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CONDUCTOR FUSING AND GAPPING FOR BOND WIRES

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Abstract—In this paper, fusing of a metallic conductor is studied by judiciously using the solution of the one-dimensional heat equation, resulting in an approximate method for determining the threshold fusing current. The action is defined as an integration of the square of the wire current over time. The burst action (the action required to completely vaporize the material) for an exploding wire is then used to estimate the typical wire gapping action (involving wire fusing), from which gapping time can be estimated for a gapping current greater than a factor of two over the fusing current. The test data are used to determine the gapped length as a function of gapping current and to show, for a limited range, that the gapped length is inversely proportional to gapping time. The gapping length can be used as a signature of the fault current level in microelectronic circuits.

1. INTRODUCTION

In 1884, William Henry Preece [1, 2] derived a fundamental law of fusing by considering the balance of heat generation (I^2R) with the heat loss (πhdl), which is approximately valid near the fusing threshold. Here we assume that the wire current is constant. The notations used are: I for the wire current, R for the wire resistance, σ is the wire electrical conductivity, h is heat loss per unit area from radiation or convection, d is for the wire diameter, and l is the wire length. Thus,

$$I_f^2 R = I_f^2 \frac{4l}{\sigma \pi d^2} = \pi hdl \tag{1}$$

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or

$$I_f = Bd^{3/2}, \quad B = \frac{\pi}{2}(\sigma h)^{1/2} \tag{2}$$

where I_f denotes the fusing current. Preece's law states that the wire fusing current is proportional to the wire diameter to the three halves power.

Preece's observation must be complemented by the other limit when the wire current is applied so quickly that heat loss is completely negligible, i.e., all the energy is used in heating up the metal. Again, the wire current is assumed to be constant. The skin effect is neglected.

$$\int I^2 R dt = I^2 \int \frac{dt}{\sigma}\frac{4l}{\pi d^2} = \frac{\pi d^2 l}{4}\int \rho C_p dt \tag{3}$$

Here ρ is the density of the metal and C_p is the specific heat (including latent heat) of the metal.

We assume the heating is uniform when there is no loss and therefore

$$I_b = Cd^2, \quad C = \frac{\pi}{4}\sqrt{\frac{\int \rho\, C_p\, dt}{\int \frac{dt}{\sigma}}} \tag{4}$$

Here I_b denotes the burst current for the wire going through melt and vaporization. The comparison of (2) with Preece's empirical data was within 10% [2] because (a) near fusing, heat loss is very much larger than the heat required to bring the metal to melt (B in (2) is much larger than $Cd^{1/2}$ in (4)) and (b) the two terms ((2) and (4)) differ in the wire diameter exponent by 1/2.

The actual fusing current for a given wire diameter cannot be determined by Preece's argument. Preece relied on empirical data to determine fusing currents for presumably 6-inch long wires (Preece's law is true if the wire is long enough so that heat loss would dominate) [1]. For metals such as gold, aluminum and copper with high thermal conductivities, it is possible to solve the one-dimensional heat equation to obtain the fusing current for a specific diameter and wire length. The lossless limit is discussed in the exploding wire literature. This paper provides (1) a method for determining an approximate fusing current for a given bond wire, (2) a lossless limiting solution where a large current is applied quickly, and (3) an approximate description for the gapping region (from the test data), when the applied current is approximately more than a factor of two over the fusing current. We distinguish fusing from gapping in that fusing is wire-opening near a threshold current and gapping can be caused by the current much larger than the fusing current. More details are discussed below.

First, a nonlinear one-dimensional heat equation in the length direction, with tabulated electrical conductivity as a function of temperature and tabulated thermal conductivity, is solved. The wire ends are connected to a heat sink and are maintained at a low temperature. The wire center has a maximum temperature. The wire center is assumed to reach the melt point. The calculated threshold values are found to be approximately 15% lower than the measured value. After the wire center begins to melt, capillary action dominates; Lord Rayleigh determined for an infinite fluid column that the maximum capillary force instability occurs at a length of $4.51d$. This can be used as an estimation of the fused length. After accounting for the shortening of the wire length by the minimum fused gap, a better agreement between the one-dimensional calculation and the measured value is obtained.

Second, the existing literature for the lossless limit is briefly reviewed. When the wire is heated quickly by an applied current, the joule heating is used solely for melting, vaporizing and bursting the wire and their corresponding actions have been measured and tabulated. This is the case when the gapping time (on the order of µs) is completely negligible and the gapping length is the wire length.

Finally, experimental data clearly shows two different ranges of wire breakage: (1) For wire currents less than a factor of two above the fusing current, the wire breakup relies on capillary force instability of the fluid column that causes a great variation in required action and fusing time and; (2) for a much larger wire current, the gapping length is empirically found to be almost linear in current and is approximately inversely proportional to the gapping time.

2. BOND WIRE FUSING ANALYSIS

Bond wires used in microelectronic circuits are good thermal conductors and thermal conduction dominates convection (by the surrounding air) and radiation in the un-melted portion of the wire. Most heat escapes through the bases of the bond wires (where the ends of the bond wires are connected to heat sinks). In this analysis, we assume that the bond wire is maintained at the ambient temperature by the heat sink and, in contrast to previous analyses, this analysis includes the phase transition of gold near the center of the bond wire. One limitation to our present analysis is that the wire ends may not be at the ambient temperature, especially when the current is applied very quickly (or for a fat and short wire).

2.1. Linear Electrical Conductivity Model

We briefly review the linear electrical conductivity model discussed in [3] and use the result later to calculate the corresponding action. The wire conductivity is described by

$$\sigma = \frac{\sigma_0}{1 + a(T - T_0)} \tag{5}$$

where $a = 3.4\times10^{-3}/\,\mathrm{K}$ and $\sigma_0 = 1/\rho_0 = 4.5\times10^5\,\mathrm{S/cm}$ at $T_0 = 293\,\mathrm{K}$.

Power dissipation at the length coordinate x is described by

$$P = \frac{J^2}{\sigma_0}[1 + a(T - T_0)] \tag{6}$$

where T is a function of x.

The heat equation can be written as

$$\frac{\partial}{\partial x}\left(\kappa\frac{\partial T}{\partial x}\right) + P = \rho C_p\frac{\partial T}{\partial t} \tag{7}$$

for $-L/2 < x < L/2$ and $T\,(-L/2) = T\,(L/2) = T_1$.

A steady state solution to the heat equation is given by

$$T(x) = D\cos\alpha x + T_0 - 1/a, \tag{8}$$

and

$$D = \frac{T_1 - T_0 + 1/a}{\cos(\alpha L/2)}, \quad \alpha = J\sqrt{\frac{a}{\kappa\sigma_0}}. \tag{9}$$

Setting $T(0) = T_m$ in (8) yields

$$I_{fuse} = \frac{\pi d^2}{2L\sqrt{\kappa\sigma_0}}\arccos\frac{T_1 - T_0 + 1/a}{T_m - T_0 + 1/a}. \tag{10}$$

2.2. Derivation of the Nonlinear Solution

The resistivity $(1/\text{conductivity} = 1/\sigma)$ does deviate from linear in temperature behavior, and for gold it can be approximated as

$$1/\sigma = \rho_0[1 + a(T - T_0)]\left[1 + b_\rho(T - T_0)^2\right] \tag{11}$$

The linear coefficient for resistivity is $a = 3.4\times10^{-3}\,\mathrm{K}^{-1}$ and the resistivity at $T_0 = 293^\circ\,\mathrm{K}$ is $\rho_0 = 2.22\times10^{-6}\,\Omega$-cm and $b_\rho = 3.534\times10^{-7}\,\mathrm{K}^{-2}$.

The thermal conductivity for gold is approximated by

$$\begin{aligned} &\kappa = \kappa_0\left[1 + b_\kappa(T - T_0)^2\right]^{-1}, && \kappa_0 = 3.18\,\mathrm{W/(cm-K)}, \\ &b_\kappa = 2.487\times10^{-7}\,\mathrm{K}^{-2}, && T_m = 1337^\circ\,\mathrm{K}. \end{aligned} \tag{12}$$

These parameters appear to fit the data given in [4]. For metals such as copper and aluminum, the empirical electrical resistivity and thermal conductivity are used for the calculation [4].

The one-dimensional governing heat equation in a steady state for a finite wire of length L, is:

$$\frac{d}{\kappa dx}\left(\kappa\frac{dT}{dx}\right)=\frac{d^2T}{dx^2}+\frac{d\kappa}{\kappa dx}\frac{dT}{dx}=-\frac{J^2}{\kappa\sigma} \tag{13}$$

The right hand side (except for the negative sign) is the ratio of the heat generation (caused by the Ohmic loss of the steady state current density J and the conductivity of the metallic wire σ as a function of T) to the thermal conductivity κ. The negative sign accounts for the heat flow direction opposite to the temperature gradient.

The heat equation can be solved by a perturbation method; however, the first-order correction term is numerically small and is not needed in most situations. An approximate solution is derived by dropping the derivative of the thermal conductivity term.

$$\frac{d^2T}{dx^2}=-\frac{J^2}{\kappa\sigma} \tag{14}$$

Note that the resulting equation is exactly solvable. Assuming its solution as $T_a = T_a(x)$, we use it for approximating the derivative of the thermal conductivity term as:

$$\frac{d^2T}{dx^2}=-\frac{J^2}{\kappa\sigma}-\frac{d\kappa}{\kappa dx}\frac{dT_a}{dx}=-\frac{J^2}{\kappa\sigma}-\frac{\kappa'}{\kappa}\left(\frac{dT_a}{dx}\right)^2 \tag{15}$$

where $\kappa'=\frac{d\kappa}{dT}$. The right hand side of the approximate equation is a known function of T and can be solved exactly.

The one-dimensional wire is assumed to extend from $x=-L/2$ to $x=L/2$. The boundary conditions are:

$$T(-L/2)=T(L/2)=T_1=\text{Ambient Temperature}=298^\circ\,\text{K}.$$

We have thus assumed the posts at the ends act as infinite heat reservoirs.

The wire has the highest temperature at the center and it fuses after the temperature at the wire center reaches the melt temperature, T_m, and after the wire has a chance to break.

Multiplying (14) by dT/dx and integrating the governing equation once from the center to point x we obtain the following equation:

$$\left(\frac{dT}{dx}\right)^2\Bigg|_0^x=2J_a^2\int_T^{T_m}\frac{\rho(T')}{\kappa(T')}dT'=\left(\frac{dT}{dx}\right)^2 \tag{16}$$

Separation and integration give

$$\int_{T}^{T_m} \frac{dT''}{J_a\sqrt{2\int_{T''}^{T_m}\frac{\rho(T')}{\kappa(T')}dT'}} = x \tag{17}$$

Note that x is a function of T and its inverse is thus the temperature distribution along the wire.

Letting $x = L/2$ gives

$$\int_{T_1}^{T_m} \frac{dT''}{J_a\sqrt{2\int_{T''}^{T_m}\frac{\rho(T')}{\kappa(T')}dT'}} = L/2 \tag{18}$$

Note that

$$J_a = \frac{4I_a}{\pi d^2} \tag{19}$$

Therefore,

$$I_a = \frac{\pi d^2}{2\sqrt{2}L}\int_{T_1}^{T_m} \frac{dT}{\sqrt{\int_{T}^{T_m}\frac{\rho(T')}{\kappa(T')}dT'}} \tag{20}$$

Including the approximate derivative term for the thermal conductivity from (16) in (15) we have

$$\begin{aligned}\left(\frac{dT}{dx}\right)^2\Bigg|_0^x &= 2J_a^2\int_{T}^{T_m}\frac{\rho(T')}{\kappa(T')}dT' + 4J_a^2\int_{T}^{T_m}\frac{d\kappa}{\kappa dT''}\int_{T''}^{T_m}\frac{\rho(T')}{\kappa(T')}dT'dT'' \\ &= \left(\frac{dT}{dx}\right)^2 \end{aligned}\tag{21}$$

Note that because the current density can be factored out in (21), we can alternatively avoid iteration by replacing the original current density amplitude J_a by the final J, and solve for the current density in one step

$$\int_{T(x)}^{T_m}\frac{dT}{J\sqrt{2\int_{T}^{T_m}\frac{\rho(T')}{\kappa(T')}dT' + 4\int_{T}^{T_m}\frac{d\kappa}{\kappa dT''}\int_{T''}^{T_m}\frac{\rho(T')}{\kappa(T')}dT'dT''}} = x \tag{22}$$

$$\int_{T_1}^{T_m}\frac{dT}{J\sqrt{2\int_{T}^{T_m}\frac{\rho(T')}{\kappa(T')}dT' + 4\int_{T}^{T_m}\frac{d\kappa}{\kappa dT''}\int_{T''}^{T_m}\frac{\rho(T')}{\kappa(T')}dT'dT''}} = L/2 \tag{23}$$

Note that the more accurate wire current I is related to the current density J by (19).

2.3. A Summary of Nonlinear Electrical and Thermal Conductivity Model

For a linear electrical conductivity profile with $d = 50\,\mu\text{m}$ and $L = 0.36\,\text{cm}$, the gold wire fusing current is calculated to be 3.012 A and for a nonlinear profile, the fusing current is 2.555 A.

This more accurate model accounting for nonlinear metal electrical and thermal conductivity gives the fusing current as follows [5]:

$$I_{fuse} = \frac{A}{L} M \tag{24}$$

where A and L are the cross-section and the length of the wire, respectively. M is the metal constant where T_0 is the ambient temperature (°C) and T_m is the melt temperature (Table 1) and is evaluated by:

$$M = \sqrt{2} \int_{T_0}^{T_m} \frac{dT}{\sqrt{\int_T^{T_m} \frac{\rho(T')}{\kappa(T')} dT' + 2 \int_T^{T_m} \frac{d\kappa}{\kappa dT''} \int_{T''}^{T_m} \frac{\rho(T')}{\kappa(T')} dT' dT''}} \tag{25}$$

where T_0 is the ambient temperature (°C) and T_m the melt temperature.

Table 1. Metal constants for calculating fusing.

Metal Type	Gold	Copper	Aluminum
M (A/cm)	4.685×10^4	6.314×10^4	3.489×10^4

2.4. Applying Heat Equation Solution to Fusing

2.4.1. Melting Segment

Consider the limit of a large constant current applied to the wire, the wire center segment is melting or even bursting. Under this condition, the wire melts (or bursts) from outside inward. The inward electromagnetic pressure (p) in the radial direction for wires with a uniform current density is given by [6]

$$\nabla p = \mathbf{J} \times \mathbf{B}$$

or

$$p = -\mu_0 \int_0^r J_z H_\varphi dr + p_0 = \frac{\mu_0 I^2}{\pi^2 d^2} \left(1 - \frac{4r^2}{d^2}\right). \tag{26}$$

Assuming that the pressure at the wire surface is zero ($p_0 = 0$), we can calculate the pressure at the wire center for a constant current of 100 A and a wire diameter of 1 mil:

$$p = \frac{\mu_0 I^2}{\pi^2 d^2} = \frac{1.256 \times 10^{-6} \times 100^2}{\pi^2 \left(2.54 \times 10^{-5}\right)^2} \approx 0.2\,\text{GPa} \tag{27}$$

Gold's melt temperature increases from 1062°C to 1120°C at 1 GPa [7]. We estimate that the melt temperature increases from the outside to the wire center for 100 A current drive is only 11.5°C.

For a typical fusing current of approximately 2 A, the wire melting temperature difference is thus negligible. We can assume that the wire cross-section has to be fully melted before the Rayleigh instability can occur.

2.4.2. Interpreting Fusing and Gapping Test Data

After the wire temperature reaches the melt point at the wire center, the governing heat equation is only applicable to the un-melted part of the wire or $-L/2 < x < -\varepsilon(t)/2$ and $\varepsilon(t)/2 < x < L/2$. This is valid because the latent heat keeps the derivative of temperature with respect to x zero, which is the same as the wire center solved in (23). The region $-\varepsilon(t)/2 < x < \varepsilon(t)/2$ must be described by a different equation. The difficulty in treating the melting segment is not the phase transition but rather the accuracy of describing convection and radiation heat losses. Also, in contrast to a fuse or an exploding wire, bond wires are not straight. We do not attempt to treat this.

After the wire center has melted, capillary action dominates; Lord Rayleigh's fluid instability theory applies [8]. Rayleigh calculated the exponential growth exponent e^{qt}, with

$$q^2 = \frac{8T_c}{\rho d^3} \frac{\left(1 - k^2 d^2/4\right)(kd/2)\, I_0'(kd/2)}{I_0(kd/2)} \tag{28}$$

(where $k = 2\pi/\lambda$ is the wave number, T_c is the capillary tension, ρ is the fluid density, I_0 is the modified Bessel function of zero order) for an infinite cylindrical fluid column. Rayleigh determined the maximum of q^2 occurs at a periodic length of $\lambda = 4.51d$. If we liberally apply Rayleigh's solution for the infinite fluid column to the melted gold segment, this length can be used as the minimum fused length. An alternative minimum length that corresponds to the onset of the Rayleigh instability may also be used. Note that (28) changes sign at $1 - k^2 d^2/4 = 0$, which gives $\lambda = \pi d$.

Given the bond wire length of 0.1524 cm (60 mils), and a reduction of $4.51d = 4.51 \times 2.54 \times 10^{-3}$ cm ≈ 0.0115 cm, the fusing current is found to be

$$I_f = \frac{A}{L}M = \frac{\pi\left(1.27\times10^{-3}\right)^2}{0.1409}4.685\times10^4 \approx 1.7\,\mathrm{A}. \tag{29}$$

Note that we are very conservative in our estimation. The one-dimensional solution only assumes that the center of the wire reaches the melt point and therefore the center of the wire still has to be completely melted before Rayleigh's fluid column instability is applicable (That is why we used Rayleigh's length corresponding to the maximum instability to compensate for the segment not being completely melted). The short length that corresponds to the onset of instability may be more appropriate for the minimum gap length. The actual comparison with specific wire parameters are given later in Table 3 [9].

With this calculation and Preece's law (2), we can determine the fusing current for any given wire length and diameter.

2.5. The Lossless Case: Minimum Action Up to Melt and Action for Wire Burst

2.5.1. Melting Start Action Assuming Linear Electrical Conductivity

If a large current is applied quickly, the thermal conduction term can be ignored and the electrical conductivity term is assumed to be linear, resulting in

$$J^2 t_f = \frac{\rho C_p \sigma_0}{a}\int_{T_0}^{T_m}\frac{dT}{T-T_0+1/a} = \frac{\rho C_p \sigma_0}{a}\ln[1+a(T_m-T_0)]. \tag{30}$$

Action for melting is thus

$$\text{Action} = \frac{A^2\rho C_p\sigma_0}{a}\ln\left[1+a\left(T_m-T_0\right)\right] \tag{31}$$

where parameters are $\rho = 19.3\frac{\mathrm{g}}{\mathrm{cm}^3}$ and $C_p = 0.129\frac{J}{g\cdot K}$. At $T = 20°\mathrm{C}$, these are given in (5) and (12). Therefore,

$$\text{Action} = \frac{\left[\pi\left(1.27\times10^{-3}\right)^2\right]^2\times19.3\times0.129\times4.5\times10^5}{0.0037}\times1.6$$

or

$$\text{Action} = 2.57\times10^{-11}\times4.84\times10^8 = 0.0125\,\mathrm{A}^2\cdot\mathrm{sec}\,.$$

This is the action needed for the metal to reach the melt-beginning for a 1 mil gold wire if current is applied so quickly that there is no heat loss. The more accurate action accounting for nonlinear electrical resistivity as a function of temperature would lead to a somewhat smaller action (Table 2). We will show in the next subsection that the action required for a 1 mil gold wire to go all the way through vaporization to burst without heat loss is $0.022\,\mathrm{A}^2\cdot\mathrm{sec}$. This would require a large current to accomplish the near-lossless case. The empirical data indicates this corresponds to the minimum action required for a one-mil gold wire when $t_f \to 0$. When the wire current is smaller, it takes longer to gap the wire and most of the action applies to the heat transfer out of the wire.

2.5.2. Burst and Melt Action for Common Metals

Tucker and Toth [10] tabulated the resistivity ($\rho = 1/\sigma$) of twenty-two common metals as a function of applied specific action ($\frac{1}{A^2}\int I^2 dt\,\mathrm{A}^2\cdot\mathrm{sec}/\mathrm{mm}^4$) and obtained specific actions for different phase transition states. Expressed in terms of the unit of mil^{-4} for $1/\mathrm{A}^2$, the action is given by

$$\text{Action} = \int_0^t I^2 dt = K_p d^4\,\mathrm{A}^2\cdot\mathrm{sec} \tag{32}$$

where the wire diameter (d) is in mils (one-thousandth of an inch). K_p is tabulated in Table 2.

Table 2. Burst and melt action coefficients for common metals.

Metal	Melt-start Action Coefficient K_p (mil^{-4}) (K_p defined in (32)).	Melt-end Action Coefficient K_p (mil^{-4})	Burst Action Coefficient K_p (mil^{-4})
Copper	0.0205	0.024	0.044
Aluminum	0.0065	0.0083	0.017
Gold	0.0113	0.013	0.022
Silver	0.0159	0.0185	0.029
Platinum	0.0039	0.0048	0.013
Nickel	0.0043	0.0053	0.014
Iron	0.0032	0.0037	0.009
Tungstan	0.0061	0.007	0.019
Titanium	0.0008	0.001	0.0049
Lead	0.0003	0.0004	0.0015
Zinc	0.0029	0.0037	0.01
Uranium	0.0017	0.002	0.009

Table 2 is applicable to a very large current that leads to the opening of the wire in a very short time because the heat loss becomes completely negligible.

2.6. Analysis of 1 mil Gold Bond Wire Test Data

2.6.1. Fusing and Gapping Length

Lord Rayleigh's instability characteristic length of $4.51d \approx 0.0115\,\text{cm}$ for the maximum instability and his instability onset length of $\pi d \approx 0.008\,\text{cm}$ ($d = 1\,\text{mil}$) will be used as a guide. In case of the melted segment in the wire, Table 3 gives the minimum gap somewhat smaller than Rayleigh's characteristic length for the maximum instability and greater than his instability onset length. The detailed physical configuration, the fluid physical parameters and the finite fluid column can influence the breakup. The last two columns of Table 3 give actions (based on fused current and fuse time) and calculated fusing current

Table 3. Bond wire test data for near threshold fusing current.

Bond Wire No.	Diameter (μm)	Length (mm)	Fusing Time (ms)	Fusing Current (A)	Gap Length After Fusing (mm)	Calculated Action ($10^{-3}\,A^2$ sec)	Calculated Fusing Current (A)
1	27.98	1.51		1.8	0.09		1.94
2	26.66	1.51		1.8	0.09		1.77
3	27.97	1.40	28	1.9	0.10	101	2.1
4	27.39	1.41			0.09		2
5	26.81	1.42	52	1.9	0.08	188	1.9
6	26.23	1.41	58.8	1.9	0.08	212	1.83
7	25.64	1.46	196	1.8	0.09	635	1.69
8	26.42	1.51	30	1.8	0.10	97	1.73
9	25.84	1.51	29	1.8	0.10	94	1.66
10	27.39	1.54	29.6	1.8	0.09	96	1.83
11	27.59	1.53	70	1.8	0.08	227	1.87
12	27.78	1.50	45	1.8	0.09	146	1.93
13	27.59	1.51	36	1.8	0.09	117	1.89
14	27.00	1.52	24	1.9	0.09	87	1.8
15	27.59	1.46	31	1.9	0.09	112	1.96
16	27.39	1.47	126	1.8	0.08	408	1.92
17	27.39	1.51	32	1.8	0.09	104	1.86
18	27.78	1.50	23	1.9	0.09	83	1.93
19	27.39	1.52	24	1.8	0.10	78	1.85
20	27.00	1.53	28	1.8	0.10	91	1.79
21	27.59	1.51	46	1.8	0.09	149	1.89
22	27.78	1.50	74	1.8	0.09	240	1.92

23	27.98	1.53	38	1.8	0.10	123	1.93
24	26.62	1.49	184	1.8	0.09	596	1.79
25	27.20	1.51	34	1.8	0.10	110	1.84
26	27.59	1.52	37	1.8	0.09	120	1.88
27	27.39	1.51	38	1.8	0.09	123	1.86
28	27.59	1.52	33	1.8	0.10	107	1.88
29	27.20	1.53	50	1.8	0.09	162	1.81
30	28.36	1.51	73	1.8	0.08	237	2
31	27.2	1.40	42	1.8	0.09	136	1.99
32	27.2	1.53	43	1.8	0.09	139	1.81
33	27.59	1.49	170	1.7	0.09	491	1.92
34	27.00	1.43	36	1.9	0.09	130	1.91
35	27.78	1.50	218	1.8	0.09	706	1.93
36	27.39	1.49	76	1.8	0.09	246	1.89
37	28.36	1.52	24	1.9	0.09	87	1.98
38	27.78	1.51	54	1.8	0.08	175	1.92
39	28.36	1.50	27	1.9	0.09	97	2.00
40	29.14	1.46	31	1.9	0.09	112	2.18
41	29.14	1.50	30	1.9	0.09	108	2.12
42	27.00	1.48	36	1.9	0.08	130	1.85
43	27.59	1.52	33	1.9	0.09	119	1.88
44	27.39	1.52	54	1.8	0.08	175	1.85
45	28.17	1.52	46	1.8	0.09	149	1.96

using the recipe leading to (29) (based on actual wire length, wire diameter and Rayleigh's length ($4.51d$)). The difference between the measured and calculated fuse current is within 10%.

2.6.2. Fusing and Gapping Time

Test data from References [9] and [11] are used for comparisons with calculated fusing and gapping times. Note that the current used for gapping in [11] is not strictly constant in time, but the action calculated is based on the actual current waveforms.

The fusing time (time to wire opening for the minimum wire current) is typically uncertain because it relies on the instability of the molten metal. The breaking of the molten segment can occur after the minimum fusing length is melted and may take a long time for the instability to cause breaking. When the fusing current is somewhat larger than the threshold value (within 20% greater than the fusing threshold) the fusing action can vary considerably (Table 3).

The gapping time for a very large current applied quickly to the wire can be very small because the very short gapping time makes the heat loss completely negligible. Therefore, in this limit the required action for gapping lies between the two actions listed in Table 2: the melt-end action and burst action but very close to the burst action. For the wire current approximately a factor of two above the threshold fusing current, a good approximation to gapping time (less than 20% error) can be determined from the burst action divided by the square of the applied gapping current. The calculated gapping time is given in the last column of Table 4.

Table 4. Bond wire test data for larger gapping currents.

Bond Wire No.	Diameter (μm)	Length (mm)	Gapping Time (ms)	Gapping Current (A)	Gap Length After Gapping (mm)	Calculated Action ($10^{-3}A^2$ sec)	Calculated Gapping Time using Burst Action (ms)
1	28.56	1.559	9.39	2.0	0.135	37.6	
2	28.85	1.590	6.84	2.2	0.158	33.1	
3	29.43	1.566	5.26	2.4	0.192	30	
4	29.43	1.573	4.25	2.6	0.214	28.7	
5	29.14	1.558		2.8			
6	28.85	1.581	3.50	2.8	0.249	27.4	
7	28.56	1.594	2.90	3.0	0.278	26.1	
8	29.43	1.578	2.64	3.2	0.392	27	
9	28.85	1.538	2.15	3.4	0.344	24.9	
10	28.56	1.539	1.93	3.6	0.350	25	1.7
11	28.85	1.544	1.64	3.8	0.394	23.7	1.52
12	27.10	1.519	1.61	4.0	0.43	25.8	1.38
13	27.10	1.533	1.31	4.2	0.482	23.1	1.25
14	28.56	1.551	1.28	4.4	0.536	24.8	1.14
15	28.27	1.537	1.19	4.6	0.580	25.2	1.04
16	28.27	1.499	1.08	4.8	0.618	24.9	0.95
17	28.56	1.527					
18	28.56	1.555	0.92	5.0	0.730	23	0.88
19	28.27	1.525	0.86	5.2	0.756	23.3	0.81
20	28.27	1.551	0.83	5.4	0.787	24.2	0.75
21	27.98	1.574	0.75	5.6	0.863	23.5	0.7
22	28.85	1.590	0.73	5.8	0.861	24.6	0.65
23	29.43	1.527	0.69	6.0	0.797	24.8	0.61

Other data [12] gave actions corresponding to small gapping time between the burst action and the melt-end action. Actions corresponding to large fusing times are very large.

2.6.3. Gapping Length versus Wire Current

The results of a linear regression analysis of gap length and wire current with 90% prediction bounds are shown in Figure 1. The prediction bounds can be interpreted as a 90% chance of capturing the next observation. The analysis shows that *there is a very strong linear relationship between current and gap length.*

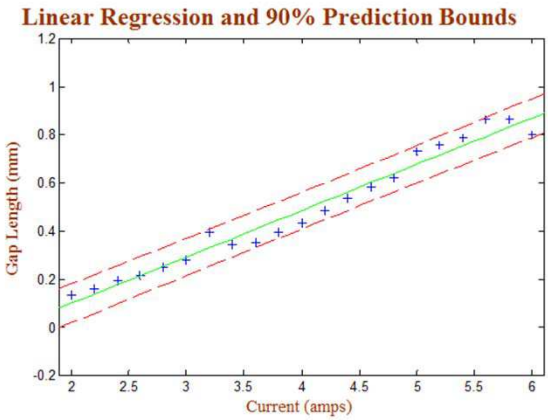

Figure 1. Current vs. gap length.

2.6.4. Gapping Length versus Gapping Time

Note that the minimum gap length corresponds to Rayleigh's length for the onset of instability ($\pi d \approx 0.08\,\text{mm}$) as shown in Table 3. The gapping length is approximately a linear function of gapping current [9]. For currents a factor of two above the fusing current, the heat loss is approximately proportional to gapping time. The lower heat loss allows more material to be melted and gapped and thus the gap length is approximately inversely proportional to the time for gapping (Figure 2). We can argue that the incremental heat loss is proportional to the melted length of the wire (which loses most heat through radiation and convection), and the incremental decrease in gapping time and the heat required to melt an incremental wire length is proportional to the gapping time and the incremental increase in gapping length. Therefore, $L_g \Delta t_g + t_g \Delta L_g \approx 0$ which is equivalent to $L_g t_g \approx$ constant. We don't expect this to be applicable to both limits of fusing threshold and exploding wire regions.

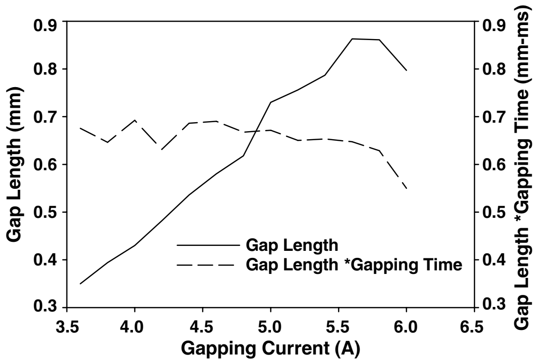

Figure 2. The gap length is approximately inversely proportional to gapping time.

3. CONCLUSIONS

We have examined two limiting cases: (1) the Preece's heat loss dominated region that describes the threshold fusing limit (which leads to a method of calculating the threshold fusing current for good thermal conducting metals such as gold) and (2) the lossless limit of the exploding wire region, where a very large current is applied to the wire very quickly (which gives us a good estimate for gapping action). Approximate methods for estimating gapping time and gapping length are also prescribed for an intermediate range of wire currents by examining the gapping test data. The wire configuration (after the current is applied to the wire), such as gapping length, can be used for investigating microelectronic circuit failures.

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