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Welding of Au Microwires by Femtosecond Laser Irradiation

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***Abstract* — An alternative wire joining method is explored that utilizes femtosecond laser pulses directed towards the contact point of two pieces of 25-µm diameter Au bonding wires typically used in microelectronic wire bonding. The two pieces are in the form of wire loops bonded onto four terminals in a crossing pattern. *In-situ* four-wire measurement is used to measure the contact resistance at the contact point of the crossed wires before and after femtosecond laser irradiation. A greater decrease in contact resistance correlates to stronger weld between the two wires. Laser parameters of pulse energy and pulse number are varied between 20 to 40 µJ and 10 to 100 pulses to develop an initial process window. With a repetition rate of 1 kHz, the corresponding average power that the crossed wires received is between 20 to 40 mW. Over 90 % of all crossed wires samples showed drops in contact resistance from 39.8 % to 83.3 %, indicating that microwelding of gold microwires is possible with femtosecond laser pulses. A welding mechanism is proposed.**

Index Terms* – *gold wire joining, femtosecond laser, microwelding, process window

I. INTRODUCTION

Conventional wire bonding methods utilizes a combination of pressure, ultrasonic vibrations, and high temperatures [1]. This method is known as thermosonic (TS) ball bonding: a solid state joining process. In the microelectronics packaging industry, TS ball bonding is the standard method to make wire bonds. However, this method requires a robust substrate to withstand the high impact force, ultrasonic vibrations, and the high temperatures (typically upwards of 150 °C). However, for soft substrates such as polymers or substrates that cannot handle the high temperatures or ultrasonic stresses, TS ball bonding is unsuitable. We present an alternative wire joining method using a femtosecond (fs) laser system which does not require external applications of pressure, ultrasonic vibrations, or high temperatures. The advantages of using a laser device for welding stems from the laser's ability of introduce a high power density while minimizing the heat affected zone [2]. Reference [3] theoretically showed that fs laser microwelding of metals is feasible with a combination of longer pulses and high fluence or a larger focal radius for a given fluence. With this information, [4] demonstrated the use of fs laser irradiation to induce the welding of microwires to a copper substrate. The present paper investigates the use of fs laser pulses to weld two free-standing Au crossed wires.

II. EXPERIMENTAL DETAILS

Two 25-µm diameter Au wires are initially wire bonded onto a ceramic substrate with Au metallization such that they cross at one point. Figure 1 illustrates eight crossed wires samples on one ceramic substrate. Femtosecond laser pulses are directed at the contact point of the crossed wires. Because the Au bond pads are located at the rim of the central cavity of the substrate, it is necessary to tilt the substrate longitudinally to an angle of approximately 8 degrees with respect to the horizontal to avoid clipping the incoming laser irradiation.

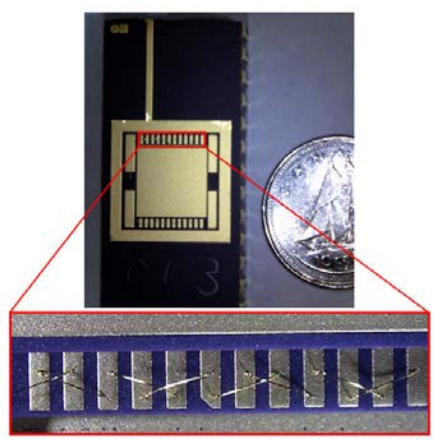

Figure 1 Gold crossed wires on ceramic substrate. Each substrate houses 8 sets of crossed wires.

The initial laser pulses were produced by a Ti:Sapphire tabletop laser which are then regeneratively amplified using chirped pulse amplification. This produces 100 fs laser pulses with a wavelength of 800 nm and a repetition rate of 1 kHz. The energy per pulse was varied between 20 to 40 µJ to produce an average power between 20 to 40 mW, respectively. These incident pulses were passed through a focusing lens (f = 5 cm) and focused onto the crossed wire samples. The laser parameters of output power and pulse number are varied in order to develop a process window for the welding of Au crossed wires using fs laser irradiation.

In-situ four-wire contact resistance measurement is used to determine the quality of the weld. When a constant current is applied across the crossed wires, the contact resistance, R_c, can be calculated provided the voltage drop is measured at the point of contact. Figure 2 illustrates a schematic of how the four terminals are set up on the substrate to measure R_c before and after fs laser irradiation. A stronger weld will correlate to a lower contact resistance. SEM imaging of all crossed wires samples was done using the Zeiss ULTRA *plus* high resolution field emission scanning electron microscope (FE-SEM) at an accelerating voltage of 20 kV.

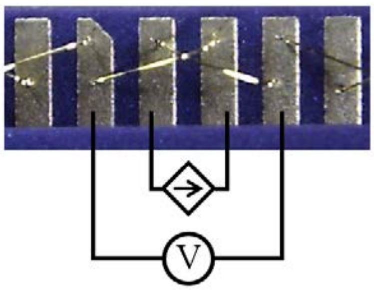

Figure 2 Schematic diagram of the *in-situ* four-wire contact resistance measurement for one crossed wire sample.

III. Results and Discussion

An initial SEM image of a typical crossed wire sample is shown in Figure 3(a). The two wires are held in place by tension making them insensitive to small vibrations and other minute disturbances in a typical laboratory setting. Figure 3(b) and (c) shows typical crossed wire samples before and after fs laser irradiation, respectively. The wires lose their smooth surface morphology after laser irradiation. The result is a laser affected zone (LAZ).

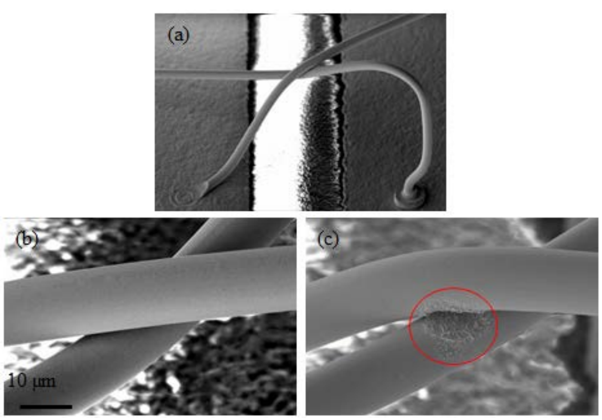

Figure 3 (a) Overview of a crossed wires sample and close-up of contact point (b) before and (c) after fs laser irradiation. The laser affected zone is outlined in red.

The output laser power (*P*) used was 20, 30, and 40 mW and the pulse number (*N*) used was 10, 20, 40, and 100 pulses. Figure 4 shows the weld morphology for each combination of laser parameter. The smallest LAZ is less than 5 µm with laser parameter setting of (*P, N*) = (20 mW, 10 pulses); and the largest LAZ is approximately 25 µm with (*P, N*) = (40 mW, 100 pulses). The LAZ also shows several different structures after fs laser irradiation. The most common morphology is the lip structure as most typically represented by (*P, N*) = (40 mW, 10 pulses). Another distinct structure is a fringe structure as shown by (*P, N*) = (20 mW, 100 pulses). There are also structures that show characteristics of both the lip and fringe structure as shown by (*P, N*) = (20 mW, 40 pulses).

Under constant pulse number, an increase in output power from 20 to 40 mW increases the LAZ in diameter and depth. An increase in the LAZ depth with increasing laser power indicates material ablation. All samples under 40 mW have the lip structure at the edge of the LAZ. Moreover, significant debris in the form of Au droplets is observed beyond the lip structure. These Au droplets range from less than 100 nm to approximately 1.5 µm. Hence, a larger lip structure and the presence of more Au debris could be the result of more molten material splashing away from the point of impact of the fs laser pulses. The observed trend is an increase in output power from 20 to 40 mW increases material ablation and generated more molten material. A similar trend is observed under constant output power and varying pulse number. The LAZ diameter increased from less than 5 µm to approximately 20 µm as pulse number increases from 10 to 100 pulses under the 20 mW. The change in LAZ diameter and depth is not as significant between 30 and 40 mW. The ideal conditions for laser microwelding are the presence of more molten material and lower material ablation [3]. Hence, using a low pulse number between 30 to 40 mW can meet these requirements.

Statistical analysis of the four-wire contact resistance measurements were done to quantify the quality of the weld. For every combination of output power and pulse number, at least four crossed wires samples were exposed to fs laser irradiation. More than 90 % of all samples showed a significant drop in contact resistance. The average contact resistance drops as a function of pulse number and output power is shown in Figure 5. Each contact resistance drop is calculated as a percentage difference using R_c values before and after fs laser irradiation. The majority of the contact resistance drops lie between 60 and 70 %. In particular under 30 mW, the contact resistance drops all fall into the 60 to 70 % range regardless of the applied pulse number.

At a constant pulse number of 10 and 20 pulses, by increasing the laser output power from 20 to 30 mW, the contact resistance drops by a significant amount. However, as the output power continues to increase from 30 to 40 mW, the contact resistance drop is not significantly different from each other compared to the 20 to 30 mW transition. A similar case is observed for the 40 and 100 pulses. The

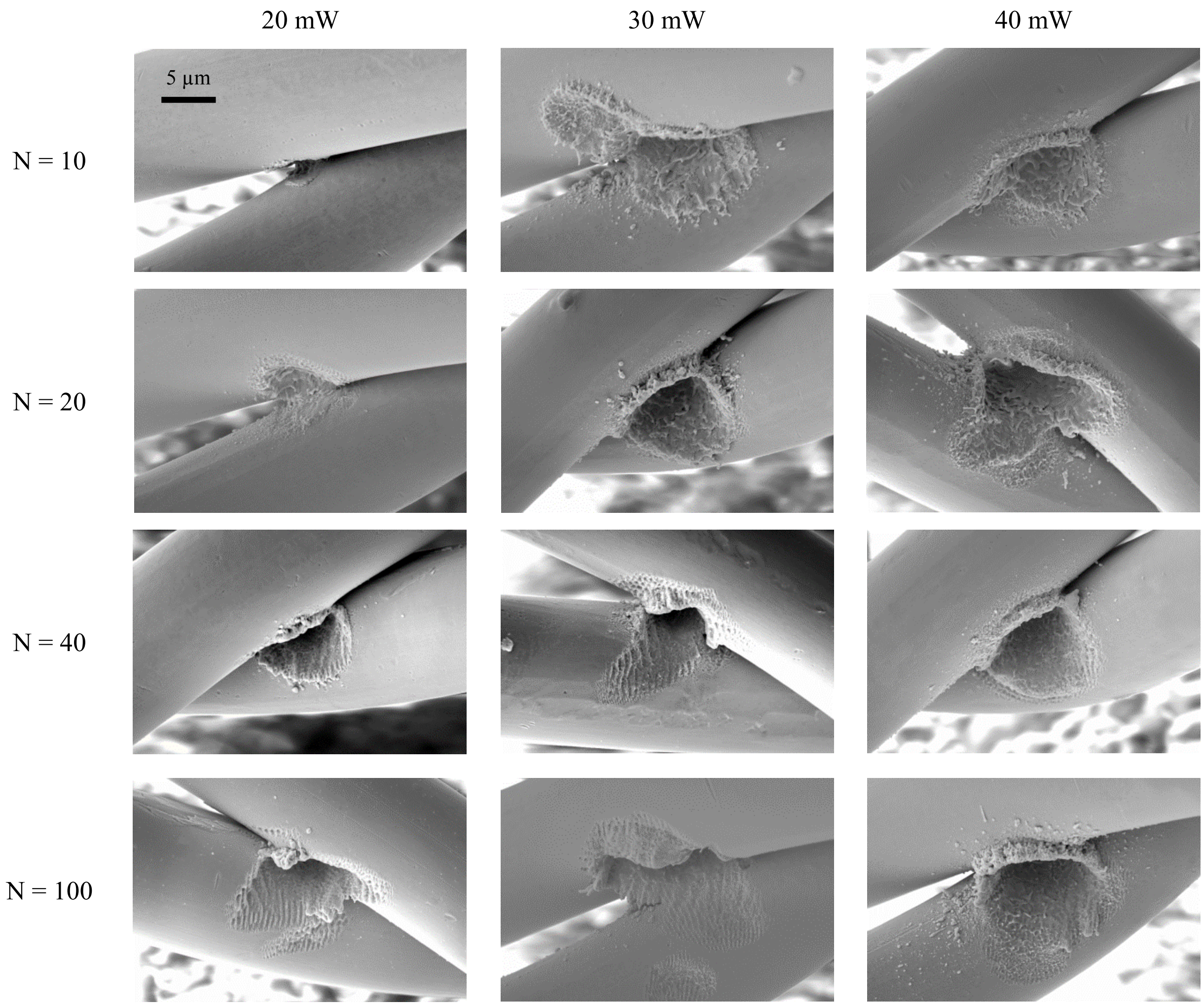

Figure 4 Weld morphologies as a function of output power and pulse number. Increasing either laser parameter correlate to a greater LAZ between the crossed wires.

transition from 20 to 30 mW does not result in a significant drop in contact resistance compared to the transition from 30 to 40 mW. Under the laser setting of (*P, N*) = (20 mW, 20 pulses), the smallest contact resistance drop of 39.8 % was observed. Under the setting of (*P, N*) = (40 mW, 100 pulses), the highest contact resistance drop of 83.3 % was observed. The overall trend observed is that a larger drop in contact resistance is observed as the output power and pulse number increases. For microwelding, using the (*P, N*) = (40 mW, 100 pulses) setting would give the best weld in terms of electrical contact [3].

The proposed welding mechanism is illustrated in Figure 6. The incoming laser irradiation is adjusted to minimize ablation but momentarily melt a thin surface layer on both wires close to their contact point. After the laser irradiation, the molten material is resolidifying but not before trying to reduce surface tension by moving slightly

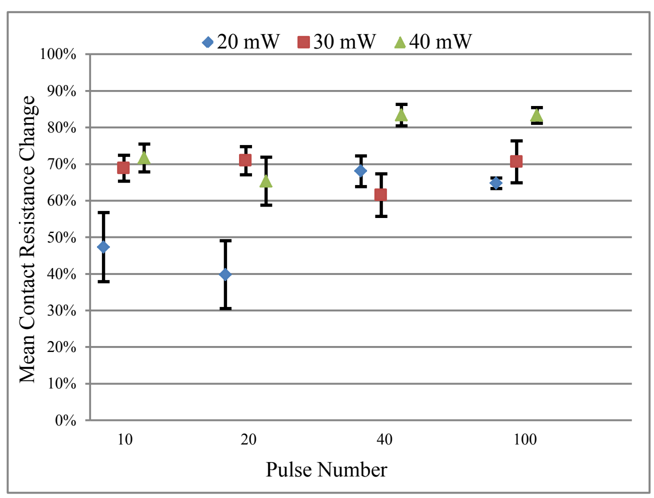

Figure 5 Average percentage drop in contact resistance of crossed wires as a function of output power with corresponding error bars.

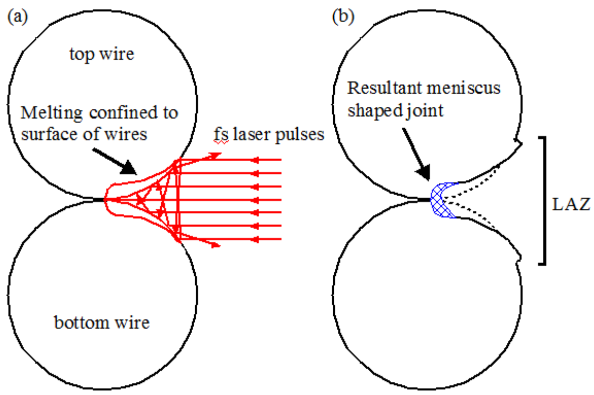

Figure 6 Proposed mechanism of microweld of the Au crossed wires (a) just before and (b) after fs laser irradiation.

towards the gap between the wires. Such pulse actions could result in the formation of a partial meniscus shaped weld metal firmly joining the two wires together. The resultant LAZ depicted is the lip structure LAZ. The diameter and depth of the LAZ increases as output power and pulse number increases. Figure 7 shows the morphology of the LAZ of the bottom wire. The dashed line represents the edge of the top wire. The morphology of the part of the LAZ highlight by the yellow circle is smoother than the rest of the LAZ. This smoothness could be evidence of the meniscus that joined the crossed wires.

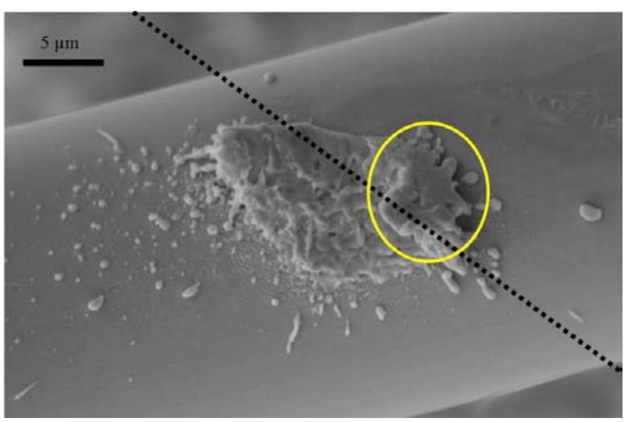

Figure 7 The LAZ after laser irradiation with (P, N) = (30 mW, 20 pulses) on the bottom wire. Its length is approximately 15 µm. The proposed meniscus is shown in yellow.

IV. Conclusion and Outlook

It was shown that fs laser pulses can join two Au microwires in air at ambient temperature without the use of additional process parameters. The pulse energy required is low compared to the maximum available of the laser used. As output power and pulse number increases, the LAZ increases in diameter and depth and the contact resistance drops increases. The highest laser parameter setting of (*P, N*) = (40 mW, 100 pulses) generated a contact resistance drop of 83 %. However, for successful microwelding, the use of (*P, N*) = (40 mW, 10 pulses) is recommended based on this process window because of minimal ablation, which leaves more molten material for the weld. Higher output power and pulse number will be investigated to determine a complete process window for the microwelding to two Au wires.

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