Elastic Properties of Bonding Wires

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Abstract

The development of microelectronics is strongly driven by requirements to reduce the dimensions of all components and, therefore, to increase the integration density and functionality. This leads, amongst others, to specific demands on the robustness and reliability of the interconnecting components used for the packaging technologies. In particular, miniaturized and/or highly stressed bonding wires need an increased stiffness and strength of the applied materials. In this context, we discuss the determination of elastic deformation properties of different gold and aluminum bonding wire materials and their relationship to the respective grain microstructure. It is shown that the Young's moduli of bonding wires depend almost solely on the elastic anisotropy properties of the different grains. Thus, Young's modulus can be directly calculated from grain orientation distribution as determined by appropriate electron backscatter diffraction analysis. Consequently, the results can be used for predicting the deformation properties and stiffness of bonding wires by a design of microstructure. Furthermore, it is possible to determine elastic properties also for process-affected wire sections like the heat affected zone and the free air ball, where no meaningful experimental mechanical testing of the elastic properties can be performed.

Introduction

In state-of-the-art highly integrated micro electronic devices such as system-in-packages and stacked-dies, system reliability is strongly influenced by wire bond interconnections. Loop stability becomes especially important in fine-pitch and long-loop applications. The loop stability is affected not only by the elastic properties of the bonding wire material itself, but also by the geometry, length and hardening behavior of the heat affected zone just above the ball where grains are recrystallized during the flame-off process [1]. For material selection and design optimization, it is necessary to know and to consider the actual elastic properties of the bonding wires.

In this study, we discuss the microstructure analysis by electron backscatter diffraction (EBSD) method and the determination of effective Young's moduli for bonding wires from crystal orientation. EBSD was applied to determine the grain orientation distribution of different gold and aluminum bonding wires. Based on the assumption that the elastic properties depend only on the crystal anisotropy and, thus, the grain orientation distribution, an effective Young's modulus was calculated directly from microstructure information for all investigated wire materials. In addition, Young's moduli of selected wires were determined experimentally in tensile tests and compared to the values calculated theoretically from grain orientation. A close agreement between prediction and experiment was found, not only validating the developed methodology, but also confirming the basic assumption of the dominating effect of grain orientation on Young's modulus compared to additional alloying influences. Furthermore, the effect of doping elements is further estimated by a simple but conservative model.

Microstructure of Bonding Wires

The microstructure of 36 different gold and aluminum bonding wires from different suppliers were characterized using the electron backscatter diffraction (EBSD) method. An overview of the used materials is shown in Table 1.

Table 1: Overview of bonding wire materials analyzed in this work

Material	Quantity	Diameter [µm]
Al	13	125 - 500
AlSi1	12	25 - 75
Au	11	18 - 32

Multiple cross sections of each wire were produced by metallographic preparation techniques in combination with ion polishing or by focused ion beam (FIB) preparation. A nearly artifact-free surface over the whole cross-section had to be assured. The samples were analyzed by a TSL-EBSD system with a DigiViewIII detector in a scanning electron microscope Zeiss SUPRA VP55. The specimens were tilted 20° to the incident electron beam and the diffraction patterns were analyzed at 15 kV acceleration voltage and 12 mm working distance. The principle of electron diffraction and formation of Kikuchi-lines is shown in Figure 1.

From the diffraction pattern of each scan point the corresponding crystal orientation is calculated. Neighboring scan points with only small differences (5°) in the orientation were merged to one grain. For the analysis in the following sections the mean orientation of each grain was used in terms of the Euler angles in the Bunge notation Φ, φ_1, φ_2 [2]. In the following figures, the microstructure is displayed in an inverse pole figure color code.

The grain size distribution was analyzed by advanced statistical methods. The analysis showed that it is necessary to perform EBSD measurements of at least three to ten wire cross sections for each wire, depending on the ratio of mean grain diameter to wire diameter.

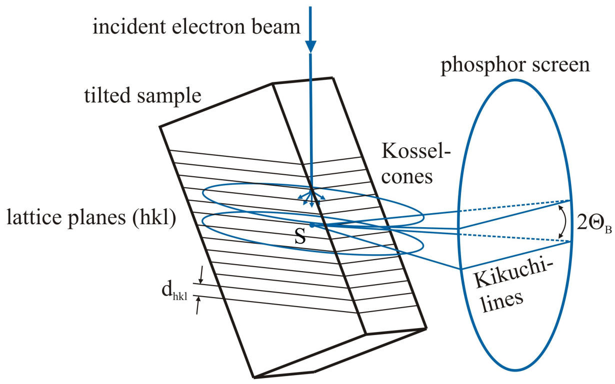

Figure 1: Principle of electron diffraction and forming of Kikuchi-lines after [3].

It can be shown that the grain size distribution follows a logarithmic normal distribution, when a sufficient number of grains is used for the analysis (> 10 000 grains). The minimum number of cross sections depends on the ratio of mean grain size to wire diameter and the width of the grain size distribution. The used evaluation procedure to calculate the mean grain size has also an influence on the statistical distribution. From the results found here an area weighted analysis is preferred. A more detailed discussion of that can be found in [4].

The investigations showed that all heavy aluminum bonding wires can be divided into two classes of Al wires: coarse-grained and fine-grained wires. The coarse-grained Al wires consist of very big grains compared to the wire diameter, see Figure 2. The majority of grains is <100> orientated.

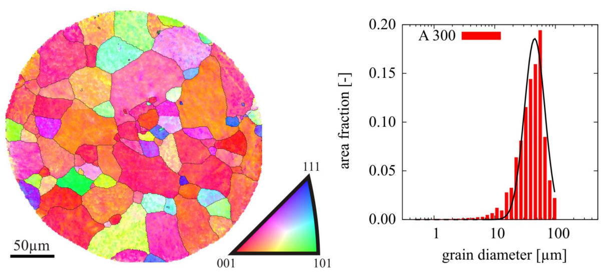

Figure 2: Microstructure of a coarse-grained heavy Al bonding wire (left) and corresponding grain size distribution of seven cross sections (right).

The fine-grained Al wires consist of very small grains compared to the wire diameter. The grains are mainly <111> orientated, even though the grains in the center of the wire are mainly <100> orientated, see Figure 3.

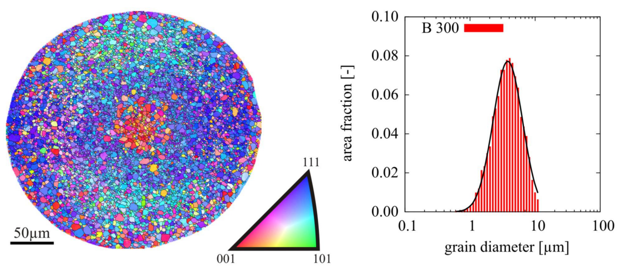

Figure 3: Microstructure of a fine-grained heavy Al bonding wire (left) and corresponding grain size distribution of three cross sections (right).

The microstructure of the AlSi1 bonding wires is similar to the fine-grained Al bonding wires, even though the absolute value of grain size is significantly lower. In addition, the small amount of <100> orientated grains in the center of the wire is lower.

The gold wires can be divided into two classes: low doped and highly doped or alloyed gold wires. The low doped bonding wires consist of a core and a surrounding peripheral region with relatively big <100> orientated grains. Between core and periphery there are small <111> orientated grains, see Figure 4. The grain size and grain orientation distributions are relatively inhomogeneous.

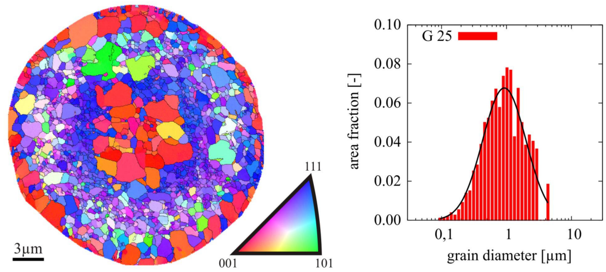

Figure 4: Microstructure of a 25 µm low doped gold bonding wire (left) and corresponding grain size distribution of two cross sections (right).

The orientation distribution of the highly doped or alloyed gold bonding wires are similar, but the <100> orientated grains are smaller and the <100> fraction is lower. The grain size distribution is more homogeneous, see Figure 5.

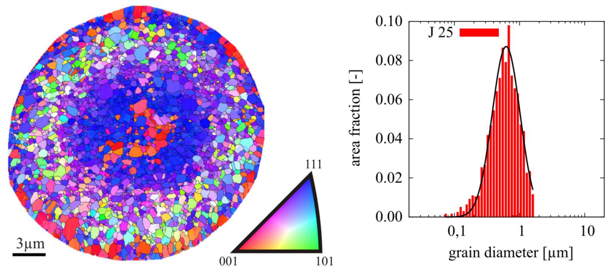

Figure 5: Microstructure of a 25µm alloyed gold bonding wire (left) and corresponding grain size distribution of four cross sections (right).

The three investigated 18 µm gold wires consist of a lower amount of <100> orientations compared to the 25 µm and 32 µm bonding wires, which are comparable.

Calculation of Effective Young's Modulus

Since typical bonding wires are very pure materials with doping contents between few ppm and at maximum one percentage of additional elements, it can be assumed that the elastic properties depend solely on the orientation of the crystals and their elastic anisotropy. The Young's modulus E for a given orientation can be calculated from the elastic compliance components S_{11}, S_{12}, S_{44} of a cubic material [5]:

$$E^{-1} = S_{11} - 2\left(S_{11} - S_{12} - \tfrac{1}{2} S_{44}\right) r_{\langle hkl \rangle}$$
$$r_{\langle hkl \rangle} = \gamma_1^2 \gamma_2^2 + \gamma_2^2 \gamma_3^2 + \gamma_3^2 \gamma_1^2 \qquad (1)$$

The orientation function $r_{<hkl>}$ is related to the Euler angles [2], which are determined by the EBSD system:

$$\gamma_1 = \sin\Phi \sin\varphi_2 \quad \gamma_2 = \sin\Phi \cos\varphi_2$$
$$\gamma_3 = \sin\Phi \tag{2}$$

The maximum value for a cubic material can be achieved for an <111> orientation, whereas the minimum value lies in the <100> orientation. For a polycrystalline metal, an effective Young's modulus can be calculated by averaging the Young's moduli of each grain. For this consideration, some assumptions are needed. First, a decision has to be made how to average the elastic properties over a part of the wire. In our case, the effective elastic properties in wire direction have to be determined from 2D-EBSD analyses of wire cross sections. So, an area weighted statistical approach to calculate the requested data should be used. Second, the nature of boundary conditions between the interacting grains during mechanical loading must be taken into consideration. In principle, the *Voigt* structure of parallel fibers and the *Reuss* structure of parallel plates define the both possible extreme situations, see Figure 6.

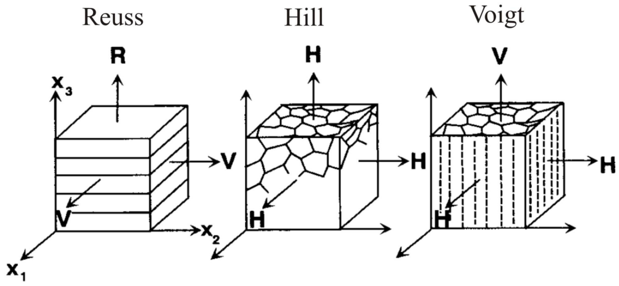

Figure 6: Different structures for averaging the elastic properties after [5].

In the case of a Voigt structure, the strains in all grains are constant, whereas in case of a Reuss structure, the stresses in all grains are constant. From that follows that the effective Young's moduli C^V and C^R can be directly calculated by:

$$Voigt \quad C^V = \sum_{i=1}^{n} E_i \frac{A_i}{A_{ges}}$$
$$Reuss \quad S^R = \sum_{i=1}^{n} \frac{1}{E_i} \frac{A_i}{A_{ges}} \quad C^R = 1/S^R \tag{3}$$

The Voigt value is the upper limit of the possible elastic Young's modulus, whereas the Reuss value is the lower limit [6]. In real polycrystals an iterative averaging procedure proposed by Hill has been proven to be useful for macroscopic specimen:

$$C^H = \tfrac{1}{2}\left(C^V + 1/S^R\right)$$
$$S^H = \tfrac{1}{2}\left(S^R + 1/C^V\right) \tag{5}$$

In the case of gold and aluminum wires three iterations were found to be sufficient to achieve $C^H = 1/S^H$, which is a demand for a quasi-isotropic material. The elastic components used in this study are shown in Table 2.

The so determined Young's moduli of the 36 different gold and aluminum bonding wires with diameters between 18 µm and 500 µm show, that there are only small differences in the elastic properties of the aluminum bonding wires, even though the orientation varies from nearly <100> to nearly <111>. The lowest determined Hill value of the aluminum bonding wires is 67.2 GPa and the highest Hill value is 72.8 GPa. Both are close to the value of quasi-isotropic polycrystalline aluminum 70.1 GPa. The reason for the only small differences is the low crystallographic anisotropy of aluminum. The minimum possible Young's modulus is $E_{<100>} = 62.8$ GPa and the maximum possible Young's modulus is $E_{<111>} = 75.3$ GPa.

Table 2: Elastic components of the compliance matrix

	S_{11}	S_{12} $10^{-11}\ m^2/N$	S_{44}
Al	1.592	-0.577	3.546
Au	2.347	-1.077	2.381
Cu	1.499	-0.629	1.325
Si	0.769	-0.214	1.258

In contrast, the results of the gold bonding wires show that the calculated elastic properties can differ significantly with wire material and wire diameter. The lowest determined Hill value of the gold bonding wires is 72.5 GPa and the highest is 93.4 GPa. Both differ clearly from the value of quasi-isotropic polycrystalline gold 77.7 GPa. The elastic properties of one bonding wire material and one diameter do not vary significantly for different positions on the wire spool or the production lot. The reason for the differences in elastic properties between individual gold bonding wire materials is the strong crystallographic anisotropy of gold. The elastic properties can range from $E_{<100>} = 42.6$ GPa to $E_{<111>} = 116.5$ GPa. The results clearly indicate that there is a big potential in more compliant or stiffer gold bonding wires by a defined design of microstructure.

Verification of Elastic Properties

For a quantitative analysis - which can serve for example as a data basis for finite element simulations of the wire sweep or other critical issues considering bonding wire material properties - it is necessary to verify the approach described previously. For this purpose, special tensile test experiments with a gauge length of 100 mm were performed for selected Au wires. The Young's modulus was determined from the first unloading segment as displayed in Figure 7.

From Figure 8 it can be seen that values calculated by the Voigt assumption are always higher and values calculated by the Reuss assumption are always lower than the experimentally measured values. However, the Hill average predicting the effective Young's modulus from grain orientation analysis is in very close accordance with the experimental results. This clearly indicates that the calculation of Young's modulus from orientation distribution gives meaningful and trustworthy elastic properties of bonding wires, also confirming the underlying assumptions.

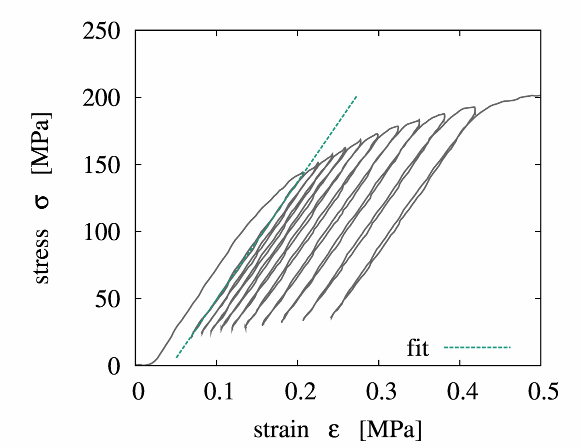

Figure 7: Stress-strain behavior of a tensile test for determining the elastic properties of a gold bonding wire.

The presented method can be applied not only for material parameter determination of wire materials but also for calculation of local elastic properties on processed wire regions like heat affected zone and free air ball. For these wire regions, no meaningful mechanical testing of the elastic properties can be performed while EBSD can easily be applied. Furthermore the method is also applicable for other crystalline pure materials from which the elastic constants are known.

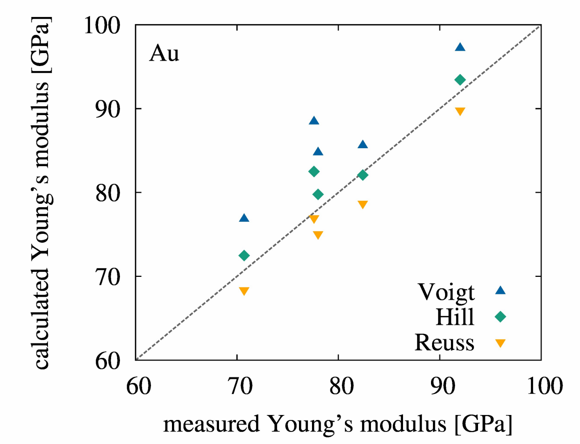

Figure 8: Correlation of calculated and measured Young's modulus for five different Au wires.

Effect of Doping Elements

Even though the results in the former section show a very good correlation between the experimental and calculated elastic properties for gold bonding wires with different amount and kind of doping elements, the theoretical effect of doping elements has to be estimated. If it is assumed that the shear modulus of a mixed crystal G_{mc} results from the volume fraction V_i/V and the shear modulus G_i of each element [7], it becomes clear that a small amount of doping elements has only small influence on the elastic properties:

$$G_{mc} = G_1 V_1 / V + G_2 V_2 / V \qquad G = E / (2(1+\nu)) \qquad (6)$$

For example: 1 mass-% of copper in gold leads to an increase in shear modulus of approximately 1.6 % and 1 mass-% of silicon in aluminum leads to an increase in shear modulus of approximately 1.8 %. The elastic constants used for this evaluation are shown in Table 2.

Consequently, the influence of typical doping or alloying elements on the effective elastic properties of bonding wires is small but can be considered.

Conclusions

In this study the microstructure of typical gold and aluminium bonding wires with diameters between 18 µm and 500 µm were analyzed by the electron backscatter diffraction method. Assuming different theoretical models, the effective Young's moduli in wire direction were calculated from the particular grain orientation distributions. The influence of grain orientation on the effective Young's modulus is rather small for aluminium bonding wires, because of the low crystallographic anisotropy of aluminium. In contrast, the effective Young's moduli of gold bonding wires can differ strongly, depending on the grain orientation distribution. The results clearly indicate that there is a big potential in more compliant or stiffer gold bonding wires by a defined design of microstructure.

For a quantitative analysis - which can serve for example as a data basis for finite element simulations of the wire sweep or other critical issues considering bonding wire material properties - it is necessary to verify the models. For this purpose, the Young's modulus of selected Au wires was determined in tensile test experiments. The results clearly indicate that the calculation of Young's modulus from orientation distribution using the iterative Hill average give meaningful and trustworthy elastic properties of bonding wires. By a simple but conservative model, the influence of doping elements on the elastic properties is evaluated to be less then 2 %. So, it is possible to quantify the elastic properties of bonding wires and process-affected wire sections from EBSD measurements.

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