

Effect of nanoscale surface topography on low temperature direct wafer bonding process with UV activation

Zirong Tang^{a,*}, Ping Peng^b, Tielin Shi^b, Guanglan Liao^a, Lei Nie^b, Shiyuan Liu^b

^a Wuhan National Laboratory for Optoelectronics, Huazhong University of Science and Technology, 1037 Luoyu Road, Wuhan 430074, China

^b State Key Laboratory of Digital Manufacturing Equipment and Technology, Huazhong University of Science and Technology, Wuhan 430074, China

ARTICLE INFO

Article history:

Received 15 September 2008

Received in revised form

27 November 2008

Accepted 25 January 2009

Available online 28 February 2009

Keywords:

Low temperature wafer bonding

Nanoscale surface roughness

Bearing ratio

Root-mean-square

UV activation

ABSTRACT

Low temperature direct wafer bonding is a promising technology for microelectromechanical systems (MEMS), sensors as well as silicon-on-insulator (SOI) materials. The bond quality is closely related to the wafer-bow, surface adhere energy and nanoscale surface topography. Effective surface activation and nanoscale surface topography evaluation is critical for the bonding process. For the low temperature silicon wafer direct bonding process with ultra violet (UV) light activation, surface nanoscale topography is modified and characterized before and after UV irradiation by the control of irradiation duration. The measured data of nanoscale topography by atomic force microscope (AFM) is evaluated by both bearing ratio and root-mean-square (RMS) approaches, from which the results are then correlated with the bond strength to understand the bonding process. It is shown that the bear ratio approach is more suitable for characterizing the surface roughness and optimizing the bonding process through the control of UV irradiation duration. The approach is also applicable to a wide variety of low temperature wafer bonding process where surface roughness is modified.

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1. Introduction

During low temperature direct wafer bonding two polished and clean wafer surfaces are brought into direct contact at room temperature and then annealed at temperature below 300 °C [1]. Since low temperature direct wafer bonding can create a strong connection between silicon and other semiconductor without high temperature, it has been attractive to a variety of applications where high temperature annealing is prohibited [2–4]. Low temperature bonding strength is closely dependent on multiple factors, including wafer-bow, surface adhere energy and surface roughness, which have characteristic length scales ranging from sub nanometer to hundreds of millimeters. Wafer-bow is the deformation of the wafer at large scale. It always blocks the two wafers from making close contact and causes inner stress. Such mechanical defects can be reduced or eliminated by improving original wafers' quality and applying proper load to wafer pairs [5].

Surface adhere energy can be improved by wafer surface pre-treat before the wafer bonding, such as the modification of the wafer surfaces either due to an increasing hydrophilicity, which increases the number of hydrogen bonds via the interface, or due to the generation of new types of chemical bonds stable already

at low temperatures. Tong et al. treated the silicon wafer surface in the HNO₃/H₂O/HF or the HNO₃/HF solution prior to room temperature contact. The bonding energy is significantly improved [6]. Ljungberg et al. [7] used H₂SO₄/H₂O₂/HF and HNO₃/HF to modified silicon surface prior to wafer bonding to get high bonding strength at room temperature. Other chemicals such as NH₃ and HF acid have also been tried for low temperature bonding [8–11]. However, the wet chemical-activated process involves difficult process control and the interfacial mechanical strength is hard to reach that of bulk silicon which may prohibit its wide applications. Another way to enhance bonding strength is through “dry” plasma or UV radiation. By applying plasma treatment to the wafer surface, prior to bonding the surface chemistry can be tailored in order to obtain maximum bond strength for low temperature thermal annealing [12–14]. However, the approach will require very costly irradiation source and bonding quality is also hard to meet the process requirements since long irradiation duration may roughen the wafer surface in order to get strong bonding. To treat the surface with UV exposure prior to conventional direct wafer bonding can also improve bonding strength significantly under low temperature, which was reported recently [15]. Dang et al. [16,17] investigated the effect of pre-treating hydrophobic and hydrophilic silicon wafers with UV at various temperatures prior to wafer bonding, and found that using short wave length UV as an activation treatment resulted in the highest bond strength. Their work showed UV activation could be a low cost approach for low temperature wafer direct bonding. However, more work still needs to be continued to understand the

* Corresponding author. Tel.: +86 2787792241; fax: +86 2787792413.

E-mail address: zirong@mail.hust.edu.cn (Z. Tang).

process, for instance, how UV exposure affects the surface nanoscale topography of wafers and how surface topography affects bond quality.

While surface adhere energy is mainly determined by the surface chemistry which can be modified through surface treatment, the interfacial surface roughness at the nanoscale plays a significant role and interacts strongly with chemical effects. Previous work has reported that the bond quality declines with increasing surface roughness, however, the surface roughness with radii of curvature was mainly analyzed in the order of micrometers. Gui et al. [18] observed that RMS roughness was limited in the evaluation of wafer bondability in terms of surface roughness and introduced an adhesion parameter, which includes both the mechanical and chemical properties of the wafer surface to evaluate the bondability of wafers. While Turner et al. [19] investigated the effect of surface roughness at the nanoscale with different morphologies achieved using a buffered oxide etch (BOE) and a combination of KOH and BOE. They also concluded that bearing ratio was a useful measure of nanoscale surface topography.

The objective of this work is to relate the surface roughness at the nanoscale to bond quality of UV-activated bonding process. Experiments of low temperature wafer bonding with UV activation of different duration are conducted and the surface nanoscale topography is measured by AFM after each treatment. Standard RMS and bearing ratio approaches are used to characterize the wafer surface topography and highlight the correlation between the bearing ratio and bonding strength to understand the UV-activated process.

2. Modeling of wafer surface roughness

Standard surface roughness can be described as the deviation in the height of the surface relative to a reference plane. One of the most commonly used parameters to characterize the surface roughness is the standard deviation, which is expressed as

$$\sigma^2 = \frac{1}{L} \int_0^L (z - m)^2 dx \quad (1)$$

where $z(x)$ is the height, L is the sampling length of the profile, and m is the mean height which is expressed as

$$m = \frac{1}{L} \int_0^L z dx \quad (2)$$

When the mean height is set to reference,

$$R_q = \text{RMS} = \sqrt{\frac{1}{L} \int_0^L z^2 dx} = \sigma \quad (3)$$

However, the standard deviation or RMS roughness does not necessarily provide sufficient information about the surface topography to investigate the process of bonding a pair of wafers. For example, Fig. 1 shows two surfaces with identical standard deviation. Surface (a) is obviously easier for direct bonding Fig. 1(b) than Fig. 1(a), since it offers a far larger direct contact area.

Surface roughness is generally represented in terms of statistical deviation from average height. When the surface chemistry is identical, it is generally assumed that the bond strength is proportional to the real area of contact. In Fig. 2, each of the small squares represents a pixel of the scanned surface, and defining the highest peak of the asperity as zero, $z(x, y)$ as a depth at the position (x, y) , and the threshold depth as z_c , the real area of contact A_c can be expressed as

$$A_c = \iint f[z_c - z(x, y)] dx dy \quad (4)$$

where $f(u) = 1$ if $u \geq 0$; $f(u) = 0$ if $u < 0$.

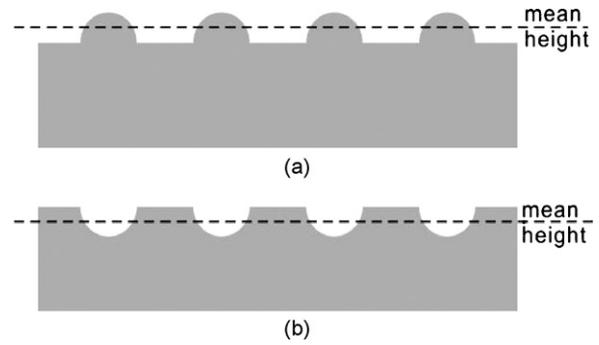


Fig. 1. Schematic of the two surfaces with identical root-mean-square (RMS) roughness, surface (a) is easier to bond to a flat surface than surface (b).

Bearing ratio is another approach to specify the quality of surface topography, which reveals how much of a surface lies above or below a given height. It is defined as being the area lying above a given depth referred to as the bearing depth to the whole sampling area. Fig. 2 also shows how bearing ratio analysis gets information at various Z heights. At Z height “a”, virtually the whole surface is included (corresponding to a bearing ratio of 100% of the area). At Z height of “b”, “c” and “d”, the bearing ratio is much decreased.

A map of the nominal bearing area for a silicon wafer surface with different bearing ratio is shown in Fig. 3, where Fig. 3(a) representing 90% of bearing ratio at bearing depth of 1.2 nm, Fig. 3(b) representing 70% of bearing ratio at bearing depth of 1.1 nm, Fig. 3(c) representing 40% of bearing ratio at bearing depth of 0.8 nm, Fig. 3(d) representing the bearing ratio of 17% at bearing depth 0.5, and the top peak is set to zero. When the bearing depth equals the threshold depth z_c , the bearing ratio is equivalent to the ratio of the real area of contact to the sampling area A_c/A_0 . Supposing that the depth distribution is known, the bearing ratio can be expressed as

$$Br = \int_0^{z_c} p(z) dz \quad (5)$$

where z_c is the bearing depth and $p(z) dz$ is the probability that the surface has the depth between z and $z + dz$. Assuming that the contact area at the nanoscale is considered to be the area enough to be the interface to contribute to the attractive force between the wafers, the bearing ratio can be used to evaluate the bonding strength, which is discussed later in this paper.

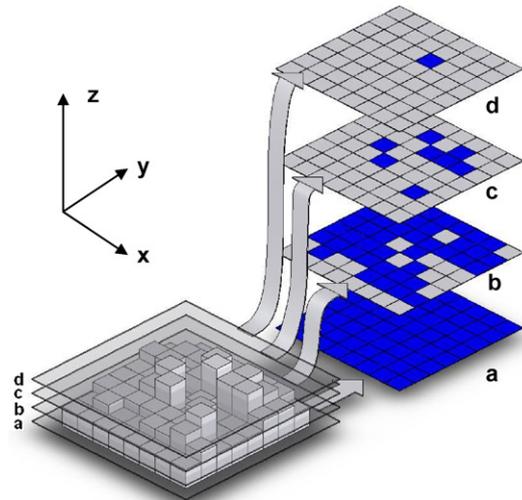


Fig. 2. Concept of bearing ratio, where darker area is assumed to be bearing area.

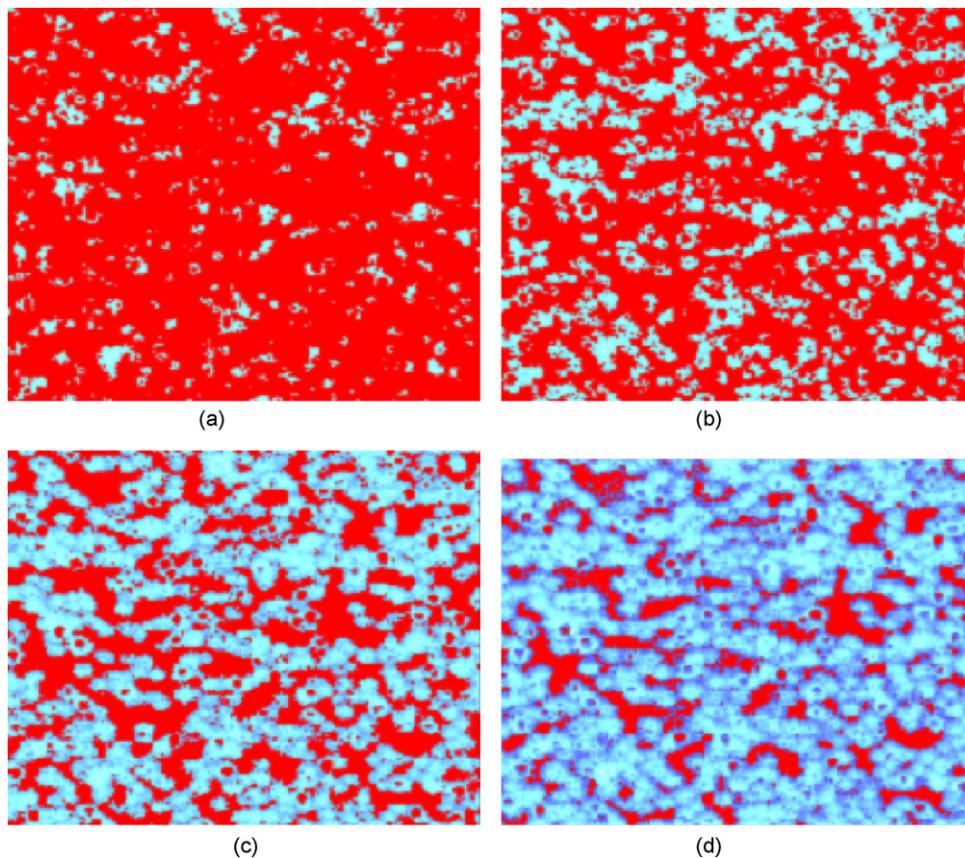


Fig. 3. Bearing ratio is the ratio of bearing area lying above a given bearing depth to the whole sampling surface: (a) 90%, bearing depth of 1.2 nm; (b) 70%, bearing depth of 1.1 nm; (c) 40%, bearing depth of 0.8 nm; (d) 17%, bearing depth of 0.5 nm; and the top peak set at zero.

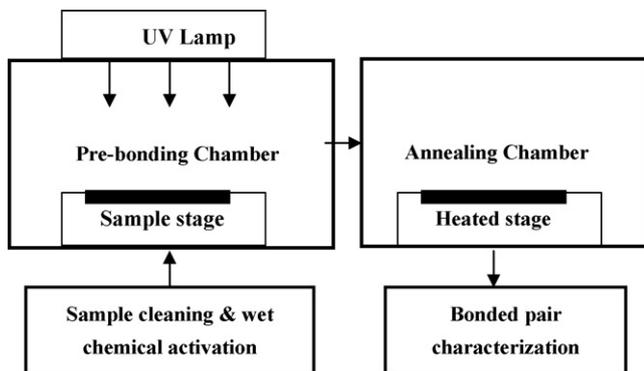


Fig. 4. Experimental setup and process flow for low temperature silicon wafer bonding with UV activation.

3. Bonding experiments

The schematic setup of the experiment is shown in Fig. 4. The UV light source applied in the experiment contains approximately 85% 254 nm wavelength irradiation and 15% 185 nm wavelength irradiation with UV intensity of 15 mW/cm^2 . During exposure, the temperature of the surface of the low pressure mercury lamp was maintained at 90°C to ensure the maximum output. Commercially available 2 in., P type, (1 1 1) silicon wafers with thickness

of $380 \mu\text{m}$ were used for bonding. The whole process is shown as follows:

- (1) All sample wafers were cleaned by acetone in supersonic cleaner for 20 min, which contributed in removing most organic contaminations. After that, deionized (DI) water was used to flush the surface.
- (2) Boil the wafers in mixture of sulfuric acid and hydrogen peroxide ($\text{H}_2\text{SO}_4:\text{H}_2\text{O}_2 = 2:1$) called SPM for 20 min. This process was to eliminate metal particle contaminations effectively and rendered the wafer surface hydrophilically. Flushing process using DI water was also employed after this process.
- (3) RCA solution which was composed of $\text{H}_2\text{O}:30\%\text{H}_2\text{O}_2:28\%\text{NH}_4\text{OH}$ (5:1:1 by volume) was used to treat the surface. After immersing the wafers in the solution for 15–20 min under 40°C , the surfaces were rendered highly hydrophilically. This process was also followed by DI washing.
- (4) Then a spin dryer was used to remove the water for 3 min under 3500 rpm for each wafer.
- (5) As the follow-up process, UV exposure was applied under atmosphere to all sample wafers for different duration while one group of samples was treated without UV exposure. The light source produced UV irradiation with the surface intensity of 15 mW/cm^2 at the distance of 5 mm where the sample wafers were placed. The exposure duration were selected for 5, 10, 15, and 20 min.

Table 1
Bond strength of wafers for different exposure duration.

Exposure time (min)	0	5	10	15	20
Bond strength (MPa)	4.2 ± 0.2	10.3 ± 0.5	6.9 ± 0.4	6.5 ± 0.4	5.2 ± 0.2

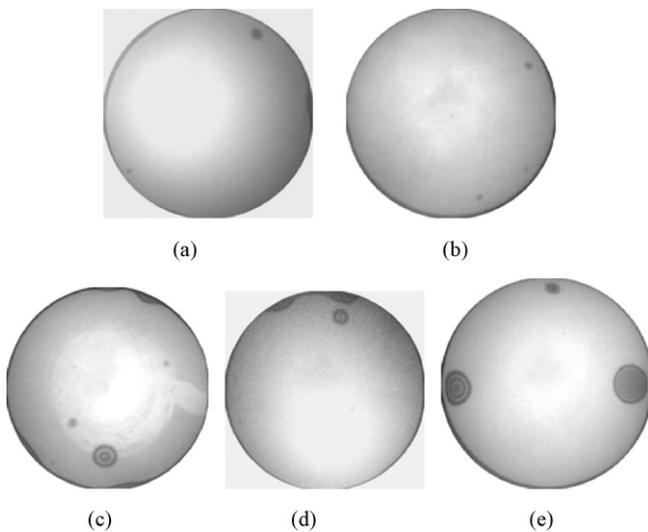


Fig. 5. IR bonding image of bonded wafers for UV irradiation with (a) and without UV irradiation, (b) 5 min, (c) 10 min, (d) 15 min, and (e) 20 min.

(6) For each group, wafers were brought into contact after wet chemical treatment and UV exposure, except the samples which were used for Atomic Force Microscope (AFM) measurements. Bonding wave was initiated when pressing the center of each wafer pair slightly and it could spread the whole surface to finish spontaneous bonding. After that, they were placed in hot plate to perform annealing under 150°C for 4 h without any external pressure.

4. Results and discussion

4.1. Bond quality characterization

Fig. 5 shows the typical infrared (IR) images of bonded wafers for without and with UV irradiation for 5, 10, 15, and 20 min, and it also shows that UV irradiation of around 5 min achieved the best bond uniformity, while too long irradiation may lead to interfacial defects. The bond strength was also measured by the single axis stretch test. For each group of wafer couple, 20 samples were tested in the pull testing. The test results were included in Table 1, where an average data was presented with standard deviation. From the table, UV exposure for 5 min rendered the highest bond strength (around 10.3 MPa) which is equal to that of bulk silicon as illustrated in Fig. 6, which shows the fractured 3-dimensional surface of bulk silicon for sample after the pulling test. We can see that UV light

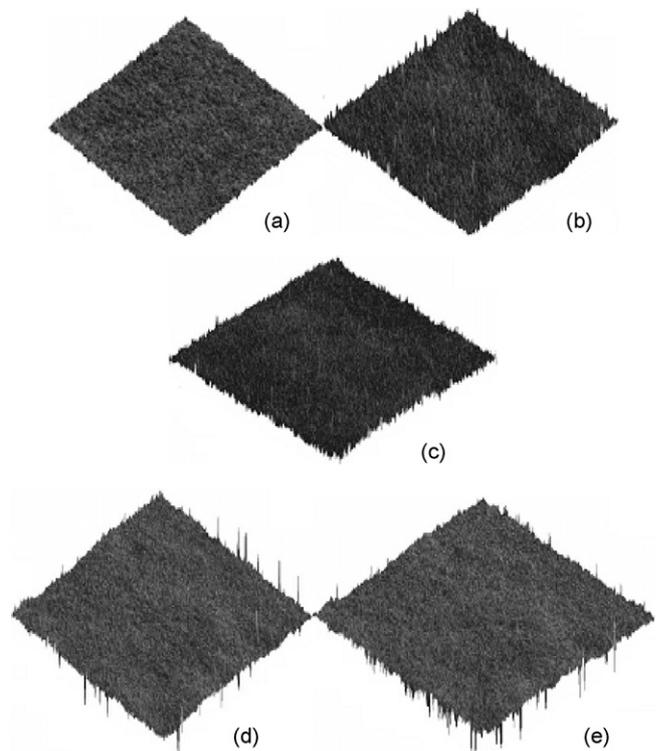


Fig. 7. Surface images by AFM of the sample wafers and the wafers irradiated by UV for (a) without UV irradiation, (b) 5 min, (c) 10 min, (d) 15 min, and (e) 20 min.

irradiation can increase the bond strength, while too long exposure duration will not increase the bond strength.

4.2. Surface topography with UV modification

In order to understand the effects of UV exposure on silicon sample surface roughness, the surface roughness of silicon sample was monitored during bonding process before and after UV irradiation. AFM was implemented to get the surface nanoscale topography. Fig. 7 is the comparison of AFM image before and after UV irradiation. The UV irradiation duration was controlled for 5, 10, 15, and 20 min. The deterioration of surface quality is clearly observed after longer UV irradiation exposure.

Based on the data obtained from AFM measurements presented as the depth distribution of silicon wafer surface, the height distribution of surface topography was statistically obtained. Fig. 8(a) shows the typical curve for height distribution of sample surface

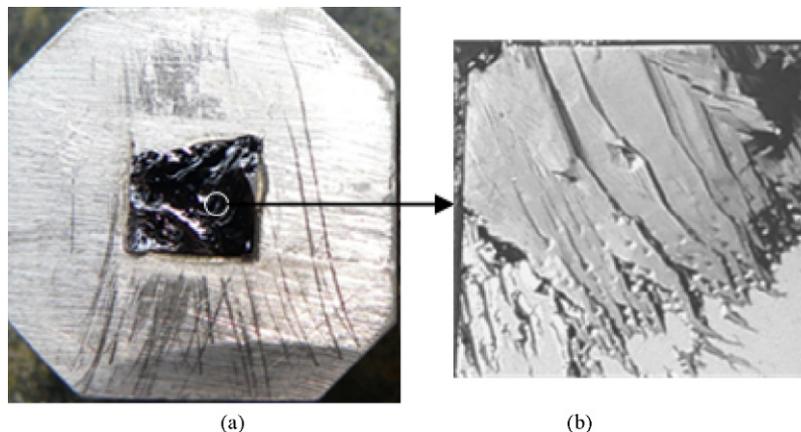


Fig. 6. Fractured surfaces after pulling test of the bond sample (a) and (b) enlarged by 200 \times .

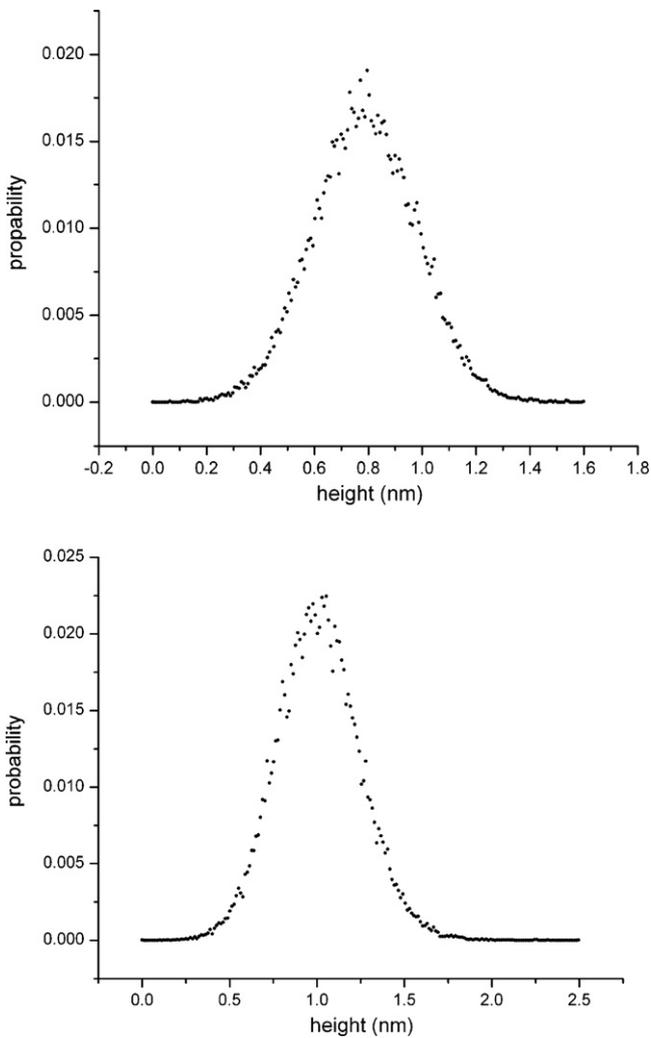


Fig. 8. The height distribution (a) before and (b) after the UV exposure.

before UV treatment, Fig. 8(b) plots the height distribution after 5 min UV treatment, where the dots have a close correlation with the Gaussian distribution.

Based on the height distribution, surface roughness was analyzed and compared with different UV exposure durations. Following previous modeling of surface characterization, RMS and bearing ratio approach were applied to interpret the surface topography. Fig. 9 depicts surface roughness RMS and Ra of samples with respect to the UV light irradiation for 5, 10, 15, and 20 min; it shows that the RMS and Ra increase as the irradiation duration increases.

Then bearing ratio approach was also applied to analyze the sample surface. Fig. 10 shows bearing ratio curve of the sample wafers with respect to the UV irradiation for 5, 10, 15, and 20 min, respectively.

At the bearing ratio of 95%, the Z displacement (corresponding to height of surface topography) increases as the UV light exposure duration increases. As shown in Table 2, the surface irradiated by UV light for 5 min got at least Z displacement at the same above bearing ratio, which corresponds to the highest bond strength. So wafers irradiated by UV for 5 min are supposed to be most easily to bond theoretically, which corresponds to the highest bond strength.

Based on the data provided in Table 1, UV exposure to wafer samples will increase bond strength, and the highest was achieved for the duration of 5 min. An explanation for the experiment results is that UV light activation treatment is thought to increase the number of hydroxyl groups and achieve a high quality bond. But the bond

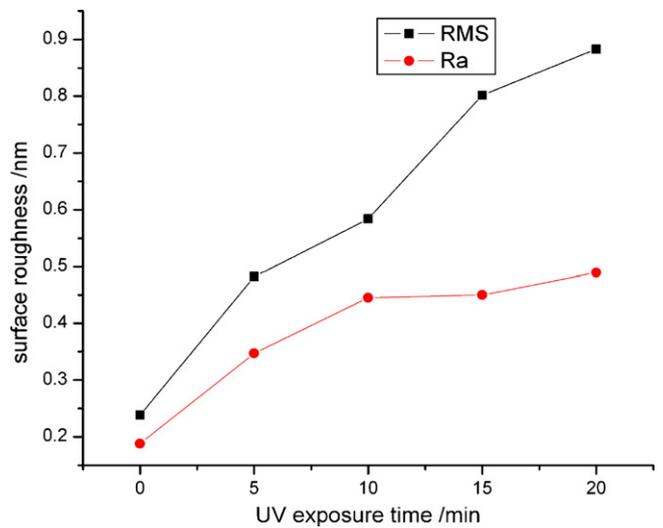


Fig. 9. RMS and Ra of the sample surface with respect to the UV light irradiation duration.

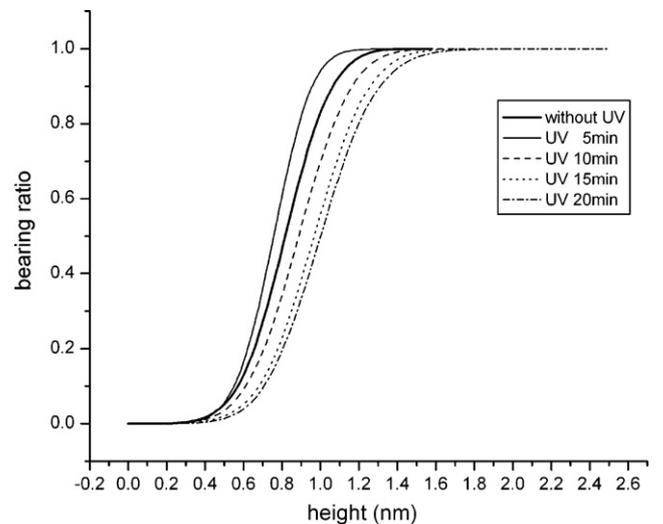


Fig. 10. Bearing ratio curve of the sample wafers with respect to the UV irradiation for 0, 5, 10, 15, and 20 min, respectively.

strength is not increased as extending of the exposure time because the UV light can modify the silicon wafer surface and change the topography of the wafer surface. The high energy light may cause many voids in the silicon surface and increase the surface roughness at nanoscale. Through the bearing ratio analysis of surface topography, short time exposure (5 min) will improve wafer surface quality, which corresponds to the highest bond strength by the bonding strength experiment. Therefore, control of surface roughness with bearing ratio characterization will help to optimize the bonding process.

Table 2
Z displacement under different surface treatment (95% bearing ratio).

UV irradiation	Bearing ratio	Displacement in Z (nm)
Without UV	94.987%	1.139
UV 05 min	94.989%	1.012
UV 10 min	95.241%	1.246
UV 15 min	94.891%	1.340
UV 20 min	95.070%	1.404

5. Conclusions

The effect of surface roughness at the nanoscale on direct wafer bonding with UV activation has been investigated. Nanoscale surface topography of wafer surface was obtained with AFM under different UV treatment duration. The surfaces of treated wafers were characterized by both RMS and the bearing ratio. The treated wafers were bonded and the bonded wafers were tested with the single axis stretch machine to get bond strength, which was shown to be a strong function of the surface topography. The wafers which were activated by UV light for 5 min get the highest bond strength. It revealed that control of exposure time is critical for the process since longer exposure time may deteriorate the wafer surface roughness. The good correlation between the bond strength and the bearing ratio for different surfaces proved that the bearing ratio is a useful characterization of the nanoscale surface topography for UV-activated process. And the approach is also applicable to a wide variety of wafer direct bonding process where surface roughness is modified.

Acknowledgements

The authors would like to thank the Microfabrication and Testing Center of Huazhong University of Science and Technology for the preparation of the samples and doing the tests. And this project was partially funded by National Major Fundamental Research Program of China (Grant No. 2009CB724204) and National Natural Science Foundation of China (Grant No. 50875103, 50805061 and 50775090).

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Biographies

Zirong Tang is an associate professor in Wuhan National Laboratory for Optoelectronics at Huazhong University of Science and Technology (HUST), Wuhan, China. He obtained his Ph.D. in Material Science and Engineering in 2001 from the University of California, Irvine, USA. His current interests are in sensors and micro/nanofabrication technologies.

Ping Peng is a Ph.D. student in the State Key Laboratory for Digital Manufacturing Equipment and Technology at HUST. He obtained his BSc (2001) in Optoelectronic Engineering and MS (2005) in Mechanical Engineering from HUST. His Ph.D. work is focusing on the silicon wafer direct bonding under low temperature.

Tielin Shi is the director of the State Key Laboratory for Digital Manufacturing Equipment and Technology at HUST. His interests are in micro/nanofabrication technologies and developing advanced fabrication systems for microelectronic industry.

Guanglan Liao is a senior research fellow in Wuhan National Laboratory for Optoelectronics at HUST. He obtained his MS (1998) and Ph.D. (2002) from HUST. His current interests are in developing gas sensors and micro/nanofabrication technologies.

Lei Nie received his Ph.D. in mechanical engineering in 2007 from HUST. He is currently a postdoctoral staff in the State Key Laboratory for Digital Manufacturing Equipment and Technology at HUST, where his major interests are in micromachining and wafer-scale packaging.

Shiyuan Liu received his Ph.D. in mechanical engineering in 1998 from HUST, and worked as a Visiting Scholar at University of Manchester, UK, from 2000 to 2001. He is currently a Professor of the State Key Laboratory for Digital Manufacturing Equipment and Technology at HUST, where his research interests are in MEMS, micro/nano-manufacturing process and equipments.