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Study on localized induction heating for wafer level packaging

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Micro-electro-mechanical systems (MEMS) are being developed as a new multi-disciplinary technology, which will undoubtedly have a revolutionary impact on the future of human life. However, with the development of MEMS technology, the packaging has become the main technical obstacle to the commercialization of MEMS. An approach to MEMS packaging by high-frequency electromagnetic induction heating at wafer level is presented in terms of numerical simulation and experimental study. The structure of inductor is firstly designed and optimized. Then the heating situation of PCB board is verified. The results indicate that the heat impact on the chip during the packaging process can be effectively reduced by local induction heating packaging, therefore the thermal stress on the chip is considerably lowered. This method can effectively improve the reliability of the MEMS devices.

MEMS packaging, numerical simulation, induction heating, structural optimization

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1 Introduction

It is generally believed that micro-electro-mechanical systems (MEMS) are micro-devices or systems in the feature sizes from sub-micron to millimeter, which mainly include the micro-structures, micro-sensors, micro-actuators, signal processing and control circuits, or even interface, communication and micro-power supply. Generally, the characteristics of MEMS are summarized as the following aspects [1–3]: miniaturized, silicon as the main materials, excellent mechanical and electrical performance, mass production, integrated and multi-crossed disciplinary, etc. Since the middle 1980s, the scientists all over the world have been greatly interested in MEMS and therefore MEMS technology has been developed rapidly under the huge financial support from the governments.

MEMS packaging technology mainly comes from IC packaging technology, such as low-temperature solder bonding, glass solder bonding, eutectic bonding, viscose bonding, etc. In order to study MEMS packaging by induction local heating, a number of domestic and abroad researchers have carried out a lot of research work related to induction heating. Thompson [4] in Wisconsin University of the United States heated 3-inch and 4-inch silicon wafers by RF induction heating and achieved silicon-silicon direct bonding in a matter of seconds. However, the silicon wafer temperature distribution was uneven due to the use of disc-type coil. In 2005, Taiwan Tsinghua University realized the infrared detector packaging by induction local heating [5]. It had a high bonding strength (up to 18.3 MPa) and superior air tightness due to reflow solder used in this method. As a result of low power frequency (400 kHz), the method could only be used for a single large-size graphics solder bonding at low temperature, but not for the wafer level bonding. Cao et al. [6] heated a square aluminum ring with 4 μm thickness and 30 μm width up to 1100°C in 150 ms.

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The frequency of induction power supply was 14.2 MHz, the power was 1000 W, and the thermal power density was as high as 9×10^{12} W/m^3. Local heating was achieved since the induction heating didn't apply to glass and the substrate temperature of glass was only 233°C. With a high-voltage DC field, T.C.C. Nguyen et al. [7] heated magnetic materials to high temperature by electromagnetic induction heating to complete the ITO glass anodic bonding within two minutes. Lin [8, 9] put forward a variety of other means of local heating, and most of which used polysilicon materials as the heating sources. By theoretical calculations and experiments, Sinder et al. [10] came to the conclusion that RTP with the thin film conductor on a silicon substrate in the vertical radio frequency (RF) magnetic field could be achieved. By numerical simulation, Xu et al. [11] came to a conclusion that the time step and grid thickness had little effect on the temperature field in a computer simulation of induction heating process. Liu et al. [12] in Huazhong University of Science and Technology presented a detailed analysis on the DBC (Direct Bond Copper) wafer' temperature distribution and deformation in the load of uniform harmonic magnetic field by numerical simulation.

This paper presents an approach to MEMS packaging by RF electromagnetic induction heating at wafer level. By numerical simulation, the structure of inductor is designed and optimized. The coil, which can form a uniform magnetic field and is suitable for wafer level packaging, is produced. By simulation analysis and experimental verification, the MEMS wafer level bonding packaging is realized.

2 Electromagnetic induction heating pri- nciple and related concepts

2.1 Basic principle of electromagnetic induction heating

Electromagnetic induction heating mainly bases on the following three principles, electromagnetic induction, skin effect and heat conduction [13]. Induction heating has been used for more than 40 years in industry and has a wide range of applications. Compared with conventional method, induction heating has many advantages such as high-temperature heating, non-contact, high heating efficiency and rapid heating. These advantage causes it favorable to complex cavity structure, less oxidation on the surface of the sample, easy to achieve automatic control, good operating environment and pollution-free.

The principle of induction heating can be understood from Figure 1. When an alternating current is loaded, the coil can produce an alternating magnetic field. Any metal material placed inside the inductor will be crossed by magnetic beams and the corresponding eddy current will be generated, which is opposite to the source current. Because of the Joule heat generated by resistance, the temperature of metal material will rise rapidly [14].

Let the alternating current in the induction coil be i_1 and

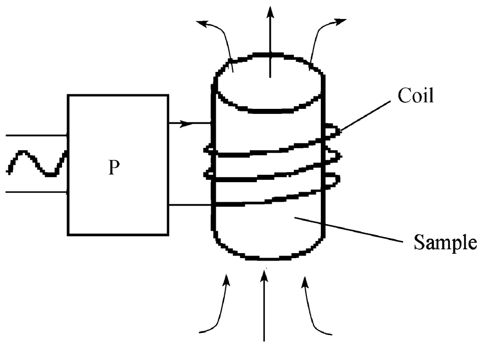

Figure 1 Schematic of induction heating.

the potential of the sample caused by the electromagnetic induction be e. The relationship among i_1, e and time t is

$$e = -\frac{\mathrm{d}\phi}{\mathrm{d}t},$$

where the negative sign shows that the inductive potential is always trying to prevent the changes of magnetic flux. If the amplitude of the flux is ϕ_m, angular frequency of the magnetic field is ω, and the frequency is f, then we have

$$\phi = \phi_\mathrm{m} \sin \omega t,\ e = -\frac{\mathrm{d}\phi}{\mathrm{d}t} = -\phi_\mathrm{m}\omega\cos\omega t.$$

The valid values for e is

$$E = 4.44 f \phi_\mathrm{m}.$$

The eddy current in the sample is i_2 and the Joule heat is Q.

The Joule-Lenz Law is $Q = 0.24 I_2^2 Rt$, where I_2 is the valid value for i_2 (A), R means the resistance of the work piece (Ω), and t is time (s). The power in the work piece is

$$P=EI\cos\varphi = 4.44 f I \phi_\mathrm{m} \cos\varphi.$$

Because of the skin effect, the eddy current generated in the work piece will decay exponentially at the cross-section from surface to center. Generally, the depth is called the the current penetration depth Δ by which the vortex strength drops to 0.368 times of the maximum value when the location moves from the surface to the center of the sample. Usually, the heat generated is proportional to the square of the eddy current, so the heat descent is faster than that of the eddy current from surface to core. It can be affirmed that 85% or 90% heat concentrates in the thin layer with⊗ thickness. The thickness can be expressed as

$$\Delta = \sqrt{2\rho/\mu\omega} = \sqrt{\rho / \pi\mu_0\mu_\mathrm{r} f}\ \text{(mm)},$$

where ρ is the resistivity of work piece (Ω·m), μ_0 is vacuum permeability (H/m), μ is work piece's permeability (H/m), and μ_r is work piece's relative permeability.

As can be seen from the formula, given the resistivity and relative permeability, the penetration depth⊗is inversely proportional to the square root of frequency f. The higher the frequency, the thinner the heating thickness.

2.2 The concept of wafer level packaging

In order to avoid damaging from processing technology and the environment, a MEMS device, such as inertial sensors, must be protected not only in its usage stage, but also in its manufacturing process. During the processes such as incising and assembling, MEMS devices are often damaged. To solve these problems, many new techniques have been developed and wafer level packaging is one of the most important types.

Wafer level packaging (WLP) means that the manufacturing processes and packaging are carried out in the silicon wafer, then single chips are formed after the wafer is cut. Chip level packaging means that only the some of the process steps are carried out in the silicon wafer firstly, then wafer is cut and a single die is packaged. Obviously, WLP is more efficient. Since MEMS packaging costs a large proportion of the entire manufacturing, the production cost can be greatly reduced by use of WLP technology. In addition, WLP can also improve the cleanness of the internal device and prevent damage of the fragile and sensitive structure from subsequent incising or other steps which will improve the reliability and the packaging yield. Figure 2 is the comparative diagram between WLP and chip level packaging.

2.3 Design and optimization for WLP by induction heating

There is a great difference between WLP and chip level packaging. Chip level packaging can be completed in any alternating magnetic field, but WLP aims at packa- ging more chips at one time, therefore, it requires a uniform alternating magnetic field. In order to ensure the packaging performance of each MEMS device, WLP requires uniform heating temperature and each ring having the same Joule heat. So WLP by induction local heating should be carried out in a uniform alternating magnetic field.

3 RF inductor and induction heating sys- tem

3.1 Design and manufacturing of RF inductor

The material of inductor is the copper pipe with a diameter of 2.5 mm and wall thickness of about 0.3 mm. Outside the pipe is the insulating layer. Inductor is made up of a planar coil at the bottom and a solenoid coil around. Considering the impedance matching of the induction heating system, the RF inductor is designed for 11 turns, which can be named as combination coil. In the experiment, the coil was inputted AC and cooling water, as shown in Figure 3. Figure 4 shows combination coil's axisymmetric planar graph and the magnetic field distribution produced by the combination coil.

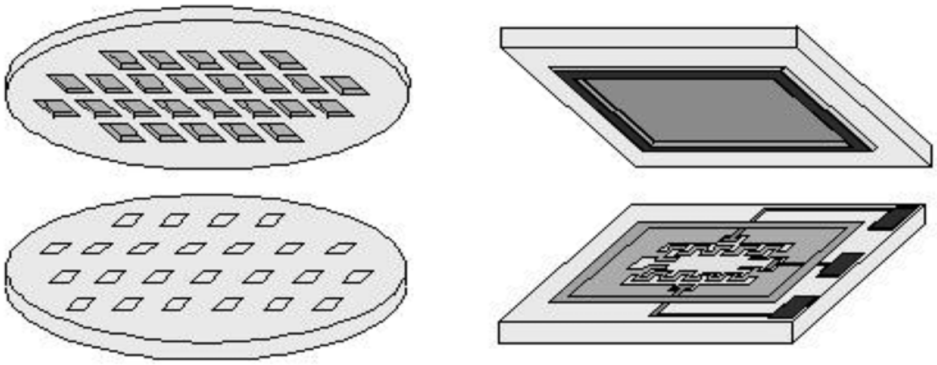

Figure 2 Wafer level bonding and chip level bonding.

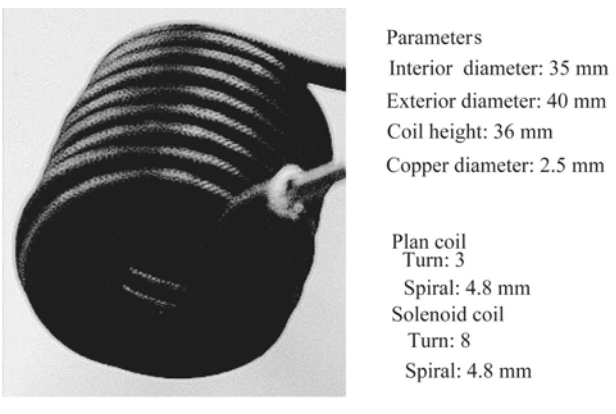

Figure 3 Combination coil.

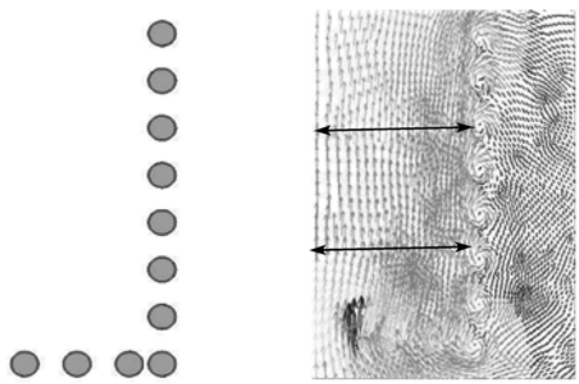

Figure 4 Combination coil and its magnetic field distribution.

Generally, induction heating makes the magnetic field perpendicular to the sample surface. When the load frequency f is 13.56 MHz and the current density J_s is 2500 A/m^2, the data of radial magnetic flux densities (B) are calculated as shown in Table 1.

From Table 1, it can be seen that at the same axis height, the magnetic field distribution is well-proportioned, the absolute deviation between the maximum flux and minimum flux is less than 4%. It can be considered as a uniform magnetic field in this calculation field. Therefore, the combination coil meets the requirement for WLP uniform heating when used in induction local heating.

3.2 Induction heating system

As shown in Figure 5, induction heating systems are generally made up of induction power, inductor, heating sample and other auxiliary devices such as matching device, cooling system, temperature measurement, transmission line, sample transmission, etc. The final experi- mental system is shown in Figure 6.

Table 1 Magnetic flux densities inside the combined coil (10^{-6} T)

Axial height (mm)	Maximum	Minimum	Difference	Deviation
12	2.6992	2.5975	0.1017	3.8%
13	2.6562	2.5941	0.0621	2.3%
14	2.6175	2.5832	0.0343	1.3%
15	2.5797	2.5650	0.0147	0.6%
16	2.5718	2.5359	0.0359	1.4%
17	2.5831	2.5007	0.0824	3.2%

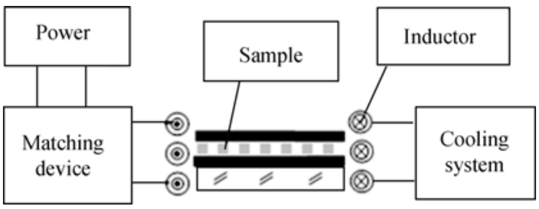

Figure 5 Sketch of an induction heating system.

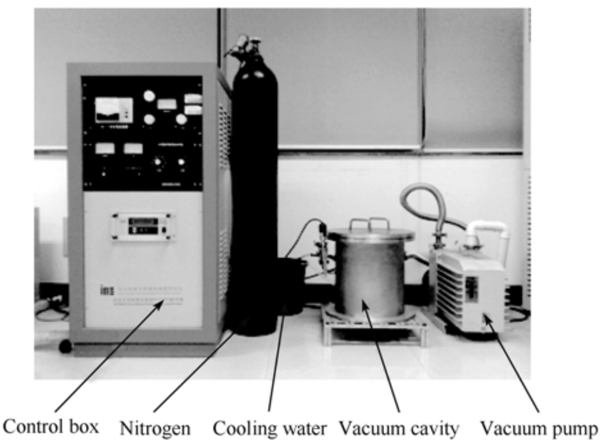

Figure 6 Experimental system.

4 Numerical simulation for WLP by induction heating

In the beginning, PCB boards with small-sized metal graphics were used in numerical simulation for WLP by induction local heating because it was simple, convenient and of low cost to produce small-sized graphics.

Figure 7 shows a PCB board with some metal rings, which are different in shapes and line widths. The thickness of metal graphics on the PCB substrate was 0.1 mm, which included 0.05 mm copper layer at the bottom and 0.05 mm tin layer on the surface. The diameter of circular ring was 2 mm, the side length of square loop was 3 mm and the line widths for different shapes were 1, 0.5, 0.2 and 0.1 mm, respectively. The substrate material was FR4 with the thickness of 1 mm.

The temperature distribution of PCB board at the end of 8 s is shown in Figure 8. It can be seen that the metal rings

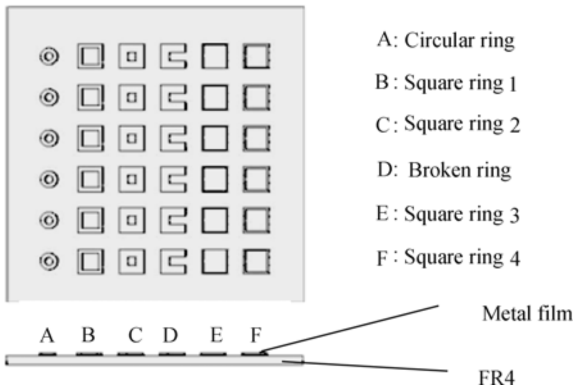

Figure 7 PCB board.

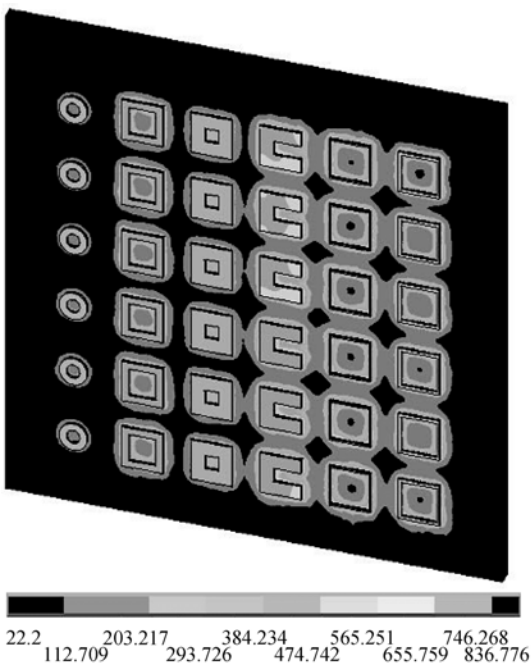

Figure 8 Temperature distribution of PCB board (t=8 s).

with the same shape and size have a uniform temperature in the uniform alternating magnetic field. It proves that the Joule heat generated by eddy current is uniform in each metal ring. This can assure each chip's package quality.

The metal ring arrays C, B, F, and E have the same shape and thickness, but have different line widths. Figure 9 shows the temperature curve for each array during the time duration from 0 to 8 s. From Figure 9, it is found that the smaller the line width, the higher the loop temperature when time is the same. Therefore, to obtain a higher temperature in a shorter time, it should be appropriate to reduce the metal ring's line width.

5 Test of WLP by induction local heating

Initially, PCB boards with small-sized metal graphics were used in the experiment for WLP by induction local heating. Figure 10 shows several PCB boards with different metal graphics. The PCB substrate material was FR4, which is insulated and not easily bended. According to the designed sizes, there were 0.05 mm thick copper film on the board and 0.05 mm thick tin film deposited on the copper film.

In the experiment, RF power supply frequency was 13.56 MHz and input power was 600 W. The coaxial cable connector connected the power with the induction coil. The experimental device is shown in Figure 11.

When PCB board was placed in the inductor, the metal rings would be heated uniformly by adjusting the axis height to assure that it was in the uniform magnetic field. The change of temperature was observed by the infrared apparatus, which has the record velocity of 25 frames per second.

Figure 10(a) shows a PCB board with same shape metal rings with different sizes. The lengths of different metal rings are 3, 2, 1 and 0.5 mm, respectively. The real-time thermal image is shown in Figure 12. Here t is the heating time, T is the maximum temperature on the PCB board.

In Figure 12, at time 0 s, the thermal image of the PCB board is totally not clear. From 0 to 3 s, the temperature of the large ring (3 mm length, 0.2 mm width) rises to 376.03°C. At 4 s, the large ring located at the left corner breaks up because the temperature is too high. From 4 to 6 s, the temperature of the large ring rises to 400°C. And at 6.5 s, all of the large rings break up. At this moment, the temperature of the middle ring (2 mm length, 0.2 mm width) rises up gradually. From 6.5 to 10 s, the temperature rises to 277.79°C, and from 18 s, the middle rings also break up because of the high temperature.

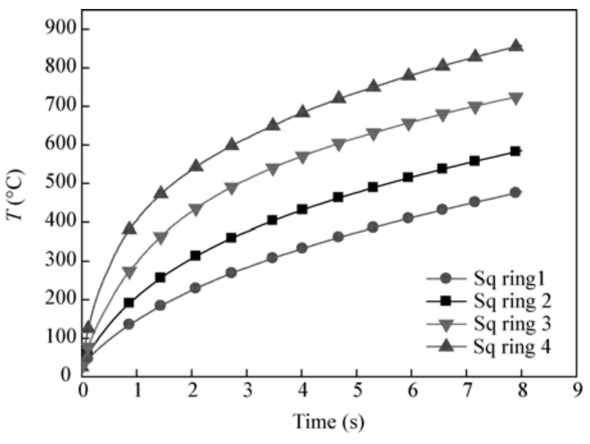

Figure 9 Temperature curves of the metal ring arrays C, B, F, E.

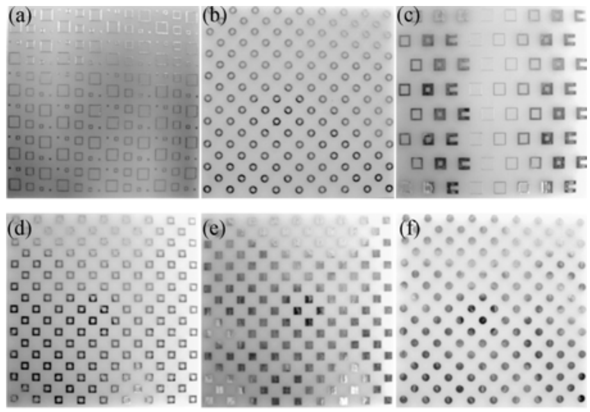

Figure 10 PCB boards with different graphics. (a) Square ring with different sizes; (b) circular rings; (c) square rings having different line widths; (d) square loops; (e) solid boxes; (f) solid rounds.

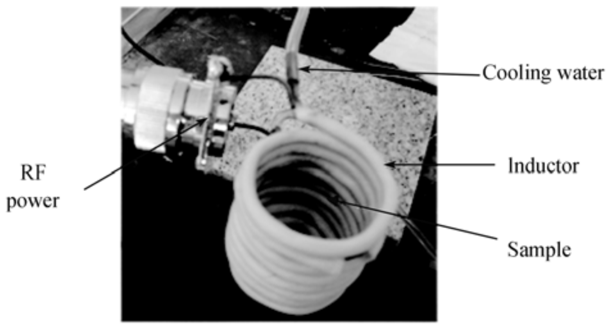

Figure 11 Experiment device of induction heating.

It is also found from Figure 12 that during the heating process, the smaller rings did not show overheated phenomena compared with the larger rings. This attributes to the size effect in induction heating[5]. When the material size decreases, the magnetic flux through the material also reduces, resulting in the lower efficiency of induction heating in small-size rings. So the Joule heat in large-size rings is much higher than that in small-size rings.

Temperature control is particularly important in electromagnetic induction local heating for packaging. If the temperature is too low, the bonding will not be reliable. If the temperature is too high, the solder will spill to decrease the bonding strength. In this experiment, temperature was controlled by adjusting the RF power and the induction heating time. For example, the tin ring with 3 mm edge length and

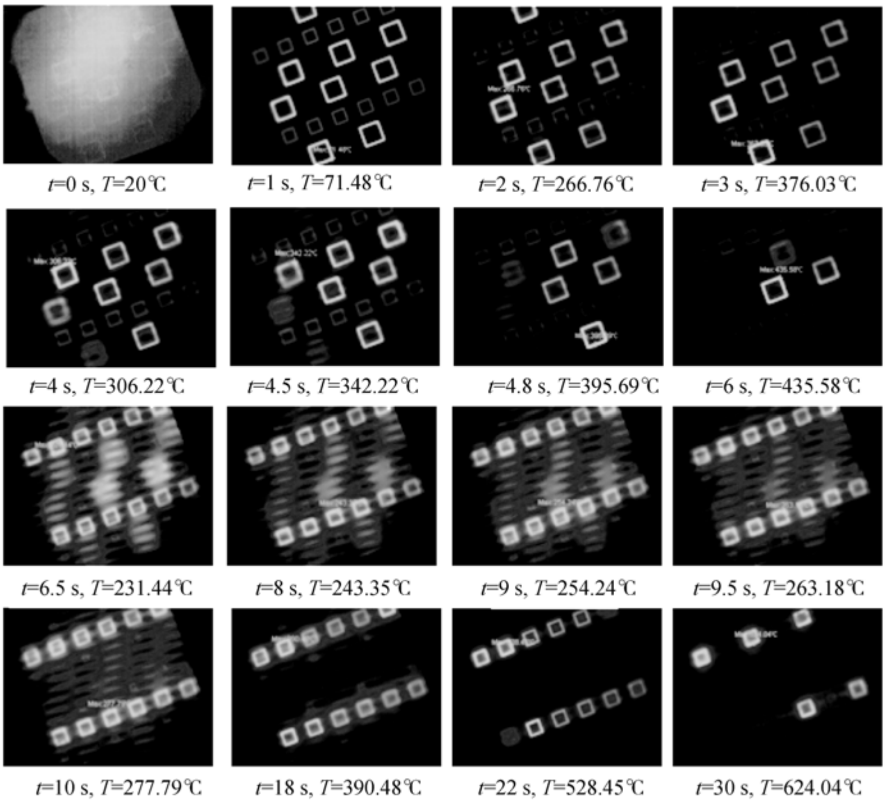

Figure 12 Infrared thermal images.

0.2 mm line width could easily reach the melting point of 232°C at 2 s by adjusting RF power to 600 W.

In order to investigate the selectivity of induction heating, the temperatures at two points in the PCB were observed. Point A is on the ring and point B is in the center of the ring on the PCB board. Their temperature curves are shown in Figure 13. At 7 s, the temperature of point A rose to 350°C linearly and the temperature of point B was about 100°C. The temperature difference is about 200°C, which proves the selective characteristics of electromagnetic induction local heating. This mainly attributes to that the rapid temperature increase of point A was because of Joule heat, and the temperature change of point B was based on heat conduction. Selective characteristics demonstrates that during the short time of packaging process, the temperature-sensitive circuits in the chip area can maintain low temperature and not be affected.

In order to investigate the uniformity of induction heating, the temperatures on a line L_{01} through all of the middle rings are shown in Figure 14. From Figure 14, it can be seen that the temperature over rings is about 120°C, and has good uniformity. This confirms that metal rings with the same shape and size can be uniformly heated in the combination coil. This characteristics can effectively guarantee each device's packaging quality. The corresponding thermal stress can be reduced because the substrate is heated at the same time.

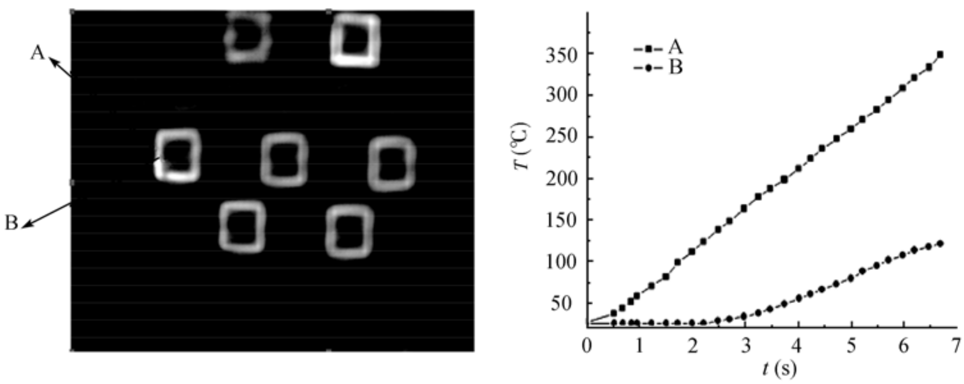

Figure 13 Temperature curves over time of point A and B.

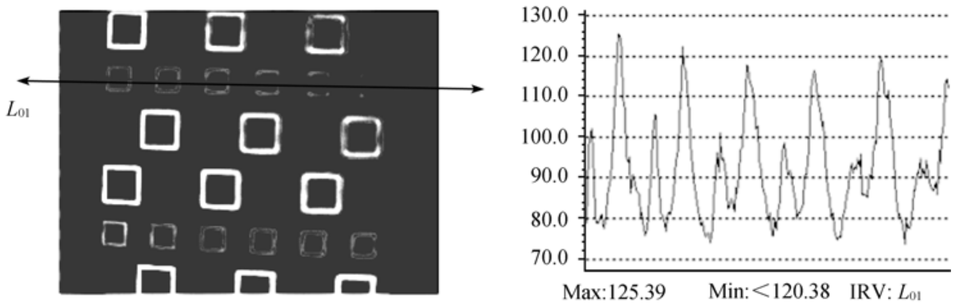

Figure 14 Temperature distribution of the line L_{01}.

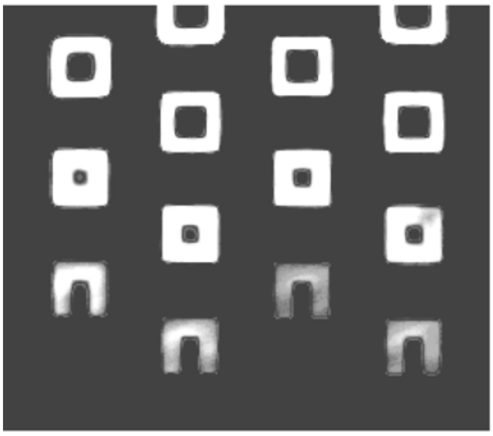

Figure 15 Infrared thermal images of rings.

To verify the effect of different line widths of ring on induction local heating, the PCB board as shown in Figure 10(c) was designed. The ring's edge length is 3 mm and line widths are 1, 0.5 and 0.2 mm, respectively. Figure 15 shows the thermal image at the same moment. It can be seen that the narrower the line width is, the higher the temperature rises. Therefore, the line width should be reduced as much as possible when designing WLP. But it should be noted that too small a line widthcauses too fast temperature rise, which could easily burn out the ring and be detrimental to reliability.

6 Summary

This paper presented an approach to MEMS packaging by RF electromagnetic induction heating at wafer level. The basic principles of electromagnetic induction heating and WLP were introduced. The structure of inductor was designed and optimized based on numerical simulation. The heating phenomenon of PCB board in the uniform alternating magnetic field was analyzed. The experiment validated that MEMS WLP by electromagnetic induction local heating in a uniform alternating magnetic field is feasible. Selective heating process can effectively reduce the impact of heat on the chips, and the uniform heating can effectively reduce the chip's thermal stress. All these factors can improve the life of MEMS devices.

It should be noted that the feasibility of WLP by electromagnetic induction heating was only validated through the PCB board in this paper, and the packaging of glass or silicon substrate has not yet been completed and is on the way.

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