# Low temperature LPCVD SiN direct bonding for sensors

C.-L. Hsu, G. Pandraud, J.F. Creemer, P.J. French and P.M. Sarro

*Abstract*— **Wafers with 30 nm and 300 nm thick Low Pressure Chemical Vapour Deposition (LPCVD) silicon-rich nitride have been successfully direct bonded to silicon-rich nitride surfaces. No polishing treatment was applied as LPCVD layers offer a Root Mean Square (RMS) roughness value lower than 0.5 nm. The result on bonding of 30 nm thick nitride films to patterned nitride layers is also presented. Finally two applications of this low temperature bonding technique developed are discussed.**

*Index Terms*— **Wafer bonding, surface cleaning, sensors.**

## I. INTRODUCTION

In the micromechanical industry, various applications require low-temperature bonding technology of processed and structured silicon wafers. Silicon to silicon bonding has been successfully studied in recent years [1] but in many cases, it is not possible or too expensive to remove processing layers as nitride or oxide before bonding. Silicon on oxide has become a standard method for producing standard substrates, such as, Silicon On Insulator (SOI) wafers [2]. Unfortunately for other layers little is known even if it is key to bond coated wafers without any deterioration in the quality of the bonded wafer pairs.

Direct bonding of silicon wafers has advantages over adhesive bonding. Spin-on glass (SOG), for instance, can be used to obtain a thin bonding layer [3] when bonding two substrates. However, the required temperature is relatively high and to our knowledge bonding on processed substrates has not yet been demonstrated. Benzocylobutene (BCB), a spin-on polymer, has good planarising properties and needs low curing temperatures. Even if successful bonding with a layer thickness as low as 200 nm was obtained [4] it is difficult to bond wafers showing a surface topography of the same order of magnitude or higher. Further polymers suffer from a lack of knowledge regarding long-term reliability, while direct bonding is already a mature technology and the industry has already investigated those issues [5].

In most cases, direct bonding can be used to bond coated wafers in the same way as uncoated silicon wafers.

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The objective of the paper is to characterize the bonding behaviour of silicon wafers coated with nitride, a commonly used coating in MEMS technology. The surface and bonding properties of standard bare silicon wafers are compared to those of silicon wafers covered with thin and thick LPCVD SiN layers as well as processed SiN layers. Beside its low roughness another advantage for choosing LPCVD deposition is the symmetry of the deposition as proven by the bow measurements. In addition, the fabrication of two systems using direct bonded nitride films will be discussed: a suspended microfluidic circuitry for in situ microscopy and an anti-resonant optical waveguide sensor.

## II. BONDING MECHANISM AND WAFER PREPARATION

### A. Chemical aspects

Direct bonding can be divided into two categories according to the surface state as either hydrophilic or hydrophobic. In the following, we will only focus on hydrophilic surface. A model to describe hydrophilic Si-Si direct bonding was presented by Stengl [6]. He suggested that the bonding process is initially based on the hydrogen-bonded network of absorbed water molecules on the hydroxylated oxide layer. Fig.1 shows the proposed model. Hydrophilic surfaces can be made through standard cleaning process, resulting in a thin oxidized layer.

### B. Wafer preparation

In our case, the wafers are hydrophilised in boiling nitric acid. The DI water rinsing step can ensure the absorption of water molecules. The bonding mechanism of $SiN_x$ - $SiN_x$ was suggested to be similar to Si-Si bonding [7]. After the standard cleaning process, a thin hydrophilic oxi-nitride layer covered the $SiN_x$ surface. So when the two surfaces were brought into close contact at room temperature, hydrogen-bridge bonding formed a weak bonding. A subsequent annealing step was done to strengthen the bonding.

## III. FULL WAFER RESULTS

First, 30 nm and 300 nm thick silicon nitride layers were deposited in a Tempress furnace using 340 sccm $SiH_2Cl_2$ and 60 sccm $NH_3$, for 4 min. 30 sec. and 43 min., respectively. As substrates, standard one side polished boron doped Si wafers were used.

Measurement of the wafer curvature were performed with a Tencor FLX 2908 before and after deposition of the nitride layers.

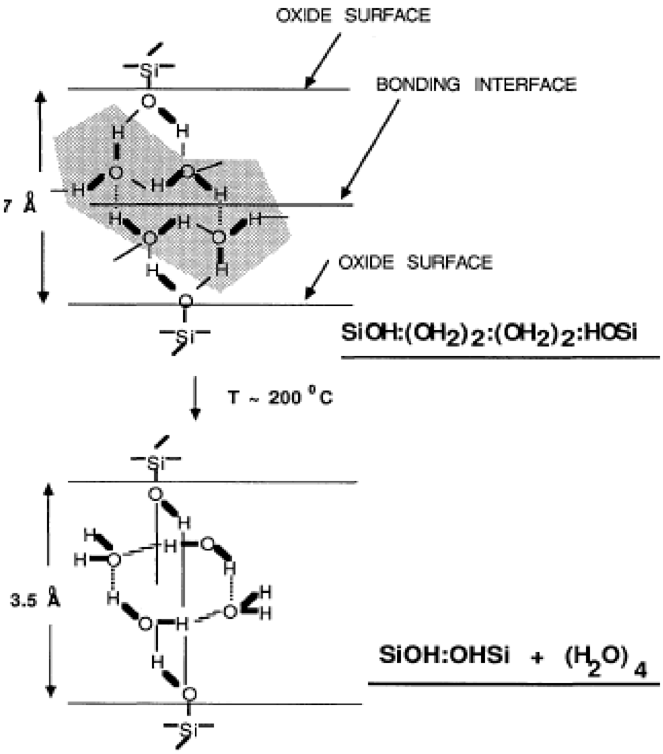



Fig. 1. Wafer bonding chemical model, taken from Stengl [6].

Wafer bow is defined as the curvature of the wafer without the thickness variation, which is the height difference between the centre of the wafer and the edge of the wafer. The bow was measured before and after the deposition of the nitride layers and no difference was shown.
Fig. 2 and 3 show the two cases considered in our study. Fig. 2 corresponds to a low curvature wafer while Fig. 3 corresponds to a high curvature.

Prior to bonding, the wafers were cleaned with fuming nitric acid 100% and hot nitric acid (65% at 105°C), followed by a quick dump rinse (QDR) with DI water. The wafers were kept wet in the QDR, rinsing several times and spin dried only just before bonding. To speed up the initial bonding a small pressure is applied until bonding initiates. Annealing was done for 4 hours ramping from room temperature to 400°C by steps of 100 °C for 1 hour in $N_2$ ambient.

We first qualified the bonding and the annealing processes on bare silicon. Bonding of these wafers gave a yield of 100 % yield. This allowed us to apply the same processes with the 30 nm and 300 nm LPCVD SiN films. The annealing step was optimised with the nitride layers as the initial annealing performed at 400 °C led to unbonded wafer pairs.

An IR camera was then used to qualify the bonding. Fig. 4 shows for example the 30 nm SiN on 30 nm SiN bonded pair.

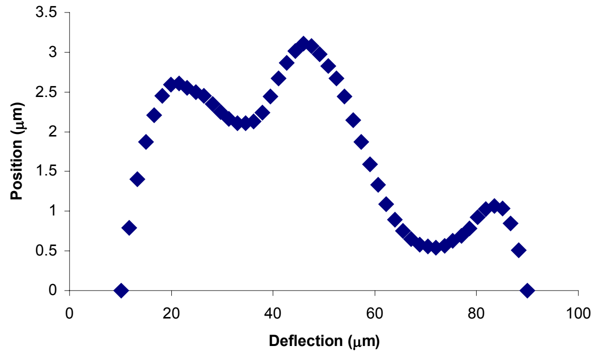



Fig. 2. Measured bow of a low curvature wafer covered with 30 nm thick SiN.

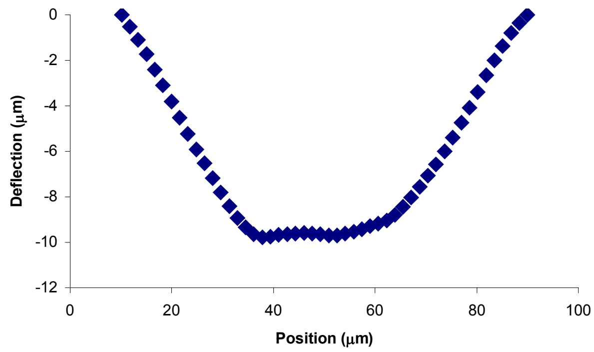



Fig. 3. Measured bow of a high curvature wafer covered with 30 nm thick SiN.

The white circle points out a void, which is a proof that in this region bonding as not been achieved. Usually unbonded circular regions are attributed to particles present even after cleaning. In our experiments we checked if any particle was left on the wafers using a grazing white light spot. However, this technique only allows the detection of large defects.

Nevertheless for both film thicknesses a 90% bonding was achieved, proving that even if nitride on nitride bonding is not commonly used it can be done by direct bonding.

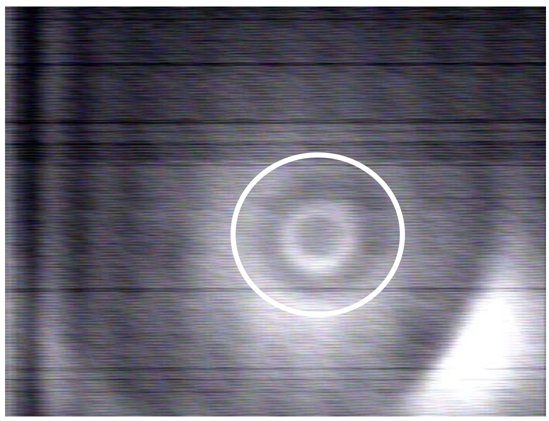


Fig. 4. Through IR transmission of a 30 nm thick SiN on 30 nm SiN bonded pair.

For the low curvature wafers we managed to bond efficiently (almost 90 % of the entire wafer bonded) while for the higher curvature we only managed to bond in the centre of the wafers where the bonding is initiated after the cleaning. The difference is due to the larger elastic deformation required to bring the surfaces into contact.

## IV. DISCUSSION

We failed to estimate the bonding energy of the bonded pairs using the crack propagation method. Nevertheless according to previous work on the subject we know that the bond strength of SiN to SiN bond is in the same range as for Si-Si hydrophilic bonding. Precisely it has been estimated between 1 and 2.8 $Jm^{-2}$.

Since the mechanism of direct bonding is based on short-range intermolecular attraction forces, surface roughness and flatness are regarded as critical parameters to determine bondability. High surface roughness or flatness will result in small contact area and lead to formation of voids.

Usually the root mean square roughness (RMS) or the mean roughness (Ra) values are used as parameters to evaluate the wafer bondability. It has been found from experiments that for a bondable wafer surface the mean roughness must be in the sub-nanometre range, preferentially less than 0.5 nm [8]. When the surface roughness exceeds a critical value, the wafers will not bond at all. Fig. 5 and 6 show the measured roughness of 30 nm and 300 nm LPCVD SiN films respectively. Both RMS values are below 0.5 nm even if thicker layers lead to higher roughness. We concentrated on LPCVD films as the technique gives better roughness values than a Plasma Enhanced Chemical Vapour Deposition (PECVD). For comparison the RMS roughness of PECVD SiN layers is higher than 0.5 nm [9] and bonding of those layers requires a reduction of the roughness by chemo-mechanical polishing (CMP) [10].

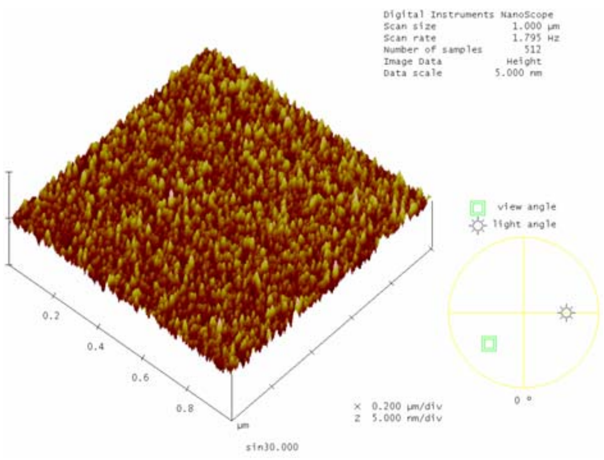



Fig. 5. AFM scan of a 30 nm thick LPCVD SiN film on Si. The RMS value was found to be 0.29 nm. The scanned area is 1 $\mu m^2$.

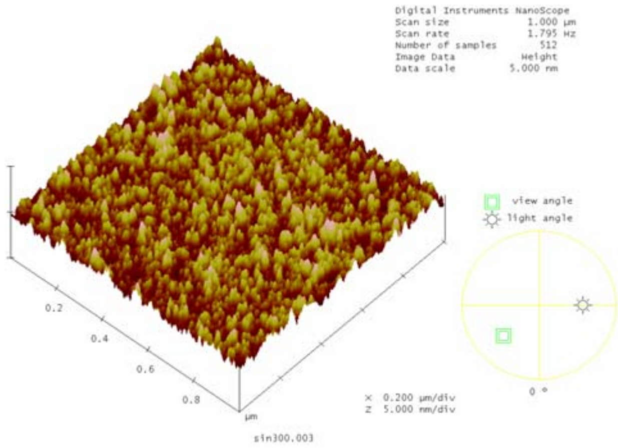



Fig. 6. AFM scan of a 300 nm thick LPCVD SiN film on Si. The RMS value was found to be 0.37 nm. The scanned area is 1 $\mu m^2$.

In many cases of patterned wafers for MEMS devices, prior to direct bonding, wafers already possess large bow due to the results of wafer manufacturing or residual stress from thin films on one side of the wafers. If the wafer bow is in a reasonable range it can be overcome through elastic deformation, but there is a limit. Several authors have investigated the condition for closing the gap formed by poor flatness at the interface. It has been reported that for 100 mm diameter process wafers, successful bonding process is expected if the ratio of the height of the gap to the lateral extension $h/r$ is no more than 5 x $10^{-4}$ [11] (with h the height of the gap and r its width). This means $h$ should be less than 25 µm. From Fig. 3 we can see that even with a high bow, we are still lower than the criteria given in [11].

Fig. 7 shows the effect of the curvature especially at the outside of the wafer.

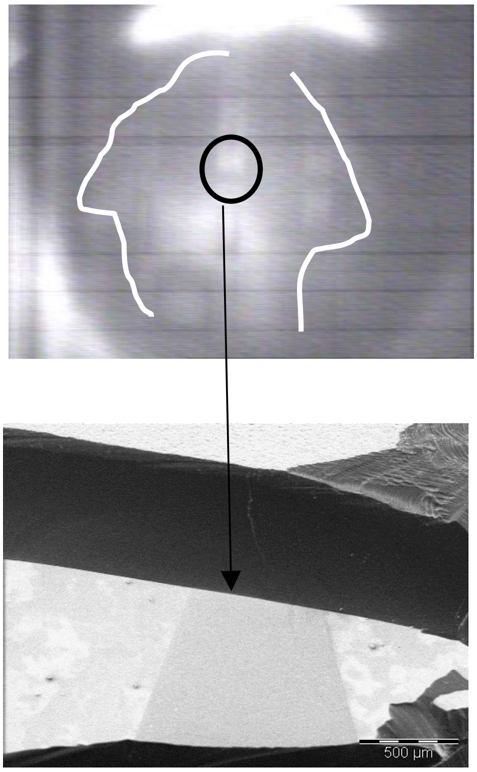
Fig. 7. 30 nm thick SiN layers on high bow wafers bonding. The bow affect the bonding as less than 40 % is bonded (inside the white line).

## V. APPLICATIONS

The purpose of the second part of the study was to see if it is possible to make patterned MEMS devices using nitride to nitride bonding. Specifically two applications were considered.

The first one concerns the sealing of a square hole covered with nitride. The sealing is done using a full wafer also covered with nitride but not patterned. It has been show that by carefully adjusting the nitride thickness the square hole can efficiently guide light in presence of liquid [12]. Such a structure also named hollow waveguide can be then considered as a sensor by following the absorption induced by a liquid presents inside the waveguide.

The second device concerns a micro fluid cell for Transmission Electron Microscopy (TEM). In that case a cavity is made between two SiN membranes (that allow a full transparency). A nitride spacer between the two membranes defines the high of the cavity. Fig. 8 shows 300 nm thick SiN spacers below a wafer covered with 30 nm SiN. A close up view shows the bonded interface.




a)

b)

Fig. 8. 30 nm SiN on 300 nm patterned SiN films: a) IR photograph of an area of a few centimetres ; b) SEM view of the indicated area (cross-section).

## VI. CONCLUSION

We have shown that direct bonding of nitride on nitride layers was successful for thin as well as for thick layers. A special attention should be paid to the curvature of the wafers. The LPCVD allows the deposition of good roughness layers and does not introduce extra deformation. We also bonded 30 nm nitride layers on patterned wafers.

We are currently characterizing the bonding strength of the bonded pairs presented in this work.


## ACKNOWLEDGMENT

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