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Integrated circuit metal in the charged device model: bootstrap heating, melt damage, and scaling laws

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Summary

Charged-device model electrostatic discharge (CDM ESD) stresses thin metal lines heavily because of strong I^2R heating, resulting in a wider linewidth requirement as thin AlCu is integrated into multilayer metal systems. Metal heating during a CDM event is shown to strongly depend on device capacitance and on temperature coefficient of resistance.

1. Introduction

Today's integrated circuits (ICs) often contain multiple layers of metal. While single-layer metal was about one micron thick, the first metal layer of a multilayer system is typically one-half micron. Also, AlCu alloys, with 1–5% Cu, are now common. We will see how these changes in IC metallization have led to increased stress on the first layer of metal when it lies in the path of a charged device model (CDM) ESD event, and will present the design equations aimed at avoiding metal damage during CDM events.

The 10 micron (μ) width that was sufficient for the CDM in 1 μ thick AlSi metal [1] has sometimes failed at 0.5 μ thickness for even wider metal, particularly for AlCu. Open circuit by metal melting/vaporization is the usual failure mechanism when using the relay-based Intel CDM simulation box [2]. The photos in Fig. 1 show examples of this with both AlSi and AlCu metal in two-layer metal systems.

Now let us examine the mechanisms of metal heating under current stress. For adiabatic heating (a reasonable assumption even for longer pulses than the

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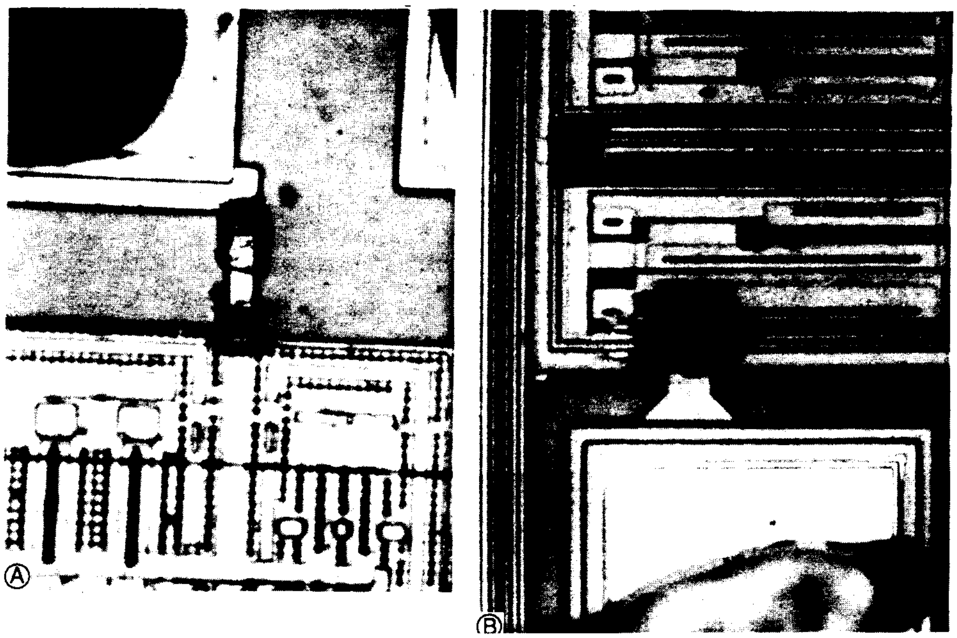

Fig. 1. CDM damage in 0.5 μ metal at around 1500 V: (a) AlSi, 10 μ wide; and (b) AlCu, 15 μ wide.

CDM [3]), the temperature rise T in metal with rectangular cross-section is calculated by solving

$$\mathrm{Cp}(T)\,\mathrm{d}T = I^2(t)R(T)\,\mathrm{d}t \qquad (1)$$

Cp is the specific heat in J/gram-K, I in amps, and R in ohms/gram. We will show that metal resistance does not affect the discharge circuit much, so that $I(t)$ can be computed separately. Details of eqn. (1) are: $R(T)=\mathrm{Ro}(1+\gamma T)$; $\mathrm{Ro}=\rho_b/(W^2 * th^2 * \rho_d)$; $\mathrm{Cp}(T)=\mathrm{Cpo}(1+\beta T)$; ρ_b = bulk resistivity, ohm-cm; e.g., 2.66 $\mu\Omega$-cm for pure Al; ρ_d = mass density of Al, 2.70 g/cm^3; W = metal width; th = metal thickness; Cpo = specific heat of Al, room temperature; 0.8996 J/gram-K; $\gamma = 0.0037$/K for Al; a measured value for AlCu is 0.0038/K; $\beta = 0.0005$/K up to the melting point (660 °C); Cp of liquid metal is constant.

If we first integrate with respect to time, and then formulate a linearized resultant temperature coefficient ($\alpha=\gamma-\beta$), eqn. (1) takes the form of $\mathrm{d}T/(1+\alpha T)$ = constant. This is integrated by elementary methods to give the following expression for the temperature rise T, up to the melting point:

$$T=(1/\alpha)(\exp(\alpha K)-1), \quad \text{where } K=\frac{\mathrm{Ro}}{\mathrm{Cpo}}\int_0^\infty I^2\,\mathrm{d}t \qquad (2)$$

This equation shows that the metal heating is very sensitive to metal width, thickness, and temperature coefficient. Note the inverse square dependence of Ro on $W*th$. The appearance of the exponential function is a consequence of the temperature coefficient α, causing "bootstrap" heating of the metal.

2. Experiments and calculations

In [1], the author showed that a flat AlSi line can absorb more than enough energy from a 120 nanosecond transmission line pulse to melt the entire line before the metal explodes and the line opens up. This was a feature of short pulses, and is surely the case with the much shorter CDM pulse. But it is not known just how hot the metal must be in a CDM event before an open circuit occurs; the onset of vaporization (2467 °C) should be an upper limit. The metal line in [1] was believed to have heated to about 1320 °C before failure, a value that is probably related to the time scale of the pulse. Recent experiments done for this paper, using AlCu metal lines, have shown the same behavior as in [1].

If the circuit model for the CDM event is known, then of course the I^2 integral in eqn. (2) can be computed and the equation readily solved. But also it is important to recognize that when capacitance C is charged to voltage V,

$$R_{\mathrm{av}} \int_0^\infty I^2 \, \mathrm{d}t = CV^2/2, \tag{3}$$

where R_{av} is an average dissipation resistance, because the CDM circuit is an underdamped series RLC as described in [2], and pictured in Fig. 2. For a metal test fixture or for an IC with good on-chip protection devices, R_{av} is dominated by arc or switch resistance. This is because the metal is only a small number of squares long and metal resistance measures only in the hundreds of milliohms per square even after self-heating. Differential resistance of an npn snapback device, exclusive of metal resistance, is typically an ohm or less [1]. But at the same time, the relay in the Intel CDM test box has been measured to have

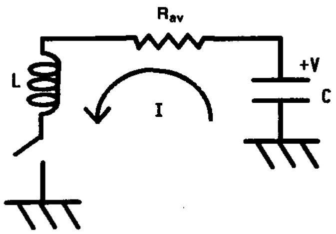

Fig. 2. Series RLC model of CDM event.

6 ohms arc resistance for 40 pF and for long pulses, and the relay arc resistance is about 11–12 ohms for a capacitance of 10 pF. While parasitics in the Intel CDM box prevent accurate measurement of the relay arc resistance at lower C, evidently the Intel CDM box treats metal lines more harshly than would an AT&T-type direct discharge [4], because Renninger's data and model for the 4 pF test fixture waveform at 1500 V work out to an R_{av} of about 55 ohms. However, his models predict something like a C^{-1} or $C^{-1/2}$ dependence for the arc resistance, and his measured discharge pulse width may be even faster due to limited oscilloscope bandwidth, both of which would lower R_{av}. Thus the departure from our relay measurements may not be severe. Recent evidence [5] suggests that actual risetimes may not be much faster than reported in [4]. In this paper, we will avoid the controversy surrounding models and results as in [4] and [5], and aim instead at approximations leading to a robust design criterion for IC leadway metal.

The above facts confirm that it is easy to neglect the contribution of self-heated metal to R_{av} even for the Intel relay CDM box, especially because most packages are below 20 pF. R_{av} will thus be considered to be the arc resistance only. While we use a constant R_{av} for each case, obtained by solving eqn. (3) for a known $I(t)$, its value actually arises from an I^2-weighted average of dynamic resistance over the time of the event. But arc resistance $R(t)$ is uncertain and highly controversial, thus we use the simplified R_{av} treatment.

The metal study of [1], as well as our more recent studies of AlCu (Fig. 3), revealed that metal resistance also increases linearly with *energy* added to the system, even through the phase change to a liquid and beyond. The linearity is

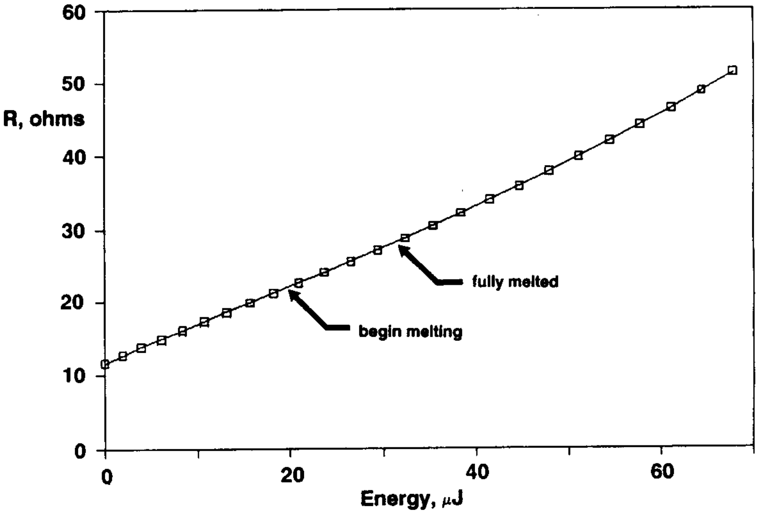

Fig. 3. Measured resistance vs. pulse energy for AlCu line.

of course expected up to the melting point because of the dominant linear temperature coefficient of resistance and the specific heat, as expressed in eqn. (1). An experimental finding of [1] and the present work is that linearity of resistance with added energy continues beyond the melting point. Equation (1) thus becomes

$$\mathrm{d}E = I^2(t)\mathrm{Ro}(1+\xi E)\,\mathrm{d}t, \tag{4}$$

where $\xi \approx \alpha/\mathrm{Cpo} = 3.67 \times 10^{-3}$ g/J for AlCu with $\alpha = 0.0033/\mathrm{K}$. The specific heat $\mathrm{Cpo}(1+\beta T) = \mathrm{d}E/\mathrm{d}T$ is used to convert the resistance temperature coefficient γ into an approximation for ξ, $(\gamma-\beta)/\mathrm{Cpo} = \alpha/\mathrm{Cpo}$. Actually, the β-dependent term of ξ is itself energy-dependent, vanishing at low energy or temperature rise. Fortunately β is small enough that we will be able to capture its effect by considering a range of values for α.

The solution of eqn. (4), paralleling eqn. (2), is

$$E = (1/\xi)(\exp(\xi K_1) - 1), \quad \text{where } K_1 = \mathrm{Ro}\int_0^\infty I^2\,\mathrm{d}t. \tag{5}$$

As stated above, the coefficient ξ has been measured to be constant to well above the point where the metal line is fully melted but, as also reported in [3], there is a point for the melted line beyond which ξ increases. For simplicity, we will consider ξ to be a constant in this work. Figure 3 shows metal R vs. energy for AlCu during a 110 nsec pulse from a 50 ohm transmission line source, deduced from the same kind of experimental data as in [1], i.e., linear voltage rise with time during the pulse. Figure 3 was deduced from storage oscilloscope measurements in which the voltage went from about 80 to 200 V.

Aluminum under current stress undergoes the transitions to the onset of melting, full melting, and vaporization as described in Table 1. Notice that joules/gram are also the units of E in eqn. (5), the units of Cpo/α.

From eqn. (5) it is clear that for a given resultant Al temperature coefficient α, the quantity $K_1 = \mathrm{Ro}CV^2/(2R_{\mathrm{av}})$ is sufficient to determine E. Figure 4 plots E vs. K_1, showing the departure from linearity due to bootstrap heating ($\alpha > 0$)

Table 1

E (J/gm)	Comment
$E_1 = 653$	metal begins melting (660 °C)
$E_2 = 1048$	fully melted (latent heat of 94.5 cal/gm absorbed)
$E_3 = 3172$	metal begins to vaporize (2467 °C)

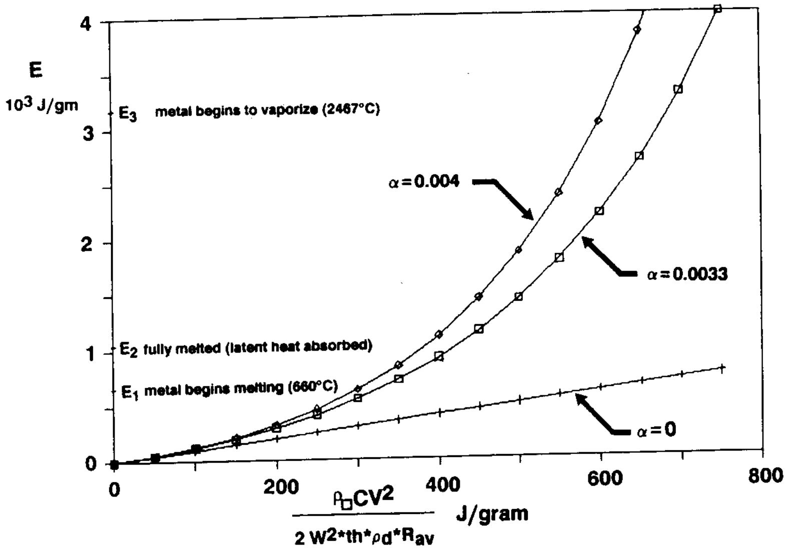

Fig. 4. Energy vs. K_1, showing effect of temperature coefficient α.

for the best known value of α, 0.0033, as well as for a maximum α value of 0.004. E_1, E_2, and E_3 are noted. Some tables of AlCu bulk resistivity [6] give values leading to a temperature coefficient γ of 0.0045 yet, as stated above, our measurements indicate little departure from the Al value. As stated earlier, the energy-dependent effect of β on ξ is such that high values of α should be considered for low energies, and low values for high energies. $\alpha=\gamma-\beta$ is most accurate near the melting point, E_1.

It is also possible to show tradeoffs in conditions for achieving E_1, E_2 and E_3. Another appropriate "universal" plot is achieved by choosing a value for ξ ($=\alpha/\mathrm{Cpo}$) and plotting contours of E_1, E_2, E_3 in the plane of CV^2/R_{av} vs. $\rho_b/W^2 * th^2$). The former, a circuit model figure of merit, is of course equal to $2\int_0^\infty I^2\,dt$. From here on we will replace ρ_b/th by $\rho_\square$ (sheet resistance or sheet rho, ohms/square), since this is what is customarily measured for metal films, so the abscissa becomes $\rho_\square/(W^2 * th)$, a metal resistance term equal to ρ_dRo. The sheet rho must be separated from the other thickness term *th* regardless, because with most modern metallization layers being a multilayer stack including Ti, W, etc., the full thickness is appropriate only for the specific heat portion. This is because the entire metal stack heats up, while the sheet rho is determined by the alloys and the thin film process, and must be measured. It so happens that Cpo $* \rho_d$ of Al and Ti match almost perfectly, so it is correct to use the total multilayer stack thickness for *th* in $\rho_\square/(W^2 * th)$, if the stack is mostly Ti and Al. Figure 5 shows this plot for $\alpha=0.0033$, noting contours of E_1, E_2, and E_3.

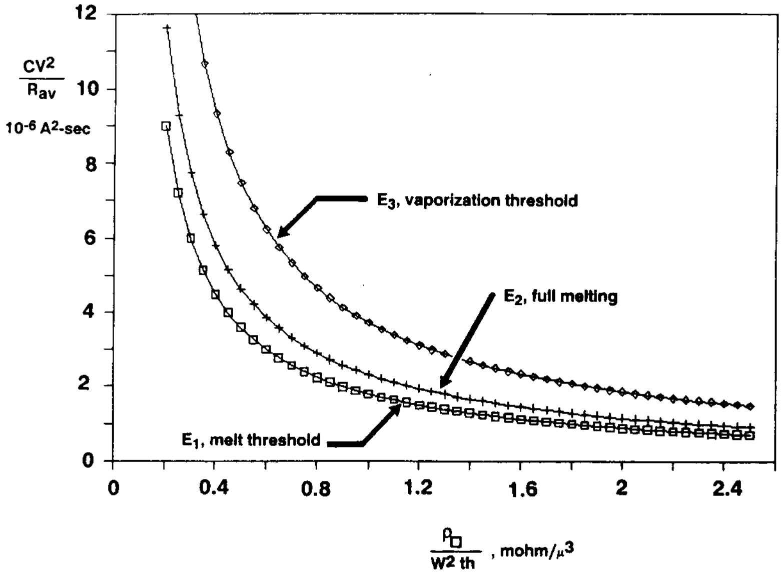

Fig. 5. Energy contours in plane of CV^2/R_{av} vs. $\rho_\square/(W^2 * th)$.

3. Discussion

Now let us use these equations and curves to examine several specific cases. The Intel relay-based CDM tester has been found to have $R_{av} = 10$–12 ohms relay arc resistance for $C = 10$–25 pF. This is a lower (and therefore more pessimistic) R_{av} than found for the direct discharge in Ref. [4], so any metal heating solution for such a relay-based tester ought to be adequate for the direct discharge as well. From our past experience, a metal line should be safe unless it is subjected to full metal melting (1048 J/gm) at least, so we will consider that to be a danger level, and a value below the onset of melting (653 J/gm) as a desirable goal.

As typical 40-pin DIP packages are 8–15 pF [7], a worst-case value of 20 pF, as well as a worst-case $R_{av} = 10$ ohms, should do well for calculating the desired half-micron AlCu metal width. 20 μ width gives 727 J/gm for $V = 1500$ V and $\rho_\square = 85$ milliohm/square (a typical measured value for a metal stack of total thickness 0.5 μ), well below full melting. But 15 μ gives 2473 J/gm, approaching the boiling point. If 10% thinning is considered (which does happen at metal steps), 20 μ just reaches full melting, but 15 μ gives 4314 J/gm, well above the onset of vaporization. The 15 μ metal destruction in Fig. 1(a) is therefore understandable, even with more optimistic values of C. 20 μ minimum metal width is therefore suggested for all 0.5 μ thick leadway metal, now that the importance of the $W * th$ product is clear.

Table 2

C (pF)	E (J/gm)	Comment
4	71.7	< 15% of heat for melting
11.85	653	metal begins melting (660 °C)
13.98	1048	fully melted (latent heat absorbed)
19.04	3172	metal begins to vaporize

From the earlier discussion of Ref. [4], we know that since the C-dependence of R_{av} for a direct discharge could be C^{-1} or $C^{-1/2}$, the I^2 integral thus would have a C^2 or $C^{1.5}$ dependence. We can solve eqn. (5) for various C in order to check the expected behavior of metal in typical 40-pin DIP packages of 8–15 pF, or in PGA packages of 20 pF or more. The capacitance C at the onset of melting, at full melting, and at the onset of boiling were found, to give Table 2. The following parameters were used:

- AlCu metal; $W = 10\ \mu$; $th = 0.5\ \mu$ but with 10% thinning at steps,
- $\alpha = 0.0033$/K; normalization to 1 gram of metals is used as usual,
- $Vo = 1500$ V, waveform as in [4], Fig. 5. Height and width each scaled as $C^{1/2}$.

Note that the waveform scaling gives an optimistic $C^{-1/2}$ dependence for R_{av}, and $C^{1.5}$ for the I^2 integral. The measured value of R_{av} at 4 pF is 55 ohms, which along with the C-dependence is sufficient to solve eqn. (5).

Clearly the 10 μ metal of this type is under considerable stress for ordinary packages in the CDM and should be widened. Use of 20 μ wide metal gives 231 J/gm even in the 19.04 pF case, well below any danger point.

It is significant to note that the human body ESD model, of longer duration but with lower I and much lower I^2 than the CDM, at 2 kV produces about one-fourth the energy required to begin melting in 10 μ wide metal. This is the result when $C = 100$ pF and $R_{av} = 1500$ ohms is used with typical metal parameters. Therefore, even 4 kV will not overstress 10 μ wide, 0.5 μ thick metal, but will raise it just to the melt threshold of 1048 J/gm. Clearly, metal damage is most likely in the case of the charged device model of ESD, because of the high current and high I^2 integral that results.

4. Conclusions

Adiabatic metal heating in ESD events is seen to be most severe for the charged device model, while the lower currents of the human body model generally produce less of an effect at the usual test voltages. If the CDM event is characterized in terms of a series RLC circuit, the amount of metal heating can be calculated as a simple function of the quantities $\rho_b CV^2/(W^2 * th^2 * \rho_d * R_{av})$ and $(\gamma - \beta)$/Cpo. Spreadsheet programs are convenient for investigating the effects of parametric variations. The metal temperature coefficient $\alpha = \gamma - \beta$

affects the strength of the exponential function that describes "bootstråp" heating of the metal. This quantity is not known for certain to change in the transition from AlSi to AlCu metal, but the increased bulk resistivity ρ_b of AlCu is sufficient to explain the observed increased susceptibility to CDM metal damage. Finally, as the technology advances and metal thicknesses decrease, it is well to widen those thinner metal layers so that the quantity $W*th$ remains constant; a minimum value of $10\ \mu^2$ appears necessary to prevent CDM damage at 1500 V.

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