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Passivation Layer for Anodic Bonding of Silicon to Glass

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In order to avoid bonding or sticking of flexible silicon elements during anodic bonding of silicon to glass, we propose to apply a passivation layer of aluminum oxide to the glass surface. The investigated passivation layer was deposited using reactive sputtering of aluminum. Its breakdown field strength was measured and its effectiveness was proved in anodic bonding experiments.

1. Introduction

The large electrostatic forces which occur during anodic bonding of silicon to glass, can deflect flexible micromachined elements on the silicon substrate. When touching the glass surface, the flexible elements may bond or adhere to the glass (Fig. 1). This usually results in the loss of functionality of the assembled device. Silicon, silicon dioxide, nitride layers and metals will permanently bond to the glass surface. No bonding will occur if the glass is covered with a metal layer, but the elements might adhere to this layer since they are attracted by strong forces (sticking effect). The bonding and sticking of flexible elements, for example paddles, is a serious problem in the assembly of micromechanical sensors. In this paper, we propose a solution to this problem.

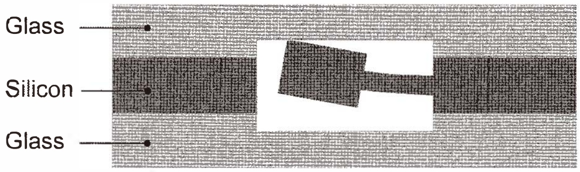

Fig. 1. Flexible silicon element touching the glass surface.

2. Properties of Passivation Layers

In order to avoid bonding and sticking effects, we propose the application of a passivation layer to the glass surface. This layer has to be patterned in order to protect those locations, which coincide with flexible elements on the silicon wafer, as well as to allow direct contact of the glass and silicon surfaces at the desired bonding sites (Fig. 2). The passivation layer should prevent both bonding and sticking.

2.1 *Anodic bonding*

Electrochemical, electrostatic and thermal mechanisms and their combinations have been suggested to explain anodic bonding.(1) For anodic bonding processes, typical Pyrex-like glass which contains about 8% of sodium oxide is used. It is assumed that sodium ions drift within the glass towards the cathode under the influence of an electric field at elevated temperatures. Consequently, a space-charge region develops at the boundary between the glass and the silicon substrate (Fig. 3).

The resulting electric field induces strong attractive forces, which cause an extremely close contact between the two materials. Consequently, surface atoms of the glass combine with silicon atoms by covalent bonds.

The passivation layer, which represents a good electric insulator, generates a distance between the positive and negative charges causing an electric field at the boundary between the two materials. Therefore it reduces the attractive force and prevents chemical bonds between the glass and silicon atoms.

2.2 *Sticking effect*

If two solid surfaces are brought in close contact, adhesive forces take effect, which have to be overcome to separate the surfaces from each other. These forces are proportional to the effective contact area between the two surfaces.(2) Therefore they are very strong if the surfaces are smooth and clean as they usually are in microtechnology.

The sticking effect occurs during anodic bonding if free-standing flexible silicon elements are placed above metalized glass areas. Due to electrostatic forces, the flexible structures are pressed against the metal layer resulting in a large effective contact area, especially if soft metal layers are involved. The effect is enhanced by the elevated temperature during the bonding process, which softens the surfaces. The adhesive forces (van der Waals forces and possibly electrostatic forces) can become so strong that the flexible elements are not released from the metal pads when the bonding process is completed.

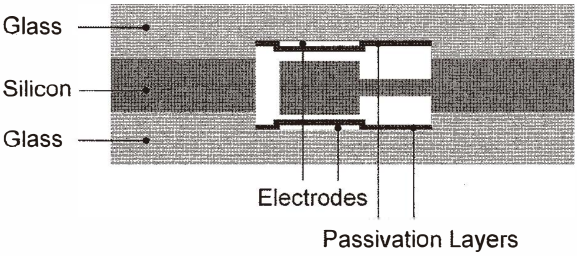

Fig. 2. Glass-silicon-glass sandwich with electrodes and passivation layers.

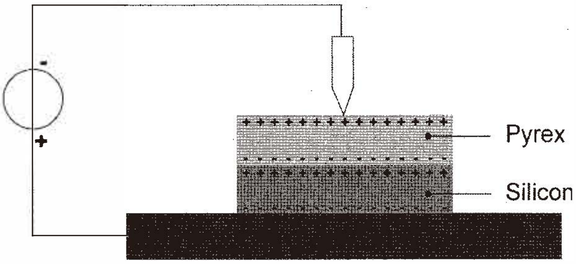

Fig. 3. Space-charge region developing during anodic bonding.

Thus, the passivation layer should exhibit a rough surface to keep the effective contact area small. Furthermore, it should be sufficiently hard, even at temperatures at which the anodic bonding process takes place.

2.3 *Passivation layer*

The effectiveness of aluminum oxide as a passivation layer was investigated. The layer was originally developed for the protection of silicon and glass against etching in a CF_4/O_2 plasma,(3) since the resulting AlF_4 layers are nonvolatile.

Aluminum oxide is an electrical insulator, which is used, for example, as a dielectric material in electrolytic capacitors. It is a ceramic material, and thus is particularly hard with a Vickers hardness between 19 and 26 GPa.(4) Aluminum oxide can be deposited by reactive sputtering of aluminum using an oxygen plasma.

3. Reactive Sputtering of Aluminum Oxide

The aluminum oxide layer was deposited using the sputtering equipment type LS440S of von Ardenne Anlagentechnik. Instead of radio frequency (RF) sputtering from a sapphire target(5) we used an aluminum target and oxygen as the reactive process gas.(6) An RF power of 300 W was used at an oxygen flow of 300 sccm. These parameter settings resulted from the maximum power without plasma ignition in the dark space and the minimum oxygen flow, ensuring that all aluminum atoms are being oxidized. Using ellipsometry, the refractive index of the deposited layer was measured to be 1.63, which is in good agreement with the refractive index range from 1.61 to 1.66 given in ref. (5). The deviation from the value of 1.8 for bulk sapphire is due to the amorphous structure of the film. For the experiments described below, a process time of 2 hours resulted in a film thickness of 500 nm. The main advantage of reactive sputtering from an aluminum target over nonreactive sputtering from a sapphire target is the high applicable RF power because of the insensitivity to thermal cracks and high thermal conductivity of metal targets that allow effective cooling. Measurements with a surface profiler showed that the use of an aluminum oxide layer increased the average surface roughness of a Pyrex layer from 1.4 nm to 1.9 nm.

4. Experiments

4.1 *Dielectric strength of reactively sputtered aluminum oxide layer*

The breakdown field strength of the 500-nm-thick aluminum oxide layer was determined by measuring its current-voltage characteristic (Fig. 4). For this purpose, a gold layer, an aluminum oxide layer and a second gold layer were deposited on a glass substrate (Fig. 5).

From Fig. 4, a breakdown voltage of approximately 170 mV can be determined, which results in a breakdown field strength of 0.34 kV/mm. This value is significantly lower than

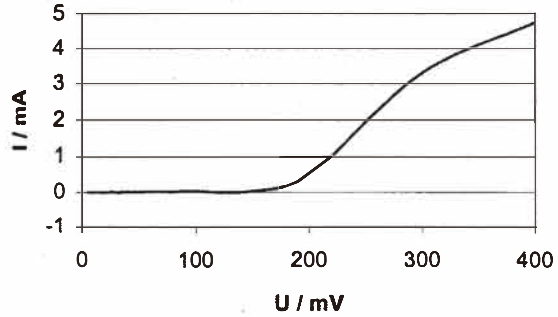

Fig. 4. Current-voltage characteristic of 500-nm-thick aluminum oxide layer.

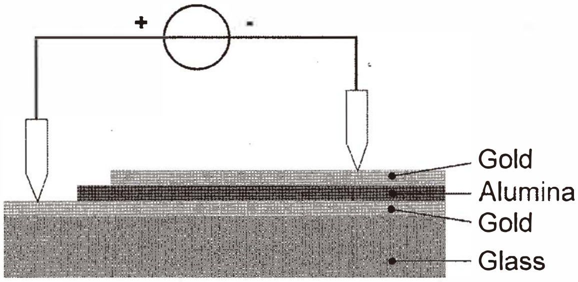

Fig. 5. Experimental setup for measurement of breakdown field strength.

the values given in the literature. For example ref. (7) has measured values between 28.5 kV/mm and 225 kV/mm for an alumina layer deposited by low-pressure plasma spray coating. We assume that the porosity of our aluminum oxide layer causes a strongly reduced effective thickness with an additional effect of converging streamlines of the electric field in the ground of the pores, resulting in a significantly lower breakdown field strength.

Since a deflected flexible element touching the glass substrate does not fill the pores of the passivation layer as the upper gold layer does in our experimental procedure, a breakdown field strength higher than 0.34 kV/mm can be expected for typical applications.

4.2 *Anodic bonding with and without a passivation layer*

The effectiveness of the aluminum oxide passivation layer was tested in connection with the assembly of a capacitive bulk micromachined acceleration sensor (Fig. 2). The metal electrodes on the Pyrex covers were omitted to enable visual inspection of the bonding results. We used an Electronic Visions AB1-PV bonding station. The bonding voltage and temperature were 500 V and 295°C, respectively. Only one Pyrex cover was bonded to the silicon wafer. The second cover was omitted to enable mechanical testing of the mobility of the silicon paddles. Cavities of 10 μm depth were etched into the Pyrex to enable free deflection of the paddles. One sample was bonded without a passivation layer. A second sample featured a 500-nm-thick aluminium oxide layer.

Fixed and free paddles can be distinguished by visual inspection. The silicon frame which holds the suspension of the paddle is bonded to the Pyrex-like glass cover . If a paddle shows the same brightness as the frame, it is bonded to the glass. If a paddle shows a different brightness from the frame, it is free. The bonding result without a passivation layer is shown in Fig. 6. The brightness of the paddles in Fig. 6 is the same as that of the outer silicon frame. The small squares that connect the suspension to the frame are brighter than the paddle and the frame. Unlike the paddle, these small squares are not bonded to the glass. Mechanical tests confirmed that the paddles were bonded to the Pyrex cover, i.e., the paddle lost its functionality.

The result of the bonding experiment with a passivation layer is shown in Fig. 7. The brightness of the paddles in Fig. 7 is different from that of the outer silicon frame.

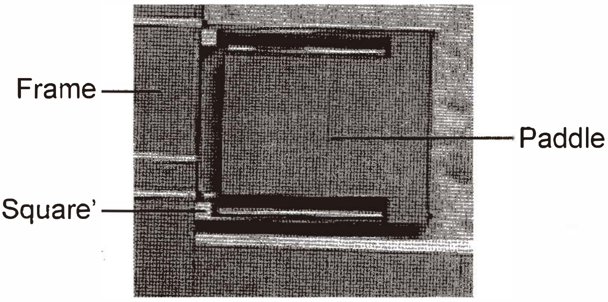

Fig. 6. Silicon structure with sensor bonded to Pyrex cover without passivation layer.

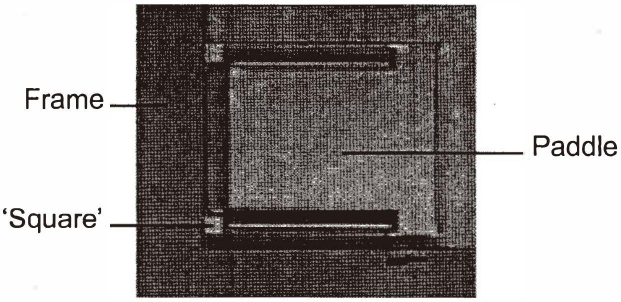

Fig. 7. Silicon structure with a sensor bonded to a Pyrex cover with an aluminum oxide passivation layer.

Mechanical tests confirmed that the paddles were still free-standing, i.e., the sensor maintained its functionality.

To obtain support regarding the reliability of the passivation layer, we bonded a silicon wafer with 94 paddles of the type shown in Figs. 6 and 7 to a Pyrex cover with electrodes and passivation layer at 500 V and 295°C. Only 2 of the 94 paddles were fixed to the cover after the bonding process. In former experiments with the same parameters, but without the passivation layer, more than half of the paddles were fixed to the cover. Therefore the use of passivation layer leads to a significant improvement in the yield.

5. Conclusion

An aluminum oxide passivation layer is well suited to prevent the bonding or sticking of flexible elements during anodic bonding. Aluminum oxide provides good electrical insulation and mechanical hardness which is essential for passivation layers. The breakdown voltage of the layer was determined and its functionality was tested in bonding experiments. It was found that using aluminum oxide passivation layers, flexible elements remain free-standing after anodic bonding.

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