Preprint. Submitted for publication in the proceedings of
2008 IEEE Ultrasonics Symposium, Beijing, China, November 2-5, 2008

PiQC – A Process integrated Quality Control for Nondestructive Evaluation of Ultrasonic Wire Bonds

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***Abstract*—Ultrasonic wire bonding is one of the most frequently used techniques in semiconductor production to establish electrical interconnections. Since wire bonded microdevices are used in safety critical systems, a single wire bond failure might cause a fatal system breakdown. Besides steadily increasing integration level and production speed there are extreme demands concerning the quality control of each single wire bond. The described process integrated quality control method, called PiQC, copes with this challenging task of a 100% wire bond inspection. Sensor signals are gained and processed during each welding process to calculate quality related values right after a bond's formation. In addition these calculated quality indices have been evaluated with respect to their expressiveness in a bond failure classification task.**

I. Introduction

As costs of field failures keep increasing in many fields of electronic applications (e.g. automotive callbacks), achievement of zero failure rates of the goods delivered to the end user becomes an imperative goal to pursue. In the field of ultrasonic wire bonding standard nondestructive mechanical test methods like the inline shear- or pull-test fail in achieving this goal. First additional test time is needed degrading the production rate and further the appplied test force may overstress the wire bond. In addition there are mechanical limits preventing inline shearing/pulling in fine wire applications with wire diameters of less than about 85 μm.

Therefore so called process integrated tests have been developed judging the bond quality by means of sensor signals acquired during bonding. In state of the art process integrated tests the wire deformation and/or the current flowing from the ultrasonic generator to the transducer are monitored. For example in [1] the time progression of the current envelope is divided into intervals which must fulfill certain criteria. A similiar method can be found in [2] where the envelope of the transducer current is compared to ”typical” current envelope progressions. An expansion to this method can be found in [3]. In [4] a process control is introduced where the wire deformation is monitored by a suitable sensor in the bondhead and a bond is said to be ”good” if the wire deformation lies within the minimum and maximum tolerance limits.

These techniques, integrated in similar ways in todays state of the art wire bonding machines, fail as reliable quality control methods. Even though the current is a (indirect) measurement for the oscillation of the bond wedge and its influence throughout the process, a direct correlation between the transducer current and the wedge tip movement could not be experimentally proven. It can be said, that a good quality bond always fulfills the criteria given in the current curve and takes on a reproducible form. Unfortunately, this cannot be said for the reverse. Current curves have been seen where the progression shows no noticable deviations, but the corresponding bonds were of bad quality. The same applies for the wire deformation. The assumption a good deformation and/or current curve means a good bond is incorrect. Both values are only required conditions but are not sufficient for good bond quality.

To achieve a reliable process integrated quality control more precise information regarding the process in the bonding area is required. In the LASOP-MST [5] project the movement of the wedge tip was monitored with a laser optic measurement system and the progression of the wedge tip velocity during welding had been identified as a very suitable value for judging a bond's quality. Nevertheless the laser interferometer integrated into the bondhead used in the project is too bulky and expensive, disqualifying its usage for modern high speed automatic wire bonders.

The PiQC system described in this paper overcomes these problems. It incorporates a new lightweight, inexpensive piezoelectric sensor and monitors further sensor signals and derived data vectors in parallel to judge every bond's quality without decelerating the production.

II. PiQC System Architecture

Fig. 1 shows the architecture of the PiQC system. The sensor signals are processed by a signal processing unit during welding (I). Beside the raw sensor signals the signal processing delivers additional derived values, especially values related to the wedge tip movement gained from the piezoelectric sensor. This multitude of signals and derived components is the input for the feature extraction component of PiQC (II). Here so called individual quality indices $q_1, \ldots, q_N$ are calculated on the basis of reference data stored in a knowledge base (IV). These individual quality indices are combined to an overall quality index Q (III) which is compared to a threshold during production for a fast good or failed bond decision.

The main contributions of PiQC, the piezoelectric sensor,

DOI: 10.1109/ULTSYM.2008.0099

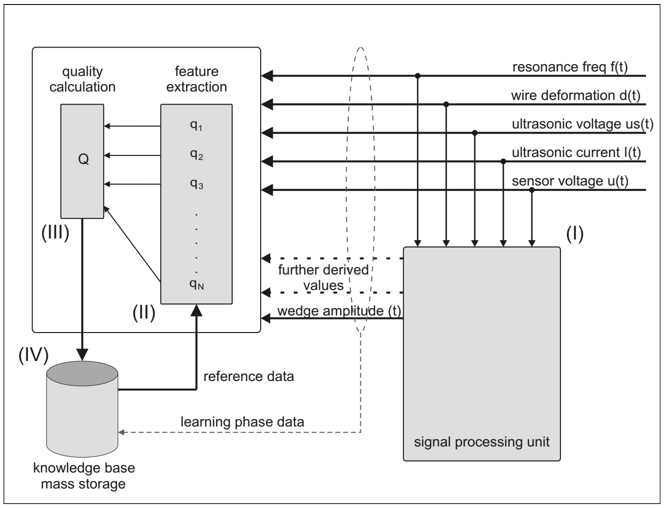

Fig. 1. PiQC system architecture

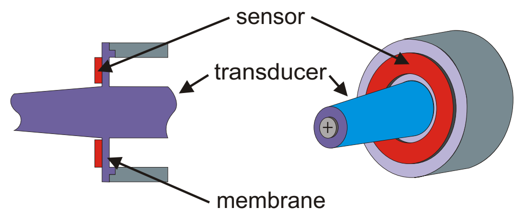

Fig. 2. Piezoelectric sensor

the concept of quality indices and the reference data calculation are described in the following sections.

A. Piezoelectric Sensor

The PiQC system uses a piezoeletric sensor to gain information about the wedge tip movement during welding. A detailed description of the sensor shown in Fig. 2 can be found in [6]. The sensor is mounted directly onto the transducer membrane at a location coinciding with a node of the longitudinal waveform. At this location the transverse elongation reaches its maximum giving the sensor signal the optimal response to process feedback at the wedge tip. In [7] it has been proven by laser interferometric measurements, that this sensor's signal correlates well with the movement of the wedge tip. Summarized this type of sensor is lightweight ($< 300\,\text{mg}$) and inexpensive and can be easily integrated into existing ultrasonic transducers.

B. Quality Indices

With the development of the PiQC system the concept of so called quality indices is introduced. A quality index is a quantitative measurement for the deviation of some sensor data acquired during welding to previously learned reference data. The basic realization of a quality index is defined over a time interval of an acquired sensor signal. For this time interval reference data are collected in a learning phase (see II-C). During production the actual sensor data of the specified time interval are compared to these reference data to calculate the quality index in the following way:

$$q_i = \left(1 + \frac{1}{\sum_{j=1}^{n} w_j} \sum_{j=1}^{n} w_j d_j\right)^{-1}$$

Where $d = (d_1, \ldots, d_n)$ is the distance vector between the reference data r of size n and the actual bond's data b for the quality index q_i. Each d_j is calculated as the squared difference of r_j and b_j and therefore $d_j \geq 0$. Hence q_i takes a value of 1.0 if there is no deviation of the actual data to the reference data and q_i decreases to zero with increasing deviation. The coefficients w_j are used to weight single data sample points, e.g. to increase some meaningful time interval's influence on the resulting q_i value.

To the described basic quality index there exist several extensions. Preprocessing operators can be used to get a derived data vector, e.g. to calculate the derivation of a sensor signal in the specified time interval. Or several time intervals of one or more sensor signals can be combined, e.g. by sample wise addition. Also it is possible to define tolerance limits t_j to allow the process to vary in these limits before the quality index value degrades indicating a deviation from the learned reference process, e.g.

$$d_j = \begin{cases} \left(\dfrac{|r_j - b_j| - t_j}{t_j}\right)^2 & \text{for } |r_j - b_j| > t_j \\ 0.0 & \text{else.} \end{cases}$$

All quality indices lie in the interval $[0, 1]$ due to the chosen distance function and the $\frac{1}{1+x}$ normalization term. Thus an overall quality index Q can be calculated from N individual quality indices $q = (q_1, \ldots, q_N)$ by a combination function $\mu(q)$. One possible realization of μ is the generalized mean function [8]:

$$\mu(q) = \left(\frac{1}{N} \sum_{i=1}^{N} {q_i}^{\alpha}\right)^{1/\alpha}$$

Simple combiners can be achieved with the following assignments of α:

$$\mu(q) = \begin{cases} \min_i\{q_i\} & \text{for } \alpha \to -\infty \text{ (Minimum)} \\ \max_i\{q_i\} & \text{for } \alpha \to \infty \text{ (Maximum)} \\ \dfrac{1}{N}\displaystyle\sum_{i=1}^{N} q_i & \text{for } \alpha = 1 \text{ (Arithmetic Mean)} \end{cases}$$

Thus the α parameter determines the systems sensitivity. Decreasing α will result in a system more sensitive to outliers in the individual quality indices. Whereas increasing α gives a more robust system but perhaps insensitive to deviations effecting e.g. only one individual quality index.

C. Reference data calculation

The described concept of quality indices is a general method to get quantitative, normalized indicators for the deviation of the actual data of a process to a learned reference. Experiments

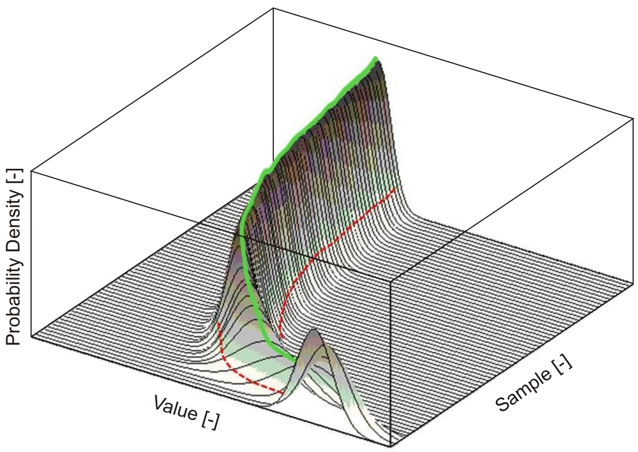

Fig. 3. Learned statistics for an individual quality index

have shown that the physical values recorded by the PiQC system vary significantly with respect to the bond surfaces, substrate materials, stiffness of the system, eigen-modes of the system, wedge and wire selection, especially when using larger wire diameters. These highly application dependant variations of the process values do not allow the use of generic reference graphs as global reference data on wire bonders. For this reason, optimized reference data has to be recorded for the evaluation of input data for every application.

Assuming the existence of a stable bond process resulting in sufficient high bond quality, reference data sets are generated in an automated learning phase. For every individual quality index the needed sensor signals are recorded and preprocessed as specified in the quality index's calculation rule. Using statistical methods a model of the respective sensor signal's or derived component's progression is created. Therefore the quality indices calculated by PiQC represent statistical features indicating the deviation from the learned reference statistic model.

The learned course of a quality index reference statistics is shown in Fig. 3. The reference calculation procedure approximates for every sample of the quality index's relevant data a probability density function from the reference bonds acquired in the learning phase. Lining up the approximated probability density functions sample by sample results in the shown probability density course. In the last step of the reference data calculation routine, the reference data vector and, if required, tolerance limits are extracted from this probability density course. E.g. the course of the statistics mean value (green) is extracted as reference and the courses of the $\pm 3\sigma$ bounds (red) are used as tolerance limits.

III. Case Study – Heavy Wire Bonding

The PiQC system has been evaluated in a heavy wire application bonding $300\,\mu$m aluminium wire onto an aluminium substrate. Reference characteristics were learned from 100 wire loops. Besides normal substrate condition four bond failure types were inserted into the test set containing 64 bonds: bonding on plastic particles caused by wear due to handling, bonding on human sweat contaminated surface (finger print), bonding with an inproperly mounted bond tool and bonding one wire onto another (double bond). The footprint of a bond on a plastic particle is shown in Fig. 4. Here the black area shows the enclosed plastic particle where no intermetallic connection between wire and substrate could be established during welding. The destructive shear test of this bond yields a shear value of 1277 cN where the overall shear value mean and standard deviation lie at 1370 cN and 77 cN. This bond would not have been detected with a destructive or nondestructive, inline test using standard 3σ tolerance. However the PiQC system detected this bond's failure by calculating the overall quality index $Q = 0.6609$ whereas all good bonds were assigned values greater than 0.96 (arithmetic mean combiner). The minimum, maximum and mean statistics of the test bond's overall quality indices are shown in TABLE I for each bond type. Here a threshold function $\tau : Q \rightarrow \omega,\, \omega \in \{\textbf{good}, \textbf{failed}\}$ with for example

Fig. 4. Footprint of bond on plastic particle after shear test

$$\tau(Q) = \begin{cases} \textbf{good}, & \text{if } Q > 0.92 \\ \textbf{failed}, & \text{else} \end{cases}$$

can be applied for a fast good or failed bond decision using the overall quality index calculated right after each bond. As shown in TABLE I, all bond failures in the test set can be detected with this threshold function.

TABLE I
Overall quality index Q

Bond Type	**# bonds**	**Q min**	**Q mean**	**Q max**
good bond	42	0.9606	0.9860	0.9986
wedge mounting	11	0.7773	0.8442	0.8786
plastic particle	4	0.6054	0.6751	0.7249
finger print	6	0.2617	0.2784	0.2927
double bond	1	0.3916	0.3916	0.3916

IV. Classifying Wire Bond Failures

In the described experiment the acquired sensor signals and their derived components show different deviations for the studied bond failures. Therefore the individual quality indices were analyzed regarding their suitability for a bond failure classification method.

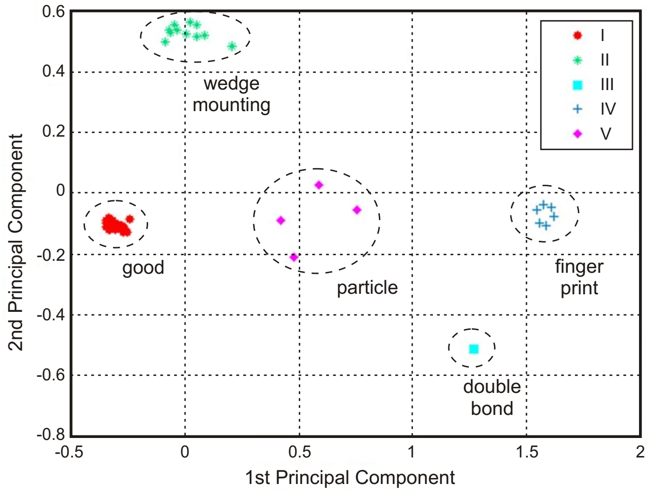

Fig. 5. Clustering of quality indices

In the case study seven individual quality indices $q = (q_1, \ldots, q_7)$ were extracted from the sensor signals. Five indices were related to the wedge tip movement gained from the piezoelectric sensor, with three of them focussing on the first important milliseconds of the wire bond process. The remaining two quality indices were calculated from the wire deformation sensor output and the resonance frequency of the ultrasonic actuator. The individual quality indices of all test bonds have been processed offline by a single linkage hierachical clustering procedure in the seven-dimensional input space. Due to the normalization step in the quality index calculation no preprocessing had to be applied. Fig. 5 shows the resulting five clearly seperated clusters mapped onto the first two principal component axis of the quality indices data set. A comparison of the bonds in every cluster with the applied bond failures shows an ideal match. All bonds assigned to one cluster belong to exactly one bond failure class as encircled in Fig. 5. For example cluster I contains only good bonds while cluster IV contains only bonds on finger prints. Therefore the calculated quality indices are suitable as input for a bond failure classification algorithm.

V. Conclusion

PiQC constitutes a nondestructive wire bond evaluation method for 100% online quality control. The parallel processing of several sensor signals, in particular of the signal from the developed piezoelectric sensor, allows the detection of common wire bond failures related to the welding process.

The introduced quality indices represent statistical features. Their definition based on time intervals of sensor signals or derived components allows the incorporation of a priori knowledge of meaningful phases in the wire bonding process. Due to the normalization step the individual quality indices can be combined to an overall quality index, even if gained from different types of sensors. By means of a threshold function this overall quality index can be used for a fast good or failed bond decision right after a bonds formation.

By learning the current bond process characteristics in the automated reference data acquisition phase the PiQC system is able to adapt to different bond processes. The reference data calculation algorithm ensures optimized reference data sets for the current production environment.

In addition to the heavy wire case study described in this paper the threshold function approach has been already integrated into Hesse & Knipps automatic wire bonders and successfully deployed to several field tests. Even in high throughput fine wire applications PiQC is able to evaluate each bond's quality online without degrading the production rate.

Furthermore the individual quality indices show different reactions to different types of bond failures. The investigation of this property revealed the individual quality indices span a vector space suitable for bond failure classification. Further research will be directed to this characteristic and the development of an online bond failure classification method.

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