Failure Precursors for Polymer Resettable Fuses

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***Abstract*—Resettable fuses have been widely used in overcurrent or overtemperature circuit protection designs in computers, automotive circuits, telecommunications equipment, and medical devices. Abnormal behavior of a resettable fuse can damage a circuit. This paper identifies and experimentally assesses the failure precursor parameters of a polymer positive temperature coefficient resettable fuse. It is shown that the degradation of the resettable fuse can be monitored, detected, and predicted based on the monitoring of these precursor parameters.**

***Index Terms*—Failure modes, mechanisms, and effects analysis (FMMEA), failure precursors, polymer positive temperature coefficient (PPTC), prognostics and health management (PHM), resettable fuse, trip.**

I. Introduction

As A CIRCUIT protection device, polymer positive temperature coefficient (PPTC) resettable fuses are widely used in automotive circuits (e.g., the protection of micromotors in window lifts, seats, and door locks), computers (e.g., the protection of the circuits in hard disk drives, interface ports, and cooling fan motors), telecommunication devices (e.g., cell phones), battery packs, power supplies, medical electronics, and so on. The failure or abnormal behavior of PPTC devices may cause damage to circuits, abnormal operation of circuits (e.g., inability to work at normal current), or unnecessary operations that force operators to switch off and on the power to reset the circuit.

Implementing prognostics and health management (PHM) for PPTC resettable fuses can reduce the damage, unnecessary operation, maintenance, and downtime of a product, thereby improving its reliability and reducing its cost. PHM is an enabling discipline consisting of technologies and methods that have the potential to solve reliability problems manifested due to complexities in design, manufacturing, environmental and operational conditions, and maintenance [1]–[3]. PHM integrates sensor data [4], [5] with models [1]–[3], [8]–[10] that enable *in situ* assessment of the deviation or degradation of a product from an expected normal operating condition (i.e., a "healthy" system) as well as assessment of the future reliability of the product based on current and historic conditions [6]. PHM can provide advance warning of failures; reduce the life cycle cost of a product by decreasing inspection costs, downtime, and inventory; and assist in the design and logistical support of fielded and future products [2].

No prior studies have reported on the *in situ* monitoring and prognostics of failures of PPTC resettable fuses in actual applications. In this paper, the potential failure precursor parameters, which are indicative of an impending failure [1], are identified by a systematic method: failure modes, mechanisms, and effects analysis (FMMEA). A series of experimental tests is conducted to verify the precursors. The monitoring of these precursor parameters will enable the implementation of a prognostics methodology that will involve trending precursor data and combining physics-of-failure models to predict the remaining useful life (RUL) of PPTC resettable fuses.

II. Potential Failure Precursor Parameters of PPTC Resettable Fuses

A PPTC resettable fuse can "trip" from its normal operational state of low resistance to high resistance in a short time when overheated by ambient heat or the Joule heat generated by high current. It can reset to its normal operational state of low resistance when the heat is removed and/or the power is switched off. Fig. 1 shows its operational process. Under a normal ambient temperature, the fuse works in a low-resistance state (like a wire) when the normal current (less than the hold current I_{hold} which is the maximum steady-state current that the PPTC device can carry without tripping at the ambient temperature) passes through it. When a fault current (higher than the trip current I_{trip} which is the minimum current that causes a PPTC device to trip at the ambient temperature) occurs, the resistance of the fuse increases sharply. Because of the sharp increase in resistance, the PPTC fuse will decrease the current to protect the circuit. A sharp increase in resistance is called a trip. After the trip, a PPTC resettable fuse does not break as does a traditional fuse. Instead, it keeps the high-resistance state and allows a small trickle current to pass through the circuit. The fuse will reset to a low-resistance state after a short time when the heat or fault current is removed and/or the power is switched off [11].

Typically, the hold current is half of the trip current [11]. When the current is higher than the trip current, the fuse will trip. When the current is lower than the hold current, the fuse will not trip. When the current is between the hold current and the trip current, the fuse may or may not trip [12]. Trip time is the time required for a PPTC fuse to decrease the current

Manuscript received December 15, 2009; revised April 29, 2010; accepted June 3, 2010. Date of publication June 21, 2010; date of current version September 9, 2010. This work was supported in part by the U.S. Army Research Laboratory and in part by NASA.

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Digital Object Identifier 10.1109/TDMR.2010.2053371

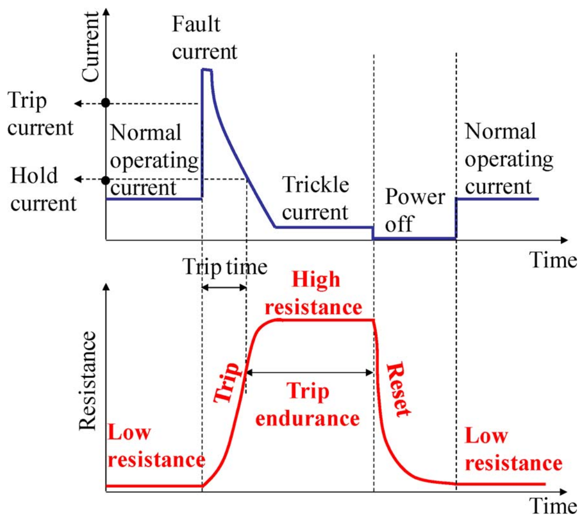


Fig. 1. Operational process of PPTC resettable fuse.

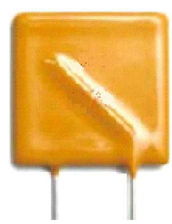


Fig. 2. Photograph of a radial through-hole PPTC resettable fuse.

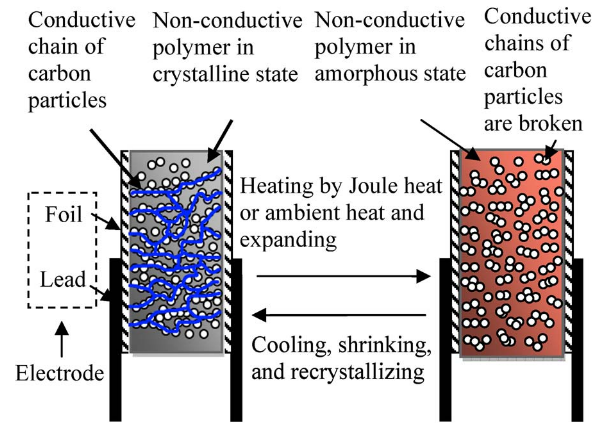


Fig. 3. Conductive chain and thermal expansion model.

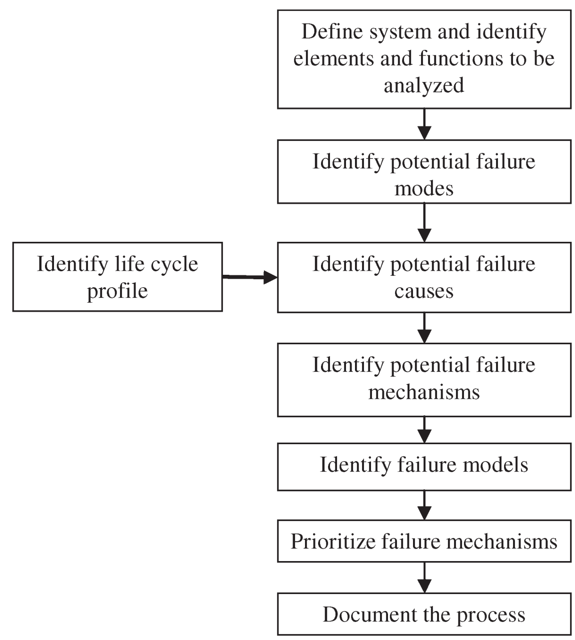


Fig. 4. FMMEA process.

of the circuit to I_{hold} at ambient temperature [11], [12]. After a number of trip-reset cycles caused by current or ambient temperature, the PPTC resettable fuse will degrade, and failures will occur.

In this paper, a radial through-hole PPTC resettable fuse, as shown in Fig. 2, is used as an example of a resettable fuse to show the internal materials and structures. Fig. 3 shows a schematic cross-sectional image. In general, radial through-hole PPTC fuses include conductive polymer composites, electrodes, and outside packages [12]. Conductive polymer composite is generally manufactured as a thin sheet and consists of nonconductive polymer (e.g., polyethylene) and conductive particles (e.g., carbon black). An electrode is used to conduct and control the flow of electricity and is typically composed of foils and leads. The foils are attached on both sides of the polymer sheet. One lead is connected to a foil by soldering. The dielectric material provides protection for the outside of the device.

There is no comprehensive theory describing the PPTC phenomenon, although many researchers have tried to derive one [13]. A conductive chain and thermal expansion model, shown in Fig. 3, is a common model for explaining the physical mechanisms of the PPTC phenomenon [13]–[18]. Conductive particles in the polymer composite at normal temperatures form many conductive paths that allow current to pass through the fuses without interruption. However, if the temperature rises above the device's switching temperature, either from Joule heat generated by high current or from ambient heat, the polymer changes its crystalline state to an amorphous state. The expansion in volume during the phase change breaks most of the conductive paths. This results in a sharp nonlinear increase in the resistance of the device. This increased resistance protects the components in the circuit by reducing the amount of current. When the fault current or high ambient temperature is removed and/or the power is switched off, the polymer starts cooling, recrystallizing, shrinking, and restoring the device to a low-resistance state.

FMMEA is a methodology used to identify critical failure mechanisms and models for all potential failure modes of a product under its operational and environmental conditions [19]–[21]. Potential failure modes and mechanisms help to identify the precursor parameters to be monitored and the relevant physics-of-failure models to predict RUL. Fig. 4 shows a schematic diagram of FMMEA.

Table I shows the FMMEA of the radial through-hole PPTC resettable fuse shown in Fig. 2. Potential failure modes include abnormal trip behavior, shifts in parameters, and physical cracks and separations. The failure criteria should be defined based on related standards, specifications, and customers' requirements. In this paper, a failure is defined as any of the following.

TABLE I
FMMEA FOR PPTC RESETTABLE FUSES (STRUCTURED AS IN FIG. 3)

Potential Failure Sites	Potential Failure Modes	Potential Failure Causes	Potential Failure Mechanisms
Conductive polymer composite	Abnormal trip behavior (e.g., trip at normal current, no trip at fault current)	Environmental and operational conditions (e.g., trip and reset cycling, thermal cycling, and moisture) and manufacturing defects	Degradation of the polymer composite
Connection between foil and polymer composite	Cracks and shift in resistance and surface temperature		Electro-migration, fatigue, and corrosion
Solder between lead and foil	Open, cracks, and shift in resistance		Fatigue and corrosion
Outside package	Cracks, separation with foil, shift in surface temperature		Fatigue and deformation

1) Fuse trips at normal current $(\leq I_{\rm hold})$ at the specific ambient temperature.
2) Fuse does not trip at fault current $(\geq I_{\rm trip})$ at the specific ambient temperature.
3) Deviations in the fuse trip time impact the typical operations of the circuit. The criterion of failure in terms of trip time is application dependent. A trip in a longer time increases the risk of damage to the circuit because of the longer exposure of the circuit to a high fault current. A shorter trip time also makes the circuit more likely to be disturbed by noisy currents, which may result in unnecessary faults in circuit operation. For example, when a motor changes its rotating direction, a high peak current may be generated. If the trip time of the fuse becomes too short, the high peak current will trip the fuse and stop the motor, and the operator must switch off and on the power to reset the fuse.

   In some cases, the designer of a circuit does not consider the reliability issues of the PPTC resettable fuse and therefore does not design sufficient margin for trip time changes. For example, the circuit may be designed to allow a 20-A fault current to pass through the circuit for 3–5 s when the trip time of the selected PPTC fuse is 4 s. If the PPTC resettable fuse degrades, the trip time may become shorter than 3 s or longer than 5 s. If the trip time is shorter than 3 s, it will stop the operation of the circuit even for short peak current noise. If the trip time becomes longer than 5 s, it will damage the components in the circuit.
4) A fuse becomes high in resistance after reset. One effect of the increase in resistance after reset is that it shortens trip time by generating more heat in the same amount of time. The other effect is that an increase in the resistance of the fuse decreases the voltage drops on other components, which may cause abnormal operation of the circuit. If the 1-h posttrip (after resetting for 1 h) resistance at 23 °C $(R_{@23\,^\circ\mathrm{C}})$ is greater than the maximum 1-h posttrip resistance at 23 °C $(R_{1\,\max\,@23\,^\circ\mathrm{C}})$ specified by the manufacturer, the fuse is considered to have failed.
5) Opens or increases in resistance occur at the physical internal connections between different parts of a fuse.
6) Physical cracks, breaks, separations, and/or degradation in the dielectric materials occur in the outside package. Fuses with these types of degradation may still function; however, the internal parts of the fuse will lose protection due to the degradation of the dielectric package. For example, moisture will corrode the electrode more easily. Furthermore, degradation of dielectric materials also causes a safety issue for the operators.

Potential causes of these failures include the degradation of materials caused by trip-reset cycling and environmental conditions, such as ambient temperature (thermal) cycles and moisture. Potential failure mechanisms include the degradation of the polymer composite, electromigration between the metals, fatigue, deformation, and corrosion.

Based on the FMMEA, the following parameters were identified as potential precursors: trip time, resistance, and surface temperature (ST). In actual applications, the current through the fuse, the voltage across the fuse, and the ST of the fuse can be monitored. Trip time can be calculated by the difference between the time when the fault current occurs and the time when the current decreases to the hold current [11]. The resistance of the fuse can be calculated by the current and voltage when the current is passing through the fuse. Trip cycle and thermal cycle tests were conducted to verify the failure precursors.

III. TRIP CYCLE TEST

The objective of the trip cycle test is to determine whether the trip time, current, resistance, and ST are indicators of degradation in PPTC resettable fuses. Referring to the manufacturer's specifications for the fuse, standards, and the requirements of customers, trip cycle tests were conducted for at least 6000 cycles at −10 °C, 23 °C, and 40 °C, respectively. Four samples were tested in each condition. In each cycle, current through the fuse, ST, trip time, and resistance in the resetting process (power switched off) of the fuse were monitored.

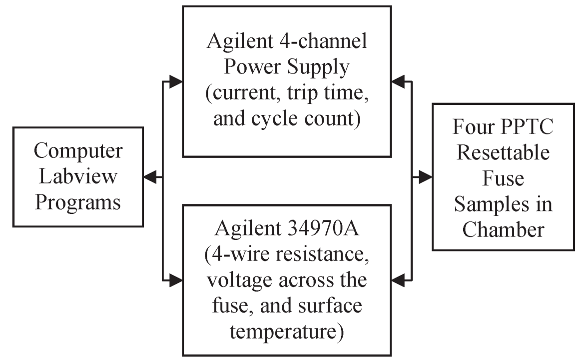


Fig. 5. Trip cycle test setup.

Fig. 5 shows the setup of the trip cycle test. One computer with the Labview program was used to control a four-channel power supply and a data logger. Each channel of the power supply provided power to one PPTC fuse. The fuses were placed inside a temperature chamber to perform the trip cycle test

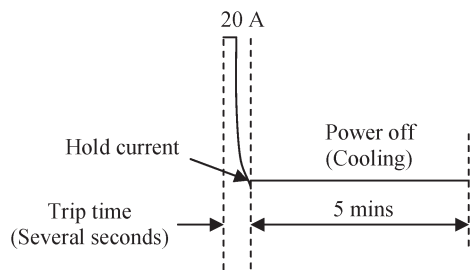


Fig. 6. Current profile in one trip cycle (current versus time).

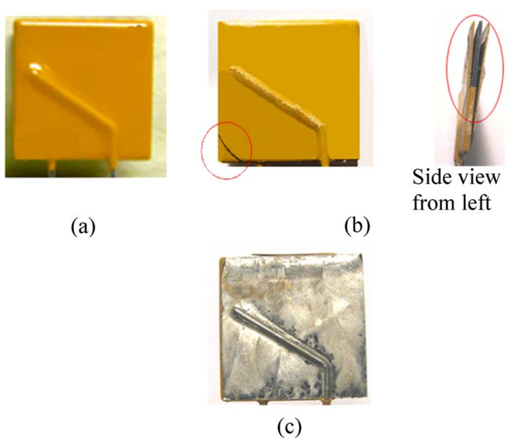


Fig. 7. Photographs of samples. (a) Before test. (b) After 6500 cycles. (c) After 28 000 cycles.

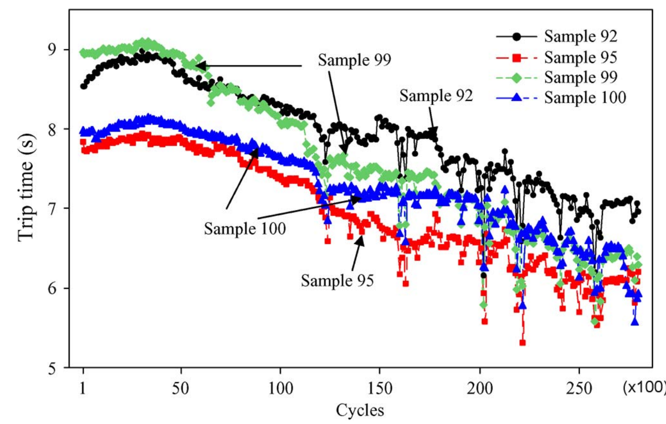


Fig. 8. Trip time decreases with cycles. (Each point is the mean of the trip time of every continuous 100 cycles.)

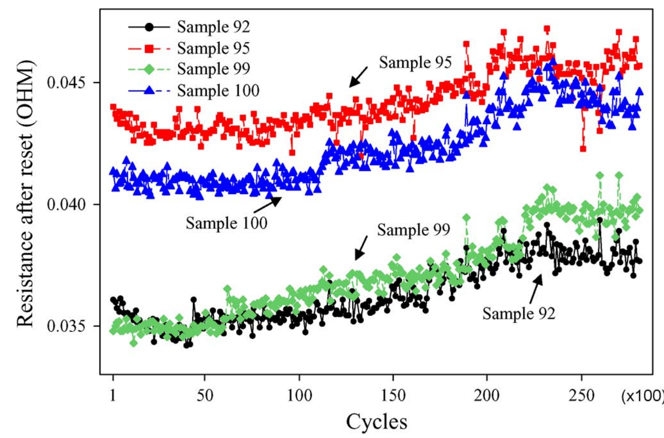


Fig. 9. Resistance after reset increases with cycles. (Each point is the mean of the resistance after reset of every 100 cycles.)

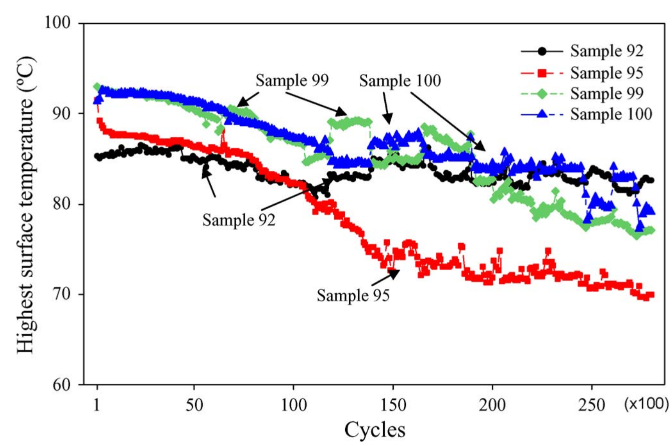


Fig. 10. Highest ST decreases with cycle. (Each point is the mean of the highest ST of every 100 cycles.)

under different temperature conditions. The Labview program recorded the time stamp when the initial high current occurred and the time stamp when the current reduced to the hold current at ambient conditions. Then, the trip time of each trip cycle was calculated. An Agilent 34970A data logger was used to monitor the resistance in the resetting process and the STs of each fuse. A four-wire connection resistance measurement was used to remove the effects of the wire and the connection. The ST was measured by thermal couples. A thermal couple was attached on each side of the fuse; the maximum temperature of these two thermal couples was used to determine the ST of the fuse.

Fig. 6 shows the current profile of one trip cycle. When the power was switched on, a high current was input to the fuse (20 A in this experiment, which was more than five times the hold current at ambient temperature conditions [11]). The fuse was heated by Joule heat and tripped to a high-resistance state in several seconds. When the current reduced to the hold current at the environmental temperature, the power was switched off for 5 min to cool the fuse and reset it to a low-resistance state.

Similar failure modes were observed in trip cycle tests under different temperature conditions, including cracks on the dielectric package and shifts in parameters, such as trip time, resistance after reset, and ST. After the trip cycle tests, all samples were still able to trip at the trip current and hold at the hold current. However, the parameters such as the trip time, resistance, and ST were shifting, which indicated the degradation of the fuse.

The test results at 23-°C and 20-A initial input current conditions are shown here as examples. Fig. 7 shows photographs of a fuse before the trip cycle test, after 6500 trip cycles, and after 28 000 trip cycles at 23 °C. Cracks and separations between the package and foil were observed on all the tested fuses. Not all of the samples exhibited complete removal of the protective cover, but the gaps between the foil and package were noted.

Figs. 8–10 show the shifts in trip time, resistance, and ST, respectively, using the data collected at 23 °C. In Fig. 8, trip times of all the tested samples exhibited a decreasing trend. Each point in the figure is the mean trip time of every 100 continuous trip cycles. The trip times in the first

TABLE II
CORRELATION COEFFICIENTS AMONG PARAMETERS AT 23 °C WITH 20-A INPUT CURRENT

	Trip time	Highest surface temperature	Resistance after reset
Trip time	1	0.95	-0.89
Highest surface temperature	0.95	1	-0.86
Resistance after reset	-0.89	-0.86	1

2000 cycles increased because the fuses were unstable. From 2000 to 5000 cycles, the change in trip time was very small. After 5000 cycles, the trip time started to decrease. The trip times from 2000 to 5000 cycles were chosen to create a baseline to define the healthy state of a fuse. This baseline could be used to conduct anomaly detection and define the failure criteria for failure prediction as well. Around 15 000 cycles, trip time decreased by 15% of the baseline. After 28 000 cycles, the trip time decreased by 25% of the baseline.

Fig. 9 shows the changes in resistance after reset with cycles at 23 °C and 20 A. Each point in the figure is the mean resistance after reset of every 100 continuous trip cycles. The resistance after 5000 trips was gradually increasing. However, the change was very small so that it was still in the healthy range defined by the manufacturer (less than $R_{1\,\max @ 23\,^\circ\mathrm{C}}$).

In Fig. 10, the highest STs in different cycles were chosen to investigate the trends in ST with cycles. Each point in the figure is the mean of the highest STs of every continuous 100 trip cycles. A decreasing trend was also shown after 5000 cycles, and the decrease after 28 000 cycles was up to 20% of the baseline ST.

High correlation among three parameters was observed. Table II shows an example of correlations at 23 °C with 20-A input current. These high correlations can enable multivariate analysis algorithms to detect anomalies.

The results show that trip time and the highest ST exhibited obvious decreasing trends after 5000 trip cycles. Resistance after resetting showed a slight increasing trend, but the shifting range was very small and still in the healthy range defined by the manufacturers. Therefore, trip time and highest ST can be used as the precursor parameters of failure caused by trip cycles. Additional experiments, such as the thermal cycle test, were conducted to verify that resistance is a precursor of failure. This will be covered in the next section.

IV. THERMAL CYCLE TEST

Environmental temperature is another factor that influences the operation of a PPTC resettable fuse. The thermal cycle test is used to investigate the effects of environmental temperature cycling. During this test, only resistance is monitored. This test can verify that resistance is a failure precursor parameter.

Based on manufacturer's specifications, standards, and expected application environmental conditions, the temperature range of the thermal cycle test was set from −45 °C to 135 °C. The profile temperature in one cycle is shown in Fig. 11.

During the test, the resistances of 20 fuses were monitored by an Agilent 34970A data logger using a four-wire connection.

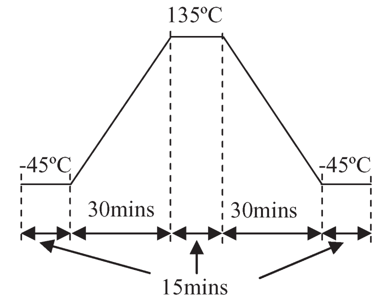


Fig. 11. Temperature cycle profile (temperature versus time).

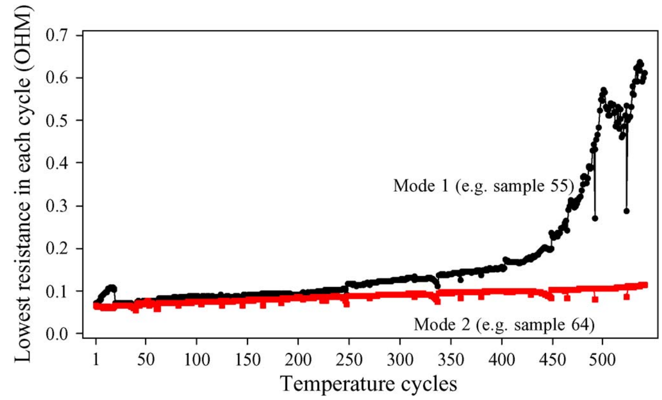


Fig. 12. Two modes of change in the lowest resistances.

TABLE III
INCREASE MODES OF THE LOWEST RESISTANCE

Increase modes of the lowest resistance	Number of samples
Mode 1: exponentially increased	14
Mode 2: linearly increased	6

In each cycle, the lowest resistance of each fuse was analyzed. The failure criterion of the PPTC fuse in terms of the lowest resistance was derived from the failure defined by the manufacturer at 23 °C: The max resistance after resetting for 1 h (max $R_{1@23}$) should be less than 0.08 Ω. Therefore, if the lowest resistances of a fuse in five continuous thermal cycles were higher than 0.08 Ω, the fuse failed. After 540 cycles, only two fuses survived. The changes in the lowest resistances had two main modes: exponentially increased and linearly increased, as shown in Fig. 12 using two typical samples. Table III shows the number of samples that belong to different modes.

In order to understand more about the resistance change of a fuse with an increase in the number of thermal cycles, the highest resistance in each cycle was also analyzed. Three different change modes of the highest resistances were observed, as shown in Fig. 13. These modes were classified as decreased exponentially, decreased and recovering, and decreased and recovered to a typical state. Table IV shows the number of samples that belong to different change modes.

V. DISCUSSION AND CONCLUSION

From the experimental results, the precursors to failure caused by the trip cycle include trip time and ST. The parameter

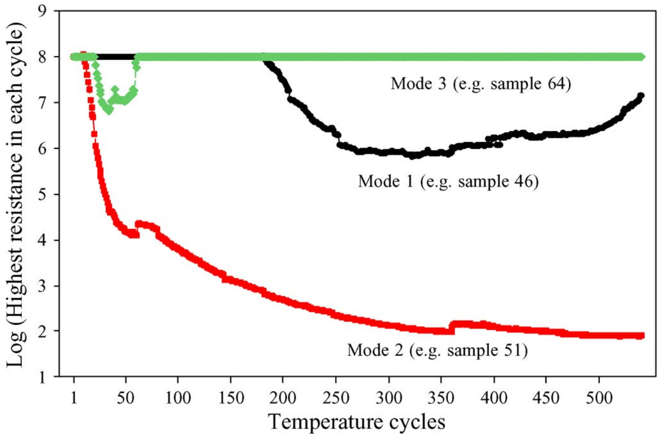


Fig. 13. Three modes of change of the highest resistances.

TABLE IV
MODES OF THE HIGHEST RESISTANCE CHANGES

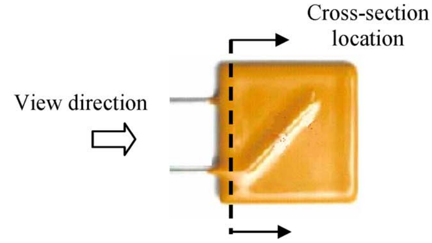
Decrease modes of the highest resistance	Number of samples
Mode 1: decreased and recovering	10
Mode 2: exponentially decreased	5
Mode 3: decreased and recovered back to typical state	5

"resistance after reset in the trip cycle" increased slightly during the tests and was still in the healthy range defined by the manufacturer. High correlation was observed among these parameters. These high correlations can enable multivariate analysis algorithms to detect the anomalies and predict the failures.

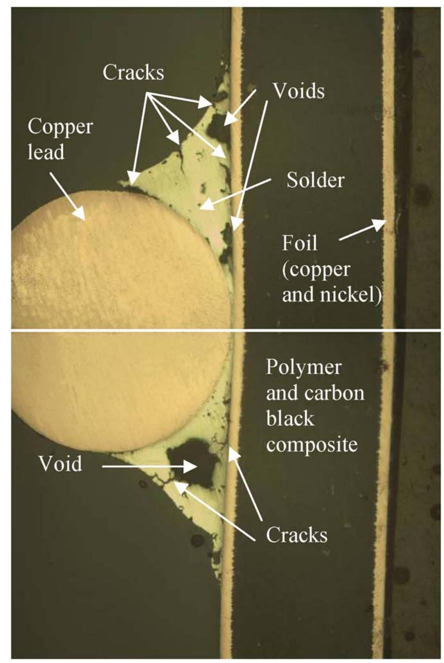
In the thermal cycle tests, resistance changed in different modes, which could indicate different failure modes and mechanisms. In actual applications, failures of PPTC fuses are caused by a combination of trip cycles and thermal cycles. The precursors of failures of a PPTC fuse therefore include all three of these parameters.

The decrease in trip time may be caused by an increase in the resistance after reset. More Joule heat is generated when the same amount of current passes through the resettable fuse. It will decrease the time needed for temperature to exceed the switch temperature of the polymer composite. The decrease of the ST may be the result of a combination of a decrease in high resistance at high temperature and the gaps at the interfaces among different parts, including the carbon particle-filled composite sheets, foils, and the package.

One of the main causes of the increase in resistance is the degradation of the carbon black particle-filled polymer composite due to changes associated with the size of the carbon black particles, the distribution of the carbon black particles, and the structures of the polymer. In a normal case, the polymer in the composite will change from a crystalline state to an amorphous state and then reset back to a crystalline state. However, after many thermal cycles, the polymer may not recrystallize to its crystalline state as normal, thereby reducing the conductive pathways and increasing the resistance.



(a)



(b)

Fig. 14. Optical microscopy photographs of solder. (a) Cross-sectional location and view direction. (b) Cracks and voids in the solder.

Other causes that lead to an increase in resistance are the cracks and voids in the connections among different parts of the fuse, such as the solder between the lead and foil. Fig. 14 shows an optical microscopic photograph of a connection (solder) between the lead and the foil of a sample after thermal cycling. The lowest resistance of this sample increased exponentially, and the highest resistance decreased for a while and then recovered to a high value.

For the decrease in high resistance at high temperatures, the causes may be the combined effects of changes in carbon particle distribution and the degradation of the polymer. Carbon black particles have a tendency to agglomerate [19]; therefore, some conductive pathways are reformed when the polymer is in an amorphous state at a high temperature, which causes a decrease in resistance with an increase in temperature. Current PPTC resettable fuse manufacturers utilize different techniques, such as making the polymer cross-linked [23] to reduce the aggregation of the carbon particles to maintain the high resistance of a PPTC resettable fuse at a high temperature. However, after many cycles, the function of the cross-linked polymer degrades due to the degradation of the polymer, and more carbon black particles may aggregate together to form more conductive pathways to reduce the resistance.

The recovery of the high resistance at high temperatures may be caused by the cracks generated in the interconnections. Further failure analysis is being conducted to identify the root causes of every change mode of the lower resistance and high resistance.

The mapping of the failure mechanisms and changes in the precursor parameters can help in determining the underlying failure mechanisms of a PPTC resettable fuse in its actual applications and in developing a proper model to predict failure. The *in situ* monitoring of precursors enables the development of anomaly detection and prediction algorithms for PHM of a PPTC resettable fuse. Based on these experiments, parameter values from 2000 to 5000 trip cycles can be used to create a baseline for anomaly detection by anomaly detection methods such as neural networks and the sequential probability ratio test. Failure prediction approaches, such as autoregressive integrated moving average and particle filter, can be used to predict failures of resettable fuses.

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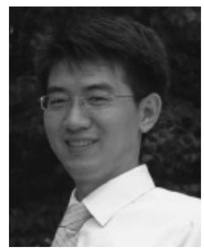

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