THE DC FUSING CURRENT AND SAFE OPERATING CURRENT OF MICROELECTRONIC BONDING WIRES

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ABSTRACT

Recent measurements made at Raytheon indicate that bonding wires used in microelectronic packages can meet the MIL-M-38510 specifications and yet overheat in operation. In this paper, fusing current theories are discussed in detail. The formulas incorporated in the MIL specs are shown to be invalid and new formulas are proposed. New equations are derived for calculating both the d-c fusing current and the maximum d-c design current for gold and aluminum bonding wire and ribbon over all practical ranges of length and cross sectional area. Equations for the fusing current and the maximum temperature of short wires are derived by solving the fundamental differential equations in such a way as to include the temperature dependence of electrical conductivity. Experimental data is found to agree with calculated values to within 10% in most cases. The formula in MIL-M-38510 was found to be greatly in error for large diameter aluminum wires used in power devices and for small diameter gold or Al-1%Si wires that are extremely long or extremely short.

ALMOST ALL low power semiconductor devices and ICs use either 99.99% gold (Au) or aluminum 1% silicon (Al-1%Si) bonding wire in diameters typically ranging from 1 to 1.3 mils to connect the bond pad of the die to the package. Power devices such as transistors typically use pure aluminum (99.99% Al) in diameters usually ranging from 5 to 15 mils. A knowledge of the d-c fusing current is necessary in both design and failure analysis. In failure analysis, the d-c fusing current can be used to bracket the current levels involved in electrical overstress. In microcircuit design, the value of the maximum allowable current is usually specified as some fraction of the d-c fusing current.

The conditions required for fusing a bonding wire depend on the current, length, cross sectional area, pulse duration, wire material, ambient temperature and parameters associated with radiation and convection. Unfortunately, there exists no generally accepted formula that will allow the d-c fusing current to be computed with reasonable accuracy over all practical ranges of diameter and length. Several contradicting formulas are in common use. The most common formulas give the fusing current as proportional to $D^{3/2}$ [1,2,3], $D^{1.0}$ [4,5], D^2 [6], D^2/L [7, 8]. The coefficients in these formulas are chosen so that they all give approximately the same fusing current for commonly used wires such as a 1 mil diameter, 50 mil long wire. These formulas err for large diameter aluminum wires used in power devices and for small diameter gold or Al-1%Si wires that are extremely long or extremely short.

This problem is exemplified by Section 3.5.5.3 in MIL-M-38510 [3] which incorporates the 3/2 power law. For 10 mil diameter aluminum wire, according to MIL-M-38510, the maximum allowed current is 15.2 amps for all lengths greater than 40 mils. This value is too large for the longer wires typically used in power hybrids and much too small for the shorter wires typically used in power transistors. For example, the measured fusing current for a 393 mil length of 10 mil diameter aluminum wire (typical of power hybrids) is 14.7 amps [9], whereas, the actual fusing current for a shorter, 80 mils wire (typical of power transistors) is about 50 amps.

There is no generally accepted equation that is satisfactorily accurate over the range of all practical diameters and lengths. The purpose of this paper is to review the existing formulas, identify their limitations, and present new accurate formulas for both the fusing current and the maximum design current.

EXISTING THEORIES AND FORMULAS

D TO THE 3/2 POWER, $D^{3/2}$ - The fusing currents of different kinds of long wires were first quantified by Preece [2] in 1884 who developed the formula:

$$I_{fl} = aD^{3/2}. \qquad (1)$$

Preece published a table for the values of the long wire coefficient, a, for several different metals that included aluminum but excluded gold. Preece's value for the constant, a, for aluminum was 7585 amp/inch$^{3/2}$ which is equivalent to 0.24 amp/mil$^{3/2}$. (As will be explained later, a wire is "long" or "short" depending on whether it is longer or shorter than the critical length L_*.) Preece's derivation [2, pp. 467-468] is summarized in Appendix B.

D TO THE 1.0 POWER, $D^{1.0}$ - In Preece's original paper, he states that wires having diameters less than 10 mils "did not follow the law of the 3/2 power" and that, instead, the fusing current for small diameter wire "is approximately directly proportional simply to the thickness of the wire" [2, 1887, p. 295]. A formula showing this 1.0 power dependence was derived by Ayrton in 1887 [4, p. 553]. Ayrton based his derivation on the assumption that the coefficient, K_k, in Eq. B-5 exhibits D dependence of the form (1 + constant/D) [5].

D SQUARED OVER L, D^2/L - When a wire is so short that almost all the electrical power dissipated can be transferred through the wire to the ends which are held at a lower temperature by the heat sunk bonds, then

$$I_{fs} = K_2 D^2/L. \qquad (2)$$

While this equation is established in the technical literature [7, 8] and is quite accurate for wires shorter than L_*, it has not been widely adopted. Eq. 2 can be derived from first principles by solving the differential equation for a thin wire heated by an electric current for the steady state case with no surface heat transfer [7]. An alternate derivation is shown in Appendix A in which the short wire coefficient K_2 in Eq. 2 is derived to be

$$K_2 = (\pi k/2c)\cos^{-1}(T_0/T_{melt}) \qquad (3)$$

where c is the square root of the Lorenz number, which is a fundamental constant based on Boltzmann's constant and the charge on an electron [10], T_0 is the temperature at the ends of the bond wire, T_{melt} is the melting temperature, and k is the thermal conductivity. As shown in Appendix A, the derivation of Eq. 3 takes into account the temperature dependence of electrical conductivity. Note that the thermal conductivity, k, is the only parameter that must be determined from experimental measurements. While the electrical conductivity for gold and aluminum varies as the reciprocal of the absolute temperature, the thermal conductivity, k, is much less temperature sensitive [11]. In aluminum, for example, the ratio of electrical conductivity at 25 °C to electrical conductivity at the melting point is approximately 4.0; for the thermal conductivity, the ratio is approximately 1.1 [12, p. 8-9]. Hence, temperature variation in thermal conductivity, k, in Eq. 3 is relatively unimportant. And, as shown in Appendix A, the calculated values of the short wire coefficient, K_2 , for 99.99% Gold, 99.99% Al, and Al-1%Si are 108, 81, and 60 amp/mil respectively. These values were calculated using the room temperature values of thermal conductivity, k. For comparison, Loh [8, p. 215] obtained a value of 106 amp/mil as an average value for both gold and aluminum. Loh used a somewhat different derivation and used the ambient temperature value of thermal conductivity and the electrical conductivity averaged between the ambient and melting temperatures.

The following new equation for the maximum temperature of the wire which occurs at mid-span is also derived in Appendix A:

$$T_{max} = T_o/\cos((I/I_f)\cos^{-1}(T_o/T_{melt})). \quad (4)$$

The value of the $\cos^{-1}$ function is in radians, not in degrees. This previously unpublished equation shows, for example, that if a short gold wire is operated at one half its fusing current and both ends of the wire are at 27 °C, then the maximum temperature at mid-span is only 110 °C. This dramatic reduction in temperature from the melting temperature is a consequence of the I^2R heating in the wire being less by a factor of about 14 (a factor of 4 due to the halving of the current and a factor of 3.4 due to the lower wire resistance at the lower temperature).

D SQUARED, D^2 - For a constant length, Eq. 2 reduces to

$$I_f = (\text{constant})D^2. \quad (5)$$

While this relationship is sometimes found in data sheets, it is invalid except for a particular value of length. One data sheet [6] states that 0.6 amps per circular mil foot is a good average value for the maximum current capability of gold or aluminum wire. This is equivalent to $I_{design} = 0.6D^2$ which evaluates to 5.4 amps for a 3 mil wire. Since a 394 mil long Al-1%Si 3 mil wire actually fuses at about 2.2 amp [9], one can readily see that Eq. 5 must be used with caution.

RAW DATA

Values of fusing current were collected from a variety of sources; some experimental values were determined by the authors. Table I lists the data for 99.99% gold wire and Table II lists data for Al-1%Si wire. Note that there is considerable scatter in the listed values of fusing currents. For example, Table I lists two different experimental values of the fusing current, I_e, for a 394 mil length of 2 mil diameter gold wire: 1.39 amp and 1.6 amp. The differences are believed to have been caused by the difficulties of controlling and measuring the many variables involved. For example, a nick in the wire will lower its fusing current. Since the fusing current typically varies as D^2, a 10% error in measuring D will result in a 20% error in calculating the fusing current. In addition, the nonlinear V-I characteristics of an aluminum bond wire make definition of the fusing current somewhat confusing [9,13]. Another source of error is imperfect heat sinking at the ends of the wire.

The various manufacturers of bonding wire have distributed data sheets and user guides that contain graphs and tables that show a linear relationship between the logarithm of the fusing current and the logarithm of the diameter for 1 ft lengths of wire. Since a straight line on a $\log(I_f)$ versus $\log(D)$ plot is indicative of the power law relationship

$$I_{fl} = K_1D^n, \quad (6)$$

the manufacturer's graphs can be converted to the power law equations listed in Table III.

Table III shows that it is well accepted in the fine wire industry that the fusing current for long 99.99% gold wires varies as $D^{1.0}$ with a 1 mil diameter wire fusing about 0.6 amp and that the fusing current for long Al-1%Si wires varies as $D^{1.3}$ with a 1 mil diameter wire fusing at about 0.5 amp.

Very little published experimental data could be found for the current carrying capability of 99.99% aluminum. One data sheet [20] lists wire fusing currents for 12 inch lengths of 1 mil diameter 99.99% gold, Al-1%Si and 99.99% Al as 0.49, 0.39, and 0.44 amps respectively. This experimental data suggests that 99.99% Al has current carrying capabilities halfway between that of 99.99% gold and Al-1%Si. Also, as shown in Appendix A, the theoretical short wire coefficient of 99.99% Al is also about halfway between that of 99.99% gold and Al-1%Si.

NEW FORMULA

Since the formula for fusing current should be accurate for both long and short wires, the formula should reduce to Eq. 6 as the length approaches infinity and to Eq. 2 as the length approaches zero. These requirements are clearly met by combining these two formulas as follows:

$$I_{sum} = K_1D^n + K_2D^2/L. \quad (7)$$

The first term of this equation, (K_1D^n), represents the current limit imposed by convective and radiative heat transfer into the surrounding environment. Because of the 1/L dependence of the second term, it dominates for short wires but allows the first term to dominate for very long wires.

The second term of Eq. 7 (K_2D^2/L) represents the current limit imposed by conductive heat transfer laterally through the wire into the heat sunk bond on both ends. Note that the fusing current becomes very large as length approaches zero.

The dividing point, L_*, between long and short wires occurs when the first (convective/radiative) term equals the second (conductive) term.

$$L_* = (K_2/K_1)D^{(2-n)}. \tag{8}$$

Wires having lengths greater than L_* and less than L_* can be defined as "long" and "short" wires respectively. "Very long" and "very short" wires can be defined as those longer than $10L_*$ or shorter than $L_*/10$ respectively.

Consider the fusing current I_* at the critical length L_*. If the wire were in a vacuum and had an emissivity of zero so that convective and radiative heat transfer were negligible, then the fusing current would be determined entirely by conduction and would be

$$I_* = K_2D^2/L_*. \tag{9}$$

If, on the other hand, the temperature of the ends of the wire tracked the temperature in the middle so that there was no heat transfer by conduction through the wire and all heat was transferred through the surface, then from Eq. 6,

$$I_* = K_1D^n. \tag{10}$$

The two currents are equal since L_* was defined as the wire length where the fusing current due to conduction alone is equal to the fusing current due to convection/radiation alone. In the practical case of a bonding wire of length L_*, which is cooled by both conduction and convection/radiation, the fusing current must be 1.414 (the square root of two) times I_*, not twice I_*, because the power per unit length in the mid-span of the wire varies as I squared, not as I. Hence, the measured fusing current is not simply I_{sum} for wire lengths in the vicinity of L_* but must be reduced by a weighting function. This weighting function must have a value of 0.707 (the reciprocal of the square root of two) when $L = L_*$ and must approach unity for extremely long or extremely short wires. A function that meets these requirements is

$$f=1/(1+0.414e^{(-(\ln(L/L*))\hat{}2/E)}). \tag{11}$$

It was determined empirically that this function gives a reasonable fit when the parameter E has the value of two. For wires differing from L_* by one order of magnitude, this function evaluates to 0.972; for wires differing by two orders of magnitude, it evaluates to 0.99999.

A generalized equation that is accurate for all practical dimensions of bonding wires can be obtained by multiplying Eq. 7 by the weighting function. The result is

$$I_{ft}= (K_1D^n + K_2D^2/L)f \tag{12}$$

where f is defined in Eq. 11.

Eq. 12 was fitted to the experimental data in Tables I, II, and III by selecting coefficients that result in the minimum error between the calculated and measured fusing current. And, as has already been explained, the current carrying capability of 99.99% Al was taken as halfway between that of 99.99% gold and Al-1%Si The results are:

$$I_{ft} = (0.6D^{1.0} + 80D^2/L)f \quad \text{(99.99\% gold wire)}, \tag{13}$$

$$I_{ft} = (0.5D^{1.3} + 40D^2/L)f \quad \text{(Al-1\%Si wire)}, \tag{14}$$

$$I_{ft} = (0.55D^{1.3} + 60D^2/L)f \quad \text{(99.99\% Al wire)}. \tag{15}$$

Most practical bonding wires are short enough to qualify as short wires so that a good estimate of the fusing current can be determined by simply using the D^2/L terms of the above equations. These short wire fusing current formulas are summarized in Table IV.

Note that the empirically determined short wire coefficients for 99.99% gold and Al-1%Si (80 and 40 amps/mil) agree fairly well with the theoretical values (108 and 60 amps/mil) that were derived in Appendix A. The differences can be explained, in part, by the fact that the temperature dependence of thermal conductivity was not included in the theoretical derivation and any temperature increase above ambient at the ends of the wire was not taken into account. Either of these effects would decrease the value of the calculated short wire coefficient. The effect of temperature on thermal conductivity is, however, of minor significance when compared to that of electrical conductivity.

By substituting the empirically determined values of K_1, K_2, and n in Eq. 13, Eq. 14, and Eq. 15 into Eq. 8, the critical length for 99.99% gold and Al-1%Si wires can be written as:

$$L_* = 133D \quad 99.99\% \text{ gold wire}), \qquad (16)$$

$$L_* = 80D^{0.7} \quad \text{Al-1\%Si wire}), \qquad (17)$$

$$L_* = 109D^{0.7} \quad (99.99\% \text{ Al wire}). \qquad (18)$$

Note that L_* evaluates to about 133 mils and 80 mils for 1 mil diameter 99.99% gold and Al-1%Si wires respectively. The ratio, L/L_*, is shown in Tables I and II. For long wires this ratio is greater than unity; for short wires it is less than unity.

Also shown in Tables I and II are the calculated currents, I_{fl} and I_{fs}, based on Eq. B-6 and Eq. 2 respectively, the weighting function based on Eq. 11, and the total calculated fusing current I_{ft}, based on Eq. 12, which is the sum of I_{fl} and I_{fs} multiplied by the weighting function, f. The last column in Tables I and II, L%, indicates the percent difference between the experimental and calculated values of fusing current. The log-percent, L%, is defined as $L\% = 100(\ln(I_c) - \ln(I_e))$ and is approximately equal to standard percentage when the percent difference is less than about 25%.

Because most practical ribbons are 99.99% gold and can be categorized as "short" (length to effective diameter ratios much less than 133), no attempt was made to quantify the fusing currents of long ribbons. The values of the fusing current for short ribbons can be calculated from the conductive (D^2/L) terms of Eq. 13, Eq. 14, and Eq. 15 by substituting D with the effective diameter (the square root of $4Wt/\pi$) and ignoring all long wire effects. The results are:

$$I_{fs} = 100tW/L \quad \text{(short 99.99\% gold ribbon)}, \qquad (19)$$

$$I_{fs} = 50tW/L \quad \text{(short Al-1\%Si ribbon)}, \qquad (20)$$

$$I_{fs} = 75tW/L \quad \text{(short 99.99\% Al ribbon)}. \qquad (21)$$

The numerical coefficients in Eq. 13, Eq. 14, Eq. 15, Eq. 19, Eq. 20 and Eq. 21 and the parameter E in Eq. 11 could be determined to greater accuracy by performing an experimental analysis, but such experimentation is beyond the scope of this study. The authors believe that more accurate coefficients would differ from the above numerical values by less than 10%.

MAXIMUM SAFE DESIGN CURRENT

The design engineer is often interested in how much current a wire can safely carry. For conservative designs, the maximum design current, I_{design}, can be taken to be one half of the fusing current based solely on the short wire model, with the convective/radiative cooling associated with the long wire model being neglected. Any convective or radiative cooling would simply represent a margin of safety. Two reasons for neglecting convection and radiation are: (1) Most practical bonding wires qualify as short wires and hence are not significantly affected by convection or radiation. (2) Various studies indicate that, for a wire in free air, heat transfer by convection is greater than that from radiation [8]. Such long wires could overheat in conditions of zero gravity (free fall), loss of hermeticity in a space application, or reorientation. This is because convective heat transfer depends on gravity (acceleration) to set up convection air currents and is strongly affected by gas composition and pressure. Convective cooling depends on the orientation of the wire with respect to gravity because the convection air currents set up by a horizontally oriented wire are different than those set up by a vertically oriented wire.

The formula for maximum allowed current in MIL-M-38510 Section 3.5.5.3 is:

$$I_{design} = Kd^{3/2} \quad (22)$$

where d is the diameter in inches and K is a constant for which a table is given for various metals. The values of K for aluminum and gold are given as 15,200 and 20,500 for lengths greater than 40 mils and as 22,000 and 30,000 for lengths less than or equal to 40 mils. This formula was clearly adapted from the long standing fusing current equation first derived by Preece in 1884 and commonly found in standard engineering handbooks [1,2,19]. This formula is not applicable to bonding wires for the following reasons: (1) Long wires smaller than 10 mils in diameter do not obey the 3/2 power law. This was recognized by Preece in 1887 in his classic paper [2, p. 295] and is apparent from the data sheets provided by bonding wire manufactures [14,15]. (2) The power law formula applies only to wires longer than about $10L_*$. (3) An apparent error was made by doubling instead of halving Preece's constant for aluminum, 7585 amp/inch$^{3/2}$: The value 15,200 amp/inch$^{3/2}$ in MIL-M-38510 was intended to be 3790 amp/inch$^{3/2}$. Based on this work, reasonable formulas for the maximum design current for gold and Al-1%Si wires and ribbons are

$$I_{design} = 40D^2/L \quad \text{(gold wire)}, \quad (23)$$

$$I_{design} = 20D^2/L \quad \text{(Al-1\%Si wire)}, \quad (24)$$

$$I_{design} = 30D^2/L \quad \text{(99.99\% Al wire)}, \quad (25)$$

$$I_{design} = 50tW/L \quad \text{(gold ribbon)}, \quad (26)$$

$$I_{design} = 25tW/L \quad \text{(Al-1\%Si ribbon)}. \quad (27)$$

$$I_{design} = 40tW/L \quad \text{(99.99\% Al ribbon)}. \quad (28)$$

The above formulas are summarized in Table IV.

The current, I_{design}, given by the above formulas will cause approximately an 83 °C temperature increase in the wire for wires shorter than L_*. For longer wires, the temperature increase will be even less than 83 °C due to the additional cooling effects of convection and radiation. Since these equations are based on heat transfer through the wire to the bond pads and not on heat transfer through the wire surface, they can also be used for plastic encapsulated parts.

SUMMARY

The commonly used formulas for fusing current were reviewed and their limitations were explained. A new derivation was presented for computing the short wire fusing current coefficient and the theoretical values were calculated for 99.99% gold, Al-1%Si and 99.99% Al conductors and shown to be in excellent agreement with experimental values. A new equation, Eq. 12, was derived and shown to match the measured fusing current to within 10 percent in most cases. This new equation is shown to be valid for 99.99% gold and Al-1%Si wires having diameters ranging from 0.3 to 10 mils. A quantitative method was presented for determining whether a wire is "long" or "short." Equations for the fusing current and the maximum temperature of short wires were derived from first principles and the calculated value of fusing current was shown to be in good agreement with measured values. Experimental data was presented from several sources. It was shown that the maximum temperature of a short wire will be no more than 83 °C higher than the temperature at the bonds if the current is limited to half the fusing current. New equations were given for maximum safe design current.

CONCLUSION

The 3/2 power law formula was found to be invalid for the fusing current of bonding wires. Accurate values for fusing currents of gold and Al-1%Si bonding wires of any length are given by new Eq. 13, Eq. 14, and Eq. 15. Formulas for the short wire fusing currents and maximum design currents are summarized in Table IV.

LIST OF SYMBOLS

a — Preece's constant, amp/inch$^{(3/2)}$. Preece's value for aluminum is 7585 amp/inch$^{3/2}$.

A — Cross-sectional area of conductor.

c — The square root of the Lorenz number, volts per degree Kelvin. The theoretical value for an ideal conductor is 1.56E-4 [10]. The experimental values for 99.99% gold and Al-1%Si, and 99.99% Al are 1.58E-4 [10], 1.49E-4 [12, p 174] and 1.46E-4 [10] respectively.

D — Wire diameter, mils.

E — The parameter in Eq. 11 that determines the width or span of the weighting function, unitless.

f — The weighting function defined by Eq. 11, unitless. This gaussian shaped function has a value 0.707 (the reciprocal of the square root of 2) when the wire length is L_* (the dividing point between long and short) and has a value of unity for very short or very long wires.

I — The d-c current flowing in bonding wire or ribbon, amps.

I_{design} — Maximum d-c design current in wire or ribbon, amps.

I_e — The experimentally measured value of fusing current, amps.

I_f — The d-c fusing current of bonding wire or ribbon, amps.

I_{fs} — The d-c fusing current of a short wire, amps.

I_{fl} — The d-c fusing current of a long wire, amps.

I_{ft} — The value of the fusing current calculated using Eq. 12, Eq. 13, or Eq. 14, amps. This total value includes all effects and predicts the experimentally determined fusing current, I_e, to within 10% in most cases.

I_{sum} — The sum obtained by adding the fusing current based on the long wire formula and the fusing current based on the short wire formula. This sum is accurate for extremely long or extremely short wires but must be reduced by a factor of 1.41 (the square root of 2) for mid-length ($L=L_*$) wires.

I_* — The fusing current of a wire when all surface heat transfer (convection and radiation) are negligible, amps.

k — The thermal conductivity of the bonding wire, watts /(cm-°K). The experimentally measured values of k at 300 °K for gold, Al-1%Si, and Al are 3.2, 1.82 [12, p. 173-174] , and 2.34 [12, p. 7] respectively.

K — The constant in Eq. 22 from MIL-M-38510 for which a table is given for various metals, amp/inch$^{3/2}$.

K_k — Heat loss per unit area due to convection and radiation, watts/cm^2.

K_1 — The long wire coefficient (coefficient of D^n in Eq. 6).

K_2 — The short wire coefficient (coefficient of $(D^2)/L$ in Eq. 2.

L — Conductor span length, mils.

L% — The natural logarithm of the calculated value of I_f minus the natural logarithm of the experimental value of I_f times 100.

L_* — The critical length defined by Eq. 8, mils. Wires much shorter than L_* are categorized as short wires and wires much longer than L_* are categorized as long wires.

n — Exponent of D in the equation for fusing current of a long wire (Eq. 6) , unitless.

P — Electrical power dissipated in wire or ribbon, watts.

Q — Heat transferred from the wire or ribbon, watts.

R — The d-c resistance of a bonding wire or ribbon, ohms.

t — Ribbon thickness, mils.

T_0 — The temperature at the ends of the bonding wire,

	degrees Kelvin. This heat sink temperature is usually taken as 300 °K (27 °C).
T_{max}	The maximum temperature of a short wire which occurs at mid-span.
T_{melt}	The melting temperature of the bonding wire, degrees Kelvin. The melting temperatures for gold, Al-1%Si, and Al are 1336, 926, and 933 °K respectively.
W	Ribbon width, mils.
σ	The electrical conductivity of the bonding wire, 1/ohm-cm.

APPENDIX A

DERIVATION OF THE FUSING CURRENT AND THE MAXIMUM TEMPERATURE FOR A SHORT WIRE.

The differential equation that relates steady state temperature along a wire to the electrical current in the wire with no heat loss by radiation or convection is [16]:

$$d^2T/dx^2 + I^2/(A^2\sigma k) = 0 \quad \text{(A-1)}$$

where T is the temperature and x is the distance along the wire. Since the electrical conductivity varies inversely as the absolute temperature according to the Wiedemann-Franz law which is

$$\sigma = k/(c^2T), \quad \text{(A-2)}$$

Eq. A-1 can be rewritten as

$$d^2T/dx^2 + B^2T = 0. \quad \text{(A-3)}$$

where the constant B is defined as

$$B = cI/kA. \quad \text{(A-4)}$$

The constant, c^2, in Eq. A-2 is a fundamental constant known as the Lorenz number which is defined in terms of Boltzmann's constant and the charge on an electron. The square root of this fundamental constant is c which has the value 1.56E-4 volts per°K.[10]

The solution to Eq. A-3 is of the form [17]

$$T(x) = C_1e^{ixB} + C_2e^{-ixB}. \quad \text{(A-5)}$$

By applying the boundary conditions

$$T(0) = T(L) = T_0 \quad \text{(A-6)}$$

which states that the two ends of the wire (one end connected to the die and the other to the post or frame) are at ambient temperature, the constants C_1 and C_2 evaluate to:

$$C_1 = T_0(1 - e^{-iLB})/(2i \sin LB) \quad \text{(A-7)}$$

$$C_2 = T_0(e^{iLB} - 1)/(2i \sin LB) \quad \text{(A-8)}$$

which allows Eq. A-5 to be written as

$$T(x)/T_0 = (\sin B(L-x) + \sin xB)/\sin LB. \quad \text{(A-9)}$$

Since the maximum temperature, T_{max}, occurs in the center of the span (at x = L/2), then

$$T_{max}/T_0 = 1/\cos(cIL/2Ak) \quad \text{(A-10)}$$

or

$$I = 2Ak/cL \cos^{-1}(T_0/T_{max}). \quad \text{(A-11)}$$

Since the fusing current, I_f, occurs when T_{max} equals T_{melt},

$$I_f = 2Ak/cL \cos^{-1}(T_0/T_{melt}) \quad \text{(A-12)}$$

or

$$cL/(2Ak) = (1/I_f)\cos^{-1}(T_0/T_{melt}) \quad \text{(A-13)}$$

which, when substituted into A-10, yields

$$T_{max}/T_0 = 1/\cos((I/I_f)\cos^{-1}(T_0/T_{melt})) \quad \text{(A-14)}$$

Since the cross-sectional area, A, of a round wire is $\pi D^2/4$, Eq. A-12 can be written as

$$I_f = K_2 D^2/L \quad \text{(A-15)}$$

where

$$K_2 = (\pi k/(2c))\cos^{-1}(T_0/T_{melt}). \quad \text{(A-16)}$$

The values of K_2 can now be evaluated. The results are summarized in Table A-1. The thermal conductivity, k, listed in Table A-1 is relatively independent of temperature. For pure aluminum, for example, the value at the melting point is only 12%

less than the value at room temperature [12, p. 8].

APPENDIX B

DERIVATION OF THE 3/2 POWER LAW FOR A LONG WIRE

The Power, P, dissipated due to current, I, in a cylindrical wire is:

$$P = I^2R \qquad \text{(B-1)}$$

where R is the resistance

$$R = L/A\sigma \qquad \text{(B-2)}$$

and σ is the electrical conductivity and A is the cross-sectional area of the wire,

$$A = \pi D^2/4. \qquad \text{(B-3)}$$

Eq. B-2 and Eq. B-3 can be substituted into Eq. B-1 to give

$$P = (4L/\pi\sigma)(I/D)^2. \qquad \text{(B-4)}$$

The heat, Q, transferred from the wire by convection and radiation at the temperature where the wire fuses, is proportional to the surface area of the wire. Thus

$$Q = K_k \pi DL \qquad \text{(B-5)}$$

where K_k is the heat loss per unit area due to convection and radiation.

Since the electrical power dissipated in the wire equals the heat transferred out of the wire, Eq. B-4 and Eq. B-5 may be equated to give

$$I_{fl} = aD^{3/2} \qquad \text{(B-6)}$$

where the long wire coefficient, a, is

$$a = (\pi/2)(\sigma K_k)^{0.5}. \qquad \text{(B-7)}$$

Eq. B-6 does not apply to wires shorter than L_*.

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TABLE I. MEASURED AND CALCULATED FUSING CURRENT FOR 99.99% GOLD WIRE

Experimental				Calculated					
D mils	L mils	Ie amps	Ref -	L/L* -	Ifl amps	Ifs amps	f -	Ift amps	L% -
0.9	12000	0.50	[15]	100.00	0.54	0.01	1.00	0.55	9.5
1.0	394	0.56	[9]	2.96	0.60	0.20	0.81	0.65	14.9
1.0	12000	0.55	[20]	90.00	0.60	0.01	1.00	0.61	10.4
1.0	394	0.55	[20]	2.96	0.60	0.20	0.81	0.65	16.7
1.0	56	1.54	[21]	0.42	0.60	1.43	0.78	1.58	2.6
1.0	55	1.55	[21]	0.41	0.60	1.45	0.78	1.61	3.8
1.0	50	1.60	[21]	0.38	0.60	1.60	0.80	1.76	9.0
1.4	12000	0.77	[15]	64.28	0.84	0.01	1.00	0.85	9.9
1.5	12000	0.83	[20]	60.00	0.90	0.02	1.00	0.92	10.3
2.0	394	1.39	[9]	1.48	1.20	0.81	0.72	1.46	4.9
2.0	12000	1.10	[15]	45.00	1.20	0.03	1.00	1.23	11.2
2.0	12000	1.10	[20]	45.00	1.20	0.03	1.00	1.23	11.2
2.0	394	1.60	[20]	1.48	1.20	0.81	0.72	1.46	-9.2
5.0	394	6.10	[9]	0.59	3.00	5.08	0.74	5.95	-2.5
10.0	12000	7.50	[20]	9.00	6.00	0.67	0.96	6.43	-15.4

TABLE II. MEASURED AND CALCULATED FUSING CURRENT Al-1%Si WIRE.

Experimental				Calculated					
D mils	L mils	Ie amps	Ref -	L/L* -	Ifl amps	Ifs amps	f -	Ift amps	L% -
1.0	394	0.49	[9]	4.93	0.50	0.10	0.90	0.54	9.7
1.0	12000	0.48	[15]	150.00	0.50	0.00	1.00	0.50	4.1
1.0	394	0.48	[20]	4.93	0.50	0.10	0.90	0.54	11.8
1.3	106	1.04	[21]	1.13	0.67	0.59	0.71	0.90	-14.5
1.5	12000	0.80	[15]	112.93	0.85	0.01	1.00	0.86	7.2
2.0	394	1.18	[9]	3.03	1.23	0.41	0.82	1.34	12.7
2.0	12000	1.20	[15]	92.34	1.23	0.01	1.00	1.24	3.3
2.0	394	1.60	[20]	3.03	1.23	0.41	0.82	1.34	-17.7
3.0	394	2.20	[9]	2.28	2.09	0.91	0.77	2.32	5.3
10.0	394	14.70	[9]	0.98	9.98	10.15	0.71	14.28	-2.9

TABLE III

EXPERIMENTALLY DETERMINED POWER LAW EQUATIONS

Pwr Law Eq.	Composition	Diameter (mils) min	max	Ref.
$I_{fl} = 0.55D^{1.00}$	99.99% gold	0.9	2.0	[15]
$I_{fl} = 0.48D^{1.32}$	Al-1%Si	1.0	2.0	[15]
$I_{fl} = 0.75D^{0.93}$	99.99% gold	0.3	10.0	[14]
$I_{fl} = 0.48D^{1.27}$	Al-1%Si	0.5	10.0	[14]

TABLE IV

FORMULAS FOR MAXIMUM DESIGN CURRENT
AND APPROXIMATE FUSING CURRENT

	Design Current (amps/mil)	Short Wire Fusing Current (amps/mil)
Gold wire	$40D^2/L$	$80D^2/L$
Al-1%Si wire	$20D^2/L$	$40D^2/L$
99.99%Al wire	$30D^2/L$	$60D^2/L$
Gold ribbon	50tW/L	100tW/L
Al-1%Si ribbon	25tW/L	50tW/L
99.99%Al ribbon	40tW/L	75tW/L

TABLE A-1

CALCULATION OF K_2 FOR THE THREE MOST COMMON BONDING WIRE COMPOSITIONS

Composition	k(300°K)	c	T_{melt}	K_2	K_2
	W cm^{-1} K^{-1}	volt K^{-1}	°K	amp cm^{-1}	amp mil^{-1}
99.99% gold	3.18 [18, p. E-13]	1.58E-4 [10]	1338 [18,p.B-19]	4.25E4	1.08E2
Al-1%Si	1.82 [12, p. 173]	1.49E-4 [12, p. 174]	926 [12,p. 378]	2.38E4	6.05E1
99.99% Al	2.37 [15, p. E-12]	1.46E-4 [10]	934 [18,p. B-7]	3.17E4	8.06E1

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