Early-State Crack Detection Method for Heel-Cracks in Wire Bond Interconnects

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Abstract
Reliability of electronic systems is finally limited due to thermo-mechanical fatigue of interconnections. Besides soldered interconnections wire bonding is one of the most commonly used interconnection technology in electronics. Due to thermo-mechanical loading wire bond technology suffers from cracking in the heel region and delamination in the interface. To increase lifetime and lower ecological impact of electronic systems, a condition monitoring concept is needed, which is able to determine the remaining lifetime of an interconnection. The scope of this paper lies in the development of a parameter measurement system for early-state crack detection in the heel region of wire bond interconnections. This parameter measurement system uses signal components generated by cyclic opening and closing of growing cracks. So it becomes possible to determine the remaining lifetime of the interconnection, which is directly connected to the lifetime of the whole system. Furthermore an analytical model is presented, which supports the experimental setup. Measured cracks are investigated by metallographic cross-sectioning of wire bonds and focused ion beam (FIB).

Introduction
Heavy wire bond connections are used in modern power electronic modules e.g. with insulated gate bipolar transistors (IGBT) to conduct the strong electrical currents. These modules are used in traction, power transmission and distribution as well as electro-mobility, often operating under harsh environmental and loading conditions. Nevertheless, lifetimes of about two decades are expected from the industry. The lifetime of power modules is mainly limited due to thermo-mechanical fatigue of electrical connections [1, 2]. Wire bonding of aluminum is still a common interconnection technology in electronics packaging. Due to external loads a wire bond is one weak point in a package. Vibrations or temperature changes can cause relative motion between different components connected via bond wire. There are two main failure mechanisms that lead to loss of electrical conductivity. First, there is the delamination between bond wire and pad (interface), which is commonly known as wire lift-off. The reason therefore lies in mismatch of the coefficient of thermal expansion (CTE) of the used materials. Heel cracking is the second failure mechanism, resulting from thermo-mechanical stresses in the wire due to heat transfer and Joule self-heating. Another reason is cyclic displacement between the two bond pads due to global CTE mismatch and vibration loads [3]. Since the heel of the wire is weakened additionally due to the bonding process, cracks are initiated in this region.

One common way of analyzing electrical conductive connections is to measure the resistance. However, the influence of cracks on the measured resistance only becomes significant if almost the whole connection cross-section is lost [4]. A parameter is needed that behaves differently.

Parameter shift can take place in two different ways (Figure 1). The first way produces sudden failures. By using this kind of parameter, a detection of early degradation states is not possible. The second way of parameter change is a failure due to degradation, where the observed parameter changes continuously until a failure criterion is reached. For detecting interconnect degradation parameters have to be identified that change continuously until failure.

![Figure 1](image.png)

Figure 1. Variants of parameter shift until a failure criterion is reached.

Destructive investigations like shear or pull tests are used to characterize the quality of wire bond interconnections. However, there is no non-destructive, electrical measurement technique available to detect small cracks in bond wires [5].

Concepts of condition monitoring
In the following, different approaches to condition monitoring will be introduced. A distinguishing feature to classify these approaches is based on the relationship they set up between external load, system behavior, parameter shift and failure. The respective relationship for each approach is visualized in block diagrams in Figure 2. Failure is defined as the end of the system’s functionality. This means that at least one parameter or one characteristic function does no longer meet the requirements. To evaluate the condition of the system with regard to an expected failure, these concepts may be applied [6]:

- Methods for measuring important system parameters (Parameter Test Method)
- Methods for estimating the condition by calculation (Life Cycle Unit)
- Methods for monitoring fuses or weak spots in the system (Condition Indicator)
The parameter test method evaluates the shift of constitutive parameters either of the whole system or of single components. For each of these parameters a threshold value is defined as failure criterion. Considering the rate of shift of important parameters, time of failure of the whole system can be predicted. In Built-In-Self-Tests (BIST), a specific version of the parameter test method, voltages and currents occurring in the system are measured and rated. The parameter test method does not work with fast changing parameters (sudden failure). In case of sudden failure, the time of failure cannot be estimated. Furthermore, in complex systems it may be difficult to identify significant parameters that can be used for condition monitoring. A major advantage of the parameter test method is its direct reference to the system’s function. Even with complex relationships between external loads, failure mechanism and parameter shift, condition evaluation may be achieved. The challenge is to identify suitable parameters for life time prediction. Therefore, slight shifts of these parameters must be recognizable long before the system fails.

The concept of Life Cycle Units uses sensors to measure relevant environmental loads continuously. The system’s life time is predicted applying previously defined failure models to the measured data. Application areas for Life Cycle Units are limited by their need for relatively complex infrastructure. Therefore, reasonable applications are condition monitoring of high-value systems and the monitoring of systems that already include most of the required hardware in their functional design. In such cases models for condition monitoring can be added for synergetic use of the existing hardware. Possible applications are control units in the aviation, train and automobile sectors.

The concept of Condition Indicators uses so called monitoring structures. The condition (working / failed) of these monitoring structures is periodically evaluated by a monitoring circuitry. A Condition Indicator consists of monitoring structures, monitoring circuitry and the algorithm to evaluate the system’s condition. The monitoring structures can be seen as “fuses” or “early warning system”. Knowledge about their condition can be used to predict the time to failure of the complete system. The monitoring structures are built in a similar technology as the weakest component of the monitored system. For this purpose the system’s most critical external loads, e.g. temperature cycles, high temperature, vibration or humidity must be identified. After identifying the weakest functional component, a suitable failure model for its technology is defined. The monitoring structures should be designed as simple as possible but close to the weakest component’s technology. According to the scalable sensitivity parameters of the failure model, the predicted life time of these structures is defined shorter than the life time of the functional structure so that each monitoring structure has a dedicated life time.

Concentrating of wire bond interconnections only the concept of parameter measurement is usable for a detection of small cracks at the early degradation state. The other two concepts are only suitable for system monitoring, but not monitoring of individual components.

Analytical modeling of growing heel cracks

Investigations of cracked heel areas in wire bonds show always cracks at the top and bottom of the heel. They start from the surface and grow towards the center of the wire cross-section. Finite element analysis shows two areas in the heel region of plastic deformation due to bending during the bond process. One area is at the top of the wire, the other at the bottom [7].

One way of modeling cracks in interconnections analytically is to use rectangular shapes. Then, the depth of the interconnection plays a subordinate role. The main advantage is an easy understanding of the influence of the crack concerning electrical conductivity and parameter variations. The basis for modeling is shown in Figure 3. Here are h the height of the investigated interconnection, a the assumed height of a crack, w the width, d the depth of the interconnection and finally z the length of the crack consisting of the two parts x and y that are not necessarily equal. The arrow shows the direction of the mechanical cyclic load. With growing x and y the crack growth is modeled, which reduces the overall cross-section of the interconnection. The shape of the wire is here for the benefit of simple mathematical description set as rectangular.

When cyclic mechanical loads are applied the two cracks are closed an opened alternating, so that the cross-sectional area of the interconnection is always smaller than in the initial non-cracked state. Knowing that the electrical resistance is not sensitive enough for detecting the difference between these

**Figure 2.** Three condition monitoring concepts consisting of parameter build-in self-test (BIST), condition indicator and life cycle unit.

**Figure 3.** Model of a wire bond interconnection for analytical consideration.
two states, the difference between two loading conditions is modeled as resistance difference because of higher sensitivity by removing the influence of the intact interconnect region. Referring to Figure 3 there are two main areas of the electrical resistance. The first is defined by the two intact areas with height $h-a$ and the second is the defective area with height $a$. The sum of both parts gives the resulting electrical resistance.

$$R = R_{\text{intact}} + R_{\text{defect}}$$

(1)

$R_{\text{intact}}$ can be seen as constant because it is not affected by the crack and therefore not changing. With resistivity $\rho$, the resistance can be calculated as follows.

$$R_{\text{intact}} = \frac{\rho}{d} [h - a]$$

(2)

For calculating $R_{\text{defect}}$, three load states have to be distinguished. If the partial crack with length $x$ is closed ideally by bending the model virtually to the left, $R_{\text{defect}_1}$ consists of height $a$ and cross-section $d(w-y)$. If the model is straight as seen in the figure $R_{\text{defect}_2}$ has height $a$ and cross-section $d(w-z)$ and finally in the case of closed partial crack $y$, $R_{\text{defect}_3}$ has the same height and $d(w-x)$ as cross-sectional area. In the following we calculate the difference between $R_{\text{defect}_3}$ and $R_{\text{defect}_1}$ and define it as $\Delta R$. The overall crack depth is always $z$ the sum of $x$ and $y$.

$$\Delta R = R_{\text{defect}_3} - R_{\text{defect}_1} = \frac{\rho}{d} [\frac{1}{w-z+y} - \frac{1}{w-x-z}]$$

(3)

Assuming that there is a tiny crack at the beginning and $x$ and $y$ grow with different velocities as it is very likely in field use, $\Delta R$ is expected not only to rise, but to fall slightly until $z$ is dominating the behavior. Additionally equation [3] is independent from the height $h$ and has the resistivity, crack height and depth of the interconnection as factor.

The propagation of the crack $z$ can be modeled with three parts. The first part gives the initial tiny crack that appears at an arbitrary point in the lifetime of the interconnection. Only one of the two variables ($x$ or $y$) behaves like this. In the discussed case $x$ has an initial, fast growing behavior. It is here assumed to happen at the beginning of the consideration. Part two consists of rising $x$ and $y$. To confirm the model, the case is considered when both partial cracks have the same length with different crack propagation velocities. In the third part one of both partial cracks dominates the resistance change usually by causing a lift-off and loss of electrical and mechanical connection.

The following Figure 4 shows all these parts and the calculated $\Delta R$ as given from the model in equation 3. The values are normalized in order to discuss the dependent behavior of the parameters. In the figure the mentioned case is shown, where $x$ and $y$ have the same value at 80 % constriction.

The green dashed line expresses the partial crack length $x$ and the pink dotted line the partial crack length $y$. The first is assumed to grow linearly with low increase in depth, after the initial cracking has taken place. Finally, $x$ dominates the cracking behavior by higher rise. The second crack part $y$ starts at about 20 % reduced cross-section to grow exponentially until 80 % of reduced cross-section and stops growing at this point. The sum of both parts is shown as $z$ with the blue dash-dotted curve. Both, $x$ and $y$ are modeled in a simple way to show the behavior of the model and explain later on the experimentally observed signals.

![Figure 4](image)

**Figure 4.** Development of crack parameters and resistance difference plotted over crack depth $z$.

Which one of both parts is growing faster than the other or dominating the cracking behavior does not matter because of the sums in equation 3. The resulting difference in resistance $\Delta R$ is shown in the red curve. It jumps to a detectable value at the beginning and is almost constant in the wide range until 80 %. Depending on the behavior of the two parts of $z$, the difference in resistance is even falling, as shown between about 40 and 80 %. As expected the value of $\Delta R$ becomes zero when $x$ equals $y$. This behavior is not dependent on the individual way of crack propagation in $x$ and $y$. Even if they are growing linearly, $\Delta R$ is decreasing. These considerations are necessary to explain the experimental observations and the cross-sections of the wires later on.

**Experiment**

**Mechanical setup:**

The experiment is set up on a piezo actuator that is used for bending the wire. This movement simulates a cyclic displacement between the two bond pads, which occurs in power devices. For the experiment, one wire is bonded between two printed circuit test boards (Figure 5). As wire material aluminum is used with a diameter of 300 µm. The wires are bonded with loop factor 15.

![Figure 5](image)

**Figure 5.** Mechanical setup for degrading wire bonds.
First tests revealed that this thickness lead to a maximum lifetime of about 4000 cycles with a cycle frequency $f_1$ of 1 Hz and cyclic displacement of 70 µm. This setup is suitable for keeping the test time short by not generating too fast degradation. The displacement of the actuator follows a sinusoidal function. As a consequence of controlling the displacement, it is force independent. Due to the displacement, the maximal stress level is localized in the two heel areas.

**Electrical setup:**

For measuring the $\Delta R$ as part of a modulated signal a lock-in voltmeter is used. A current of 0.5 A is applied on the bond wire as basis for the modulation. A 4-wire setup was structured with the lock-in voltmeter and the current source. By stimulating the wire with the piezo actuator at frequency $f_1=1$ Hz, the resistance $R$ changes in the case of a present crack at the same frequency. The difference between the above discussed cases is modulated as signal to the frequency of the stimulation as $\Delta R$. The lock-in voltmeter acts as extremely narrow band-pass filter. The stimulation frequency is provided as a reference for the center frequency of the filter. The measurement setup is shown in Figure 6.

![Figure 6. Measurement setup for detecting small cracks in wire bonds.](image)

In the experiment, a digital-signal-processor-based dual-phase lock-in voltmeter is used. The phase difference between stimulation and reference signal is constant; nevertheless a single-channel lock-in amplifier could be used instead. The direct current through the bond wire causes a voltage drop. As a modulation base, this direct current offset is needed, but for the lock-in amplifier it is disadvantageous. A high-pass filter is set to a frequency of 0.2 Hz to suppress the non-alternating signal components. It avoids the following gain stage from being overdriven and allows a high pre-amplifier gain of 78 db. This setup results in a maximum input voltage of 2.5 µV at the stimulating frequency. The time constant of the lock-in voltmeter acts reciprocally to its bandwidth. So, 5 s time constant is chosen to realize an adequately smoothing to the output and reach high accuracy. Experiments are made without mechanical stimulation to widely exclude wrong results caused by slowly drifting equipment. The drift of the test equipment is lower than 2.5 nV in a period of 10 hours, which is less than 0.1 % of the full scale.

**Results**

Since the output signal of the lock-in voltmeter expresses the amplitude of the sinusoidal changing resistance difference, it expresses the condition of the wire bond very well. In the measurement, signal amplitudes around 1 µV are expected. For measurement, four equally bonded wires are used. To investigate the crack depths and validate the presented model, the degradation is stopped at different stages beginning at 488 cycles over 686 and 1257 till 3293 cycles. The results are shown in Figure 7. The first thing that is noteworthy is a good reproducibility of different experiments. At the beginning, there is always a small region with an instant rise to about 0.45 µV. The section with falling signal can be observed at all four curves. A change in behavior takes place after 2500 cycles. Now the crack growth dominates the behavior of the signal, leading to sudden failure. The spikes in the blue dotted curve show sudden opening and closing directly before the sudden failure.

![Figure 7. Measured cyclic resistance difference, expressing the condition of the investigated wire bond interconnection.](image)

The falling curves can be explained by different crack-growth velocities of the two parts in $z$ (Figure 3). One commonly used failure threshold is a signal rise of 20 % according to e.g. IPC 9701A. This threshold, beginning at the first maximum of the signals, limits the useful lifetime of the investigated bond wire to 2750 cycles. The falling signal curves can be used for an estimation of the remaining lifetime. Defining a threshold of 90 % of the initial maximum, gives a reproducible point in time where about 50 % of lifetime remains. Every other definition shifts this value in time. If the minimum at about 2450 cycles is reached and the signal begins to rise, only 10 % of lifetime remains until a failure occurs. This point can be used as last and most urgent indicator for replacing a monitored system.

To correlate the resulting crack depths with the measured signals, cross-sections of the heel regions are made. Due to not perfect symmetry of the wires, the side with more plastic deformation from the bond process fails first. As shown in Figure 7 the wire with more than 3000 load cycles has no longer electrical contact. So only three wires are cross-sectioned and investigated by optical analysis. Figure 8 shows the three wires. From left to right the wires with 488, 868 and 1257 cycles are shown. As expected the cracks in the heel region are growing.
Further FIB investigations show larger crack lengths as optically observed. Figure 9 shows that the crack depth is more than twice as deep as the optical observation has revealed.

Conclusions and Outlook

In this paper a parameter measurement based condition monitoring approach is developed that is able to detect cracks in the heel region of bond wires in a very early stage. The observed curves follow all the same trend and are exactly reproducible due to consequently developed experimental setup. This novel measurement technique shows at the beginning a large rise to a value around 0.45 µV. That can be explained by initially cracking of the surface near material. Another reason for the initially rising curves of ΔR could be an elongation of the whole bond wire during the first loading cycles due to the applied shear force. In contrast to the commonly used direct current resistance measurement a wide area of falling signal amplitude can be observed. The reason lies in two cracks, growing into opposite directions starting at the top and bottom of the bond wire. In the case of different cracking velocities the observed signal trend can be described analytically. This behavior can be used to determine the remaining lifetime of a wire bond through prominent points in the graph. The first would be the local maximum at the beginning, the second the local minimum during the development of the curve and the third prominent point would be a change of e.g. 20 %, which indicates the failure according to common standards. Best suited for condition monitoring is the local minimum of the measured signal. The time span left to failure from this point on has always the same normed length to failure. If this behavior changes, an easy indicator for an upcoming failure is found.

The correlation between real crack depths, which can be observed by FIB analysis and measured signal amplitude builds the basis for further investigations.

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