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Cu-Cu Room Temperature Bonding - Current Status of Surface Activated Bonding(SAB) -

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The surface activated boding (SAB) is a highly potential method providing a low temperature bonding process. The idea is base on the fact that the atomically clean surfaces are very reactive and easy to be bonded at low temperature or even at room temperature. In the past several years, industrial applications of the SAB method have been focused in development of high density electronic packaging, high density interconnect between LSI and substrate in chip on chip configuration, as well as wafer on wafer bonding for 3D integration of semiconductor devices. Wafer bonding is now the focus of interest, since no other process than SAB is found adequate as a low temperature process. Two new approached to bonding ionic wafers are also introduced to overcome the problem of SAB in wafer bonding using either a nano-adhesion layer or a sequential plasma activation process.

Surface Activated Bonding (SAB)

Low temperature process has long been a technological goal of interconnect and boding of solid materials. The surface activated boding (SAB) is a highly potential method providing a low temperature bonding process. The idea is base on the fact that the atomically clean surfaces are very reactive and easy to be bonded at low temperature or even at room temperature. The root of the technology dates back to experiments of NASA for adhesion in ultra-high vacuum as the space environment in ’70. Considerable progress in UHV bonding was made in ’80 in Japan by several research groups.

In the past several years, industrial applications of the SAB method have been focused in development of high density electronic packaging, high density interconnect between LSI and substrate in chip on chip configuration, as well as wafer on wafer bonding for 3D integration of semiconductor devices. Wafer bonding is now the focus of interest, since no other process than SAB is found adequate for wafer bonding. The most successful industrial application of SAB was achieved in fabrication of clad foils such as metal-metal or metal-polymer. Cu-Cu laminate is used as a build-up layer of high-density printed circuit board, and Al-Al clad is used as a part of pressure release valve for Li battery for which almost 10,000,000 pieces per month are fabricated.

The concept of SAB originates from the question how to bond inorganic materials such as metals or ceramics directly without intermediate at low temperature. Aluminum which is a very active and easily oxidized element was found to be bonded by SAB to various metals and ceramics at room temperature [1]. High resolution TEM showed that atomically direct bonding is achieved at the interface between Al-Al and Al-Si_3N_4, at the same time certain amorphous layer is found in the boned interface depending upon the atmosphere under the influence of ion beam bombardment [2]. More details of the interface structures in the terms of dependence of the surface treatment and bonding environments were investigated for Al-stainless steel interface, Al-Si, Ai-SiO_2[3], Al-Al, Al-Al_2O_3 interfaces[4].

Mechanism of the Room Temperature Bonding

The most important conclusion of the series of the studies of the room temperature bonding is that certain process of ion beam bombardment or energetic particles bombardment is an essential process for room temperature bonding, although the physical or chemical phenomena at the surfaces might be very complicated, but anyway, something should happen by removing the surface layer which is stabilized by native oxide formation or certain contamination, or both. Recontamination or re-oxidation occurs definitely since the bonding process is carried out always at non-ideal condition, even if the atmosphere of the bonding is in ultra-high vacuum. However we observe no bonding or weak bonding if such surface treatment is not applied before bonding, and such the surface treatment is prerequisite for the bonding at room temperature. In these sense, it would be quite reasonable to call this method of the low temperature bonding 'surface activated bonding'. However there is no definite boundary between the surface activated bonding and the conventional solid state bonding.

Let look at the results of the solid state bonding of Cu. Figure 1 shows the bond strength of Cu-Cu solid state bonding in the dependence of the bonding temperature. As seen in the figure, usually almost 700˚C is required to obtain the highest value of the bond strength in case of the conventional diffusion bonding. However, using the surface activation method, that is Ar ion beam bombardment, the bonding temperature is reduced drastically down to 200˚C. This is the case in that the surface roughness was in the range of 20 nm which is obtained by commercial process of cold-rolling or ultra-high precision cutting of metal surfaces. In case that the surface roughness is getting smaller, around 2 nm, by CMP, the bonding at room temperature becomes possible. It means that the surface roughness is a very important factor enabling low temperature bonding.

Re-oxidation of Cu surfaces lead to decrease in bond strength as shown in Figure 2 (left). Exposure of 0.2 Pa·sec of the activated Cu surface to residual gases is critical for room temperature bonding, which corresponds to continuous growth of oxide covering Cu surface. The surface roughness of 2-3 nm is critical for room temperature bonding of Cu-Cu as shown in Figure 2 (right). However this condition is valid only in case that the bonding pressure is limited up to 10 MPa. For Cu-Cu laminate fabrication using high pressure over 700 MPa by cold rolling, the room temperature bonding is still possible with a roughness larger than 20 nm. So the plastic deformation is the other factor influencing the bonding characteristic.

Ion beam bombardment for activating the surfaces to be bonded may induce a large amount of lattice defects in the surface areas, even though Ar of only less than 10^{13}dose/cm^2 is irradiated to sputter the surface layer of few or several tens of nano-meter thickness, according to the thickness of the surface oxide. As indicated by XPS analysis shown in Figure 3, Cu surface after CMP is covered by 2-3 nm of contamination and hydro-oxide, and 7-8 nm of CuO and Cu_2O. Larger irradiation will cause to roughening the surface, therefore 8-15 nm is removed from the surface by Ar irradiation. The defects thus induced at the surface might enhance the diffusion at the contact area to contribute an ultimate contact for bonding. Figure 4 is the high resolution TEM image of the bonded interface between Cu and Sn, showing an intermediate layer consisting of small grains of Cu-Sn intermetallic compound which would not be grown as they are at room temperature, if they are brought only into contact.

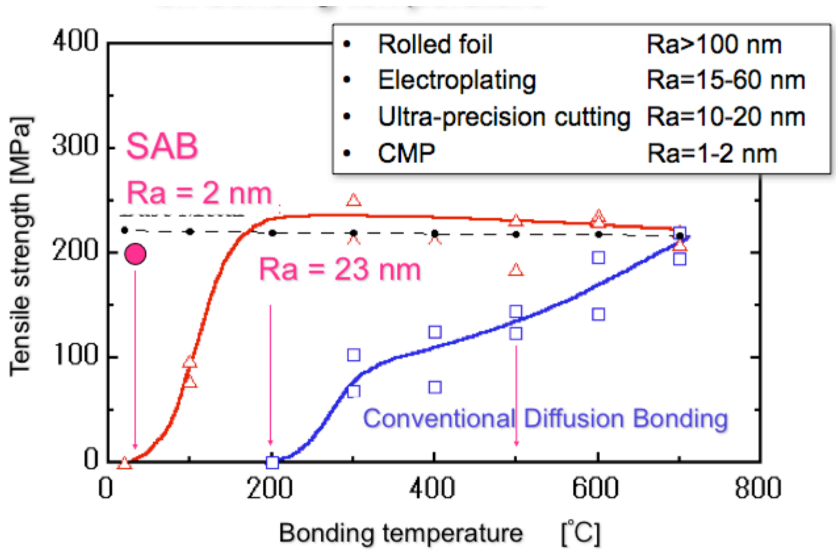


Figure 1. Tensile strength of Cu-Cu joint bonded by SAB method and conventional diffusion bonding method in dependence of the bonding temperature.

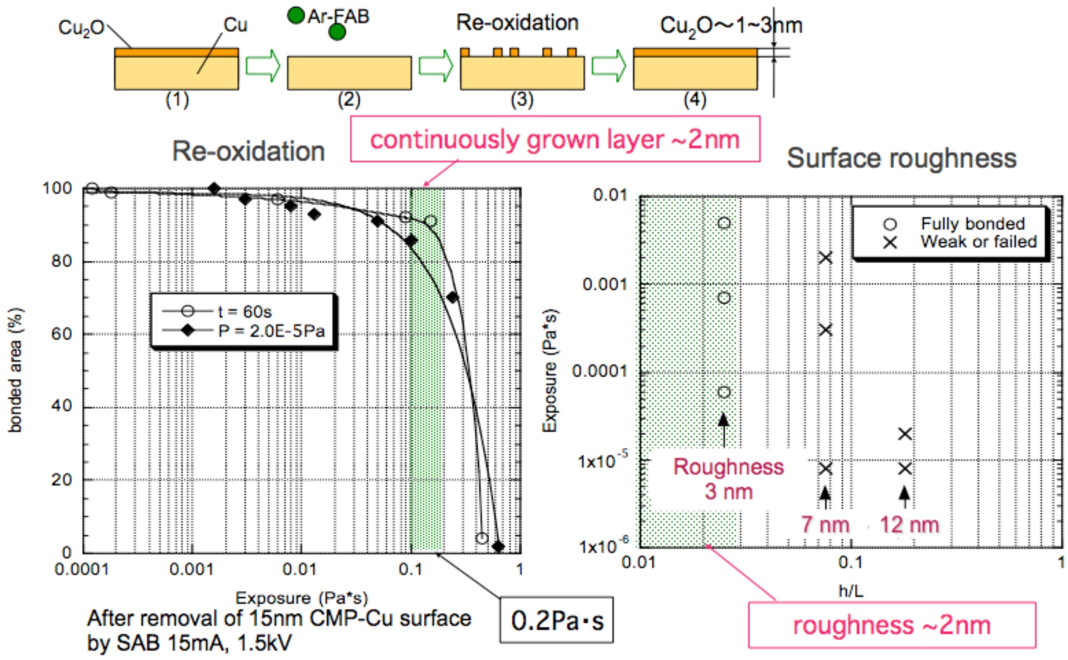


Figure 2. Bonded area of Cu-Cu SAB at room temperature in dependence of the exposure of the surfaces to residual gases prior to bonding (left), and the bonding results in dependence of the surface roughness (right).

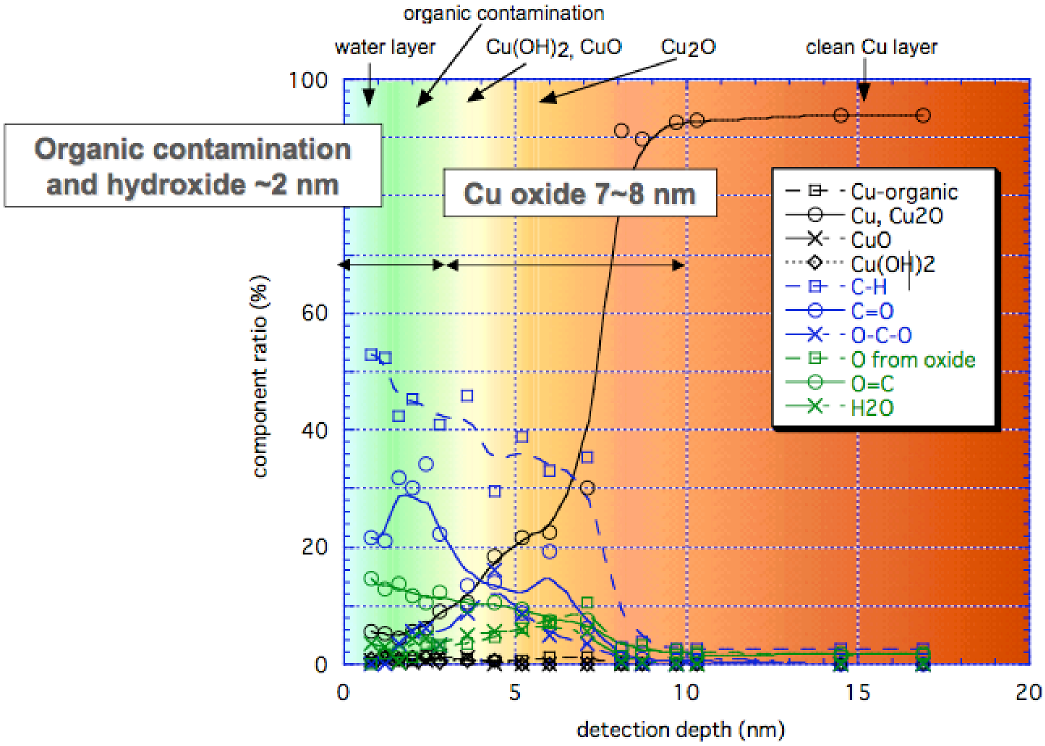


Figure 3. The structure of CMP-Cu surface examined by XPS.

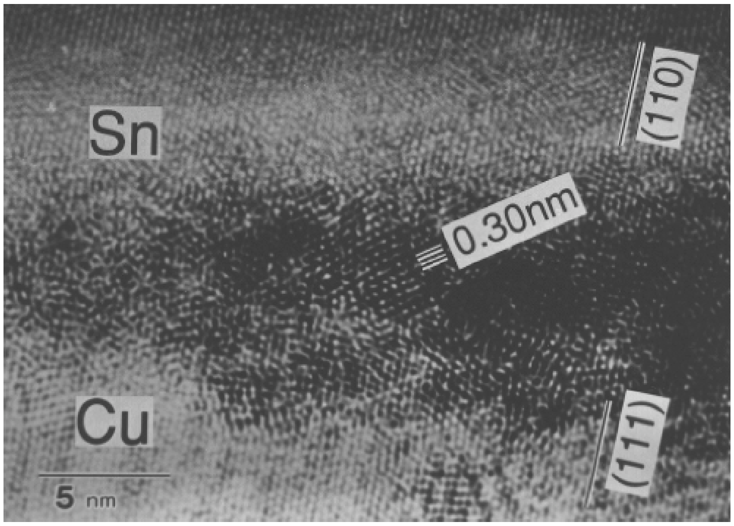


Figure 4. TEM image of Cu-Sn interface bonded by SAB at room temperature.

Cu-Cu direct bonding at room temperature

The possibility of the application of SAB in the field of microelectronic packaging was demonstrated on Cu-Cu, and Pb-Sn solder to Cu for the first time at the conference [5], and developed further to lead the concept of the bumpless interconnect for hetelogenious microsysytem integrations [6]. The SAB method was revealed to be capable to bond not only metals but also bond semiconductors in wafer scale. It was shown for Si-Si[7], Si-GaAs[8], and Si-LiNbO3[9], showing the high potential of SAB for MEMS fabrication process and packaging applications. The recent progress is compiled in the special session of SAB in the Proc. ICEPT 2006[10].

Cu-Cu direct bonding is gathering increasing interest in 3D integration in wafer scale. For high density interconnect in the scale of 1 µm level, a low temperature process is inevitable to realize high accuracy of alignment. For the sake of demonstration of SAB feasibility, SAB apparatuses were developed, which enable the alignment accuracy as low as 1 µm for both the chip and wafer samples, and succeeded in the chip-scale bumpless interconnect of 100,000 pins which consist of 3 µm electrodes in the area of about 12mm^2 and were tightly bonded as shown in Figure 5 [11].

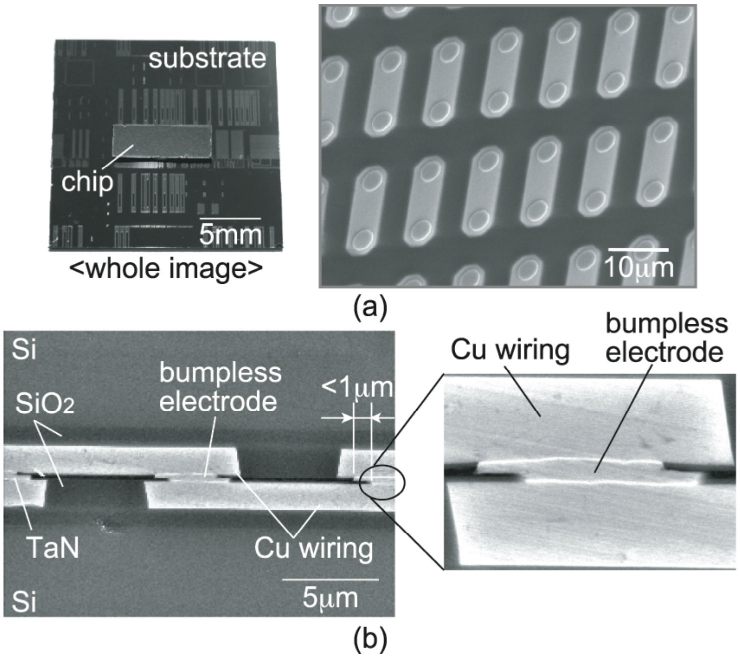
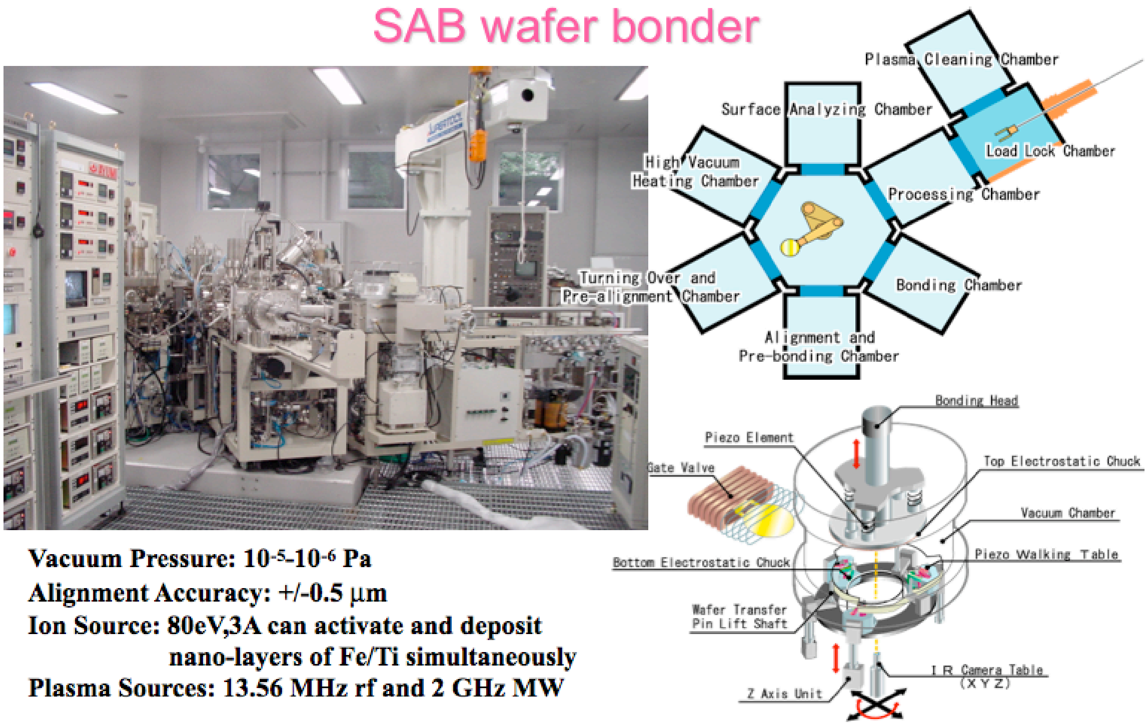


Figure 5. (a) Chip-scale Cu bumpless electrodes with the diameter of 3µm, and (b) cross section of a pair of bonded electrodes

Moreover, a wafer scale Cu-Cu direct bonding was also performed successfully [12]. 12.5 million electrodes with the dimensions of 30 x10m^2 were fabricated with the photolithography at intervals of 10 µm in the array of 10x10mm^2, and there were 100 arrays in a wafer. After that, the CMP process was applied on the electrodes to flatten the surface and to decrease their height difference.

The test vehicles were bonded in a SAB wafer bonder. It consists of vacuum chambers for the airlock, surface cleaning, analysis, alignment and bonding surrounding a center chamber with a transfer arm as shown in Figure 6. The surface cleaning was carried out by Ar ion beam of 50eV for 90s to etch surfaces to a depth of about. The wafers were bonded under a contact load of 2.5x10^{3}N (about 7 MPa on each electrode) in the bonding chamber. The vacuum pressure of the chambers and the paths between them was kept about 2.0x10^{-7}Pa so that the exposure is far lower than 0.1Pa·s. Figure 7 shows the IR transparent images of the bonded wafers. All the electrodes were successfully bonded with no void, and the misalignment was as small as 2µm all over the wafer.



Vacuum Pressure: 10^{-5}-10^{-6} Pa
Alignment Accuracy: +/-0.5 μm
Ion Source: 80eV,3A can activate and deposit nano-layers of Fe/Ti simultaneously
Plasma Sources: 13.56 MHz rf and 2 GHz MW

Figure 6. High accuracy wafer bonder for SAB process.

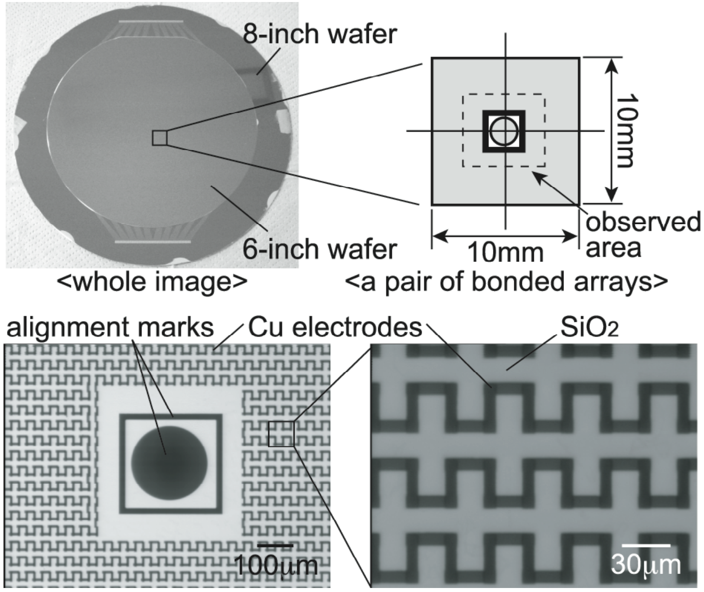


Figure 7. IR transparent images of SAB wafers with 12.5 million Cu electrodes in the bonding alignment accuracy within 2μm.

New Approaches to Ionic Wafer Bonding

The only disadvantage of SAB was laid in its difficulties to bond ionic materials to each other, which include glass, sapphire, silicon dioxide and $LiNbO_3$. The reason of the incapability of SAB for ionic materials is still not clear but it was assumed that ionic materials surface is spontaneously polarized at different levels by means of ion beam bombardment which is use for surface activation prior to the bonding. In order to get rid of these difficulties, two approaches for the modified SAB were developed. In the first approach, the wafers are bonded after activation with a modified hollow cathode Ar-low energy ion source capable of sputter cleaning and depositing Fe simultaneously on the wafers. Probably Fe thin layer or clusters might shield the surface polarity of the ionic materials and therefore the wafers are bonded very strongly [13]. In the second approach, the wafers are activated with sequential plasma activation process using RF plasma of oxygen and radical one after another in low vacuum and bonded in ambient [14]. The both method above are applied well for wafer bonding of ionic materials at room temperature. The advantage of the sequential plasma activation process is that the bonding process is carried out in atmospheric pressure or in air, whereas SAB requires always a certain vacuum. On the other hand, void formation at elevated temperatures at the bonded interface can not be avoided in case of the sequential plasma process, because water molecules absorbed on the wafer surfaces are inevitable for bond formation. Typical results are shown in Figure 8.

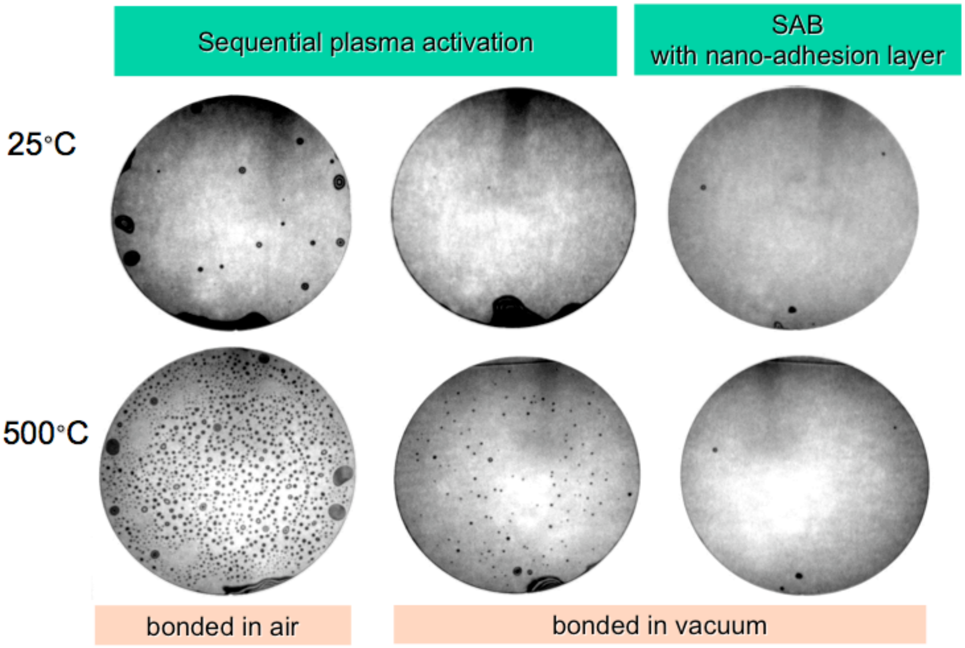
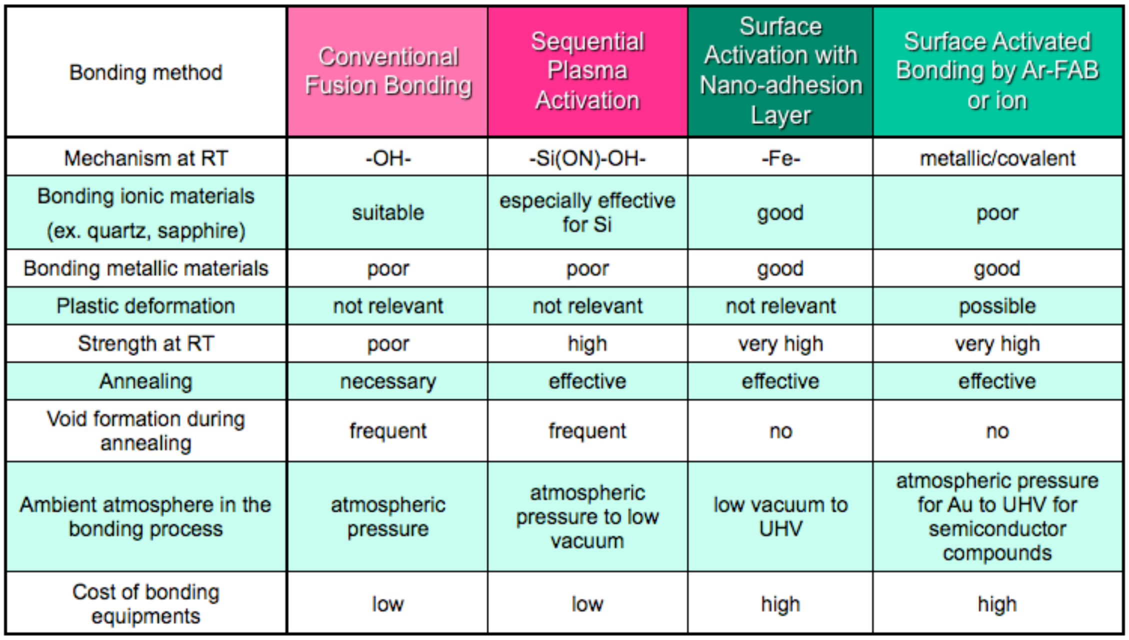


Figure 8. Comparison of void formation between sequential plasma activation and SAB, as well as bonded in air and in vacuum.

Conclusion

Finally the current SAB techniques are listed and compared with the conventional wafer bonding method in Table 1. Introduction of the surface activation process is a consequence if one considers the nature of the solid surface to be bonded, and technologically a low temperature process is needed. The bonding process is not a single physical process but combined with inhomogeneity of the interface structures and properties. It is the reason why a precise control of the interface will be necessary to develop the conventional bonding process to an innovative technology.

Table 1. Comparison of SAB methods with the conventional fusion bonding method



Bonding method	Conventional Fusion Bonding	Sequential Plasma Activation	Surface Activation with Nano-adhesion Layer	Surface Activated Bonding by Ar-FAB or ion
Mechanism at RT	-OH-	-Si(ON)-OH-	-Fe-	metallic/covalent
Bonding ionic materials (ex. quartz, sapphire)	suitable	especially effective for Si	good	poor
Bonding metallic materials	poor	poor	good	good
Plastic deformation	not relevant	not relevant	not relevant	possible
Strength at RT	poor	high	very high	very high
Annealing	necessary	effective	effective	effective
Void formation during annealing	frequent	frequent	no	no
Ambient atmosphere in the bonding process	atmospheric pressure	atmospheric pressure to low vacuum	low vacuum to UHV	atmospheric pressure for Au to UHV for semiconductor compounds
Cost of bonding equipments	low	low	high	high

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