Prediction of Maximum Temperature Rise in Multi-Finger Transistor Structures using Normalization

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Abstract
A new method for the analysis of self-heating temperature rise in multi-finger transistor structures is described. The method is based on a normalization of coupling in a predictor multi-finger structure, which is then applied to other structures in the normalized domain. Predicted results for normalized maximum temperature rise a variety of multi-finger structures are compared to analytic and numerical thermal simulation and found to be within 5%, making the method very useful for fast exploration of a design space.

INTRODUCTION

Manufacturability of integrated circuits is a topic that is concerned not only with tolerances and capabilities of the fabrication process itself, but also with the attention paid in the design phase to the position of the design in yield space. Parametric yield can be adversely affected by sensitivity to manufacturing tolerances brought about by a design that is positioned close to the edge of acceptability even for the nominal case. There are a number of important issues to be addressed in modeling for manufacturability - the factor specifically addressed by this work is the maximum operating temperature in multi-finger transistor devices [1]. Lower maximum device operating temperatures make a design less susceptible to manufacturing variations, and dramatically improve long-term reliability. Accurate prediction of this temperature is therefore a key issue for both circuit design and reliability.

Maximum temperature rise is typically predicted using thermal simulation. The two most widely used approaches are analytic techniques [2], where the 3D heat equation is solved subject to simplified boundary conditions for a heat generation region providing a reasonable approximation of an operating transistor. This typically turns out to be a substrate of finite thickness with adiabatic (perfectly insulating) top and sides, and a uniform backside temperature. Numerical thermal simulation [3] solves a discretized version of the heat equation by finite difference, finite element or other methods, and is more general in its capability to handle arbitrary geometries, backend structures and boundary conditions. For homogeneous substrates, the problem can be solved assuming thermal conductivity K is independent of temperature, then the effect of the temperature dependence $K(T)$ taken into account separately. Multiple sources are handled in the constant K case using superposition.

Whatever the method, the quantity of interest is the temperature at a point in space due to the action of a thermal source. This point can be chosen within (or very close to) the source to characterize self-heating of a single transistor, or at a point farther away corresponding to the position of another device to characterize thermal coupling between devices.

THERMAL COUPLING IN MULTI-FINGER DEVICES

As an illustration of the importance of thermal coupling on structures such as multi-finger transistors that place thermal sources in close proximity, analytic simulation was used to predict the temperature profile through the centers of a five finger transistor structure modeled as five 0.5 μm wide, 20 μm long and 0.1 μm thick sources spaced 0.1 μm below the surface of a 100 μm thick substrate. The result is shown in Figure 1. Since K was assumed constant for this case, as it is throughout this work, the temperature is expressed relative to the maximum temperature in a single finger, and is therefore independent of the value of K. Figure 1 shows the temperature distribution of each finger acting alone, and the cumulative effect of all 5 acting together. This analysis indicates that the effect of thermal coupling cannot be ignored in the structure – the maximum temperature of the center finger is almost twice what it would be if the finger did not experience coupling.
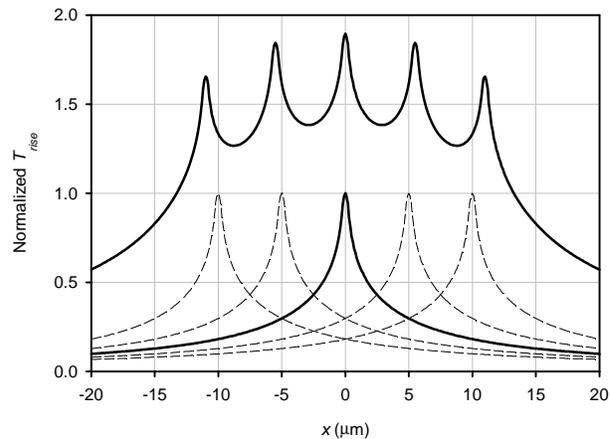

Figure 1. Temperature profiles through the width symmetry line of a five-finger array composed of 0.5x20 μm fingers (top) and the profiles of the isolated fingers (bottom). Temperature is normalized to the maximum in a single finger.

In order to incorporate thermal issues into the circuit design and layout process, it is necessary to evaluate the thermal properties of different transistor structures. Single transistor structures are modeled using a per-device thermal resistance, which is normally incorporated into the electrical compact model so that the electrical and thermal problems are solved simultaneously by the circuit simulator in an implicit fashion [4]. However, few commercially available circuit simulators offer the option of allowing for modeling of thermal coupling between devices [5]. In the absence of this capability, a lumped per-device effective thermal resistance is normally used for a structure in which thermal coupling is strong, such as a multi-finger transistor. Efficient evaluation of the effective thermal resistance is one of the central problems in characterizing the thermal behavior of multi-finger structures.

While technology limits will place bounds on the length, separation and possibly number of fingers in a multi-finger structure, within these constraints there is considerable room for optimization. Currently, the thermal design space for multi-finger structures is explored by explicit thermal simulation of each candidate structure, a long and tedious process which also makes insight into qualitative behavior difficult to obtain. The contribution of this work is the development of a new strategy for prediction of the maximum temperature rise in a multi-finger structure based on a normalized approach. With this technique, structures with different finger length, separation and number of fingers can be compared very quickly to arrive at a coarse solution that can be polished with thermal simulation if necessary.

NORMALIZATION APPROACH

Figure 1 illustrates that the increase in temperature rise in a multi-finger structure arises from coupling contributions created by the spatial temperature distributions of proximate sources. The problem of prediction of coupling can therefore be restated as that of predicting the temperature distribution around a single finger as a function of its geometry. The effect of coupling is then determined by summing the coupling contributions for a given finger due to each other finger, in other words evaluating the spatial distribution at the appropriate spacings.

To illustrate the nature of the problem, Figure 2 plots the spatial temperature profile as a function of orthogonal distance from the long source edge for three sources covering a reasonable practical range for multi-finger devices: 0.5x10, 0.5x20 and 0.5x40 μm. The source depth, thickness and substrate conditions are identical to those used to construct Figure 1. As in Figure 1, the temperature of each source is normalized to its maximum temperature. The effect of geometry is very clear in this plot – the longer emitter stretches the profile away from the edge of the source (at 0.25 mm). For the same inter-finger spacing, a multi-finger structure composed of 10, 20 or 40 mm long individual devices will show a different coupling characteristic, since the temperature contributions at the finger spacings will be different.
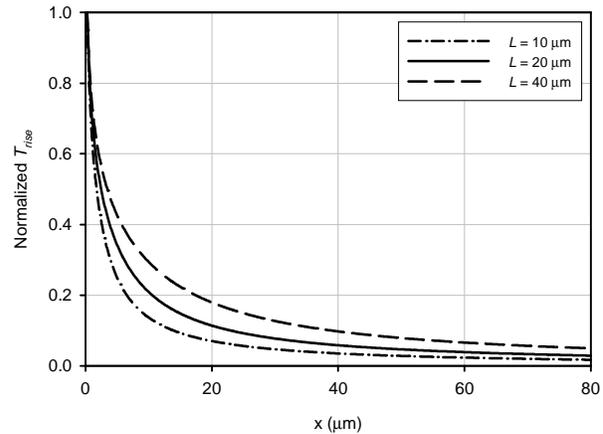

Figure 2. Temperature normalized to source maximum as a function of distance from the long edge of the source for 0.5x10, 0.5x20 and 0.5x40 μm sources.

For an arbitrary length, determination of the specific coupling characteristic using analytic or numerical thermal simulation is required in order to obtain the necessary values. Quick exploration of the design space and physical insight into the magnitude of coupling effects at different spacings and finger lengths is hampered by this need for per-device simulation.

A solution to this problem lies in the determination of a distance scaling function that will create self-similarity of the temperature distributions of different geometry devices, i.e. a source length dependent mapping M of the physical distance x from the source edge to some new value $M(x,L)$. If the mapping function has the property of removing the dependence of the final mapped distributions on L, the results will be self-similar. In this event, repeated simulations are not necessary, since a single characteristic can be used to determine the actual physical values of temperature distribution by the inverse mapping $M^1(x,L)$ for any particular x and L.

The nonlinear mapping function $M(x,L)=x/L^{0.72}$ has been found to provide excellent results. Figure 3 shows the same temperature data for the three devices represented in Figure 2 replotted as a function of the normalized distance quantity $x/L^{0.72}$. The effect of this normalization mapping is to almost entirely remove the dependence of the temperature distribution on the length of the source. Since the three curves are nearly indistinguishable, this single characteristic can be used to predict the actual temperature profile adjacent any of these sources just by normalizing the physical location using the mapping function. Note that although only three discrete values of source length are considered, the well-controlled behavior of temperature as a function of length in a rectangular source suggests that the profiles of a source with

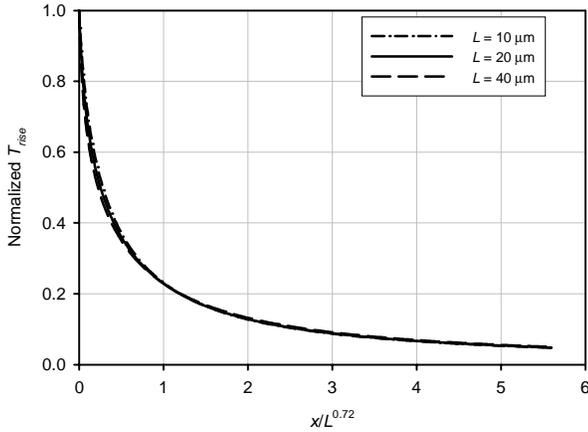any length between 10 and 40 μm will be equally well represented.

Figure 3. Normalized temperature as a function of normalized distance from the source edge for 0.5x10, 0.5x20 and 0.5x40 μm sources.

The usefulness of this technique in predicting maximum temperature rise for multi-finger structures derives from the observation made earlier that the multi-finger prediction problem is really the requirement to sum temperature contributions from adjacent sources at locations given by the inter-finger spacing. Since the $L^{0.72}$ normalization essentially removes the differences between structures with lengths between 10 and 40 μm, the required coupling contributions for multi-finger structures composed of uniform fingers of any length in this range can be found by normalizing the inter-finger spacing, and summing contributions at the appropriate multiples of this value. For the example of Figure 1, the normalized inter-finger spacing is $5/20^{0.72} = 0.58$, so the temperature increase of the center finger would be predicted by summing twice (one for each finger) the coupling values at normalized distances 0.58 and 1.2, i.e. $2*0.26 + 2*0.19 = 0.9$, making the normalized temperature 1.9, which corresponds exactly to the value of the center peak in Figure 1.

In practice, therefore, the temperature profile for a source of one length in the range 10 to 40 μm can serve as a predictor of the characteristic of another length, so only a single, accurate distribution is required from thermal simulation, with the translation between lengths occurring through the normalization mapping.

As a test of the accuracy of this approach, the spatial temperature distribution of the 20 μm long source was used as a predictor of the distributions of the 10 and 40 μm sources, and the difference expressed as a percentage of the correct value. If the normalization were perfect, this quantity would be exactly zero over all normalized distances. Its deviation from zero is a measure of the error involved in translating between two distributions using the normalization

mapping function. Figure 3 shows the distribution of the prediction error.
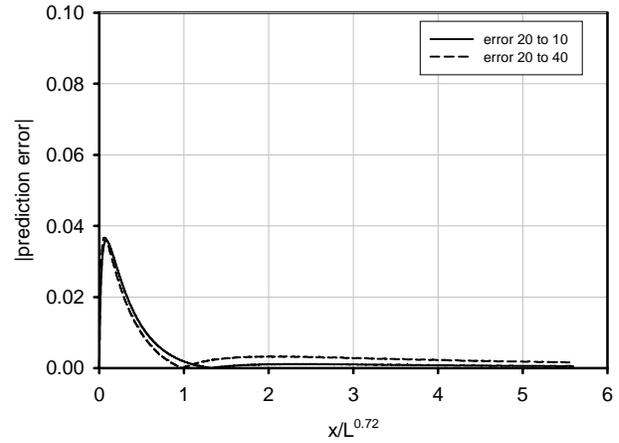

Figure 4. Error in using the 0.5x20 μm device as a predictor of the 0.5x10 and 0.5x40 μm devices based on the scaling approach from Figure 2.

The magnitude of the errors in Figure 4 correlate with the obvious similarity of the curves in Figure 3. The peak error is less than 4%, and is a fraction of a % over most of the normalized distances shown. The maximum error occurs at very small values of normalized distance – to estimate a lower bound for normalized distances of practical interest, an inter-finger spacing of 5 mm and emitter length of 40 mm gives a normalized spacing of $5/40^{0.72} = 0.35$. At this point the prediction error is already less than 2%, and falls dramatically from that point on.

The result in Figure 4 can also be used to estimate the accumulation of error as structures of increasing number of fingers are considered. The prediction of a 0.5x10 or 0.5x40 μm multi-finger structure based on the normalized characteristic of the 0.5x20 μm source will sample the error in Figure 3 at multiples of the normalized inter-finger spacing. While the maximum error contribution is clearly from the closest fingers, which also make the largest contribute to coupling, the error even for this case is at most 2% for the first fingers and much lower thereafter. The error accumulation in prediction of multi-finger arrays with many fingers is therefore not a problem.

NORMALIZED CHARACTERISTIC

The accuracy of the length normalization prediction strategy suggests that a suitable representation of the effect of number of fingers and finger length for a 0.5x20 μm structure can be generated once, and the corresponding effect in any other device related to that of the 0.5x20 μm structure through an expression of the inter-finger spacing in normalized space using the mapping function described earlier. Although the individual 0.5x20 mm structures still need to be simulated using analytic or numerical means, the

characteristics only need to be generated once, and the process can be very easily automated.

Figure 5 plots the maximum temperature rise of a uniform multi-finger structure relative to that of a single finger of the same length as a function of the number of fingers and the inter-finger spacing expressed as a fraction of the unit normalized spacing $S_U = L^{0.72}$. Results for all three of the lengths considered in Figures 2-4 are shown to demonstrate the usefulness of this approach. The similarity of the three sets of curves is a function of the ability of the length normalization mapping function to express the coupling in a manner which is almost independent of length, and which led to the low prediction error in Figure 4.
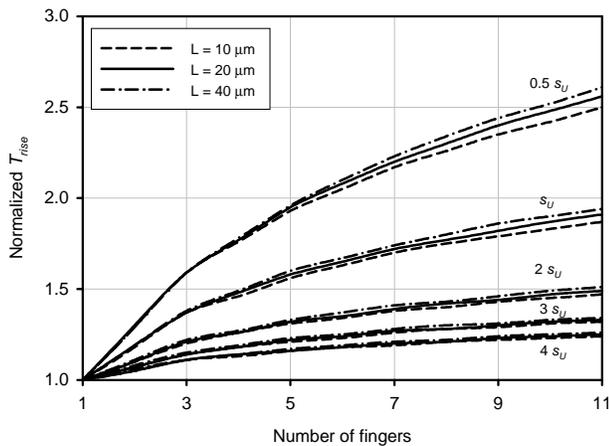

Figure 5. Normalized maximum temperature rise increase for multi-finger structures at multiples of the normalized unit inter-finger spacing.

These results support the usual intuitive conclusions regarding multi-finger structures. For a given inter-finger spacing, the increase in maximum temperature is more severe for a larger number of fingers, since the total amount of power dissipation is increased. The maximum temperature increase is also more severe for or a decreasing inter-finger separation for a given number of fingers, since thermal sources are moved closer together and interact more strongly.

The use of normalized quantities makes the characteristic of Figure 5 a compact and very powerful representation of the effect of number of fingers and inter-finger spacing on the thermal penalty in a multi-finger structure, since it allows immediate determination of the tradeoffs between various structures. For example, the increase in maximum temperature rise in a 5 finger structure composed of 10 μm long fingers with 5 μm inter-finger spacing can be found by first determining $S_U = 10^{0.72} = 5.3$. The inter-finger spacing of 5 μm therefore corresponds to $5/5.3 = 0.9 \ S_U$. Interpolating between the 0.5 and 1.0 curves in Figure 5 yields an increase in normalized temperature of approximately 1.65, i.e. a 65% penalty in maximum temperature for the multi-finger array compared to the temperature of a single finger. Transferring this point to the left on Figure 5 suggests that approximately the same

increase in temperature rise can be obtained in a three-finger structure by spacing the fingers at 0.5 S_U. If 20 μm fingers are chosen for this structure, $0.5 S_U$ corresponds to 0.5*20 0.72 = 4.3 μm spacing.

One limitation of the method represented by Figure 5 is that only relative maximum temperature increase is determined. Although the tradeoffs between different structures can be immediately determined in terms of increase relative to a single factor, absolute temperatures, which are the important quantity for reliability, are not. However, it is a very simple matter to relate relative temperature to absolute through the single finger thermal resistance and required power density. This adds little to the overall process compared to per-device thermal simulations. A subsequent paper will also detail a method for combining these two tasks into one graphical operation.

CONCLUSIONS

A new method has been presented which allows the increase in maximum temperature in a multi-finger structure to be estimated quickly and efficiently. The method is based on a length normalization mapping which creates a self-similarity in spatial temperature profile between thermal sources with a range of lengths, and therefore allows the results for a set of structures at a single length to be used as the predictor of structures with any other length and inter-finger spacing.

ACKNOWLEDGEMENTS

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