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Low-Temperature Direct Bonding of 3D-IC Packages and Power IC Modules Using Ag Nanotwinned Thin Films

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ABSTRACT

Ag has the lowest stacking fault energy of all metals, which allows twin formation to occur more easily. The (111)-preferred orientation Ag nanotwinned films is fabricated by either sputtering or evaporation method exhibit columnar Ag grains grown vertically on Si substrates. Ag nanotwinned films have a (111)-preferred orientation with a density about 98% and diffusivity that is 2 to 5 orders of magnitude higher than those of (100) and (110) surfaces. Low temperature direct bonding with (111)-oriented Ag nanotwins films is proposed to fulfil the requirements for wafer-on-wafer (WoW), chip-on-wafer (CoW), and chip-on-wafer-on-substrate (CoWoS) advanced 3D-IC packaging, with the process temperature drastically reduced to 100°C. Such an innovative bonding method also provides a promising solution for die attachment of Si chips with DBC-ceramic substrates for power module packaging.

KEYWORDS

(111)-Preferred Orientation, 3D-IC Wafer Bonding, Ag Nanotwinned Film, Low Temperature Bonding, Power Module Die Attachment, Sputtering and Evaporating

INTRODUCTION

Twins and twin boundaries are defects of interest for enhancing technological materials because they may influence, positively or negatively, different properties. Twinning has remarkable effects on the thermal stability, as well as mechanical and electrical properties, of FCC metals. Since their discovery, nanotwinned materials have opened new avenues of research and applications. The nanotwin structure consists of a high density of nano-scaled lamellae with twin spacing below 100 nm in a columnar grain structure. As a result of nanotwinning, numerous coherent twin boundaries are stacked within the grain. They separate the internal grain into distinct twin and matrix lamellae regions. The orientation of twin lamellae mirrors its corresponding matrix lamellae across the twin boundary. The twin boundaries are specifically structured to follow the ordered arrangement of nano-scale twin lamellae in the grains. Therefore, nanotwinned materials have greatly improved material properties as compared with the bulk material.

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The mechanism of the formation of nanotwin structures has become a research topic of great importance. Numerous theories have been introduced to explain the occurrence of twinning. Although the cause of twinning formation has been discussed from various viewpoints, its fundamental origin can be simply addressed via an analysis of energy. A crystal structure with a continuous lattice exhibits the lowest free energy state of that collection of atoms. Thus, variation from such a structure could result in an increase in the energy of the bound atoms. The formation of twins creates a distinct lattice compared to the matrix. The twin boundary is established in the region where twin and matrix meet to fulfil the minimum interfacial energy requirement. The twin boundary is a single plane of atoms connecting two non-mixing phases. Such an arrangement ensures that the structural change across the twin boundary is less abrupt because there is no significant lattice discontinuity. Therefore, whilst the energy level at a twin boundary is higher than in the rest of the crystal, the difference in energy levels is negligible. A similar phenomenon of close-to-minimum energy can also be observed within all types of intergrowths, where the crystal orientation across the intergrowth boundaries behaves similarly to the crystal orientation across twin boundaries.

Nanotwin structures offer promising characteristics in broad applications like the development of nano-devices in optical systems, nano-electromechanical materials, high-performance mechanical structures, and biological sensing (Sun, 2018). To date, comprehensive coverage of nanotwinned metals is available based on the FCC materials. Efforts on other nanotwinned structures, such as hexagonal closed-packed (HCP) or body-centred cubic (BCC) metals, alloys, and synthetic materials, continue to be an essential part of exploration. Furthermore, the nanotwinned structures are known to be beneficial alternatives in numerous material areas like mechanical structures (Anderoglu et al., 2008; Yu et al., 2013) and interconnection materials in the integrated circuit industry (Cheng et al., 2017; Zheng et al., 2021). Clearly, many research options for focusing on nanotwinned hierarchical materials are available for the near future. Advanced technological fields require materials that can meet the relevant field-specific requirements. Therefore, future research on nanotwinned structures will not be restricted to one area of application. Instead, their potential will expand into new areas of work.

The increasing dependence on electrical devices for comfort, transportation, and healthcare in modern society has motivated the development of power modules wherein discrete component implementation would require paralleling of several power semiconductor devices, such as diodes, metal oxide silicon field effect transistors (MOSFETs), and IGBTs. Die attachment provides not only joining but thermal conduction between power devices and DBC substrates. Nowadays, with rapid and comprehensive development, power modules must meet stricter requirements. Given the current pursuit of weight reduction and miniaturization, as well as the need to maintain reasonable efficiency at high power and voltage ratings, the development of power module packaging has never been more challenging. A traditional soldering die attachment method has limitations for the operation of power devices due to the low melting temperature of most solder alloys. On the other hand, Ag or Cu sintering presents a risk of damage to power modules during the die attachment process.

For a more compact and efficient package, power module packaging technologies were evolved by introducing flip-chip soldering and direct substrate cooling. Also, the improved design with ribbon bonding and direct substrate cooling was launched to reduce the packaging height. Later, more advanced modules were introduced with direct lead bonding technologies and alternative substrates. Nowadays, with rapid and comprehensive development, the power modules are urged to meet stricter requirements. The pursuit of lightweight and downsizing, as well as the maintenance of a reasonable efficiency at high power and voltage ratings, results in a more challenging development of power module packaging.

In response to the higher demand of advanced power modules, the next-generation power modules packaging technology is focused on improving energy density and reliability while reducing losses and costs. Among the latest commercial power modules, there have been many innovative designs to improve the limitations of the traditional power module packages in one or multiple aspects. In the aspect of semiconductor dies, a shift from Si-based devices to WBG devices is expected to meet the exceeding demand for higher power density and efficiency. While the SiC manufacturing process has reached maturity, the prices are forecasted to decrease in the future.

In addition, the three-dimensional integrated circuit (3D-IC) has been verified as a leading approach to achieve high-density integration with a small form factor, high performance, low power consumption, and low cost. It also presents a promising solution to overcome the limitations of Moore's law. The introduction of low temperature bonding approaches to the semiconductor industry may overcome issues related to the cracking of thinned and fragile wafers during bonding, performance degradation under high bonding temperature (> 260°C), serious wafer/chip warpage and bond misalignment, and compatibility with the back-end process conditions and materials (Ko & Chen, 2012). The low temperature bonding technology provides an attractive route to 3D-IC fabrication because it can serve as both the electrical and mechanical interconnection between the adjacent device layers. Wafer direct bonding refers to the adhesion of two solids with sufficiently clean and flat surfaces by attractive forces without the use of adhesive layers or application of external forces (Christiansen et al., 2006). The two bodies are placed into close contact so that bonds can form across the interface. Generally, two crystals with matching orientation should be able to merge into one crystal; two misoriented crystals would form a grain boundary at the interface. Standard wafer bonding of Si wafers in air is attributed to relatively weak intermolecular attractive forces like van der Waals or hydrogen bonds. Thus, additional annealing at elevated temperatures is required to strengthen the bonds across the interface, as required for most technological applications. This usually involves some chemical reaction of atoms or molecules at the interface.

Direct bonding offers high density, good alignment, stress-free bonding, and hermetically-sealed bonding structures. The process is a more viable method of managing the thermal issues caused by the conventional bonding methods (e.g., high bonding temperature). The strong metallurgical bonds formed in direct metal bonding offer very high electrical and thermal conductivity without degradation of mechanical strength at lower bonding temperature (Yang et al., 2020). However, the process requires very high standards for the surface properties in terms of flatness, smoothness, and cleanliness. An appropriate bonding environment and flat surfaces with surface roughness on the nanometer scale are required for bonding integrity. These challenging conditions have become limitations in its application. Today, most wafer bonding processes are conducted in ambient air at room temperature. In some cases, however, the bonding may also be performed in different atmospheres and temperatures. For example, wafer bonding of III-V compounds, the most commonly known of which is GaAs, is frequently conducted at elevated temperatures (around 500°C) in a hydrogen atmosphere. On the other hand, wafer bonding under high vacuum conditions allows for even higher bond strengths and reduced bonding temperatures for materials like Si. Various attempts have focused on metal-to-metal direct bonding as the interconnections for electronic devices.

In recent years, nanotwinned materials have attracted great attention in many research areas. It has been extensively studied to improve the material properties for various applications. Nanocrystallisation of metals promotes drastic growth in the grain boundary volume fraction. This, in turn, significantly changes the physical, mechanical, and chemical properties in comparison to the those of random-grained counterparts (Sun et al., 2018). Nanotwinned structures have proven to be a kind of novel structure that confer many advantageous properties. Great progress has been made in understanding the properties of nanotwinned structures via many studies, computational simulations, and theoretical research. Experimental studies on nanotwinned materials have demonstrated improvements in properties like strength and hardness, ductility, strain hardening, and electronic and optical properties. Recently, nanotwinned FCC materials like Cu and Au have become a popular research topic in physics, materials science, and mechanics due to the unique microstructures and superior material properties.

Studies have reported successful evidence of direct bonding of bulk metals like Cu, Ag, and Au. However, each of these highly conductive metals face unique challenges and difficulties based on inherent qualities. As a result, the implementation of nanotwinned films is introduced to improve the bondability of the bulk metals. Juang et al. (n.d.) demonstrated a Cu-to-Cu direct bonding technique with a short bonding time of five minutes by electroplating (111)-oriented nanotwinned Cu films (Juang, 2018). The study proposed that, under thermal compression, the contacted and noncontacted regions along the bonding interface induce creep by surface diffusion such that atoms migrate from the strained region to the unstrained region (void). The result is a new atomic bonds of Cu-to-Cu across the interfaces. Liu et al. (2014) further reported low-temperature direct bonding using highly (111)-oriented nanotwinned Cu films, which exhibited excellent bonding quality with virtually no voids observed at the smooth bonding interface when the bonding time was shortened to 30 minutes. Due to the fast Cu diffusion on (111) planes, the bonding condition can be lowered to fit the application in 3D-IC packaging. That approach provided a breakthrough in metal-to-metal direct bonding; the bonding temperature can be lowered to 200°C, presenting an alternative over the use of solder for interconnections (Liu et al., 2014). Upon further investigation into the properties of nanotwinned materials that feature low temperature bonding, nanotwinned Au films with high (111) orientation were fabricated by periodically reversed electroplating with an on-time current density of 0.5 ASD and off-time current density of 0.125 ASD (Wu et al., 2018). With surface roughness controlled, the Au-to-Au direct bond showed a satisfactory performance, wherein all the bonded samples failed at either the film/substrate layer or at the Si substrates, implying a stronger bonding strength than the maximum shear strength of 40.8 MPa measured by bond-testing equipment. In FCC metals, as twin boundaries are formed for their preferred state to release strain, the stress-relaxed nanotwinned film can be of lower energy than the strained structure. As in Cu, the diffusion rate of the (111) surface being much higher than that of other surfaces in Au drives atoms to diffuse along the surface, increasing the likelihood of successful direct bonding.

Ag nanotwinned films have also been fabricated on Si substrates by magnetron sputtering method (Chuang et al., 2020; Wu et al., 2021). Those studies showed that the resulting Ag films had a high density of (111)-textured nanotwins with spacing of 2 to 50 nm. In addition, the Ti thin film not only acted as an adhesive layer at the Ag/Si interface but resulted in a buffer effect of the Ti interlayer for the epitaxial growth of nanotwinned Ag films on Si chips. Due to the high production efficiency and low cost of the evaporating process in comparison with those of sputtering, this study also produced Ag nanotwinned films on Si substrates using an evaporating method assisted by ion beam bombardment for the first time (Wu & Chuang, 2021). The results indicated that, with ion beam assistance, Ag thin films with a highly <111> textured structure can be evaporated on Si chips. In contrast, Ag films deposited without ion beam assistance exhibited mostly fine grains accompanied by certain random annealing twins. Furthermore, Ag (111) nanotwinned structures form after post-deposition ion bombardment of the Ag films on Ti pre-coated Si substrates without Ag (111) seed layers (Lee et al., 2021). For the mechanism of enhancing nanotwin formation in Ag films deposited with both simultaneous ion beam assistance and post-deposition ion bombardment, a modified stress relaxation model is proposed. The tensile stress in solidified deposited Ag film is relieved by the compressive stress introduced by the ion bombardment, resulting in the formation of strain relaxed nanotwins.

Since (111)-textured Ag nanotwins possess the advantage of high atomic diffusivity, it is expected that for applications in Si/Si wafer bonding of 3D-IC front-end Systems on Integrated Chips (SoIC) stacking devices and back-end Chip on Wafer on Substrate (CoWoS) advanced packages, and in Si/DBC ceramic substrate die attachment of power IC modules, the processing temperature can be effectively reduced. In fact, in comparison to the deposition of Cu nanotwinned film by electroplating with high-speed stirring, the sputtering or evaporation deposition of Ag nanotwinned film is a convenient, dry, and environmentally friendly process. In addition, the Ag nanotwinned film possess the additional advantages of higher diffusivity, oxidation resistance, lower melting point, and softness. It is suggested to be superior to Cu nanotwinned film for application to low temperature direct bonding. Since Ag oxide can be decomposed at about 175°C, Ag-Ag with nanotwinned structure has also been reported to be directly bonded at 200°C in air atmosphere (Chang et al., 2021, 2022).

Low temperature direct bonding via the (111)-oriented Ag nanotwins films is proposed to fulfil the requirements of various applications stated above, with process temperature drastically reduced to below 150°C. This provides a solution for advanced 3D-IC and power module packaging. This study provides a comprehensive overview of Ag nanotwinned film and its application in low-temperature direct bonding. The discussion focuses on the influence of the Ag nanotwins on the material properties. The authors aim to offer better insight into the Ag nanotwinned materials, their modified properties, and potential applications.

EXPERIMENTAL

Magnetron sputtering deposition is commonly used to deposit different types of thin films on Si substrates. The process relies on the ejection of atoms by the bombardment of a solid of liquid target by energetic particles, mostly ions. The dislocation of metal atoms is caused by the collisions between high energy ions with surface atoms. The ejected neutral atoms travel through the plasma and condense on the wafer in the opposite side of the target. In contrast with other deposition techniques, sputtering deposition generates high-energy flux; the additional energy is thought to be the reason for the formation of continuous smooth metal film more readily.

In this study, high density Ag nanotwinned films were deposited on Si wafers by magnetron sputtering at room temperature. To increase the adhesion of Ag thin films with Si wafers, an additional Ti thin film was precoated on the Si substrate. During the sputtering process, the Ar pressure was fixed at 0.67 Pa (5 mTorr), the base pressure of the vacuum chamber was lower than 6×10^{-4} Pa (5×10^{-6} Torr), and the distance between the substrate and the target was kept at 10 cm. The deposition rates of the Ag and Ti films were 1.35 nm/s and 0.1 nm/s, respectively, for a sputtering power of 200 W.

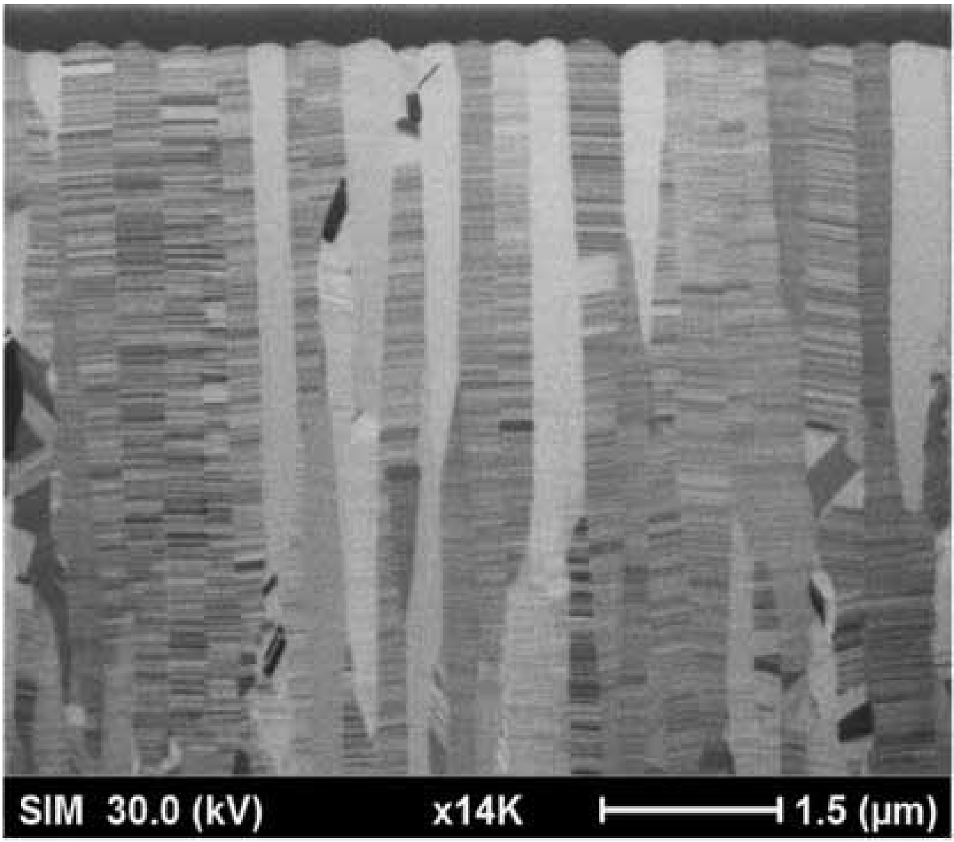
After the Ag and Ti films were sputtered on the Si substrates, a focused ion beam (FIB, Hitachi NX2000) was used to observe the cross-sectional grain structures of Ag nanotwinned films. The crystal orientations of the surfaces of the sputtered Ag films were identified by X-ray diffraction (XRD, PANalytical-X'Pert PRO). The cross-sectional microstructures of the nanotwins in the sputtered Ag films were further observed with transmission electron microscopy (TEM, FEI Tecnai G2 F20). The crystal structures were identified by selected area electron diffraction (SAED) taken from the TEM specimens. In addition, the crystal orientations and twin densities were analysed by electron backscatter diffraction (EBSD, JEOL JSM-7800F). The Si/Si wafer bonding and Si/DBC ceramic substrate die attachment were performed in a vacuum furnace with a pressure about 5×10^{-3} Torr. The DBC alumina substrates with Cu/Ni/Pd/Au metallization were used in this study. The ceramic substrates are provided by Summit-Tech Resource Corp. After bonding, the interfaces were prepared for metallographic observations using a focused ion beam (FIB). The microstructure of the interface in the wafer bonded Ag nanotwinned films were also observed with transmission electron microscopy (TEM, FEI Tecnai G2 F20). For quantitative analysis, the bonded samples were further examined by die shear test (DAGE4000) to evaluate the bondability of the Ag nanotwinned films via the direct bonding technique. An average value for the adhesion test was presented by DAGE 4000 based on at least five measurements.

RESULTS AND DISCUSSIONS

A typical FIB microstructure of the cross-section of Ag nanotwinned film sputtered on Si wafer precoated with Ti thin film is shown in Figure 1. The secondary electron figure clearly revealed that the Ag columnar grains aligned in parallel and have been observed to grow in the normal direction to the Si substrate. In addition, a high density of nanotwins piled up on each other in parallel are contained in these slender Ag columns. The width of these Ag nanotwinned columns, as measured from Figure 1, ranged from 0.1 to 0.5 µm. Previous work by Wu et al. (2021) also showed that the top surface of the Ag nanotwinned films had an equiaxial grain structure with roughness of 10 to 20 nm, as determined by Atomic Force Microscopy (AFM). In fact, such surface roughness did not compare well to those of the other reported nanotwinned films with additional flattening processes.

The great difference of surface roughness within the Ag nanotwinned film suggested that the substrate surface can affect the surface roughness of the thin film.

Figure 1. FIB metallography of the cross-section of Ag nanotwinned films sputtered on a Ti precoated Si substrate



The distribution of crystal orientations of the nanotwinned boundaries in Ag nano-twinned film sputtered on Si wafer was identified by electron backscatter diffraction (EBSD). The typical inverse pole figure of the columnar Ag nanotwinned grains in Figure 2 revealed that most of the columnar Ag grains were highlighted in blue, corresponding to the highly preferred (111)-grain orientation with density 80%. In addition, most of the equiaxed grains were located within the transition layer under the Ag nanotwinned layer. The average width of the Ag columns was about 0.2 μm. The distribution of Σ3 coincident twin boundaries within the Ag film was marked with white lines in the orientation image map (OIM), where the proportion of coincident Σ3 twin boundaries to the total grain boundaries in the Ag films was as high as 65%. Furthermore, the proportion of CSL-Σ9 near twin boundaries was above 10%. It is undoubtedly true that the Ag film has a very high twin density, which is consistent to the FIB cross-sectional metallography in Figure 1. In fact, the top-view EBSD inverse pole figure mapping reported in Wu (2021) indicated that only (111) grains existed on the surface of Ag nanotwinned films, with a very high density of (111) orientation of 98%. Furthermore, the XRD spectrum shown in Figure 3 indicated that the Ag films sputtered on Si wafers had a strong

Ag (111) peak and no other crystal orientations, confirming the (111)-textured characteristics of the Ag nanotwins.

Figure 2. EBSD analysis of the nano-twinned Ag film with a crystal orientation inverse pole figure (IPF)

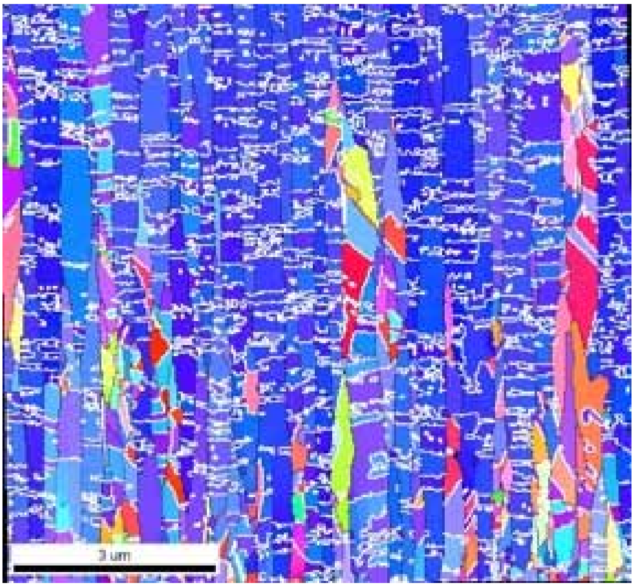
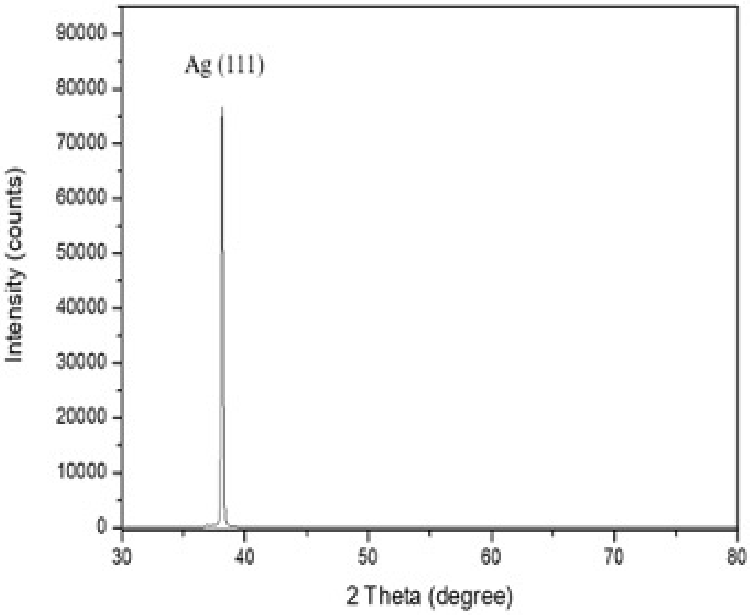
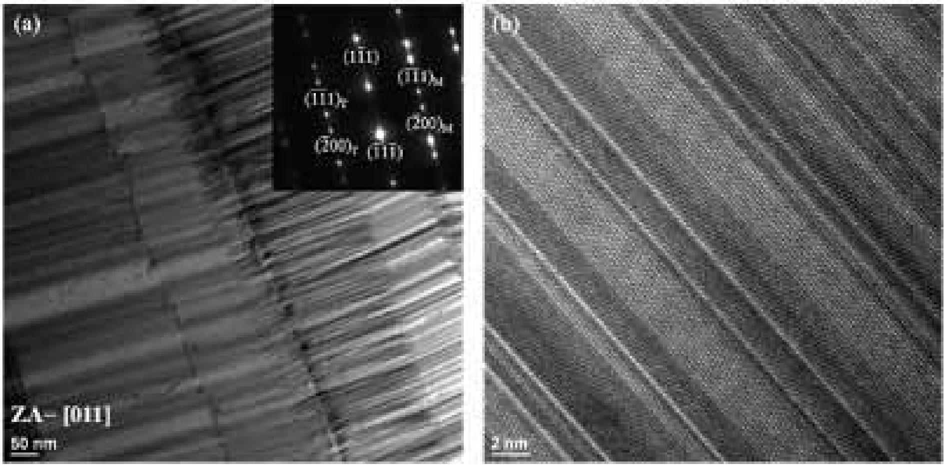


Figure 3. XRD spectra of Ag film sputtered on a Si substrate



The Ag nanotwinned columns had widths of 100 to 500 nm, as measured from the TEM micrograph in Figure 4a. The twin spacing, measured in the HR-TEM micrograph of the Ag nanotwinned film, ranged from 1 to 10 nm. It had an average value of about 4 nm, as shown in Figure 4b. In addition, the Ag (111) twin boundaries in Figure 4b revealed a very fine atomic spacing of about 0.24 nm. The twin characteristics were evidenced by the symmetry relationship between $()_M/()_M$ and $()_T/()_T$ in the inset of Figure 4c. This presents a selected area electron diffraction (SAED) pattern taken from the [011] zone axis, where the labels M and T indicate the diffraction dots of the matrix and twins, respectively. The three middle dots represent the co-plane (11)/(1) of the matrix and twins.

Figure 4. Cross-sectional TEM micrograph of sputtered nanotwinned Ag film on a Si chip precoated with a Ti adhesive layer with ion beam assistance: (a) bright field image; (b) high resolution HR-TEM image; and (c) selected area electron diffraction (SAED) pattern



The concept of direct bonding of Si wafers deposited with high density (111)-oriented Ag nanotwinned films is schematically presented in Figure 5. For the evaluation of such an application of Si wafer bonding in advanced 3D-IC packages, Ag nanotwinned films with a thickness of 5 µm were sputtered on Si chips and then placed face-to-face in a vacuum furnace (see Figure 5). After heating at temperatures of 150°C and 200°C for 30 minutes with an external pressure of 20 MPa, the Ag nanotwinned films on both Si chips were successfully bonded together (see Figures 6b and 6c, respectively). When the bonding temperature was reduced to 100°C for 30 minutes, many voids formed at the interface between Ag nanotwinned films. However, these interfacial voids were diminished by lengthening the bonding time to 60 minutes (see Figure 6a). The results evidenced that the Si wafers could be bonded satisfactorily at an extremely low temperature of 100°C. The direct Ag-to-Ag bonding with no visible voids was achieved at a low bonding temperature of 100°C, where the satisfactory bonding quality was such that the bonding interfaces in Figure 6 are hardly distinguishable. It is known that the highly (111)-oriented Ag nanotwins had an advantageous effect on direct bonding due to the enhancement of surface diffusivity. The Ag nanotwinned structure is likely to enhance the atomic diffusion at the interface of the attached films. In addition, it will overcome the energy barrier to reduce the surface energy for well-defined bonding. This would explain that sound bonding was achievable even at bonding conditions of 100°C for an hour. Subsequently, the bonded cross-sections in Figure 6 indicated the highly (111)-preferred grains of the Ag nanotwinned film remained after the bonding process at various temperatures. This indicates that the nanotwinned columnar grains presented excellent thermal stability in the bonding process, in which no obvious grain growth was observed within the nanotwinned structure.

Figure 5. Schematic presentation of the application of Ag nanotwinned film (nt-Ag) to low temperature direct Si/Si wafer bonding: (a) before bonding; (b) after bonding

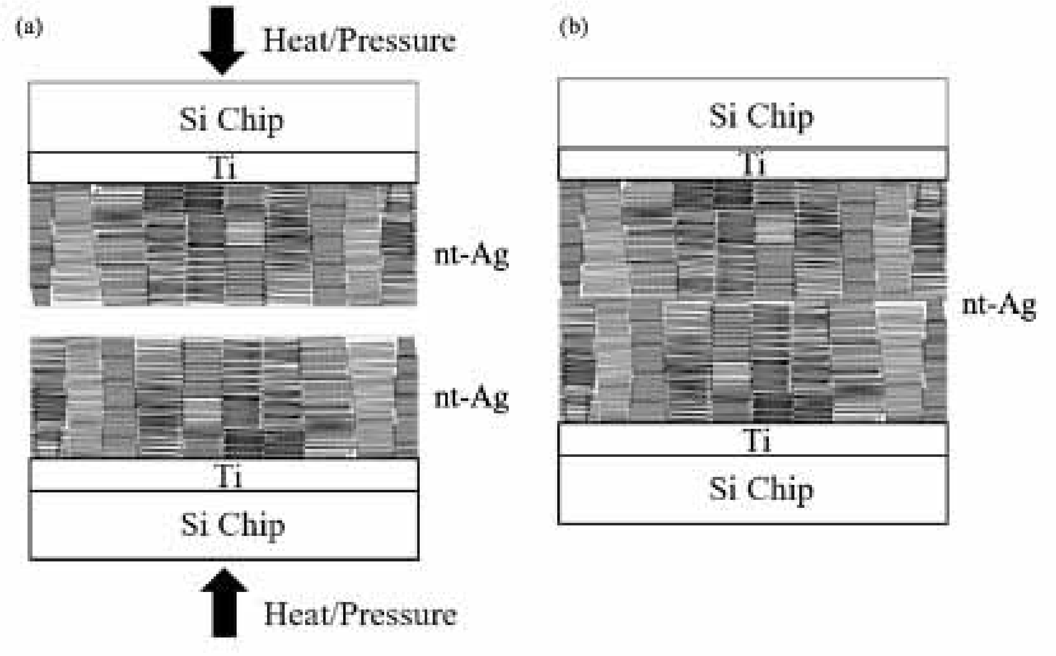
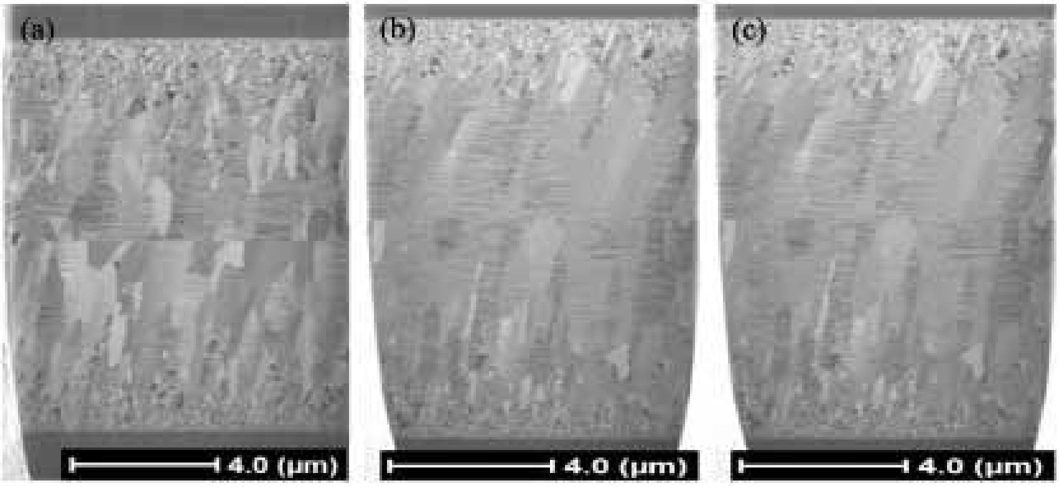
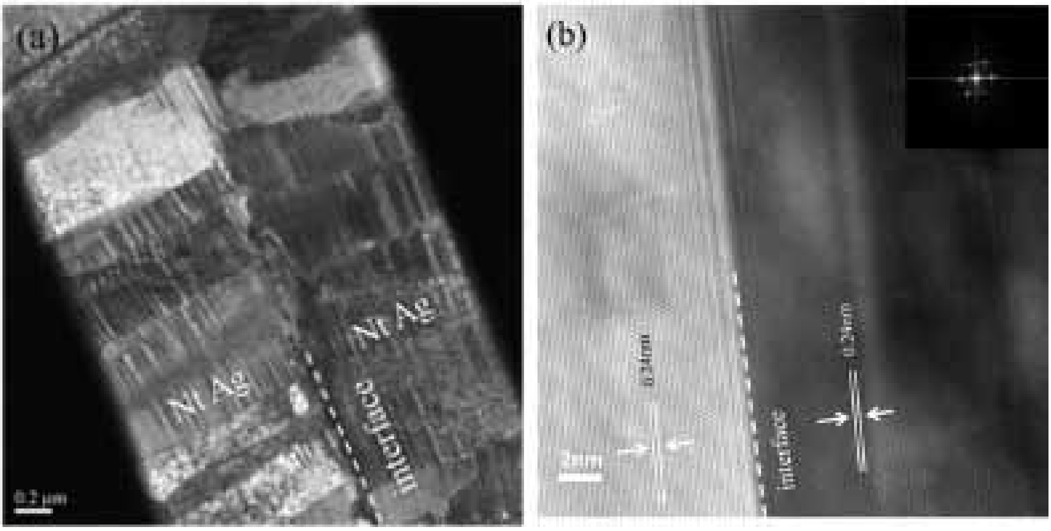


Figure 6. Interfacial microstructure of the nano-twinned Ag films sputtered on Si substrates directly bonded under various conditions: (a) 100 °C, 60 min; (b) 150 °C, 30 min; (c) 200 °C, 30 min



For a closer microstructural observation of the bonding interface after bonding at 200°C for 30 minutes, TEM was adopted (see Figure 7). The bonding interface was indicated by the dashed line. It can be observed that the nanotwinned Ag films were in close face-to-face contact without voids at the bonding interface in Figure 7a. Numerous Ag nanotwins stacked on one another within the columnar grains. In addition, the HR-TEM image in Figure 7b indicates that the lattice planes on both sides of the bonding interface were Ag (111). The upper-right corner image in Figure 7b shows the diffraction pattern after fast Fourier transformation (FFT), where the Ag nanotwinned film remained highly (111) oriented even after the direct bonding process. The measured twin spacing between the lattice planes was about 0.24 nm. The results further confirmed the thermal stability of the nanotwinned films after bonding and the fast diffusion path from Ag (111) planes, where the average twin spacing was found to be like that of before the bonding process. In addition, the size of the twin could affect the surface diffusivity. Smaller average twin thickness allows more twins to be stacked within the Ag columnar grains parallel to the substrate surface. As the twins are defects that promote atomic diffusion during the bonding process, the Ag atoms can diffuse more rapidly to the surface, thus better bonding quality can be expected with lower bonding pressure, time, and even temperature.

Figure 7. Bonding cross section TEM image after bonding at 200°C for 30 minutes: (a) bright field image; (b) high resolution HR-TEM image with SAED pattern in the upper-right corner



To identify the effect of Ag nanotwins with (111)-preferred orientation to the bondability, the authors compare the direct bonding of three types of (111)-oriented Ag nanotwins proportion. The results in Table 1 reveal that Ag thin film with more (111)-oriented nanotwins will form less pores at the bonding interface, thus better performing in the die shear tests. Especially at low bonding temperatures, the bonding samples show excellent direct bonding and an ability to withstand shear force over 9 MPa. However, the bonding samples with less (111)-oriented nanotwins require higher bonding temperature to achieve similar bondability (as in the samples with more (111)-oriented nanotwins).

Table 1. Bonding performance of (111)-oriented Ag nanotwins in different proportion.

(111)-ratio	**99.4%**		**73.4%**		**15.8%**	
Bonding temperature and time (°C-mins)	**Porosity (%)**	**Shear strength (MPa)**	**Porosity (%)**	**Shear strength (MPa)**	**Porosity (%)**	**Shear strength (MPa)**
100-60	7.36	10.01	-	-	-	-
150-60	1.01	7.52	70.3	4.3	-	-
200-30	0.85	6.91	8.32	7.52	100	3.25
250-10	0.95	8.44	3.83	9.81	20.61	17.82
250-30	-	-	~0	9.79	3.89	>28

Figure 8 illustrates another concept regarding the use of Ag nanotwins for the die bonding of high-power modules. An example of this application was investigated by sputtering a (111)-Ag nanotwinned film with a thickness of 2 µm on a Si chip and then bonding with a direct bonded copper (DBC)-Cu (0.635 mm)/alumina substrate surface finished with a Ni (75 µm)/Pd (4.5 µm) /Au (0.1 µm) metallic multi-layer. Figure 9 shows that an intimate bonding interface between Ag nanotwinned film and Ni/Pd/Au surface finished DBC alumina substrate without any voids can be obtained after bonding at 150°C for 30 minutes under an external pressure of 30 MPa. These results evidence the feasibility of the die bonding of Si chips with DBC-ceramic substrates at a low temperature of 150°C using high density (111)-textured Ag nanotwins.

Figure 8. Schematic presentation for the application of Ag nanotwinned film (nt-Ag) on low temperature direct die attachment of Si chip with DBC-ceramic substrate: (a) before bonding; (b) after bonding

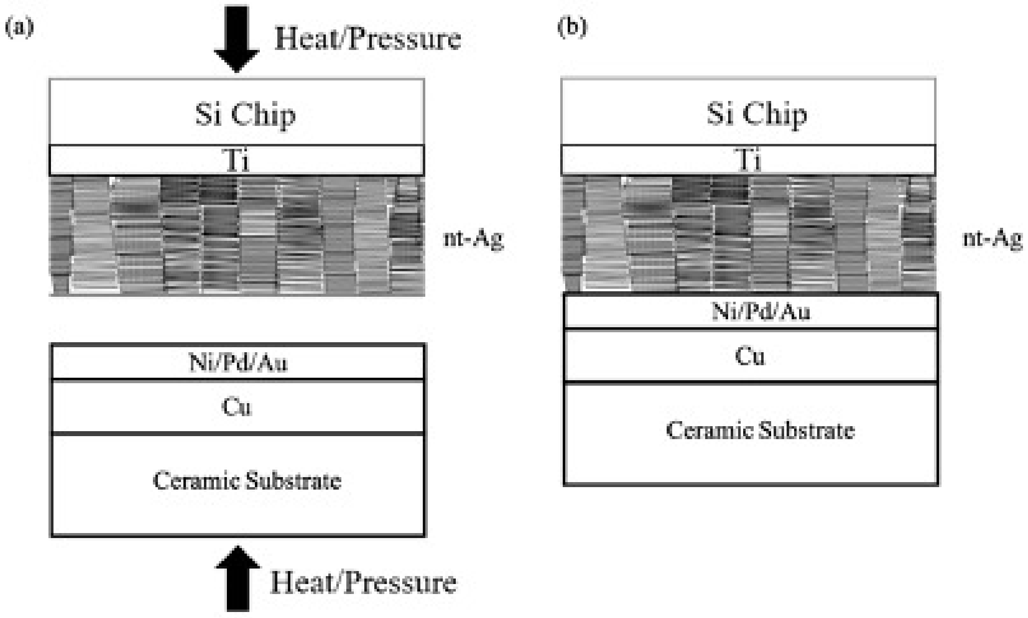
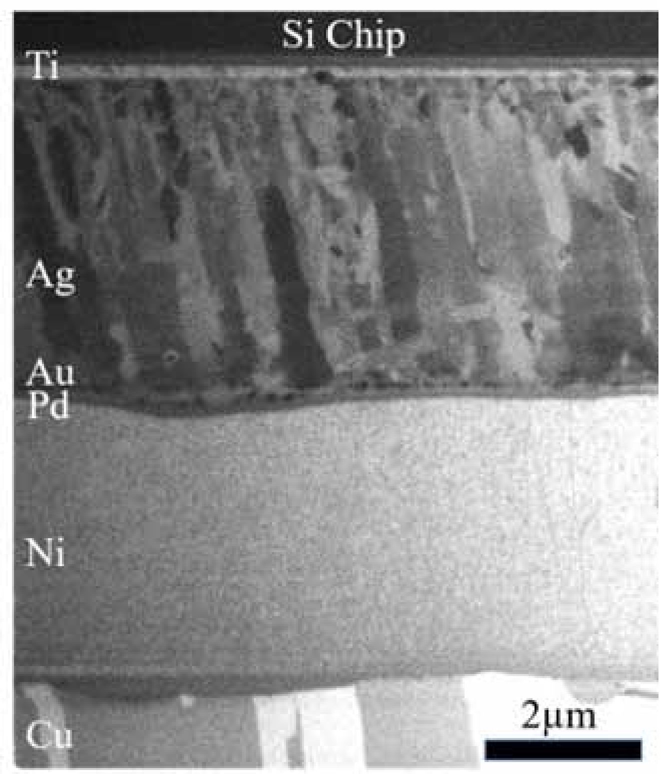
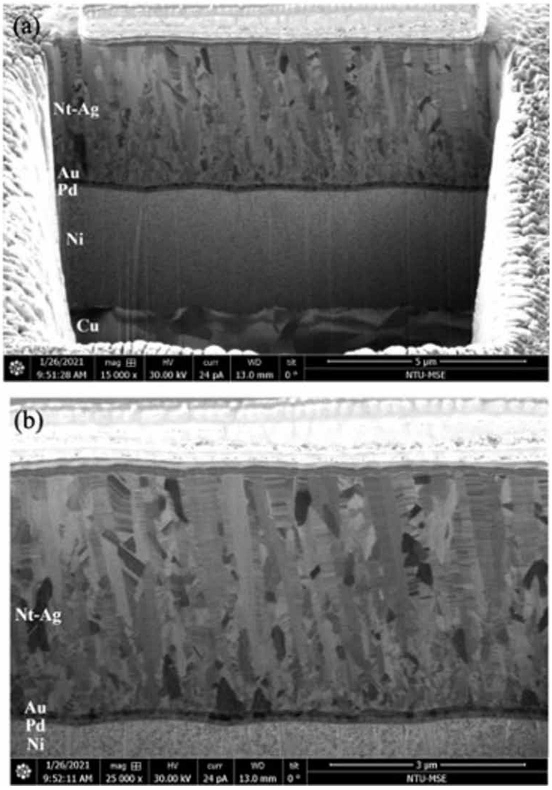


Figure 9. Microstructure of the low temperature directly bonded interface between nano-twinned Ag films sputtered on Si substrates and DBC-alumina ceramic substrate with Ni/Pd/Au surface finish



This study proposed an alternative process for this application of die bonding to the fabrication of power modules by the sputtering of Ag nanotwinned films on DBC alumina substrates and then direct bonding with Si chips with or without deposition of Ag nanotwins. Figure 10 presents an example of the sputtering of Ag nanotwinned film on a Ni/Pd/Au surface finished DBC alumina substrate. It is evidenced that the sputtered Ag film has a high density of (111)-oriented nanotwins. EBSD analysis indicated that the Σ3 twin boundaries in the Ag films comprised 58% of the total grain boundaries. The thickness of transition layer from random grains to nanotwins was about 0.2 μm, less than that deposited on Si chips. The DBC alumina substrate sputtered with such a nanotwinned Ag film (Nt-Ag) can also be satisfactorily bonded with a bare Si chip without Ag nanotwinned film at 150°C for 30 minutes under an external pressure of 30 MPa.

Figure 10. Cross-sectional FIB ion image of: (a) sputtered Ag nanotwinned film on DBC-alumina substrate with Ni/Pd/Au surface finish; (b) higher magnification



CONCLUSION

Ag films containing nanotwinned columnar grains with a high density of (111)-orientation of about 80% have been fabricated by magnetron sputtering process in this study. EBSD analyses indicated that the proportions of coincident $\Sigma 3$ twin boundaries to the total grain boundaries in the cross-section and the top surface of sputtered Ag films reached 65% and 98%, respectively. Such (111)-textured nanotwins have much higher diffusivity than (110) and (100) orientations, providing potential applications for low temperature direct bonding of Si chips. Experimentally, direct Si/Si bonding has been evidenced under conditions of 150°C and 200°C for 30 minutes using (111)-oriented Ag nanotwinned films. Satisfactory bonding interfaces can even be achieved at a temperature as low as 100°C for 60 minutes under bonding pressure of 20 MPa. The FIB images of the bonded cross-sections revealed that the sound bonding with almost no voids existed at the bonding interface. The Ag nanotwinned structure did not degrade even after the bonding process; this indicated the superior thermal stability of the Ag nanotwinned film. Furthermore, the die attachment of Si chips with DBC-alumina substrates was presented under bonding conditions of 150°C for 30 minutes under 30 MPa. The excellent bonding interface can also be accomplished due to the highly (111)-oriented grains of the film surface, which provide a rapid diffusion path for bonding. Optimized film deposition condition that engenders high density of (111)-oriented nanotwins is expected to present a more suitable condition for direct bonding of Ag nanotwinned film, especially at low temperatures.

CONFLICT OF INTEREST

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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