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Laser cuts increase the reliability of heavy-wire bonds and enable on-line process control using thermography

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ABSTRACT

The active thermal cycling lifetime of heavy wire bonds decreases significantly with increasing wire diameter. This paper presents an innovative method for shaping the wire bond in the bonding region such that the thermo-mechanical load on the interface region between wire bond and semiconductor metallization is significantly reduced. The efficiency of the approach has been validated using finite element simulations and power cycling experiments. Moreover, the method can be used as a 'non-destructive' in-situ measurement technique, in which crack growth can be determined based on thermography measurements of the trenches, which act as magnifiers for the thermography camera and eliminate preconditioning such as using black colouring.

1. Introduction

In standard power modules Al thick wire bonds are a lifetime limiting element during fast active power cycling. This is due to the mismatch of thermal expansion coefficients (CTE) of aluminium and silicon, which causes a repeating plastic deformation in the aluminium during repeating temperature changes. In many cases, the result is material degradation of the aluminium in the region near the bond interface, which eventually results in wire lift-off and deterioration of the modules' functionality. However, technology development has aimed to overcome this weakness in order to increase the lifetime of modules. One approach is based on the reduction of plastic strains using alternative wire materials like Cu or new scandium-based aluminium (AlX) alloys with yield strengths much higher than that of aluminium [1]. However, the use of Cu as a wire bond material leads to issues in the process yield due to the high bonding forces needed. Moreover the technology needs a Cu chip metallization, which is non-standard in power semiconductors.

Another approach, proposed in this paper, reduces plastic strains by geometrical modifications to the bond wedge. It is based on the well-known observation that wires with smaller diameters show a higher lifetime. Of course, the reduction of wire bond diameter cannot be a solution to increase the lifetime. On the one hand, the space available for the wires and the corresponding bonding process limit the number of wire bonds and the size of the wire diameter. On the other hand, a large wire diameter is necessary for the high current levels needed by power electronic components. Good technical compromises (costs and performance) have been realized with diameters between 300 μm and 500 μm.

Recent results also quantify this effect. Fig. 1 shows for example shear force measurements after active power cycling experiments of different wire diameters [2]. All experiments performed in temperature hubs from 75 to 105 K show the same trend. Shear forces decrease with increasing thermal cycles. Analysis of the shear modes and cross sections show that this is correlated to fatigue crack growth in the aluminium wire near the aluminium silicon interface. The reason is the CTE mismatch of the used materials (aluminium and silicon), which results to cyclic mechanical stresses in thermal cycling. This leads to cyclic plastic deformation of the aluminium and its fatigue. If thick wire bonds are compared to thin ones, this effect is much more pronounced. Therefore shear forces decrease much faster for thick wire bonds.

This paper presents a new method in order to utilize this effect for lifetime improvement without reduction of wire diameter.

2. Approach for geometrical adaptation

The initial step was to introduce trenches in the bond area which grow in depth from one trench to the other and from the centre of the bond towards the end of the bond (Fig. 2). The goal is to reduce the stress in the connection zone of the bond. From a process point of view, creating such trenches during the bonding step itself would be very advantageous. Also the mechanical removal of material after bonding requires strong forces and may introduce cracks. Therefore it is

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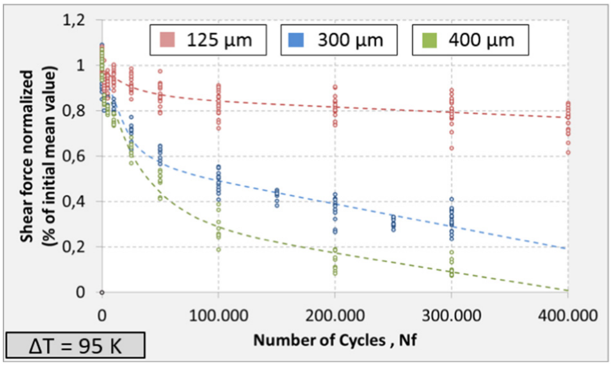

Fig. 1. Average shear forces after power cycling for different wires [2].

proposed to cut the outlined trenches with a laser into the aluminium [3,4]. It was anticipated that this approach of wire bonds with trenches should have about the same behaviour as a complete removal of the aluminium to form a wedge.

The positive effect from this modification was observed on a qualitative level [4]. But a more detailed analysis of the lifetime experiments is given in this paper and a quantitative estimation of the effect is given based on a new thermo-mechanical FE (finite element) model.

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3. Thermomechanical FE model of a modified wire

To investigate the effect of the trenches on the thermomechanical behaviour of the wire, finite element simulation models were set up. In the initial step, both the normal untreated wedge and a wedge with a number of trenches with increasing depth, were modelled to evaluate the different interface load situation for a modified wedge. In the simulations, the wires were loaded with thermal cycles of 100 K temperature rise. This load corresponded to the temperatures measured during the active cycling tests as presented later. Thermal imaging results out of the active cycling test suggested that there is no significant temperature distribution across the bond area, so that in the model, temperature is applied uniformly within the bonded area.

The numerical mesh was arranged according to the findings from [5]: The area 20 µm above the interface has always been meshed with an edge length of 10 µm and four elements in height. The mesh in the remoter areas, also where the laser cuts are located, can be much coarser.

For evaluation, the plastic strains accumulated per cycle in the area of the bond connection were analyzed. These inelastic deformations cause damage to the material, eventually leading to crack formation and gradual crack growth during cycling. An overview of the comparative results is given in Fig. 3. The load reduction observed on the tail side

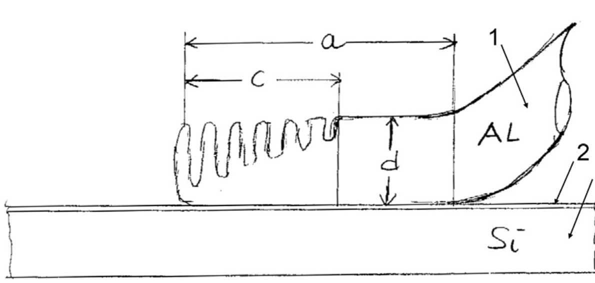

Fig. 2. Approach for reducing stress by forming trenches [3]: 1) wire cross-section; 2) substrate; 3) metallization; a: bonded section; c: length of tapered section; d: wire gauge,

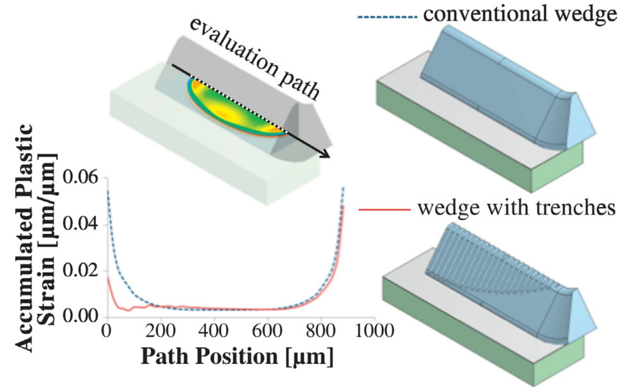

Fig. 3. Simulation results for a conventional wedge compared to a wedge with trenches.

of the wedge showed a smaller accumulated plastic strain and thus a longer lifetime for the wire bond.

In order to estimate the effect on lifetime, a more detailed model was set up with a simulation approach introduced in [6], which was shown to enable calculation of lifetime for different wire diameters [5] and applied to compare different wedge geometry modifications [7]. For the analysis shown here, the shape of the trenches was modelled according to cross-sectional images of laser-cut wedges that were tested in a prior step as discussed below. The model calculates the load situation for different crack lengths and evaluates the plastic strain.

From the following equation the speed of crack propagation is evaluated [6]:

$$\frac{dA}{dN} = C_1 \left(\Delta\varepsilon_{pl}\right)^{C_2} \tag{1}$$

The parameters C_1 and C_2 of the crack growth approach were adopted from [5], where they had been successfully calibrated for the same 400 µm Al-H11 wire and the same temperature-controlled power cycling conditions used in the experiments presented here. The damage parameter, $\Delta\varepsilon_{pl}$, was always averaged across a volume, which has been found to be mesh-independent, 25 µm in front of the singular crack tip.

For the trenched wedge, the load situation is different on both ends (see Fig. 3, left). Therefore, crack propagation has been calculated separately for both ends. As before, the load was a constant temperature swing based on the temperature controlled power cycling tests performed.

Fig. 4 displays example results of the calculated crack propagation of 400 µm Al-H11 wires on silicon. For the modified wire, crack propagation was slower, even more so on the tail side where the trenches were deepest. As could be expected, for the unmodified wire the predicted crack progression rate is equal for both ends of the wedge. Fig.

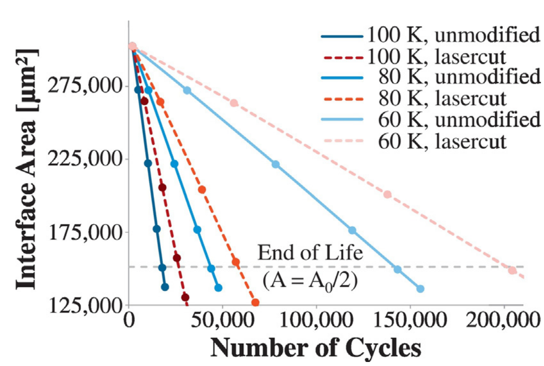

Fig. 4. Calculated interface degradation of 400 µm Al-H11 wires for different load cases with and without wedge modification.