Over-Temperature Predictions by a Transient R-C Model


Center of the Integrated Logistics Support
Chinese Military Headquarters
Longtan, Taoyuan
Taiwan, 336
Phone: 886-3-4807753
Fax: 886-3-3900119

*Department of Physics and Chemicals
Chinese Military Academy
Feng-Shan, Kao-Hsiung
Taiwan
Phone & Fax: 886-7-7429442

er-mails: thchang@ap06.ccit.edu.tw and sulu@cc04.ccit.edu.tw

**Semiconductor Laboratory
Chung Cheng Institute of Technology
Tashi, Taoyuan
Taiwan, 335
Phone & Fax: 886-3-3900119

er-mails: wllu@cna.edu.tw and jglo@cna.edu.tw

***Dept. of Mathematics and Physics
Chinese Naval Academy
Tso-Ying, Kao-Hsiung
Taiwan
Phone: 886-7-5834700 ext. 1219/1217
Fax: 886-7-5850329

er-mails: wllu@cna.edu.tw and jglo@cna.edu.tw

Abstract

The conventional technique for over-temperature protection of circuits is to use comparators to compare the voltage of temperature sensors with a reference voltage, and take action if the voltage difference reaches a critical value. In this paper, the researchers propose a software precaution strategy to determine whether the final steady state temperature of a circuit is beyond the preset temperature, and/or to judge whether the working condition is abnormal, by a new transient methodology. In this new technique, an R-C (Thermal Resistance - Heat Capacitance) circuit model is built and the RC characteristic values as well as the other parameters of this circuit model is obtained from the transient temperature profile. Next, the steady state temperature is calculated from the transient temperature data and the derived parameters. Based on this new method, a real time prediction strategy is developed to check whether a circuit is beyond a preset temperature or a power limit. Validation studies indicate that the new methodology, which makes the over-temperature protection function more reliable and sensible, can be used to assist over-temperature protection of a circuit or a system.

Key words: R-C Circuit Model, Real Time Temperature Prediction, Transient Temperature Response, and Over-Temperature Prediction.
1. Introduction

It is well known that over-temperature operations can excite failure mechanisms that can lessen the life cycle of the circuits or systems. To this end, over-temperature protection is an important function for all circuits. Many protective methods are used for over-temperature detection in a circuit, but all of these methodologies do not respond until the temperature reaches a preset critical value. Therefore, a large safety margin is needed in order to prevent circuit damages caused by over-temperature. To obtain a faster and reliable temperature prediction, an R-C circuit charging model is proposed to simulate the complete temperature profile from transient to steady state. As the temperature response of a circuit can be described by a simple R-C model, all the parameters used to determine the temperature condition can be obtained by a curve fitting process. In this way, the steady state temperature of the circuit can be easily determined from the transient R-C formulations with only one or two sampled temperature data. To make the methodology more efficient for various applications, the identical RC values under the same environments are proposed to predict the steady state temperature in different power input conditions. Using this methodology, both theoretical and experimental results verified that the RC values obtained from the same environments under different power input conditions are closely matched. For over-temperature prediction, the new methodology can be employed in two ways; one way is to determine whether the final state temperature will be beyond a preset value, and the other way is to determine whether the power is beyond limit with a preset RC value. Though very useful, this methodology is nevertheless limited. It can be used in any circuits or systems, only the transient temperature profiles of the circuits or systems can be represented by a simple R-C charging model.

2. Temperature Calibration and Experimental Setup

The test chip, containing polysilicon sensors and heaters, is packaged in a 208-pin PQFP (plastic quad flat package)\(^1\). To ensure the resistance and the temperature (R-T relationship) relationships of the sensors are correct, each of the sensors is calibrated using a standard temperature sensor (PT-111)\(^2\) in an oil bath constant temperature oven, the results from which are shown in Figure 1. After powers of 1, 2 and 3 Watts are applied, respectively, to the test chip, the resistance of polysilicon sensors are measured and transformed into temperatures by the calibrated R-T relationships as shown in Figure 1. Figure 2 shows the temperature response profiles of the experiments in a free air convection environment. In this Figure, the resistances are measured every 5 seconds for 10 minutes to ensure that the steady state temperature is reached, so there are 120 sampled points in each of the curves.

The temperature measurement experiments in this work are fully automated with the personal computer (PC) as shown in Figure 3. The PC controls all the instruments through an IEEE 488 bus, and the instruments include an HP6623A programmable power supply which controls the supplied voltage, an HP3478A digital multimeter (DMM) which monitors the current across the heater, and an HP3421A data acquisition control unit which measures the resistance variation for each of the sensors.

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\(^2\) A Temperature Sensor for a Wide Range of Applications, PT-111, Omega Engineering, Inc., 1990
3. The Thermal R-C Modeling

It is reported that the transient temperature behavior for a circuit during power-on period is analogous to the voltage behavior of an R-C electric circuit during charging periods\(^5,6\). The I-V relationship for a typical charging R-C circuit is given by the relation,

\[
V(t) = IR \left\{ 1 - \exp\left(\frac{\text{t}_a}{\text{RC}}\right) \right\}, \quad t > 0
\]  

(1)

where the voltage \( V \) is analogous to the temperature, the current \( I \) is analogous to the power generated and/or delivered, the resistance \( R \) is analogous to the thermal resistance, and the capacitance \( C \) is analogous to the heat capacitance of the system. From equation (1), the sampled temperature response, \( T_A \) and \( T_B \), during power-on stage at time \( t_a \) and \( t_b \), respectively, with initial temperature \( T_I \) can be represented as follows,

\[
T_A = T_I + T_R \left( 1 - \exp\left(\frac{-t_a}{RC}\right) \right)
\]  

(2)

and

\[
T_B = T_I + T_R \left( 1 - \exp\left(\frac{-t_b}{RC}\right) \right)
\]  

(3)

and \( T_R \) is the temperature difference between the initial temperature and the steady state temperature. Substituting \( t = \infty \) into equation (2) or equation (3), the steady state temperature \( T_S \) can be expressed as follows,

\[
T_F = T_I + T_R
\]  

(4)

Subtracting equations (2) and (3) from equation (4) and after rearrangement, one can obtain,

\[
T_F = T_A + T_R \exp\left(\frac{-t_a}{RC}\right)
\]  

(5)

and

\[
T_F = T_B + T_R \exp\left(\frac{-t_b}{RC}\right)
\]  

(6)

respectively. The derivation of equations (5) and (6) lead to our One Sampled Datum (OSD) method, which will be discussed later.

After moving the \( T_A \) and \( T_B \) in equations (5) and (6) to the left hand sides and dividing equation (5) by equation (6), one can obtain,

\[
\frac{T_F - T_A}{T_F - T_B} = \exp\left(\frac{t_b - t_a}{RC}\right)
\]  

(7)

and

\[
T_F = \frac{\exp\left(\frac{t_b - t_a}{RC}\right) \times T_B - T_A}{\exp\left(\frac{t_b - t_a}{RC}\right) - 1}
\]  

(8)

or

\[
T_F = \frac{K \times T_B - T_A}{K - 1}
\]  

(9)

where \( \exp\left(\frac{t_b - t_a}{RC}\right) \) is represented by \( K \). Equation (9) leads to the Two Sampled Data (TSD) method, which is a modified OSD method. The TSD method based on equation (9) can be used to predict the temperature state in real time. With different ways to choose the RC value, this method can also be employed to determine whether abnormal power and/or environment change appear during operation. Both of the OSD and TSD methodologies will be discussed in the next section.

4. Experimental Results and Discussion

To extract the parameters (\( RC, T_I \), and \( T_R \)) in equations (2) or (3) for different power cases, curve fitting processes are executed. Table 1 lists the curve fitting results from Figure 2 for each power input in free air convection. Note that the first sampled point’s temperature is \( T_I \), the initial temperature, in Table 1 and in all of the calculations later in this paper. To reduce the \( \chi^2 \) (the sum of the squares of the deviations from the measured and fitting data), a good fitting result (smaller \( \chi^2 \)) is difficult to obtain if room temperature (about 25 °C) is employed as the initial temperature. Besides, the initial temperature \( T_I \) can be eliminated from both OSD (from Equations (5) or (6)) and TSD methods (from Equations (8) or (9)). Therefore, the initial temperature \( T_I \) is adjusted to meet the best fitting results.

Table 1. The fitting parameters of the temperature profiles of 1 Watt, 2 Watt and 3 Watt heat power by the RC model curve fitting in free air condition. Where the \( \chi^2 \) is the sume of the squares of the deviations from the measured and fitting data. \( T_{F^\prime} \) is the initial and \( T_{S^\prime} \) rising temperature which is the temperature difference between \( T_I \) and \( T_R \).

<table>
<thead>
<tr>
<th>Power</th>
<th>( \chi^2 )</th>
<th>RC</th>
<th>( T_I )</th>
<th>( T_S )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Watt</td>
<td>0</td>
<td>98.89</td>
<td>40.13</td>
<td>16.59</td>
</tr>
<tr>
<td>2 Watt</td>
<td>0.05</td>
<td>95.97</td>
<td>57.27</td>
<td>31.97</td>
</tr>
<tr>
<td>3 Watt</td>
<td>0.05</td>
<td>96.5</td>
<td>78.43</td>
<td>50.96</td>
</tr>
</tbody>
</table>

To simplify the curve fitting process and reduce the numbers of sampled data without losing the extracted parameters’ accuracy, the authors selected three transient sampled points which are the temperature measured at the 20th, 50th, and 70th seconds and use a three points curve fitting process for each of the power cases. Table
2 lists the results of the three points curve fitting scheme in free air convection condition. The good results in these Tables demonstrate that accurate parameters can be obtained from a faster curve fitting from three transient points instead of a complete curve fitting from all of the 120 points. Table 3, obtained from both the 120 points and the three points curve fitting process, lists the RC values with different input powers in three different environment conditions. The RC values in Table 3, inside and outside the parentheses, are the results of three points and 120 points curve fitting, respectively. It is shown in Table 3 that the RC values obtained from three points and 120 points curve fitting are close to each other in the same environment with different power input conditions. Namely, a good fitting result of few sampled points from transient can be used to replace a large number of sampled data from transient to steady state.

Table 2. The extracted curve fitting parameters of the temperature profiles of 1 Watt, 2 Watt and 3 Watt heat power by the three points (20th, 50th, 70th) data fitting in free air condition. Where the RC values are close to Table 1. \( T_p \) is the initial and \( T_F \) is rising temperature which is the temperature difference between \( T_i \) and \( T_F \).

<table>
<thead>
<tr>
<th>Power</th>
<th>RC Value</th>
<th>( T_i )</th>
<th>( T_F )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Watt</td>
<td>98.89</td>
<td>40.13</td>
<td>16.6</td>
</tr>
<tr>
<td>2 Watt</td>
<td>95.59</td>
<td>57.3</td>
<td>32.17</td>
</tr>
<tr>
<td>3 Watt</td>
<td>98.76</td>
<td>78.6</td>
<td>50.3</td>
</tr>
</tbody>
</table>

Table 3. The RC values inside and outside the parentheses are the results of three points and 120 points curve fitting, respectively. The extracted RC values of the temperature profiles of 1 Watt, 2 Watt and 3 Watt heat power by RC model curve fitting in different environments which include the free air convection, the bathed oil, and the forced air convection conditions.

<table>
<thead>
<tr>
<th>Environment</th>
<th>RC Value</th>
<th>Free Air Convection</th>
<th>Oil Bath</th>
<th>Force Air Convection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Watt</td>
<td>[98.89],98.89</td>
<td>[37.75],37.89</td>
<td>[41.06],41.13</td>
<td></td>
</tr>
<tr>
<td>2 Watt</td>
<td>[95.59],95.97</td>
<td>[35.03],35.21</td>
<td>[43.67],43.55</td>
<td></td>
</tr>
<tr>
<td>3 Watt</td>
<td>[98.76],96.50</td>
<td>[40.86],40.75</td>
<td>[50.02],50.31</td>
<td></td>
</tr>
</tbody>
</table>

The steady state temperature \( T_F \) is directly predicted from equations (5) (or (6)) with one sampled point (the corresponding measured time) and the extracted parameters from the above curve fitting process. Figure 4 plots the predicted steady state temperature for each of the power input conditions by this One Sampled Datum (OSD) method from each of the 120 sampled points shown in Figure 2. After comparing Figure 2 and Figure 4, it is concluded that the steady state temperature can be fast and accurately predicted by this OSD method.

Figure 4. Steady state temperature is deduced from OSD method which uses just one sampled datum. The steady state temperatures are calculated from each sampled point, and the parameters in equation (2) or (3) are obtained by RC model curve fitting of 1 Watt to 3 Watt power in free air convection condition, respectively.

Although a fast and accurate steady state temperature prediction from transient data has been derived, the disadvantage of the OSD is clear. Thus, the curve fitting processes must be employed on each of the power conditions since different heating power provides different \( T_F \). However, the close results of the RC values in the same environment with different power inputs as shown in Table 3 leads to the development of the TSD (Two Sampled Data) method. In TSD method, only one fast curve fitting process is first executed at a certain power condition for the determination of the RC parameters, and the steady state temperature \( T_F \) for the same circuit can be next predicted through equation (9) with any two of the sampled data and their measured times. The predicted steady state temperature by the TSD method with two consecutive sampled data are plotted in Figure 5(a). In Figure 5(a), the RC parameter obtained from 1 Watt power input is employed for all of the three power input curves in free air convection environment. Figure 5(b) and Figure 5(c) resemble the prediction process in Figure 5(a), but the environments are in forced air convection\(^7\), and in oil bath\(^8\), respectively.

Figure 5(a). The TSD method from equation (8) to calculate the predicted temperature condition by two sampled data. The sampled time interval is 5 second and the power of 1 to 3 Watt in free air condition which makes the chip reaching to 56.7°C, 89.7°C and 129.5°C, respectively.
The application of the TSD method in over-temperature protection can be also explained by equation (9). This method can be applied in two ways; one way is to predict the values of over-temperatures, and the other method is to predict the abnormal working power conditions which cause over-temperatures. The first application of the methodology is similar to the above mentioned temperature prediction method. Therefore, after obtaining the characteristic RC values from curve fitting process, the predicted temperature condition can be derived directly from equation (9) with the sampled data and their corresponding measured times. If the input powers and/or the environments are suddenly changed which result in the sampled data abnormal during operation, the predicted temperatures will be changed simultaneously so that the abnormal conditions can be monitored.

The over-temperature prediction methodology above is somewhat complicated and inefficient since a curve fitting process and resistance-temperature transformation are needed. Therefore, a modified methodology that needs neither curve fitting process nor the R-T transformation process is proposed for over-temperature prediction. In this modified methodology, a preset RC value and a test process in normal working condition (rated working power and environment) are first performed in order to obtain a predicted normal working resistance (or voltage). To obtain the normal working resistance, the same predicting method is applied in equation (9), but the terms of resistances (or voltages) are employed instead of the terms of temperatures. Equation (9) is modified by switching temperatures to resistances, to reflect the following relation,

$$R_F = \frac{K \times R_B - R_A}{K - 1}$$  \hspace{1cm} (10)
Over-Temperature Predictions by a Transient R-C Model

Figure 6(a). The application of TSD method which is used the present RC values in one Watt constant (normal) power input in free air condition. The RC values are preset from 10 to 40 in a step of 5 and the sampled time interval is 5 second.

Figure 6(b). The TSD method with the present RC (equal to 25) is used to predict the abnormal working condition, when the normal and abnormal power sequence is applied. The curve marked - △-“Normal Power Response” is the sensor’s resistance response to the normal power condition, and the curve marked - ▼- “Abnormal power response” is the sensor’s resistance response to the abnormal power condition, the curve marked - ■- “Normal Power Predicted by TSD” is the predicted resistance from normal power condition, and the curve marked - ●- “Abnormal Power Predicted by TSD” is the predicted resistance from normal power condition, respectively.

5. Conclusion

The R-C models for transient temperature are well established, but this paper first proposes the R-C model concepts to steady state temperature prediction and over-temperature protection using transient temperature data. For the OSD method, parameters for each of the power input conditions are first extracted from the curve fitting process. Then, the steady state temperatures can be accurately derived by only one sampled data with its sampled time. For the TSD method, two sampled data are employed to predict the temperature conditions with only one curve fitting process, and to predict the abnormal working conditions without an RC curve fitting process (which can be replaced by a preset RC method). From the experimental data, it is validated that the TSD method gives direct assistance to the temperature prediction easily and rapidly. In conclusion, for circuits over-temperature protection, the TSD method can be used to determine whether the steady state temperature will be beyond a preset protection temperature, and whether the working power/environment will become abnormal without temperature transformation and curve fitting process in real time. Accompanying this new over-temperature prediction methodology with over-temperature protection designs in circuits will make over-temperature protection more sensible and efficient.

References


About the authors

Kun-Fu Tseng received his Ph.D. Degree in Electrical Engineering from the Department of Electronic Engineering at Chung Cheng Institute of Technology in 1998, where he earned a B.S. Degree in 1986, and an M.S. Degree in 1992, respectively. He joined the Cen-
Ting-Haun Chang received his Ph.D. Degree in Applied Physics from the Department of Applied Physics at Chung Cheng Institute of Technology in 1998. He earned a B.S. Degree at Soochow University in 1984 and an M.S. Degree at Chung Cheng Institute of Technology in 1991. He joined the Department of Physics and Chemicals at Chinese Military Academy in 1998. Assistant Professor Chang’s research interests are mainly in CMOS gate length extraction.

Ching-Hsing Kao received his Ph.D. Degree in Electrical Engineering from the Department of Electrical Engineering of National Tsing Hua University in 1990. He joined the Department of Applied Physics at Chung Cheng Institute of Technology in 1990. Associate Professor Kao’s research interests are mainly in thermal stress and strain analysis of IC packaging.

Wei-Lee Lu received his Ph.D. Degree in Applied Physics from the Department of Applied Physics of Chung Cheng Institute of Technology in 1995. He joined Department of Mathematics and Physics at Chinese Naval Academy as a Associate Professor in 1995. Associate Professor Lu’s research interests are mainly in temperature dependent characteristics of carrier mobility in CMOS devices and he is recently involved in the coordination of the ethics courses in the Chinese Naval Academy.

Jeen Gee Lo received his Ph.D. Degree in Applied Physics from the Department of Applied Physics of Chung Cheng Institute of Technology in 1992. He joined the Department of Mathematics and Physics at Chinese Naval Academy as a Associate Professor in 1992. Associate Professor Lo’s research interests are mainly in CMOS devices parameter extraction and process simulation.

Luke Su Lu received both M.S. and Ph.D. Degrees in Electrical Engineering from the Department of Electrical Engineering at University of Illinois in Urbana Champaign. He joined Department of Applied Physics at Chung Cheng Institute of Technology in 1987, and as a Professor in Applied Physics in 1993 at the same institution. He is now Vice Dean of Studies of the Chung Cheng Institute of Technology. He research interests including CMOS low temperature characteristics, Radiation Hardness of the CMOS devices, thermal analysis of the IC packaging and design of experiments. He is a member of American Physical Society, Institute of Electrical Engineer, and IMAPS societies.

Ben-Je Lwo biography was not available at the time of the manuscript publication.