Micro-welding using laser-generated ultrasound

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Abstract

We demonstrate a novel micro-welding process in which laser-generated stress waves produced close to the bonding site assist in the formation of direct metal-metal bonds. The process has been used to attach copper-bumped silicon flip-chips to silver-metallized substrates. De-bonding tests were used to study qualitatively the resulting chip-substrate bonds. It was found that generally the copper-silver welding strength exceeded the adhesion strength between bump and chip. Individual bump shear tests were carried out after de-bonding and showed shear strengths of ~116 MPa. In addition, scanning-electron-microscope (SEM) and focused-ion-beam-scanning-electron-microscope (FIB-SEM) imaging were used to analyse the test samples, revealing that the welding was direct copper-silver solid-state diffusion welding. This new process allows direct metal-metal bonding at low temperature and with localized control over the bonding parameters. Applications are envisaged in advanced electronics packaging where low process temperature or high operational reliability are required.

Introduction

With the ongoing consumer demand for smaller and faster information processing devices, flip chip assembly is emerging as the preferred surface mount technology, replacing ball grid array (BGA), micro-BGA and chip-scale packaging [1]. Flip chip assembly allows the attachment of unpackaged electronic devices to a substrate in a face-down configuration, with electrical connections being provided via conducting "bumps" which also set the standoff height (i.e. gap between device and substrate). Flip chips are still predominantly integrated circuits (ICs), although other components such as passives, detector arrays and MEMS devices are also starting to appear in flip-chip form. Many micro-joining technologies have been developed for flip chip mounting, such as the C4 soldering process, thermo-compression bonding, thermosonic bonding and conductive adhesive packaging [2-4]. With the drive to miniaturisation in electronics manufacturing, new micro-welding technologies are needed to support further downscaling [5].

In this paper we present preliminary results for a new micro-welding process based on laser-generated ultrasound (LGU). Like conventional thermosonic bonding it is a solid-state welding process in which stress-cycling at the bonding interface facilitates bonding. However, rather than employing a conventional ultrasound source, the process relies on the stress transients produced by confined laser ablation of a sacrificial layer or tape placed in close proximity to the bonding site. This mode of stress wave generation is well known from other fields such as metal peening and materials inspection [6,7]; however, it has not previously been applied to solid-state micro-welding. A potential advantage of the proposed approach is that it allows local control over the bonding parameters which may make it easier to overcome some of the technical issues encountered with conventional thermosonic bonding, in particular those associated with achieving uniform bond strength over large areas.

Figure 1 illustrates the basic concept of the new process, as applied in the present work. Light from a high-power, high-repetition-rate, short pulse laser passes through a transparent bond head and is focused onto the sacrificial layer which is sandwiched between the bond head and workpiece. Confined ablation of the sacrificial layer leads to pressure transients which are coupled through to the underlying bonding site where they facilitate bonding. In the present work we used a nanosecond pulsed fibre laser operating at 1064 nm wavelength. The sacrificial layer comprised a 75 µm-thick tungsten foil which acted as an infrared absorber, with an overlying glass layer that generated the ablation pressure and protected the bond head.

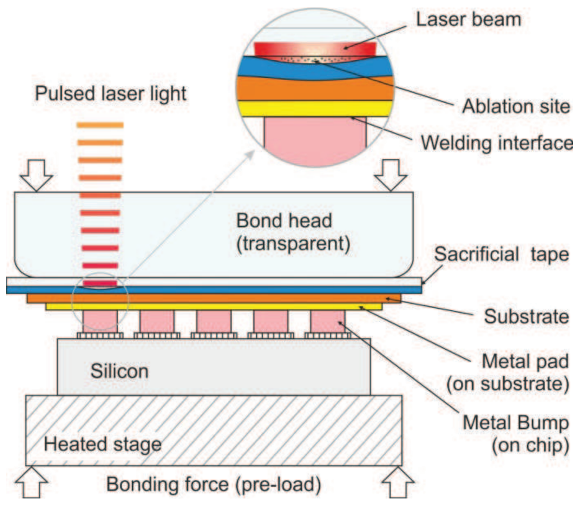

Fig. 1. Laser-ultrasonic micro-welding process as applied to flip chip assembly.

Methodology

Proof-of-concept trials were carried out using a custom flip chip bonder which was adapted from our previous research [8]. The modified system, shown schematically in Fig. 2, comprises a 6-axis micro-positioner (Newport HXP100 Hexapod) for substrate alignment, a sample platform with vacuum holding capability, a bond head equipped with a load cell for monitoring the static bonding force, and an optical alignment system based on a microscope and CCTV camera. Both the sample platform and the bond head incorporate glass windows, allowing illumination of the workpiece from above and below. The system includes two infrared laser sources: a 20 W maximum average power, 1064 nm wavelength, nanosecond pulsed fibre laser (SPI Lasers type SP-020P-A-EP-Z-A-Y) and a 30 W, 970 nm wavelength fibre-pigtailed laser diode (IPG Photonics type PLD-33-974) operated in CW (continuous wave) mode. The pulsed laser beam, which drives the confined ablation, is delivered from above via a galvo scanner (Raylase type SS-II-15). The scanner is fitted with an f163mm f-theta lens, resulting in a focal spot of ~55 μm diameter on the sacrificial tape. The CW beam is delivered from below and is used to pre-heat the workpiece to the required bonding temperature. In the current set-up this beam heats a small silicon plate that is instrumented with a thermocouple, allowing closed loop control of the temperature.

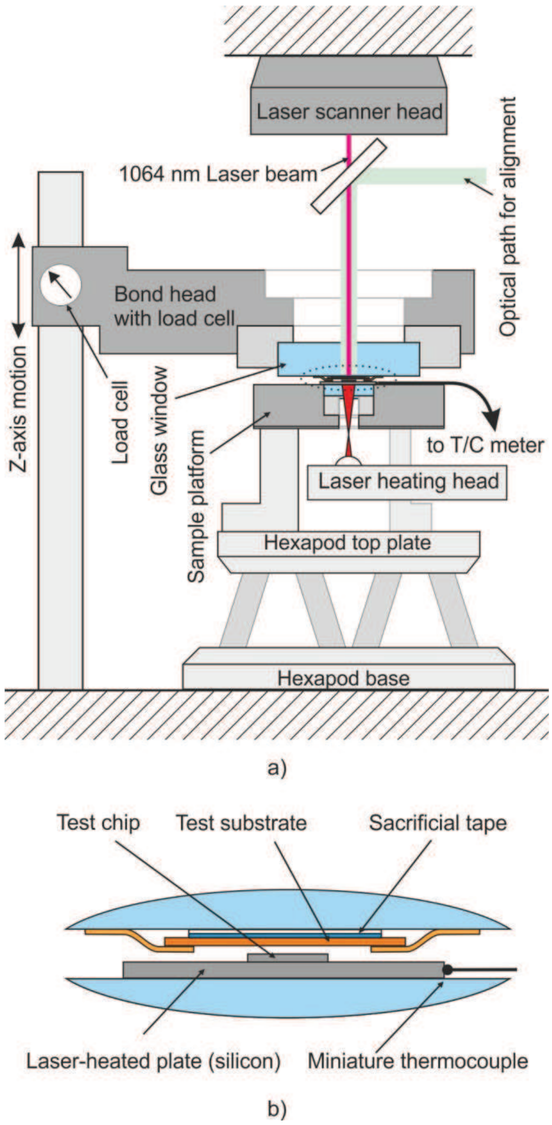

Fig. 2. Custom flip chip bonder: a) overview; b) close-up showing test substrate and chip, sacrificial tape, and laser heated plate with thermocouple.

For these initial experiments the substrate was attached to the underside of the bond head window with adhesive tape, with the sacrificial tape being sandwiched in between window and substrate, as shown in Fig. 2b. The sacrificial tape was a bilayer, comprising a 75 μm-thick tungsten foil with a 1 mm-thick glass cover layer. Inspection of these layers after bonding indicated that most of the ablation damage occurred in the glass.

Bonding tests were carried out using commercial silicon microchips and silver-metallized substrates. The microchips were $4.1 \times 3.6\ mm^2$ with 91 unevenly distributed peripheral I/Os bumped with copper studs that were 60 μm in diameter and 50 μm in height and mostly arranged on 90 μm pitch. There were also 56 evenly distributed larger copper studs; these were 120 μm in diameter and 50 μm in height and arranged in an 8 × 7 matrix on 500 μm pitch at the chip centre. The substrates were in the form of a stainless steel foil (200 μm thick) with a silver conductor layer formed by stencil printing and nano-sintering. Each substrate was $9.2 \times 9.2\ mm^2$ and topped with a central silver pad $5.6 \times 5.6\ mm^2$ in area and 12 μm thick.

The key input variables for the LGU micro-welding process are the pulsed laser parameters (pulse fluence, repetition rate and burst duration), the bonding force and the bonding temperature. In the experiments reported here a series of 10 ms duration pulse bursts was applied to each flip chip assembly. Each pulse burst comprised a sequence of 28 ns FWHM pulses at 80 kHz repetition rate, with single pulse fluences of $\sim 8\ J/cm^2$ at the exposure site. The burst duration was chosen to be similar to the typical formation time of thermosonic bonds [9,10]. Also the bonding temperature (160 °C) and bonding force (98 MPa) were chosen to be commensurate with typical values used in conventional thermosonic bonding. The bonding force was sufficient to deform the silver layer so as to form many micro-contacts, but not large enough to cause plastic deformation of the copper bumps. The laser power was the maximum for which the ablation damage did not fully penetrate the glass cover layer. Pulse bursts were applied at 528 sites arranged in a 24 × 22 array on 0.25 mm pitch. The individual sites were not aligned to the I/Os on the microchip, and the array covered an area larger than the chip.

The procedure followed in each trial was as follows. The chip and substrate were mounted on the bonder and aligned relative to one another laterally. Previously the orientation of the sample platform would have been adjusted to ensure good parallelism between bond head and platform under loaded conditions. The bond head was then lowered, first to bring the chip and substrate into contact and then to apply the required load. The CW laser heating was then applied, and the temperature of the laser-heated plate ramped up and held at the bonding temperature while the pulsed laser was fired. Finally the laser heating was removed, the work piece cooled to room temperature and the bonding force removed.

De-bonding tests were used to study the resulting chip-substrate bonds. In these tests, bonded samples were pried open using a scalpel and examined by microscope. In addition scanning-electron-microscope (SEM) and focused-ion-beam-scanning-electron-microscope (FIB-

SEM) imaging were used to further analyse the test samples. In order to quantitatively examine the micro-welding strength, a shear tester (Nordson DAGE S250G-4000plus) was used to test the shear strengths of individual bumps. The shear test processes were closely monitored using an optical microscope to ensure smooth and well-balanced testing.

Results

In the de-bonding tests it was found that most of the bumps separated from the chip and remained welded to the silver layer on the substrate. Fig. 3 shows SEM images of typical Cu bumps at various stages of the process. Fig. 3a shows typical bumps on a chip, while Fig. 3b shows the same region of the chip surface after de-bonding, with cavities in the top dielectric layer where the bumps have been pulled away. Fig. 3c shows the transferred bumps which are now on the silver layer.

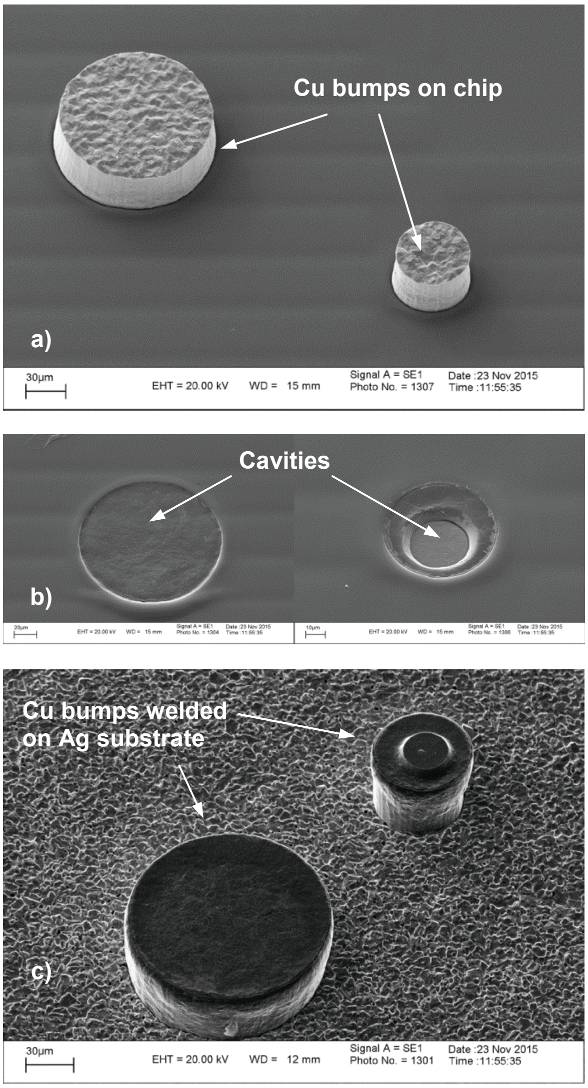

Fig. 3. SEM images showing: (a) bumps on chip prior to bonding, (b) cavities on chip after de-bonding, and (c) bumps on substrate after de-bonding.

FIB-SEM cross-section analysis confirmed that the copper-silver bonds were direct solid-state metal-metal welds. Fig. 4 shows a typical result. The image shows a clear bonding line between the copper bump and silver pad with no evidence of an intermetallic layer; there was also no evidence of melting along the interface.

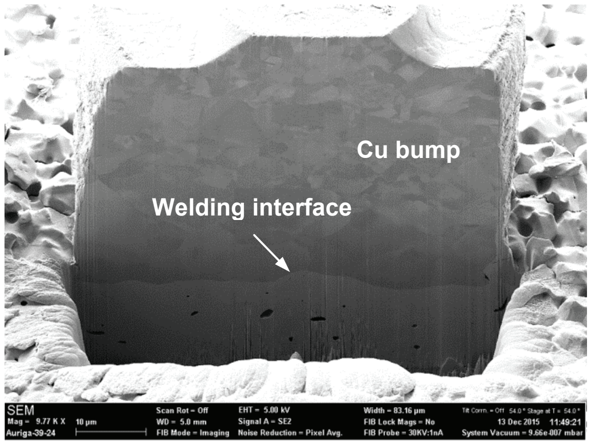

Fig. 4. FIB-SEM cross-section of a typical copper-silver joint formed by laser-ultrasonic micro-welding.

Shear strength measurements on 10 individual large-size copper bumps transferred to a silver metallized substrate ranged from 117 to 158 gf/bump. The average shear strength was 133 gf/bump which is equivalent to 116 MPa. Two types of failure mode were observed, as shown in Fig. 5. One type is a bonding failure at the copper-silver welding interface and the other is mainly a cohesive failure within the electroplated copper.

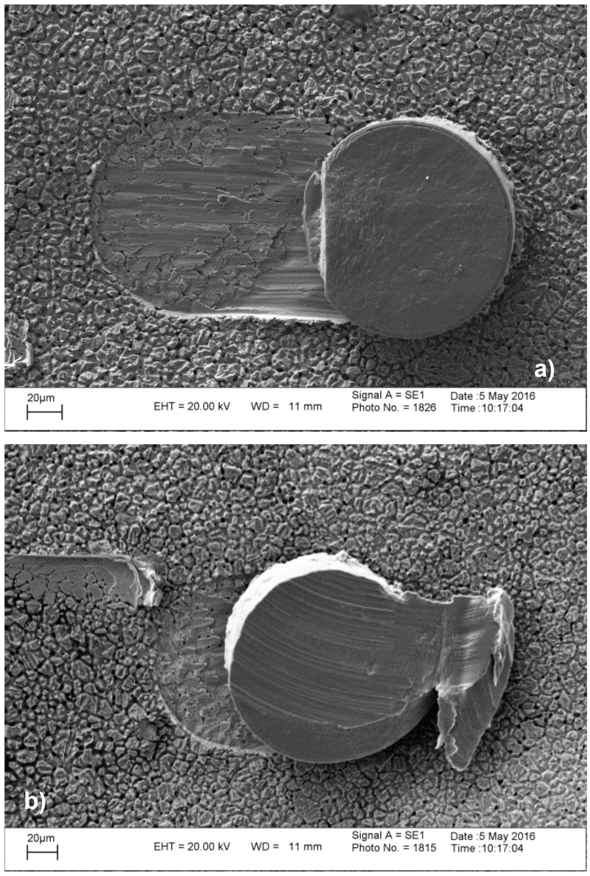

Fig. 5. Shear test failure modes: (a) failure at the Cu-Ag welding interface; (b) bulk failure within Cu bump.

Discussion and Conclusions

To our knowledge this is the first study to investigate the feasibility of solid-state micro-welding using laser generated ultrasound. The experimental results obtained confirm that strong copper-silver bonds can be formed using this novel welding approach, and that the technique is applicable to fine-pitch flip chip assembly. De-bonding tests revealed that the copper-silver bond strength exceeded the adhesion strength between bump and chip. Moreover, individual bump shear tests yielded an average bond strength of ~116 MPa. This is higher than the yield strength of pure copper which explains why cohesive failure of the copper bumps was seen in some cases.

Although the mechanism underlying the new process is not yet fully understood, we believe that the ultrasonic stress waves generated by the confined laser ablation of the sacrificial tape are key to successful bonding. Control experiments carried out with the fibre laser operating in CW mode, and delivering the same average power, showed no bonding.

This is a conceptually new, low temperature micro-welding technique applicable to flip chip bonding. It allows direct metal-metal welding without the need for interconnect fillers such as solders or conductive adhesives. Furthermore it allows controlled delivery of ultrasonic excitation over large areas. We believe there are potential applications in low-temperature packaging and in power electronics packaging where the packaged devices need to serve in a high temperature environment.

Acknowledgments

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