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Scalable Batch Transfer of Individual Silicon Dice for Ultra-Flexible Polyimide-Based Bioelectronic Devices

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Abstract— **Demands on flexible neural interfaces in terms of functionality, spatial resolution and longevity have increased in the past years. These requirements can be met by sophisticated integrated circuits developed in CMOS (complementary metal oxide semiconductor) technology. Embedding such fabricated dice into flexible polymeric substrates greatly enhances the adaption to the mechanical environment in the body. With the process developed here, 100 % of individual dice (n = 34, 390 x 390 µm²) could be transferred simultaneously into polyimide (PI) substrates with simple and exact positioning (0.2° rotational and 5 µm translational error). Levelled layer build-up and standard microfabrication technologies could be used for CMOS-post-processing in order to manufacture metal interconnections between contact pads of 100 µm thin dice and PI insulation as selectively patterned device substrate. The process allows for individual positioning according to desired shape of the final chip-in-foil-system and for upscaling the number of dice to be transferred. Furthermore, final distribution and embedding of dice on the flexible substrate is independent from their distribution on the CMOS fabrication wafer the and does not require additional adhesion promoters. During fabrication the transfer method is insensitive to high temperatures (450 °C in this study) and hence enables a wide range of post-processes. Shear strength between dice and PI substrate was characterized by shear tests and results (58.1 ± 13.7 MPa) are in the range achieved with the adhesive benzocyclobutene (BCB).**

I. INTRODUCTION

Bioelectronic systems have the potential to restore or maintain function in patients with neurologic deficits by providing a link between the human nervous system and a technological system [1–3]. While such systems become more sophisticated, the need for high integration density and spatial resolution, besides long-term functionality, is large. High spatial resolution by increasing the electrode density [4], as well as high complexity level of integrated circuits (ICs) are realized in sophisticated complementary metal-oxide semiconductor (CMOS) technology. However, the mechanically stiff silicon dice induce a foreign body response, that leads to tissue encapsulation of implants and insulation of electrode contacts from neurons which in return compromises chronic studies and applications [5, 6]. It has been shown that this effect can be minimized by matching the implants mechanical properties to the host tissue and making the implant conformable to mimic the biological surface shape. Conformability leads to intimate contact and therefore high efficacy and minimal invasiveness [3, 7, 8]. Polyimides (PI) are chemically and mechanically stable, compatible with standard microfabrication technologies and able to conform to curvilinear structures such as the brain [7]. They are excellent materials for flexible substrates, as shown in several studies [9–11]. Therefore, chip-in-foil systems were proposed, that combine small CMOS dice and flexible PI substrates, which allows the development of bioelectronic devices with complex functionality and good adaption to the biomechanics of the host tissue [3, 12, 13].

Cost in fabrication of CMOS dice, however, is determined by area. Arrangement of ICs with minimal distance on the CMOS wafer is essential to reduce wasted space due to separation of individual dice and enhance yield. In some cases distribution of dice on the foil is desired as on the fabrication wafer [14]. However, if distribution of these dice on a flexible target substrate differs from the initial distribution on the fabrication wafer, single dice have to be moved individually to the desired position [15–18]. This can be rather complex when several dice with dimensions of a few hundred micrometres have to be transferred, aligned and embedded into a flexible substrate. Especially, when the final system requires for precise interconnection between contact pads on different dice, in a distance which is some magnitudes larger than the die-size itself, rotational and translational error must be minimal.

The present work describes a process for transfer, alignment and contacting multiple dice of arbitrary shape and size into flexible PI-based substrates with target positions on the PI independent from the die position on the fabrication wafer. Dice with edge lengths of few hundred µm and thicknesses in the range of 100 µm and smaller are difficult to handle individually. This process is based on placement of individual dice into cavities in a silicon carrier wafer which allows for further levelled standard microfabrication steps e.g. photolithography, physical vapor deposition and grinding. Precise positioning is guaranteed, setting the relative position of contact pads on all dice prevents shorting of contacts or contact pads from not being connected. All process steps and materials used allow temperatures up to 450 °C. After the dice are ground to the desired thickness, the chip-in-foil system can be released from the carrier. For implants, further challenges have to be taken into account, such as restricted choice of materials which need to be biocompatible and long-term resistant against the corrosive biological environment.

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II. MATERIALS AND METHODS

A. *Manufacturing and Transfer Process*

First step is the carrier fabrication. Cavities which determine die position and orientation on the final devices were etched through a 4-inch silicon wafer (Si-wafer) by deep reactive ion etching (DRIE) (STPS Technologies, United Kingdom). A sacrificial layer consisting of 15 µm of copper (Cu) was deposited by galvanic deposition. Next, UV-light-deactivated adhesive tape (E3125 KL, LINTEC Corporation Advanced Materials Operations, Japan) enabled fixation of the dice on the front side (Fig. 1A) and after placement, the backside of dice and carrier was levelled by grinding (DAG810, Disco Corporation, Japan). 5 µm of PI (BPDA-PPD) were applied by spin coating and soft cured at 90 °C for 5 min for die fixation from the backside (Fig. 1B). Prior to fully curing the PI at 450 °C for 10 min, the E3125 KL tape was UV-exposed and removed. Device base substrate, thin-film metal interconnects and top insulation (Fig. 1C) were fabricated as follows. 5 µm of PI were applied as device base to the front side by spin coating and soft cured at 90 °C for 5 min. PI above contact pads of the dice was opened by reactive ion etching (RIE) in oxygen plasma (STPS Technologies, United Kingdom). Image reversal resist AZ 5214E (MicroChemicals GmbH, Germany) was spin coated, exposed and developed, followed by an oxygen flash (80 W, 30 s) in an RIE machine and sputter deposition of the tungsten-titanium (WTi) and gold (Au) metal layer stack (50 nm/300 nm/50 nm of WTi/Au/WTi) was performed in an Ardenne CS730 (Von Ardenne GmbH, Germany). Excess metal was removed by lift-off in dimethylsulfoxide (DMSO), isopropanol and deionized (DI) water. To enhance adhesion to the PI base, an oxygen flash was performed prior to spin coating 5 µm of PI as top insulation, soft curing at 90 °C for 5 min and fully curing at 450 °C. Then the PI on the carrier backside was removed by RIE, the frontside PI was opened above the contact pads of the metal layer stack and the individual devices were separated. Afterwards, the dice were thinned to the desired thickness of 100 µm by grinding from the backside (Fig. 1D). After exposure, the wafer was removed from the UV-deactivated tape (Fig. 1E) and finally, the devices were released from the carrier by etching the Cu-layer selectively with Cu(II)-Cl solution at 45 °C (Fig. 1F) and rinsed with DI water.

B. *Yield Analysis and Positioning*

The dice used in this study were square-shaped with rounded edges and an edge length of 390 µm. One corner was designed with a visibly larger radius of curvature to preclude incorrect insertion orientation in the cavity. The dice were equipped with a metal structure on top, each with two contact pads (60 x 60 μm^2 and 90 x 90 μm^2), connected by an interconnect line. The metal structure consisted of 200 nm of sputtered aluminium. Rotational and translational error was analysed with optical micrographs and GIMP software (gimp.org, The GIMP development Team, USA).

C. *Mechanical Characterization*

To characterize the adhesion performance of transferred dice to the PI substrate, shear tests were conducted with a DAGE4000 Multipurpose Bondtester (Nordson Dage, United Kingdom) with a 10 kg cartridge, a test speed of 200 µm/s and a shear height of 50 µm. Individual samples were subjected to accelerated aging and therefore stored 16 days in phosphate-buffered saline (PBS) at 60 °C in a dry-heat chamber (Heraeus Holding GmbH, Germany). Samples were fixated during shear testing to an aluminium oxide ceramic by a layer of RS PRO 473-461 superglue (RS Components GmbH, Germany). Focused ion beam (FIB) cutting and scanning electron microscopy (SEM) of surfaces and cross sections was performed in a Scios 2 HiVac (Thermo Fisher Scientific, Waltham, MA, USA).

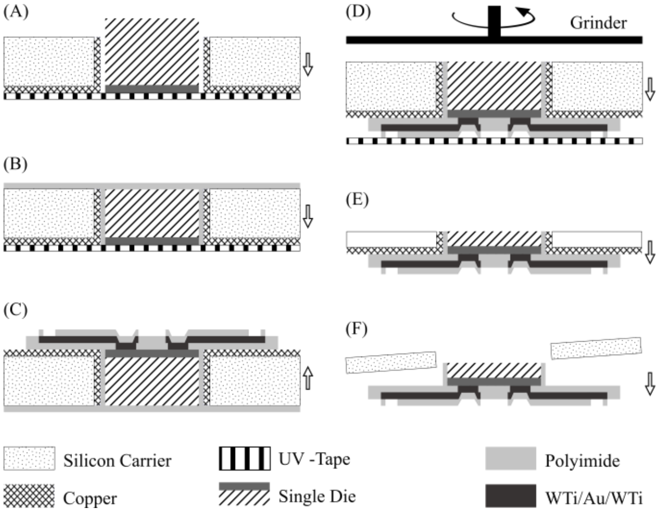

Figure 1. Simplified sketch of the process sequence for the simultaneous transfer of multiple dice (solid grey line indicates the topside of the die with connection pads of the CMOS structure) into a polyimide-based substrate and electrical interconnection of individual contact pads on the dice. The arrow points towards the top side of the carrier wafer.

III. RESULTS

A. *Transfer Process*

Placement of dice in the cavities of the transfer carrier was uncomplicated. The cavities were designed slightly larger than the dice to ensure uncompromised insertion while having tight fit. Figure 2.A shows a die from the topside of the transfer carrier placed in a cavity with the metal structure and the copper surface that serves as sacrificial layer in a later step of the transfer process. Sidewalls of the cavities were deposited with copper over the entire height. The adhesion of dice to the UV-Tape was sufficient. After soft curing of the PI on the transfer carrier backside, the front side of the dice could be embedded into the PI substrate on the front side of the transfer carrier. Figure 2.B shows three dice placed in the cavities of the transfer carrier after grinding the dice to the desired thickness of 100 µm from the backside. Thinning was performed without displacement or tearing out of dice. Transfer of all dice into PI substrates was therefore successful and contacts could be established with sputtered thin-film metal interconnects. Figure 3.A shows a final device with three 390 x 390 μm^2 large and 100 µm thin Si-based dice, embedded into a PI substrate with a total thickness of 10 µm and a metal line for interconnection of three individual dice by connecting in total six contact pads in series. Figure 3.B shows an SEM image of the cross section of the polyimide/metal/polyimide interface and the dashed line

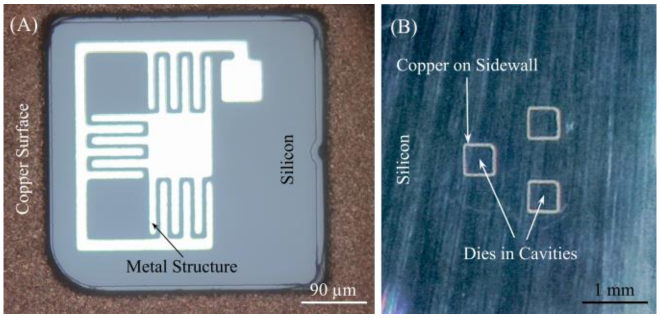

Figure 2. A: Optical micrograph of a die placed in a cavity from the topside of the transfer carrier with the metal structure and the copper surface that serves as sacrificial layer in a later step of the transfer process. B: Optical micrograph of three dice placed in the cavities of the transfer carrier after grinding the dice to the desired thickness of 100 µm from the backside.

indicates the position of the gap between released carrier wafer and single die with no disruption or kink of the metal interconnect. Figure 3.C shows an SEM image of the cross section at the interface between polyimide and die with the metal interconnect forming a continuous via through the dry etched polyimide layer for die contact. The maximum temperature during fabrication was 450 °C, without any restrictions present.

B. Yield Analysis, Positioning and Mechanical Characterization

With the process at hand, 100 % (n=34) of dice could be transferred simultaneously into a PI substrate with one single carrier wafer. Dice were placed and embedded with low rotational and translational error of 0.21° ± 0.1° and 5 µm ± 0.5 µm, respectively. After determination of their exact position, the dice were subjected to shear test. The shear strength was measured to be 58.1 ± 13.7 MPa, a value comparable to dice attached with benzocyclobutene (BCB), a commonly used adhesive for attachment [19, 20]. After accelerated aging at 60 °C in PBS the average shear strength drops to 15.2 ± 10.5 MPa. Figure 4.A shows a scanning electron microscopy image of the PI surface after shearing-off a die with and Figure 4.B shows a close-up view on the imprint topography in the PI due to the metal structures on the die. In both cases, pristine and aged, there were no signs of air inclusions in the PI underneath the dice. As shown in the SEM images (Figure 4), the PI surface is rather smooth without any entrapped voids and shows a clear imprint of the die topography with its metal structures.

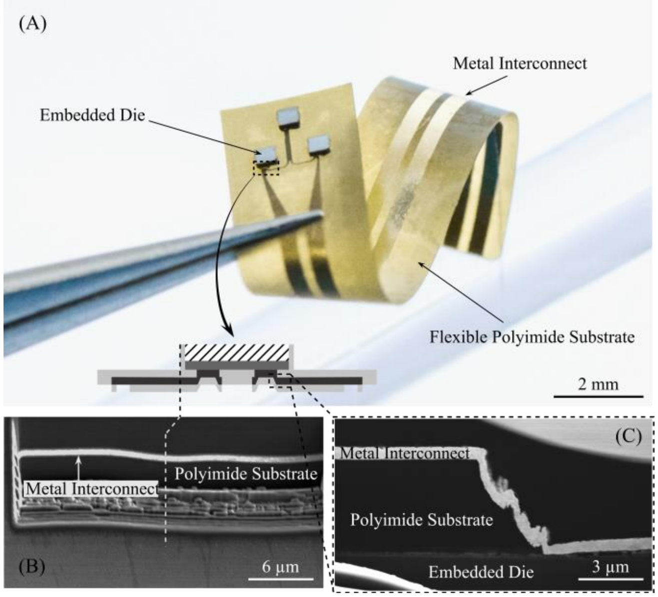

Figure 3. A: Flexible polyimide-based device with three silicon-based dice (each 390 x 390 µm² and 100 µm thin) connected by sputter- deposited metal interconnects held by tweezers and pressed against a micropipette-tip. The inset shows a schematic cross-section of the respective device. B: SEM image of the cross section of the polyimide/metal/polyimide interface. The dashed line indicates the position of the edge of a single die. C: SEM image of the cross section at the interface between polyimide and die with the metal interconnect forming a via through the dry etched polyimide for die contact.

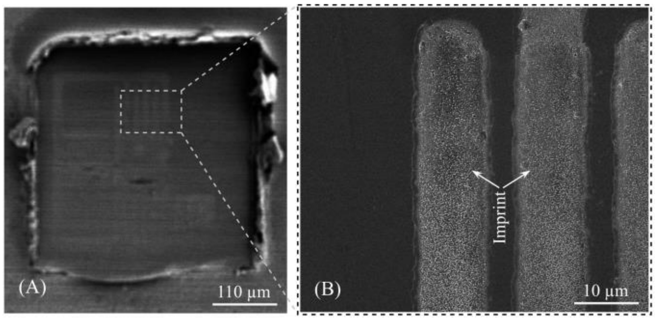

Figure 4. (A): Scanning electron microscopy image of the polyimide surface after shearing-off a die. (B): Close-up view on the imprint topography in the polyimide due to the metal structures on the die.

IV. DISCUSSION

All dice from a total number of 34 dice could be transferred at once. The positions of the cavities in the carrier were spaciously chosen, therefore a much larger number of transferred dice should be feasible, if a certain device design would require this and a carrier with an equivalent number of cavities would be fabricated. The positioning of dice was precise enough in a way that all contact pads on the dice could be met by the sputtered interconnect lines and no contact pads were shorted. The metal-deposition method is suitable for interconnection through micron-scaled PI-based vias [21]. A significantly smaller size of contact pads than required for wire bonding is thus possible. The process also eliminates the mechanical stress of bonding which enables thinner dice. An even lower translation error of the dice, possibly required for smaller or more densely distributed contact pads could be achieved if the cavities are designed smaller or the sacrificial copper in the cavities is deposited thicker, resulting in a tighter fit of the dice in the transfer carrier. The adhesion of dice on the PI is in the same range achieved with BCB. The fact that due to the process design, PI is present not only on the flat surface of the die but also covering its perimeter can have a beneficial influence on the adhesion by fixating the die also on its sidewalls. The observed decreasing shear strength after immersion of the samples in PBS and storage for 16 days at 60 °C could possibly be induced by swelling of the PI and therefore lower adhesion between substrate and die. Further studies have to be conducted to investigate the PI surface for possible Cu residues and to fully encapsulate the die into the PI foil. However, the smooth surface of the PI without any voids underneath the dice indicates a properly cured polymer, which is facilitated by allowing one side of the PI layer to exchange with the surrounding atmosphere while curing.

V. CONCLUSION

In this work, a novel microfabrication process sequence was developed where multiple dice can be transferred simultaneously into mechanically flexible polyimide substrates and interconnected with great precision. Rather high process temperatures (450 °C), needed for curing of the polyimide, were feasible and did not compromise the transfer of dice. The process allows for arbitrary die-shapes, sizes and positions on the polyimide substrate and eases handling of small dice since grinding to the desired thickness is performed after any handling, transfer, embedding and interconnection.

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