SILICON CARBIDE DIE ATTACH SCHEME FOR 500^{o}C OPERATION

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Abstract

Single crystal silicon carbide (SiC) has such excellent physical, chemical, and electronic properties that SiC based semiconductor electronics can operate at temperatures in excess of 600^{o}C well beyond the high temperature limit for Si based semiconductor devices. SiC semiconductor devices have been demonstrated to be operable at temperatures as high as 600^{o}C, but only in a probe-station environment partially because suitable packaging technology for high temperature (500^{o}C and beyond) devices is still in development. One of the core technologies necessary for high temperature electronic packaging is semiconductor die-attach with low and stable electrical resistance. This paper discusses a low resistance die-attach method and the results of testing carried out at both room temperature and 500^{o}C in air. A 1 mm^2 SiC Schottky diode die was attached to aluminum nitride (AlN) and 96% pure alumina ceramic substrates using precious metal based thick-film material. The attached test die using this scheme survived both electronically and mechanically performance and stability tests at 500^{o}C in oxidizing environment of air for 550 hours. The upper limit of electrical resistance of the die-attach interface estimated by forward I-V curves of an attached diode before and during heat treatment indicated stable and low attach-resistance at both room-temperature and 500^{o}C over the entire 550 hours test period. The future durability tests are also discussed.

INTRODUCTION

High temperature electronics and sensors are needed in harsh environment space and aeronautical applications such as inner solar system exploration or aeronautic engine *in situ* monitoring and local intelligent control (with electronics/sensors located in an aeronautic engine environment). Single crystal silicon carbide (SiC) possesses such excellent physical and electronic properties (wide energy band gap and low intrinsic carrier concentrations) that SiC based semiconductor electronics can operate at temperatures in excess of 600^{o}C, well beyond the high temperature operation limit for silicon-based semiconductor devices. Various SiC semiconductor devices have been demonstrated to be operable at temperatures as high as 600^{o}C [1, 2], but only in a probe-station test environment partially because packaging technology for high temperature (500 ^{o}C and beyond) devices is still in development. One of the core technologies needed for successful high temperature electronic packaging to meet these needs is electrically conductive die-attach technology.

Precious metal (such as gold) thick-film metallization (of ceramic substrates) has been used in traditional electronics hybrid-packaging. Recently, gold (Au) based thick film materials, which are normally processed at high temperatures (850^{o}C), was proposed for hybrid packaging to achieve 500^{o}C operation [3]. Since then, electrical interconnection elements based on Au thick film material for high temperature chip level packaging have been electrically tested at high temperature [4]. This paper reports results of testing, at both room and elevated temperatures, of a thick- and thin-film based low resistance die-attach scheme for SiC sensors and electronics operable up to 500°C.

SAMPLE FABRICATION

Thick Film Material

Thick film metallization materials are usually composed of (1) metal (such as gold) micro powder, (2) inorganic binder (such as metal oxides), and (3) organic vehicle (carrier) [5]. Screen printing techniques are usually employed for patterned thick-film coatings on ceramic substrates to provide suitable thickness and uniformity control. During the initial drying process (at ~150°C) following the printing, most of organic vehicle evaporates and the paste turns into a semi-solid-phase mixture of metal powders and inorganic binder. During the following curing process (~ 850°C recommended for best adhesion on alumina substrates) a solid metal thick film forms through molecular/atomic diffusion at micro-powder boundaries while the inorganic binder molecules migrate to the metal/ceramic (e.g. Au/AlN) interface forming reactive binding chains at the interface. Au thin wires can be bonded directly onto Au thick film metallization pads (surface) to provide for electrical interconnection in packaging. Some new thick film materials (e.g. DuPont5771) may apply to various ceramic substrates such as alumina and aluminum nitride (AlN)[5] (AlN is desirable for its high thermal conductivity and coefficient of thermal expansion that nearly matches SiC). The main application of thick film materials is hybrid-packaging of traditional electronic circuits (operable at T < 150°C) for high frequency, high performance, and high reliability operation. In this work Au based thick-film material is used as a conductive die-attach bonding material for thin film processed SiC devices.

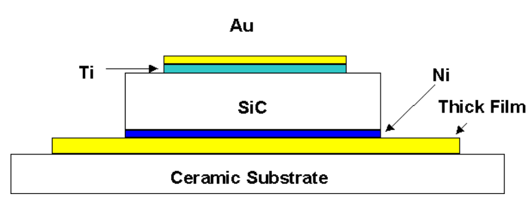

Figure 1: Schematic diagram of as-fabricated SiC device and die-attach structure.

Device Fabrication and Die-attach

N-type (nitrogen, ~ $10^{18}/cm^3$) Si terminated 4H-SiC wafer was used for test device fabrication. The wafer (unpolished side) backside was first coated with nickel (Ni) thin film (~ 6000 Å) by electron beam evaporation. The SiC wafer was then annealed at 950°C in argon tube furnace for 5 minutes forming an ohmic contact on the backside of SiC wafer. Following the annealing, a second layer (3000 Å) of Ni was electron beam evaporated onto the wafer backside. The device structure on the front side of SiC wafer was fabricated by electron-beam evaporation of thin (100 Å) titanium (Ti) and Au thin (4000 Å) films on cleaned SiC wafer patterned by liftoff. The Ti interlayer was used to improve interfacial adhesion of metal thin film on the polished front side of SiC and also to reduce the forward dynamic resistance of the device. After dicing, the 1 mm x 1 mm diode chips were then attached to the ceramic substrate (either AlN or alumina) using DuPont 5771 Au thick-film material. This thin and thick film process for SiC device results in a low resistance die-attach structure which is required for packaging many devices, especially, power devices with vertical topologies.

The optimum process for attaching SiC dies (with Ni contact) to the ceramic substrate was investigated. The Au thick-film uniformity issue was addressed first. As mentioned in last section, the organic vehicle of "raw" thick film materials evaporates during the initial drying process. Since the thick film material is sandwiched by the ceramic substrate and the SiC die, the escaping organic vehicle molecules have a relatively long way to migrate to escape from the sides. During rapid drying this may somewhat distort the thick film distribution, therefore, causes non-uniform thick film distribution between the die and the substrate. A slower drying process (120^{o}C – 150^{o}C) was critical to keep the thick-film bonding layer uniform and the die parallel to the substrate after the curing process. It was also necessary to consider reducing the amount of organic vehicle evaporated during die-attach processing. A two step process was used. A thick film layer was first screen-printed on the substrate and cured at 850^{o}C. The SiC die was then attached to the cured thick film pattern with a minimal amount of subsequent thick film.

The second parameter needed be optimized was the final curing temperature. A lower final curing temperature (with respect to standard curing temperature of 850^{o}C) was desired in order to minimize the curing effects on the interfacial properties of Au/Ti/SiC device. To determine an optimized final curing temperature for the die-attach processes, micro-structure and surface composition of the thick film cured at various temperatures was investigated. As shown in Figure 2a, the surface of thick film cured at

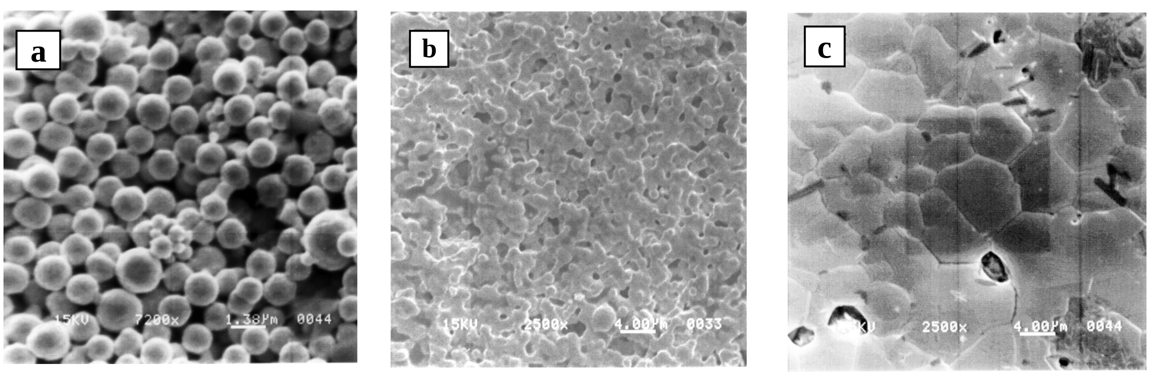

Figure 2, Scanning Electron Microscope (SEM) micrograph of thick film surfaces cured at 500^{o}C (a) for 25 min, 600^{o}C (b) for 20 min, and 850^{o}C (c) for 15 min. (a) Micro powder structure indicating insufficient boundary diffusion. (b) Chain structure replaces powder structure indicating a critical curing condition. (c) Large grain structure and smooth surface indicating solid thick-film formation.

500^{o}C showed very sharp micro powder structures indicating that there was insufficient diffusion to form a solid film at this temperature. The thick film surface cured at 850^{o}C (Figure 2c) showed large grain sizes and a relatively smooth surface indicating thick film formation. The thick film surface cured at 600^{o}C (Figure 2b) showed that powder structure has been replaced by net and chain structures indicating a critical curing condition necessary for formation of coherent thick film. Based on this result, 600^{o}C was selected as the preferred final die-attach processing temperature. Auger Electron Spectroscopy was used to characterize the surface compositions of the thick film surfaces cured at 500, 600, and 850°C. In addition to expected normal levels of carbon and oxygen surface contamination, copper and lead (oxides as binders) were found on the surfaces of all three samples. Silver was also detected on the surfaces. Compared to the sample surfaces cured at 500 and 600°C, binder concentrations on the sample surface cured at 850°C were relatively lower indicating high curing temperature is preferred for binder molecules migration to the interface with ceramic substrate. So the first layer of thick film screen-printed on the substrate was cured at 850°C for best adhesion. Since the thick film material used as die-attach binding material "sees" metals on both sides (Au thick-film on the substrate and the Ni thin film on the backside of the SiC die) it seems less likely that the binders should significantly segregate to the interfaces.

Thick film material was also used to reinforce the top Au thin film for better wire bonding. The Au thin-film metallization area was coated with thick film on the top then dried at 150°C for 10 minutes. The thick film on the device top was cured during the final die-attach process (at 600°C). Au 0.001" diameter wire was bonded on the top Au thin-film metallization pad with a thick-film overlayer by thermal-press bonding technique.

TEST AND RESULTS

The attached SiC Schottky diode (Figure 1) was periodically characterized by current - voltage (I-V) measurements at both room and elevated temperature for a total of 550 hours. A minimum dynamic resistance (dV/dI) in a high current (forward bias) region of the I-V curve was used to estimate the upper limit of resistance of the die-attach structure (both interfaces and materials), as shown in Figure 3. This dynamic resistance, dV/dI, includes forward dynamic resistance of Au/Ti/SiC interface, SiC wafer bulk

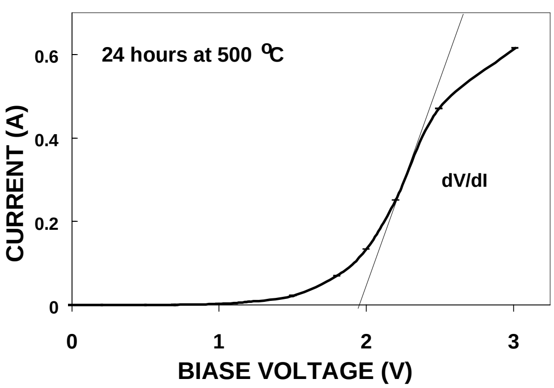

Figure 3: The device raw I-V curve measured at 500 °C after 24 hours heating at 500°C in air. The definition of minimum dynamic resistance, dV/dI, is illustrated as 1/slope of the I-V curve. The reverse current (not shown) was low compared to forward current. The I-V shows a typical diode behavior.

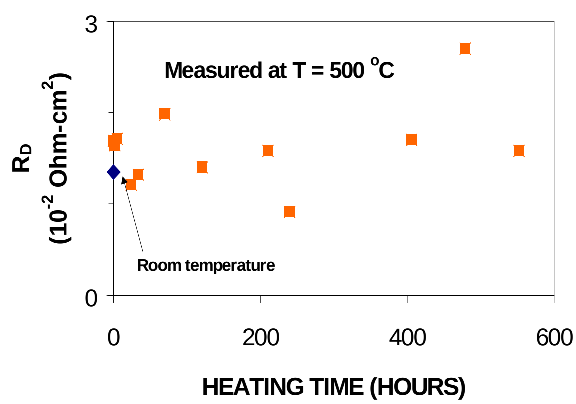

Figure 4: Minimum dynamic resistance calculated from I-V data vs. heating time at 500°C. This resistance includes resistances contributed from the Au(Ti)/SiC rectifying interface, SiC wafer, the die-attach materials and interfaces. Resistances of the bonded wire and the test leads have been subtracted.

resistance, the die-attach materials/interfaces resistance, bonded wire resistance, and the test leads resistance in series. The resistance contributed from test leads and bonded wire can be measured (~ 0.4Ω at 500°C) independently and subtracted. The attached device was first characterized with I-V measurements at room temperature. The device exhibited rectifying behavior and the lowest dynamic resistance after subtracting test-leads/bond-wire resistance, R_D (as was done for all dynamic resistance in the following discussion), measured under forward bias was ~ 1.35 Ω, as shown in Figure 4. The temperature was then ramped up to 500°C (in air) and the diode was *in situ* characterized periodically by I-V measurement for 70 hours. The lowest dynamic resistance under forward bias was less then 2 Ω. The diode was then cooled down to room temperature and characterized again. The lowest forward dynamic resistance measured was 0.79 Ω (not shown). The diode was heated up to 500°C in air and characterized periodically for a total of 550 hours. The minimum dynamic resistance (under forward bias) was 1.4 - 2.7 Ω. It is worth noting that the device's I-V curve changed somewhat with time during heat treatment at 500°C. However, the dynamic resistance of attached diode remained comparatively low over the entire test duration and temperature range indicating a low and relatively stable die-attach resistance (it depends on if the forward resistance of the Au/Ti/SiC interface is dominant).

The preliminary results of mechanical shear strength, which was measured at room temperature, of the dies attached using the process discussed above were satisfactory (> 6lbs). Detailed mechanical test results will be published later after more systematic study.

DISCUSSION AND SUMMARY

Au thick film (DuPont 5771) and (Ni) thin film based SiC die-attach scheme was developed and electrically tested at elevated temperatures for application in high temperature chip level packaging. An Au/Ti/SiC device with a backside Ni thin-film metallization was successfully attached to a ceramic substrate, using thick-film as conductive bonding layer, with low attach resistance (10^{-2} Ω-cm^2) and demonstrated successful operation at 500 °C in oxygen-containing ambient for 550 hours.

The detailed thermal, chemical, and metallurgical behavior of Au/Ni/4H-SiC system at high temperature oxygen ambient is largely unknown, therefore, it is difficult, without further investigation, to predict a longer-term (10^3 - 10^4 hours) high temperature electronic performance of this die-attach scheme. However, it is very likely that Au and Ni form an alloy at Au/Ni interface. The oxidation behavior of the AuNi alloy at 500 - 600°C and the electrical properties of AuNi/Ni_XSi_Y/SiC system after sufficient heating (Ni forms silicides on SiC surface at high temperature) require further investigation. If it is the case that a Ni rich alloy forms at the Au/Ni interface during initial heating, it might be possible that part of the Ni oxidizes over longer term exposure to high temperature and oxygen. If so it might be helpful to introduce a multi-layer thin film metallization system with a diffusion barrier layer (silicide, carbide, or nitride [6]) to improve the resistance to oxygen at high temperature.

The room temperature mechanical properties of thick film metallization on various substrates, Au wire-bond on Au thick-film, and SiC semiconductor die-attach (without thin film metallization) using thick-film materials have been evaluated previously [3, 5]. However, equivalent mechanical tests at elevated temperatures remain to be carried out in future work in order to more completely validate thick film material application for high temperature electronic packaging.

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