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Development of technology for deposition of thick copper layers onto ceramic substrates applied in power electronics

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Abstract

The basic element of the design of a power module is a metallized ceramic substrate. In this work, the formation of metallization coatings by the method of thermal transfer of metallization pastes (Mo-Mn-Si + binder) for alumina and aluminum nitride ceramics was carried out. The fixing of the metallization coating on the ceramic substrate was performed by firing at a temperature of 1320 °C. The subsequent deposition of the copper layer was carried out by the method of cold gas-dynamic spraying (CGDS) followed by annealing of the deposited coating. For high-quality adhesion, the optimum annealing temperature was 1000 °C.

Keywords

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Key findings

- The technology of a two-layer metallization coating on ceramic substrates made of aluminum nitride and oxide was developed.
- The resulting copper coatings are characterized by a strong adhesive bond with the base and low electrical resistance (at the level of $3\cdot10^{-6}$ Ohm·cm).
- For high-quality adhesion, the optimum annealing temperature was 1000 °C.

1. Introduction

Cold gas dynamic spraying (CGDS) is a relatively new modification of cold spraying techniques that uses converging-diverging (De Laval) nozzle at a supersonic velocity to accelerate different solid powders towards a substrate on which they are plastically deformed. This deformation results in adhesion to the surface. CGDS is one of the innovative cold spraying processes with fast-growing scientific interests and industrial applications in the fields of aerospace, automotive and biotechnology. Cold spray research and development efforts have doubled during the last decade and along with new industry applications and novel demands provide both a strong body of knowledge and market pull to identify and address these roadblocks. [1, 2]. Due to the high strain rate deformation of particles in (CGDS), in situ investigation is challenging. Metallurgical bonding is one of the main adhesion mechanisms of particles during coating buildup [3]. The properties of the kinetically deposited coating layer are significantly affected by the microstructure of the coating. The most powerful influencing factors in microstructural evolution of kinetic-sprayed coating layers are instant generation of thermal energy and high-strain, high-strain-rate plastic deformation at the moment of particle impact [4]. Heat treatment of the 316 L austenitic steel coating improves its mechanical properties [5]. In [6] the microstructure of the coating obtained by cold gas-dynamic spraying was investigated. A $Cu\text{-}Al_2O_3\text{-}Zn$ powder blend was sprayed onto a copper substrate to restore a worn copper contact wire. The coating thickness was 1–2.5 mm. Improved adhesion strength was achieved through substrate surface preprocessing with coarse Al_2O_3 particles.

To obtain the pattern of an electronic power module, ceramic substrates should be metallized. Therefore, conducting layers, over 300 μm thick, are deposited by different techniques to form multilevel metallization [7]. While in production and operation, the metallized structures of power modules are exposed to thermal and mechanical stresses.

The research objective is to optimize the technique of thick copper layers deposition onto ceramic substrates used in power electronics.

We considered the use of finely-dispersed PMVD-0, PMVD-1 and coarse PMC-1 copper powders for their sputtering by gas dynamic cold spray technique (GDCS).

After preliminary experimental studies of gas dynamic cold spray technique (GDCS), we made a choice of PMC-1 copper powder (GOST 4960-2009) as the most appropriate, affordable and cheap.

The basic element of the power module structure is considered to be a metallized ceramic substrate with the power semiconductor crystal, which is used for implementing two main functions: firstly, for electrical isolation of conductor buses patterned on one or both sides; secondly, for the conductance of heat emitted by the active elements of the electronic power module to heat radiators. Besides their high heat conductivity, the substrates of power modules must be very strong, heat- and chemically resistant. In this regard, we use the substrates made from different grades of aluminum oxide ceramics and aluminum nitride ceramics providing high dissipation capacity. Based on the properties analysis carried out for ceramic materials applied by DBC technology abroad [8, 9], we come to the conclusion that aluminum oxide ceramics with the content of aluminum oxide exceeding 95% is more frequently used, but aluminum-nitride ceramics with the content of nitride oxide, which is more than 98%, is suitable for the circuits with high specific dissipation capacity. Taking into account their main characteristics, aluminum-oxide ceramic substrates for DBC boards made by CETC (China) are comparable with BK96 substrates produced by JSC NEVZ-Ceramics (Russia). However, their characteristics are inferior to the ones of BK100 ceramics produced by JSC NEVZ-Ceramics (Russia), where the content of the basic substance is equal to 99.7% (in contrast to VK-96 ceramics with 96% content of the base material).

With regard to their physical properties, aluminum-nitride ceramics (AlN) is characterized by high thermal conductivity (170–200 W/m·K) and electrical resistance stability (10^{13}–10^{14} Ohm·cm) when the temperature is increasing [10–13]. In Russia JSC NEVZ-Ceramics specializes in manufacture of aluminum-nitride ceramic substrates [9]. Produced at this enterprise, aluminum-nitride substrates are characterized by high thermal conductivity of 160–185 W/m·K, isolation and strength parameters at the level of world's brands, such as MARUVA (Japan), LEATEC (Taiwan), ClecGroup (China), CeramTec (Germany).

The substrates are produced by slip casting technique followed by annealing of aluminum-oxide ceramics at 1650 °C and aluminum-nitride ceramics at 1850 °C.

2. Experimental

Metallized coatings (MC) formation was tested by the heat transfer of two metallization pastes compositions for aluminum-oxide and aluminum-nitride ceramics.

Pastes compositions:

A. Mo-Mn-Si+Ta_2O_5+ZrO_2+TiH_2+binder.

B. Mo-Mn-Si+ binder.

The organic binder for the metallization pastes contains: ethylcellulose-100, α-terpineol, dibutylphthalate and oleic acid.

Surface preparation is considered to be one of the main stages of metallized coating formation on ceramics. Ceramic substrates had been mechanically polished before metallization to obtain alignment and surface roughness of R_a = 0.15 μm.

MC bonding on the ceramic substrates was achieved via its annealing. In this regard, nitrogen-hydrogen through- and pusher-type furnaces were used. The furnaces consist of 5 mullite muffles, which are 90 cm long. The muffles are located in series to provide a continuous channel with 3 temperature ranges. Annealing was carried out with 30 minutes exposure at 1320 °C.

The GDCS technique is based on acceleration of 1–150 μm particles with a supersonic gas flow up to the speed of 500–1200 m/s. The particles colliding with an obstacle tend to bond on it without melting [14, 15]. Meanwhile, the substrates are not strongly affected by temperatures.

Sputtering was carried out on VK-96 aluminum oxide substrates with the dimensions of 30×29×0.3 mm, and with a Mo-Mn-Si sublayer being 10–20 μm thick. PMC-1 copper powder was used for sputtering.

Formation of metallized coatings from copper powders was carried out according to typical GDCS diagrams with the use of a planar contracting-expanding nozzle with 3.05×3.05 mm critical cross section and 9.5×3.05 mm exit geometry. The rate of powder consumption from a dispenser was set to 0.1 g/s. The distance of sputtering was equal to 30 mm; the nozzle scanning velocity against the substrate varied from 5 to 50 mm/sec. Air was chosen as a carrier and working gas. The deposition was conducted on the GDCS ITAM SB RAS test installation. The substrates were split into two batches after sputtering. Then annealing was carried out in the hydrogen medium at different temperatures to determine the optimal thermal mode.

3. Results and discussion

Since the products obtained are operated in air, the resistance of the coatings in aggressive media (acids or base solutions) was not determined. It is also known that semiconductor devices with these products are operated at low temperatures (not exceeding 125 °C). For this reason, the thermal stability of coatings was not studied. The most important performance characteristics of coatings are adhesion resistance and low electrical resistivity.

The key parameters were determined after annealing as follows: the measured values of adhesion and intrinsic resistance were compared with the same parameters for DBC-substrates produced in Germany and China (Table 1). 1000 °C appeared to be the optimum annealing temperature for adhesion. The best results are peculiar to DBC-substrates with the lowest resistance, which is close to the resistance of pure copper. The substrates with thick copper layers sputtered by the GDCS technique are characterized by the key parameters close to the values of DBC-substrates, despite the use of copper powder to obtain the copper coatings.

Table 1 Measurement results of adhesion and intrinsic resistance.

No.	Sample	Adhesion MPa	Average value of intrinsic resistance $\rho \cdot 10^6$, Ohm·cm
1	GDCS, Al_2O_3 + MoMnSi + Cu, 850 °C	63.7	2.95
2	GDCS, Al_2O_3 + MoMnSi + Cu, 850 °C	51.7	3.05
3	GDCS, Al_2O_3 + MoMnSi + Cu, 950 °C	65.3	3.18
4	GDCS, Al_2O_3 + MoMnSi + Cu, 1000 °C	66.2	3.22
5	GDCS, Al_2O_3 + MoMnSi + Cu, 1000 °C	67.2	3.30
6	GDCS, AlN + MoMnSi + Cu, 850 °C	8.3	2.91
7	GDCS, AlN + MoMnSi + Cu, 850 °C	6.3	2.81
8	GDCS, AlN + MoMnSi + Cu, 950 °C	20.2	2.92
9	GDCS, AlN + MoMnSi + Cu, 1000 °C	31.3	3.07
10	GDCS, AlN + MoMnSi + Cu, 1000 °C	33.0	2.98
11	DBC, Al_2O_3 + Cu, 1065–1080 °C (Germany)	59.0	2.40
12	DBC, Al_2O_3 + Cu, 1065–1080 °C (China)	28.5	2.90

4. Conclusions

The technology of applying a two-layer metallization coating on ceramic substrates made of nitride and aluminum oxide was developed. Initially, a layer of molybdenum-manganese-silicon was deposited on the surface of the substrates by burning in a nitrogen-hydrogen medium for 30 minutes at a temperature of 1320 °C. At the second stage, a layer of copper was deposited by the CGDS method with a flat Laval nozzle. The working gas was air. After deposition, annealing was carried out in hydrogen atmosphere. The optimal annealing temperature was 1000 °C. The obtained coatings are characterized by a stable adhesive bond of the copper coating with the base (the adhesion value exceeds 60 MPa) and low electrical resistance (at the level of $3 \cdot 10^{-6}$ Ohm·cm).

Supplementary materials

No supplementary materials are available.

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Conflict of interest

The authors declare no conflict of interest.

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