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Room Temperature Bonding of Heterogeneous Materials for Near-Infrared Image Sensor

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Abstract

Room temperature bonding technique using cone-shaped microbump with the aid of ultrasonic vibration is applied to fabrication of a near-infrared (NIR) image sensor. The image sensor is fabricated using chip-on-chip of InGaAs photodiode array on InP substrate and Si CMOS readout IC. The pixel pitch is 25 μm to compose quarter-VGA class (320 × 256 pixels) resolution. A high quality imaging of heated object is demonstrated.

1. Introduction

Imaging is a very important technology for medical and health-care applications. Near-infrared (NIR) image particularly brings us a very useful information such as information of a living body [1]. To observe NIR signal, material which has an energy gap smaller than Si in a photodiode is desirable because Si photodiode has threshold wavelength, which is about 1.1 μm. Concerning signal read-out and processing, on the other hand, Si CMOS is in fact unique to provide practical solution. Therefore, chip-on-chip integration of heterogeneous materials is indispensable to fabricate NIR image sensors.

To stack heterogeneous materials, low-temperature bonding is strongly demanded to minimize residual mechanical strain generated by the difference in thermal expansion coefficient between the materials. Solder bump bonding using indium has been used to stack photodiode array of III-V compounds on Si CMOS to fabricate NIR image sensors. However, even indium solder requires to bond at temperatures about 200 ºC. Besides, solder bump bonding encounters constraints in shrinkage of bump pitch due to undesired reflow of the solder.

In this work, we fabricate NIR image sensor using ultrasonic bonding of cone bumps. The ultrasonic bonding of cone bump makes it possible to realize a large number of inter-chip connections at room temperature [2,3]. To fabricate a NIR image sensor, an InGaAs photodiode array on an InP was stacked on Si CMOS readout IC by the cone bump. The image sensor contains 320 × 256 pixels, which corresponds to the quarter video graphic array (qVGA).

2. Experimental and Results

Fabrication Process of NIR Image Sensor

To fabricate a NIR image sensor, a photodiode array and a readout IC were fabricated on InP and Si wafers, respectively. CMOS readout IC was fabricated using the 0.35 μm standard CMOS process. The CMOS readout IC chip includes an array of pixel circuits. Au cone-shaped bumps were fabricated on the CMOS readout IC. The fabrication process is as follows: A TiW film and a Au film were deposited by sputtering in sequence as a seed layer (Fig. 1(a)). A photoresist pattern having undercut holes was formed by photolithography (Fig. 1(b)). Electroplating of Au was applied to fill the undercut holes in the photoresist film (Fig. 1(c)). The photoresist was removed by acetone. The Au film and TiW film were removed by dry etching followed by annealing at 300 ºC for 15 min (Fig. 1(d)). Figure 1(e) shows an optical micrograph and an SEM image of Au cone bumps on the CMOS readout IC.

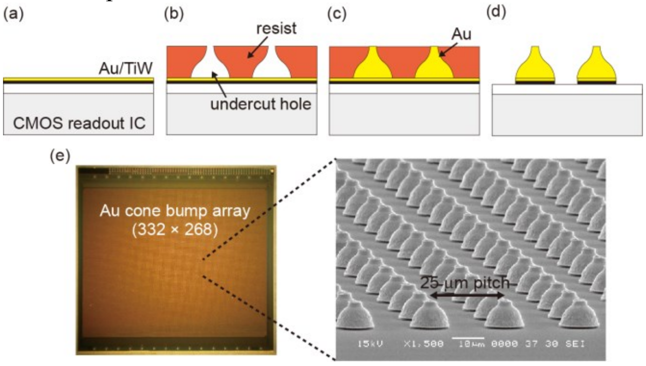

Fig. 1 (a), (b), (c), and (d) show fabrication processes of the Au cone bump on a CMOS readout IC. (e) Optical micrograph and SEM image of Au cone bumps (top size: 3-4 μm, bottom size: 12-13 μm, height: 8-9 μm) on a CMOS readout IC.

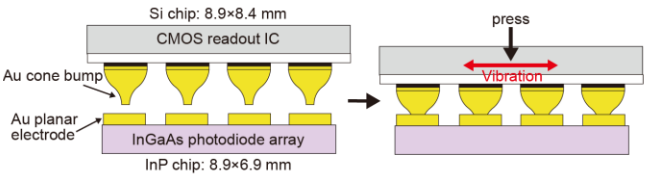

Fig. 2 Schematic illustration of ultrasonic bonding of the Au cone bump.

InGaAs photodiode array was fabricated on an InP wafer. The array size is 320 × 256. Each pixel size in the photodiode array is 25 μm × 25 μm. Au electrodes on the photodiode array were fabricated by a liftoff process.

Then, the photodiode array was stacked on the CMOS readout IC by ultrasonic bonding of the cone bump (Fig. 2).

Prior to bonding, electrodes on the photodiode array and the cone bumps on the readout IC were treated with Ar plasma to clean the electrode surface and the bump surface. Ultrasonic bonding of the cone bump was carried out at room temperature in ambient air. Ultrasonic was applied to a CMOS readout IC chip. Bonding conditions are shown in Table I.

Table I Bonding conditions.

Temperature	Room temperature
Amplitude (μm)	1.5
Frequency (kHz)	48.5
Force (N)	667.3
Time (s)	0.5

Electrical Connection Test Using TEG Chip

Electrical connection tests using daisy-chain measurement were carried out. TEG chips having daisy-chain pattern were prepared for this purpose (Fig. 3(a)). The number of inter-chip connections designed in a daisy-chain pattern was 79,328. The daisy chain composed of 26 sub-chains. The sub-chains contained 2412-4288 bump connections. A 320 × 256 array of the Au cone bumps on the Si chip was bonded to another Si chip having Au planar electrodes. Bonding condition is summarized in Table I.

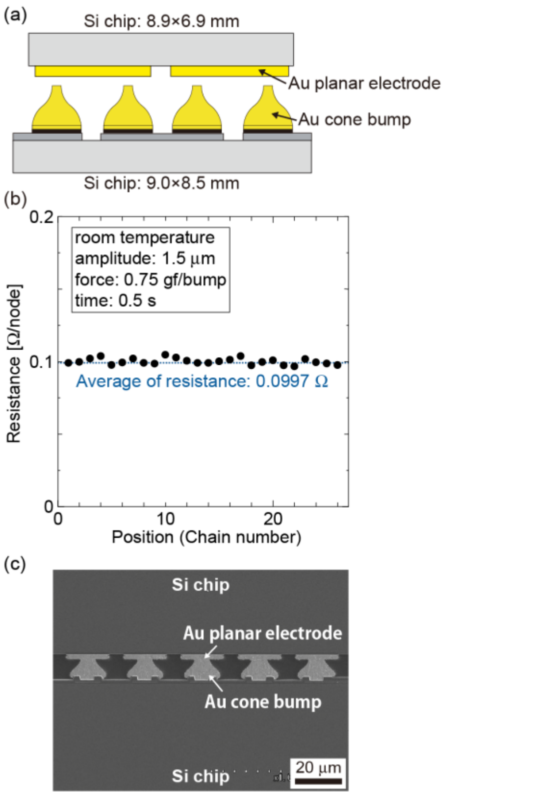

Fig. 3 (a) Schematic illustration of TEG chips for daisy-chain measurement. (b) Results of daisy chain measurements. The daisy chain consists of Au planar electrodes on Si and the Au bumps on Si. (c) Cross-sectional SEM image of bonded chips.

Figure 3(b) shows result of the daisy-chain measurement. We find that complete bonding of the 320 × 256 array was realized and the value of the resistance per connection node was almost constant over the chip area. Figure 3(c) shows a cross section of bonded interface. We find that Au cone bumps were surely bonded to Au planar electrodes.

Evaluation of NIR Image Sensor

A newly developed InGaAs/InP photodiode array having high resolution structure was bonded to a CMOS readout IC. A 320 × 256 photodiode array was connected to each pixel circuit in the CMOS readout IC through bump connection. Figure 4(a) shows an optical photograph of the NIR image sensor in a ceramic package. The image sensor was built into a camera frame with infrared optics. Figure 4(b) shows experimental setup. In this experiment, the radiation of infrared from a soldering iron was observed. Figure 4(c) shows a NIR image of the soldering iron heated to 300 ºC. We can clearly see the radiation of infrared. This result demonstrates that a number of inter-chip connections can be formed without critical damage to the photodiode array and the CMOS readout IC using ultrasonic bonding of the cone bump.

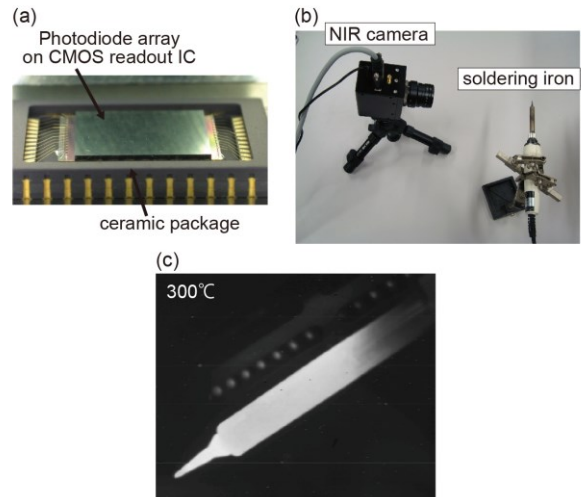

Fig. 4 (a) Optical photograph showing the NIR image sensor in a ceramic package. (b) Experimental setup. (c) NIR image of the soldering iron obtained at 300 ºC.

3. Conclusion

We fabricated NIR image sensor using room-temperature ultrasonic bonding of Au cone bumps. The sensor consists of a stack of InGaAs photodiode array on an InP and Si CMOS readout IC. The number of active pixels is 81,920 (320 × 256) where each pixel size is 25 μm × 25 μm. NIR signal was observed by using the fabricated NIR image sensor. The technology will provide higher resolution than the present by simply shrinking the size of Au cone bumps.

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