# Experimental Study on the Footing Effect for SOG Structures Using DRIE

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**Abstract**: This paper experimentally studies the effects of the conductivity of a silicon wafer and the gap height between silicon structures and glass substrate on the footing effect for silicon on glass (SOG) structures in the deep reactive ion etching (DRIE) process. Experiments with gap heights of 5, 20, and 50μm were carried out for performance comparison of the footing effect. Also, two kinds of silicon wafers with resistivity of 2~4 and 0.01~0.03Ω·cm were used for the exploration. The results show that structures with resistivity of 0.01~0.03Ω·cm have better topography than those with resistivity of 2~4Ω·cm; and structures with 50μm-high gaps between silicon structures and glass substrate suffer somewhat less of a footing effect than those with 20μm-high gaps, and much less than those with 5μm-high gaps. Our theoretical analysis indicates that either the higher conductivity of the silicon wafer or a larger gap height between silicon structures and glass substrate can suppress footing effects. The results can contribute to the choice of silicon type and optimum design for many microsensors.

**Key words**: footing effect; silicon on glass; deep reactive ion etching.
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## 1 Introduction

The combination of silicon on glass (SOG) bonding and deep reactive ion etching (DRIE) is promising for the realization of high aspect ratio structures, which results in large proof-mass and capacitors. Therefore, SOG is attractive for high-performance inertial sensors, such as accelerometers and gyroscopes[1~3]. The SGADER (Silicon Glass Anodic-bonding and Deep Etching Release) process was developed by our lab based on this idea and widely used[4]. In the DRIE process, the etching rate is dependent on geometrical patterns[5]. Therefore over-etching is inevitable when RIE lag or inverse RIE lag occurs. When the ions reach the insulation layer after silicon structures are etched through, they accumulate and build up an electric field which expels and deflects the following etching ions from their previous trajectories to attack sidewalls. This significant phenomenon, known as the footing or notching effect, greatly decreases the uniformity of structures and arouses undesirable effects. For example, Lee *et al*.[6] discovered undesired driving characteristics in comb actuators induced by footing effects.

To protect devices from damage by the footing effect, many studies related to their applications were carried out[7~10]. There are also etching systems available on the market that adopt additional low frequency RF bias voltage that can depress the footing effect. However, these approaches are costly or difficult to realize due to excessive dependence on the equipment or the operator's experience and skills. However, Matsuura et al. reported a simple and easily realizable method by patterning a conducting metal layer onto the glass and electrically connected it with silicon substrate to release the charges[11]. Afterwards, Yoshida *et al*.[12] presented a more refined version of this work. Although the work of Refs.[11, 12] provided a good anti-footing solution, the effects of other key parameters on the footing effect were not investigated, such as the distance between the silicon structures and glass substrate and the conductivity of the silicon wafer. However, for many microsensor designs, these parameters should be considered since they have close relationships with the performance of the sensors. Taking a gyroscope as an example, a larger anchor height helps to achieve higher quality factors, but the longer etching also makes silicon structures with more deteriorative uniformity. The hardness of silicon single crystal is dependent on doped impurities[13,14], which means the conductivity of the silicon wafer has an effect on the anti-shock capability of the sensors. Although high doped impurities increase the conductivity of the silicon wafer and enhance the efficiency of readout circuits, they might decrease the hardness of the silicon wafer. Therefore, the interrelationships must be understood to account for the tradeoffs and make an optimum design for a microsensor.

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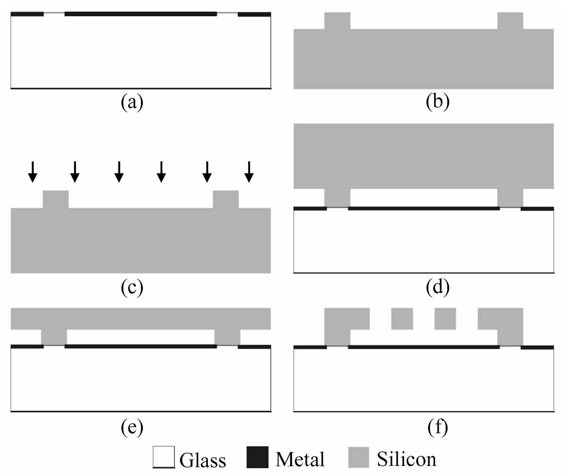


Fig.1　SGADER process　(a) Metal sputtering; (b) Trenches etching; (c) Ion implanting; (d) Anodic bonding; (e) Silicon thinning; (f) Structures releasing

To gain deep insight into these problems, the effects of the conductivity of the silicon wafer and the gap height between silicon structures and glass substrate on the footing effect were studied experimentally. Experiments with gap heights of 5, 20, and 50μm were carried out for performance comparison of the footing effect. Also, two kinds of silicon wafers with resistivity of 2～4 and 0.01～0.03Ω·cm were used for the exploration.

## 2　Fabrication process

Figure 1 is the SGADER process used in our lab, in which the method reported by Matsuura et al.[11] was adopted for improving the footing effect. First, 200nm-deep shallow trenches are etched by BHF ($NH_4F$ : HF = 5 : 1) on a glass wafer using photoresist as the mask, where a Ti/Pt/Au layer about 240nm in thickness is sputtered using a SFI (Sputtered Films, Inc.) physical vapor deposition (PVD) sputtering system to define electrodes by lift-off process, and the electrically conducting layer to evacuate build-up charges formed on the glass surface simultaneously. Then, steps 5μm in height are made with the STS Multiplex ICP ASE System in a silicon wafer to define anchors. Phosphorus ion implantation follows, using a Varian-Extrion CF-3000 implanter to obtain ohmic contacts with electrodes after the photoresist is removed. Afterwards, the glass wafer and silicon wafer are bonded using a EVG 501 bonder under the 10 minute anodic process under the conditions including 350℃ temperature, 1000V voltage, 1000N force, and $3\times10^{-3}$ mbar pressure. Then, the silicon substrate is thinned to about 85μm by KOH. Finally, movable structures are released with the STS Multiplex ICP ASE System using aluminum as the mask.

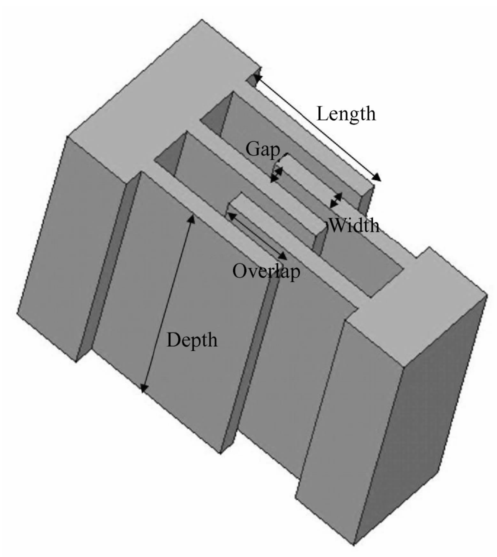


Fig.2　Schematic view of comb fingers

## 3　Experiments and results

Figure 2 is the schematic view of comb fingers investigated in this study for the performance comparison of the footing effect. Since it is periodic in the *y*-direction, only a unit is illustrated. The starting length, width, and depth of comb fingers are 44, 5, and 80μm, respectively, and the overlap and gap between two neighboring combs are 22 and 4μm, respectively. The gap height between comb fingers and glass substrate is varied for the investigation. The silicon wafers are n type with (100) orientation, double-side polished, 4 inches in diameter, and 400μm in thickness. Pyrex 7740 glass wafers 520μm thick are bonded with the silicon wafer because of its approximate coefficient of thermal expansion with silicon. In the experiments, the ICP system of STS and Bosch DRIE process were used. The detailed etching parameters are shown in Table 1. The passivation/etching time configuration was 7s/7s at the beginning and changed to 6s/7s after 30min.

In the experiments, five samples of each species were randomly chosen for study, and the topography of structures of comb fingers was investigated by optical measurement. The topography of every five same-species samples agrees well with each other. Figures 3 and 4 show the SEM (scanning electron microscopy) pictures of upside-down comb fingers with resistivity of 2～4 and 0.01～0.03Ω·cm after three minutes and five minutes overetching, respectively. Their gap

Table 1　Recipe of ICP DRIE process

| Cycle | Coil power/W | Platen power/W | Pressure /mTorr | Gas flow/sccm | | | Time /s | Over-run time/s |
|---|---|---|---|---|---|---|---|---|
| | | | | $SF_6$ | $C_4F_8$ | $O_2$ | | |
| Etching | 600 | 13 | 15 | 130 | 0 | 19.5 | 7 | 1 |
| Passivation | 600 | 0 | 15 | 0 | 100 | 0 | 7 | 0.5 |

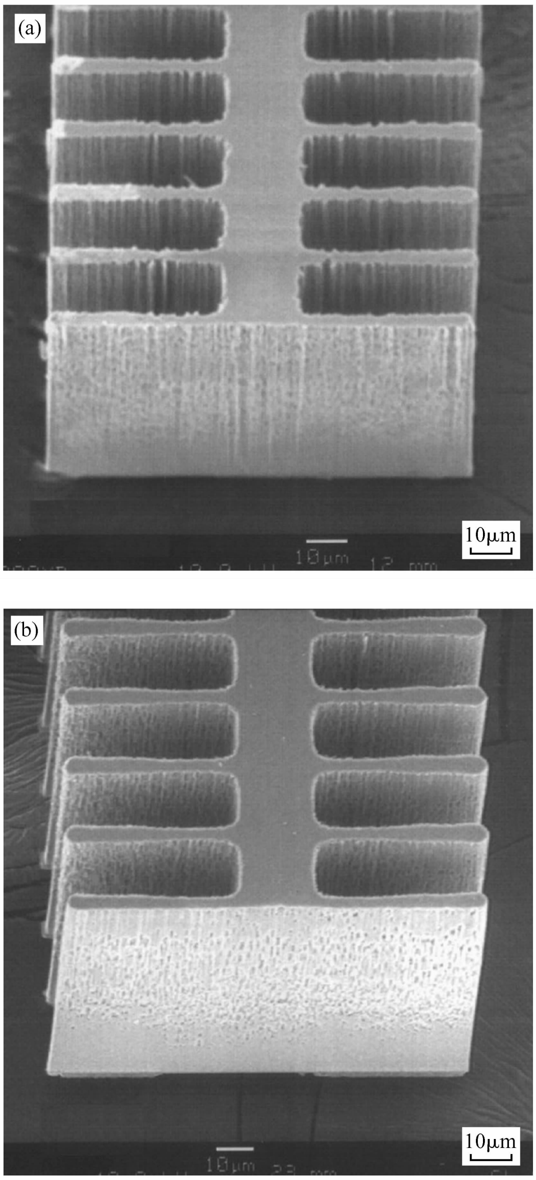


Fig.3 Comb fingers with different resistivities overetched for three minutes (a) 2～4Ω・cm; (b) 0.01～0.03Ω・cm

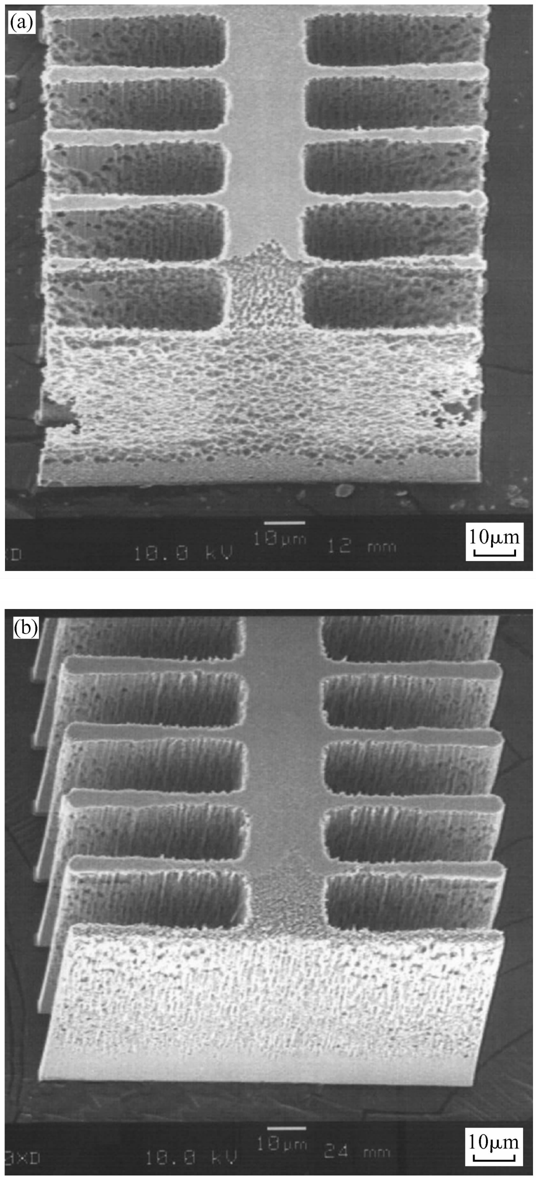


Fig.4 Comb fingers with different resistivities overetched for five minutes (a) 2～4Ω・cm; (b) 0.01～0.03Ω・cm

heights between silicon structures and glass substrate are both 20μm. Figure 5 shows the SEM photos of comb fingers with gaps of 5, 20, and 50μm between silicon structures and glass substrate after three minutes overetching, respectively. Their resistivities are all 2～4Ω・cm. The results reveal that either a higher conductivity silicon wafer or a larger gap height between silicon structures and glass substrate can help to improve the footing effect.

## 4 Discussion

Local electric fields and ions scattering effects were found responsible for the footing effect by Hwang and Giapis[15] using Monte Carlo simulation and they achieved good agreement with the experimental results. Similarly, these two factors are considered as the probable explanation for our experimental results as well. In Figs. 3 and 4, the comb fingers with resistivity of 2～4Ω・cm are more damaged than those with a resistivity of 0.01～0.03Ω・cm. A plausible reason for this phenomenon is that the potential difference between two sidewalls is larger in the former case than that in the latter. In the etching process, the sidewalls of the trenches accumulate the charges. Additionally, after the movable structures are etched through, the ions reach the surface of the conducting layer and the charges are transferred to silicon structures. The charges are mobile in the silicon and will reach equilibrium. However, they can not build up an equilibrium distribution immediately due to their limited mobility in silicon and will produce a potential difference between the two sides of the silicon structures. When the ions pass through this in-

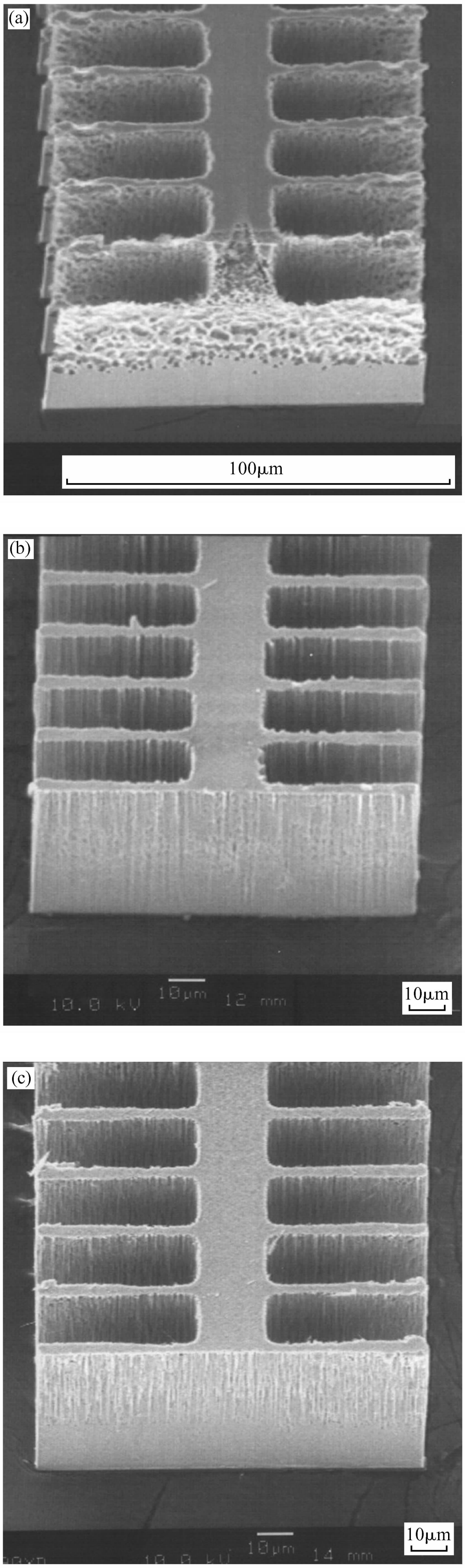


Fig. 5　Comb fingers with different gap heights between silicon structures and glass substrate　(a) 5μm; (b) 20μm; (c) 50μm

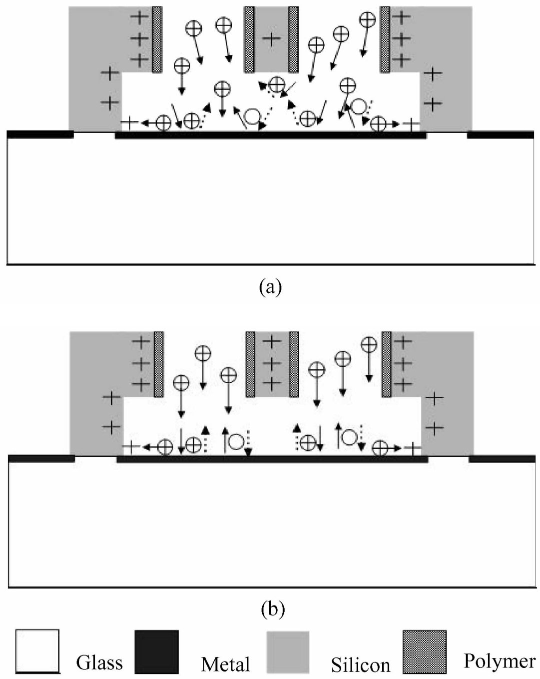


Fig. 6　Schematic drawing of charges transferring in silicon substrate and ions scattering　(a) 2～4Ω・cm; (b) 0.01～0.03Ω・cm

duced electric field, they are bent to attack the sidewalls, leading to passivation failure and surface roughness. A higher conductivity silicon wafer is more efficient to transfer charges and reach equilibrium faster than lower conductivity silicon. Thus, higher conductivity silicon decreases the number of bending ions attacking the sidewalls and improves the footing effect. Figure 6 is the schematic drawing. In Fig. 6(a), the difference of accumulated charges between two sides of the silicon structures is much larger due to lower conductivity and lower charge-transfer efficiency, and results in a stronger electric field than that in Fig. 6(b). Thus, more ions are forced to deviate from their vertical trajectories to attack the structures, including the diffuse reflected ions.

In Fig. 5, the comb fingers with 5μm-high gaps above glass substrate are more overetched than those with 20μm-high gaps and 50μm-high gaps after three minutes overetching. The comb fingers with 20μm-high gaps are overetched more than those with 50μm-high gaps. A possible reason is that more rebounded ions from the glass reattack the structures in the former case. When the ions hit the surface with a certain velocity, they rebound up like balls rebounding from a wall. The rebounded ions may undergo a complicated path, such as colliding with the subsequent downward etching ions, changing their previous trajectories, and then colliding with others. Although they loose their kinetic energy gradually and slow down, some ions with large initial velocity may still get through the

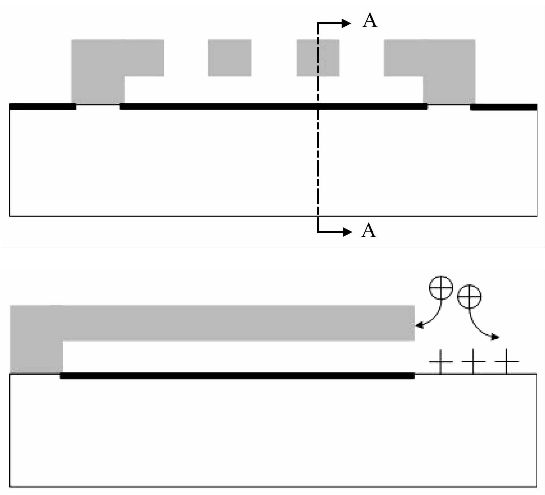


Fig.7 Schematic of charges buildup on glass where is not covered by metal layer

collision, and physically bombard the bottom and the sidewalls of released structures. The schematic drawing is shown in Fig. 6(a). If the gap height between the silicon structures and glass substrate becomes larger, the attack on the bottom of silicon structures can be improved. Because longer paths produce more collisions, it is more efficient to loose kinetic energy and decrease the number of re-bombarding ions, therefore improving the footing effect. From this discussion, we predict that either a higher conductivity of the silicon wafer or a larger gap height between silicon structures and glass substrate can improve footing effects.

The two endmost combs are more overetched than the other ones in Figs. 3, 4, and 5. This is because the two combs are above the edge of conducting metal layer and not covered completely. Charges are built up on the other side of surface of Pyrex 7740 glass, and then arouse footing effects. The schematic is shown in Fig. 7. Details on this point can be found in Ref.[11].

## 5 Conclusion

In this paper, the effects of the conductivity of silicon wafer and gap height between silicon structures and glass substrate on the footing effect for SOG structures in the DRIE process are experimentally investigated. Experiments with gap heights of 5, 20, and 50$\mu$m were carried out for performance comparison of the footing effect. Also, two kinds of silicon wafers with resistivity of 2～4 and 0.01～0.03Ω·cm were used for the exploration. The results show that the structures with a resistivity of 0.01～0.03Ω·cm have better topography than those with resistivity of 2～4Ω·cm; and the structures with 50$\mu$m-high gaps between the silicon structures and glass substrate suffer somewhat less of a footing effect than those with 20$\mu$m-high gaps, and much less than those with 5$\mu$m-high gaps. From the qualitative theoretical analysis based on the experiments, we deduce that either a higher conductivity of the silicon wafer or a larger gap height between the silicon structures and glass substrate can improve footing effects. Comparing the results of samples with different conductivity can contribute to the choice of silicon type; and comparing results of samples with different gap-heights can be contribute to the tradeoff between quality factors and etching uniformity for the optimum design of a microsensor.

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# 反应离子深刻蚀中硅/玻璃结构 footing 效应的实验研究

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**摘要：** 针对反应离子深刻蚀中硅/玻璃键合结构的 footing 效应问题，用实验方法进行了研究.通过 2～4 和 0.01～0.03Ω·cm 两种不同电导率的硅结构过刻蚀的对比，以及对 50，20 和 5μm 三组不同间隙高度的器件结构过刻蚀的对比，揭示了单晶硅结构的电导率及器件结构和玻璃衬底间隙高度对 footing 效应的影响.实验结果显示电导率为 2～4Ω·cm 的硅结构比电导率为 0.01～0.03Ω·cm 的硅结构 footing 效应严重；硅结构和玻璃衬底的间隙为 5μm 的比间隙为 20 和 50μm 的 footing 效应严重.对这一现象的理论分析认为，被刻蚀的硅的电导率越高，硅结构与玻璃衬底的间隙越大，footing 效应越不明显.本文中不同电导率和不同间隙高度的实验对比结果可以为硅微传感器材料类型的选取和器件的优化设计提供参考.

**关键词：** footing 效应；硅/玻璃键合；反应离子深刻蚀

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