Characterization of SOI Wafers Fabricated by a Modified Direct Bonding Technology

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Abstract

A modified direct bonding technique employing a wet chemical deposition of SiO_2 film on a wafer surface to be bonded is proposed for the fabrication of Si-SiO_2-Si structures. Structural and electrical quality of the bonded wafers is studied. Satisfied insulating properties of interfacial SiO_2 layers are demonstrated. Elastic strain caused by surface morphology is investigated. The diminution of strain in the grooved structures is semi-quantitatively interpreted by a model considering the virtual defects distributed over the interfacial region.

Key Words(중요용어) : Silicon Direct Bonding, Silicon-on-Insulator, Elastic Strain, Groove

1. Introduction

During last few years direct wafer bonding (DWB) technology, which allows to join mirror-polished semiconductor or other wafers without the application of any glue and opens up the possibility to prepare combinations involving single crystalline materials, has found a wide variety of applications to make different devices[1-3]. In the area of silicon-on-insulator(SOI) the technology is an attractive alternative to other SOI methods because of maintaining the silicon layer bulk quality and the flexibility in controlling SOI layer thickness[4]. High quality bonded SOI wafers are expected to play a major role in VLSI products[5].

It is, however, not easy to fabricate large-area bonded wafers being void-free and having low-strain, even either electrically conducting or insulating interfaces. Simultaneous formation of chemical bonds over the whole contact area is impeded by surface morphology since the wafer surfaces are never perfectly smooth. Non-flatness of the wafer surfaces resulted in the appearance of elastic strain in the interfacial region of bonded SOI wafers[6,7], which was estimated as $\sigma_{max} \equiv 0.09$GPa in the direction perpendicular to the interface for wafer thickness of about 0.5mm[6]. Trapped air or gas appearing during high-temperature annealing also breaks the continuity of the interface[3]. Our earlier works showed direct bonding of oxide-free silicon wafers, one of which had a regular network of meso-scale grooves on a surface to be bonded, could be realized with an improved quality[8,9]

Conventional DWB methods for SOI wafers involve the preliminary thermal oxidation of one or both wafers to be bonded. As a rule, high-temperature treatment results in deteriorating electro-physical parameters of silicon wafers.

This paper presents a modified method to fabricate SOI structure, employing chemical coating method of SiO_2 film from the solution of hydrolyzed tetraethoxysilane(TEOS), without thermal oxidation before bonding. The model explaining the experimentally observed elastic strain diminution in the grooved structures is suggested.

2. Experimental

Commercially available mirror-polished FZ silicon wafers with (111) or (100) orientation and of about 0.5 mm in thickness were used. After a standard RCA cleaning, the surface of one wafer from each pair was twice covered with TEOS solution by centrifuging with subjection to destruction at 300℃ for 1 min after each covering. Grooved Surface Bonding(GSB) procedure is performed to bond the wafer coated by TEOS to the other one containing the net of grooves with meso-scale depth. The surface of the other wafer was prepared as a square network of grooves with the width, spacing and depth 50㎛, 200㎛ and 0.3~0.5㎛ respectively. Wafer mating was performed in deionized water of 18MΩcm with a subsequent spin drying of face-to-face pairs. Dried pairs were kept in air at 95℃ under the pressure of 0.1N/mm^2 for 4h and then subjected to annealing at elevated temperatures.

The structural quality of bonded compositions was studied by X-ray diffraction topography (XRT), transmission electron microscopy(TEM) and IR spectroscopy techniques. Thickness and refraction index of SiO_2 layers were determined by ellipsometrical measurements on the wave length λ=0.63㎛. Film resistivities were calculated from I-V characteristics measured in a special screened installation. C-V measurements were made by Hg electrodes. Dielectric constant was determined from capacitance measurements by the capacitance bridge SWM3-2. XRT method was used for the investigation of interfacial elastic strain.

3. Results and discussion

Table 1 shows parameters of SiO_2 layers obtained by modified technique in comparison with the conventional one: thickness(d, ㎛), resistivity (ρ_v ,Ωcm), breakdown voltage(V_{br}, V) and refraction index(n).

One can see that silicon dioxide layers obtained from TEOS films by GSB procedure demonstrate sufficiently high dielectric quality. High refraction index (n>1.45) is due to silicon accumulation by the dielectric layer during bonding procedure.

TABLE 1

Type of Silicon	d	ρ_v	V_{br}	n
(111) n-type, $\rho_v = 15\Omega \cdot cm$	1.1	2×10^{15}	80	1.62
(100) p-type, $\rho_v = 20\Omega \cdot cm$	0.9	1.5×10^{12}	80	1.5
(111) n-type Thermal oxide, 1250℃ 2h. dry O_2	1.0	1×10^{15}	100	1.5

Maximum breakdown strength in the designed dielectric layers was not more than 3.0×10^6 V/cm; dielectric constant was $\varepsilon_i \simeq 4.0\pm0.24$. Fixed charge for both types of oxide films was about $10^{-7}C/cm^2$, i. e. fixed trap concentration N_{tr} was about $10^{12}cm^{-2}$ and surface state density at minimum $N_{ss,\min} \simeq 10^{12}cm^{-2}eV^{-1}$.

Fig. 1 presents the TEM cross-section image of the TEOS SOI structure. The micrograph confirms the presence of the amorphous layer at the interface. The amorphous layer thickness depended on the TEOS film composition and the temperature treatment regime.

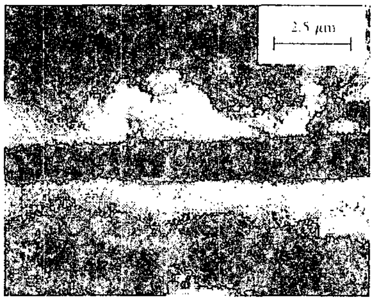

Fig.1. TEM cross-section image of the TEOS SOI structure. TEOS oxide film was formed during annealing at 1000℃-1h. followed by 1150℃-2h.

A wavy contrast was observed on X-ray topographies of Si-SiO_2-Si bonded compositions with smooth and grooved bonding interfaces caused by periodically distributed surface micro-roughness. Analysis of X-ray images from grooved structures led to the conclusion that the free surfaces of the groove and the lattice planes in their vicinity are remarkably bent.

The experimental data could be explained with attracting the simple geometrical models of wafer contact. Fig. 2 shows the geometry of the surface waviness at the contact between two smooth wafers. During bonding, the largest amount of stress comes from the places where the asperities of the wafer are aligned with respect to each other shown in Fig. 2(a). Bonding results in the conformity of the rough surfaces while the smoothen interface becomes the source of periodically distributed elastic strain in Fig. 2(b).

Fig. 3(a) displays the contact between two surfaces, one of which is covered by orthogonal net of grooves. The net period is chosen close to that of the surface waviness and the groove depth is much more than the amplitude of waviness U_0.. Provided that the area covered with the grooves is large(in our systems it consists about 36% of the total wafer area), the probability for an asperity to align with a groove is rather high. In doing so, the maximal distance between the opposite surfaces $4U_0$ is decreased by the value δU_0, which in our systems consists approximately 15% from $4U_0$. Therefore, the effective decrease of the surface waviness in grooved structures takes place and, taking into account the linear dependence U_0 value on the level of elastic strain, we obtain strain diminution also by 15%.

Except of this reason, the experimentally observed substantial diminution of elastic strain in the structures formed by GSB technique can be explained also by bending and relaxation of the groove free-surfaces as it is shown in Fig. 3(b).

Naturally, the elastic relaxation of groove-free surfaces, shown schematically in Fig. 3(b) as their bending, should effectively screen the strain fields from bonded areas, which decreases the total elastic deformation. For the calculation of elastic fields, the special models were suggested, using concepts of interfacial virtual defects whose characteristics are wholly determined by surface micro-roughness and bonding boundary configuration. The detailed description of these models is out of this presentation.

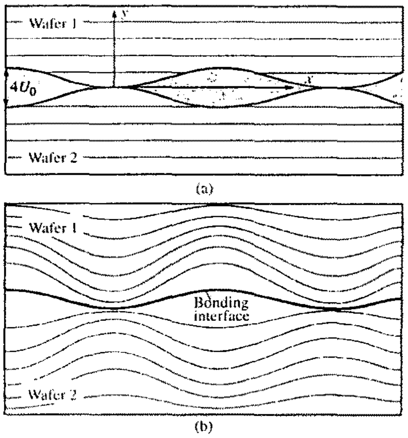

Fig. 2. (a) Geometry of the surface waviness in the contact between smooth surfaces, where U_0 is amplitude of surface waviness and T period and (b) schematic presentation of the strain by the bonding process.

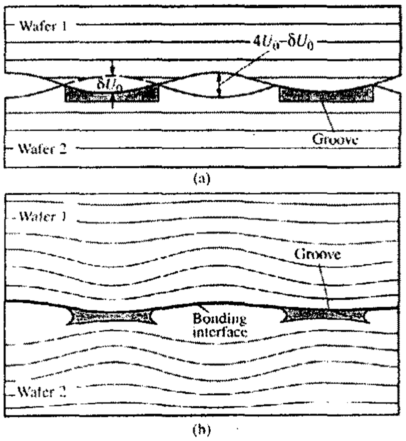

Fig. 3. (a) Scheme showing the contact between smooth and artificially grooved surfaces. δ is an effective decrease of surface waviness and (b) schematic presentation of strain introduced diminution via bending the free surfaces of the grooves

The results of the elastic dilatation $\varepsilon = \delta V/V$ (relative local elastic change of the volume) calculation in the two-dimensional approximation (planar deformation case) are presented in Fig. 4. The comparison between the dilatations $\varepsilon(0,y)$ and $\varepsilon'(0,y)$ of smooth and grooved interfaces respectively varying with the distance from the interface shows that the maximal absolute value of the latter (at the point y = 20 μm) 0.34×10^{-4} is 4 times lower than that for smooth interface, $\varepsilon=1.2\times10^{-4}$.

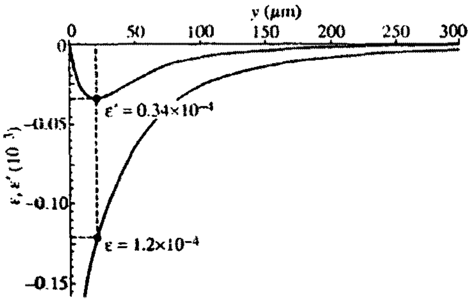

Fig. 4. Elastic dilatation at the bonding boundary: $\varepsilon(0,y)$ for the smooth(the lower curve) and $\varepsilon'(0,y)$ for the grooved(the upper curve) interfaces.

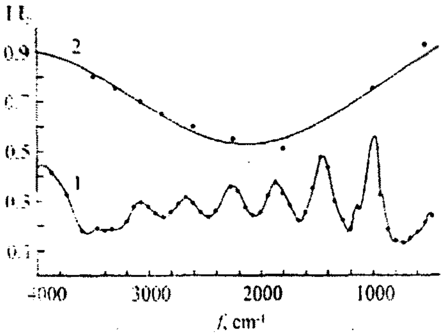

Fig. 5. Relative transparency(relative to silicon wafer) of SOI. 1; with smooth bonding interface; 2; with grooved bonding interface.

Fig. 5 presents IR transparency spectra of Si-SiO_2-Si bonded samples with smooth(curve 1) and grooved(curve 2) interfaces respectively. The oscillations were interpreted due to the elastic strain at the bonding boundary. The corresponding calculations were done by using the theory of dispersion filters[10]. The stress value in the perpendicular to the interface direction was 0.6 GPa for the smooth structures and 0.05 GPa for the grooved ones. Thus, manufacturing the net of meso-scale grooves on the surface of one wafer prior to bonding allowed to reduce interfacial elastic stress by more an order of value.

4. Conclusion

A rather simple and versatile method for the fabrication of Si-SiO_2-Si structures with satisfied structural and insulating interface quality has been proposed. Manufacture of regular net of grooves on the wafer surface to be bonded allowed to reduce the stress caused by surface morphology by more than an order of value. The suggested model explained the observed strain decrease as due to:

(i) effective diminution of the amplitude of surface waviness resulted from the contact between smooth and grooved surfaces,

(ii) stress relaxation at the free surfaces of artificial grooves.

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