Modeling Feedback Effects in Metal Under ESD Stress

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***Abstract*— The feedback model of on-chip interconnect metal heating during electrostatic discharge (ESD) is extended to capture and simplify overall behavior of the metal. Of greatest interest to risk assessment is the peak temperature T_{max} reached during an ESD event, and it is discovered that T_{max} for Human Body and Charged Device Model (HBM, CDM) events follows its own simplified feedback equation with constant parameters. These constants are a function of the electrical and thermal properties of the metal layer. The result is a simple relation between T_{max} and current density for the HBM or CDM event under consideration, a valuable aid to risk assessment and design rule checks. The summary equations capture the results of many detailed finite element and numerical convolution calculations of heat flow for on-chip metal.**

Keywords- thermal feedback, ESD; IC metal; metal self-heating; TLP; HBM; CDM; thermal impulse response, temperature coefficient of resistance

I. INTRODUCTION

Resistive self-heating of interconnect metal during ESD pulses has been treated as a feedback model [1], having a time-dependent thermal impedance Z(t) as an essential part. Z(t) per unit of cross sectional area has decreased in recent years due to scaling and dispersal of metal into multiple small lines with much more oxide exposure, higher surface-to-volume ratio, plus nearby metal for heat conduction. But scaling also leaves less room for margin, introduces surface scattering, and forces us to calculate and measure the limits of the metal. If the goal is to present designers with current density limits for HBM and CDM tests, one must first find impulse response Z(t) for a test pattern representing typical design conditions in the given metal layer, as in Figure 1, and resulting in uniform heating to a single temperature (a very good worst-case approximation). Z(t) is computed from a (differentiated) finite element model (FEM) calculation of uniform power step response, or from transmission line pulse (TLP) measurement [1,2]. Interpreting TLP requires an independent dc measurement of α, the metal temperature coefficient of resistance (TCR, or tempco), as in the familiar expression,

$$R(t) = R_0(1+\alpha T(t)) . \quad (1)$$

The full feedback model of Figure 2 has its feedback element scaled by TCR α, and is solved by the equivalent implicit equations for T(t) from [1],

$$T(t) = P_0(t) * Z(t) + \alpha[T(t)P_0(t)] * Z(t) \text{, or}$$

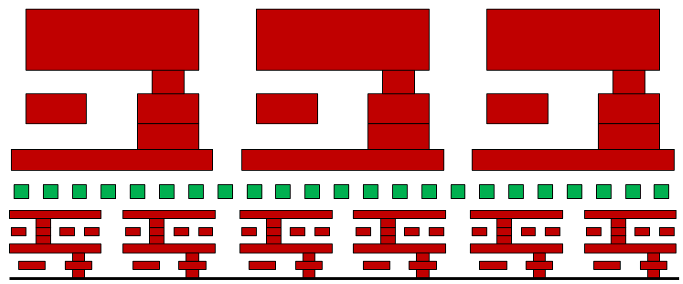

Figure 1. Cross-sectional view of heated lines (middle) surrounded by oxide and "dummy" metal and via layers above and below.

$$T(t) = \frac{P_0(t) * Z(t)}{1-\alpha \frac{[T(t)P_0(t)] * Z(t)}{T(t)}} \text{, } \quad (2)$$

where * is the convolution operator. $P_0(t)=I^2(t)R_0$, the input power with no self-heating. As the ESD event for HBM or even CDM often has high source impedance (e.g., 1500 ohms for HBM) compared to the rest of the circuit, we will use current sources as a worst-case condition.

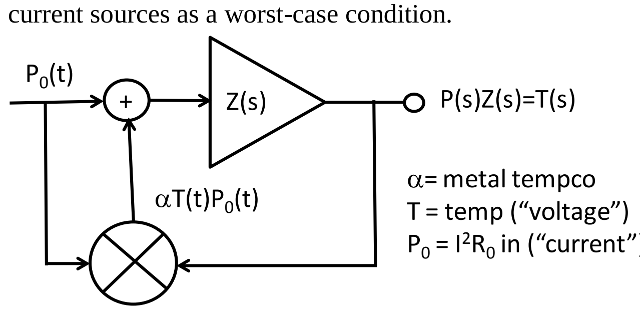

Figure 2. Feedback model of interconnect metal heating, as in [1].

T(t) is the temperature above initial T_0, and α, or TCR, is the (positive) tempco of the metal (0.0025/°C is a book value for Cu films). Once there is a known thermal circuit (impedance Z(t), or Z(s) in the complex frequency domain) for the heat flow, this power function can be applied as if it were a current, as the 1-D heat flow equation (with T(t) like voltage) is solved by lumped or distributed R-C networks. Test patterns as in Fig. 1, along with typical metal IC layouts, heat uniformly enough under pulse conditions to be modeled in this way [1].

For ESD events, T(t) has to be calculated from Eqs. (2) iteratively. Of greatest interest is peak temperature T_{max}, as the temperature waveform takes on a time scale determined by

$P_0(t)$ and Z(t). Thus we are interested in overall trends for T_{max} if they can be discerned. In this work we report that a simplified feedback model (Figure 3) applies generally to T_{max} for HBM and CDM ESD events, using constant coefficients Z_{th} and α_{eff}.

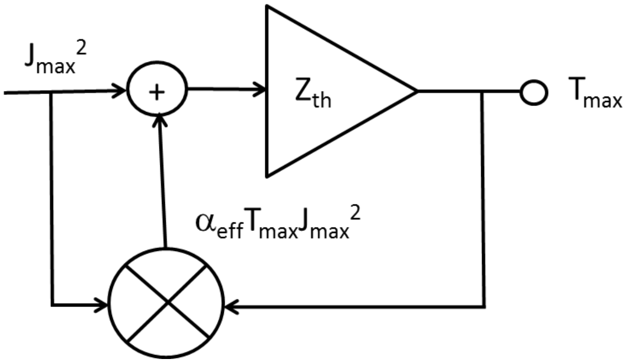

Figure 3. Simplified feedback model for T_{max} during ESD.

J_{max} is maximum current density during the pulse, and thus scales the test voltage to the line being considered. The result is that for T_{max}, Eqs. (2) are replaced by

$$T_{\max} = \frac{J_{\max}^2 Z_{th}}{1-\alpha_{eff} J_{\max}^2 Z_{th}} \quad . (3)$$

We start by developing temperature waveforms and outlining how (3) was shown to be true. Then we address how to predict Z_{th} and α_{eff} for metal lines with varying electrical properties under HBM and CDM stress.

II. Temperature Waveforms for a Test Pattern

A. Setting Up the Thermal Impedance Function

The work reported in [1] was largely based on our ability to characterize a metal test pattern with a thermal impedance Z(t), derived from the step response of a wide test pattern layer to uniform power input, using known thermal properties of the materials used in the semiconductor process. Figure 4, from [1], shows a portion of a test pattern (designed much like Fig. 1) after 200 nsec of uniform heating of M5, shown in false colors. The full step response vs. time (where temperature is nearly uniform over the test pattern) is done by FEM and yields a curve like Figure 5(a). This is shown as a smooth curve, but the FEM points are generated at a gradually expanding time scale from left to right, in order to save computer time. To obtain a suitable thermal impulse response Z(t) the function needs to be differentiated, normalized to the power input, and arrayed in uniform time steps. Cubic spline code in Visual Basic for Applications (VBA) is readily found on the Internet and is applied to interpolate and yield uniform time steps for step response and Z(t); the result is shown in Figure 5(b). Z(t) is then convolved with any arbitrary power input function (e.g., derived from HBM, CDM or transmission line pulse (TLP) waveforms) to give temperature T(t). This "thermal Ohm's Law" is quite useful for these cases that reduce to one-dimensional situations at worst. The convolution can be done with open-source VBA code for Microsoft Excel [3], code that also was used in [1].

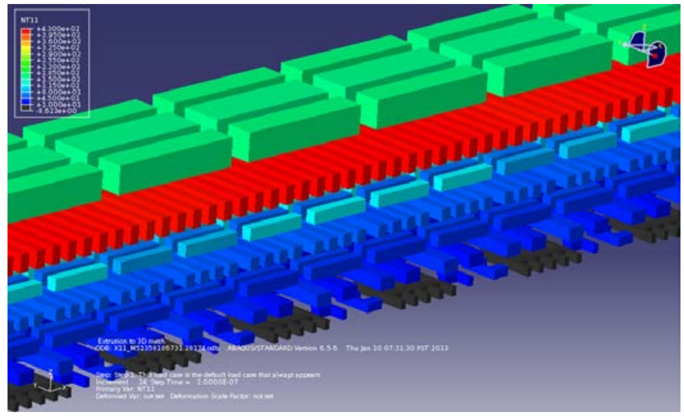

Figure 4. Typical FEM result after 200 nsec for a power step input to wide metal lines (red) as in [1]. Upper metal is thermally floating.

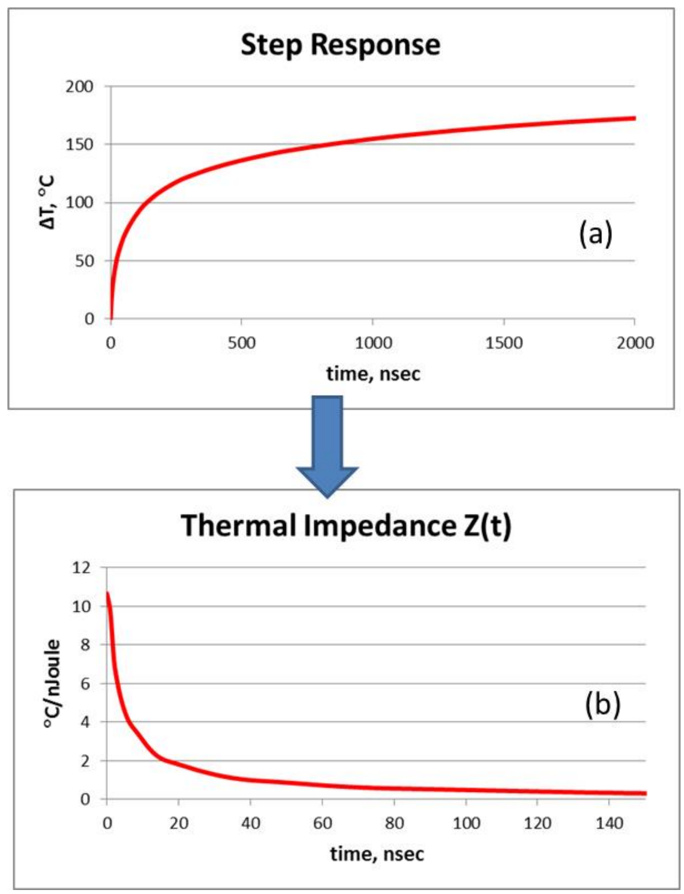

Figure 5. (a) Temperature increase of a metal test pattern in response to uniform power input, 0.6575W in this case. (b) Derived impulse response.

The experimental TLP studies and modeling of [1] showed that the above method is effective and gives cross-checked results, even when the 50-ohm TLP impedance changes the feedback situation. When the TCR is known, the line itself can serve as a temperature monitor *in situ* and be compared with theory. We gained so much confidence in the FEM-based simulations and TLP experiments in the work leading up to [1] that only perfunctory TLP cross-checks are now done to confirm that the FEM work is sensible. It seemed more productive to examine T_{max}, what controls T_{max}, and how to anticipate process-related changes to T_{max}.

B. HBM and CDM Temperature Waveforms

The HBM waveform used for iterative calculations of temperature (Eqs. (2)) uses the standard circuit model of 100 pF capacitance and 1500 ohms resistance. 3.54 μH of inductance is used to produce 0.74A/kV worst-case peak current as in the HBM test specification [4]. A typical temperature waveform resulting from iterative solution of Eqs. (2) using Z(t) and $I(t)^2R_0=P_0(t)$, as described above, is shown in Figure 6. The breadth of Z(t) and feedback effects combine to make the T(t) waveform understandably broader than the HBM current waveform.

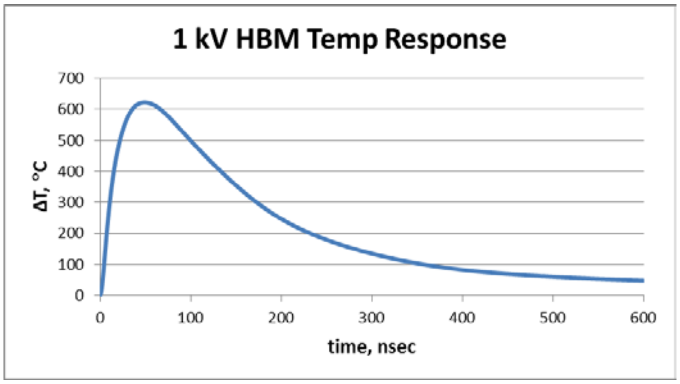

Figure 6. Temperature waveform of a typical mid-level metal test pattern with 0.5 μm^2 cross-section, subjected to a 1kV HBM pulse.

For a "strong" 250V CDM waveform to be used for simulating temperature waveforms, while being in general agreement with the waveform properties in the test specification [5], we made some arbitrary choices. We took a critically damped waveform with C=20 pF, L=6.737 μH and R=37.7Ω, and therefore

$$I(t) = \frac{V_0 t}{L} \exp(-t/\sqrt{LC}) \,. \quad (4)$$

This has I_{peak}=5.0A for V_0=250V and is shown in Figure 7.

An example of a CDM temperature waveform is in Figure 8. It is much wider than the CDM current waveform because of convolution with the much broader Z(t), but T_{peak} still takes place in the first few nanoseconds.

III. HBM AND CDM RESULTS

A. HBM Feedback Equation

The essential T_{max} result (3) was found from many temperature waveforms by plotting inverse quantities as in Figure 9. These were computed from Eqs. (2) or by FEM, the FEM now with complete consideration of resistive tempco and feedback. Electrothermal properties were first confirmed with TLP experiments as in [1] and as described above. Repeatedly, a straight line with slope-intercept yielded $1000/Z_{th}$ and α_{eff} for these metal test patterns in 14 and 10 nm processes. A range of voltages produced a range of J_{max} and T_{max} values for both HBM and CDM, and always produced a good straight line fit as in Fig. 9. Note that a given J_{max} goes as V_0/A, with V_0 the test voltage and A the metal cross-sectional area, so a scan of J_{max} covers a region in the V_0-A plane.

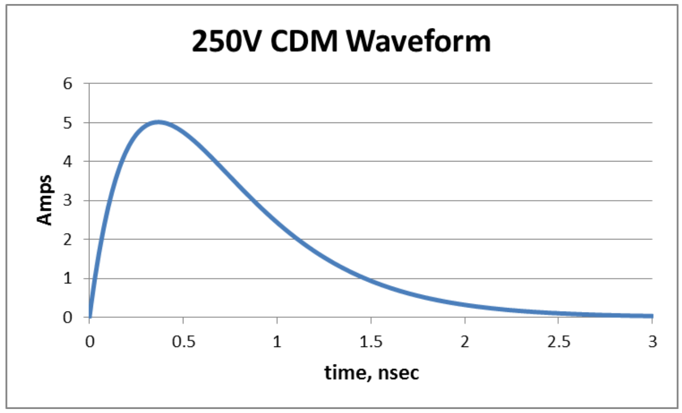

Figure 7. CDM current waveform at 250V charging voltage.

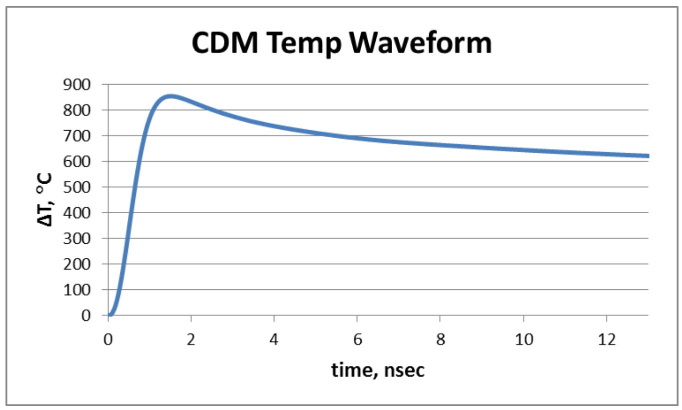

Figure 8. CDM temperature waveform example at 250V, for an upper-level metal test pattern.

Fig. 9 gives Z_{th}=96.61°C/(A/μm^2)^2, α_{eff}=0.0018077/°C from the slope and intercept. From Eqs. (2), the same results are expected if $P_0(t)$ is invariant due to, say, higher R and lower $I^2(t)$, as long as the TCR, α, is the same. But of course α usually does vary as R for a given metal layer, since metal resistivities commonly vary due to changing amounts of temperature-independent scattering, such as impurity scattering or surface scattering. If T-independent R_1 adds to R_0 from Eq. (1), then Matthiessen's Rule suggests that

$$R(t) = (R_0 + R_1)\left(1 + \frac{R_0}{R_0 + R_1}\alpha_0 T(t)\right); \quad (5)$$

the new TCR α´ is diluted and R·α´ (Ω/°C) should be constant. Even if the R·α´ product varies a bit, calculations over a span of R and α yield more linear relations and point to a Z_{th} mostly dependent on R and α_{eff} mostly dependent on α (TCR), as follows for HBM on the metal layer of Fig. 9:

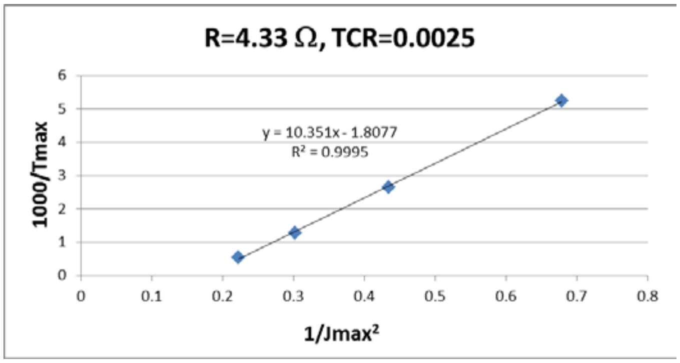

Figure 9. Inverse quantity plot for HBM, 0.8-1.4kV. R is resistance of a mid-level metal test pattern at T_0, 0.5 um^2 cross-section.

$$Z_{th} = 21.268R + 4.5228$$
$$\alpha_{eff} = 0.4311 * TCR^{0.9142} \quad . (6)$$

Z_{th} and α_{eff} have constants that are functions of (relatively stable) process materials and geometries, but as the electrical properties (R,α) change with process development and manufacturing, the functional form is needed. With relations like (6) for each metal layer in HBM and CDM, T_{max} as in (3) can be plotted versus J_{max} as in Figure 10 (done in accordance with two examples of (5)), so that the designer knows at a glance if the HBM or CDM event in question will cause melting (above 1050 °C temp rise). The goal of these studies is to capture such results for each metal layer in a single spreadsheet, one page each for HBM and CDM, as a convenient final result for the designer. Z_{th} as in (6) is of course pegged to a certain test pattern length and width, but those quantities are replaced with process E-test parameters in the design guide spreadsheet.

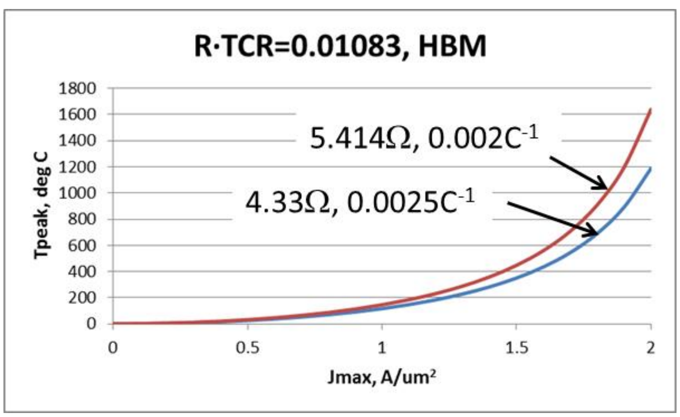

Figure 10. T_{max} vs. J_{max} for HBM from Eq. (3); constants from Eqs. (6).

B. *CDM Feedback Equation*

The same kind of calculations and plots can be made for CDM, starting with current waveforms scaled to Fig. 7, and yielding temperature waveforms resembling Fig. 8. Results are plotted in Figure 11 for a typical metal layer.

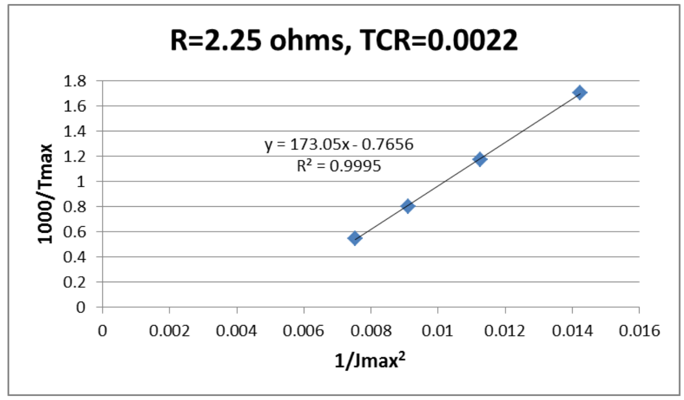

Figure 11. Inverse quantity plot for CDM, 200-275V. R is resistance of an upper level metal test pattern at T_0, 0.5 um^2 cross-section.

For this case of an upper level metal test pattern in CDM, Z_{th}=5.779°C/(A/μm^2)^2, α_{eff}=0.0007656/°C from the slope and intercept. More generally, we find, for that layer, that

$$Z_{th} = 2.568R$$
$$\alpha_{eff} = 0.348 * TCR \quad . (7)$$

Now if as in the HBM case R·α′ is constant, or 0.00495, we apply (3) in the same way as in Fig. 10 to obtain Figure 12. As before with HBM, the higher TCR of 0.0025/°C produced slightly lower temperature. Note that the maximum plotted current density of 10A/μm^2 corresponds to our Fig. 7 CDM waveform through 0.5 μm^2, and resulted in maximum temperature just short of melting.

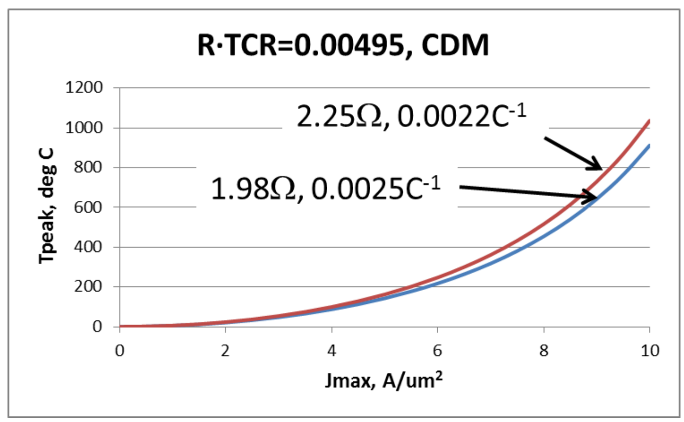

Figure 12. T_{max} vs. J_{max} for CDM from Eq. (3); constants from Eqs. (7).

C. *Minimum Cross-sectional area for HBM and CDM*

Expressions like Eqs. (6) and (7) are readily combined with Eq. (3) in a spreadsheet to yield results like Figs. 10 and 12. At the same time, we can solve Eq. (3) to obtain J_{max} for crossing a critical temperature, such as 1050°C, as the threshold of Cu melting. Once we have the J_{max} for an HBM or CDM event (II.B), the associated I_{max} for the target voltage then determines the minimum cross-sectional area of the metal. This is expressed as

$$A = I_{\max}\sqrt{\frac{Z_{th}(1+\alpha_{eff}T_{\max})}{T_{\max}}}\ . \quad (8)$$

Suppose, as indicated above, that we choose target voltages of 1kV HBM and 250V CDM, as also suggested by the Industry Council on ESD Target Levels [6, 7]. Then with appropriate process and thermal simulation data, we quickly arrive at Z_{th} and α_{eff} and have all we need to plot minimum cross-sectional metal area versus metal layer number for both HBM and CDM, as in Figure 13.

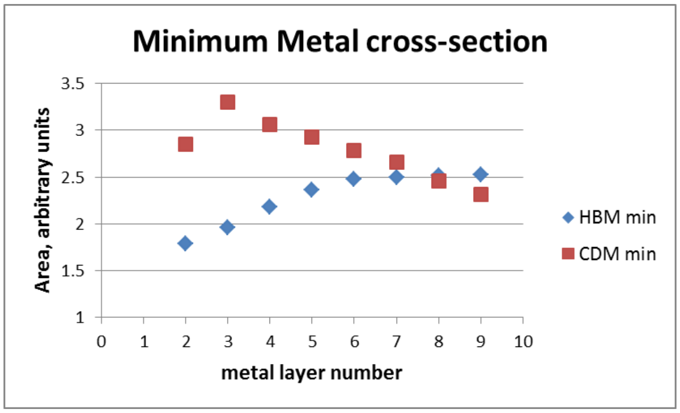

Figure 13. General trend of minimum cross-sectional area (in arbitrary units) as a function of metal layer for HBM (1kV) or CDM (250V) peak temperature to be limited to 1050°C.

The trend illustrated in Fig. 13 can be expected for any contemporary CMOS process with multiple layers of metal. Heat flow is mostly constrained by inter-layer dielectric (ILD), so the distance of the metal from the silicon substrate heat sink is critical. Also, metal wires of smaller width and pitch at lower layers mean a larger surface-to-volume ratio and even more heat flow at lower layers. But at the same time, effective resistivity of the metal rises at the lower layers due to surface scattering and other process-related properties. These effects offset one another to varying degrees, as seen in Fig. 13, according to how the $P_0(t)$ for HBM or CDM relates to Z(t) on the time scale. The HBM pulse is wide enough to capture much of Z(t) for the lower layers, i.e., heat flows to the substrate. The effect, as expected, weakens as one advances up the metal stack, but is also counteracted by the improving metal resistivity. For CDM, Z(t) looks almost adiabatic (step function) on the higher layers but at the bottom layers even CDM can start to feel the substrate. CDM reaches a worst case at M3, as seen in Fig. 13, due to resistivity combined with some isolation from the substrate. At higher metal levels, CDM gradually improves due to improving resistivity, even though Z(t) is becoming closer to adiabatic.

IV. Discussion

The preceding results have been based on the simplifying assumptions of (1) infinitely compliant current source for HBM or CDM event, and (2) threshold temperature (e.g., 1050°C for Cu metal) as a design limit. Those work as worst-case bounds for finding safe design limits, but we should discuss the implications.

The feedback equation as in Eq. (3) always has a condition for going to zero, meaning divergence to infinite temperature. But with the positive TCR required for this condition, it also means infinite resistance and power consumption, requiring a pure current source that is not possible at such a boundary condition. But the divergence condition is not really of interest; we care about cases with less feedback where the ESD event is effectively a current source. With 1500 ohms series resistance, HBM is the best example of an ESD event that is usually close to a pure current source for most metal lines of interest. But CDM series resistance is based on the spark resistance (37.7Ω for Fig. 7) and is much more likely to be influenced by temperature rise of a finite length metal line. That can be favorable, of course, causing the positive feedback to go negative once the line length resistance exceeds the ESD network output impedance. This was all treated in [1] for the TLP example of 50 ohms, where the influence of test pattern line length on TLP data becomes clear--a longer length will turn positive feedback into negative feedback sooner because of its regulation of the current, much like a lamp filament on a voltage source. With each feedback case sensitive to the initial metal resistance, we cannot reach the generalized worst-case data for the current source ESD as in Figs. 6-13. But it is clear, from the more generalized feedback treatment in [1], how to examine an individual case beyond the current source model.

Threshold temperature just below melting is a good choice for keeping the worst cases from suffering any metal damage due to the phase change. But as pointed out in [1], a few nanoseconds above melting may not cause electrical failure, but the lines re-solidify with a large number of grain boundaries and the result is an electromigration (EM) hazard [8]. This is one of the few proven examples of latent ESD damage. It is important to avoid any kind of melting events under actual use conditions, even though they are hard to detect under test conditions. These simple calculations put bounds on the conditions and give us confidence in the design rules.

While the general feedback expression, Eq. (2), was derived and solved in [1], it is not fully understood why Eq. (3) works so well for our ESD waveforms. Some insights can be gained by looking at the extreme case of Z(t) as an impulse function, having zero width and a finite integral. The convolution integrals of Eqs. (2) now simply integrate $P_0(t)$ and multiply by a constant, and $\alpha_{eff} = \alpha$; no iteration required. The full effect of α, the TCR, is felt because Z(t) is infinitely narrow compared to $P_0(t)$, whatever it is. For HBM, the real Z(t) has some width but note that Fig. 9 gives α_{eff} that is 72.3% of α. In our CDM case, Fig. 11 (admittedly with wider Z(t)), the α_{eff} is only 34.8% of α. The CDM result for the same metal layer and Z(t) as Fig. 9 is α_{eff} equal to 44.8% of α, showing how the Z(t) is quite wide compared to the CDM $P_0(t)$. Clearly the

TCR is felt less when convolution spreads out the functions in time and weakens the resistive tempco effect.

The multiplications, convolutions and iterations of Eqs. (2) make it difficult to explain, with mathematical rigor, the success of Eq. (3) for the kinds of $P_0(t)$ and $Z(t)$ that we encounter. It could be significant that our $P_0(t)$ for both HBM and CDM is a double-pole exponential waveform with real decaying frequencies. Meanwhile, $Z(t)$ could probably be expressed accurately as a sum of positive exponentials in real decaying frequencies. The general proof of Eq. (3)'s viability from these essentials is yet to be achieved.

V. CONCLUSIONS

Metal interconnect self-heating and heat flow during ESD events is complicated but certain essentials can be described through a feedback equation requiring iterative convolution to generate a temperature waveform [1]. These results can be further captured by noticing that maximum temperature T_{max} follows a simple two-parameter feedback equation, and that the parameters for HBM and CDM vary predictably with electrical properties of the metal. The result is a simple design guide for current density T_{max} limits that is adjusted quickly with process changes. Above melting (~1050 °C for Cu), the "equivalent temperature rise" is still captured, understanding that latent heat of fusion occupies hundreds of equivalent degrees. But the metal is known to be changed irreversibly. The simple current source model used here almost always applies to HBM but is a worst case for CDM, where long leadway lines can cut down on the amount of positive feedback due to self-heating. Methods for solving those cases appeared earlier [1].

The simplified feedback equation, Eq. (3), for T_{max} can be equipped with proper parameters with a few simulations for each metal layer, using a proper CDM and HBM current profile and a single simulation of stepped power response, using "effective" thermal properties. As electrical parameters (resistivity, TCR α) change during process development far more than thermal properties of materials, the feedback equation parametric trends with electrical properties can be expressed in functional form, and the overall feedback equations captured in a spreadsheet. This final compact document serves as a very efficient guide for IC designers.

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