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Process integrated Wirebond Quality Control and its Industrial Verification

Sebastian Hagenkötter, Michael Brökelmann, Hans J. Hesse
Hesse & Knipps GmbH
Vattmannstr. 6
33100 Paderborn, Germany
Tel. +49-5251-1560-31, Fax. +49-5251-1560-97, Email info@hesse-knipps.com

Abstract

The lifetime and reliability of electronic systems are highly dependent on the quality of the electrical interconnections. With wire bonding beeing still a state of the art connection technology 100 % quality control techniques are mandatory in those applications. So called process integrated quality control techniques have emerged as suitable online exhaustive test method superior to mechanical inline tests having several drawbacks regarding speed, bond stress and bonder dynamics. For ultrasonic wire bonding it is still state of the art to monitor the wire deformation and the ultrasonic current to judge the quality of the bonded interconnections. But "normal" wire deformation and current characteristics do not guarantee good bond quality in every case. Therefore beside these established signals the PiQC^{TM} system additionally monitors the ultrasonic frequency progression and further signals gained from a newly developed sensor integrated into the transducer. The lightweight sensor does not disturb the ultrasonic system during bonding but providing a signal very sensitive to the mechanical vibrations at the tip of the bonding tool. This sensitivity was studied and optimised by scientific analysis of the electromechanical transfer by means of analytical models as well as corresponding measurements. Since several months the PiQC^{TM} system is successfully applied in industrial applications at customer site. Valuable experiences gained in these field tests will be discussed in this paper.

Keywords: Wire Bonding, Quality Control, PiQC

1. Introduction

One of the most important methods used for electrically connecting semiconductor devices is ultrasonic wire bonding. The connections between the electrodes of a substrate and the ultra fine wires are made by an ultrasonic friction welding process at room temperature. The continually rising number of I/O-ports in microelectronic devices increasingly demands an integrated bond quality monitoring system.

Wire bonding technologies are widely used in electronic systems destined for aeronautics, astronautics and automotive applications etc.. Quite often these systems are safety critical. This result in extreme demands concerning the quality of each single wire bond, since a single imperfection in one of the wire bonds might result in failure of the whole system.

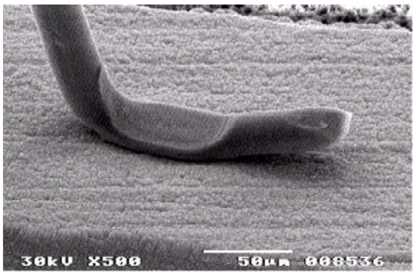

Figure 1: A typical wire bond

One of the primary responsibilities of electronic manufacturers is to guarantee certain quality levels of the production. The proper documentation of each single production step has become mandatory. Bond quality monitoring is a first step towards a more reliable production. It attempts to monitor the quality of a wire bond by observing certain process parameters and their evolution during the formation of a wire bond.

Because of restrictions in mass production the bonding process is unfortunately not accessible by direct measurement. Thus, current bonding systems usually use the wire deformation to predict the bond quality, which fails in some cases when the wire is deformed though no adhesion has occurred.

The aim is to monitor the friction welding process within the bonding zone in order to conclude to the quality of each bond.

2. Integrated quality control techniques

Since the beginning of industrial usage of ultrasonic bonding in electronic applications in the 1960's there is the aim to monitor the bond process and to judge the quality of the electrical and mechanical properties of the interconnections. Because the direct properties strain and stress in the bonding zone during the friction welding process are not accessible in mass production all practical methods are “indirect”. It must be the aim to get as much as possible characteristic information about the physical processes within the bonding zone. As more characteristics about the bonding process are accessible as better the bond quality can be judged.

A great number of bond quality monitoring techniques have been examined and developed in order to monitor the bonding process and to determine whether or not a bond has been completed successfully. One can differentiate these methods in:

- Offline method (mechanical test, destructive and non-destructive)
- Inline method (mechanical, non-destructive test)
- Online method (process integrated method)

So-called offline methods usually consist of an evaluation of the process quality after the process has been completed. These process monitoring methods generally rely on a statistical model of the process, and the individual test results are treated as samples of a random process. If the sample result does not comply with certain requirements, a readjustment of the process parameters is made and some specimen or even entire production lots might be rejected, in extreme cases.

The most elementary off-line test methods are destructive and non-destructive pull- or shear-tests. Both methods require an "un-productive" additional process step in which the components are taken from the production process to a test system (pull and/or shear tester). Destructive tests have the additional disadvantage that it is, of course, impossible to test all bonds in such a way.

The inline method is generally non-destructive and the test apparatus (pull and/or shear tester) is integrated into the machine. The test requires no operator intervention. These methods bear the risk of damaging or weakening the bonds, without this showing up in the test. The settings for the inline test process are complicated and must be carried out with great accuracy. Moreover, the cycle times are considerably increased as the inline test can only be carried out after a wire is bonded, adding more time to the process. The reliability of both the offline and the inline method depends greatly on the accuracy of the applied statistic model.

Compared to off-line methods, online methods are performed in real time during the bond process. Without additional time consumption, all wires can be controlled (100% control). A particular benefit of online methods, when compared to offline methods, is that they permit an automated feed-back to the machine and thus can be used for a closed-loop process control technique. In contrast to inline methods integrated systems for online quality control are neither influencing the bonds at all nor decelerate the production speed. As a consequence, research has concentrated on developing online process monitoring techniques which allow evaluating online, while the bond is being formed, whether or not it has been formed successfully.

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. Additionally in new systems with a digital ultrasonic generator there exists the possibility to also monitor the course of the ultrasonic frequency as the instantaneous resonant condition of the vibration system.

Even though the current is a measurement for the oscillation of the 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 fulfils the criteria given in the current curve and takes on a reproducible form. Unfortunately, this can not be said for the contrary. Current curves have been seen where the progression shows no noticeable deviations, but the bonds belonging to it were of bad quality. The same applies for the wire deformation as well as for the frequency. These criteria are only necessary conditions but are not a sufficient condition for good bond quality.

3. Sensor based process integrated Quality control

From the above, we can see that more precise information regarding the process in the bonding area is required to improve the quality control. This can be achieved by acquiring more signals which reflect the mechanical conditions at the wedge tip. A sensor capable of monitoring these mechanical vibrations can either be integrated in the transducer or can be assembled outside the transducer on the bondhead or in the clamping support of the electronic components to be bonded. External sensors like a laser interferometer [1] are not considered here as they are only suitable for exploration of the bond process under laboratory conditions and are not suitable for automatic operation under production conditions.

An integrated sensor needs very small dimensions towards the wave propagation if the progression of the oscillation of the transducer or the wedge tip is to be recorded. The sensor additionally has to fulfill the following requirements:

- Frequency rang up to the megahertz scale at vibration amplitudes within the nanometer scale
- High sensitivity to changes of the external load
- Low influence to the transducer and no aging
- Low weight and installation space
- Easy application and low manufacturing effort
- Low maintenance and calibration effort
- Low cost

A detailed description of how such a sensor could be integrated into a bondhead can be found in [2].

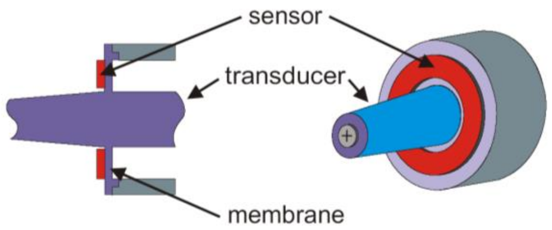

Figure 2: Alignment of a piezo sensor on the transducer membrane [2]

For this type of integrated piezoelectric sensor the generated voltage is proportional to the strain at the location of the sensor. Since the system vibrates in a well known modeshape, it is sufficient to measure the vibrations at one point of the system only. But the placement of the sensor is important to get optimal sensitivity to the load fluctuations at the wedge tip.

To be able to evaluate the sensing behaviour with varying positions and sensor characteristics an analytical rod-type model and an FEM-model were built. In particular the transfer function between the velocity of the wedge tip and the sensor signals as well as the sensitivity to changes in the mechanical load at the bonding zone were of special interest.

The ultrasonic bonding system is composed out of a few geometrical simple bodies. The system consists of the basic elements taper (horn), cylinder and torus (connecting parts and piezoelectric elements) and bending beam (bonding tool).

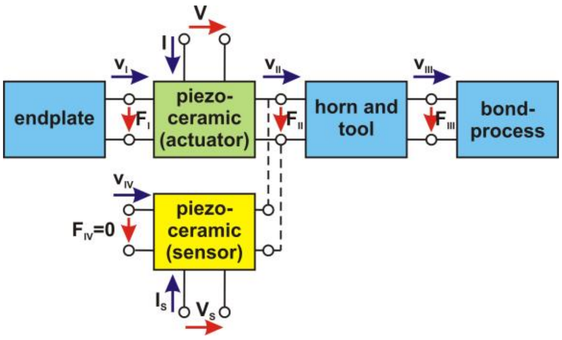

Figure 3: Modular four- and six-port system

All these elements are coupled by transition and boundary conditions. The mechanical elements have two borders each with two boundary conditions for velocity v_i and force F_i at the boundary cross-section i. The piezoelectric element has six boundary conditions because of the additional electrical quantities current I and voltage V. Each element can be understood as a four-port or a six-port system respectively. It should be noted, that only longitudinal vibrations of the transducer and only transversal vibrations of the wedge are considered. Now for each of these continua the equation of motion for harmonic vibrations can be found in a general form as

$$\frac{\partial^2}{\partial t^2} u(x,t) = c^2 \cdot \frac{\partial^2}{\partial x^2} u(x,t) \qquad (1)$$

with displacement u, element coordinate x, time t and wave speed c. With knowledge of the boundary conditions the solution for the steady state case can be found.

The power flow at the ports is given by the product of the generalized force and velocity variables respectively. At each port one of these two can be defined as a dependent variable. By this means the driving voltage U is an independent variable while the current I und the sensor voltage V_S (open sensor-electrode) are dependent variables.

With this model it is easily possible to derive the transfer function between the wedge tip velocity and the current or the sensor-voltage respectively (see Fig. 4). But even all other system variables, like the vibration modeshape can be derived from this model. The influence of parameter variations can be studied without big effort.

This model was validated experimentally. Measured and calculated admittance characteristic matched very well.

Using the analytically calculated relationship between velocity on the wedge tip and the signal at the sensor, it was possible to conclude the optimal placement of the sensor that yields a constant transfer behavior in the desired frequency range.

It turned out that it is optimal to mount the sensor 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.

Figure 4 illustrates the quotient of the sensor voltage and the velocity of the wedge tip gained from a laser optic measurement, a Finite Element analysis and from the described analytical 1-dim. continuum model. In the frequency range, the quotient delivers, as expected, a constant value.

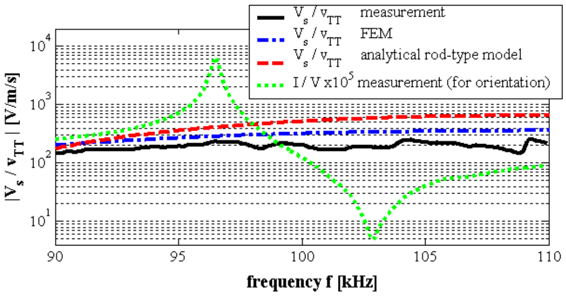

Figure 4: Transfer function between transducer tip velocity and sensor voltage

The potential of the integrated piezoelectric sensor has been proved in experiments. Mechanical disturbances and contamination of the welding partners could be recognized by this method. Figure 5 shows a experiment to illustrate the sensitivity of the sensor in comparison with the transducer current. The system was vibrating in steady state at resonance when it was disturbed by a mechanical impact at the tip of the wedge. The phase-locked-loop (PLL) controller used in the experiment puts the system back into steady state quite fast. The four disturbing force-burst are clearly reflected in the sensor signal while they can not be seen in the current signal. The experiment revealed that the signal of the additional piezoelectric sensor is much better suited for signal processing, than the current signal .

The sensor delivers the additionally measured values with sufficient quality to collect the friction and other effects caused by bonding.

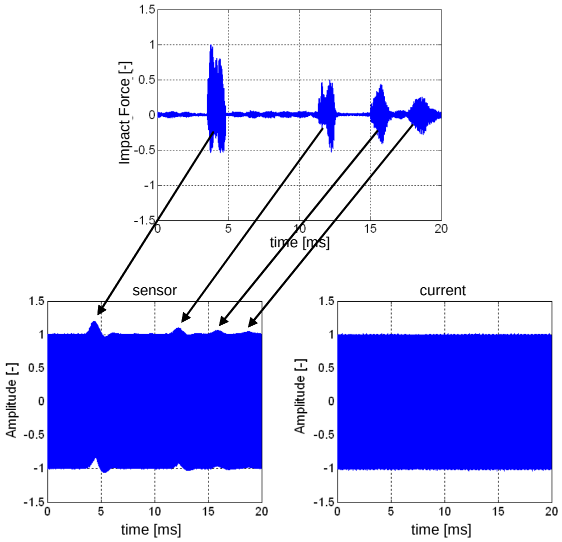

Figure 5: Influence of an impact like disturbance at the wedge tip on the sensor signal and the transducer current at free resonant vibration

4. PiQC^{TM} – Multidimensional Quality Control

The process integrated quality control solution of Hesse & Knipps, called PiQC^{TM} [3], brings together state of the art quality control signals with the described sensor based approach by means of multidimensional signal processing. Figure 6 shows the system architecture of PiQC^{TM}. Process feedback signals processed by PiQC^{TM} are acquired from the ultrasonic generator (ultrasonic voltage, ultrasonic current, ultrasonic frequency course), the bonder kinematic (wire deformation) and from the previously described transducer integrated piezoelectric sensor (I). In particular from the latter further signals are derived during welding, e.g. a signal related to the amplitude of the bondtool tip. This multitude of acquired signals and derived components is the input for a feature extraction unit (II), which calculates so called individual quality indices Q_{Wedge}, $Q_{Friction}$, $Q_{Ultrasonic}$, $Q_{Frequency}$ and $Q_{WireDeformation}$. These features describe the deviation of the current bond process to a reference process by means of normalized scalars grouped according to the input base signals. Finally the individual quality indices are combined to a single overall quality index Q taking values to 100% for good bonds and degrading to 0% for bonds of low quality (III). The overall quality index is compared online to a user programmable threshold for a fast good/failed bond decision.

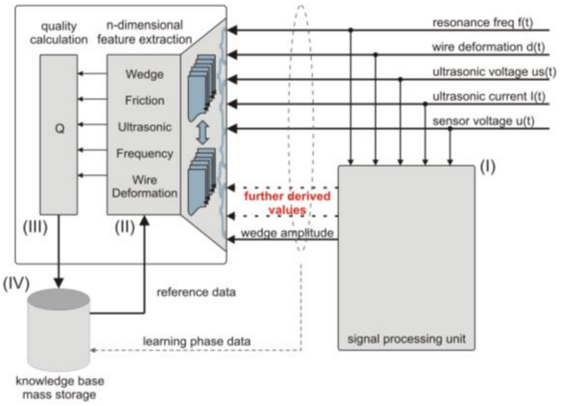

Figure 6: PiQC system architecture

The reference data used in the feature extraction unit are calculated from statistical characteristics of a stable bond process sample recorded in an automated learning phase and are stored in the PiQC^{TM} sytem's knowledge base (IV). The learning phase is necessary because of application dependent variations in the acquired process feedback signals, e.g. due to different substrate materials, wire diameters, wire materials, etc..

5. Industrial Applications of Process integrated Quality Control

The PiQC^{TM} system have been subject to several tests in the field during its pilot phase. The next sections outline results first of an customer ordered application trial and second of a fine wire application at customer site.

5.1 PiQC^{TM} Application Trial

The goal of an internal customer ordered application trial was to ensure that PiQC is able to detect common type of bond failures in a specific bond process setup. Therefore bond failures were intentionally applied to a stable bond process, e.g. by manually displacing bonds on pad edges or by scratching pad surfaces. Starting with figure 7 (i) a bond with overdeformation due to short tail can be detected by PiQC^{TM} calculating an overall quality index of 68% . Figures 7 (ii) and (iii) show bonds on pads with scratched surfaces. The more the bond is formed on scratched area the more the overall quality index degrades. The bond with only its heel affected by the scratch (ii) gets a quality of 59% and the bond welded completely onto the scratch is assigned a quality index of 19%.

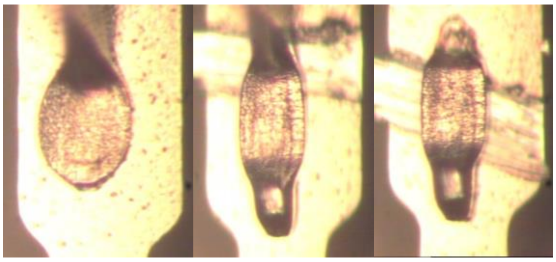
(i) (ii) (iii)

Figure 7: Bond failure examples

The correlation between degrading bond quality and the degradation of the calculated quality index can in particular be verified by manually displacing bonds. Figure 8 (i) shows displaced bonds on bond pads. The left bond is placed almost entirely on the pad. About one half of the middle bond is welded to the pad surface (50%) whereas the right bond only touches the pad with about 25% of the bond foot. The PiQC^{TM} system calculates descending overall quality indices of 99%, 29% and 0,2% for this bonds.

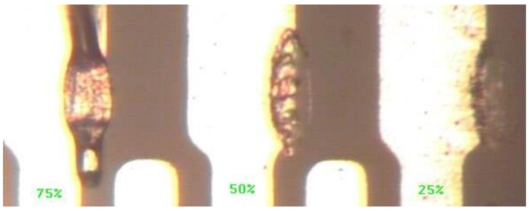

Figure 8: Displaced pad-bonds

The same quantitative relationship can be verified for misplaced bonds on chip surface. The optimal chip bond (s. figure 9 left bond) gets a quality index of 100% whereas the middle chip bond near the pad edge gets 76% and bonding in between two pads (bond on the right) results in a quality index of 62%. In the latter case the quality index does not degrade as far to zero as in the case of the 25% bond in figure 8 because more or less two thirds of the welding area are still on pads.

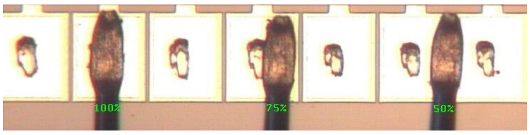

Figure 9: Displaced chip-bonds

All verified bond failures of the application trial and corresponding calculated overall quality indices are shown in table 1. For comparison a downgraded PiQC^{TM} system has been installed in this application trial running in parallel to the full featured quality control. The third column lists quality indices calculated by this downgraded PiQC^{TM} system using only ultrasonic current, ultrasonic voltage and wire deformation as feedback signals. Using only latter state of the art process feedback signals only about on half of the bond failures can be detected. In particular bond failures related to the surface condition do not show up in this signals, e.g. misplaced pad bond (50%), misplaced chip bonds or bond slighty affected by scratch. Using the multidimensional quality control of the PiQC^{TM} system incorporating signals from the new developed sensor all bond failures can be detected, i.e. misplaced bonds on pad connectors and chip surfaces, bonds on scratches/particles and bonds with too much deformation, e.g. due to short tails. In addition it was verified that degrading bond quality results in degrading overall quality indices.

Bond Failure	Overall Quality Index	Quality Index (current and deformation)
optimal pad bond	100 %	100 %
misplaced pad bond 75%	99 %	100 %
misplaced pad bond 50%	29 %	100 %
misplaced pad bond 25%	0,2 %	10 %
optimal chip bond	100 %	100 %
misplaced chip bond 75% on chip	76 %	96 %
misplaced chip bond 50% on chip	62 %	98 %
particle on bondpad	0,02 %	9 %
scratch on bondpad 1	59 %	100 %
scratch on bondpad 2	19 %	69 %
too much deformation	76 %	81 %
too much deformation due to short tail	68 %	80 %

Table 1: Bond failures application trail

5.2 PiQC^{TM} Evaluation in the Field

A customer of Hesse & Knipps verified the PiQC^{TM} system in his production environment. The results of a test with bonds of 180 modules each containing about 200 wire loops made of 25 µm Al wire are presented here. Among the test set of 36000 bonds the PiQC^{TM} system detected different bond failures. Six of them are shown exemplarily in figure 10.

On the IC side a failed bond was detected, bonded on a FR 4 particle (i). The calculated overall quality index for this bond is 1%. This failure type could also be detected for a pad bond (ii). As the bond was not bonded directly on top of the particle the quality index takes a higher value of 36%. In figure 10 (iii) the light contours of lint under the bond foot can be seen. This bond failure was detected with an overall quality index of 26%. Faulty gilding of a pad has been recognized by PiQC^{TM} by calculating a quality index of 9% (iv). Common substrate contamination by tin spillings or flux residues are shown in figure 10 (v) and (vi). Failed bonds on these contaminations has been detected with quality indices of 13% and 37%. All bond failures of this production test are listed in table 2.

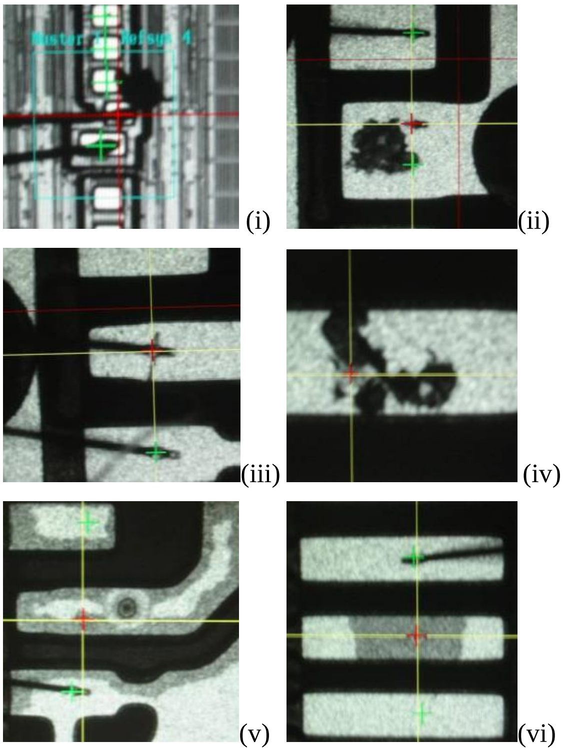

Figure 10: bond failure examples

The customer also applied an optical quality control to the bonded modules afterwards. It turned out that no more bond failures could be found other than the ones detected by PiQC^{TM}. In this field test there were neither false negatives nor false positives among the monitored bonds. The PiQC^{TM} system has demonstrate its ability in a real production environment and its worth to mention that the PiQC^{TM} system monitored all bonds online without decelerating the production.

Bond Failure	Overall Quality Index
optimal bond	100 %
bond on particle	5 %
light chip contamination	54 %
light pad contamination	53 %
lint	26 %
FR4 particle (pad)	36 %
FR4 particle (chip)	1 %
tin spillings	39 %
faulty gilding	9 %
flux and tin spillings	13 %
fingerprint	40 %
bond on particle	9 %
tin spillings	14 %
flux	41 %
flux	37 %
bond on particle	15 %

Table 2: Bond failures field test

6. Summary

Process integrated quality control techniques allow a 100% test without decelerating production. The more signals are collected from different kinds of sensors the wider is the decision basis for judging bond quality.

The transducer integrated sensor delivers signals more sensitive to wedge tip movements than state of the art process feedback signals. The sensor is lightweight and does not influence the bonder dynamics.

The PiQC^{TM} system of Hesse & Knipps comprises a multidimensional quality control incorporating state of the art process feedback signals, i.e. ultrasonic current, ultrasonic voltage and wire deformation, and in addition the ultrasonic frequency course and a signal processing unit for the transducer integrated sensor signals. The quality calculation algorithm takes all this signals into account to judge every single bonds quality online right after welding.

PiQC^{TM} has been succesfully deployed into the field. Application trials and customer reports document succesfull integration of the system into production environments. Different types of bond failures have been detected during production without decelerating the process. In the field test at customer site the quality values calculated by PiQC^{TM} showed an ideal match with the optical inspection result. Neither false negatives nor false positives quality predications have been found.

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