EARLY DETECTION OF AVALANCHE BREAKDOWN IN EMBEDDED CAPACITORS USING SPRT

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Abstract: Early detection of avalanche breakdown in an embedded planar capacitor dielectric is addressed in this paper. These failures were observed during accelerated temperature and voltage aging of embedded planar capacitors. At the time of avalanche breakdown there was a sharp drop in the value of insulation resistance. There was no trend in the values of insulation resistance before failure, making the detection of these failures challenging. However it was observed that the value of dissipation factor fluctuated before the drop in the insulation resistance. A statistical hypothesis test known as the sequential probability ratio test (SPRT) was applied to the dissipation factor data to detect an increase in the variance of dissipation factor. This approach provided a means for early detection of avalanche breakdown failures.

Key words: Embedded planar capacitor, temperature and voltage aging, avalanche breakdown, prognostics and health management.

Introduction: An embedded planar capacitor is a thin laminate embedded in a printed wiring board (PWB) (as shown in Figure 1) that functions both as a power and ground plane pair and as a parallel plate capacitor. These capacitors have been found to reduce the required number of surface mount capacitors, which can lead to product miniaturization [1] and also improve the electrical performance (such as by reducing electromagnetic interference) [2][3] of the PWB. A reduction in the required number of surface mount capacitors is achieved due to a low value of parasitic inductance [4] associated with embedded planar capacitors. The use of embedded planar capacitors is gaining importance with an increase in the operating frequency and a decrease in the supply voltage in electronic circuits [5].

The dielectric material that is widely used in embedded planar capacitors is a composite of polymer and high dielectric constant ceramic. The advantage of using a polymer-ceramic composite is that it combines the low temperature processability of polymers along with the high dielectric constant of ceramics [6]. For commercial applications, unimodal or bimodal barium titanate (BaTiO\(_3\)) particles in an epoxy matrix are used. BaTiO\(_3\) is a ferroelectric material and can have a dielectric constant as high as 15,000 in the crystalline phase [7]. For epoxy-BaTiO\(_3\) composites, it has been observed that the
dielectric constant increases with ceramic loading of up to 55-60% by volume, and then decreases due to an increase in porosity [8]. Typically, the maximum loading for BaTiO$_3$ particles is lower than 50% by volume, since high filler loading can cause adhesion problems with the metal electrodes [9]. This limits the maximum dielectric constant of the composite to close to 30 in commercially available dielectrics [10].

Although embedded planar capacitors have many advantages, the reliability of these devices will determine the breadth and success of their practical application. Failure of an embedded planar capacitor can lead to board failure since PWBs with these capacitors are not reworkable. A drift in the electrical parameters of embedded planar capacitors can hinder these capacitors from performing their intended function. Health monitoring of embedded planar capacitors can provide advanced warning of an impending failure which can help to minimize unscheduled maintenance in systems using these capacitors. Prognostics is the process of predicting the future state of a system based on current and historic conditions [11]. Prognostics and health management (PHM) permits the reliability of a system to be evaluated in its actual life-cycle conditions, to detect impending failures, and mitigate the system risks.

The failure mode of an embedded planar capacitor can be a change in capacitance, dissipation factor, or insulation resistance beyond a specified limit (this limit can be defined based on the application). The effect of various environmental and bias stresses on the electrical parameters of these capacitors has been summarized in Table 1. The change in capacitance is gradual whereas the change in insulation resistance and dissipation factor is sudden under these stress conditions. Prognostics of failures as a result of a gradual change in capacitance can be performed readily since there is a trend in the values of capacitance. However, it is challenging to predict the insulation resistance and dissipation factor failures which take place suddenly and have no trend before failure. Insulation resistance and dissipation factor failures are the result of the same phenomenon, namely the formation of a conducting path across the dielectric.

This paper provides an approach to detect in advance the sudden insulation resistance/dissipation factor failures in embedded planar capacitors. A commercially available embedded planar capacitor with epoxy-BaTiO$_3$ composite dielectric was investigated in this study. The environmental stress condition that was investigated is temperature and voltage aging. A statistical tool which is known as a sequential
probability ratio test (SPRT) was applied to the dissipation factor data to predict insulation resistance/dissipation factor failures in advance.

Table 1: Effect of Various Environmental Stress Conditions on the Electrical Parameters of Embedded Capacitors

<table>
<thead>
<tr>
<th>Environmental stresses</th>
<th>Electrical parameters</th>
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<tbody>
<tr>
<td></td>
<td>Capacitance</td>
</tr>
<tr>
<td>Temperature and voltage aging</td>
<td>Gradual decrease</td>
</tr>
<tr>
<td>Temperature-humidity bias</td>
<td>Gradual increase</td>
</tr>
</tbody>
</table>

**Test Vehicle:** The test vehicle was a 4-layer board in which layers 1 and 4 were the signal layers, and a commercial planar capacitor laminate formed layer 2 (power plane) and layer 3 (ground plane). The test vehicle consisted of two groups of capacitors, A and B, as shown in Figure 2. On each board, there were 80 square capacitors of group A (small capacitors) each with an area of 0.026 in$^2$, and 6 square capacitors of group B (large capacitors) each with an area of 0.19 in$^2$. The capacitance of group A and group B capacitors were about 400 pF and 5 nF respectively. The design of this test board was first used in the NCMS embedded capacitor project [13].

Figure 2: Test Vehicle of Embedded Capacitors

The power plane was etched at various locations to form discrete capacitors, and the ground plane was common to all capacitors as shown in Figure 3. The dielectric was a composite of BaTiO$_3$ particles of mean diameter equal to 0.25 µm loaded 45% by volume in bisphenol-epoxy resin. The dielectric thickness was 8 µm and the dielectric constant of the composite was 16 at 1 KHz.
Temperature and Voltage Aging: The electrical parameters (capacitance, dissipation factor, and insulation resistance) of 33 out of 80 capacitors of group A were monitored in-situ during aging. The capacitance and dissipation factor were measured by an Agilent 4263B LCR meter at 100 KHz. Insulation resistance was measured by an Agilent 4339B high resistance meter using a bias of 10 V. The failure criteria selected were a 20% decrease in capacitance, an increase in dissipation factor by a factor of 2, or a drop in insulation resistance below 10 MΩ.

A failure terminated temperature and voltage aging test was conducted at 125°C and 285 V that lasted for 500 hrs. The stress levels, especially the voltage, were rather high as compared to the typical operating conditions of embedded planar capacitors, so these failures may differ from those occurring under normal operating conditions of embedded planar capacitors. Further aging experiments under non-accelerated conditions are required to establish the extent to which the failures observed are similar to those occurring at much lower stress levels. The first measurement performed at 125°C was used as the baseline value to detect any shift in the electrical parameters. Subsequently, a voltage of 285 V was applied across all the capacitors, and measurements of electrical parameters were performed in-situ. The failure modes observed were a gradual decrease in capacitance, and a sharp drop in insulation resistance. The values of dissipation factor were observed to be correlated with the values of insulation resistance, and exhibited an increase at the time of failure as a result of a sharp drop in insulation resistance. Prognostics of capacitance failures are not addressed in this paper since this has been reported elsewhere using a model-based approach [14].

A typical plot of insulation resistance during aging is shown in Figure 4. The failures were sudden implying avalanche breakdown (ABD), and no trend was observed in the values of insulation resistance before failure. 31 out of 33 small capacitors failed by this failure mode.
The value of dissipation factor (DF) was found to increase at the time of those failures which were due to a sharp drop in insulation resistance. In some capacitors, the value of DF at the time of these failures was well below the failure criterion of DF (Figure 5) while in other capacitors the value of DF went above the failure criterion (Figure 6). This phenomenon implies that the values of dissipation factor are correlated with the values of insulation resistance. Physically a low resistance path is expected to be formed in the dielectric during aging that leads to a decrease in the insulation resistance and hence an increase in the dissipation factor.

Figure 4: Typical Plot of Insulation Resistance of Small Capacitors (Group A)

Figure 5: An Increase in the Values of DF at the Time of IR Failure

Figure 6: An Increase in the Value of DF above the Failure Criterion at the Time of IR Failure
**Early Detection of Insulation Resistance Failures:** No trend in the values of insulation resistance was observed before failure, making the prediction of this failure challenging. After conducting preliminary analysis on the dissipation factor data, it was observed that the values of dissipation factor started to fluctuate before insulation resistance (IR) failure, as shown in Figure 7. No such fluctuations were observed in the insulation resistance data. This may be because dissipation factor is an AC measurement (measured at 100 KHz) and insulation resistance is a DC measurement. In addition to these fluctuations an increasing trend in the values of dissipation factor was also observed in all capacitors (even in the capacitors that did not fail). A gradual increase in the value of dissipation factor (not leading to failure by the dissipation factor failure criterion) seems to be an effect of temperature and voltage aging. The reason for this gradual increase was not investigated since it did not lead to failure.

![Figure 7: Fluctuation in the Values of Dissipation Factor before Insulation Resistance Failures](image)

It is clear that both mean and variance of dissipation factor changed with time. The shift in mean is not expected to be a precursor to insulation resistance failure since this shift is common to all capacitors including the non-failed capacitors. Hence, the increase in variance before the insulation resistance failure was evaluated as a possible failure precursor. In order to separate the mean and variance shift, the first derivative of the dissipation factor was calculated according to the following formula:

\[
\left[ \frac{d(DF)}{dt} \right]_i = \frac{DF_{i+1} - DF_i}{\Delta t}; \quad i = 1, 2, 3, ..., 499
\]  

(1)

where \(DF\) is the dissipation factor, \(t\) is the time, \(i\) is the time stamp or index, and the value of \(\Delta t\) is equal to 1 hr, which was the measurement interval. A plot of first derivative of dissipation factor for the same capacitor (as shown in Figure 7) is shown in Figure 8. A statistical tool known as the sequential probability ratio test (SPRT) was utilized to detect a shift in the variance of dissipation factor before insulation resistance failure. The use of SPRT in prognostics of electronic components has already been demonstrated [15][16].
Sequential Probability Ratio Test (SPRT): The SPRT is a statistical hypothesis test that determines whether or not the test data falls into the probability density distribution of the training data that serves as a base line [17]. The SPRT detects changes in mean and variance of the test data by means of a statistical test in which null and alternative hypotheses are compared with each other. The null hypothesis is where the test data is a normal distribution with a mean of 0 and a variance of $\sigma^2$ which is extracted from the training data set. There are four alternative hypotheses that represent the abnormal test data and are known as: the positive mean test, the negative mean test, the normal variance test, and the inverse variance test, which are explained in Table 2. The value of $M$ and $V$ has to be determined by the user.

![Figure 8: Derivative of Dissipation Factor](image)

Table 2: Null and Alternative Hypotheses for SPRT

<table>
<thead>
<tr>
<th>Alternative hypotheses</th>
<th>Mean</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Null hypothesis ($H_0$)</td>
<td>0</td>
<td>$\sigma^2$</td>
</tr>
<tr>
<td>Positive mean test</td>
<td>$+M$</td>
<td>$\sigma^2$</td>
</tr>
<tr>
<td>Negative mean test</td>
<td>$-M$</td>
<td>$\sigma^2$</td>
</tr>
<tr>
<td>Normal variance test</td>
<td>0</td>
<td>$\sqrt{\sigma^2}$</td>
</tr>
<tr>
<td>Inverse variance test</td>
<td>0</td>
<td>$\sigma/\sqrt{V}$</td>
</tr>
</tbody>
</table>

In statistical hypothesis testing it is necessary to define the probabilities of committing errors. While accepting or rejecting the null hypothesis ($H_0$), it is possible to perform two types of errors: rejecting $H_0$ when it is actually true (type I error) and accepting $H_0$ when it is actually false (type II error) [17]. The type I error is denoted as $\alpha$ and is known as the false alarm probability or size of the critical region. The type II error is denoted by $\beta$ and is known as the missed alarm probability and $(1-\beta)$ is called power of the critical region.

In the current case, since the variance of dissipation factor is increasing, only the normal variance test is conducted. The normal variance test evaluates whether the variance of the test data is shifted by $V$ in the positive direction, which is expected to be an indication that the embedded capacitor is degrading. After application of the Neyman-Pearson method (which determines the alarm criteria) [18], the criterion for SPRT alarm is given by the following equation:

$$\sum_{i=1}^{n} \frac{x_i^2}{2 \sigma^2} \left(1 - \frac{1}{V}\right) - \left(\frac{n}{2}\right) \ln V \geq \ln \left(\frac{1-\beta}{\alpha}\right)$$

(2)
Application of SPRT to Temperature and Voltage Aging Data: For the application of SPRT to the derivative of dissipation factor data the training period was selected as 25 data points out of a total of 499 data points. Capacitors that failed during the initial training period were excluded from this analysis. The excluded capacitors included 7 small capacitors (group A). In addition to this, 2 small capacitors (group A) that did not fail during the 500 hrs of aging were also excluded. Finally the total number of capacitors on which SPRT was applied was 24 small capacitors (group A).

It was observed that changing the values of $\alpha$ and $\beta$ (that changed the alarm thresholds) did not affect the time-to-first SPRT alarm. This non-dependence was due to a higher value of SPRT index (by at least an order of magnitude) than the alarm threshold. The value of $\alpha$ and $\beta$ was selected as 0.001. The time-to-first SPRT alarm did depend on the value of the variance factor, $V$, so an optimum value of $V$ was determined for these capacitors. The value of $V$ should be positive and not equal to 1. The value of $V$ was varied from 1.1 to 10 in steps of 0.1 and the time for the first SPRT alarm was recorded for each value of $V$.

The methodology of SPRT is explained using the data of the capacitor that is shown in Figure 7. The effect of variance factor ($V$) on the time-to-first SPRT alarm is shown in Figure 9. It is clear from the figure that SPRT was able to provide an early warning of the failure (that actually took place at 292 hrs) for all values of variance factor (between 1.1 and 10).

![Figure 9: The effect of Variance Factor ($V$) on the Time-to-First Alarm for One Capacitor](image)
The value of SPRT index and SPRT alarms for the same capacitor (whose data is shown in Figure 7) is shown in Figure 10 and Figure 11 respectively (at a value of $V=10$). It can be seen than whenever the value of SPRT index is greater than the alarm threshold, there is a corresponding alarm. The alarms are however not continuous since the SPRT index was reset after each alarm. Since the fluctuations in the dissipation factor continued, the SPRT index again became greater than the alarm threshold and the alarm was triggered again.

**Observations and Discussions:** SPRT was applied to all 24 small capacitors (group A) and it was observed that SPRT detected failures in advance in 8 out of 24 capacitors. The values of the SPRT alarm time corresponding to the two extreme values of variance factor (1.1 and 10) are summarized in Table 3. It can be seen that in some capacitors, SPRT was not able to detect failures in advance when the value of variance factor was 10. This implies that for the current system the value of variance factor should be close to 1. It should be noted that bringing the value of variance factor too close to 1 might lead to false alarms.
Table 3. SPRT Alarm Time at the Two Extreme Values of Variance Factor (V)

<table>
<thead>
<tr>
<th></th>
<th>Actual TTF (hrs)</th>
<th>SPRT Alarm time (hr)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>V=1.1</td>
</tr>
<tr>
<td>1</td>
<td>292</td>
<td>252</td>
</tr>
<tr>
<td>2</td>
<td>410</td>
<td>301</td>
</tr>
<tr>
<td>3</td>
<td>497</td>
<td>310</td>
</tr>
<tr>
<td>4</td>
<td>383</td>
<td>203</td>
</tr>
<tr>
<td>5</td>
<td>477</td>
<td>427</td>
</tr>
<tr>
<td>6</td>
<td>233</td>
<td>198</td>
</tr>
<tr>
<td>7</td>
<td>362</td>
<td>148</td>
</tr>
<tr>
<td>8</td>
<td>172</td>
<td>147</td>
</tr>
</tbody>
</table>

SPRT was not able to detect failures in all 24 capacitors. The reason for this was investigated using statistical techniques. Statistical analysis was performed on the time-to-failure data of small capacitors (group A) using Weibull software. It was observed that failures followed two different distributions, which are designated as mode I and mode II failures. A mixed Weibull distribution was applied as shown in Figure 12. It was observed that most of the failures that were detected in advance by SPRT belonged to mode II. The values of parameters of the Weibull 2 parameter distribution were obtained for mode I ($\beta=1$ and $\eta=130$) and mode II ($\beta=6$ and $\eta=444$) failures (where $\beta$ is the shape parameter and $\eta$ is the scale parameter of the distribution). The mechanism of failure of these two failure modes appears to be different based on the difference in their $\beta$ values. From the values of $\beta$ it is observed that mode I failures have a constant hazard rate whereas mode II failures are in the increasing hazard rate region of the bathtub curve, which is a characteristic of wearout failures.

![Figure 12: Unreliability versus Time for Small Capacitors (group A)](image)

**Conclusions:** A new technique has been developed that can be used to predict avalanche breakdown in embedded planar capacitors. This failure mode was observed during accelerated temperature and voltage aging and was observed as a sharp drop in the value of insulation resistance after avalanche breakdown. Prediction of this failure was difficult
since there was no trend in the values of insulation resistance before failure. However, it was found that a failure precursor to avalanche breakdown was an increase in the variance of the dissipation factor. The sequential probability ratio test (SPRT) was applied to the dissipation factor data to perform early detection of these failures.

It was observed that SPRT was able to detect failures in advance in only a fraction of the total failures. Statistical analysis of these failures revealed two failure distributions, with a constant hazard rate (random failures) and an increasing hazard rate (wearout failures). SPRT was able to detect failures in advance in only the wearout failures. Future research in this area will focus on devising a methodology that can address random failures also and developing a monitoring setup that can be integrated on a PWB to perform early detection of these failures.

References:


