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A digital technique for diagnosing interconnect degradation by using digital signal characteristics

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ABSTRACT

Interconnects are responsible for mechanical and electrical connection of electronic components, and they are essential in the operation of electronic components. Stress-induced substances can degrade interconnect properties and functions because they exert stress conditions such as chemical stress to interconnects. Chemical stress from moisture or contaminants causes corrosion to interconnects, and as a result interconnect failures occur in which the interconnects cannot conduct the intended functions. Since interconnect failure disturbs the connection between electronic components, it can cause ensuing failures such as electronic failures. Many approaches have been developed to detect interconnect degradation and prevent ensuing failures. In industrial fields, approaches to detect interconnect failure based on DC resistance have been widely used since DC resistance can capture electrical discontinuity. However, approaches based on DC resistance have a problem because they usually require additional sensing devices or circuitries. This study introduces a new approach to interconnect failure detection using digital signals. The proposed method using digital signals detects interconnect failures without additional sensing devices. Interconnect failure detection can be conducted by monitoring and analyzing the signal characteristics of the transmitted signal because digital signal is continuously generated and transmitted in electronics to control the electronic components and communicate between the components, and also because digital signal is in high-speed, the characteristics of the transmitted digital signal is deteriorated by physical damages on transmitted circuitries such as corrosion on interconnects. We designed accelerated life tests (ALT) of interconnects under chemical stress in order to demonstrate failure detection capability. While solder joints were exposed to chemical stress and corroded gradually, the digital signal characteristics were monitored with DC resistance simultaneously and analyzed by Sequential Probability Ratio Test (SPRT) to determine the times-to-failure of the solder joints. The test results demonstrated that the proposed approach based on digital signal can detect interconnect failures earlier than the DC resistance, which means that the proposed approach can enable electronic components to detect interconnect failures by themselves.

1. Introduction

Electronic systems are usually exposed to stress sources that can induce various stresses such as thermal, mechanical, and chemical stress. Parts of electronics are also affected by stress. In the case of interconnects intended to connect electronic components in electronics, the stress conditions often damage interconnects due to crack or corrosion, which initiates on the surface and propagates inward. When the mechanical and electrical connection of interconnects are deteriorated due to damages, interconnect failures can occur during damage progression. For instance, moisture and contaminants, which are 25% of the stress-induced sources in electronics [1], can exert chemical stress to interconnects in electronics. The chemical stress gradually corrodes interconnects from surface to inward and deteriorates the physical property of interconnects. The failure of interconnects can ultimately cause malfunction and failure of the entire electronics since the interconnect failure leads to electrical discontinuity. Thus, detection of interconnect failure is important and approaches to detect interconnects failure have been developed to avoid the failure of entire electronics.

Monitoring DC resistance is one of the widely used approaches to detect interconnect failure. DC resistance can indicate electrical discontinuity and capture deterioration process prior to complete disconnection [2]. Therefore, in order to prevent electronic failures by detecting interconnect failures, DC resistance has been used as a failure precursor because it tends to deteriorate prior to failure. In previous

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studies of chemical stress experiments, Liu et al. [3] and Mostofizadeh et al. [4] have monitored DC resistance to use it as a failure criterion during salt spray tests on solder joints. As corrosion of the solder joints progresses, electrical discontinuity increases gradually due to exposure of solder joints and causes DC resistance to increase. The experiments using the salt spray test [3,4] determined the failure criterion of solder joints when DC resistance increased over a pre-determined threshold.

However, the approach based on DC resistance often requires additional sensing devices or circuitries such as a data logger or an event detector [2,5]. In order to manage electronics by replacing or repairing failed interconnects, the sensing devices require additional access to interconnect which may disturb operation and management of electronics. Moreover, faster failure sensing is required for the efficient management of electronics in the field. Since electrical continuity scarcely deteriorates at the initial stage under stress conditions, it may be difficult to sense the initial stage of failures, which progresses from the surface of a conductor by using the measurement based on DC resistance. In the case of a chemical stress condition, Mori et al. [6] investigated that the tin in Sn-Ag lead free solder alloy dissolved faster than pure tin when solder joints of tin-based solder alloy were exposed to aqueous sulfuric and nitric acid. The lead free solder alloy is usually used in electronics, however, monitoring based on DC resistance may have difficult to detect the beginning of corrosion. Thus, new approaches are required to detect a solder joint failure more sensitively without installing additional devices or circuitries for efficient management of electronics.

Approaches for sensing interconnect failures have been developed continuously to improve electronics management. Tang et al. [7] used a digital speckle system to monitor strain of solder joints and detect latent solder joint failure during vibration tests. The method can sense the failure with filtered strain data by the spectral kurtosis. Chang et al. [8] applied acoustic emission testing to detect solder joint failure on printed-circuit board. The approach using acoustic emission can detect earlier than monitoring DC resistance during bend tests. The sensitivity of the approach based on DC resistance can be improved by decreasing the monitoring intervals. Qi et al. [9] demonstrated the improved approach based on DC resistance with an oscilloscope during thermal cycling tests of solder joints. However, the existing studies still require additional sensing devices or circuitries.

In order to detect interconnect failures, this study introduces a novel approach based on the skin effect of digital signal that is generated and propagated in electronics. Due to the skin effect, digital signal propagates through the exterior site of the conductor, and can be affected adversely by damages on the exterior site. The approach is based on changes in digital signal characteristics caused by damages of the exterior site of the interconnect. In order to demonstrate the capability of the approach based on digital signal, Accelerated Life Test (ALT) under chemical stress condition was designed to corrode gradually from exterior to interior of interconnects. Sequential Probability Ratio Test (SPRT) was used to determine a failure threshold based on measurements of intact interconnects, demonstrating the capability of digital signal statistically by comparing it with the approach using DC resistance.

2. Method

2.1. Degradation of digital signal

In this paper, The approach based on digital signal characteristics is used to detect failures without installing additional measurement devices because the digital signal is a high speed signal that propagates through electronics. When a high speed signal with several hundred megahertz or more is propagated through the conductor, it is concentrated on the exterior of the conductor due to the skin effect. The skin effect causes variations in electrical density between the exterior and the central part of the conductor since the eddy current from the high speed signal offsets the central current and intensifies the exterior current. The electrical density variation can be represented by the skin depth(δ), which is the depth of a conductor where 63% of currents are transmitted. It is represented in the following equation with the frequency of signal (f).

$$\delta=\sqrt{\frac{\rho}{f\pi\mu}} \tag{1}$$

where ρ and μ denote the conductor resistivity and the material's permeability, respectively. Since higher frequency induces the shallower skin depth, 63% of current is concentrated in shallow layer and propagated with high frequencies. Thus, the transmitted current would be denser with higher frequencies.

In designing a circuit for high speed signals, impedance of transmission lines including interconnects should be controlled precisely to maintain a digital signal integrity during transmission. The impedance of the transmission line may deteriorate due to damages such as corrosion, and it makes a signal reflection on the points where the conductor impedance is deteriorated. Since the signal reflection interferes with the transmission of the digital signal, the signal integrity may be deteriorated, and degradation of the integrity can be accelerated when dense signals are reflected due to the skin effect with high frequencies.

The approach using the skin effect has been studied for interconnect failures. Studies demonstrated the failure detection capability of the skin effect using RF signal under mechanical stress condition [10]. Moreover, failure mechanism was diagnosed by analyzing relative change of RF signal [11], and the remaining useful life of interconnects was predicted based on the prognostic algorithms [12].

On the basis of the studies of interconnect failure sensing using the skin effect, the skin effect by the digital signal was studied to detect interconnect failures under mechanical stress condition [13]. The study applied cyclic shear force to one specimen and measured the digital signal characteristics continuously. Another study indicated that digital signal characteristics were statistically different between intact interconnects and damaged interconnects under thermomechanical stress condition [14]. Based on the repeatability of the statistical difference, the study demonstrated that the digital signal characteristics can detect interconnect failures using the skin effect repeatedly. In our previous study, we also tried to detect interconnect failure by corrosion under chemical stress condition with continuous measurement of digital signal characteristics [15].

2.2. Digital signal characteristics

Degradation of a digital signal integrity can be detected by analyzing the digital signal characteristics. One of the general methods is an eye diagram. The digital signal is a high speed signal that contains information only with a logical zero and a logical one state and, it transits between the two states continuously during transmission. Since the transition is continuous, a digital signal can be represented as a continuous waveform. In order to visualize the continuous waveform as a schematic, the waveform is sampled with a regular unit interval based on clock-based trigger, and it is visualized in a diagram by superimposing the transition edges as shown in Fig. 1. The diagram is named an eye diagram due to its shape and an analysis of the eye diagram consistency indicates the digital signal integrity.

Since the eye diagram is superposition of sampled digital signal based on time and voltage axes, the diagram can be represented by horizontal histogram for time variance or vertical histogram for voltage variance. The eye parameters shown in Fig. 1 are quantitative indices based on statistical characteristics for the histogram. For example, when two horizontal histograms are created across a narrow strip, two means of each histogram represent ‘crossing point’, which provides the eye crossing voltage. When times of the eye crossing points on the