Electromigration in TaAl Thin Film Heater Material

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Abstract

Electromigration is usually observed in metal conductive lines of electronics chips. However, under conditions of high temperature and high current density, electro-migration will also occur in thin film resistor material. The electromigration in a thin film resistor will cause resistance degradations and result in resistor opens.

In this paper, electromigration failure mechanism in TaAl thin film resistor is discussed based on microstructural analysis. In addition, resistance degradations due to electromigration are characterized, and a model based on experimental data is generated to quantitatively describe this new phenomenon.

Introduction

A thermal inkjet printhead uses thin film resistors as a heat element, which will generate enough energy to superheat the ink above the heaters. The superheated ink will be vaporized and generate bubbles to eject ink droplets out of nozzles above the heaters. A heater stack consists of a thin film resistor layer and several passivation layers on top of the resistor layer. Typically, the passivation layers include (from top to bottom) Ta layer, SiC layer and SiN layer. The materials suitable for thin film resistor application must satisfy a number of strict requirements, including 1)low Thermal Coefficient of Resistance (TCR); 2)minimum resistance changes after high current density and high temperature stresses (as well as after fabrication processes); 3)low thermal coefficient of expansion mismatch with adjacent layers; 4)compatible with semiconductor process; 5)high heater stack reliability. Several materials are being employed for thin film heater application, including HfB_2, TaAl, TaN and Diamond-like Carbon (DLC) films. The most popular material is TaAl thin film.

TaAl thin film is fabricated with sputtering process using a Ta-Al alloy target or Ta and Al dual target. Due to the quench kinetics in sputtering processes, as-deposited Ta-Al film is in an amorphous state. At this state, the bonding energy between Ta and Al is not as high as the ones in crystalline TaAl. Consequently, physical properties of amorphous TaAl will be different from crystalline TaAl. Hence, it could be imagined that an amorphous TaAl thin film will behave differently compared with crystalline TaAl.

During printhead printing, a heater is driven by a fire pulse with about one to two microsecond in width and hundreds of milliamperes in amplitude. At the end of a fire pulse, the heater temperature will reach its peak value. Amorphous TaAl thin film is very stable with low current and low temperature stressing. However, under high current and high temperature stressing, a thin film TaAl resistor will experience material degradation, which will result in heater resistance decreasing and heater stack blistering in the worst case. Normally, heater stack blistering happens at cathode side, which is similar to the electromigration failure mode in an Al conductive line. In this paper, the electromigration failure mode in a TaAl thin film resistor is discussed based on microstructural analysis (SEM, TEM and Auger), electrical measurement of resistance degradation and heater reliability testing. In addition, resistance degradation is characterized with a model based on experimental data.

Experimental

In order to investigate heater material and resistance degradation under current and temperature stressing, the current passing through a thin film resistor and the peak temperature of the thin film resistor should be controlled. The control of a constant current is achieved by using a pulse signal generator with a constant current source, and the constant peak temperature is controlled by adjusting fire pulse width according to a finite element thermal simulation. In addition, wet-fire method and dry-fire method were used to collect experimental data in this work. Wet-fire test is to stress a heater with ink present on top of heater, i.e. in normal printhead working modes. Dry-fire test is to stress a heater at wafer level without ink present on top of the heater, which is a simple method for investigation of current and temperature effect on heater material without considering ink interaction with the heater stack. The advantage of dry-fire test includes 1) It is an accelerated reliability test at the wafer level, so it could be used for quick comparison of different material processes in heater reliability; 2) Since Kelvin sensing heater structures are used, currents and resistances can be measured accurately; 3) It is a simple method for investigation of heater material/resistance degradation; 4) Since dry-fire is similar to the worst scenario of printhead heater during de-priming, it could be used for a quick estimation of heater material design margin. However, as mentioned earlier, since ink interaction is excluded from dry fire test, dry fire test will be different from wet fire test for several reasons 1) excluding effects of cavitation force and ink interaction with Ta; 2) using shorter pulse to get the same TaAl peak temperature expected in wet fire. Dry fire has proved to be a useful method to test heater material reliability.

SEM, TEM and Auger depth profile techniques are used in this work for materials analysis. It is necessary to point out that in order to avoid charging effect during Auger Depth Profile, a parallel lapping was used to remove the dielectric layers above a heater layer. In addition, during sample preparation, cautions are needed in order to avoid artificial effects.

Result and Discussion

Heater Material Degradation

1. Electromigration

During printhead reliability testing, TaAl thin film resistors repeatedly failed in a fuse mode at cathode side, which was very similar to electromigration in an Al conduct line (Figure 1 and Figure 2). Figure 1 is a top view of a failed heater and Figure 2 is a cross-section of a failed heater. These two pictures revealed two basic features of this common failure in TaAl thin film resistor: 1) TaAl thin film always opened in a fuse mode at 1/3 heater length away from cathode metal edge; 2) Protective layers above TaAl will delaminate from TaAl surface. TEM cross-section of a failed TaAl thin film resistor (Figure 3) indicated that voids formed inside TaAl film and concentrated on cathode side of TaAl resistor. Due to its similarities to the electromigration in Al conductor lines, this failure mode in a TaAl layer is named electromigration failure.

Figure 4 to 9 illustrate a progress of TaAl thin film degradation. Figure 4 is a TEM cross-section of an as-received TaAl thin film. The parallel striations inside TaAl layer were due to the rotation of magnetic field behind a TaAl target during sputtering deposition. Auger depth profile analysis showed no Al-rich interfaces for this as-received TaAl film (Figure 5). However, after initial stressing of TaAl thin film resistor, a TEM cross-section picture (Figure 6) showed a light-contrast layer existing at the interface between TaAl film and the top protective layer. Since TEM observation was under Bright Field condition, light-contrast layer implied that the atomic mass of this layer was smaller than the atomic mass of TaAl layer. In addition, Auger depth profile result (Figure 7) indicated that Al-rich layers were formed at the top and bottom surfaces of TaAl. Since Al only existed in the TaAl film, it is logical to assume that Al-rich layer is due to Al segregation from TaAl layer. With further stressing, voids began to form inside the TaAl layer (Figure 8), and segregated Al layer became thicker (Figure 9). With more and more voids formed, TaAl layer collapsed at voiding region and the top SiN layer delaminated from TaAl layer. Since the protective layers (SiN and SiC) above TaAl normally possessed compressive stresses, the protective layers bubbled up after delamination and was observed as a heater blistering. After delamination, TaAl temperature will be increased dramatically while driven by a fire pulse, because there was no top layer to dissipate the heat generated inside TaAl layer, and this resulted in a fuse-open of TaAl layer. TaAl layer usually opened at the position of about 1/3 heater length away from the cathode metal edge, where the largest thermal gradient (i.e., dT/dx, x is the distance from a electrode) existed,. The larger the temperature gradient is, the larger thermal fatigue will be, so a TaAl layer will fail at this position. In a summary, based on microstructural analysis, an electromigration mechanism of TaAl thin film is described as follows: 1)Al segregated to the top and bottom surfaces of TaAl due to current and temperature stressing; 2)Voids formed inside TaAl layer and concentrated at cathode side; 3)TaAl collapsed at voiding region, and top layer SiN delaminated from TaAl due to internal compressive stress 4)TaAl opened in a fuse mode at position with the largest dT/dx. A schematic drawing of this mechanism is shown in Figure 10.

2. Thermal Segregation

As mentioned earlier, an as-deposited TaAl is in an amorphous state, which means Al and Ta atoms are loosely bonded together compared with crystalline TaAl. Hence, the melting temperature of such amorphous TaAl could be lower than the one of crystalline TaAl (about 2100 °C for $AlTa_2$).[1] This hypothesis was confirmed by a TEM microstructural analysis on annealing TaAl films. The results showed that microstructure changes of TaAl film were negligible after annealing for one hour at 550 °C and 650 °C, respectively. However, after one hour annealing at 750°C, voids developed inside TaAl thin film, which were similar to the final stage of an electromigration degradation (Figure 11). The reason is that Al will undergo segregation/re-distribution at the Al melting temperature or TaAl recrystallization temperature (660 °C to 750°C) due to the weak bond between Ta and Al. Note that thermal segregation of Al is purely due to high temperatures, while Al segregation caused by electromigration is due to both high temperatures and high currents.

Heater Resistance Degradation

The electrical properties of a material will correlate with its material properties. Since a TaAl film experiences material degradation, as expected, electrical properties of a TaAl film would also change correspondingly. Heater resistance change over heater life is one of the phenomena that reflect TaAl electrical degradations. Variation in resistance could cause instabilities on the heater operating point, drop-mass and drop-velocity. Consequently, printing quality will be degraded. In addition, the decrease in heater resistance will cause an increase in heater current and result in an early failure of the TaAl resistor due to accelerated electromigration. Figure 12 shows heater resistance changes over heater life. Both AC and DC resistances were measured for comparison. An AC resistance is measured while a heater is driven by a nominal fire pulse, i.e., a resistance value under high current and high temperature. A

DC resistance is measured using small current so that no thermal effect is induced. Hence, the difference between AC and DC resistance values is due to the thermal effect and relates to the Thermal Coefficient of Resistance (TCR) of a TaAl film. Typically, resistance decreased rapidly at first and then slowed down afterward until it reached a constant value. The initial heater resistance decreased was due to electromigration in the TaAl layer. As discussed earlier, Al segregated out from TaAl and formed two Al-rich conductive layers paralleled with the TaAl layer, as a result, total net resistance of a heater was decreased. At mid-life of a heater, equilibrium was established between Al segregation and Al back diffusion or Al segregation and TaAl voiding, which resulted in a small or no change in heater resistance. At the final stage of a heater life, enough Al segregated out and positive Al TCR compensated for the negative TaAl TCR, hence, AC resistance increased and DC resistance kept constant. This phenomenon was more prominent in thinner TaAl films, since a thinner Al layer was necessary to effect a change in a thinner TaAl layer.

Since heater resistance change is due to electromigration, it should be described by the Black Equation as shown below. Black equation is widely used to quantitatively describe electromigration in Al conductor lines.

$$C = A \times J^{n} \times e^{Q/kT}$$

where, C is the relative resistance change, J is TaAl current density (mA/um^2), T is peak TaAl temperature (Kelvin), K is Boltzmann's constant = 8.617E-5 eV/Kelvin, Q is the activation energy derived from the lab data. Similarly, A and n are constants derived from the lab data.

Figure 13 is a set of family curves modeled by using Black's equation and experimental data collected at five million fires of a heater.[2] The curves indicate that resistance change is related to TaAl temperature and current. An important observation is that heater resistances will significantly change between 700 °C and 750 °C, which is consistent with previous observation, i.e., a TaAl film will experience significant degradation between 650 °C and 750 °C.

Another interesting observation is that the TaAl resistance will recover once stressing is stopped. Figure 14 shows resistance degradation/recovery curves (four cycles) for a heater that was stressed for five million fires and recovered for 12 hours. It is worthwhile to mention that a heater did not fully recover, and the recovering percentage of the heater resistance depended upon accumulated stresses (i.e., the total amount of time a heater has been fired). Once the stressing was resumed, resistance change would return to the original curve with continuous stressing. The reason for this phenomenon is still not fully understood. One hypothesis is that during stressing a heater, an equilibrium is achieved between Al segregation and Al back diffusion. Once the stressing is stopped, the equilibrium will not exist anymore, and the heater resistance will recover due to some relaxation mechanism. Also, the unrecoverable residual of heater resistance change probably reflects a real material damage.

Conclusion

TaAl thin film resistor will experience electromigration under high current and high temperature stressing. This is due to Al segregation from TaAl film and void formation inside TaAl film. In addition, pure thermal stressing with a temperature above Al melting temperature also can cause Al segregation. As a result of the material degradation, heater resistance will change over heater life, which can be quantitatively modeled. In addition, due to relaxation mechanisms, heater resistance will recover after a stressing is halted.

References

1. P.R. Subramanian, Phase Relationsips in the Al-Ta System, Met. Trans. (A), 21A, 1990
2. R. Cornell, Lexmark internal report, 1999

Biography

Yimin Guan received his M.S. in Materials Science from Charlmers University of Technology in Sweden in 1994 and a Ph.D degree in Materials Engineering from Auburn University in 1998. Since 1998 he has worked for Lexmark International, Inc. as a Materials Engineer. His work has primarily focused on the Inkjet Chip Development.

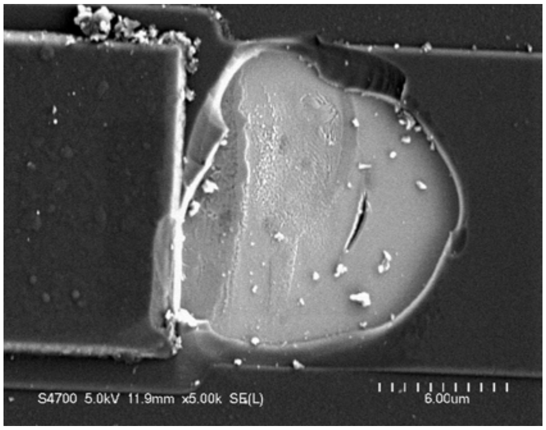

Figure 1. Top-view of a Failed Heater Stack

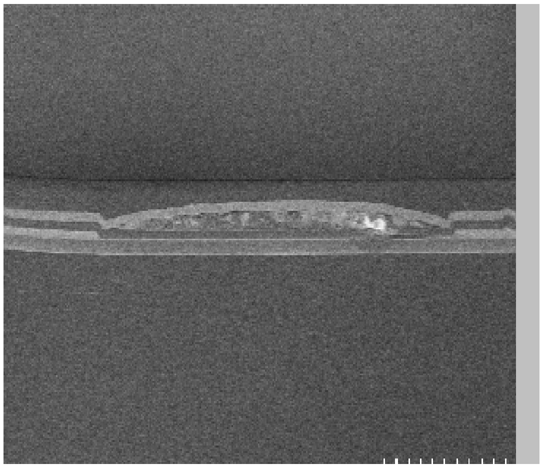

Figure 2. Cross-section of a Failed Heater Stack

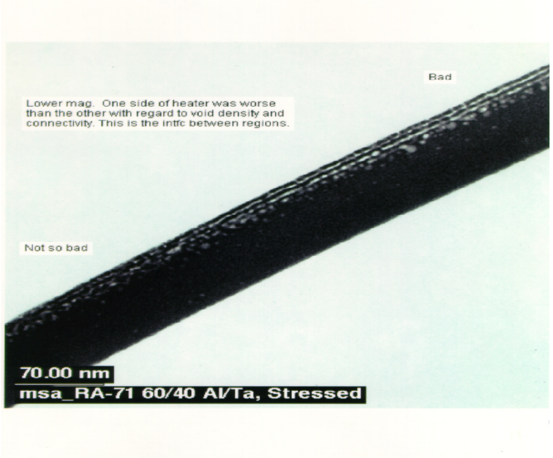

Figure 3. TEM Cross-section of a Failed TaAl Film

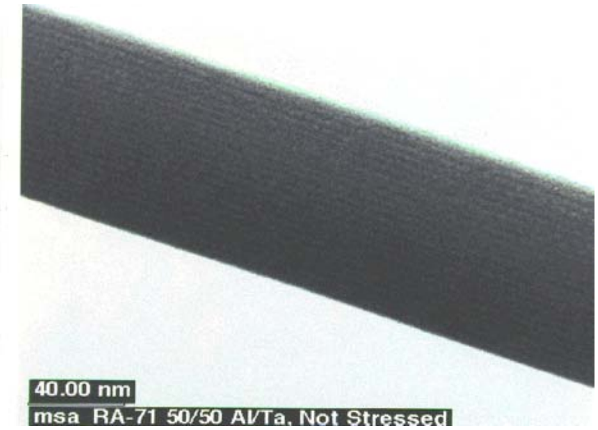

Figure 4. TEM Cross-section of an As-received TaAl Film

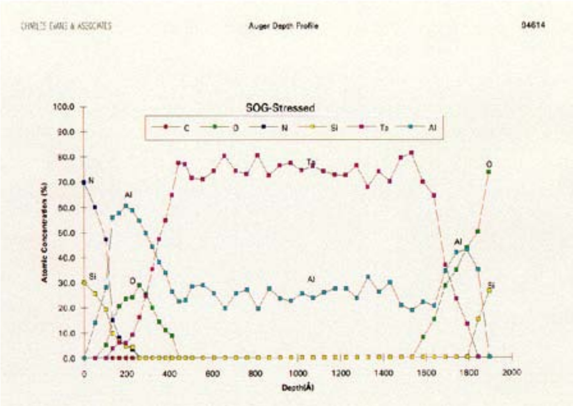

Figure 5. Auger Depth Profile of an As-received TaAl Film

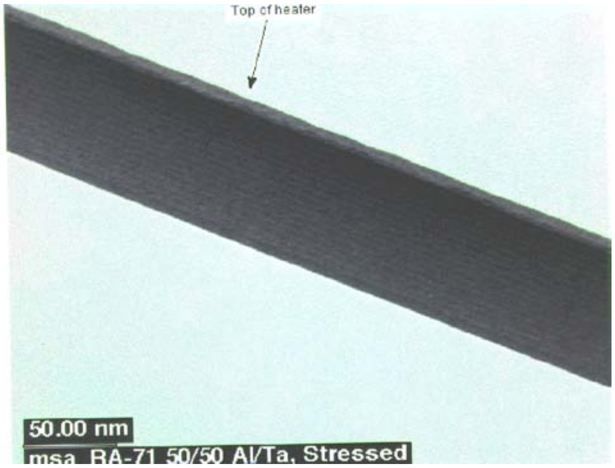

Figure 6. TEM Cross-section of a TaAl Film after Initial Stress

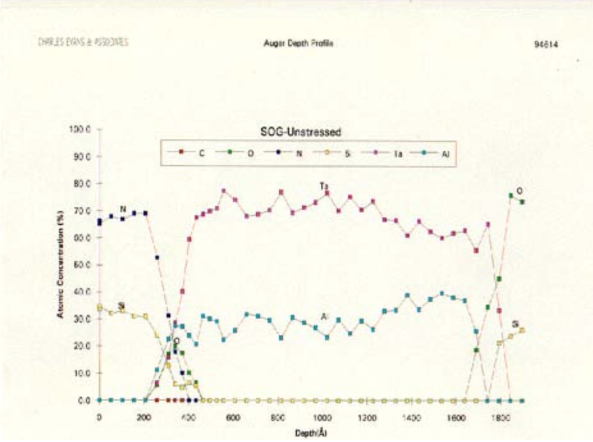

Figure 7. Auger Depth Profile of an As-received TaAl Film

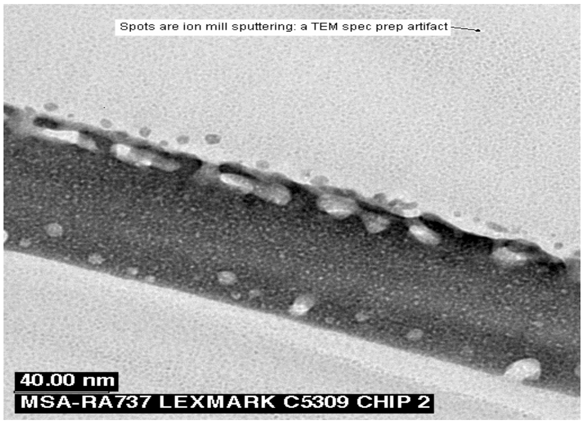

Figure 8. TEM Cross-section of a TaAl Film after Long-term Stress

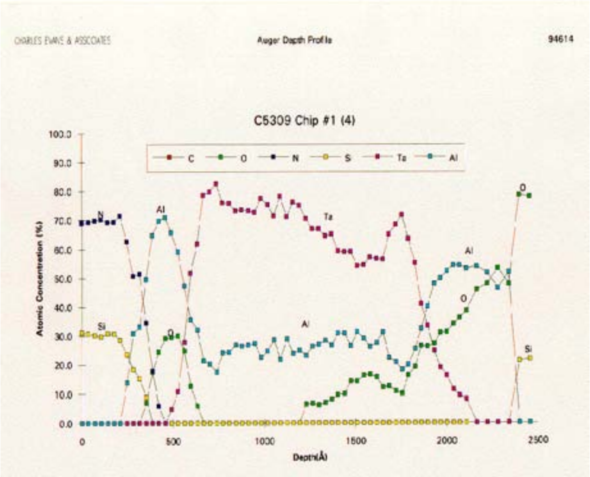

Figure 9. Auger Depth Profile of a TaAl Film after a Long-term stress

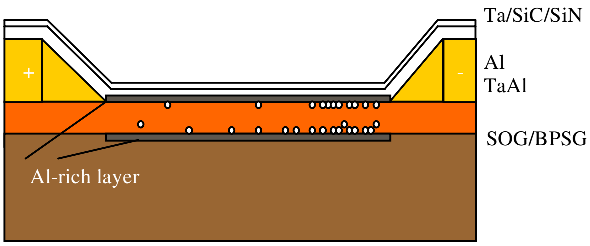

Figure 10 (a) Schematic of Heater Stack after Initial Stress

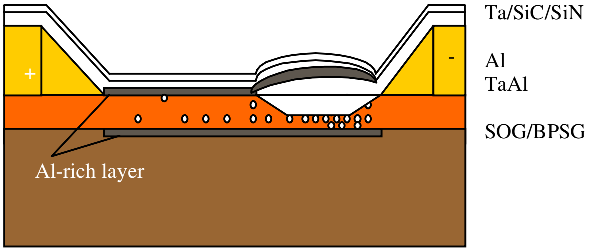

Figure 10 (b) Schematic of Heater Stack after Delamination of Protective Layers

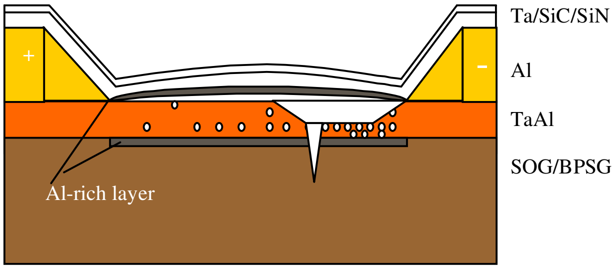

Figure 10 (c) Schematic of Electromigration Failure in Heater Stack

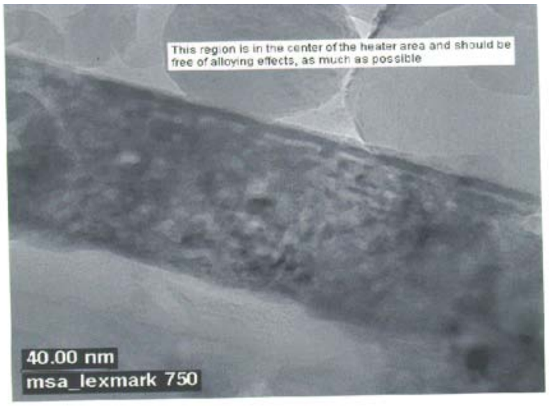

Figure 11. TaAl Voiding due to Thermal Annealing

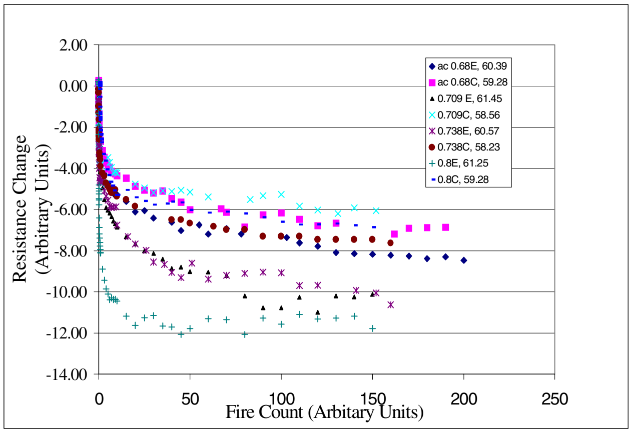

Figure 12. Resistance Change over Life

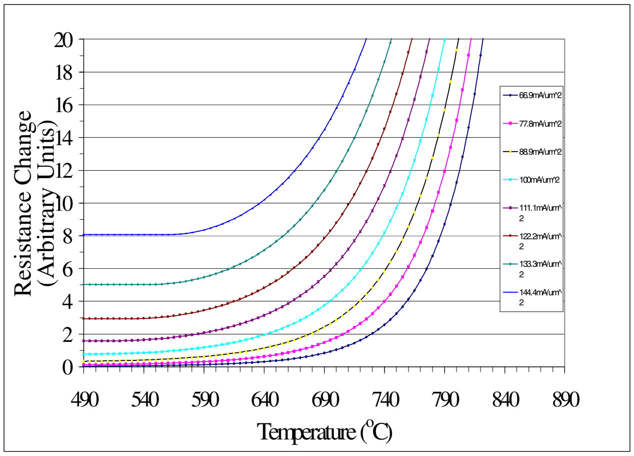

Figure 13. Heater Resistance Change vs. Current and Temperature

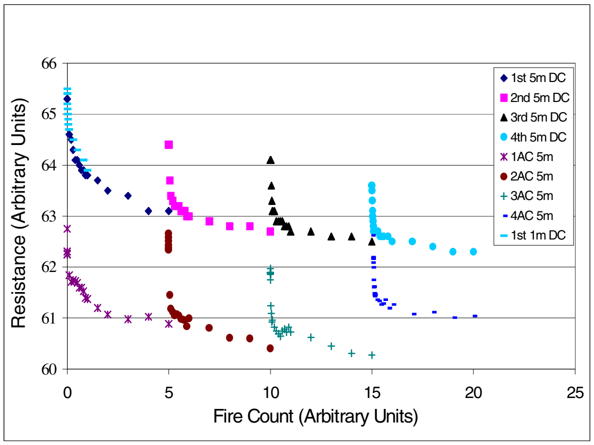

Figure 14. Heater Resistance Degradation and Recovery