Thermal stability of back side metallization multilayer for power device application

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1. Introduction

Power devices have attracted as Electric Vehicles (EV) and super luminosity Light Emitting Diode (LED) application [1–5]. Power converter needs to be miniaturized with high efficiency because the mounted space is restricted. Many groups tried to progress the power density by increasing operation temperature using Silicon Carbide (SiC) and related materials [6–11]. While operating temperature of Si device is typically lower than 150 °C, SiC devices can operate at over 200 °C. In such a condition, it needs to reconsider the materials of die bonding and the thin films on the device for durability at high temperature because the speed of intermetallic diffusion accelerates. The devices have two contact areas located on the top (anode) and the back side (cathode) of the device within a diode. The device requires ohmic contacts with low specific resistance. Die bonding is an important technique for the power device mounting because of its high operation temperature and mechanical stress caused by wide range temperature cycling. Bonding strength between a substrate and a chip through die bonding material might be affected by metal diffusion of the metallization multilayer located at back side of the device. Some groups described about the thermal stability of metal thin films [12–19]. Ti has good characteristics for Schottky contact on SiC [12,13], and Au is used in integrated circuits through ages because of its conductivity with difficulty to oxidize. Hanamura et al. reported that Ti/Ni/Ag multilayer was peeled off since nickel silicide on the back side of the SiC device became depleted [18]. Sozza et al. described about the diffusion condition of the multilayer over 400 °C and the reliability of Ti/Pt/Au on SiC MESFET focused on electrical resistance [19]. It is required to understand and establish two important issues on bonding with the SiC device; (1) interfacial reaction between a SiC semiconductor substrate and the back side metallization layer of the SiC device, (2) interfacial reaction between the back side metallization layer of the SiC device and a die bonding material. We focused on the second requirement, since there were few reports about them. To simplify experiments, a Si substrate was used in this study. We tried to use high melting point metals as a barrier metal, such as Ti, Ru, Pt, Ta, and W for the back side metallization multilayer and studied their thermal stability.

Metal nanoparticles have been paid attention for the die bonding material because of the fusion bonding at lower temperature, comparing with its bulk state. Ag paste including nano-sized Ag particles was introduced by some groups for die bonding [19,20], however, Ag had less ion migration reliability. We newly developed an Au paste including sub-micrometer-sized Au particles for die bonding and evaluated its bond strength after the high temperature aging when the metallization multilayer described above was used.

2. Experimental

2.1. Thermal stability test of metallization multilayer

It is required that the speed of diffusion between the layers is very slow on metallization multilayers around 300 °C. In this...
study, high melting point metal such as Ti, Ru, Pt, Ta and W were used as a barrier metal, and Au was chosen as top of the multilayers. We fabricated five types of metallization multilayers on each Si wafer with a diameter of 3 in. by using DC-magnetron sputtering at room temperature as described below: composition(thickness), Ti(50 nm)/Au(100 nm), Ti(50 nm)/Pt(50 nm)/Au(100 nm), Ti(50 nm)/Ru(50 nm)/Au(100 nm), W(50 nm)/Au(100 nm) and Ta (50 nm)/Au(100 nm). The base and working pressure were $1.0 \times 10^{-3}$ Pa and $6.7 \times 10^{-1}$ Pa, respectively. After dicing the wafers to 1 cm $\times$ 1 cm, samples were put into an oven (STH-120, ESPEC Corp.) at 300 $\degree$C for 300 h without atmosphere control. After the high temperature aging, the surface was observed using an optical microscope, Scanning Electron Microscope (SEM) and Auger Electron Spectroscopy (AES) (PHI670, ULVAC-PHI, Inc.). Depth profile of atomic composition was measured by using AES with a sputtering rate of 2.7 nm/min, which was calibrated to the sputtering rate of SiO$_2$. Evaluation area was about 5 $\mu$m $\times$ 5 $\mu$m.

Fig. 1. Schematic of process condition on die bonding.

![Fig. 1. Schematic of process condition on die bonding.](image1)

Fig. 2. Schematic of measuring the bond strength using shear tool.

![Fig. 2. Schematic of measuring the bond strength using shear tool.](image2)

Fig. 3. SEM images of the multilayer surface before (a-1) and after (a-2, b, c, d, e) the high temperature aging test. (a), (b), (c), (d), and (e) show the metallization of Ti/Au, Ti/Pt/Au, Ti/Ru/Au, W/Au, and Ta/Au, respectively. All the layers were deposited on Si substrate by DC-sputtering method.

![Fig. 3. SEM images of the multilayer surface before (a-1) and after (a-2, b, c, d, e) the high temperature aging test.](image3)
2.2. Thermal stability of die bonding by using Au paste

We developed an Au paste including sub-micrometer-sized Au particles (AuRoFUSE™ TR-191R, Tanaka Kikinzoku Kogyo K. K.). Sub-micrometer-sized Au particles were dispersible in higher alcohols with tiny amount of surfactant, therefore Au content was over 80 wt% in the Au paste. Test sample was fabricated as follows: Si wafer with metallization multilayers were diced into 2 mm × 2 mm for an upper chip and 8 mm × 8 mm for a lower substrate. Metallization multilayers on the chip and the substrate were exactly the same. The Au paste was coated on the lower substrate using printing technology through a metal mask with an open aperture of 5 mm × 5 mm and 30 μm thick. After the chip was put onto the paste coated on the substrate, the sample was bonded together by using a flip chip bonding machine (Model 6000, HiSOL Inc.) with controlling the temperature and the pressure as shown in Fig. 1. The bonding process was divided to three parts, (1) temporary bonding, (2) full bonding, and (3) release and cooling. At the temporary bonding, the sample was pressed with 1 MPa to keep parallel between the chip and the substrate with increasing temperature from 25 to 200 °C. After the temperature achieved to 200 °C, the pressure was changed to the bonding pressure which was set between 1 and 10 MPa within 2 min. At the full bonding, the bonding pressure was kept with increasing temperature from 25 to 350 °C. Then, the pressure was kept at 350 °C for 10 min. Finally, the sample was released from the pressure with natural cooling. The sample was left in an oven at 300 °C within

Fig. 4. AES depth profile of the multilayer before (a-1) and after (a-2, b, c, d, e) the high temperature aging test. (a), (b), (c), (d), and (e) show the metallization of Ti/Au, Ti/Pt/Au, Ti/Ru/Au, W/Au, and Ta/Au, respectively.

![Graphs](attachment:image_url)

2.2. Thermal stability of die bonding by using Au paste

Fig. 5. Bond strength depending on the bonding pressure was plotted in case of the Ti/Pt/Au multilayer. Error bars represented the maximum and the minimum values on each condition. The temperature at the full bonding was inserted in the graph.
1000 h as the high temperature aging. Shear strengths corresponding to the bonding pressure were measured using a bond tester (Series 4000, Dage Japan Co., Ltd.). Bond strength is evaluated as shear strength in this study. Shear speed was 10 μm/s, and gap distance from the substrate to shear tool was 50 μm as shown in Fig. 2. In addition, bond strength was monitored after the high temperature aging.

3. Results and discussion

3.1. Depth profile and morphology of metallization multilayer after the high temperature aging

3.1.1. Ti/Au multilayer

SEM images and AES profiles of each sample were shown in Figs. 3 and 4, respectively. Ti/Au was used as a reference. Fig. 3a-1 shows the SEM image on Ti/Au multilayer before the high temperature aging, and the flat surface was observed without significant morphology. Fig. 4a-1 shows the depth profile of atomic composition on Ti/Au multilayer in an initial state. The depth profile clearly showed the layered structure. High concentration of Si around 25% at short sputtering time was due to the ghost on the AES analysis, and this ghost was also monitored in other samples. Optical image on the Ti/Au sample after the high temperature aging showed that there were many small grains, and some square grains. SEM image showed that square grains were in a few micrometer-size as shown in Fig. 3a-2. Fig. 4a-2 showed the depth profile of atomic composition on the Ti/Au sample after the high temperature aging, and indicated that Ti layer existed on the top of the multilayer and Ti–Au alloy layer was formed. When the signal corresponding to Si was treated as ghost, Au:Ti was about 2:1, which was ideal condition judging by binary phase diagram. In addition, edge on each layer was broad. This result means that metallic diffusion was occurred. Square grains were identified as Si by AES analysis. These results explain that Ti/Au multilayer is not accepted for high temperature application.

3.1.2. Ti/Pt/Au multilayer

We used Pt to prevent diffusion of Ti–Au. The SEM image of Ti/Pt/Au after the high temperature aging test showed the flat surface as shown in Fig 3b. Fig. 4b shows the depth profile of atomic composition on the multilayer, and each element existed individually. In fact, the Pt layer acted as a barrier to the diffusion of Au into Ti. Thermal stability of Ti/Pt/Au system agreed with other experiment over 400 °C for 144 h [21]. Layer boundary between Au and Pt was relatively sharp compared with that on Pt/Ti and Ti/Si. The result was caused by reactivity between Au and Pt. In fact, there is no alloy between Au and Pt in this temperature range from a point of binary phase diagram. P(Ti) phase might be formed between Pt and Ti boundary and was reported as a diffusion barrier by Tison and Drobek [22]. They indicated that P(Ti) compound provided a protective covering for the underlying Ti film. Once it formed, it serves as a barrier to additional diffusion at lower than 400 °C. Since Ti has stabilization behavior to SiC substrate, Ti/Pt/Au is acceptable for metallization of power device application.

3.1.3. Ti/Ru/Au multilayer

Ru was selected for blocking the diffusion of Ti–Au. Optical image and SEM image of Ti/Ru/Au after the high temperature aging showed that there were very small spotty areas all over the surface. The SEM image showed that it had slightly rough surface with a small scoop, which was corresponding to the spotty area as shown in Fig. 3c. This scoop was confirmed as Ti–Si compound by AES analysis. The depth profile of atomic composition showed that each element existed individually as shown in Fig. 4c. Composition change from Au to Ru was precipitous because there was no reaction between Au and Ru in this temperature range. Composition changes from Ru to Ti and from Ti to Si were smooth. TiRu phase might be formed between Ru and Ti boundary, and acted as diffusion barrier.

3.1.4. W/Au multilayer

W was used as an alternative material to Ti, because W can react with Si directly and is difficult to be oxidized compared with
Ti. W/Au multilayer had a flat surface judging from optical images, however, SEM image showed that the surface was slightly rough as shown in Fig. 3d. The depth profile of atomic composition on the multilayer after the high temperature aging showed that each element existed individually as shown in Fig. 4d. W layer acted as a diffusion barrier reported by Sinha [23] since there is no solubility or intermetallic formation in the W–Au system. However, Canali et al. reported that Au on the top layer diffused through the W and Ti layer penetrated into the GaAs after thermal aging at 185℃ for 10,000 h [24]. It means that W–Au system is defective in long term thermal stability.

Fig. 7. Qualitative analysis on the cross section of Ti/Au system after the high temperature aging test for 300 h (from Fig. 6c) by using EPMA.

3.1.5. Ta/Au multilayer

Ta was used as an alternative material to Ti with the same reasons for W. Optical and SEM image of Ta/Au after the high temperature aging showed that very small spotty areas were widely spread. The SEM image showed that it had some projections on the surface, the size of which was from sub-μm to a few μm as shown in Fig. 3e. The result was caused by grain boundary diffusion of Au–Ta grain reported by Christou and Day [25]. They also showed that reaction layer of Au–Ta was formed over 350 °C. The depth profile of atomic composition on the multilayer after the high temperature aging showed that each element existed individually as shown in Fig. 4e.
respectively. Closed circles, squares, and diamonds show Ti/Au, Ti/Pt/Au, and Ta/Au, respectively.

Judging from AES analysis, metallization multilayers except for Ti/Au were nominated for high temperature durability. However, the surface was slightly changed on Ti/Ru/Au, W/Au and Ta/Au.

3.2. Bond strength characteristics using the Au paste

Firstly, the initial bond strength corresponding to the bonding pressure was evaluated using Ti/Pt/Au system. The bonding temperature was set to be 350 °C since the temperature at the full bonding would be higher than that on the high temperature aging test (300 °C). There were no significant changes of bond strength against the bonding pressure as shown in Fig. 5. Error bars show the maximum and the minimum bond strength at each condition (N = 10). Sufficient bond strength was obtained even at lower bonding pressure of 1 MPa. Main fracture mode was inner fracture on the Au paste layer at the bonding pressure of 1 MPa, and changed to substrate fracture over 5 MPa. These results showed that at least 5 MPa was needed for acceptable bonding at the full bonding process. On the high temperature aging test, we prepared the samples with the bonding temperature of 350 °C and the bonding pressure of 5 MPa.

We applied Ti/Au, Ta/Au and Ti/Pt/Au for the high temperature aging test of bonded sample. Ti/Au was used as a reference. Ta/Au and Ti/Pt/Au were used as representatives of double and triple layer on the back side metallization, respectively. Qualitative analysis on cross section of bonded area was observed using Electron Probe Micro Analyzer (EPMA, JXA-8500F, JEOL Ltd.) after the cross section was prepared by using a cross section polisher (SM-9010, JEOL Ltd.)

Fig. 6 shows the cross section SEM (composition) image of bonded sample before and after the high temperature aging. The SEM image of the Ti/Pt/Au sample at the initial state was shown in Fig. 6a, which shows that fusion bonding occurred on each Au particles and very small voids spread. The same morphology was observed at the initial state of the Ti/Au sample and the Ta/Au sample. After the high temperature aging test, unified structure including the Au past layer and the metallization layer was observed on the Ti/Pt/Au sample as shown in Fig. 6b. There were no voids on the boundary between the Au paste layer and metallization layer. Gaps were observed on the boundary with the Ti/Au sample as shown in Fig. 6c. In addition, Ti/Au layer was tattered. Fig. 7 shows the qualitative mapping of elements on Fig. 6c by EPMA. The gaps of the boundary represented the voids or residual carbon corresponding to the component in the Au paste. The element mapping suggested that Ti diffused to Si layer and Si diffused to Au layer. The voids between the Au paste layer and the metallization layer were observed after 500 h, and they grew up after 1000 h on Ta/Au sample as shown in Fig. 6d. Analyzing from EPMA, Ta diffused to Si layer and Si diffused to Ta layer. (data not shown) This characteristic was caused by metallic diffusion as same as the Ti/Au sample. In addition, there were a few pinholes on Ta/Au layer. Remarkable voids were caused by metallic diffusion which affected adheriveness and affinity between the multilayer and the Au paste layer. In contrast, the Au particles fused and unified on the high temperature aging test. As the results, small voids on the initial state as shown in Fig. 6a might be concentrated at the boundary between Au paste and the chip or the substrate. These results showed that Ti/Pt/Au metallization was superior to Ti/Au and Ta/Au metallization on using the Au paste for die bonding material. Time dependence of the bonding layer thickness was measured by using SEM. As the result, the changes were negligible with the thickness of 2.75 μm. Such a thin bonding layer must be cost effective with high reliability on the high temperature despite using Au.

Bond strength corresponding to metallization multilayer at 300 °C with the holding time was plotted in Fig. 8. Bond strength decreased drastically after 300 h on the Ti/Au sample. Main fracture mode at 300 °C after 300 h was boundary fracture around the metallization and the Au paste layer. This result was caused by the gaps on the boundary of the Au paste layer and the metallization layer as described above. Bond strengths decreased gradually with the holding time on the Ta/Au sample. Bond strengths at 300 °C after 1000 h were about half corresponding to the values at the initial state. Main fracture modes after 500 h and 1000 h were boundary fracture around the metallization and the Au paste layer. This result was caused by the gaps as discussed above. On the other hands, stable bond strengths were obtained on the Ti/Pt/Au sample. The bond strengths after 1000 h had over 40 MPa, which was about 10 MPa higher than that at the initial state. Main fracture mode over 300 h was chip or substrate fracture. This result was attributable to the unified structure. The gap between the paste and the multilayer, and large voids were unacceptable for die bonding in the terms of thermal and electrical conduction. Since there were no gaps and voids on the Ti/Pt/Au sample, Ti/Pt/Au was passed the requirement for metallization multilayer on Au paste as die bonding material.

4. Conclusion

We examined metallization multilayer for the back side of the power device with high temperature durability. Some metals with high melting point were selected for a barrier metal, and Au was chosen as a top surface. Because of the diffusion between Ti and Au, Ti was detected as top surface on Ti/Au multilayer and Ti–Au alloy existed. Each element existed individually on Ti/Pt/Au, Ti/Ru/Au, W/Au, and Ta/Au after the high temperature aging. Bond strength on using Au paste for die bonding material was evaluated after the high temperature aging when Ti/Au, Ta/Au and Ti/Pt/Au were used as the metallization multilayer. Ti/Pt/Au had acceptable performance over 40 MPa with unified structure after exposing at 300 °C for 1000 h.

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References