning from the early 1800s. Until that time, available light sources consisted of candles, oil lanterns, and gas lamps. In 1809, an English chemist, Humphrey Davy, started the journey to the invention of a practical incandescent light source. He used a high power battery to induce current between two charcoal strips. The current flowing through the two charcoal strips produced an intense incandescent light, creating the first arc lamp.

In 1820, Warren De la Rue made the first known attempt to produce an incandescent light bulb. He enclosed a platinum coil in an evacuated tube and passed an electric current through it. The design was based on the concept that the high melting point of platinum would allow it to operate at high temperatures and that the evacuated chamber would contain less gas particles to react with the platinum, improving its longevity. Although it was an efficient design, the cost of the platinum made it impractical for commercial use.



Early light bulb with a platinum filament. Although functional, its cost made the bulb commercially impractical.

Throughout the 1800s, many scientists and inventors strove to create a cost effective, practical, long-life incandescent light bulb. The primary hurdle was creating a long-lived, high-temperature filament--the key to a practical incandescent light. Many high-melting-point materials were explored in inert/evacuated chambers in the process.



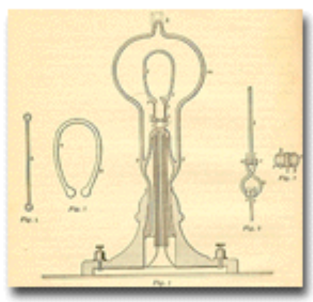
Thomas A. Edison holding one of his famous light bulbs.

Men such as William Robert Grove, Frederik de Moleyns, W.E. Staite, John Daper, Edward G. Shepard, Heinrich Gobel, C. de Chagny, John T. Way, Alexander de Lodyguine, Joseph Wilson Swan, and Thomas A. Edison dedicated their time and efforts in the race to develop the first practical incandescent light bulb.

Breakthroughs for Edison and Swan came in 1879, when they independently developed the first incandescent lamp that lasted a practical length of time -- at best a mere 13.5 hours. Their separate designs were based on a carbon fiber filament derived from cotton. The next stage of development focused on extending the practical life of the carbon filament bulb. Edison developed bamboo-derived filaments in 1880 that lasted up to 1200 hours.

The efficiency of an incandescent lamp design centers about attaining high filament temperatures without degradation and loss of heat. Edison's early selection of carbon, the highest melting temperature element, with a melting point of 3599°C or 6510°F seemed the obvious choice. The problem with carbon is that at high operating temperatures it evaporates, or sublimes, relatively quickly at 0.1 torr at 2675°C, resulting in short filament life.

The early solution to this dilemma was to operate the filament at lower temperatures to attain reasonable life. However, the incandescent brightness of the bulb was sacrificed in the process.



A drawing of an early light bulb design by Edison. Edison tried numerous different materials and designs before he was successful in developing a practical incandescent bulb.

Other light bulb inventors tried two new filament materials to improve bulb brightness. In 1898, Karl Auer used osmium, which has a melting point of 2700°C (4890°F). Then in 1903, Siemens and Halske worked with tantalum, which melts at 2996°C (5425°F). These elements drew attention because they could operate at higher temperatures with longer life and less evaporation.

Then the invention of ductile tungsten, a much improved filament material, sparked the development of the modern tungsten filament incandescent light bulb by the General Electric Company and William Coolidge in 1906-10. This is the light bulb we know today. Ductile tungsten has many favorable properties such as:

- a high melting point: 3410°C (6170°F)
- low evaporation rate at high temperatures: 10^{-4} torr at 2757°C (4995°F)
- tensile strength greater than steel

Because of its strength, ductility and workability, tungsten can readily be formed into the filament coils, used to enhance performance in modern incandescent bulbs. Due to its high melting point, tungsten can be heated to 3000°C (5432°F), where it glows white hot providing very good brightness. However, the early tungsten filaments still sublimed too quickly at such high temperatures. As they sublimed, they also coated the bulbs with a thin black tungsten film, reducing their light output.

Inert gases such as nitrogen and argon were later added to bulbs to reduce tungsten evaporation, or sublimation. While these gases reduced evaporation and increased filament life, they also carried heat away from the filament, reducing its temperature and brightness. Winding the wires into fine coils, as used in modern incandescent filaments, reduced convective heat loss, allowing the filament to operate at the desired temperatures.

Modern incandescent bulbs are not energy efficient, only four to six percent of the electrical power supplied to the bulb is converted into visible light. The remaining energy is lost as heat. However these inefficient light bulbs are still widely used today due to many advantages such as:

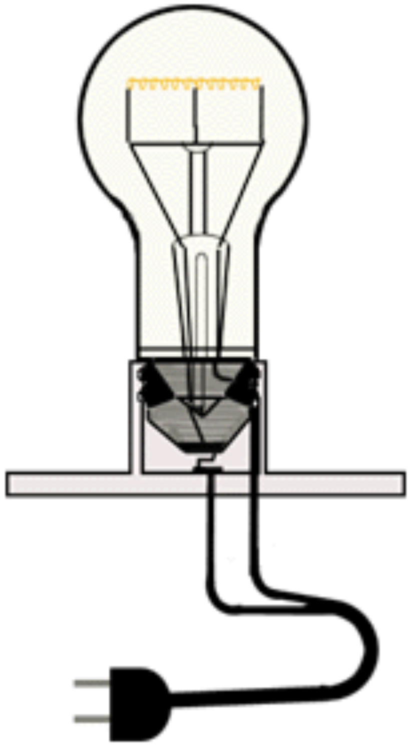
- wide, low-cost availability
- easy incorporation into electrical systems
- adaptable for small systems
- low voltage operation, such as in battery powered devices
- wide shape and size availability

http://invsee.eas.asu.edu/nmodules/lightbulbmod/comp.html

Incandescent Bulb Manufacture

The tungsten filament in a modern light bulb is supported by several molybdenum wires. The ends of the support wires are imbedded in a glass button at the top of the glass support rod. The copper and nickel lead-in wires, which carry the current to the filament, are supported by a glass support stem. One lead-in wire is soldered to the metal contact at the base of the bulb, while the other is electrically connected to the side socket contact. The contacts are separated by an insulating plate. An electrical current can pass in either direction through the filament.

During manufacture, the bulb is evacuated through the exhaust tube and filled with nitrogen/argon gas. The bulb is partially re-evacuated and the lower end of the tube heat-sealed. The lead-in wires are soldered to their contacts and the glass bulb cemented to the threaded metal base.



List of Components

1. Filament
2. Support Wires
3. Button
4. Button Rod
5. Stem Press
6. Lead-in Wires
7. Threaded Metal Socket
8. Side Contact Of Socket
9. Base Contact Of Socket
10. Lead Wires To Electrical Sockets
11. Insulating Plate
12. Seal-off Point Of Exhaust Tube
13. Insulating Cement
14. Exhaust Tube

Components in a modern incandescent light bulb

http://invsee.eas.asu.edu/nmodules/lightbulbmod/filament.html

Incandescence

Why does a filament give off light?

A light bulb is “turned on” by passing an electric current through its filament, heating the filament until it is “white hot.” The high temperature of the filament--up to 3000°C, causes it to give off visible light by a process called incandescence. Incandescence is defined as the emission of visible light by a hot body. Any hot object gives off incandescent light. The higher the temperature of the object, the brighter the light given off. Examples of incandescent objects include hot coals in a campfire or barbecue grill, the sun, light bulb filaments and the burners on electric stoves, which glow dull red when their temperature is on high. Electric stove burners are just above the minimum incandescence temperature visible to the human eye, about (390°C).

Electric stove burners turned on "high".

How Does Temperature Affect Incandescence?

The incandescence of objects at any temperature can be predicted using Planck's law, which assumes an object is a black body radiator. A black body radiator emits only its own light and does not reflect outside light. Planck's law describes the energy intensity of all the different colors, or wavelengths of light, emitted.

Planck's Law:

$$R_\lambda = \frac{37418}{\lambda^5\,[e^{14388/\lambda T} - 1]}$$

gives the total energy radiated from the object (R_λ), in watts per square centimeter, as a function of wavelength (λ) in micrometers (μm) and the surface temperature (T) in Kelvin.

The color of the light emitted is related to the wavelength at which the light intensity is greatest, which is given by Wien's law (obtained from Planck's law by differentiation):

Wien's Law: $\lambda_{max}\,T = 2898$

where λ_{max} is the emission wavelength with the greatest intensity and T is the surface temperature.

Together, these laws predict the light given off by a light bulb or any incandescent source. The color of the light given off results from the combined intensity of the various wavelengths of visible light emitted.

What features should a light bulb filament material have?

Using Plank's law and Wien's law you can predict the wavelength and intensity of light emitted by a filament at different operating temperatures. Since, only light visible to the eye is useful, the greater the fraction of visible light emitted by the filament, the more efficient it will be. The largest fraction of visible light is emitted from a filament operating at ~5000 K. More light is emitted at higher temperatures, but more of it is out of the range of visible light. Inventors have used these principles to invent and improve incandescent filaments.

Many filament materials were pursued to optimize visible light emission and filament longevity in the race to build a better incandescent light bulb. Some of the more prominent materials explored for use in incandescent filaments were carbon (C), osmium (Os), tantalum (Ta), platinum (Pt) and tungsten (W).

To optimize the visible light emitted and longevity of a filament, the material from which it is made must withstand high temperatures. Two of the most significant failure mechanisms to be avoided are melting and evaporation, or sublimation, of the filament. At progressively lower temperatures sublimation resistance improves dramatically.

Why use Tungsten filaments?

The filaments used in early light bulbs were made of carbon. However, the carbon filament can not survive for long at temperatures higher than 2100°C. Carbon vaporizes from the filament at these temperatures, shortening the life of the filament. The bulb gives off only dim light at lower filament temperatures.

Tungsten filaments offer the best combination of high melting point and low vapor pressure for all known elemental filament materials. This allows the filament to be heated to higher temperatures and provide brighter light with good longevity. However, even tungsten filaments fail.

http://invsee.eas.asu.edu/nmodules/lightbulbmod/meathisttime.htm

Timeline

1809

Humphry Davy, an English chemist, used a high powered battery to induce an electrical current between two strips of charcoal. The current flow through the high impedance material induced light creating the first arc lamp.

1820

Warren De la Rue made the first known attempt to produce an incandescent light bulb. He enclosed a platinum coil in an evacuated tube and passed an electric current through it. The design postulated the high melting point of platinum would allow it to operate at a higher temperature and the evacuated chamber atmosphere would contain less gas particles to react with the platinum.

1840

William Robert Grove, an English scientist, succeeded in lighting an auditorium with incandescent lamps. The lamps were constructed of platinum coils encased in an inverted glass sealed by water. Unfortunately, the platinum coil lamps were too expensive and impractical for commercial use.

1841

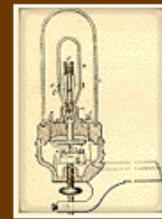
Frederik de Moleyns, received the first patent for an incandescent lamp. The design specifications involved mounting a powdered charcoal filament between two platinum wires in a glass bulb under vacuum. As the filament reacted at high temperature with air, the air present in the lamp was evacuated to extend filament life.

1845

W.E. Staite, an American, patented a second incandescent electric lamp in England. Thomas Wright obtained the first patent for the arc lamp.

1846

John Daper patented a platinum filament incandescent electric lamp. The high melting point of the filament allowed it to operate at a higher temperature than many other metallic elements that were tested. Due to a phenomena known as black body radiation, higher temperature filaments produce more visible light. The high cost and scarcity of platinum deemed this design impractical for widespread commercial use.



1850

Edward G. Shepard, an English scientist, made an incandescent lamp using a charcoal filament. Joseph Wilson Swan, also English, started work on carbon filaments using paper. Carbon filaments provided a low cost and practical filament material based on the technology available in 1850.

1854

Heinrich Gobel, a German watchmaker who immigrated to New York, used a carbonized bamboo filament secured in a glass container for his incandescent electric lamp design.

1856

C. de Chagny, a French engineer, patented an incandescent lamp with a platinum filament for use by workers in mines.

1860

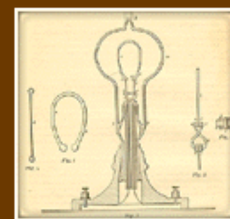
John T. Way demonstrated that sending electricity through mercury vapor contained in a glass tube could produce light, the precedent for the development of the modern fluorescent light. The electric current that ran through the vaporized mercury excited the gas to a higher energy state. As the excited gas atoms return to their ground energy, their excess energy is given off as visible light.

1872

Alexander de Lodyguine, a Russian physicist, developed an incandescent lamp using a graphite filament within a glass bulb filled with nitrogen. The city of St. Petersburg installed 200 of Lodyguine's bulbs. However, the bulbs were plagued by cost and reliability concerns and proved impractical.

1879

Both Thomas A. Edison of the United States and Joseph Wilson Swan of England, produced carbon filament incandescent lamps that burned for a practical length of time. Edison used carbon fiber derived from cotton. His first bulbs lasted for 13.5 hrs. Later improved bulbs of this design lasted for 40 hours.



1880

Edison discovered that bamboo produced a better carbon fiber filament. The new lamps lasted for 1200 hours.

1893

Heinrich Gobel, won a court decision against Thomas A. Edison and received credit as the inventor of the electric incandescent lamp.

1898

Karl Auer, a German scientist, introduced the osmium filament for use in light bulbs. Osmium's high melting point of 2,700 °C and increased lifetime at high temperatures were appealing.

1902

Light bulbs made with osmium filaments were produced commercially. Although the bulb was more cost effective to operate than the carbon bulb, the scarcity and high cost of osmium substantially raised the price of osmium bulbs, making them impractical.

1903

Siemens and Halske of Charlottengurg produced tantalum filament bulbs. Tantalum has a melting point of 2,996 °C and excellent practical manufacturing properties. It is ductile and can readily be drawn in to fine filament wire.

1904

Willis R. Whitnew developed a metalized, or metal coated, carbon filament that preceded the development of the tungsten filament.

1906

General Electric Company patented a method for making tungsten filaments for use in incandescent lamps. The high melting point of tungsten, (3,410°C), its low vapour pressure (for example, 10^{-4} torr at 2,757°C), hence low evaporation rate at high temperature, and relatively low cost provided clear advantages over previous filament materials.

1907

The first commercial tungsten filament for incandescent lamps became available in the United States. Tungsten wire manufacturing was still costly and difficult, but the problem was to soon be overcome.

A modern tungsten light bulb filament.

1910

William D. Coolidge, an American, developed an improved method to produce drawn tungsten filaments. In the Coolidge process, a fine tungsten powder is pressed into long bars with one square inch cross-sections. These bars are sintered by electric heating in a pure hydrogen atmosphere to temperatures near the melting point. They are then fabricated into wire by a process known as hot "stretching" within a well-defined range of temperatures, where the fibrous structure is gradually extruded into wire filaments.

1925

Incandescent bulbs with frosted glass interiors were produced. The frosted glass filters out undesirable wavelengths of light emitted by the filament to produce a "soft " light.

1930

Photo flash light bulbs were introduced in photography.

1960

Brighter halogen-filled incandescent lamps were introduced. Halogen gas slows the filament evaporation rate allowing it to operate at higher temperatures.

1991

Philips, a Dutch company, developed a light bulb that uses magnetic induction to excite a gas to emit light. There are no parts to wear out in this design, so the expected lifetime for a bulb is 60,000 hours.