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Photoluminescence Characterization of Interface Quality of Bonded Silicon Wafers

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Wafer-to-wafer bonding is implemented in fabrication of backside illuminated (BSI) complimentary metal-oxide-semiconductor image sensor (CIS) devices in volume manufacturing. A wafer with illuminated imager and a wafer with readout and image processing electronics are fabricated separately and assembled using wafer-to-wafer bonding. Since the illuminated imager and a wafer with readout and image processing electronics are facing each other at the bonded interface, the quality of wafer-to-wafer bonding interface can affect the performance of finished devices. Room temperature photoluminescence (RTPL) technique was studied as a non-contact, in-line characterization technique for assessing bonding interface quality. Ordinary and bonded, 200 mm Si wafers, with different surface finishing conditions, were characterized by RTPL under two different excitation wavelengths (650 nm and 827 nm) to investigate the effects of surface finishing conditions. Significant variations in RTPL spectra and intensity, suggesting potential electrical property variations, were observed from bonded wafers. RTPL characterization results on ordinary and bonded wafers are introduced as a potential technique for in-line bonding interface quality monitoring.
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Wafer bonding has become a very powerful technology and has been widely used for micro-electro-mechanical systems (MEMS) and micro-optical-electro-mechanical systems (MOEMS) over the last decade.[1–5] Backside illuminated (BSI) complimentary metal-oxide-semiconductor image sensor (CIS) devices became a very important wafer bonding-based application to overcome the pixel area limitation by metal interconnects in conventional CIS devices.[6,7] The backside has to be fully available for capturing light after the wafer processing to maximize image signal by maximum utilization of chip area.

For successful BSI CIS device fabrication, void-free wafer bonding, uniform Si wafer thinning without severe damage, backside wafer treatment, metal interconnect and color filter formation within CMOS device fabrication compatible temperature are required.[8,9] Since the device performance is influenced by subtle residual process-induced variations such as contaminants, stress and bonding interface quality, advanced characterization techniques for early in-line detection of potential problems are strongly desired.

To achieve high and stable production yields, a very robust and highly reliable wafer bonding technique must be established before going any further. Defects in bonded wafers have been major obstacles for BSI CIS mass production for years.[9] Three types of bonded wafer imaging techniques using infrared (IR) transmission, ultrasonic and X-ray topography have been developed for bonding quality characterization to look for the source of bonding problems.[10] Particles, local deformation of Si and surface roughness are found to be the major sources of void formation at the bonding interface.[11] Three basic steps of Si wafer bonding (i.e. surface preparation, contacting and annealing)[2] have been significantly modified for higher bonding process yield and bonding quality improvement. Cleaning, surface activation and alignment process steps are commonly used in addition to the three basic steps.[1] With the aid of various bonding quality characterization techniques, wafer bonding process has been optimized over the years. However, bonding quality characterization techniques are limited by the mechanical properties of wafer bonding.[10] Potential influence of bonding interface conditions on electrical properties of bonded wafers was overlooked for many years. The importance of optical characterization, related to electrical properties of bonded wafers, was not fully appreciated until recently. Demands for high performance BSI CIS devices lead the industry to look for new in-line characterization techniques related to electrical properties of bonded Si wafers.

Contaminants, stress, strain, defects and/or wafer bonding quality, including bonding strength, can influence electrical properties of bonded Si wafers. For characterizing electrical properties, electrodes or probes are required. These require either additional process steps or physical contacts for characterization. For economically viable, in-line monitoring of electrical properties of bonded wafers, a non-contact characterization technique is preferable. A photoluminescence (PL) characterization technique using an external optical excitation source can meet both the requirements for non-contact and sensitivity to the electrical properties.[12–14] Room temperature PL (RTPL) has been used in characterizing casted multi-crystalline Si bricks and wafers for solar cell applications as a raw material quality monitoring technique for many years.[15,16] The RTPL technique has been used for characterizing metal contamination, various process induced damage of Si (i.e, plasma process induced damage (PPID), implantation induced damage, residual damage after implant activation annealing), surface passivation, dielectric/Si interface quality etc.[17–24] The same technique can be applied to in-line monitoring of bonding interface quality through the correlation between electrical properties and PL spectra (including intensity) of bonded Si wafers.

In this study, ordinary and bonded, 200 mm Si wafers with different surface finishing conditions were characterized by RTPL. RTPL is examined as a potential in-line characterization technique for bonded Si wafers for BSI CIS applications.

Experimental

Description of silicon wafers.— To investigate the effects of surface finishing on RTPL spectra and intensity, three types of ordinary 200 mm Si(100) wafers (A, B and C) with different surface finishing conditions were prepared. Next, three types of bonded 200 mm Si (100) wafers (D, E and F) with different surface finishing conditions were prepared for studying the bonding interface quality variations between wafers using RTPL characterization. Details of the ordinary and bonded Si wafers are summarized in Fig. 1.

The effect of surface grinding and grinding damage on RTPL spectra and intensity were tested using wafer A with a ground front side surface and ordinary finishing on the backside of the single side polished (SSP) wafer. Approximately 120 μm from the front surface was removed by mechanical grinding. Wafers B and C are ordinary SSP and double side polished (DSP) wafers with thicknesses of 730 μm.

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Wafer ID	Description	Surface Condition		Thickness (mm)	Schematic Illustration of Cross- section	Purpose of PL Characterization
		Front Side	Backside			
A	Front Side Ground	Very Rough	Rough	0.61		Grinding Damage
B	Single Side Polished	Mirror	Rough	0.73		Reference
C	Double Side Polished	Mirror	Mirror	0.73		Reference
D	Bonded	Rough	Rough	1.46		Surface Condition
E	Bonded	Mirror	Rough	1.46		Surface Condition
F	Bonded	Mirror	Mirror	1.46		Surface Condition

Figure 1. Descriptions of Si wafers characterized in this study.

Bonded wafer D was prepared using two SSP wafers with oxide layers. Bonded wafers E and F were prepared using a pair of SSP/DSP wafers and a pair of DSP/DSP wafers, respectively. All bonded wafers were bonded from the polished side of ordinary SSP or DSP wafers. The identical thermo-compressive bonding conditions were used for all bonded wafers.

RTPL system.— The RTPL spectra were collected using a fully automated, thermoelectrically (TE) cooled IR spectrograph system (WaferMasters MPL-300) through an objective lens and passed through a combination of filters. The RTPL system is capable of handling 200 mm and 300 mm diameter Si wafers, either ordinary or bonded. The exposure time for RTPL measurements was in the range of 20 ∼ 1000 ms per point. RTPL line scans and wafer mapping, up to ∼60,000 points per wafer, were done to gain information on RTPL spectra and intensity variations between wafers. Typical full wafer mapping, up to 15,000 points, requires about 1.0 ∼ 1.5 hours depending on exposure time (i.e. RTPL intensity from Si wafers). The possible source of RTPL spectra and intensity variations were analyzed considering the wafer surface finishing conditions and bonding process conditions.

Visible (VIS) and IR, cw laser lines of 650 and 827 nm were used to excite RTPL spectra which were measured. The cw laser beam size on the wafer surface was approximately 50 μm in diameter. The incident laser excitation power at the wafer surface was fixed at 20 mW for 650 nm excitation and 50 mW for 827 nm excitation. The incident power at the wafer surface was set low enough to avoid wafer heating.

The penetration depths in Si of the excitation wavelengths of 650 nm and 827 nm are ∼4.0 μm and ∼10 μm, respectively, based on the absorption coefficients of Si at the excitation wavelengths. It is known that the photo-excited electrons and holes in high quality, lightly doped Si wafers can travel up to a few millimeters (several times the thickness of ordinary Si wafers) and can detect the variations in the backside surface finishing, passivation and/or contamination. The RTPL technique is very sensitive, not only to the bulk Si properties, but also to the surface/interface properties related to the electronic properties, which could impact on BSI CIS devices.

Results and Discussion

Raw RTPL spectra from wafer center.— RTPL mapping was done, for all wafers, from both (front and back) sides under 650 nm and 827 nm. Relatively large variations in RTPL spectra and intensity distribution were measured from the surface of the ground wafer (Wafer A) and the bonded wafers (Wafer D - F). The within wafer variations of RTPL spectra and intensity are described in the following subsection.

To quickly compare RTPL spectra and intensity between wafers, RTPL spectra from the center of individual wafers is plotted in Figs. 2a–2d. From the surface ground wafer (Wafer A), almost no

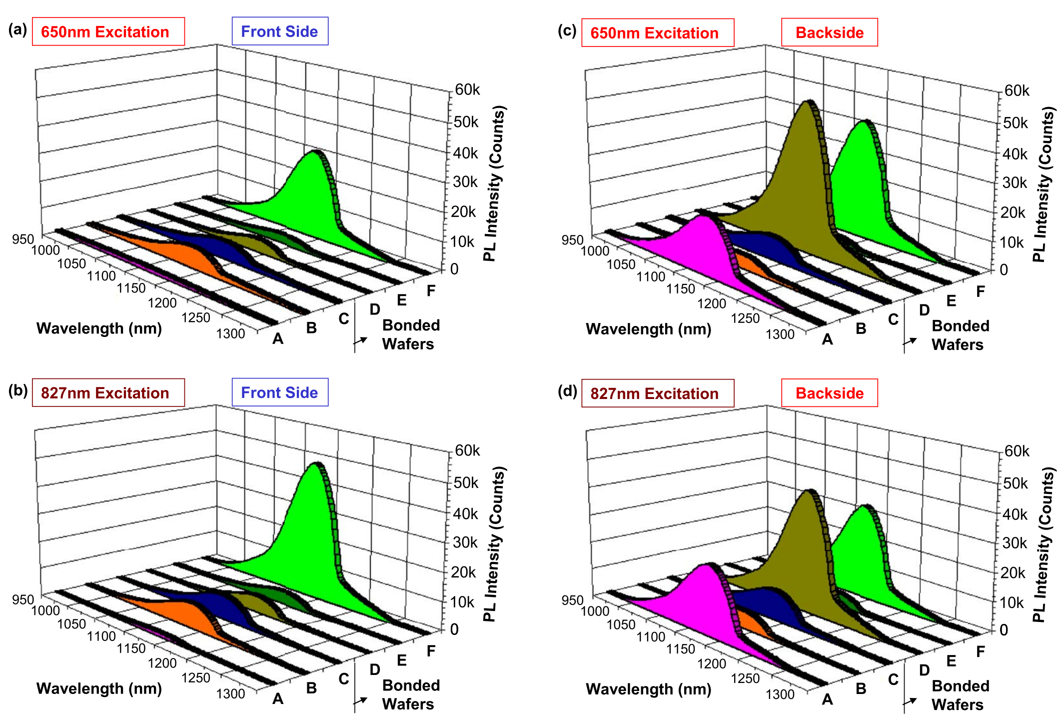

Figure 2. RTPL spectra from the center of Si wafers. RTPL spectra are from the front side under (a) 650 nm excitation and (b) 827 nm excitation. RTPL spectra from the backside under (c) 650 nm excitation and (d) 827 nm excitation.

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measurable RTPL signal was detected from the front side (grinded side) measurement. Large RTPL intensity variations were measured among other wafers (Wafer B–F) from front side measurements. Backside measurements showed significant RTPL intensity variations, within and between groups (ordinary wafers and bonded wafers). The trend of RTPL spectra and intensities under 650 nm and 827 nm excitation were almost the same when RTPL measurements were done from the same side (either front side or backside).

When the RTPL spectra and intensities of the same wafer were compared, from different sides, RTPL spectra and intensity were quite different. The order of magnitude of RTPL intensity among wafers was also different between the front side and backside measurements. This strongly suggests that the RTPL spectra and intensity were strongly influenced by the surface finishing conditions. Among the wafers, the surface ground wafer (Wafer A) showed the largest difference in RTPL spectra and intensities between front side and backside measurements. The surface damage from the ground side significantly modified the RTPL spectra and intensity of the front side (ground) measured RTPL signal. The mechanical damage in the ground side is largely responsible for the weakening and spectral change of RTPL signal.

Normalized RTPL spectra from wafer center.— It is difficult to compare the spectral change between RTPL spectra with similar spectral distribution and different intensities. To make the comparison of spectral distributions between RTPL spectra, all RTPL spectra were normalized in Figs. 3a–3d. As seen in Fig. 3a, the 650 nm excited RTPL spectra measured from the front side of the surface ground wafer (Wafer A) showed very noisy (weak) and broad RTPL spectrum compared to those from the other wafers. The broadening of RTPL spectra was not observed from the same wafer under 827 nm excitation. This is due to the Si lattice damage from mechanical surface grinding being concentrated near the surface and shallower than the probing depth (∼10 μm) of 827 nm excitation. All RTPL spectra showed an intensity maximum around 1140 nm which corresponds to the band-to-band PL transition. However, there were clear trends of broadening of RTPL spectra in ordinary wafers compared to the bonded wafers. The spectral change (broadening) and peak shift are due to the difference in the thickness of the Si wafers. A PL signal is emitted within Si wafer by e-h recombination. The majority of PL signals have photon energies smaller than the bandgap (Eg) of Si and are easily emitted from the Si wafer without reabsorption by the wafer itself. When the PL signal is emitted from the Si wafer to free space, photons are reflected by both sides of the Si/air boundary. Some photons can escape from the wafer and others are reflected back to the Si wafer. The reflected photons are reflected from the other side of the wafer again and some of the photons reflected from the other side of the Si surface can exit the wafer. The photons with and without reflection from the other side have differences in travel distance and interfere with each other. This generates constructive and destructive interference at the emitting surface, depending on the photon energy (wavelength) and thickness of Si wafer. The refractive index (RI) can be considered to be constant within a Si wafer if there is no reflecting boundary within the wafer. Any disruptions at the bonding interface will result in RTPL intensity and spectral changes, including peak shift.

The surface topology or surface finishing conditions of Si wafers strongly affect the PL spectra due to the change in photon escape probability. It was reported that DSP Si wafer peaks around 1140 nm and Si wafers with textures on both sides peak around 1170 nm due to enhancement of the emission of long-wavelength photons.[25] A peak shift up to 30 nm towards the longer wavelength side was reported. We have found similar effects in both ordinary Si wafers and bonded Si wafers with different surface finishing conditions.[26] Careful analysis and interpretation of PL spectra must be done, considering wafer thickness and/or surface finishing. This wafer thickness and surface finishing dependence of PL spectra can be used for bonded wafer characterization.

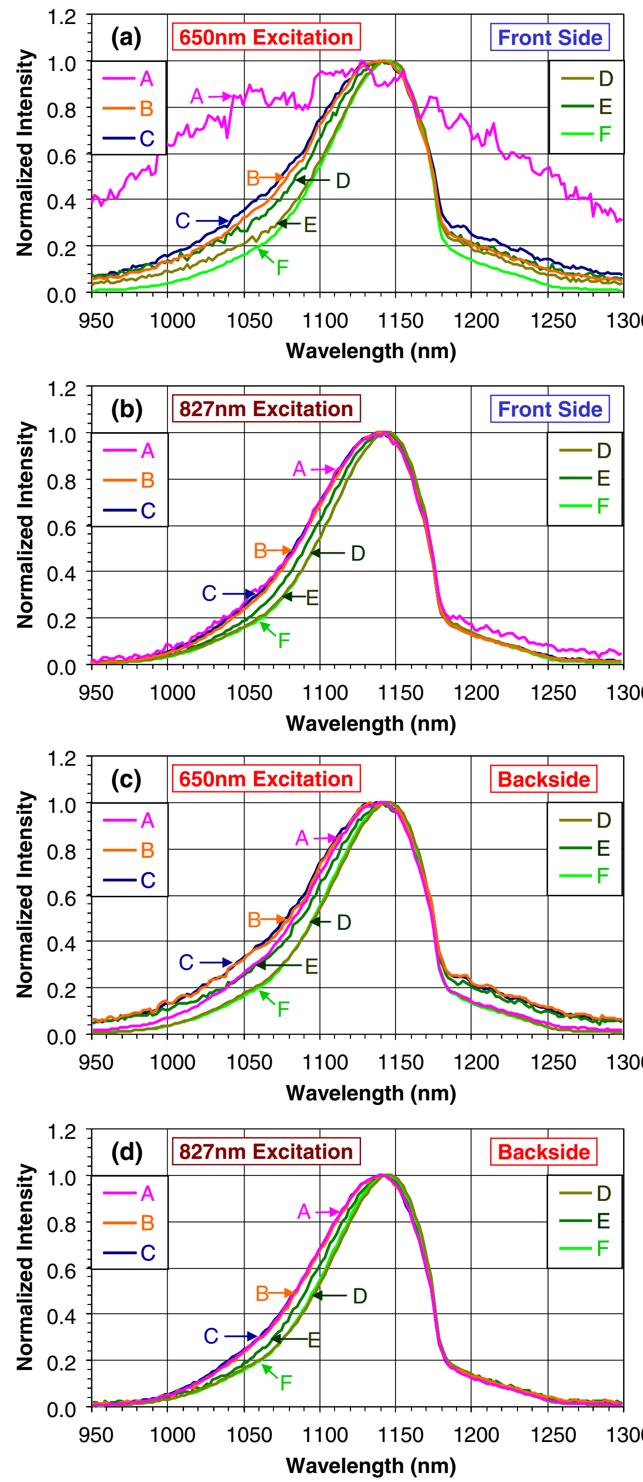

Figure 3. Normalized RTPL spectra from the center of Si wafers. Normalized RTPL spectra are from the front side under (a) 650 nm excitation and (b) 827 nm excitation. Normalized RTPL spectra from the backside under (c) 650 nm excitation and (d) 827 nm excitation.

RTPL intensity difference between wafers.— Intensity of RTPL spectra measured from the center of both sides of wafers under 650 nm excitation and 827 nm excitation are summarized in Fig. 4. Significant RTPL intensity variations between wafers were observed.

In general, ordinary wafers showed very uniform RTPL intensity across the wafer, regardless of the surface conditions (polished or rough surface). RTPL signals from the front side of surface ground

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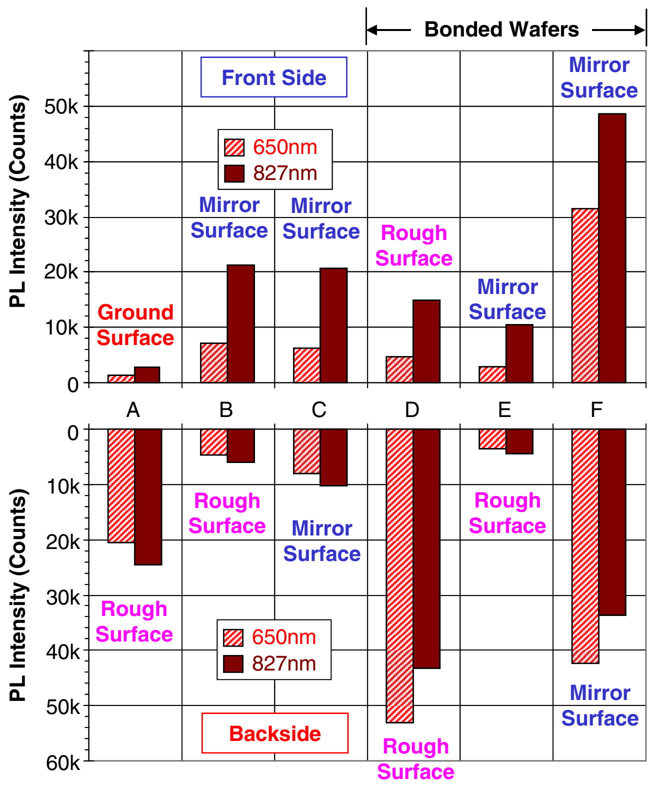

Figure 4. Summary of RTPL intensity and surface conditions of Si wafers. RTPL intensity measured at the center of wafers from the front side and backside under 650 nm excitation and 827 nm excitation.

wafer (Wafer A) were very weak and broad as seen in Figs. 2a–2b and Figs. 3a–3b. It is difficult to compare the RTPL intensity and spectra with other ordinary wafers. However, consistently uniform, weak and broad RTPL spectra from the ground side of the wafer can be interpreted as the presence of significant mechanical damage on the ground side, across the wafer. The polished side of surfaces of ordinary wafers (Wafer B–C) showed generally strong RTPL intensity. The unpolished backside surface of the ground wafer (Wafer A) showed unexpected RTPL intensity enhancement. The backside surface handling (or treatment) for the front side grinding may have improved backside surface passivation and resulted in the unexpected RTPL intensity enhancement.

For bonded wafers, very large RTPL intensity variations were observed within wafer and wafer-to-wafer. Since all ordinary wafers (either SSP or DSP wafer) showed uniform RTPL intensity, the RTPL intensity variations are the results of the wafer bonding process. Thus, the comparison between RTPL spectra and intensity, measured from the center of a bonded wafer, do not properly represent the difference between bonded wafers (Wafer D–F). RTPL wafer mapping on the entire surface is required to properly characterize the bonded wafers, as shown in the following subsection. The bonded interface quality can be characterized by RTPL wafer mapping. The RTPL wafer mapping results can provide useful guidelines for the bonding process optimization.

RTPL mapping of bonded wafers.— RTPL wafer mapping and Y-line scan measurements from the front side of bonded wafers (Wafer D–F) and the DSP (not bonded) wafer (Wafer C) under 650 nm and 827 nm excitation are summarized in Fig. 5. All bonded wafers showed very large within wafer RTPL intensity variations. The DSP (not bonded) wafer (Wafer C) showed very uniform RTPL intensity across the wafer except for a few measurement points with abnormal RTPL intensity. The abnormal RTPL intensity enhancement or suppression is often observed from areas of different surface passivation quality. The maximum value of RTPL spectra was simply plotted. The RTPL peak broadening and shift were ignored for simplicity of RTPL measurement data interpretation.

The bonded wafers (D and E) showed very distinct radial line patterns of RTPL intensity minima under both excitation wavelengths (650 nm and 827 nm). This coincided with the pattern of the wafer bonding fixture used. External pressure was applied to a pair of wafers being bonded through the radial fixture which is in direct contact with the pair of wafers being bonded. The non-uniform pressure applied to the pair of wafers being bonded resulted in RTPL intensity variations (bonding interface quality variations). The difference between 650 nm and 827 nm excited RTPL mapping and Y-line scan results can provide information on the nature of the source of the RTPL intensity variation, such as depth and possible impact on the electrical properties near the bonded interface.

Wafer F (both mirror surfaces) did not show the radial fixture pattern on the RTPL intensity wafer maps which simply plot the maximum intensity. Since the RTPL intensity was almost 10 times stronger than those from the bonded wafers D and E, the difference was not as obvious from the RTPL wafer mapping in the form of simple RTPL intensity maximum values. However, RTPL wafers maps using peak broadening and shift showed the same radial patterns seen in the bonded wafers D and E.

We have examined a greater number of 300 mm bonded Si wafers using different bonding techniques and apparatus using multiwavelength RTPL wafer mapping. RTPL wafer maps with a three-pronged star and circle, similar to the Mercedes-Benz logo, were observed from the majority of bonded wafers. Some bonded wafers showed more variations than others in the parametric bonding process optimization experimental matrix. Chuck structure, chuck conditions, chucking vacuum pressure, applied force during bonding, starting gap between wafers, wafer bending time before bonding, annealing conditions (temperature, time, ambient, apparatus, direction of gravitational force etc.) were varied to identify the source of interface quality variations observed by RTPL wafer mapping. We have identified that the artificial (symmetric) patterns on RTPL wafer maps are fingerprints of a wafer bonding fixture. The unexpected bonding interface quality variations observed from RTPL wafer mapping could introduce unwanted BSI CIS device performance variations. Careful interpretation of RTPL spectra variations can provide additional clues for bonding process and technique improvements which are not available from conventional void detection techniques for bonded wafers based on IR transmission, ultrasonic and X-ray topography.

Pixel size of CIS devices has been constantly scaled down and is approaching ~1.0 μm. BSI CSI devices are actively developed using bonded wafers for further scaling and improvement of device performance. Improvements in critical CIS device performance parameters, such as dark current, which suffers from defects, stress and accidental metallic contamination during processing, are required for manufacturing high performance CIS devices. For BSI CIS devices, more stringent monitoring and control of process and material parameter are required. This multiwavelength RTPL wafer mapping technique can be implemented for bonding interface quality in-line monitoring technique.

Summary

BSI CIS devices are being actively developed using wafer bonding techniques. A wafer with illuminated imager and a wafer with readout and image processing electronics are fabricated separately and assembled using wafer-to-wafer bonding. The illuminated imager and a wafer with readout and image processing electronics are facing each other at the bonded interface. The quality of the wafer-to-wafer bonding interface can affect the performance of finished devices. Wafer-to-wafer bonding is already implemented in fabrication of BSI CIS devices in volume manufacturing, but in-line monitoring of bonding interface quality is not satisfactory.

A room temperature photoluminescence (RTPL) technique was studied as a non-contact, in-line characterization technique for assessing bonding interface quality using various bonding conditioned and

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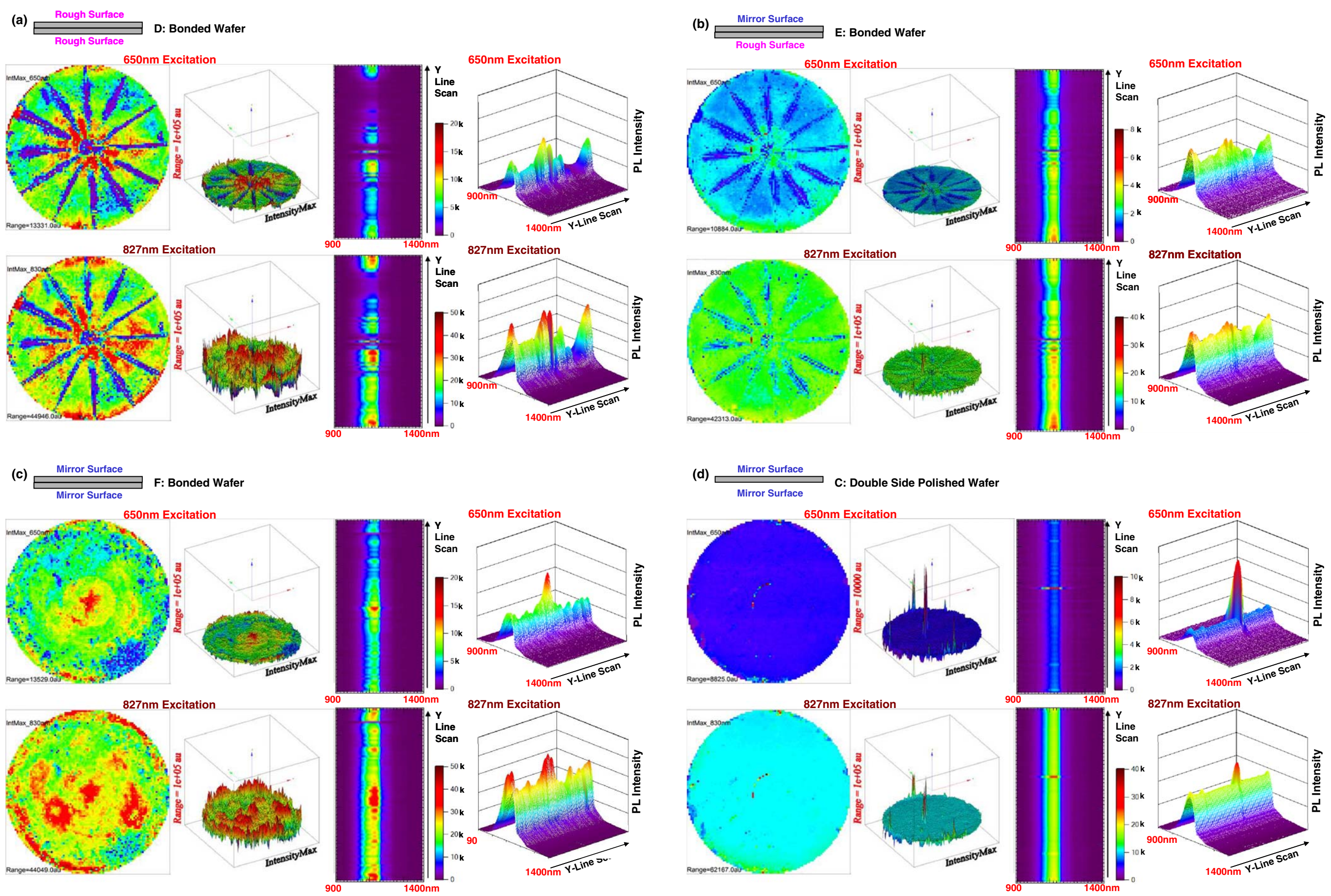

Figure 5. Summary of RTPL wafer mapping and Y-line scan from the front side of bonded wafers under 650 nm and 827 nm excitation: (a) Wafer D (both rough surfaces), (b) Wafer E (mirror surface on the top and rough surface on the bottom), (c) Wafer F (both mirror surfaces) and (d) Wafer C (double side polished).

(front and back) surface finishing conditions. Ordinary and bonded, 200 mm Si wafers, with different surface finishing conditions, were characterized by RTPL under two different excitation wavelengths (650 nm and 827 nm) to investigate the effects of surface finishing conditions and bonding techniques. Significant variations in RTPL spectra and intensity, suggesting potential electrical property variations, were observed from bonded wafers. Very distinctive patterns in RTPL wafer maps, related to how the pressure is applied to the pair of wafers being bonded, were observed. Multiwavelength RTPL characterization results on ordinary and bonded wafers are introduced as a potential technique for in-line bonding interface quality monitoring.

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