Tungsten Filament Heating Effects

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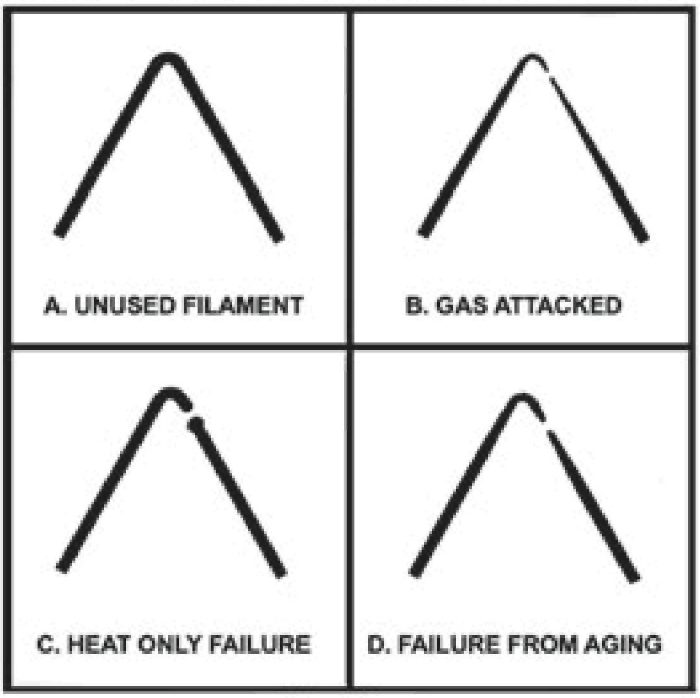
The subject of SEM saturation was discussed on the microscopy list server and off list I was asked why filaments burn out on the side leg instead of at the tip. I have degrees in electronics technology and in chemistry as well as being a microscopist. So I investigated this subject and performed some experiments to verify my results.

According to Ohm's Law, one would expect that the highest resistance would be at a sharply bent tungsten "V" and that is where the filament would be expected to burn out. However, observations of the phenomenon show this is not where the filament burns out. Something else is going on. Haine (1961-62) states that heated tungsten filaments and wires have two processes at work (besides resistance). One is continued thermal evaporation of the tungsten metal with age and the other is erosion of the filament by residual gas. In a good vacuum, the latter is a minor process but may not be eliminated. Figure one shows some of these filament effects. Over saturation, "equipotentials" or the real cause of false saturation peaks will not be discussed here. Let's just look at the factors involved in a filament burn out and a few more physical processes.



A. UNUSED FILAMENT

B. GAS ATTACKED

C. HEAT ONLY FAILURE

D. FAILURE FROM AGING

Figure One
VARIOUS TYPES OF FILAMENT FAILURES

A straight wire of tungsten (W) or nichrome heats up uniformly except at the ends. At the ends, the mounting posts cool the wire. The factor that comes into play is a heat sink effect from the process of heat conduction. By careful experimentation on a bent filament or wire, other factors that cause the sides of a filament to be hotter than the tip are revealed. One main factor is adjacent indirect side filament heating by th filament leg. The opposite leg subtends a certain solid angle defined by the geometry of the two wires. The heat radiated towards the other leg causes the temperature of that leg to be a higher temperature. The other leg does the same to the first leg. This mutual heating is a major factor in side wire filament heating, vaporization, melting, and failure.

Why is the tip cooler? At the outer bent surface of the tip, radiated heat does not heat up another part of the filament. Any radiated heat is lost into space from the extra surface area from the bent curve of the filament. At the tip, the slightly higher radiated heat loss from this extra curved surface area and a slower process of heat conduction cause the tip to run very slightly cooler.

Why doesn't the side wire burn out half way down the sides? The wires are further apart from each other and thus are cooler. The subtended solid angle is less further down and so less indirect heating takes place further down the wires. The reverse is also true. As you go up the side legs the solid angle gets larger and the mutual side heating is more pronounced. So metal evaporation over time thins the side wire near the tip because of this geometry.

Haine says one can grind the tip of a filament flat in order to raise the tip temperature to that of the sides of the filament. Unfortunately decreasing the cross sectional area should decrease filament life. However, the reverse should also be true. If you raise the surface area of the side wires, attach more mass, or use a thicker diameter wire on the sides; it should lower the temperature of the sides to match the tip. It's cheaper and more practical to just install a new filament.

I have deliberately avoided one issue. The temperature of the filament affects the evaporation rate and is usually the only factor that affects filament life for a microscopist. Eventually the evaporation history, the temperature profile history, and the way you treated the tungsten will all add up. The filament will become thinner even at grossly under saturated or lower filament temperatures, given enough time. With aging, thermal evaporation preferentially thins the hotter side wire(s) more than the tip area. This increasing resistance generates more heat at the future point of failure. This resistance effect can be seen in a standard resistivity formula.

$$R = \rho L/A \tag{1}$$

The formula variables are resistance, resistivity, length, and cross sectional area; respectively. As the cross section decreases, then the resistance increases. That resultant higher resistance lowers the total amount of heat generated but the filament still burns out. This is explained in more detail below.

As the thinning progresses, the solid angle is decreasing. At the same time, the mass and the surface area at the point of failure are both decreasing with progressing thinning. The net effect is that less side radiation heating takes place. However, it is too late! Once you pass a certain point, the geometry does not matter anymore. The evaporative thinning process described by Haine has become fatal. Ohm's law now has the final say. Your filament side wire has thinned out to become a super hot I^2R fuse wire. The fuse wire melts and then blows out. Only a broken side wire gap remains.

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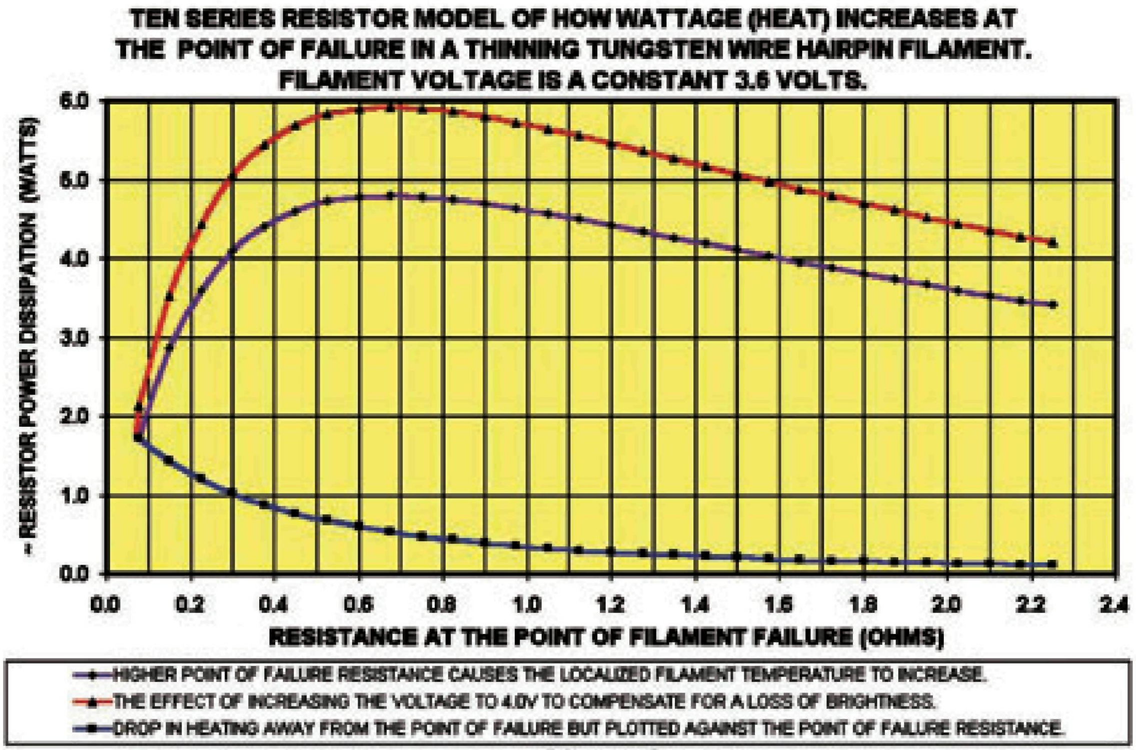

Chart One

Detailed analysis of the final failure

How can all these factors decrease, as well as the overall heat generated, and the wire still melt? That gets into the Stefan-Boltzmann law and some complicated calculations and interactions. My goal is to keep it simple.

Chart One shows the changing dynamics of the resistance and wattage *at filament saturation temperatures*. At a *constant* filament power supply voltage, a filament can be modeled electrically as ten 0.075 ohm resistors all connected in series as 1.2 mm wire segments. The same total current is flowing through each resistor. However, it is the power or the wattage being generated and dissipated by each resistor segment that matters on a thinned filament.

$$\text{Total Power} = V^2/R_{\text{total}} = \sum_{1}^{10}\left(I^2 \times R_i\right) \qquad (2)$$

Initially in a new filament, each resistor dissipates the same amount of heat at a saturation current level. At some point, *one resistor* starts to increase in resistance at the eventual side-leg-segment point-of-failure. That simulates the increased resistance from resistivity and thinning. This localized increased resistance initiates a fatal thermal runaway process shown in Chart 1 as the steep slope of the pink (second from top) curve. As the resistance starts to climb *at the point of failure*, the localized temperature of that tungsten resistor segment also rises. The plotted wattage is the amount of heat that must be dissipated by that failing resistor in this mathematical model and simulation. Before the peak is reached, the already failing and very hot 'tungsten resistor segment' cannot dissipate that extra heat. It melts.

Each simulated heated tungsten filament resistor initially dissipates 1.73 watts at a constant high temperature. This is the normal hot 0.075 ohm resistive operating point shown as the black square data point at the start of the pink and blue curves.

The red curve (top) shows how increasing the filament voltage (temperature) makes the slope steeper during failure and the filament burns out faster.

The blue curve shows the wattage, or heat, being dissipated by any one of the other nine resistors. It ignores heat conduction from adjacent resistors in this ideal situation. This wattage is plotted against the resistance of the changing resistor segment, for comparison. The blue wattage is less than the original amount of heat those individual segments or resistors dissipated when the filament was new. They are running cooler than the point-of-failure resistor or segment.

Overall, it is clear that a lower total amount of heat is being generated from the thinning. However, the remaining generated heat is being shifted onto the failing resistor location and away from the other nine resistors making up the virtual filament in this mathematical simulation. The current is less because of the increased resistance of the failing grain boundaries, evaporation of the crystals, and the resistivity. Recall that each 'tungsten resistor segment' is already at a high operating temperature. The pink peak is *almost three times* the wattage normally seen by a hot 'tungsten resistor segment' in a brand new filament. So the thinning wire must melt before the peak is reached and it does at normal saturation levels and self-bias.

The curves in Chart One show how a failing resistor would act if that resistor had an infinite wattage rating. A tungsten wire has a finite wattage rating. If any resistive subdivision of the tungsten filament exceeds its wattage rating, then it will burn out at that location before its peak heat dissipation is reached.

How all these different areas interact with the various factors is more complicated than represented here. I tried to give a simple interpretation that most of us would understand. So, now you should have a basic understanding of how the physics and electronics causes a tungsten filament to be hotter on the sides, why a side wire burns out instead of the tip, and how the fatal thermal runaway process causes the final failure of a tungsten filament. ■

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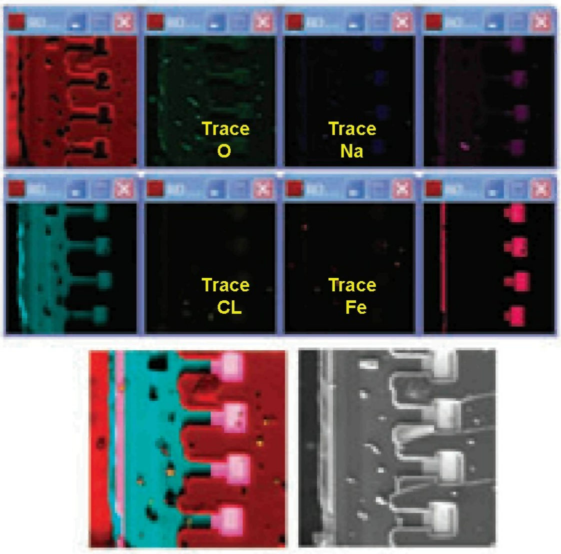

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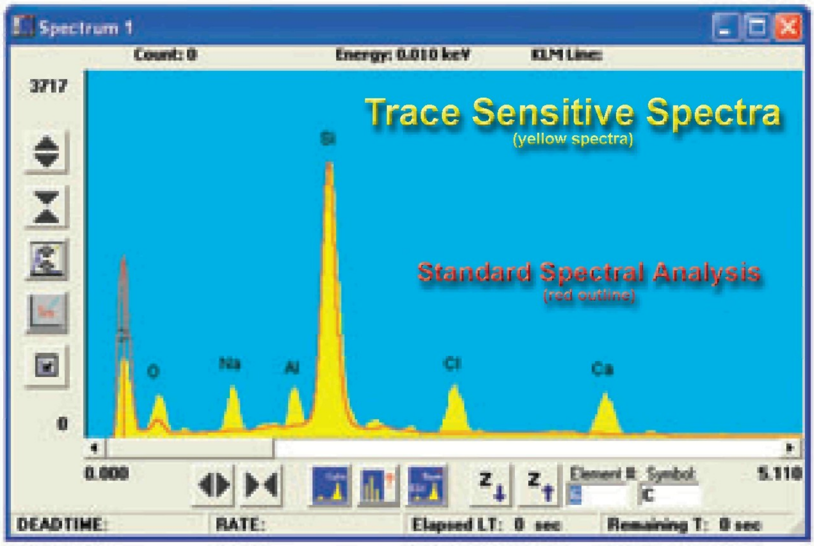

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