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A new DRIE cut-off material in SOG MEMS process

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Abstract: The silicon on glasses process is a common preparation method of micro-electro-mechanical system inertial devices, which can realize the processing of thick silicon structures. This paper proposes that indium tin oxides (ITO) film can serve as a deep silicon etching cut-off layer because ITO is less damaged under the attack of fluoride ions. ITO has good electrical conductivity and can absorb fluoride ions for silicon etching and reduce the reflection of fluoride ions, thus reducing the foot effect. The removal and release of ITO use an acidic solution, which does not damage the silicon structure. Therefore, the selection of the sacrificial layer has an excellent effect in maintaining the shape of the MEMS structure. This method is used in the preparation of MEMS accelerometers with a structure thickness of 100 μm and a feature size of 4 μm. The over-etching of the bottom of the silicon structure caused by the foot effect is negligible. The difference between the simulated value and the designed value of the device characteristic frequency is less than 5%. This indicates that ITO is an excellent deep silicon etch stopper material.

Key words: SOG process; DRIE cut-off layer; ITO film; foot effect

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1. Introduction

MEMS inertial devices have excellent market competitiveness due to their small size and low cost and have been widely used in the field of consumer electronics[1, 2]. However, with the growing demand, performance has also become a concern. This requires new structures or structures with larger mass, because the increase in structural mass will reduce the mechanical noise and improve the sensitivity of the device[3].

Generally speaking, there are two kinds of processes for bulk silicon processing: the silicon on insulator (SOI) process and the silicon on glasses (SOG) process[4, 5]. In the SOI process, 30–100 μm thick SOI top silicon is used as the structural layer and the deep silicon etching Bosch process is used to etch top silicon to the buried oxygen layer. Hydrofluoric acid is then used to etch the buried oxygen layer to realize the release of the structure[6]. SiTime Corporation's silicon crystal oscillators and gyroscopes from the University of California, Irvine all use this process and show excellent performance[7, 8].

However, there are also some problems in this process. First, the presence of the foot effect makes the bottom of the silicon structure under-etched or over-etched, causing the deviation of the actual size of the device from the design value[9]. Another problem is the release of HF acid to the buried oxygen layer, for the corrosion process is slow, and the feature size of the silicon structure should not be too large. The excessive size needs a long release time, which causes over-etching of the anchor point portion, and the support of the device is affected[10].

There are two advantages to SOG process. First, the cut-off layer of deep silicon etching in SOG can be made of materials with better conductivity, which reduces the foot effect. Second, the silicon structure is usually anodically bonded to the substrate, the material of the sacrificial layer is generally metal, and the removal of the sacrificial layer does not damage the anchor point, so there is no special requirement for the feature size of the structure, so it has better structural applicability[11]. This process is used to make Silicon Sensing's ring gyroscopes[12].

Although the SOG process has lower cost and better structural applicability than SOI, there are few studies on the sacrificial layer material. Aluminum is used at Peking University[13], but there is no detailed report on the effect of etching. Moreover, aluminum will generate cracks in anodic bonding[14, 15], and in theory, cracks cannot prevent F ions from etching the anchor region. In this paper, ITO material is proposed to be the sacrificial layer, it is easy to remove, and the foot effect can be reduced. The light-transmitting characteristics also help to monitor the preparation of the structure during the etching process and reduce the over-etching of the structure. This is a good choice for a sacrificial layer material and deep silicon etching cut-off material.

2. Principles

This paper describes the principle of the foot effect in detail[16]. During the etching process, the fluoride ions used for silicon etching are positively charged and bombard the bur-

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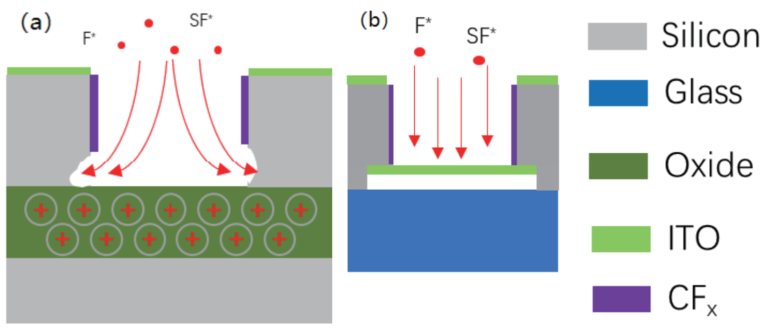

Fig. 1. (Color online) DRIE process. (a) Foot effect on SOI. (b) DRIE on SOG.

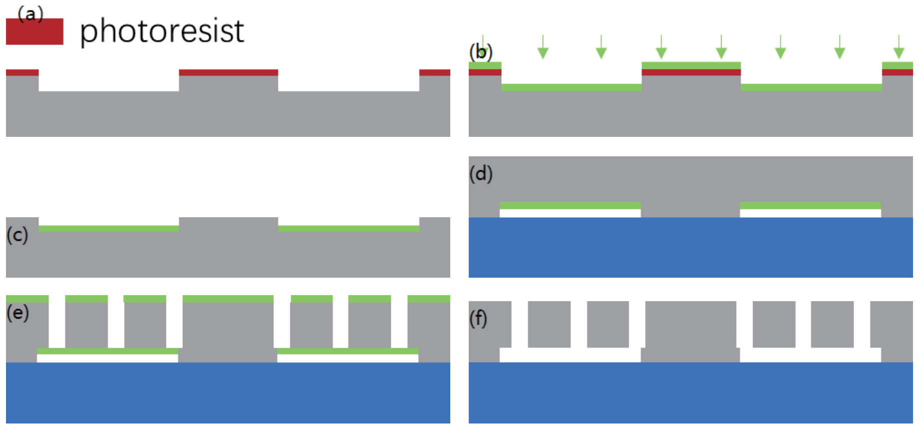

Fig. 2. (Color online) The preparation of structures. (a) Etching with glue mask drilling. (b) ITO sputtering. (c) Lift off. (d) Anodic bonding. (e) DRIE. (f) Release.

ied oxygen layer, so that there is a certain accumulation of positive charges on the surface of the silicon oxide. Under the action of electrostatic repulsion, the direction is deflected and starts to bombard the bottom of the sidewall of the silicon structure, thereby the foot effect forms. The principle is shown in Fig. 1(a).

According to the principle, if the silicon oxide material used as the etching cut-off layer is replaced with a conductive material, then the charges will not accumulate on the cut-off layer, the fluoride ions etching silicon will not be deflected, and the etching situation at the bottom is the same as the upper part of the sidewall, which conforms to the Bosch etching mechanism, forms a balance between passivation and etching, and reduces the foot effect, as shown in Fig. 1(b).

The etching of the silicon structure in the SOG process is different from SOI, it is hollow under the cut-off layer, and the cut-off layer also acts as a support layer for the silicon structure. After the silicon structure is processed, the cut-off layer cannot be broken, because the broken cut-off layer cannot prevent fluoride ions from entering the cavity between the glass substrate and the silicon structure. On the one hand, the fluoride ions in the cavity may accumulate on the glass surface, affecting the direction of movement of subsequent fluoride ions. On the other hand, fluoride ions may bombard the anchor point. The silicon oxide formed by the anodic bonding of silicon and glass at the anchor point is not good, it has poor corrosion resistance and etching properties. Excessive fluoride ions bombard the anchor point position, which will affect the bonding effect. So, the cut-off layer should have small stress. After the silicon structure is etched cleanly, it is ensured that the suspended film of a certain size will not be broken under the action of its own stress.

Considering the requirements of conductivity, etching resistance, and low stress, ITO is chosen as the material for the cut-off layer and sacrificial layer etched in the SOG process. Another advantage of ITO is its light transmittance. The etching of the silicon bottom can be observed from the glass side of the bonding wafers. The engraving time is different because the patterns are of different sizes and the same pattern located in different positions on the wafer. Generally, the maximum etching time is set in production, and a margin is added to ensure that all structures can be completely etched. By using ITO as the cut-off layer, it can be observed at any time whether the structures at different positions are etched to the end. This reduces over-etching and helps to maintain the morphology of the device.

3. Experiments

3.1. SOG process with TGV

The preparation of the structure is shown in Fig. 2. First, the movable area at the bottom of the structure is etched using a photoresist as a mask on one side of the 100 μm double-polished silicon wafer. After etching, an ITO film with a thickness of about 150 nm is grown by magnetron sputtering. Then a lift-off process is used to remove the ITO and photoresist from the bonding area. Next, the processed silicon wafer is anodically bonded to a 300 μm thick BF33 glass. After cleaning, a pattern with ITO as an etching mask is made on the silicon side. Finally, deep silicon etching and release are performed.

It is not easy to realize the airtight side leads on the glass substrate, and it is best to use the through glass vias (TGV) ver-

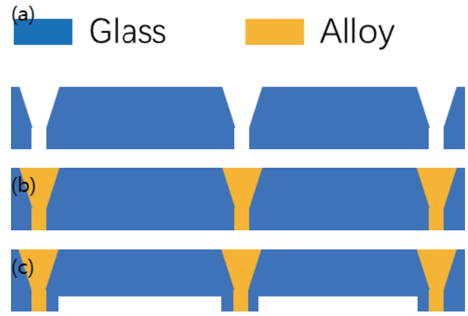

Fig. 3. (Color online) The process of glass cover plate with filled vias. (a) Laser drilling. (b) Electroplating. (c) Active area etching.

Fig. 4. (Color online) Package with anodic bonding.

tical lead scheme or silicon-glass composite cover. The TGV is used by the Silicon Sensing Corporation, and the electroplating process is used for metal filling in vias[17]. However, for deep hole electroplating, a seed layer needs to be sputtered on the sidewall first, and it is a little difficult to realize the electroplating. Up to now, this process has only been adopted by the Silicon Sensing Corporation.

The laser drilling method was used by the author, which can realize the preparation of tens of micrometer diameter holes on a 300 μm thick silicon[18]. Due to the rough sidewalls of the holes, it is difficult to achieve good coverage of the sidewalls by the seed layer sputtering, so it is not suitable for filling vias with the electroplating process. Vias are filled by the electroforming method, and the filled metal is an alloy of aluminium and zinc[19]. By adjusting the ratio, the melting point of the alloy is lower than 400 °C, which is a suitable temperature for the preparation of MEMS devices

According to the electroforming filling method, a low-cost and high-yield MEMS device fabrication method is designed in this paper (as shown in Fig. 3). The preparation of the cover plate with through vias is as follows. First, laser drilling is used to punch holes on a 300 μm thick wafer. The holes are filled by electroforming, and then the excess metal is removed by a double-sided CMP process. Finally, the active area of the structure is etched out by using CrAu as a mask, and then the mask is removed. Corrosion of Cr and Au was carried out with ammonium cerium nitrate solution, iodine and potassium iodide solution, respectively, these solutions were almost not corrosive to the metal in vias.

The released structure is bonded with the cover plate with filled through holes as shown in Fig. 4, and a complete process flow of a MEMS device is realized. This method is suitable for the fabrication of devices such as accelerometers and gyroscopes.

3.2. ITO sputtering

In the experiment, it was found that the sputtering process parameters of ITO had little effect on the improvement of the foot effect, and all of them could achieve a good suppression. However, there are two points to be noted.

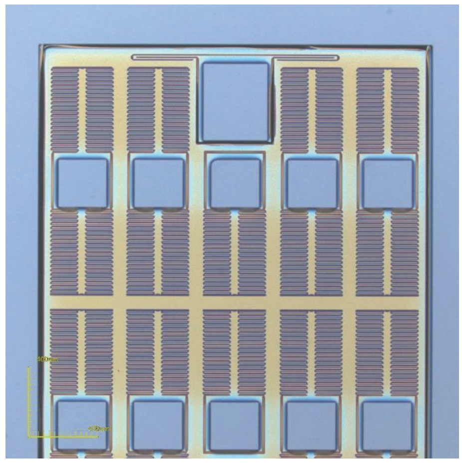

Fig. 5. (Color online) The etched silicon wafer on Glass

First, the thickness of ITO should preferably be greater than 150 nm, and the ITO film less than 150 nm is not rigid enough and is easily broken under the action of its own stress.

The other is the sputtering process parameters. During the sputtering process of ITO, a certain amount of oxygen is usually doped to adjust the composition ratio of oxygen in the material, thereby improving the conductivity and crystal phase characteristics of ITO. The purpose of adjusting the amount of oxygen here is to improve the density of ITO. In the experiment, it was found that the ITO film without oxygen doping during sputtering has good compactness. When it is soaked and peeled off in an acetone solution, it is difficult for acetone to pass through the ITO and interact with the photoresist under the film, resulting in difficult peeling. Doping a certain amount of oxygen during the sputtering process can effectively reduce the density of ITO and reduce the difficulty of stripping.

After the experiments, the selected ITO sputtering conditions are DC sputtering, the power is 150 W, the sputtering pressure is 1.5 mT, the flow ratio of oxygen to argon is 8%, and the sputtering rate is about 25 nm/100 s, and the target material is ITO compound with a 99.5% purity, the sputtering machine is PVD75 from Kurt Lesker.

3.3. Deep silicon etching

The bonding wafer is etched using Oxford Plasmalab System100 deep silicon etching equipment. When the equipment was put into use, the original engineer helped to develop a process suitable for bonding wafer etching. There are two steps: the first step is passivation, and the second step is etching. During passivation, the flow of C4F8 gas was 200 sccm, the ICP power was 1300 W, and the processing time was 2 s; during etching, the flow rate of SF6 was 200 sccm, the ICP power was 1600 W, the electrode power at high frequency was 40 W, and the processing time was 2.4 s. When glue or silicon oxide is used as a mask, the etching depth of each 100 loops of silicon is between 40 to 45 μm, and this process condition is also used for ITO mask etching of silicon oxide, the etch selectivity ratio of silicon and ITO is about 26 500[20].

4. Results and discussion

An accelerometer using a comb electrode is used to veri-

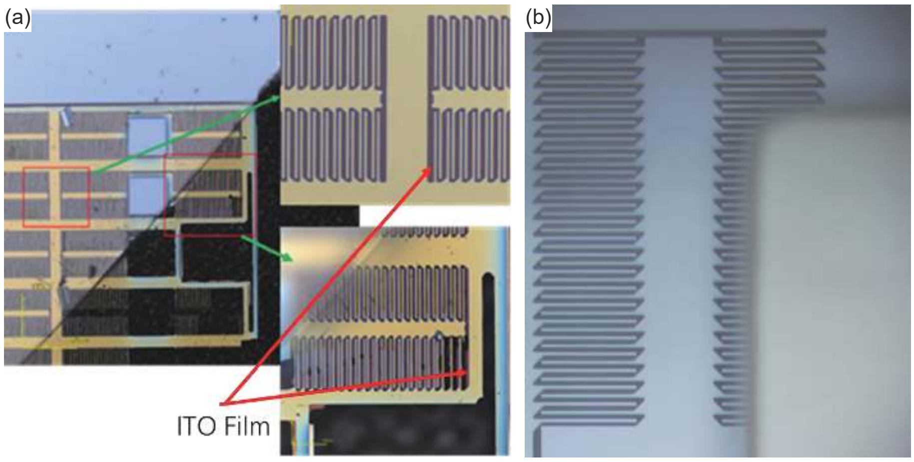

Fig. 6. (Color online) The etched structures. (a) ITO cut-off film. (b) The released and packaged structures.

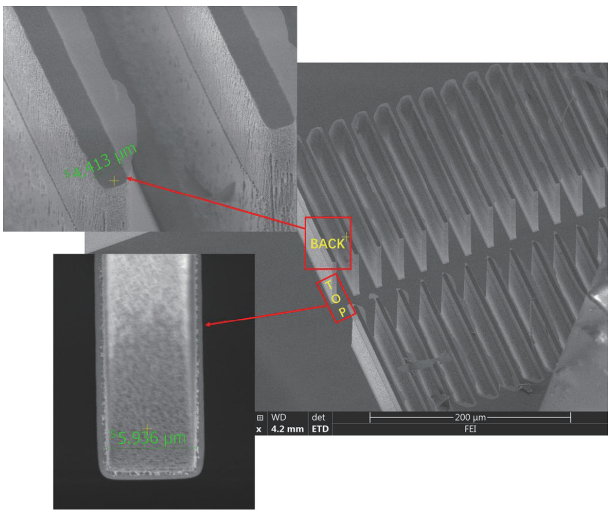

Fig. 7. SEM results of the comb beams in SOG process.

fy the proposed process scheme and the effect of ITO on the foot effect. The designed accelerometer has a comb spacing of 4 μm and is made of 100 μm thick silicon. It can be seen that after processing, the ITO film remains intact, and there is no cracking due to etching or structural stress, which can prevent the etching gas from entering the gap between the silicon layer and the glass substrate, and so no charge accumulation layer is formed. The etched accelerometer is shown in Fig. 5 from the glass side.

To observe the effect of the ITO film on the foot effect, the etched structure was split, and the glass of just one device was split, while the silicon structure remained, and this device is analysed. Even under the impact of the splinter, most of the ITO film is still well preserved, which further verifies the reliability of the film, as shown in Fig. 6(a). The ITO film is etched in sulfuric acid and hydrogen peroxide mixed solution, and the structure is released and packaged, as shown in Fig. 6(b).

Here, the cleaved silicon structure was observed by SEM as shown in Fig. 7. Due to the low stiffness of the comb-tooth structure and easy fracture, it is difficult to preserve the complete comb-tooth structure when it is split. Here, the part of the comb-tooth structure was measured, as shown in the figure. The SEM test results intuitively show that the ITO film has a strong inhibition of the foot effect. There is almost no obvious over-etching at the bottom of the silicon sidewall, but

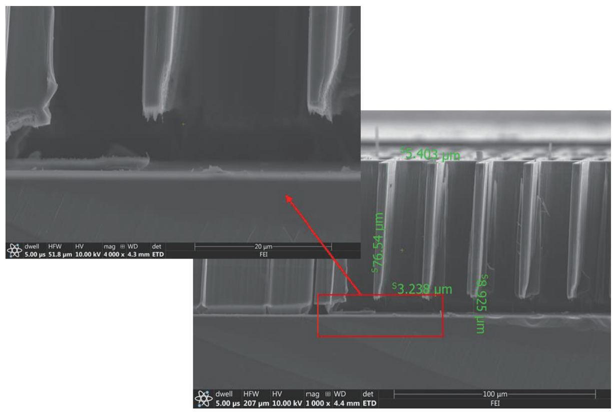

Fig. 8. SEM results of the comb beams in SOI processs.

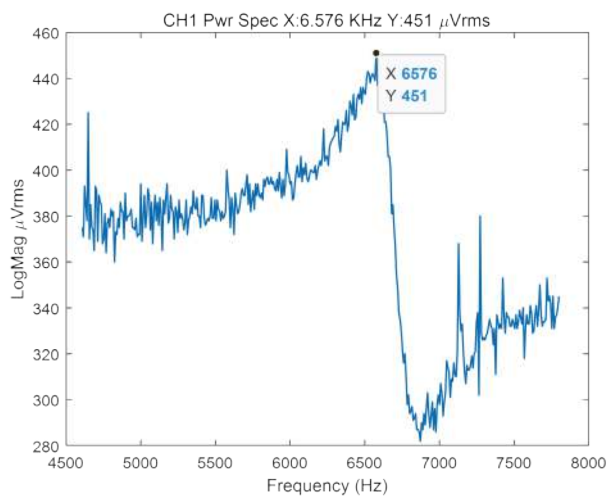

Fig. 9. The frequency domain response of a prepared accelerometer.

the beam has a wide top and a narrow bottom, which is caused by the inappropriate etching conditions, but not the foot effect. The deep silicon etching conditions still need to be optimized.

By contrast, the post-etch morphology of the structure with silicon oxide as the cut-off layer in a SOI process is shown in Fig. 8, the narrow comb structures are over etched due to the footing effect, the depth of undercut part is about 9 μm. Obviously, the etch results need to be optimized considerably for production.

The released structure was tested with a dynamic signal analyzer HP 35665A. On a 4-inch wafer, the resonant frequency of the device was distributed between 6.3 and 6.6 kHz, as shown in the Fig. 9. The design value is 6.5 kHz, both are in good agreement, which also proves the good consistency between the prepared structure and the layout design.

Therefore, the ITO thin film used in the SOG process, as the cut-off layer and sacrificial layer materials of deep silicon etching, can suppress the influence of the foot effect on the structure size and has a good effect on maintaining the structure and morphology.

5. Conclusion

In this paper, a method of using ITO thin film as the material of the deep silicon etching cut-off layer is proposed to suppress the foot effect of the bottom of the etching, and it has a good effect. The method is integrated into the MEMS accelerometer processing of the SOG process. The size deviation of the bottom surface and the front surface of the prepared accelerometer is small, and its operating frequency is in good agreement with the design value.

It is a pity that the ITO film produced by magnetron sputtering is relatively dense, and the corrosion can only be carried out by a highly corrosive solution such as sulfuric acid and hydrogen peroxide. This solution has a strong corrosive effect on the general electrode metal. The metal wiring on the surface of the glass substrate also limits the application range of the ITO film. Therefore, the TGV packaging process is adopted in the design of this paper, and there is no metal material in the cavity. If the ITO film can be replaced with other materials that are easy to corrode, but resistant to etching, then this method will have wider applications.

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References

[1] Acar C. High-performance 6-Axis MEMS inertial sensor based on through-silicon via technology. 2016 IEEE International Symposium on Inertial Sensors and Systems, 2016, 62

[2] Tjulkins F, Nguyen A T T, Hoivik N, et al. 3-axis MEMS accelerometer-based implantable heart monitoring system with novel fixation method. 2013 IEEE 63rd Electronic Components and Technology Conference, 2013, 510

[3] Johnson B, Christ K, Endean D, et al. Tuning fork MEMS gyroscope for precision northfinding. 2015 DGON Inertial Sensors and Systems Symposium, 2015, 1

[4] Kuisma H. Glass isolated TSVs for MEMS. Proceedings of the 5th Electronics System-integration Technology Conference, 2014, 1

[5] Taheri-Tehrani P, Defoort M, Chen Y, et al. Epitaxially-encapsulated quad mass resonator with shaped comb fingers for frequency tuning. 2017 IEEE 30th International Conference on Micro Electro Mechanical Systems, 2017, 1111

[6] Rödjegård H, Johansson C, Enoksson P, et al. A monolithic three-axis SOI-accelerometer with uniform sensitivity. Sens Actuat A, 2005, 123/124, 50

[7] Yang Y, Ng E J, Ahn C H, et al. Mechanical coupling of dual breathe-mode ring resonator. 2013 Transducers Eurosensors XXVII: The 17th International Conference on Solid-State Sensors, Actuators and Microsystems, 2013, 502

[8] Senkal D, Askari S, Ahamed M J, et al. 100K Q-factor toroidal ring gyroscope implemented in wafer-level epitaxial silicon encapsulation process. 2014 IEEE 27th International Conference on Micro Electro Mechanical Systems, 2014, 24

[9] Kim J, Park S, Kwak D, et al. Robust SOI process without footing and its application to ultra high-performance microgyroscopes. Sens Actuat A, 2004, 114, 236

[10] Seok S, Lee B, Kim J, et al. A new compensation method for the footing effect in MEMS fabrication. J Micromech Microeng, 2005, 15, 1791

[11] Ma Z, Wang Y, Shen Q, et al. Key processes of silicon-on-glass MEMS fabrication technology for gyroscope application sensors. Sensors, 2018, 18, 1240

[12] Townsend K, Durston M. Rate sensor with quadrature rejection. USA Patent, US13698339, 2013

[13] Li Y, Yang Z, Yan G. An improved method to remove anti-footing Al layer after DRIE. 2009 4th IEEE International Conference on Nano/Micro Engineered and Molecular Systems, 2009, 868

[14] Hu L, Xue Y, Shi F. Interfacial investigation and mechanical properties of glass-Al-glass anodic bonding process. J Micromech Microeng, 2017, 27, 105004

[15] Hu Y Q, Zhao Y P, Yu T X. Fractal pattern formation in anodic bonding of pyrex glass/Al/Si. Int J Nonlinear Sci Numerical Simul, 2008, 9, 315

[16] Zhang J, Huang Q A, Li W H. Simulations for surface evolvement and footing effect in ICP DRIE fabrications. J Phys: Conf Ser, 2006, 34, 522

[17] Nomura K, Okada A, Shoji S, et al. Application of I-structure though-glass interconnect filled with submicron gold particles to a hermetic sealing device. J Micromech Microeng, 2016, 26, 105018

[18] Yang F, Han G, Yang J, et al. Research on wafer-level MEMS packaging with through-glass vias micromachines. Micromachines, 2018, 10, 15

[19] Gu J, Xia X, Zhang W, et al. A modified MEMS-casting based TSV filling method with universal nozzle piece that uses surface trenches as nozzles. 2018 19th International Conference on Electronic Packaging Technology, 2018, 536

[20] Cai M, Si C, Han G, et al. Deep silicon etching of bonded wafer based on ITO mask. J Micronanoelectron Technol, 2020, 57, 11

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