

Glowing Contact Physics

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Abstract – There has been very little published research on glowing connections, especially their mechanisms and properties. In this study, oxide conductivity, surface x-ray maps, temperature measurements, and electrical waveforms were used to identify the structure and composition of glowing connections. It is shown that a glowing connection consists of a glowing molten liquid filament, which produced the orange glow that meanders on the surface of a solid copper oxide bridge that forms between two wires. Temperature and video measurements indicate that the glowing filament is in a liquid state. With the addition of oxide bridge resistivity measurements, the saw-tooth voltage pattern, typically seen in currents below $5A_{rms}$, has been explained. Also, when the glowing connection was slowly cooled, an impression of the glowing filament remained on the solid oxide. Subsequent SEM and x-ray mappings of this glow track revealed a track rich in copper, oxygen, and sulfur. This glow track explains the occasional low resistance path across the wires that can occur when the solid oxide bridge remains intact after cooling. Measurements in vacuum showed that oxygen was necessary to sustain the glowing filament even if there was a preexisting CuO oxide bridge present. Physical parameters affecting glow characteristics will be discussed; especially the semi-conducting nature of the copper oxide, and a model of the glowing contact, based on this data, that show some of the significant factors controlling the glow.

Keywords: *Glowing contact, Copper oxide, Arcing, CuO, Cu₂O, Oxidation, Resistivity, Conductivity, Glowing Filament*

I. INTRODUCTION

Glowing contacts, while initially investigated in 1977 for their role in electrical fire initiation, are a relatively poorly documented phenomena [1,2]. Glowing connections, due to the overheated conditions that they can cause and the potential fire hazard, need to be studied. It is suspected that glowing connections can occur in virtually any type of electrical circuit; including residential 115 V_{ac} wiring, dc automotive applications, aerospace applications, etc. Factors controlling glow initiation and sustainability depend on current, wire geometry, and material, and have been created with currents as low as $0.25 A_{rms}$ [3,4]. Recently, there has been interest in glowing connections and their affect in residential series arcing, especially with PVC insulated wiring [3]. The CPSC reports 163,000 total residential electrical fires, from which 40,100 were started from

electrical distribution equipment in 1997 in the US alone with a property loss of over \$676M [5]. There is a need to better understand the properties and characteristics of glowing connections, especially for residential applications.

This study focuses on characterizing glowing connections for copper wire using 115 V_{ac} nominal line voltage with currents below $10 A_{rms}$. The knowledge of past researchers is extended by characterizing the glowing connection itself and by developing a mathematical model of the glow to further the understanding of the glowing contact.

Bridge and glowing filament temperature measurements and conductivity measurements are used to develop a thermo-electric model of the oxide bridge to explain the measured saw-tooth voltage waveshapes. The model helps to identify how physical parameters (conductivity, heat capacity, material density, thermal conductivity, geometry) produce the glowing voltage waveform.

II. BACKGROUND

A study by NBS in 1977 described loose wire nuts that create high resistance - glowing connections [1]. Newbury, et. al, described a glowing process in loose aluminum wire/brass and iron connections that formed high temperatures [6]. Ettling identified the oxidation process of the interface as the initial start of the glow formation [7]. Sletbak, et. al, showed current and voltage waveforms that corresponded to a glowing connection on copper and identified the oxide as Cu₂O [4]. However, they did not distinguish between the glowing filament and the solid oxide bridge or their oxidation states. Also, they did not consider the self-heating of the oxide in their resistivity measurements [4]. Aronstein has shown over many years that glowing contacts in various connector types and receptacles, especially in aluminum wiring, pose a serious safety hazard [8,9]. Japanese researchers and Babraskus have also documented and imaged the glowing “worm” in various wiring devices but do not cover any detailed information about the glow [10-14]. All of these researchers, with the exception of Sletbak, did not investigate the details of the glowing connection but rather just identified them as a

potential cause for overheating and initiators of electrical fires.

This author has reported images, similar to those by the Japanese researchers, but with correlated current and voltage waveforms [3]. Also, reported was not only the creation of overheated connection point, but also the interaction of the glowing connection with PVC insulation that could ignite gases evolved from the overheated insulation [3].

All these studies have shown that a glowing connection can be created from, not only copper, but also many different types of conductor materials, by having a loose connection that forms a resistive film on the surface at an interface but have not done an in-depth study of the glowing contact itself.

III. EXPERIMENTS AND RESULTS

This section details each of the individual experiments conducted on glowing contacts using a resistive circuit with a 115 V_{ac} line voltage source. Fixed wire-wound power resistors controlled current. Generally, many tests were conducted at 2 A_{rms} unless otherwise noted. Previous studies [3] have shown that the glow voltage had an unusual saw-tooth shape at currents below 5 A_{rms}, and it was determining what caused these shapes that was one item of interest. Other investigation goals were to verify that the glow was a liquid, to estimate current flow by resistivity, and to identify the types of copper oxides in the glow track and in the solid bridge that forms between conductors.

A). CREATING A GLOW AND TEMPERATURE MEASUREMENTS

Glowing contacts, using copper wire from Alfa Aesar (99.9% purity), were produced with the setup shown in Fig. 1. The moving electrode was spring loaded with about 1 N of spring force. The make/break action was obtained by manually turning the micrometer with light force until current flowed. The make/break action was rapidly performed (~3 Hz) in order to condition the copper wire surface. When a glowing condition began to form, as detected by an increased voltage across the gap and by drag on the micrometer due to sticking and by the drawing out of an oxide filament, the make break frequency was reduced. At this point the micrometer was slowly turned out to extend the glowing bridge to as long a length as possible without breaking. Typically, the bridge would break and had to be reformed by subsequent make/break action. Frequently, it was not possible to remake current flow due to the insulating nature of the copper oxide bridge unless the oxide was removed.

Fig. 1 shows the test setup, similar to [3] with the addition of a micro-positioning stage used for positioning a fine 0.127 mm (0.005" diameter), bare wire Pt-Pt/Rh (Type R) thermocouple (TC), Omega #P13R-005, to make a direct

temperature measurement of the oxide and the glow. This was done by positioning the end of the TC bead directly in line with the oxide bridge and moving the stage so that the TC bead touched the oxide bridge. The micro-positioner consisted of an x-axis stage for moving the TC inline with the oxide, a z-stage for height adjustment and angular adjustment by bending the wire into position. Since the glow actively meanders around on the solid oxide surface, the position of the glow was visually monitored, through the optics, to determine when the glow touched the TC. When the glowing filament touched the TC, the camera and data acquisition system were manually triggered. This PC controlled camera also had a synchronized data acquisition system, enabling the verification of the glowing filament touching the TC with a simultaneous sharp increase in TC temperature.

According to the manufacturer, the response time of this TC was 40 ms when immersed in water. It was expected that the glowing filament temperature would be modulated by power dissipated in the filament created by the 60 Hz current. However, the modulation of the temperature, when using the 0.005" diameter TC wire in this study, would not be detected. Rather, with this response time, the TC would respond to the average temperature of the glow. The TC, amplifier/zero reference (Omega Omni-Amp IIB-RS), and optical isolator (Nicolet Isobe) were calibrated by two different methods. The first involved injecting a known millivolt signal from a Keithley 6487 picoammeter/voltage source for initial calibration and measuring the output from the isolator, with a Keithley 182 voltmeter, to generate a calibration curve based on published type R millivolt tables. The second method used the definite point calibration method using the boiling point of water and the freezing point of pure molten copper to adjust the initial calibration.

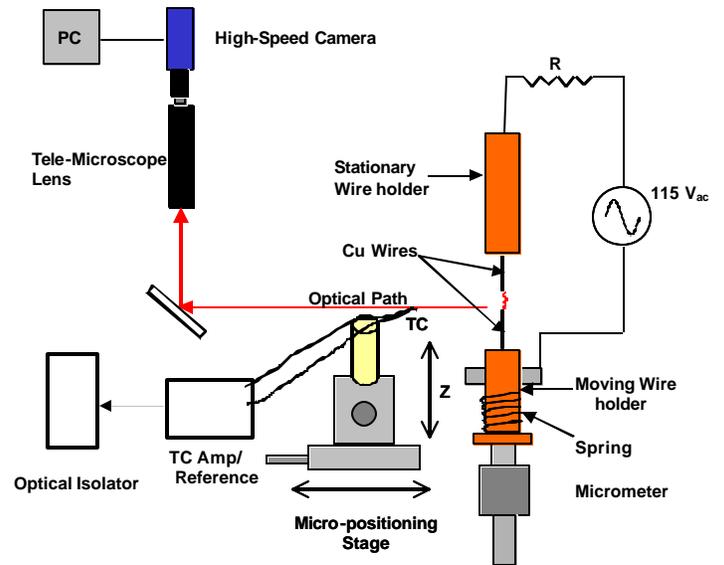


Figure 1. Setup used to produce, image, and record glowing contact properties. TC, mounted to the micropositioner, was used to measure oxide and glow temperatures.

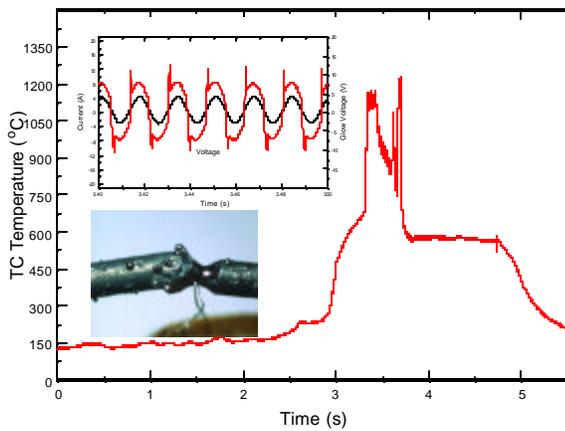


Figure 2. Temperature measured on oxide bridge at $2.5A_{rms}$ as the glowing filament moved across the oxide surface.

Fig. 2 shows an example of the TC results. The inset shows the corresponding voltage and current waveshapes near the peak temperature. These waveshapes were the same for the entire time. The TC and the filament can be seen in the single image taken at 3.5 s. The glowing filament, in this example, remained in contact with the TC for $\sim 1/2$ second. The filament tends to move relatively slowly on the bridge surface when compared to 60 Hz modulation of the filament temperature.

Fig 3 shows selected data, taken from plots similar to Fig. 2, from 13 tests conducted at various currents. The results, peak temperature of the glow and typical oxide temperature, show an increase in the glowing filament temperature with increasing current. As the current increased to $7.5 A_{rms}$, the glowing filament temperature rose towards the vaporization temperature of CuO . The oxide temperature reported was the temperature when the glow was on the opposite side of the solid oxide where the TC was touching. As the glow moved around the oxide, toward the TC, the oxide temperature began to rise. The motion of the glowing filament appeared to be random as it slowly moved about the oxide bridge, likely from thermal gradients changing the solid oxide resistivity.

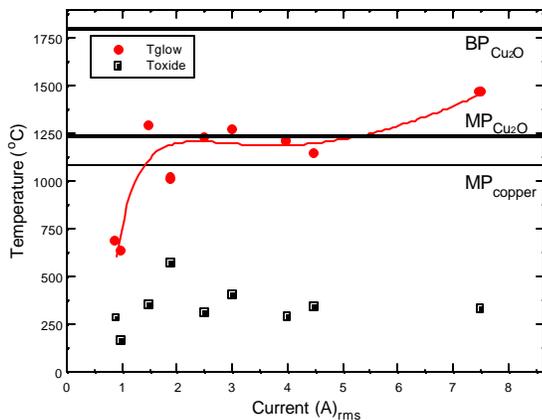


Figure 3. The measured glowing filament temperatures were typically near the melting point of Cu_2O and increased above $7.5 A_{rms}$.

B). MICROGRAPHS AND X-RAY MAPPING

It has also been found that, occasionally, a low resistance can occur across the oxide bridge, even in the cold state. Typically, if the glow extinguishes, the connection becomes insulating ($> 20 k\Omega$) due to the high resistivity of the copper oxide. Frequently, during glowing, the oxide will crack and current flow will cease, and a quick reconnection of the cracked, but still hot, oxide surfaces will sometimes allow the glow to reignite but, typically the oxide cools so fast rapidly increasing oxide resistivity as to prevent current flow, that in order to reestablish current flow, the oxide must be removed. However, under certain conditions, especially when the current is slowly lowered, or the glow is slowly extinguished by removing the oxygen source (see vacuum measurements) to prevent thermal shock, an impression of the glowing filament can be seen, under a microscope, to remain on the solid oxide bridge spanning the two opposing copper wires. In this case, resistance measurements, across the copper wires, of an intact sample revealed a low resistance of about 0.2Ω . These conditions can be important for practical wiring devices.

Optical, SEM, and x-ray mappings of the oxide bridge confirmed the bridge, in Fig. 4, to be made up of copper and oxygen and the black color would indicate a CuO oxide. However, more laborate testing is needed to measure the actual oxidation state of the oxide, especially since it has been shown that nonstoichiometric ratios ($Cu_{1-y}O$) can be made depending on oxygen pressure and temperature [15]. Similar analysis of the glow track, seen in Figs. 5-6, revealed the track to be rich in copper, oxygen, and sulfur. The sulfur probably came from impurities in the metal that coalesce from the bulk and collect in the hot molten liquid. That is the glowing filament. Again further measurements are necessary to confirm the oxidation state of the glow track. However, the low resistance and red color would suggest a large amount of elemental Cu present in the track along with Cu_2O , and the sulfur particles. It is known that as the temperature of copper approaches $1000 \text{ }^\circ\text{C}$, Cu_2O is the favored reaction rather than CuO [16]. So, the glow track may consist of semi-conducting Cu_2O and perhaps some pure copper atoms or copper in a range of oxidized states.

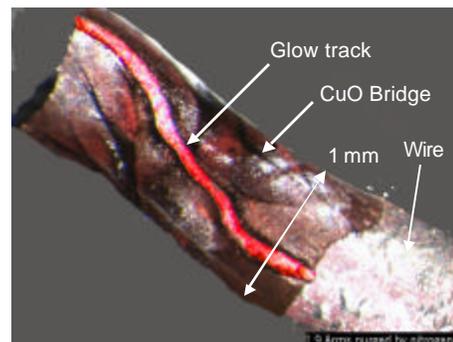


Figure 4. Optical image of glow track impression on bridge.

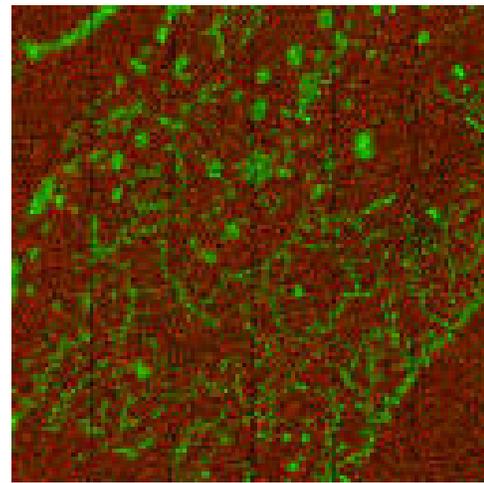
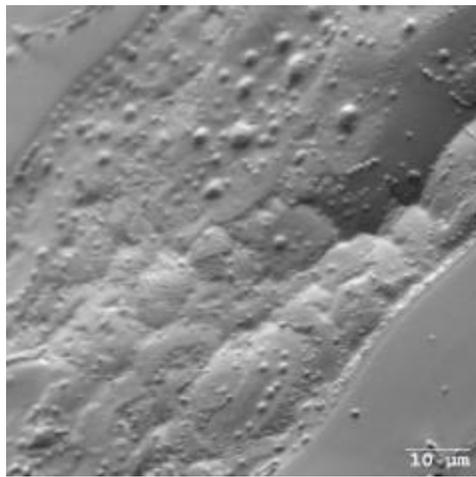


Figure 5. SEM image of the glow track (last location of glowing filament before the filament extinguished) that remained on the CuO and an overlaid elemental x-ray mapping of the same area showing copper (red), and sulfur (green).

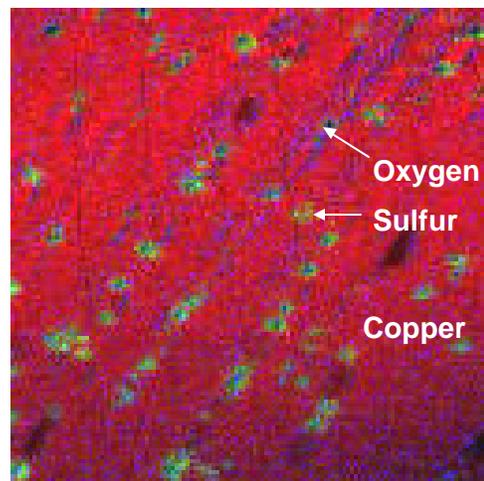
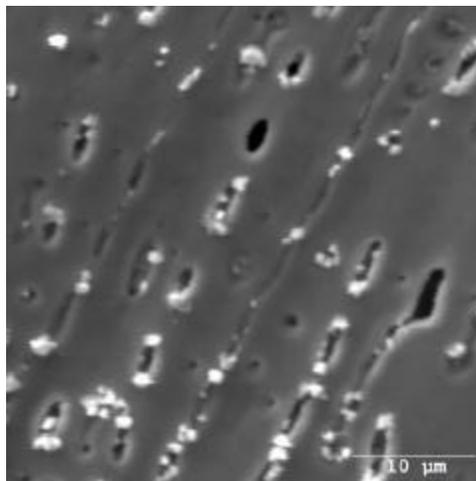


Figure 6. SEM image and corresponding overlaid line scan x-ray mappings of the glow track reveal a copper (red) rich surface with oxygen (blue) and sulfur (green) impurities. Sulfur impurities were located in the holes in the surface.

C). *CUO RESISTIVITY*

This section reports the resistivity measurements of the solid oxide bridge that forms between the copper wires due to the intense heat from the glowing filament. These measurements, coupled with the temperature measures, show that the oxide resistivity was too high to conduct any significant current, except near the part directly below the glowing molten pool of copper oxide.

The black color of the oxide bridge indicated that the bridge consisted nominally of CuO. However, existing literature shows that, depending on temperature and the partial pressure of oxygen, the oxide can be deficient in copper resulting in a nonstoichiometric ratio of Cu_{1-y}O that results in a p-type semiconductor that affects conductivity [15]. Resistivity measurements, over a furnace temperature range of 20 °C to 750 °C, were made on the solid oxide

bridge samples. Samples, without the glow track, were created using the fixture in Fig. 1 at 2 A_{rms} . 1mm diameter copper wire was used to produce oxide bridges, 2.3 mm in length and 1.3 mm in diameter. After growing the oxide for a predetermined time to achieve the desired length, current was stopped, the sample was allowed to cool and then the oxide bridge was broken off from the copper wire. The ends of the sample were filed flat (red colored oxide (likely Cu_2O) was noted and removed from the interface surface, and the sample was placed between two copper plates as shown in Fig. 7. The bottom plate had a hole, 1mm in depth, for locating and holding the sample. A copper weight, 0.3 kg, was placed on the upper electrode (2.5 cm diameter copper disk) to provide a good connection. A ceramic spacer (1.3 mm thick) was used to cantilever the upper disk electrode to insure good contact between the sample and the copper electrodes. This fixture was then placed in a Thermolyne model 1500 furnace and the temperature was increased to 750 °C. Flowing UHP

nitrogen over the sample minimized further oxidation of the sample, under high temperature.

Resistance measurements were made by using a regulated constant voltage DC source at 170 V_{dc} in series with a 118 kΩ resistor to limit the current to approximately 1 to 1.5 mA_{dc} through the sample, depending on the sample resistance. This low sensing current, prevented self-heating of the sample, especially as the resistance dropped, resulting in a sample temperature controlled solely by the furnace temperature. The sample voltage was monitored and recorded every 2 seconds with a Fluke Hydra data acquisition system. A type k thermocouple was located in the lower copper electrode, near the sample, to monitor sample temperature.

Fig. 8 shows the resulting resistivity, based on resistance and geometry measurements, for two different samples. Sample 1 was tested once. The second sample was tested three times, with each successive test, the electrodes were cleaned and the top surface of the sample was lightly filed. The bottom remained in the locating hole for all three runs.

The resistivity measurements, shown in Fig. 8, reveal a positive and negative temperature coefficient for copper oxide. As the temperature increased, the resistivity initially dropped then rose. Further increase in temperature then caused the resistivity to dramatically drop above 300 °C.

Conductivity (σ) curves, for these data, shown in Fig. 9, allows the calculation of the band gap energy (thermal energy needed excite electrons into the conduction band) of the oxide using the following equation.

$$\sigma = A e^{-E_g/2kT} \quad [1]$$

where E_g is the band gap or activation energy, $k = 1.38 \times 10^{-23} \text{ J/}^\circ\text{K}$, and T is temperature in degrees °K, and A is a constant. The slope of the curves obtained from plotting the log of the conductivity against $1/T$ gives the band gap energy for the oxide as seen in Fig. 9. At lower temperatures, the band gap energy is low because of the combination of charge carriers from both intrinsic valance and extrinsic charges from a nonstoichiometric ratio contribute to conductivity. At increased temperatures, above 300 °C, the higher band gap reflects only the intrinsic conductivity of the semiconducting oxide, since all the extrinsic carriers have already been excited into the conduction band.

Another set of measurements was made on sample 2 to test the reproducibility without cleaning or filing the sample between runs. Resistivity and conductivity results are shown in Figs. 10 and 11. These show much more consistent reproducibility than the previous figures indicating possible contact resistance variability, at least for the beginning of the curves in Fig. 9.

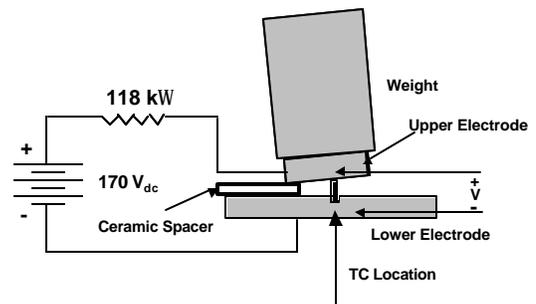


Figure 7. Resistivity measurement apparatus.

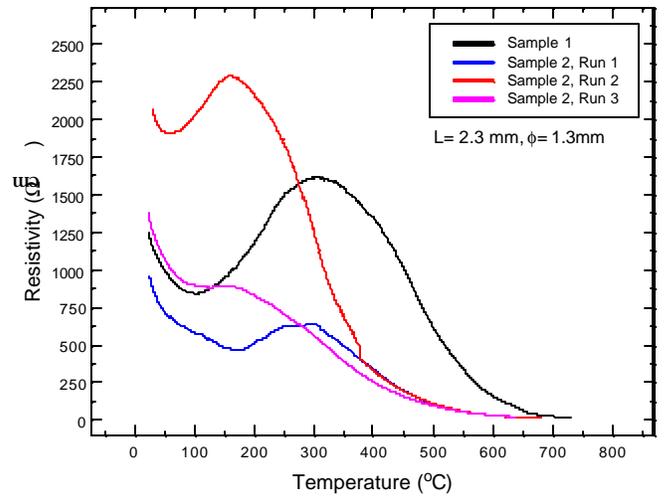


Figure 8. Resistivity, ρ , calculated from measured resistance and sample length, L , and diameter, ϕ ($R = \rho L/A$).

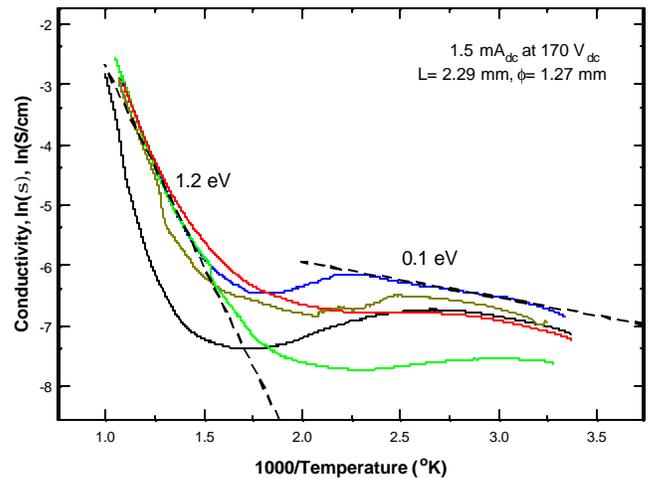


Figure 9. Conductivity results of Fig. 8 indicate uniform slopes (band gaps) even though there was variation in the resistivity values, especially at lower temperatures.

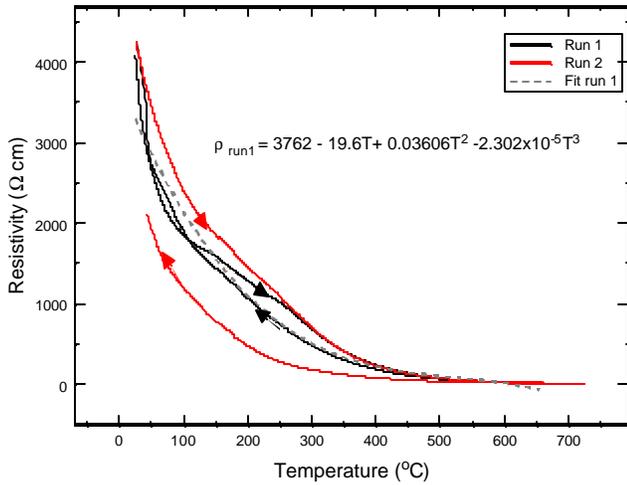


Figure 10. Repeated heating and cooling of sample 2 shows little hysteresis and reproducible resistivity results.

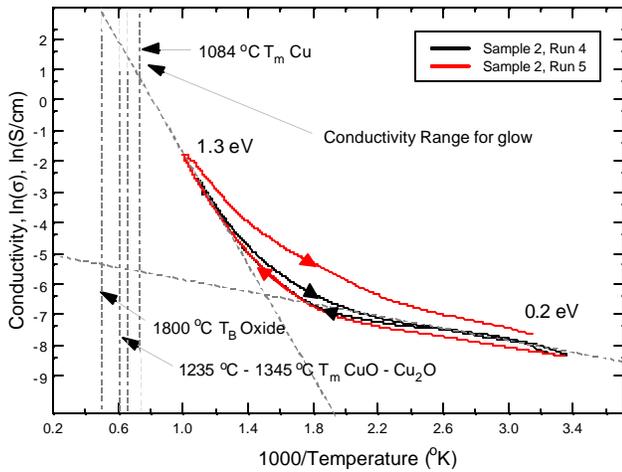


Figure 11. Plotting conductivity results for Fig. 10 along with key temperatures show, if the conductivity curve was extrapolated into the key temperature regions, the resulting conductivity would agree with measured dynamic resistance values.

Dynamic resistance, resistance during glowing (Fig. 12), was obtained by dividing the measured voltage across the glowing connection in Fig. 1 by the current. The rapid change in resistance near the zero crossings suggests that the glowing filament extinguished due to a reduction in temperature as the current approached zero. The change in slope of the voltage, around current zero, corresponds to a sharp increase in resistance. It is postulated that the glowing filament, above the melting point of copper, consists nominally of molten Cu_2O based on the oxidation rates of copper at high temperature and measurements [16].



$$k'' = 957e^{-37700/RT} \quad (\text{g}^2/\text{cm}^4 \text{ h}) \quad [3]$$

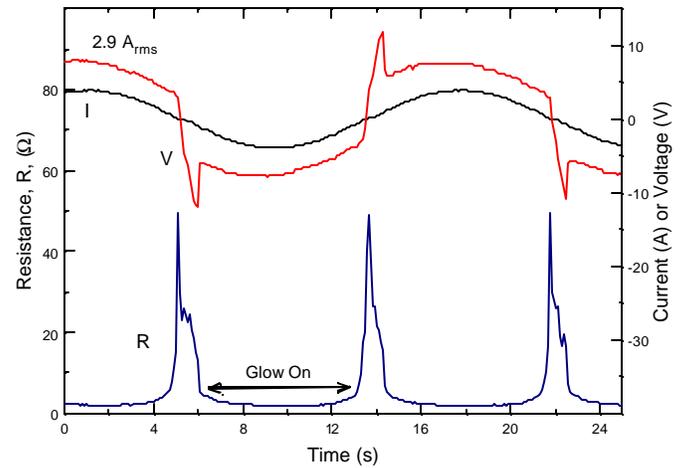


Figure 12. Dynamic resistance of glowing contact (2.9 A_{rms} , 1mm diameter copper) shows large increase in resistance near current zero.



$$k' = 0.0268e^{-20140/RT} \quad (\text{g}^2/\text{cm}^4 \text{ h}) \quad [5]$$

k' and k'' are corresponding oxidation rates [16]. A phase diagram for copper and oxygen show the range of temperatures (1091 °C to 1345 °C), which depend on the oxygen content for molten copper oxides [17]. Since the oxygen content depends on the diffusion rate and temperature (pressure was atmospheric), the molten oxide may consist of a range of oxidation states. Whatever the oxidation state, it appears that when the filament temperature drops below the melting point of the oxide filament, the resistance increases as seen in the dynamic resistance measurements. As the temperature drops, the oxidized copper begins to transform into CuO . The current, around zero crossing is flowing through the solid copper oxide that is transforming, depending on the available oxygen partial pressure.

The effect of current on filament temperature was also apparent when testing steady state conditions to measure the minimum current that would support the glowing filament. The voltage in the circuit, Fig. 1, was lowered by using a variac while the rms voltage across the glowing contact was measured using a Fluke 83 multimeter, until the glow extinguished at 0.25 A_{rms} as seen in Fig. 13. The value of glow extinction current shows that as the power drops below 5 W the glowing filament extinguishes.

The exponential increase in resistance with decreasing current would imply that the resistance of the glowing filament increases as its temperature decreases with decreasing rms current. The temperature of the glowing filament is still oscillating at 60 Hz similar to the dynamic resistance curves in Fig. 12. So, the glowing filament will still extinguish, briefly, at each zero crossing, when the rms current is below about 5 A_{rms} . Above 5 A_{rms} the voltage saw-

tooth pattern disappears and the waveform looks more sinusoidal, indicating that the glowing filament temperature never drops below the freezing point of the oxide, even at the zero-crossings.

Temperature measurements of the oxide bridge, Fig. 3, along with the resistivity measurements in Figs. 8 and 10, indicate that only a portion of solid oxide, last in contact with the glowing filament, would be hot enough to conduct current to produce the resistances seen near current zero (Fig. 12) and at extinction (Fig. 13), in the 5 to 80 Ω range. Since the molten glowing filament is constantly changing shape, yet the measured glowing voltage is consistent, would imply a sharing of current between part of the solid oxide and the glowing filament.

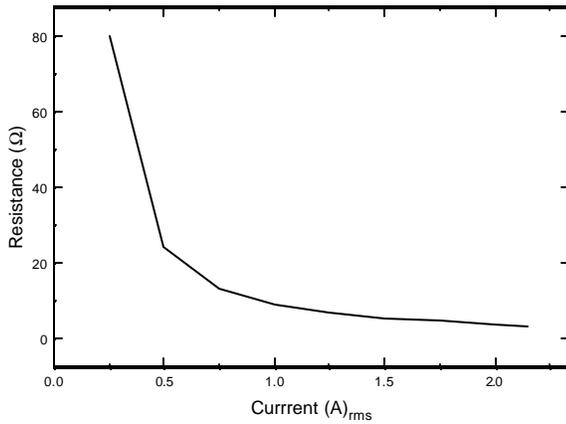


Figure 13. The measured resistance of glowing contact over a range of currents (1 mm diameter wire). Glowing filament extinguished at 0.25 A_{rms}.

D). MEASUREMENTS IN VACUUM

A test was conducted to determine if the amount of available oxygen was reduced, could the glowing contact be established and would an existing glowing contact extinguish. A second fixture, for creating glowing contacts, was developed with the ability to control the atmosphere surrounding the glowing contact as seen in Fig. 14. It consisted of a similar setup to Fig 1, except that a glass cylinder surrounded the wires and was sealed against o-rings as shown. This sealed system allowed for a partial vacuum to be pulled and Ultra-High Purity (UHP) nitrogen to be purged into the system. A solid state, vacuum pressure gauge, Honeywell model 19C015PV5L, was used to monitor the pressure in the chamber and a stainless steel vacuum bellows allowed for the motion of the wire inside the vacuum chamber to create the glowing connection.

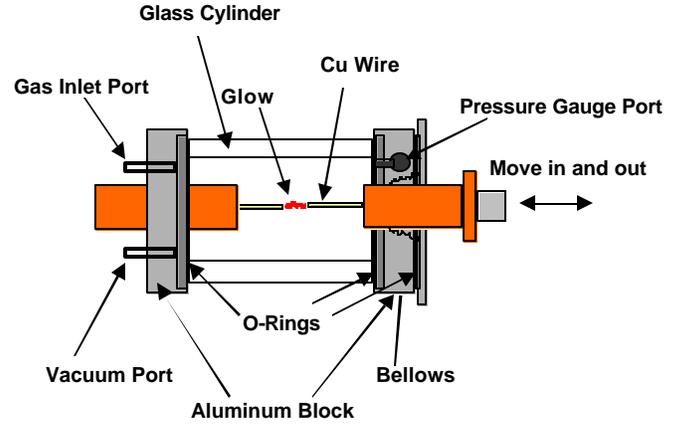


Figure 14. Apparatus used to create a partial vacuum around the glow or to replace oxygen in the air with dry nitrogen.

For this test, OFHC pure 1mm diameter copper wire was used in order to eliminate oxygen as a source from the metal. With clean copper wires at a pressure of 60 kPa, it was not possible to initiate a glowing connection.

To determine if oxygen was necessary to sustain a glow, a glow was initiated in air at standard pressure. The chamber was then evacuated and, as the pressure reached 58 kPa (436 Torr) the glow self-extinguished. Similarly, in another test, when the pressure was kept near atmospheric, 101 kPa, by replacing air in the chamber with UHP N₂, the glow also self-extinguished when the oxygen dropped below a critical level. The lack of O₂ was critical rather than the pressure.

This, vacuum testing showed that the partial pressure of O₂ at glow extinction was 12 kPa (90 Torr), assuming 20% oxygen content, at this pressure, the glow would extinguish due to a lack of oxygen to allow the oxidation process represented by eq. 2 to form Cu₂O to create the glowing filament. If the glowing track, see Fig. 4, pre-existed on a cold copper oxide bridge, upon initiating current flow, the glow would initiate and then immediately disappear, similar to a fuse vaporizing.

IV. MODEL

An electro-thermal model was developed by considering the glowing contact to be a cylindrical uniform glowing filament in parallel with the full length of the oxide bridge. By ignoring convection, an estimate of the glowing filament temperature can be calculated along with showing the dominant physical parameters that control the glowing process. Using the measured current and glowing voltage, the electrical power, IV_g, can be equated to the sum of the power lost to conduction, radiation, and thermal capacity as follows:

$$IV_g = KA(T_g - T_o)/L + 4\sigma T^4 + C_p \delta v \Delta T/t \quad [6]$$

where K is the thermal conductivity of Cu_2O , not found in literature, but created a piecewise linear equation based on selected data from [18] for molten copper; $K = 443 - 0.0847T$ for $T < 1200$ °K and $K = 844 - 0.4174T$ for $T \geq 1200$ °K with K in $\text{J/m}^\circ\text{K}$. The specific heat, C_p , for Cu_2O ($C_p = (48.56 + 7.50T - 0.056T^2 + 0.014T^3 - 0.760/T^2)/\text{MW}_{\text{Cu}_2\text{O}}$ with T in $(^\circ\text{K}/1000)$ and $\text{MW}_{\text{Cu}_2\text{O}} = 143.08$ g/mol) was obtained from the NIST database. The cross-sectional area, A , of the glowing filament was determined from SEM photos and video - radius of filament 125 μm). The glowing filament length, L , (0.3 cm), δ density of the glowing filament (used 6.3 g/cm³ for copper oxide), v volume of the glow ($L \times A$), $\sigma = 5.67 \times 10^{-8}$ W/m²°K⁴ Stefan-Boltzman constant, ΔT change in glowing filament temperature with time, and t is time.

The current and voltage data, from Fig. 12, was used to calculate the temperature using equation 6. A crude Excel spreadsheet model was developed to iteratively calculate the glowing filament temperature. The thermal conduction term was obtained by assuming the entire glowing filament to be one discrete element with a uniform temperature and the oxide bridge to be another discrete element at a percentage (54%) of the glowing filament temperature. The thermal difference between these two elements multiplied by the thermal conductivity and divided by the length between elements (radius of the oxide bridge, 0.05 cm) determined the watts loss of the filament from thermal conduction. Heat capacity was obtained by using the thermal gradient with time, using an estimated initial condition of 1200 °C for the filament temperature based on TC measurements.

Results from this model, Fig. 15, indicate the oscillation of the temperature, 1200 °C to 1300 °C, was in the range of melting points (1091 °C to 1345 °C) depending on oxidation state. The model also showed that increasing the conductor area, which increases thermal conduction, would lower the temperature and increase the extinction current. Similarly, a material with a higher thermal conductivity will increase the extinction current and make it harder to sustain a glow. However, materials such as steel have a lower thermal conductivity than copper, so it would be easier to initiate and sustain a glowing connection with steel.

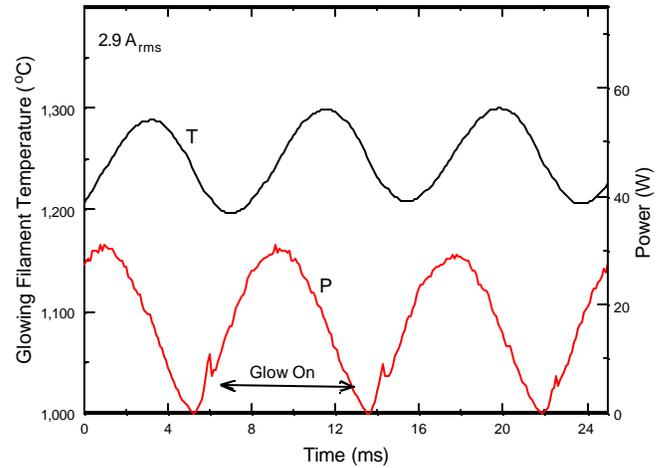


Figure 15. Calculated temperature from model using measured power.

VI. DISCUSSION

Visual and resistivity measurements have shown that a glowing connection can be considered a parallel or parallel/series circuit consisting of a liquid glowing filament and a solid oxide bridge. Measurements also suggest that the glow is a molten metal/metal oxide filament of copper in some degree of oxidation state, likely Cu_2O since this reaction is more favorable at molten oxide temperatures, while the bridge is predominantly CuO or a mixture of metal deficient p-type non-stoichiometric Cu_{1-y}O .

Based on oxide bridge resistivity and oxide temperature measurements when glowing, it was determined that the resistivity of the solid bridge was too high for significant current conduction, except near the liquid metal filament where the temperature was high enough to reduce the resistivity of the solid oxide.

Electrical data showed a saw-tooth pattern, at currents below 5 A_{rms} , indicative of an extreme change in the resistivity of the contact. This suggests that the glow switches off near current zero, and the solid CuO that was last closest to the liquid then carries the current. This can be seen in the dynamic resistance plot showing the rapid rise in resistance near current zero. By extrapolating the conductivity curve in Fig. 11, the drop in conductivity as the temperature drops, closely matches the measured dynamic resistance in Fig. 12 as well as the steady state values obtained in Fig. 13.

The TC temperature measurements of the oxide while glowing show, along with the measured results of resistivity in the furnace, that the resistivity was too high for any significant current flow in the solid oxide, with the possible exception of the oxide adjacent to the molten copper oxide filament which was above the copper oxide melting point.

The measured temperature of the liquid metal glow, Fig. 3, was around the melting point of Cu_2O , 1235 °C. When the current increased to 7.5 A_{ms} , the glowing filament temperature increased to 1730 °C. This supports the theory that with higher currents, the glowing filament temperature approaches the oxide vaporization temperature, 1800 °C, and becomes unstable. Exceeding this temperature would lead to an unstable liquid/vapor interface that would arc, which could explain why it is more difficult to sustain a glow for any long period of time at higher current levels.

The glowing filament does not appear to possess the properties of a plasma unless arcing occurs, either from an abrupt interruption of the current or the current level is such to exceed the oxide vaporization temperature. Plasma temperatures would also produce a green spectral emission that has not been detected.

Even though the TC was carefully calibrated and was electrically isolated, the temperatures measured are subject to error. The long time constant, 40 ms, of the 0.005" diameter wire prevented an accurate measure of the glowing filament temperature modulated by the 60 Hz current. Using a 0.003" diameter TC wire, some of the temperature modulation could be measured but the time constant was still too long. Other sources of error include inconsistent or poor contact of the TC to the oxide bridge and glow and electrochemical reaction with the TC wire.

The model needs to be further refined by breaking the oxide bridge and glowing filament into smaller discrete elements and use the resistivity data obtained from measurements of the CuO in the calculations rather than the measured power. This would provide a better estimate of temperature and would better correlate with the saw-tooth voltage waveform pattern.

The glowing filament does not always appear to fully bridge the copper wires, but rather terminates on the oxide surface, leading to the combination of resistivity of the liquid and solid determining the resistance. Further, the glowing voltage does not increase with time even though the length of the oxide and glowing filament does. This would suggest that as the length increases, the resistivity must drop and/or the conducting area must increase with time since and the, the current is fixed and the voltage across the contact remains constant. To decrease resistivity and increase conducting area, the glowing filament temperature must increase with time as the glow lengthens in order to maintain a constant resistance.

VI. CONCLUSIONS

Various measurements have added to the understanding of glowing wire contacts. These results showed that the

copper glowing contact could be considered a parallel or parallel/series combination of a glowing liquid, consisting of $\text{Cu}/\text{Cu}_2\text{O}$, and a solid bridge of CuO . The solid oxide bridge, in contact with the liquid oxide, carried a small percentage of the current when the glow was on, however, near current zero, the glow extinguished, when the current was below approximately 5 A_{ms} , and the part of the solid bridge, adjacent to where the glow extinguished, carries all the current during the cooling period. This cooling of the oxide produced the saw-tooth voltage pattern typically seen in currents below 5 A_{ms} . The saw-tooth waveform becomes more sinusoidal at higher currents because the liquid oxide is hotter and does not extinguish, even near current zero.

Temperature measurements confirmed that the glowing liquid is near the melting point of Cu_2O (1235 °C) and increases, towards the boiling point of 1800 °C with currents above 5 A_{ms} . A solid track of Cu_2O and Cu can create a low resistance path, even after the glow is stopped. This can occasionally occur, if the oxide bridge does not crack, and can lead to immediate reignition of the glow with the reapplication of voltage.

A glowing filament could not be started on clean fresh copper wires in an oxygen-deprived environment. Surprisingly, the glowing filament could not be restarted or sustained when the partial pressure of oxygen dropped below 12 kPa (90 Torr). It was postulated that the reason for this was that the glowing filament was composed of molten Cu_2O and molten Cu and without enough oxygen present; the reaction to produce Cu_2O could not be sustained. This occurred even when there was a CuO bridge preformed between the wires.

The thermo-electric model supported measured temperature results and showed that the saw-tooth voltage waveform could be due to the filament temperature dropping below the freezing point of the copper oxide in the glowing track.

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