

Room temperature Cu–Cu direct bonding using surface activated bonding method

T. H. Kim,^{a)} M. M. R. Howlader, T. Itoh, and T. Suga

Research Center for Advanced Science and Technology, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8904, Japan

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Thin copper (Cu) films of 80 nm thickness deposited on a diffusion barrier layered 8 in. silicon wafers were directly bonded at room temperature using the surface activated bonding method. A low energy Ar ion beam of 40–100 eV was used to activate the Cu surface prior to bonding. Contacting two surface-activated wafers enables successful Cu–Cu direct bonding. The bonding process was carried out under an ultrahigh vacuum condition. No thermal annealing was required to increase the bonding strength since the bonded interface was strong enough at room temperature. The chemical constitution of the Cu surface was examined by Auger electron spectroscopy. It was observed that carbon-based contaminations and native oxides on copper surface were effectively removed by Ar ion beam irradiation for 60 s without any wet cleaning processes. An atomic force microscope study shows that the Ar ion beam process causes no surface roughness degradation. Tensile test results show that high bonding strength equivalent to bulk material is achieved at room temperature. The cross-sectional transmission electron microscope observations reveal the presence of void-free bonding interface without intermediate layer at the bonded Cu surfaces. © 2003 American Vacuum Society. [DOI: 10.1116/1.1537716]

I. INTRODUCTION

The wafer direct bonding technique has been intensively studied by many research groups and applied to the fabrication of microelectronics, optoelectronics, and microelectromechanical systems.^{1–5} In general, high temperature annealing is required to increase the bonding strength. However, the process temperature must be reduced to avoid quality degradation due to thermal damage of temperature-sensitive devices. In addition, a low process temperature process is advantageous in terms of the manufacturing cost. Therefore, lowering the temperature for wafer direct bonding is a key issue in various future device applications.

Copper has attracted much attention in the area of very large scale integration (VLSI) interconnection technology as the most prospective candidate for the conducting material due to its high electrical conductivity and high electromigration resistance compared with aluminum.^{6,7} Recently, the size of VLSI circuits has remarkably shrunk, resulting in a highly reduced metal wire interconnect pitch. The reduction in interconnect pitch has led to an increase in interconnect resistance and capacitance (*RC*) that is the cause of signal transmission delay (*RC* delay).^{8,9} The *RC* delay is the main limiting factor of the device performance in terms of operating speed. To solve the *RC* delay problem, low-resistivity metallization with low-*k* dielectrics is required.¹⁰ Until now, aluminum has been the most widely used material for interconnects in VLSI. However, aluminum has been found to be no longer useful to reduce *RC* delay due to its higher electrical resistivity ($2.65\mu\Omega\text{ cm}$) rather than that of Cu ($1.67\mu\Omega\text{ cm}$).¹¹ Therefore, the use of Cu instead of alumi-

num is critical to reduce the *RC* delay and the Cu–Cu direct bonding technology will play an important role in future VLSI interconnects for high speed operation.

Several experiments on Cu–Cu direct bonding have been reported by some researchers.^{12–14} Although simple bonding methods were presented in those works, high external pressure and annealing or toxic chemical cleaning processes were necessary to achieve reasonable bonding strength. In our study, the surface activated bonding (SAB) process was used to bond Cu-coated wafers at room temperature without any wet chemical process. SAB is a process that joins similar or dissimilar materials by means of the adhesion force between atoms of two atomically clean surfaces in an ultrahigh vacuum (UHV) at room temperature.^{15,16} The highly accelerated argon fast atom beam physically bombards contaminants and oxides on the wafer surface, resulting in sputtering.

The objectives of this work are to bond Cu-coated Si wafers at room temperature without adhesive materials by using the SAB method and to characterize the Ar-processed Cu surface and bonded interface through tensile pulling tests, Auger electron spectroscopy (AES), atomic force microscopy (AFM), and transmission electron microscopy (TEM) observations.

II. EXPERIMENTAL PROCEDURE

A. Samples

Diffusion barriers of SiO₂/SiN/TaN/Ta (12/70/15/15 nm, respectively) were prepared on a *p*-Si(100) wafer (8 in.). The Cu thin film was deposited on the barrier layered Si wafer by the sputtering method. The thickness of Cu is 80 nm and total thickness of the thin films deposited on the Si wafer is 192 nm.

^{a)}Author to whom correspondence should be addressed; electronic mail: kim@su.rcast.u-tokyo.ac.jp

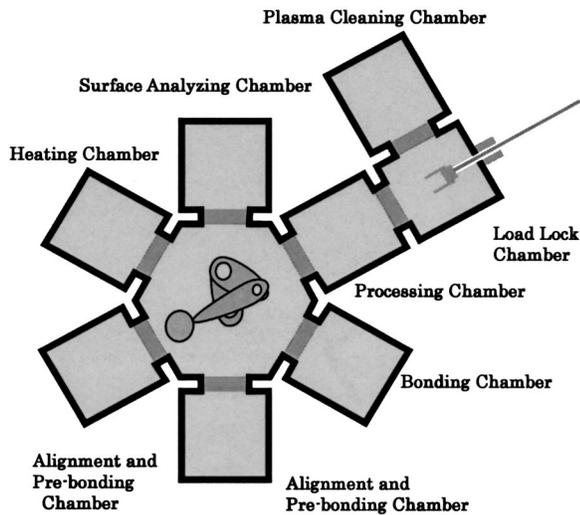


FIG. 1. Schematic view of surface activated bonding machine.

B. Surface activation

The Ar ion beam was generated by the gridless end-Hall ion source (MK II, Commonwealth Scientific Corp.).^{17,18} A low energy and high current ion beam can be achieved by that structure and it generates ions of 40–100 eV. The ions incident onto a sample surface are neutralized by an electron beam to avoid charging damages. Instead of a cathode, we used an electron gun for neutralization to avoid contamination due to cathode sputtering by Ar ion bombardment. The anode of the ion gun for ion acceleration was operated at 80 V and 2.92 A. The flow rate was set to 3 sccm. The Cu surfaces were cleaned by the accelerated Ar ion beam for 60 s. For the uniform activation of the entire wafer area, the substrate is rotated during the Ar ion beam process.

C. Bonding procedure

The SAB machine developed consists of a transfer chamber surrounded by a processing, an analyzing, a heating, a turning over/preliminary alignment, an alignment/preliminary bonding, and a bonding chamber as shown in Fig. 1. The machine is located in a 10 000 class clean room.

Two wafers are loaded into the load lock chamber and transported to the process chamber. The surface activation is performed in the process chamber by an Ar ion beam. Details of the ion gun operation are described in the previous section. One of the surface activated wafers is transferred to the turning over chamber and turned over. Two wafers are transferred into the preliminary bonding chamber and brought into contact to give initial bonding under a load of 50 kgf. After preliminary bonding, the prebonded wafer pair is finally cold rolled by a roller of 1000 kgf load in the bonding chamber. The roller pressure range is limited up to ± 5 cm from the wafer center to avoid wafer breakage during the pressing process. All chambers keep UHV ($\sim 10^{-8}$ Torr) during the bonding processes. Details of the bonding machine are given elsewhere.¹⁹

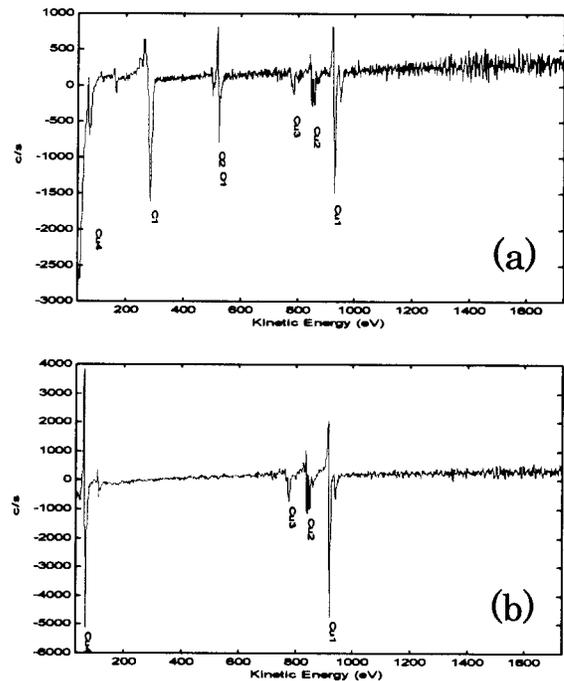


FIG. 2. Auger spectra of Cu surface (a) before and (b) after Ar ion beam bombardment for 60 s. After 60 s Ar ion beam treatment, oxygen, and carbon peaks are almost removed.

III. RESULTS AND DISCUSSION

A. Auger analysis of Cu surface

The clean surface is requisite for direct bonding. In air, oxides and carbon-based contaminants on the wafer surface hamper direct bonding. AES (Model15-110B, ULVAC) observation was performed to investigate the Cu surface cleanliness before and after the Ar ion beam process. The electron beam energy for a Cu surface analysis was set to 3 keV.

Figure 2(a) shows the spectrum of the bare Cu surface before Ar ion beam bombardment. The strong carbon and oxygen peaks due to organic contaminants and native metal oxides on a Cu surface are observed. As shown in Fig. 2(b), however, carbon and oxygen peaks are almost removed after the cleaning process using Ar ion beam bombardment for 60 s. This indicates that the Cu surface is sufficiently clean and active for direct bonding. The threshold energy of Cu sputtering by Ar ion was measured to be 25 eV by Mayer *et al.*²⁰ As confirmed in our experiment, Ar ion bombarding energy of 40–100 eV is sufficient to clean the Cu surface. The total time of a Cu sample transportation from the process chamber to the analysis chamber after Ar ion beam bombardment and Auger analysis was about 15 min. During that time, the copper surface may be reoxidized due to residual gases (O_2 , H_2O) in the chamber. But Auger analysis results show that reoxidation of the cleaned surface during transportation is not so critical.

B. AFM analysis of Cu surface

Surface roughness is a critical factor in wafer direct bonding. The wafer surface is microscopically rough. An increase

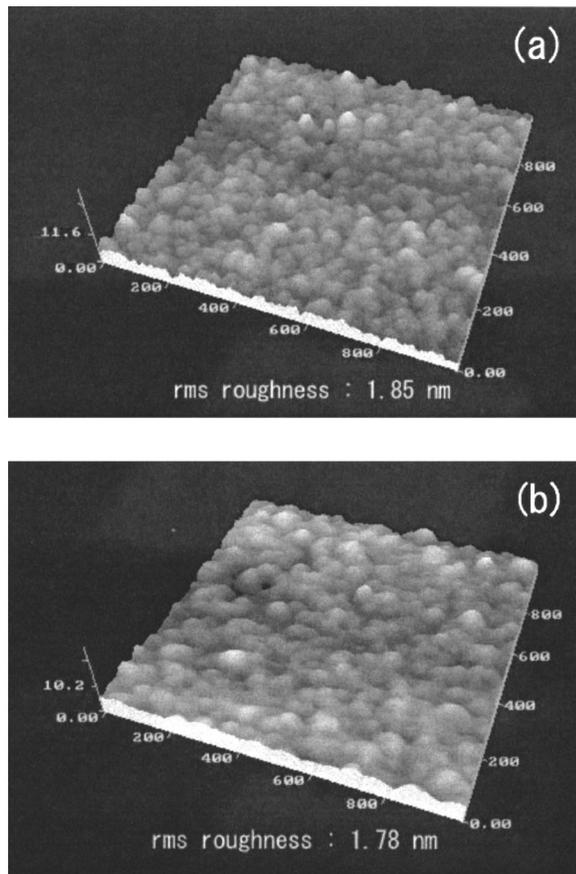


FIG. 3. AFM images for Cu surface : (a) before and (b) after Ar ion beam bombardment. The respective rms roughness is 1.85 and 1.78 nm. Scanning area is $1 \times 1 \mu\text{m}^2$.

in surface roughness lowers the bonding strength including the formation of voids due to nonintimate contact between two surfaces. Therefore, the surface must be flat for intimate contact with reduced gaps between mated wafers.

AFM (JSPM-4210, JEOL) was used to investigate the topography of the Cu surface. It was operated in the noncontact mode and the scan area is $1 \times 1 \mu\text{m}^2$.

Figure 3 shows the three-dimensional AFM images of a Cu surface before and after Ar ion beam bombardment. The measured root mean square (rms) values of the Cu surface before and after Ar ion beam bombardment for 60 s are 1.85 and 1.78 nm, respectively. The result indicates no remarkable change in surface roughness after Ar ion bombardment. In general, energetic ion bombardment for a long time will increase surface roughness. However, the Cu surface after Ar ion beam bombardment is rather slightly smoother than the original surface. This is a somewhat unexpected result. The decrease in rms roughness is presumably due to a surface cleaning effect by Ar ion beam bombardment. In other words, low energy Ar ion beam sputtering for a short time removes only oxides or carbon-based contaminants on the Cu surface, resulting in a clean and flat surface with reduced rms roughness.

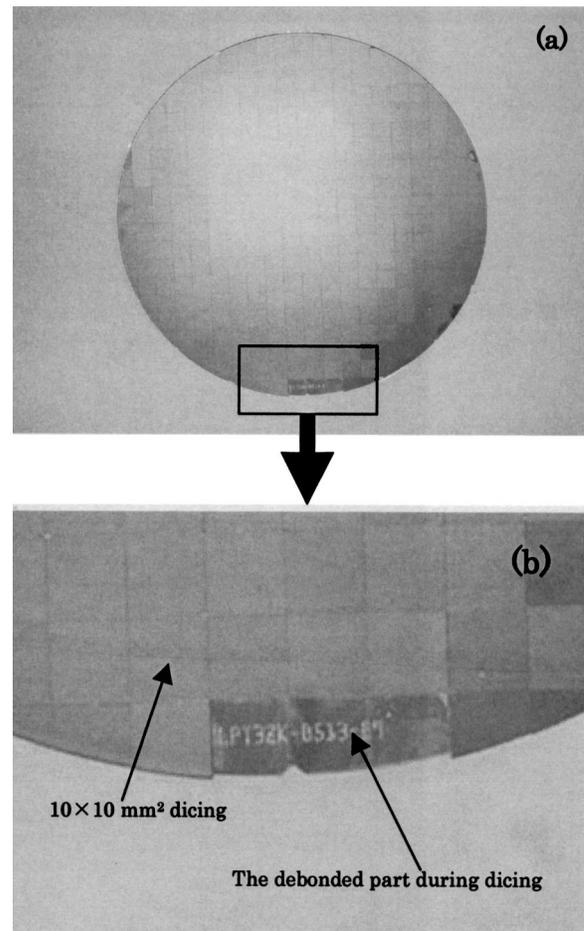


FIG. 4. Dicing of 8 in. Cu–Cu bonded wafers into $10 \times 10 \text{ mm}^2$. (a) A top view of fully bonded wafer pair after dicing, and (b) a magnified image of the wafer pair. A few pieces on the wafer edge are debonded during dicing.

C. Tensile test

Bonding strength is an important concern for actual device application in the industry. The bonded interface must withstand external mechanical stress during wafer sawing or the back thinning process for device fabrications.

Tensile pulling tests were carried out to measure the bonding strength. Samples for the tensile tests were prepared by dicing the bonded wafer into $10 \times 10 \text{ mm}^2$ pieces. The sample pieces were glued to metal bars fitting them to the tensile machine.

Figure 4(a) shows the top view of the bonded wafer pair after the sawing process. The whole bonding area of the 8 in. wafer is so tight that most Cu sample pieces withstand the external stress during the wafer sawing process. Only three pieces on the wafer edge were debonded from the bonding interface during sawing as shown in Fig. 4(b). Tensile tests indicate that the wafer pair is very tightly bonded together over the whole wafer area. The bonding strength was so high that it was impossible to separate the bonded interface. Figure 5(a) is a side view of the bonded sample glued to a metal bar and plate before the tensile test. Figure 5(b) is the result of a tensile test. Figures 5(c) and 5(d) are the images of the debonded sample. The samples were fractured either from

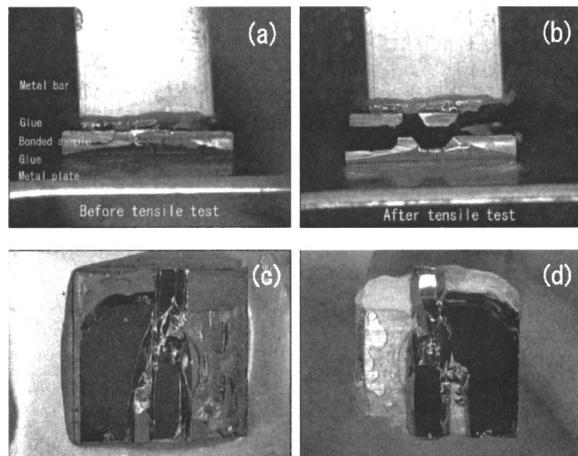


FIG. 5. Fracture image of Cu–Cu interface by tensile test. Side view of bonded sample (a) before test and (b) after test. (c) (d) Top views of the debonded sample; where bulk fracture across the diffusion barrier layers is seen.

the bulk material or from the glue. The fracture from the glue or bulk has occurred below approximately 6.47 MPa. It was impossible to debond the Cu–Cu interface due to poor addition of the glue and the mechanical weakness of the diffusion layers. This result means that the actual bonding strength of the Cu–Cu interface is higher than the measured value of 6.47 MPa. High bonding strength is obtained throughout the whole bonded wafers regardless of the cold-rolled place on the wafers.

D. TEM observation of the bonded interface

Undesirable intermediate layers or voids at the interface may degrade the bonding quality. The intermediate layer may result from incomplete removal of oxides or formation of damages due to excessive Ar ion bombardment. In order to identify the presence of intermediate layers and voids, TEM observation was carried out. The cross section images of the sample were taken by TEM (JEM-4000fx.) operated at 400 kV for electron beam acceleration. The sample for cross sectional TEM observations was prepared by the Ar ion milling process using the Precision Ion Polishing System (Model 691 PIPS, GATAN Inc.). The Ar ion beam acceleration voltage was 4.5 kV and incident angle was $\pm 4^\circ$.

Figure 6(a) shows the low magnification TEM image for the Cu–Cu bonded sample. In this picture, the barrier layers (Ta/TaN/SiN/SiO₂) of the upper wafer are invisible since they were removed by the Ar ion milling process. As shown in this picture, no intermediate reaction layer is observable at the bonded interface.

Since a Cu surface has microroughness on it, microvoids may take place at the bonded interface. However, high-resolution TEM reveals that the two Cu surfaces are tightly bonded without any voids. As shown in Fig. 6(b), two mated Cu surfaces make intimate contact without a gap by conforming to the opposite Cu surface. We consider that the intimate contact is attributed to the plastic deformation of two contacted surfaces, resulting in the broadened contact

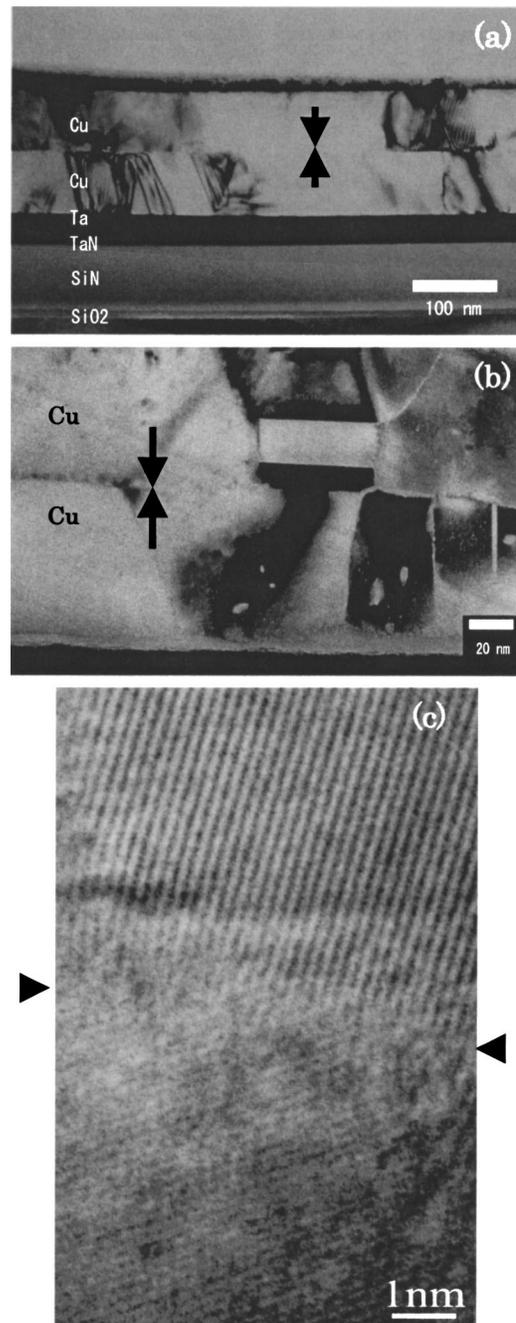


FIG. 6. TEM image of the bonded Cu–Cu interface: (a) low magnification TEM image of the bonded sample; (b) high-resolution TEM image, and (c) magnified high-resolution TEM image showing the bonded lattice structure at the interface.

area at the interface. The deformation is thought to be due to an attractive intermolecular force (van der Waals attraction force) between two Cu surfaces.²¹ The broadened actual bonding area contributes to the high bonding strength of the Cu–Cu interface.

Figure 6(c) shows the high-resolution TEM picture showing the bonded lattice structure of the Cu interface. The presence of atomically fine bonding between two Cu films is confirmed. No intermediate layer or voids at the interface is

observable and the two bonded lattices are continuously translated at the Cu–Cu interface.

IV. CONCLUSIONS

Cu–Cu direct bonding at the wafer level was performed at room temperature using the SAB method with a low energy Ar ion beam. Surface analysis by AES indicates that main chemical constituents on the Cu surface are carbon and oxygen and a chemical-free Cu surface is obtained by Ar ion beam bombardment for 60 s. AFM measurements show that surface roughness does not remarkably change by the Ar beam process. The rms roughness of 1.78 nm is smooth enough to cause intimate contact by plastic deformation of the Cu surface due to the atomic attracting force. The tensile tests show that uniform and strong bonding equivalent to bulk material is achieved at room temperature by the SAB method. TEM investigations reveal that no voids or intermediate layers are observable at the bonded interface. Plastic deformation of the Cu surface to compensate surface roughness is also observed.

ACKNOWLEDGMENT

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¹J. B. Lasky, *Appl. Phys. Lett.* **48**, 78 (1986).

²S. Bengtsson, *J. Electron. Mater.* **21**, 841 (1992).

³O. Zucker, W. Langheinrich, and M. Kulozik, *Sens. Actuators A* **36**, 227 (1992).

⁴K. L. Enisherlova, T. F. Rusak, E. N. Chryvakova, and R. N. Vinogradov, *Mater. Sci. Eng., B* **46**, 33 (1997).

⁵D. Sparks, G. Queen, R. Weston, G. Woodward, M. Putty, L. Jordan, S. Zarabadi, and K. Jayakar, *J. Micromech. Microeng.* **11**, 630 (2001).

⁶P. L. Pai and C. H. Ting, *IEEE Electron Device Lett.* **10**, 423 (1989).

⁷T. Nitta, T. Ohmi, T. Hoshi, S. Sakai, K. Sakaibara, S. Imai, and T. Shibata, *J. Electrochem. Soc.* **140**, 1131 (1993).

⁸K. C. Saraswat and F. Mohammadi, *IEEE Trans. Electron Devices* **ED-29**, 645 (1982).

⁹M. T. Bohr and Y. A. El-Mansy, *IEEE Trans. Electron Devices* **45**, 620 (1998).

¹⁰Y. Morand, *Microelectron. Eng.* **50**, 391 (2000).

¹¹S. P. Murarka and S. W. Hynes, *Solid State Mater. Sci.* **20**, 87 (1995).

¹²A. Fan, A. Rahman, and R. Reif, *Electrochem. Solid-State Lett.* **2**, 534 (1999).

¹³K. N. Chen, A. Fan, and R. Reif, *J. Electron. Mater.* **30**, 331 (2001).

¹⁴Y. A. Li, R. W. Bower, and I. Bencuya, *Jpn. J. Appl. Phys., Part 1* **37**, 1068 (1998).

¹⁵H. Takagi, K. Kikuchi, T. R. Chung, and T. Suga, *Appl. Phys. Lett.* **68**, 2222 (1996).

¹⁶H. Takagi, R. Maeda, T. R. N. Hosoda, and T. Suga, *Jpn. J. Appl. Phys., Part 1* **3**, 1589 (1999).

¹⁷H. R. Kaufman, *J. Vac. Sci. Technol. A* **5**, 2081 (1987).

¹⁸T. Suga, M. M. R. Howlader, T. Itoh, C. Inaka, Y. Arai, and A. Yamaguchi, 51st Electronics Computer, and Technology Conference, FL, 2001, p. 556.

¹⁹J. M. E. Harper and J. J. Cuomo, *J. Vac. Sci. Technol. A* **3**, 2693 (1985).

²⁰T. M. Mayer, J. M. E. Harper, and J. J. Cuomo, *J. Vac. Sci. Technol. A* **3**, 1779 (1985).

²¹Q.-Y. Tong and U. Gosele, *Semiconductor Wafer Bonding* (Wiley, New York, 1999), p. 79.