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Improved Si–Si Waferbonding as a Step toward Lighter, More Accurate Microelectromechanical System (MEMS) Gyroscopic Sensors

by Henry Gagliardi and Robert Benoit

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14. ABSTRACT

A quad-mass gyroscope (QMG) is a microelectromechanical system that can be used to sense rotation by detecting the change in motion of four masses. Our goal is to produce a lighter, more accurate gyroscopic sensor than what is currently available for handheld navigational devices. This research focuses on wafer-level packaging using silicon fusion bonding (Si–Si bonding), which will allow us to produce 156 QMGs per run while being cost-effective and time-efficient. One issue with wafer-level packaging is the effect fabrication-process thermal budgets have on device performance. This research investigates the effect of various surface treatments such as RCA cleaning, vapor hydrofluoric acid etching, and Ar/O_2 Plasma Cleaning on Si–Si bond strength to improve bond quality at low temperatures while preventing damage to the packaged devices.

15. SUBJECT TERMS
silicon, Si, Si waferbonding, microelectromechanical system, MEMS, MEMS packaging

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1. Introduction

Silicon (Si) fusion or silicon direct bonding is a process in which two wafers are chemically bonded together. The goal of this work is to bond a capping wafer (Cap Wafer) to a wafer with fabricated microelectromechanical system (MEMS) devices (Device Wafer). But for short-loop testing, bare wafers are used. Our goal ultimately is the production of a lighter, more accurate gyroscopic sensor than what is currently available for handheld navigational devices. This research focuses on wafer-level packaging using silicon fusion bonding (Si–Si bonding), which will allow us to produce 156 quad-mass gyroscopes (QMGs) per run while being cost-effective and time-efficient. One issue with wafer-level packaging is the effect fabrication-process thermal budgets have on device performance.

1.1 Si–Si Waferbonding

There are two main types of fusion bonding: hydrophilic and hydrophobic. These are classified based off the termination of the Si molecule. If they are terminated via hydroxyl groups, then the wafer is hydrophilic. Hydrophobic bonds are formed when the Si is terminated by a hydrogen (H) or fluorine (F) molecule.

Si also grows an oxide (SiO_2) layer on its surface very rapidly when exposed to atmosphere. For many wafer designs, this does not impact the process; however, native oxides can inhibit hydrophobic Si fusion bonding.[1] To bond the wafers, this native oxide must be removed through various methods of surface preparations. These surface preparations ultimately determine the type of bond and have a direct impact on the bond's strength.[2] Si will bond at room temperature once the oxide is stripped. However, annealing the wafer strengthens the bond due to the additional energy helping drive interface reactions, allowing more bond sites to form. Occasionally gases trapped in the substrate can be released during the bonding process and will accumulate in little bubbles at the bond interface. These bubbles usually diffuse out within a few days to a week.[3] Dust particles can also create voids between the two wafers, creating areas that are not well bonded.

1.2 Si–Si Bond Testing

We tested a variety of surface-preparation methods as well as anneal durations and temperatures on 150-mm, <100> Si wafers with a resistivity of 1–30 Ωcm. Our goal was to yield a result close to the strength of bulk Si (0.23 mJ/cm^2).[2] All of the surface-prep methods had to be dry methods because if there was any residual water or liquid in the final MEMS devices, the surface tension of the water could destroy them. Thermal budget at temperatures greater than 200 °C are limited to 1 h to prevent activation of getters on the Cap Wafer. Every test began with cleaning both wafers to remove organic (via RCA1 clean) and metallic contaminants (RCA2) as described in Table 1. Table 2 is an outline of the various surface preparations. The 200 °C/400 °C Primaxx vapor hydrofluoric acid (vHf)–Clusterline CLC 200 bond test was not completed due to mechanical issues with the CLC 200.

Table 1 RCA1 (5:1:1) and RCA2 (6:1:1) cleans used to prepare wafers for bonding

RCA1	RCA2
200 mL H_2O	300 mL H_2O
40 mL NH_4OH (29%)	50 mL HCl (38%)
40 mL H_2O_2 (30%)	50 mL H_2O_2 (30%)

Table 2 Experimental conditions and results

Tool	Recipe	Anneal	Surface energy (mJ/cm^2)
Primaxx vHF	HF flow = 600 sccm, press = 125 Torr, 60 s	Room temp. bond	0[a]
		400 °C, 12 h	0.022911
Primaxx vHf–CLC 200 Argon (Ar)	Same as above and below	400 °C, 1 h	0.00620555
		200 °C, 24 h; 400 °C, 1 h	NA
CLC 200 Ar	Power = 300 W, press = 75 mTorr, 10 s	400 °C, 1 h	0.0056186
		200 °C, 24 h; 400 °C, 1 h	0.0155232
PVA Tepla Ion40	Power = 400 W, press = 100 mTorr, 5 min	400 °C, 1 h	0.0199328
		200 °C, 24 h; 400 °C, 1 h	0.0201608

[a] The wafers split apart when the razor blade was inserted.

We experimented with various anneal times, even considering doing a 24-h anneal at 400 °C. After speaking with the manufacturer of the getter material (SAES Getters), we learned we are limited in our processing time to keep the getter from becoming depleted. However, from this we learned the getter could sit at temperature for long periods provided it is under the activation temperature (200 °C). Our plan then shifted to using two main recipes to test our wafer bonds: a 24-h 200 °C anneal followed by a 1-h 400 °C anneal, and a 1-h 400 °C anneal. The bonding and anneal were performed under vacuum in a Suss SB8e waferbonder. The tool pumped down for 12 h at a temperature of 200 °C to reach a base pressure of 5 μTorr before pressing the wafers together with a pressure of 1875 Torr.

To test the strength of the bond we used a crack-test method developed by Maszara et al.[4] The test consists of inserting a razor blade into the seam of the bonded wafers and measuring the crack propagation using an IR camera. Maszara's formula (Eq. 1) was used to calculate the surface energy γ (a measure of bond strength), where E is the modulus of Si and L is the crack length. It is depicted in Fig. 1.

$$\gamma = \frac{3Et^3y^2}{8L^4} \tag{1}$$

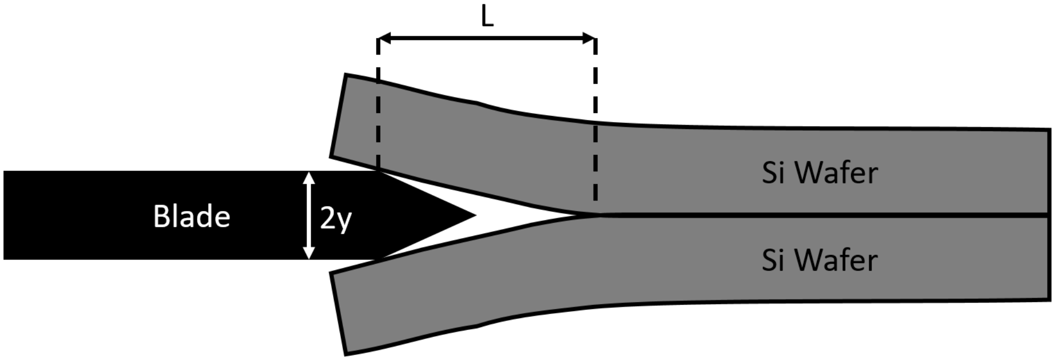

Fig. 1 Maszara's method for calculating surface energy γ for two wafers bonded together

The first method we tested to remove oxide was a vHF etch in a Primaxx vHF Etcher. The vHF reacts with SiO_2, stripping it off the wafer surface leaving bare Si behind with some F as well. This is a hydrophobic method because of the presence of F terminating the Si bond sites. This bonding method is fairly weak at low anneal temperatures and incredibly strong at high temperatures. Initial results of bonding at 400 °C for 12 h were promising, yielding a bond strength of 0.0229 mJ/cm^2; however, due to both the thermal constraints on the getter and that F will poison the getter, this method is unsuitable to use on both wafers.

The second method we tested was using the vHF for one wafer (the Device Wafer) and an Ar etch for the other (Cap Wafer with getter). An Evatec Clusterline 200 (CLC) equipped with a surface clean chamber was used for this experiment. This method allowed us to safely remove the native oxide and activate the bonding interface without the risk of poisoning the getter. These bonds were comparable in strength to the wafer pair prepared with only vHF.

The third method of wafer prep we tested was Ar etching of both wafers. One of the major benefits on this method was that the tool we used would hold the wafers in vacuum until they were ready to be unloaded. On top of that, the CLC uses a removable cassette to load wafers so it was only a matter of removing the cassette, which could be carried to the bonder to unload. This helped decrease the amount of exposure to the atmosphere, where free molecules can bond to the activated surface, and could be a major contributor to a decrease in bond strength.

The last surface prep method we tested was an O_2 plasma activation in a PVA Tepla Plasma Cleaning tool. This is the only hydrophilic method we tested.[5] Unlike the previous methods, the O_2 surface activation does not etch the native oxide off.

Instead, it relies on the RCA clean,[*] which leaves the wafer hydrophilic, while the O_2 plasma generates dangling bonds at the wafer surface, which facilitates wafer-to-wafer bonding.

2. Conclusion

We increased the Si–Si bond strength by 10× and decreased the number of defect sites between two bonder wafers over the course of this investigation (Fig. 2); however, the best results are still an order of magnitude below the bond strength of bulk silicon (0.23 mJ/cm^2). Possible improvements could be gained from using alternative tools for plasma activation (O_2 plasma RIE or O_2/CHF_3 plasma), increasing the anneal temperature to 650 °C, or increasing the applied pressure during bonding. This could be accomplished by adjusting the pressure setting in the SB8e or by reducing the contact area through etching the Cap Wafer. These will be the effort of future investigations.

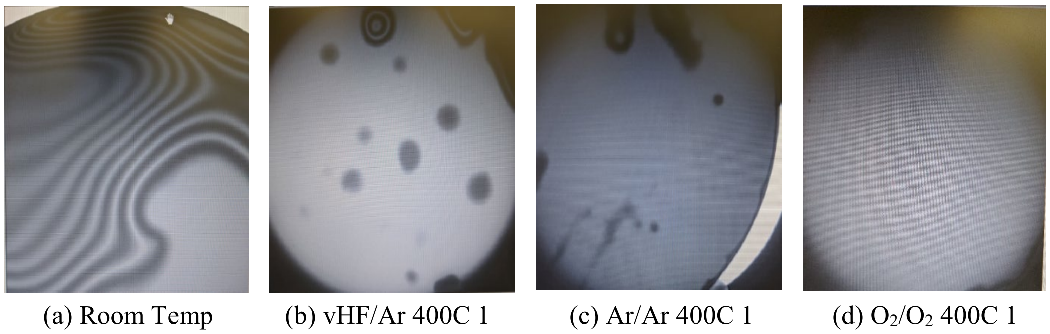
(a) Room Temp (b) vHF/Ar 400C 1 (c) Ar/Ar 400C 1 (d) O_2/O_2 400C 1

Fig. 2 IR images of bonded wafer pairs showing reductions in the number of defect sites through different surface preparations

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[*] A standard of multistep cleaning of Si wafers created in 1965 at the Radio Corporation of America.

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List of Symbols, Abbreviations, and Acronyms

Ar	argon
F	fluorine
H	hydrogen
IR	infrared
MEMS	microelectromechanical system
NA	not applicable
QMG	quad-mass gyroscope
Si	silicon
vHF	vapor hydrofluoric acid

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