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SiC DIE-SUBSTRATE CONNECTIONS FOR HIGH TEMPERATURE APPLICATIONS*

Zbigniew Szczepański[1], Ryszard Kisiel[1]

Silicon carbide (SiC) became very attractive material for high temperature and high power electronics applications due to its physical properties, which are not attainable in conventional Si semiconductor. However, the reliability of SiC devices is limited by assembly processes comprising die attachment and interconnections technology as well as the stability of ohmic contacts at high temperatures.

The investigations of a die to substrate connection methods which can fulfill high temperature and high power requirements are the main focuses of the paper. In our researches following die attach technologies were applied: adhesive bonding with the use of organic and inorganic conductive compositions, solder bonding by means of gold germanium alloys, die bonding with the use of thermal conductive adhesive foil and joining technology based on low temperature sintering of silver nanoparticles. The applied bonding technologies are described and obtained results are presented.

Keywords: SiC, die bonding

1. INTRODUCTION

Silicon carbide (SiC) has gained increasing importance due to its advantages which created new possibilities for this semiconductor material in particular for high temperature and high power applications. Silicon carbide during the last years became the most developed and promising semiconductor material. Many publications

[1] Institute of Microelectronics and Optoelectronics Warsaw University of Technology, Koszykowa 75, 00-662 Warszawa, Poland, e-mail address: kisiel@imio.pw.edu.pl

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which appeared in world literature indicate that this material is the most suitable for high temperature electronics [1-5].

The reliability of SiC devices is limited by applied materials and assembly processes comprising die attachment and interconnection technologies [6-8]. as well as by the stability of ohmic contacts [9-10]. So, packaging technology plays main role in high power and high temperature devices. One of the main processes of packaging technology is die attachment process. Die bonding ought to assure mechanically reliable connection to the substrate and high thermal conductivity to effectively transfer the heat from power chip to the package. Low thermal resistance of bonding material ensure high operating temperature. Other properties like suitable coefficient of thermal expansion (CTE) of die, bonding materials and substrate is also important. Matching CTE of the die and substrate permit to avoid the stresses in the connection.

Only a few of the known bonding technologies can fulfill the demands of high power applications. Eutectic AuSi die binding, very popular in silicon technology, cannot be used for SiC die due to strong atomic bond in hexagonal crystallographic SiC lattice. Anodic bonding and silicon direct bonding are widely used in silicon sensor technology [11], but for SiC power devices they have not practical application. Sn-Pb very common solder alloys, due to low melting temperature are not interesting solution for high temperature applications. Tab. 1 presents some properties of die attach materials studied in literature [10].

Hard solder alloys based on gold are interesting approach for SiC devices assembly [12-13], since they have melting temperature above 250°C. Good candidates for high temperature applications are eutectic alloys Au-Sn (Te = 280°C) and Au-Ge (356°C). These solders are characterized by good wettability to the substrate metallization, high thermal conductivity and very good solder joint strength.

Table 1. Major properties of selected die attach materials.
Tabela 1. Podstawowe właściwości materiałów łączeniowych.

Material	T_m [°C]	T_{max} [°C]	λ [W/mK]	CTE [10^{-6}/°C]	G [GPa]
Au88Ge12	356	320	52	12	
Au80Sn20	280	250	58	16	68
P-1011*	-	350	1.29	37	-
H20E-HC*	-	300	3.5	26	
H20E-HC*	-	200	9.96	53	
QMI-3555R[a]	~400	300	80	16	11.5
FO-3, FO-13[b]	450	300	~60	25	
Tape 3M**	-	250	-	-	0.1
Ag nano[c]	-	500	240	19	9

[*]- adhesives made by Epoxy Technology,
[a]- silver filled glass made by Loctite,
[b]- silver filled glass made by ITME, Poland,
[**]- thermally conductive tape made by 3M,
[c]- Ag nanopowder made by AMEPOX Ltd, Poland.

Adhesive bonding with the use of organic conductive compositions is very common assembly process used in low power silicon devices, but for SiC power devices has limited application. Some of these compositions based on polyimide matrix (e.g. P-1011 Epoxy Technology) characterize high thermal resistance, what allows for working temperature even above 300ºC [14], but its insufficient thermal conductivity limits its application in SiC power devices. Better solutions are inorganic conductive compositions based on silver filled glass (e.g. FO-3, FO-23) which are good alternative for high temperature applications [15-16]. These compositions have satisfactory adhesion and provide high thermal and electrical conductivity, what is main demand for power electronics. The last option for SiC die attach are silver nanoparticles sintered in low temperature, which allow to obtain high temperature joint resistance with the good thermal conductivity. This die attach process has developed during the last years [17-18] and is still in research phase [19-20]. This bonding technique can be used for high temperature SiC devices, where the operating temperature may be above 500ºC and where none of the known solders and conductive adhesives can work. Some of above mentioned die attach processes have been taken into account and applied in our researches. The adhesion of SiC die to ceramic substrate bonded by different technologies as well as their stability in temperatures above 300°C applications were measured and analyzed.

2. EXPERIMENTAL PROCEDURE

Our studies were focused on the following die attach technologies:
1. solder bonding by means of gold-germanium eutectic alloys,
2. adhesive bonding with the use of organic conductive compositions,
3. adhesive bonding with the use of inorganic conductive compositions,
4. die bonding with the use of thermal conductive adhesive tape,
5. die bonding with the use of silver nanoparticles.

The scheme of test sample for adhesion measurements is presented in Fig. 1. The SiC die bottom surface as well the surface of thick film on alumina substrate were prepared for joining. For adhesive bonding with the use of organic or inorganic conductive bonding, the SiC die was cleaned in organic solvents (trichloroethylene, acetone and propanol). For bonding with the use of Au-Ge solder and Ag nanoparticles after cleaning, on the SiC bottom surface the adhesive layers of Ni (100 nm) and Au (400 nm) were deposited by evaporation. The ceramic substrates were cleaned in acetone before use. Two types of thick film pastes onto alumina substrates were applied : P-205 (Ag-Pd-Pt paste produced by ITME) and P-301 (Au paste produced by ITME).

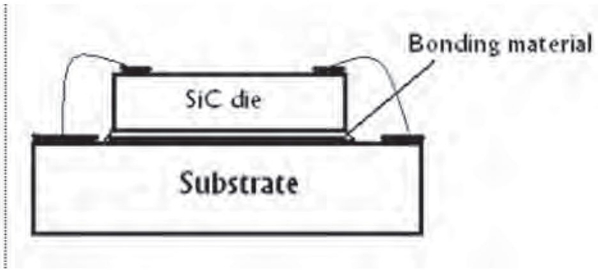

Fig.1. The scheme of investigated test sample.
Rys. 1. Schemat struktury testowej.

3. EXPERIMENTS AND RESULTS

The condition for performing the experiments and results of adhesion measurements at room temperature are presented in Tab. 2.

Table 2. The results of adhesion measurements for investigated bonding technologies.
Tabela 2. Wyniki badań adhezji dla badanych materiałów i technik łączeniowych.

Die bonding technology	Process temp. [°C]	Max operating temp. [°C]	Shear strength [N/cm²]
Au88Ge12	400	330	N/A
P-1011	150	350	150
FO-3, FO-23	560	350	>200
3M 9890	25	260	30
Ag nano	300	400	160

Among bonding materials for SiC die, hard solder of eutectic gold-germanium alloy with melting temperature of 356°C was applied in our research. Gold-germanium performs with the thickness of 50 μm was placed between SiC die and substrate with Au thick film. To accomplish this process gold metallization on SiC die was deposited too. The joint was formed during soldering in temperature 400°C. The mechanical and physical properties of such formed solder connections will be taken into account in the next step of our researches.

As an example of adhesive bonding EPOTEK P-1011 has been chosen. This adhesive is characterized by high adhesion (shear strength 150 N/cm^2) and high temperature resistance. The SiC dies with two types of top metallization were used: Al and Au. For SiC die with Al top metallization adhesive die connections after long term ageing at 300°C for 200 hours kept good mechanical strength. Unfortunately, during the ageing process (at 400°C) SiC dies with Au top metallization, silver electromigration was observed after 100 hours of heating. Ag migrate from the bottom of die to the top SiC die surface with Au. So, applying adhesives with Ag for SiC with Au top metallization is not proper solution.

The next assembly technology which was applied in our researches for SiC die connection is adhesive bonding with the use of inorganic composition, based on silver filled glass. Due to its high thermal conductivity (above 60 W/m K) and high operation temperature, this composition can fulfill demands for high temperature and high power applications. The composition was stencil printed on thick film gold on alumina substrate (stencil thickness 70 μm) and fired in belt furnace with 40 min. total firing cycle and 20 min firing at peak temperature of 500°C. Some cracks on the edges of SiC structure was observed. Firing time was changing to reduce cracking at edges. By changing firing parameters no significant reduction of cracking was observed. After 24-48 hours of ageing above 300°C, adhesion drastically decreased and SiC die fall down form the substrate. The degradation occurs between SiC surface and the inorganic composition. To improve the adhesion between SiC surface and inorganic composition the plasma oxidation of SiC surface was applied in the next series of experiments. Such prepared samples were characterized by good adhesion.

Very easy joining method with the use of the thermally conductive adhesive transfer tape allows to realize die bonding at room temperature. As adhesive transfer tape ceramic filled acrylic with the thickness of 100 μm and 250 μm was applied. Such thermally conductive tape offers the combination of thermal conductivity, electrical insulation, sufficient adhesion and ease of assembly.

The last assembly approach applied in our researches uses silver nanoparticles. In the researches silver powder with particles diameter of 20÷30 nm was used, together with organic additive which prevents the silver particles sintering at room temperature. Such silver composition was deposited on ceramic substrate pad metallization, consisted of thick film gold and silver evaporated layer. Next SiC die with Ti-Ag metallization was placed onto substrate bonding pads. Pressure sintering of silver nanoparticles at temperature above 250°C was applied. During sintering heated work holder and heated electrode with external pressure (30 N/cm^2) was applied which enhances the sintering process, due increasing of the surface contacts between silver particles. Sintering process was carried out for 40 min. Bonds with good mechanical connection, and probably good high thermal conductivity was obtained. Silver layer increases adhesion between the die and substrate pads. The stability of

Ag nanoparticle sintering was investigated in non destructive test during ageing at 300°C. Every 24 hours, after conditioning at room temperature, the shearing stress 100 N/cm^2 was applied to SiC die. During the fourth measure (after 100 h firing) the SiC die was sheared by stress 16 N/cm^2. The observation of shear surface permit to indicate the presence of Ag oxide on almost whole shear surface.

4. CONCLUSIONS

On the ground of survey on various approachable die attach technologies a few of them which accomplish high temperature demands were chosen and tested.

Taking into account obtained researches results, the best solution for high power and high temperature electronics are two die attach technologies: silver glass die attachment and die bonding with the use of low sintered silver nanoparticles. Silver glass die attach is good alternative for SiC die bonding, where high temperature and high power occur. Silver powder with particles diameter of 20÷30 μm were applied with success in the researches. Mechanical strength and thermal conductivity of SiC die connection is very good and thermal ageing at 350°C during 100 hours not degrades of die connection.

Die bonding with the use of organic conductive compositions based on poliimide matrix can be apply even up to 350°C but not for power devices due to low thermal conductivity of organic adhesives.

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TECHNIKI MONTAŻU STRUKTUR SiC DO PODŁOŻA DLA ZASTOSOWAŃ WYSOKOTEMPERATUROWYCH

Z pośród półprzewodników szerokopasmowych węglik krzemu (SiC) stał się najbardziej obiecującym materiałem dla przyrządów mocy pracujących w wysokich temperaturach. Jest on obiektem szczególnego zastosowania wszędzie tam, gdzie wymaganiom wysokotemperaturowym nie może sprostać Si. Niezawodność przyrządów z SiC w wysokich temperaturach jest ograniczona przez procesy montażu obejmujące montaż struktur do podłoża , wykonywanie połączeń elektrycznych oraz przez brak stabilności wysokotemperaturowej kontaktów omowych.

Główna uwaga w tym artykule została zwrócona na problemy związane z montażem nieobudowanych struktur SiC do podłoża. Dokonano przeglądu różnych technologii montażu struktur SiC do podłoża z ceramiki alundowej, które mogą spełniać wymagania pracy w wysokich temperaturach. W badaniach wykorzystano następujące techniki montażu: klejenie kompozycjami organicznymi lub nieorganicznymi, lutowanie lutami Au-Ge, klejenie przy zastosowaniu adhezyjnej folii ceramicznej oraz spiekanie niskotemperaturowe za pomocą pasty utworzonej z nanocząsteczek srebra. We wnioskach dokonano oceny analizowanych technik montażu w oparciu o wyniki uzyskane w badaniach własnych.

Słowa kluczowe: SiC, montaż struktur