Validated Simulation of the Ultrasonic Wire Bonding Process

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***Abstract*—Ultrasonic wire bonding is an indispensable process in the manufacturing of power semiconductor devices. These devices consist of one or more semiconductors in a common housing with integrated connectors. To interconnect individual components, wire bonds are used. Bonding machines form a joint between bond wire and components using ultrasonic vibration. In high power applications, such as electric vehicles, wind turbines and solar power systems, the thermal and mechanical limits of aluminum interconnects are nearing. The limits could be overcome using copper wire bonds, but their manufacturing poses challenges due to the harder material, which leads to increased wear of the bond tools and to less reliable production. Parameter values for which a stable process can be maintained can only be changed within a small range, making it necessary to compute suitable parameters beforehand. To this end, and to gain insights into the process itself and allow automated process parameter adaptation at runtime, the ultrasonic bonding process is modeled. The process model is composed of several partial models, which were introduced before. This paper focuses on the validation of a coupled point contact model which is used to calculate the friction and bond formation in a discretized bonding area. By doing this, new insights into the bonding process can be shown. For example, the growth of the welded area in the interface of wire and substrate during the bonding can be shown for different points in time. At the end, an experimental validation of the process model reveals a high model quality. This is one major step towards truly understanding the parameter influences on bond quality.**

Keywords— ultrasonic wire bonding; process parameters; copper wire

I. INTRODUCTION

Power-semiconductor modules are used to control and switch high electrical currents and voltages. Within the power module, wire bonding is used to form the electrical interconnections between an integrated circuit semiconductor and a direct bonded copper substrate (DBC). In the past, aluminum wire has been the material of choice, but a rapidly changing market of high power modules requires a material with advanced mechanical and electrical properties. For this reason, several semiconductor companies are aiming to integrate copper wire bonding technology into their assembly lines. The process of heavy wire wedge bonding is usually under ordinary air conditions. For this reason, copper reacts immediately with the oxygen from the air and forms an oxide layer already before the process is started. It is challenging to remove the oxide mechanically because it is ductile and not brittle as aluminum oxide. This makes it harder to remove the oxide layers based on relative motion instead of breaking apart brittle layers due to mechanical deformation. Once the surfaces are cleaned and activated, the contact partners generate a strong bond connection. The main settings for this process are bonding time, normal force and ultrasonic power. High normal forces and high ultrasonic power result in a good cleaning and activation of the copper surface, but also deform the wire significantly. Especially, high ultrasonic power results in a strong reduction of the yield strength and therefore in a high degree of wire deformation. In combination with high normal forces, the wire moves too far into the groove of the tool. In consequence, the tool touches the substrate and the ultrasonic power is not applied into the joining area. This has a negative impact on the process stability and the wear of the tool. In addition, the resulting stresses lead to high deformations in the heel regions of the bond connections which promote heel fractures.

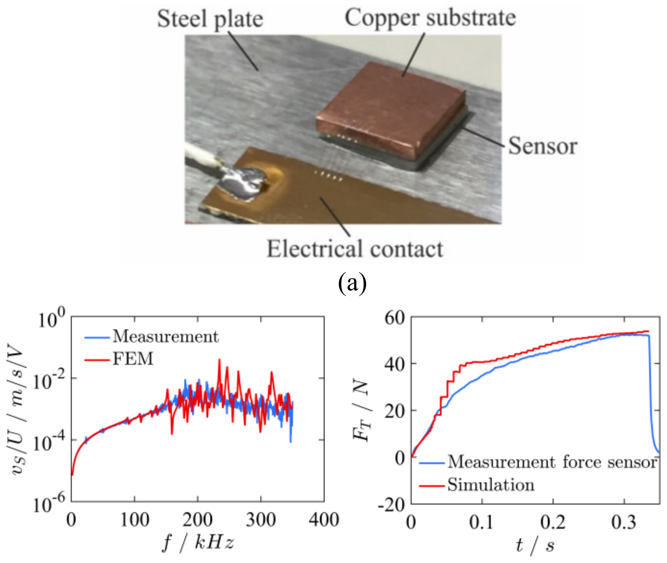
To overcome these drawbacks of copper wire, a full process model was created by combining individual partial models. This model was used to adapt process parameters at runtime using model-based multiobjective optimization [1], [2]. As a result, it is possible to determine optimal process parameters using simulations only. Some of the partial models have been introduced before [3], [4], [5] such as the detailed point contact model of ALTHOFF et al. [6], [7]. The aim of this model is to simulate the bond formation for a discretized bonding area. Micro welds are computed while simulating a bond process to identify welded partial areas.

II. VALIDATION OF THE POINT CONTACT MODEL

One major advantage of the chosen modularization into separate partial models is that individual partial models can be isolated for parameterization and validation. Since the detailed point contact model is of major importance for full model simulation results, special care has to be taken to ensure its correctness. To isolate the corresponding parts of the real process, and to compare measurements and simulation results, model inputs and outputs are measured and compared with each other.

A. Measurement of tangential forces

As already mentioned, the actual bond formation is modeled with a friction model that divides the contact area into individual partial area. Each partial area is modeled as a point contact element and has a corresponding normal force, friction coefficient, contact stiffness and degree of freedom (DOF). The sum of all friction elements represents the behavior of the entire contact. To isolate the corresponding parts of the real process, and to compare measurements and simulation results, the transversal displacement of the wire was measured by using a laser vibrometry as introduced before [5]. Model output is the tangential force during the bonding process and the relative probability of welded partial areas in the contact of wire and substrate. In the first step, the tangential force was measured with a piezoelectric force sensor. The sensor was developed specifically for measurements in the wire bonding process in order to achieve high measurement accuracy at the process frequency of 60 kHz. The sensor consists of a layer of piezo-electric shear material and a layer of a bondable copper substrate which has been tested and electrically contacted to the ground, using thin aluminum bonds (see Fig. 1.(a)). The characterization of the sensor was made with modal and harmonic finite element analysis (FEA). The study has shown that the first disturbing resonances are present at 150 kHz (see Fig. 1.(b)). As it is operated at 60 kHz, it is guaranteed that the sensor has a good response characteristic up to twice the operating frequency.



(a)

(b) (c)

Fig. 1. Overview of the force measurement system (a) and the corresponding frequency response at the sensor edge (measurement and simulation) in (b). Simulation results of tangential force F_T and comparison with experimental measurement (c)

The resulting tangential force was recorded during bonding on the sensor. The applied ultrasonic voltage amplitude and the normal force are initially ramped up from rest over the time span of 35 ms. Afterwards, they are held constant throughout the bond duration. Fig. 1.(c) shows the envelope of the resulting tangential force measurement. A comparison between measurement and simulation results using similar process parameters indicates a good agreement. In both cases, a saturation of the tangential force can be observed.

B. Identification of welded areas

The quality of a bonding connection depends mainly on the amount of welded areas in the contact of wire and substrate. Standardized shear tests can be used to obtain information about the critical strength of wire bonds, but they are not suitable to identify the effective welded area in the interface. Therefore, an image processing approach is used to compare the simulated welded areas from the process model with the characteristic surface texture of welded copper after pull tests for different points in welding time. To investigate the time-dependence of the welded area, a loop was bonded and the destination bond was evaluated. It was found advantageous for repeatability to use the destination bond, since the prior source bond is more influenced by disturbances. The source bond was bonded with full duration of 335 ms, whereas the destination bond process was terminated prematurely in several 5 ms steps from 0 ms to 100 ms and in 10 ms steps from 100 ms to 300 ms. Following this, the bond loop was pulled and the weaker destination bond failed. This way the welded area could be photographed with a digital microscope. Fig. 2. shows a typical fractured surface of a bond connection terminated at 160 ms. The bright and shiny areas as well as the deep black areas (1) in the center of the bond are present right from the beginning of the process and were identified as very smooth surfaces with no visible roughness. They were identified as not being welded. The first welded bonds are observed approximately after 30-35 ms. Simultaneously, the size of the brown areas (2) increases with longer bond duration and increased bond strength. By pulling the bond, bonded areas are broken. For copper, a ductile fracture surface is expected. The honeycomb structure of those fracture surfaces was recovered in the brown areas (2). The remaining area (3) cannot be assigned to either welded or non-welded state with certainty. Instead, it is assumed that it is a mixture of bonded and unbonded areas. For further investigations, pictures of 20 bonds for each time step were taken. Further processing was done in MATLAB. First, the RGB (red green blue)-values of the welded areas were determined and a RGB-filter was set in a way that the unwelded areas are neglected and the welded areas are remaining. By using this method, it is possible to find equivalent RGB-values of the welded areas (2) in mixture of bonded areas in (3) which have been taken into account. Each filtered image is then transformed into a logical array that represents a single pulled bond. This way, 20 arrays with entries of 0 for unwelded areas and entries 1 for welded areas are generated for each time step. They are averaged into a single array which contains the frequency of occurrence of welded areas within the bond surface. For a large number of bonds per time step, this is equivalent to the local probability of welded areas.

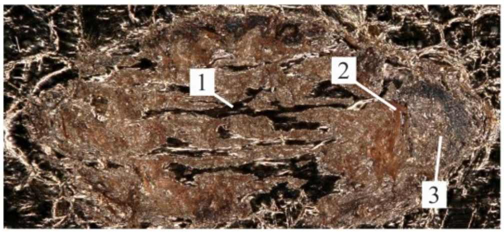


Fig. 2. Example of a typical fractured surface of a bond connection at 160 ms

The analyzed images in Fig. 3. (a-f) show that the probability of welded partial areas rise with bonding time. The rate of area correlates strongly with the growth of shear strength. First micro welds can be observed after 45 ms at the positions where the force is induced by the tool [3]. On the basis of these results, we can assume that the frictional power has its highest point at the periphery of the contact area. With increasing duration, an elliptical ring occurs. This has also been observed by ALTHOFF et al. [6] using low ultrasonic power and high bonding force. Due to low excitations, the maximum sticking force in the center of the bond is not reached, so the wire does not start to slip on the substrate. Without relative movement, it is not possible to achieve a proper bonding connection.

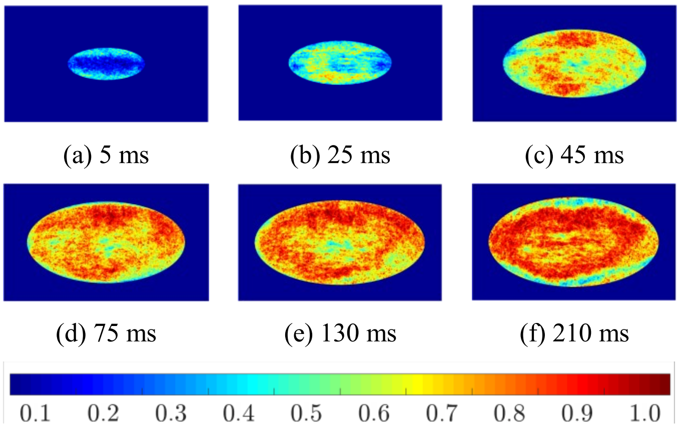


Fig. 3. Comparison of the relative probability of welded partial areas at different points in time (imaging process)

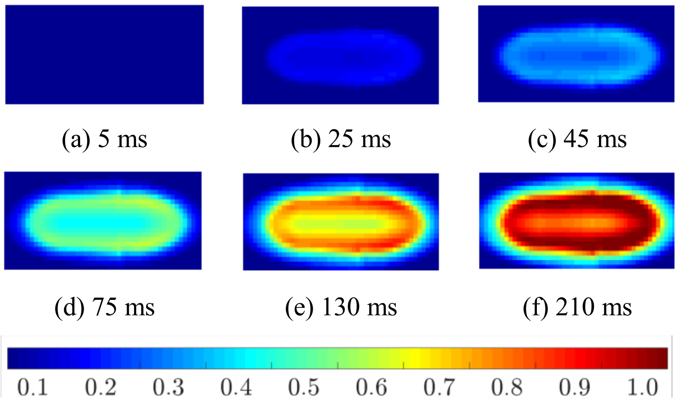


Fig. 4. Comparison of the relative probability of welded partial areas at different points in time (simulation)

Thus, this demonstrates the necessity of the chosen modeling approach with discretized contact areas to simulate the bond formation. The results from the model with the same process parameters are shown in Fig. 4. There is a satisfactory agreement between the experimental and simulation results. The growth of micro welds starts from outside and comes to an end on the inside of the connection.To determine the total welded area A_{eff} for each time step, the logical array is multiplied with the area of each pixel of the images. To validate this computation and in turn the determined welded area, shear strength was computed from welded area and compared to reference measurements using standard destructive shear tests of equally created bond loops. Using the material shear strength τ_m and the determined welded areas, the maximum shear force of the contact can be calculated as

$$F_S = \tau_m A_{eff} \, . \tag{1}$$

In order to estimate the shear strength of a 500 µm thick copper wire, a piece of it was sheared with a shear testing machine. The maximum value amounts to $\tau_m = 167$ MPa. Then the results of the imaging-process are used to calculate the maximum shear force for different bonding times. The result is presented in Fig. 5. It shows a similar behavior as reference measurements which have been done with a shear testing machine, also shown in Fig. 5. It becomes apparent that relevant shear forces can only be observed after approximately 45 ms. After a strong increase of shear force, the values of shear force remains constant at the end of the process. This happens because of the high amount of already bonded partial areas.

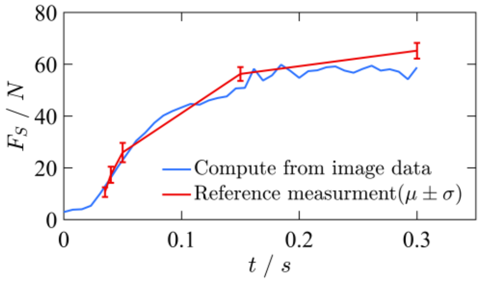


Fig. 5. Computed and measured shear forces F_S for different points in time t

III. PROCESS MODELLING RESULTS

As described previously, it is hard to find proper bonding parameters that yield high process stability. State of the art is to bond with a great variety of parameters and to test the results. This can be accelerated with careful design of experiments (DOE), but is still time consuming. A main problem is that a statistically relevant amount of bond connections has to be tested for each set of parameters using destructive methods. This is manual work. This approach is very time-consuming to find proper parameters. These determined parameters are only valid for a specific wire-substrate-combination and can also be influenced by the individual clamping device. Fig. 6. shows a parameter space of a typical copper bonding process. The parameters ultrasonic voltage U_S and normal bonding force F_N were varied between plus / minus 30 % around a nominal value. Results of same bond strength are depicted with the same color. The probability of tool-substrate contacts is visualized with red lines. The lower left corner or the parameter space is unusable because of lift offs due to the small amount of friction power. By contrast, the risk of a tool substrate contact increases with higher ultrasonic voltage and normal forces, which can be seen in the upper right corner. Tool substrate contacts should be prevented in the production of wire bonding connection, as they damage the substrate surface. Therefore the highest values of shear strength cannot be reached.

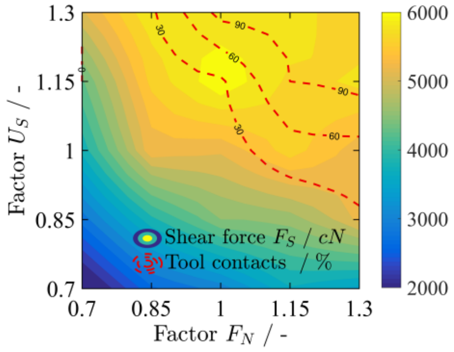


Fig. 6. Measured results for different process factors of ultrasonic voltage U_S and normal forces F_N

Simulations using the full process model enable us to do the same experiments computationally (illustrated in Fig. 7.). The introduced model of the bonding process covers the main physical effects. For example, it can be shown that small factors for ultrasonic power can be compensated with higher normal forces. These results demonstrate that the modeling approach is able to find proper bonding parameters without expensive and time consuming experiments.

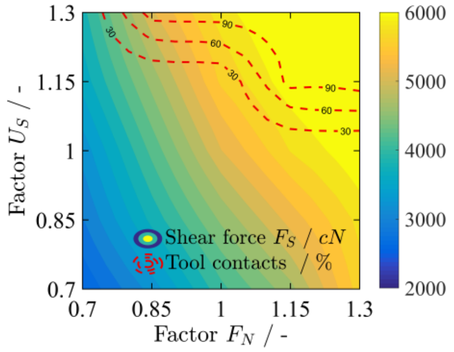


Fig. 7. Simulated results for different process factors of ultrasonic voltage U_S and normal forces F_N

IV. CONCLUSION

Heavy copper wire bonding has big advantages like high electrical and thermal conductivity and mechanical stability. But these advantages come at the cost of a process more sensitive towards parameter changes and variations in the environment. It was therefore desired to introduce a modeling approach which could compensate such influences. This was achieved by first setting up a detailed model of the bonding process, which can be used to calculate the relevant criteria bond strength, tool wear, tool-substrate contacts and bonding duration. By performing RGB thresholding and filter operations it has been shown a temporal sequence of the bond formation in measurement and simulation for the first time. A good agreement between microscope images and simulations was found. To further verify the results of the model, an integrated force sensor was developed and validated by tests and FEM analysis. The time dependence of the tangential force during the bonding process can be shown. This measurement has also delivered a good agreement with the modeling results. At the end, a validated model has been used to simulate the bonding process in great detail. This led to a great increase in knowledge about the process itself and allows for determination of optimal process parameters using simulations only. Thus it can be used to reduce time and costs for finding proper parameters.

V. ACKNOWLEDGMENT

This research and development project was funded by the German Federal Ministry of Education and Research (BMBF) within the Leading-Edge Cluster Competition it’s OWL (intelligent technical systems OstWestfalenLippe) and managed by the Project Management Agency Karlsruhe (PTKA). The authors are responsible for the contents of this publication.

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