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Research Article

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Chip bonding of low-melting eutectic alloys by transmitted laser radiation

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Abstract: Present-day thermode bond systems for the assembly of radio-frequency identification (RFID) chips are mechanically inflexible, difficult to control, and will not meet future manufacturing challenges sufficiently. Chip bonding, one of the key processes in the production of integrated circuits (ICs), has a high potential for optimization with respect to process duration and process flexibility. For this purpose, the technologies used, so far, are supposed to be replaced by a transmission laser-bonding process using low-melting eutectic alloys. In this study, successful bonding investigations of mock silicon chips and of RFID chips on flexible polymer substrates are presented using the low-melting eutectic alloy, 52In48Sn, and a laser with a wavelength of 2 µm.

Keywords: chip bonding; eutectic alloys; polymer substrates; transmission laser bonding.

1 Introduction

The technological advancements of complex and individualized electronics products, such as radio-frequency identification (RFID) chips, will lead to significant changes in the requirements for their manufacturing processes in the coming years. It is, therefore, necessary to push the envelope of key processes in order to maintain viable and profitable automated production. Present-day assembly systems are mechanically inflexible, difficult to control, and will not meet future manufacturing challenges sufficiently. As one of the key processes in the production of integrated circuits (ICs)/semiconductors, chip bonding has a high potential for optimization regarding process duration and process flexibility. The overall objective is to increase the productivity of the bonding process by reducing the process time and by increasing the process flexibility. For this purpose, the current adhesive technologies are to be replaced by a transmission laser-bonding process using low-melting eutectic alloys. Therefore, in contrast to applying indirect heat by means of a thermode (adhesive bonding technology), the scientific challenge is to investigate whether a eutectic connection using laser radiation with a wavelength of 2 µm, whose bond energy can be delivered directly to the joining interface, is feasible. The aim is to produce stable and electrically conductive connections on flexible polymer substrates, which are becoming more and more commonly used, with minimal thermo-mechanical loading. In this study, results are presented on the transmission laser bonding of mock silicon chips and industry-standard RFID chips onto flexible polymer substrates using the low-melting eutectic alloy 52In48Sn.

2 State of the art

The electrical and mechanical connection of ICs to substrates can be achieved in various ways: including variants of soldering as well as adhesive technologies [1]. The two common methods of metal-based chip bonding are eutectic bonding and the reflow soldering [2–9]. These methods require an activation temperature in the fusion region between substrate and component, which is generally significantly higher than the glass transition temperature of the polymers. For this reason, the bonding technology of polymers is challenging compared to conventional rigid, non-organic materials, such as silicon or ceramics. The high temperature results in a loss of structural integrity

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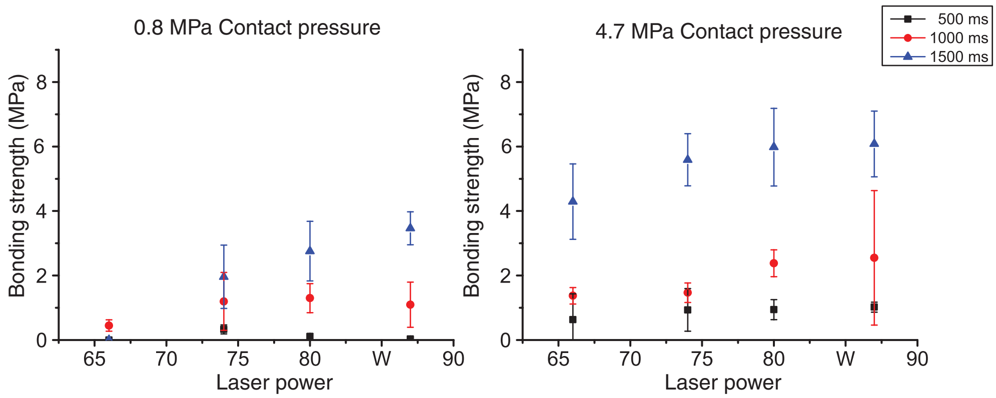


Figure 1: Indium-tin – laser power vs. bonding strength with different contact pressures for Si-Si compounds. Wavelength 1070 nm [14].

of these polymer substrates [10]. Additionally, as a solder joint cools, residual stresses can form due to the chip, substrate, and solder having different coefficients of thermal expansion and cooling rates. This can further weaken the bond connection [4]. The bonding process requires a melting or thermal-activated fusion in the bonding zone. This thermal load depends on the intermetallic diffusion, recrystallization properties, and the melting temperatures of the materials. With eutectic bonding, lower temperatures can be used for the process, reducing residual stresses and allowing the use of substrates with low glass transition temperatures. Therefore, connections with low-melting, electrically conductive eutectic alloys are demanded. Eutectic alloys have the unique property of forming mechanically and electrically stable bonds at temperatures below the melting points of the individual elements. These alloys play a vital role in the manufacturing, packaging, and interconnection of electrical components with low thermal budgets.

Recent investigations by Akin et al. have used eutectic compositions of indium-tin (52 wt% In, 48 wt% Sn, or 52In48Sn) and indium-bismuth (66 wt% In, 34 wt% Bi, or 66In34Bi) to bond silicon ICs onto polycarbonate (PC) substrates at lower than conventional temperatures [2, 3]. Heating the system (chip and substrate) to 130°C for 15 min using the 52In48Sn eutectic composition leads to successful bonds between the ICs and polymer substrates without exceeding the glass transition temperature of the polymer [2–4]. Drawbacks of this process are the need to heat all components in the system to the bonding temperature and the resultant long heating time required to achieve bonding.

Localized heating is employed to reduce the thermal load of sensitive components, for example, by localized eutectic bonding, localized melting compounds, solder bonding, or transmission laser bonding (TLB) [11–13]. TLB is generally used to bond a transparent to an opaque material with or without the use of an intermediate layer. For this purpose, the energy is induced by means of a laser within or near the bonding layer, which is necessary to build an intermetallic phase or melt the solder. For this, it is not necessary to heat the entire substrate or component to an elevated temperature. Moreover, the required thermal load is induced locally, so that the thermally affected zone is minimized. There have also been trials using TLB, with a wavelength of 1075 nm, to create eutectic joints between silicon chips and silicon substrates. Figure 1 shows the bonding strength with different downward forces for Si-Si compounds [14]. The use of laser radiation has a high potential to optimize the bonding procedure by reducing thermal loads, decreasing process times, and increasing process flexibility.

3 Experimental setup

As mentioned previously, an increase in the process efficiency can be achieved by introducing the energy directly into the joining zone. For this purpose, laser radiation with a wavelength of about 2 μm is used because it has a transmittance of over 50% for uncoated silicon. The remaining laser radiation is largely reflected at the boundary layer and does not cause any significant interactions with the material. In contrast to the indirect heating by means of thermode (adhesive bonding technology), the energy can be introduced locally. By the use of a fiber laser, it is possible to precisely apply the bonding energy and achieve localized heating as well as a minimal interaction with the environment [15].

The specifications of the laser source used are shown in the table in Figure 2. The laser was developed by the company LISA Laser Products OHG, 37191 Katlenburg-Lindau, Germany. Although this laser is produced for soft tissue surgery, the provided wavelength of 2013 nm is well suited for laser transmission bonding of silicon. The source can operate in continuous wave mode and in pulsed wave mode with pulse durations of 50–1000 ms with a power output between 5 and 70 W.

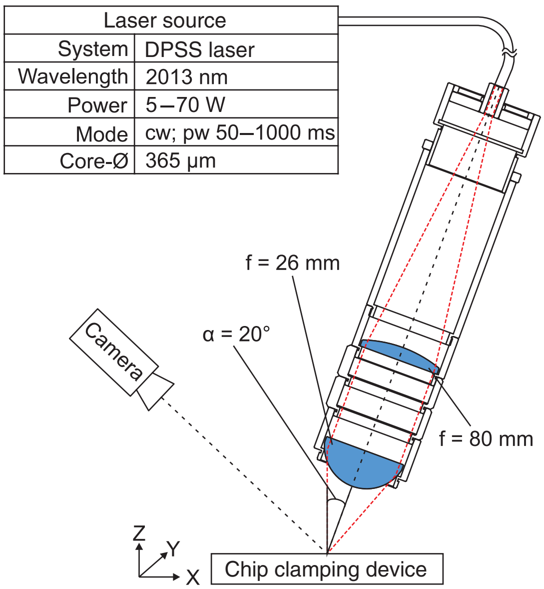


Figure 2: Schematic optical assembly.

As shown in Figure 2, the schematic optical assembly consists of a laser source (including fiber), an observing camera, the laser head, the clamping devices, and an axis system. The laser head is mounted at an angle of 20° from vertical to prevent back reflection damage by laser radiation. All experiments are carried out at the focal length of the optics where the resulting process spot diameter is 123 µm. A high-resolution zoom camera is also mounted to observe the process. The clamping devices, described in more detail below, can be moved by means of a high-precision axis system in three axes. The positioning is, thus, performed manually with the monitoring camera and the axis system.

Because of its low eutectic melting temperature, the alloy 52In48Sn provides the possibility to bond on polymer substrates. At the eutectic temperature of approximately 417 K, which is slightly below the melting temperature of indium, an In-rich matrix is formed with a temperature-dependent tin content of about 11 w% at 417 K and 12 w% at room temperature. The alloy obtains semiconducting properties by decreasing the temperature down to 286 K. The coating of this eutectic alloy on the chips is made by thermal vaporization with an electron beam evaporator and the related eutectic alloy components. For this purpose, the vapor deposition LAB500plus of the company Leybold® Optics was used. Figure 3 shows a schematic illustration of the layer structure of the bond partners. The polymer foil is vapor coated with a 50-nm-thick layer of chromium. This chrome layer serves as an adhesion promoter and as a diffusion barrier. As shown, a foil with an applied aluminum antenna is used for the RFID bonding tests. The eutectic bonding partners are deposited on the Si-chip and the polymer foil. The layer thickness of the eutectic chip component t_C to be evaporated is determined stoichiometrically by: $t_C = \frac{\rho_F \cdot t_F \cdot m_C}{\rho_C \cdot m_F}$, where ρ_F and ρ_C are the densities of the foil and chip coatings, respectively, m_F and m_C are the eutectic weight percentages of the foil and chip coating, respectively, and t_F is the thickness of the coating on the foil. Specifying the thickness of indium deposited onto the substrate to be 1 µm, the resulting thickness of tin deposited onto the chip is calculated to be 1.17 µm. These layer thicknesses are held as constants throughout all the experiments.

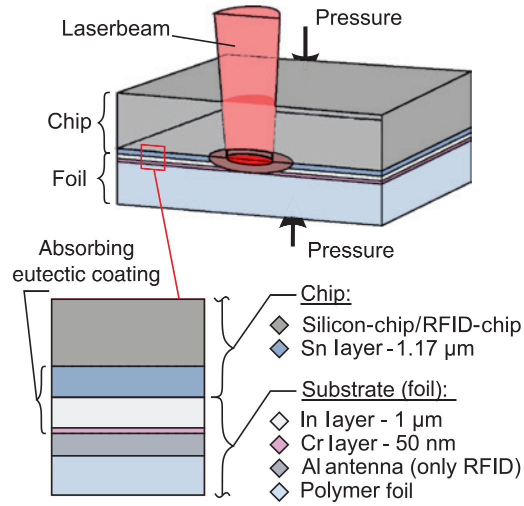


Figure 3: Schematic illustration of the layer structure.

In this study, two different types of chips are tested. The majority of the investigations are carried out using mock large-format silicon chips to increase ease of handling, and results from these primary investigations are then applied to the RFID chips. Figure 4 shows the dimensions of the two chip types as well as the two different clamping devices. The larger mock chips have dimensions of 10 mm × 10 mm with a thickness of 0.52 mm. By contrast, the RFID chip dimensions are approximately 480 µm × 420 µm with a thickness of approximately 100 µm. Also seen in Figure 4 are the two copper pads on the bottom of the RFID chip, which are the intended points of connection to the aluminum antenna on the polymer substrate.

The figure shows a schematic illustration of the two fixtures designed for the investigation of the laser-compressive bonding of eutectic alloys. The fixture for the mock chips consists of a chip and a downholder. A set screw in the matrix exerts a defined torque on a counter plate and, thereby, a steady pressure to the chip held against the counter plate. The contact pressure results from the torque, M_A. In this study, M_A was varied from 0.03 Nm to 0.13 Nm. The fixture for RFID-chips consists of a baseplate and a pressure plate between which the chip and substrate are compressively held together. Silicon wafers are diced to a thickness slightly thinner than the RFID chips and used as a holder and mask (as shown in Figure 3) with holes etched using deep reactive ion etching. The holder has a precisely machined square cutout for the RFID chip to sit in, whereas the mask has two holes aligned with the copper contact pads of the chip to allow laser radiation through and acts to provide counterpressure against the chip. A constant pressure is applied to the substrate and chip via a predefined torque of 0.07 Nm in each of the screws in the pressure plate.

The experimental methods used differ according to the chip type to be tested, as described in the following.

3.1 Large-format mock chip methods

The chip and foil is positioned using a high precision three-axis stage. A single pulse of laser radiation is delivered to the centre of each clamped chip with various pulse durations ranging from 500 ms

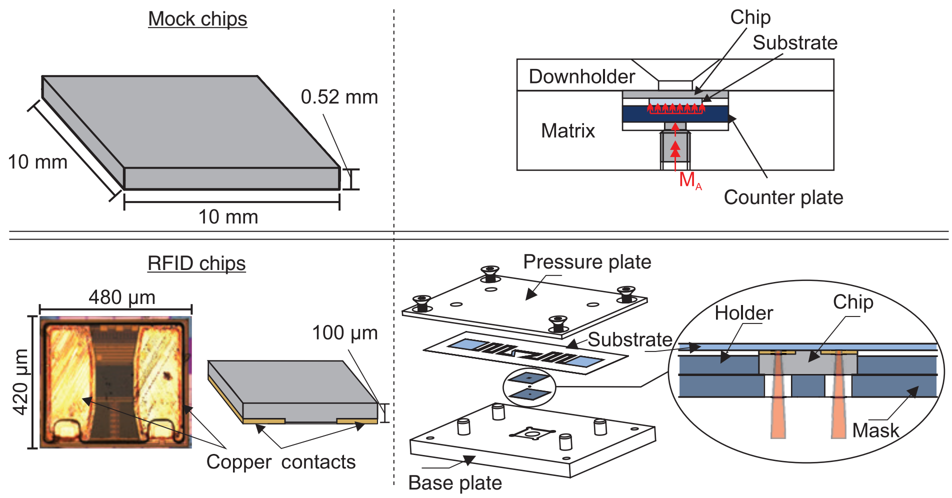


Figure 4: Different chip types with their respective clamping devices.

to 1000 ms, pulse powers ranging from 45 W to 70 W, and clamping torque M_A ranging from 3 cN · m to 13 cN · m. To evaluate bonds, samples are sheared and then analyzed using a scanning electron microscope (SEM) and energy-dispersive X-ray spectroscopy (EDX). Cross sections of intact bonds are also analyzed using EDX line scans across the bond interface.

3.2 RFID chip methods

Eutectic transmission laser-bonding tests are conducted on the RFID chips depicted in Figure 4. The modified clamping device is used to hold the foil and chip in place during the process and is positioned using a high-precision three-axis stage. Two pulses of laser radiation are delivered to each chip; one on each copper pad. In order to find a set of parameters, which achieved bonding, pulse powers are varied from 10 W to 50 W, pulse durations are varied from 100 ms to 400 ms, while clamping pressure is held constant by maintaining a tightening torque of 7 cN · m in each screw of the pressure plate. Select bonded RFID chips were then analyzed in more detail using X-ray tomography, SEM, and EDX scans.

4 Experimental results

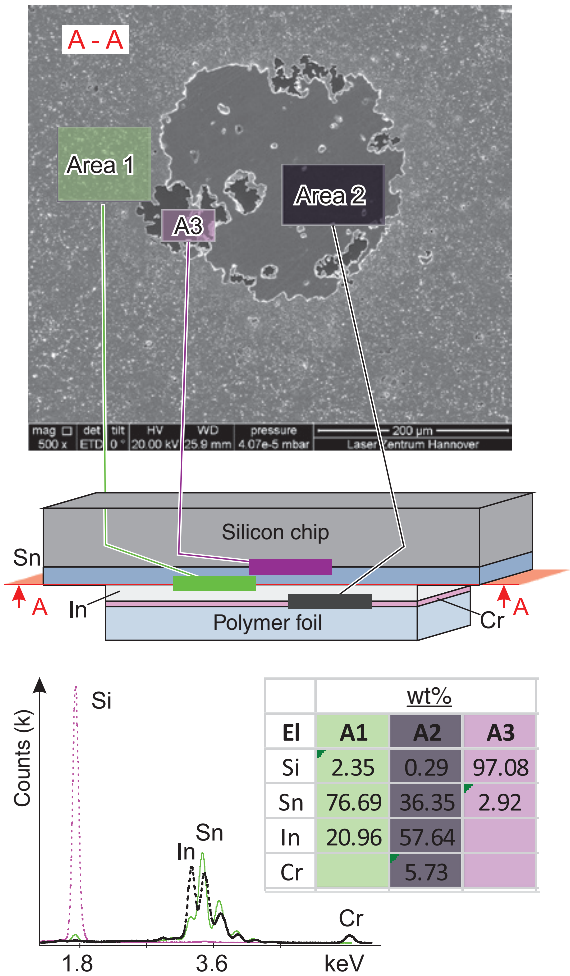
The results are equivalently subdivided into the chip types in the areas of Mock chip results and RFID chip results.

4.1 Mock chip results

Within the scope of the investigations, a single pulse of laser radiation is delivered to the center with various process parameters of each clamped chip. In this study, the parameters were examined within the mentioned limits.

Because of the holding of the shear tester used, the shearing partners must be of different sizes to allow them to be clamped and separated. The rigid chips are larger than the substrates due to the construction of the clamping device. In consequence, the chips are clamped in the shear tester, and only the substrates can be sheared off. Because of the flexibility of the foils, no significant results could be determined so far. However, an increasing trend of the shearing force with rising pulse energy and the pressure force can be seen. Therefore, a similar course as in the investigations of the silicon-silicon compounds by Hoff et al. (see Figure 1) is to be expected [14]. Additionally, no damage could be observed by the visual analysis of the microscopic and the SEM images of the film surfaces.

In order to draw conclusions on the chemical composition of the bond, surface areas of the sheared bond partners were examined by X-ray spectroscopy. Figure 5 shows the SEM surface image of a sheared silicon chip. Essentially, three areas can be distinguished. In the largest area, Area 1, a weight percentage (wt%) of 76.7% tin and 21% indium is detected. The EDX analysis method involves a certain penetration depth, whereby also 2.35% of silicon is detected. Because of the weighting of the elements from Area 1, it can be assumed that a process-related indium-tin bonding has taken place. The analysis of Area 2 shows a share of 5.73% chromium in addition to 57.6% indium and 36.35% tin. This compound suggests that the coating has dissolved from the polymer foil in this area. Thus, the indium-tin compound formed in this area has stronger bonding forces than the bonding of the chromium with the foil. In Area 3, there is 97% silicon. Here, the indium-tin compound also has a stronger bonding strength than the bonding of the tin to the chip.



El	A1	A2	A3
	wt%		
Si	2.35	0.29	97.08
Sn	76.69	36.35	2.92
In	20.96	57.64	
Cr		5.73	

Figure 5: X-ray analysis of the chip surface. Process parameters: power 70 W, pulse duration 1 s, torque 0.13 Nm.

When the sheared substrate is viewed, an inverse composition is obtained. A major part of the area is equivalent to Area 1 of approximately 75 wt% indium and 22 wt% tin. This suggests that the compound has taken place at the interfaces, but the mixing has not been able to spread through the entire layer. In some areas, the material has been removed, and mainly, the underlying polymer is detected.

In order to determine the influence of the downward force by the tightening torque and the pulse duration on the element composition, investigations were carried out and evaluated by EDX spectroscopy. Figure 6 shows the elementary weight distribution of the bond constituents against the minimum and maximum values of the torque and the pulse duration analyzed on the sheared substrates. The proportions of chromium and silicon changes negligibly, while the eutectic components, indium and tin, converge to the eutectic composition with increasing torque and increasing pulse duration. This trend suggests

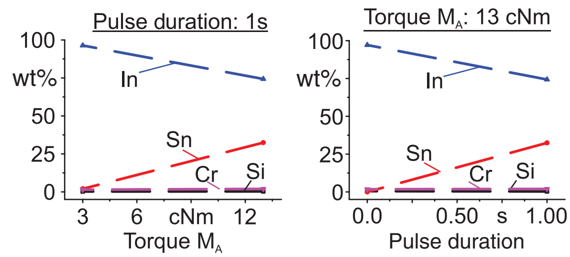


Figure 6: Tendency of the element composition of the bonded substrates with increasing torque and increasing pulse duration.

that increasing pulse duration and tightening torque promotes a mixing of the two elements to form the eutectic alloy. As expected, there is an inverse trend when analyzing the bond constituents on the chips: the tin content starts high and decreases, while the indium content starts low and increases.

As stated previously, in addition to the sheared samples, cross sections of intact bonds using EDX line-scans across the bond interface (Figure 7) were analyzed. Through the progression of the element composition, conclusions can be drawn about the position of the applied layers. From the elementary distribution, it can be assumed that a compound of tin and indium has been formed. Considering the elementary weight distribution at the distance, *xi*, of the boundary surface to the silicon or

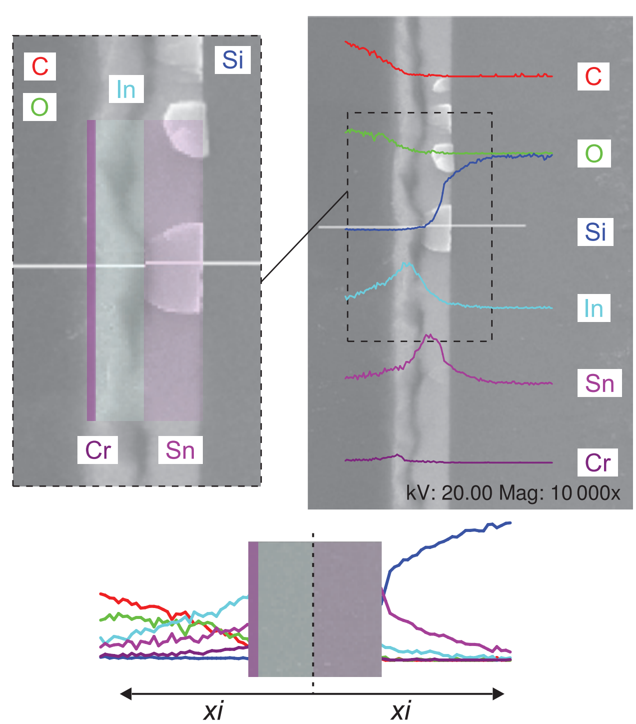


Figure 7: Line scan of a cross section. Process parameters: power 70 W, pulse duration 1 s, torque 0.13 Nm.

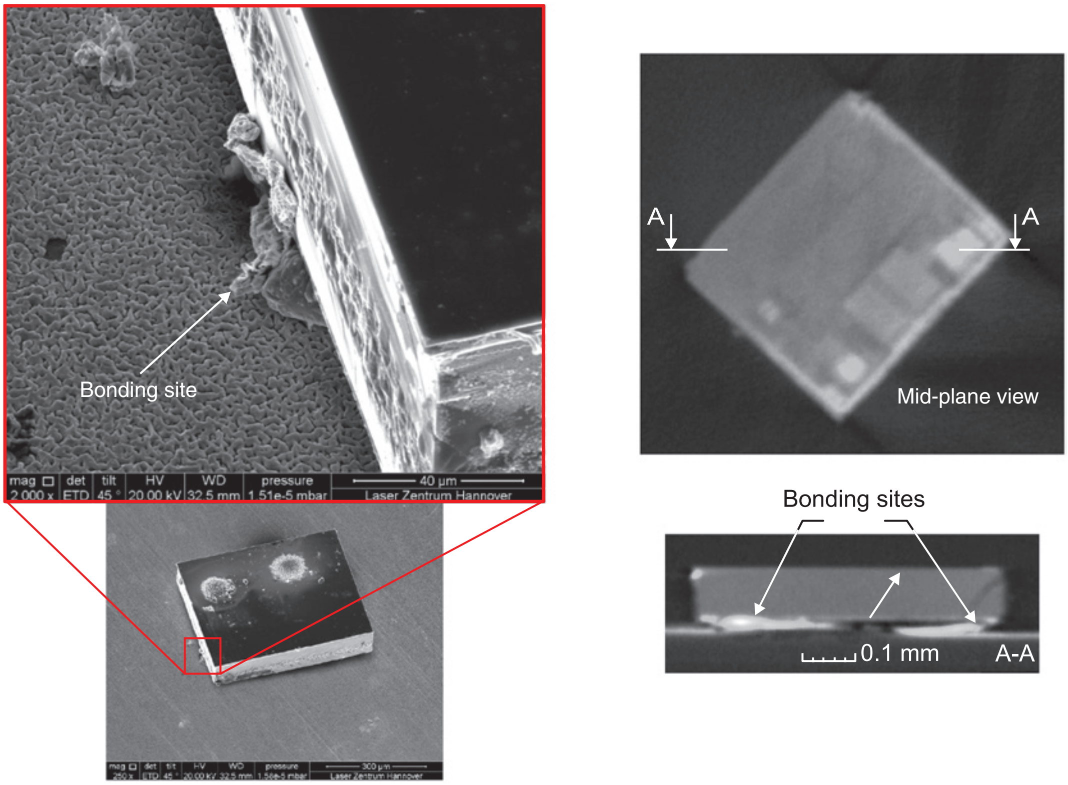


Figure 8: Left side: SEM image of bonded RFID chip (50 W, 250 ms); right side: tomography cross sections of bonded RFID chip (50 W, 250 ms).

the polymer, the weighting of the tin and the indium on the polymer side is significantly higher. Therefore, diffusion appears to increase in the direction of the polymer.

4.2 RFID chip results

When transferring the results gained from the bonded mock chips to the RFID chips, it is found that it is possible to bond the chips with pulse powers between 30 W and 50 W with pulse durations between 200 ms and 250 ms. Therefore, the energy range of a single pulse required to achieve bonding is between 6 J and 12.5 J. The detailed SEM images shown in Figure 8 on the left side clearly show the regions through which the laser pulses were delivered along with a close-up image of one of the bonding sites. The visible surface damage observed at the two laser radiation coupling points may be attributed to the unoptimized prototype assembly and the resultant undefined downward forces. Investigations by Akin et al. have shown that the contact pressure has a decisive influence on the resulting eutectic connection [2]. Furthermore, contaminants on the surface of the chip may have also lead to unwanted radiation absorption at the surface. The small regions of melted material, which are observed under the chip are hypothesized to be bonded sites.

Cross sections of a bonded chip and substrate are shown in the tomography scans in Figure 8 on the right side. As noted in the figure, these cross sections are taken diagonally across the chip with the mid-plane view showing parts of the inner circuits and copper pads. These scans reveal that the bonding regions are present throughout the midsection of the chip. It can also be seen that the copper contact pads appear to be delaminating from the silicon body of the chip. Although the chip is shown to be bonded to the substrate, it is unclear if or how much damage was incurred to the chip due to the bonding process. As this is a preliminary proof to show that bonding is possible, there are still further possibilities to tune the parameters in order to optimize the bonding process.

5 Conclusion and outlook

In this study, the feasibility for transmitted laser bonding of Si chips on flexible polymer substrates was demonstrated. It was proved that it is possible to bond mock silicon chips coated with 52In48Sn alloys without inducing thermo-mechanical stress on the substrate. The bond quality seems to depend essentially on the contact pressure and the laser energy. With increasing pressure and pulse duration, the degree of intermixing of the eutectic connecting elements also increases. The assumption suggests that this intermixing can be further enhanced by an optimization of the process conditions and parameters. A connection without thermo-mechanical stress of the flexible substrate could also be produced for the RFID chips. So far, however, these successful bonds have been associated with damage to the chips. It is assumed that the results of the RFID chips can be significantly improved with optimized clamping and beam guidance. These improvements would ensure a well-defined contact pressure and precise positioning of laser radiation. Finally, by raising the downward force, the contact pressure is increased, and it is expected to reduce the laser power required to generate bonds.

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