Preliminary Die Shear Test of SiC Die with Patterned Pt Metallization Attached to (Au)Pt/HTCC Alumina

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Abstract

Gold (Au) thick-film paste based conductive die-attachment has been previously demonstrated for packaging silicon carbide (SiC) ICs with $TaSi_2$/Pt/Ir/Pt electrical contact metallization for 10,000 hours continuous electrical operation in 500 °C air ambient without observable failure or degradation. In this paper, the die-shear strength was measured on 5 mm x 5 mm SiC die with hexagon-shaped backside multilayer TaSi2/Pt/Ir/Pt metallization patterns terminated with a thin-film Pt layer attached to Pt and Au/Pt metallized high temperature co-fired ceramic alumina (HTCC) substrates. The final attachment firing of the die-attach assemblies was at 600 °C for 3 hours in air ambient. The preliminarily measured average die-shear strength of 5 mm x 5 mm SiC attached to Pt/HTCC substrate was about 13.6 kg (> $6x10^5$g). The die-attach assemblies with Au/Pt/HTCC alumina substrates showed ~ 39% shear strength improvement compared with those with Pt/HTCC alumina substrates. As the first step, the die shear strength per effective unit area validates the room temperature mechanical performance of the Au thick-film paste based die-attach scheme for Au or Pt terminated IC die on (Au)/Pt/HTCC substrates.

These preliminary die shear results enable the co-fired Pt/HTCC packaging process to be consistent with conventional electronic packaging sequence, ie., (Au)Pt/HTCC alumina packages with SiC ICs attached and wire-bonded can now be attached to (Au)Pt/HTCC alumina circuit boards using Au thick-film at 600 °C temperature that both SiC ICs and thermos-sonic bonding wires can withstand. This allows Au/Pt/HTCC packaged SiC ICs to become commodity products for users to test and select for subsequent installation onto multi-chip circuit boards.

Keywords: high temperature, packaging, die attach, die shear, HTCC, Au thick - film.

1. INTRODUCTION

Sensors and electronics capable of operation at 500 °C are required for long term Venus surface missions, as well as for in situ monitoring and control of next generation aeronautical engines [1]. High temperature sensors and electronics can also find many applications in military, and energy and automobile industries [2,3]. A high temperature durable die-attachment scheme is the first step to implement a die-attach and wire-bonding based chip-level packaging to wide band gap semiconductor based high temperature harsh environment microelectronics integrated circuits (ICs). Gold (Au) thick-film paste based conductive die-attachment [4] has been electrically demonstrated with an innovative Pt metallized high temperature co-fired ceramic alumina (Pt/HTCC) packaging system for silicon carbide junction field effect transistors and resistor integrated circuits (SiC JFET-R ICs) for over 10,000 hours continuous electrical operation in 500 °C air ambient without observable failure or degradation [5]. The preliminary die-shear strength was measured on 5 mm x 5 mm SiC die with hexagonal shaped backside multilayer metallization patterns terminated with a thin-film Pt layer attached to Pt and Au/Pt metallized HTCC substrates. The test results mechanically validated the Au thick film paste based die-attach scheme.

These die shear results also provide insight into attaching Au/Pt/HTCC packages to a compatible circuit board at an acceptable temperature to ensure the procedure of co-fired Pt/HTCC packaging process is consistent with the conventional electronic packaging sequence wherein packaged IC chips are mounted onto the circuit board as the second step. Previously, Pt/HTCC packages had to be attached to a circuit board at 850 °C first before the IC die-attachment to the package and wire-bonding. This avoided undesired exposure of the IC die and thin Au bonding wires to the 850 °C temperature. Previous test results revealed that both SiC JFET-R chips and bonding wires can

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withstand 600 °C exposure in air. This paper demonstrates clear initial feasibility of attaching (Au)Pt/HTCC alumina packages with SiC IC die and bonded wires to (Au)Pt/HTCC alumina circuit boards at 600 °C at which both SiC ICs and bonding wires can safely withstand.

2. EXPERIMENTAL

The SiC die measured 5 mm x 5 mm x 350 microns (thick) were partially metallized with a high temperature durable thin-film stacks of $TaSi_2$/Pt/Ir/Pt on the backside. The wafer was annealed at 500 °C for 10 hours in 2% H_2/Ar forming gas, SiC chip fabrication is described in detail elsewhere [6]. Shadow-masked deposition was employed to render chip backside metallization pattern with hexagon-shape as shown in Figure 1, wherein blue is metallization stacks, white is unmetallized SiC. The hexagon apothem of metallization pads is 500 µm, and the apothem of hexagon unit cell is 710 µm. The surface area of a hexagon pad is 0.866 mm^2. The actual area percentage of the metallization patterns to the total surface area of the die is about 50% after dicing. The die were then standard P-cleaned followed by 60 seconds of standard buffered oxide etching (BOE).

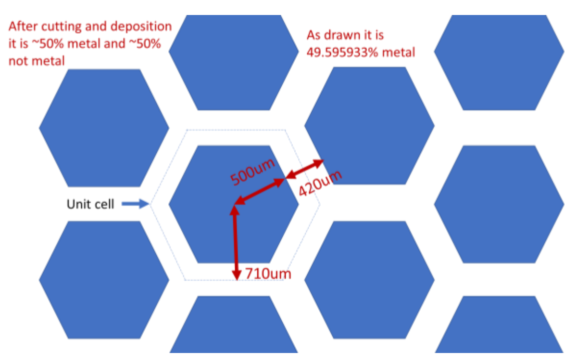

Figure 1. Shadow-masked hexagonal $TaSi_2$/Pt/Ir/Pt metallization design for backside of SiC die. The ratio between metallized and nonmetallized areas is about 1:1.

The high temperature co-fired ceramic alumina substrates with Pt metallization (Pt/HTCC) were commercially made using a standard HTCC process of Pt/HTCC chip package manufacture [7]. The substrates measure 18.3 mm (0.72 in) x 16.5 mm (0.65 in) x 0.41 mm (0.016 in) (thick). For some of the shear test samples, a layer of DuPont 5063D Au thick-film was coated on Pt surface and heat-treated using vendor-recommended temperatures profile in air ambient of drying at 150 °C for 15 minutes and then firing at 850 °C for 20 minutes to form an Au thick film layer on top of co-fired Pt metallization. Two or four SiC die were attached to each substrate using DuPont 5063D Au thick - film paste. The die attach was performed on Tresky T-3000 die-bonder. Wet Au paste was first stamped on the substrate with Pt (or Au/Pt) surface metallization. The area of the stamped paste was slightly smaller than the die size, so the paste material did not extrude then protrude beyond the die area, to avoid forming raised edges surrounding the die. Such raised edges of die-attach material surrounding the die may generate unreal die shear results. The SiC die was picked from gel-pack box and placed on the wet Au paste pad. The assembly was dried first at 150 °C for 15 minutes then heat treated at

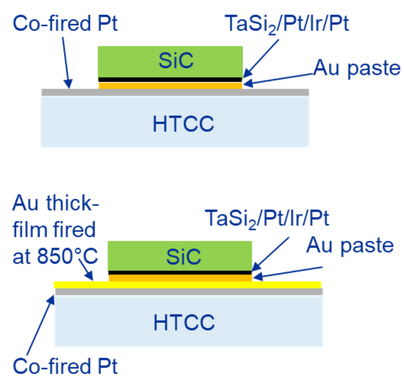

Figure 2. Illustrations of die shear samples with (lower) and without (upper) Au thick film coating fired on Pt/HTCC substrate.

600 °C for three hours in a box oven, with a temperature rate of 3 °C / min. for both up- and down-ward ramps, in air ambient.

Die-shear test was performed on a Nordson DAGE Bond Tester. The machine calibration procedure for the shear module uses a factory jig and NIST traceable

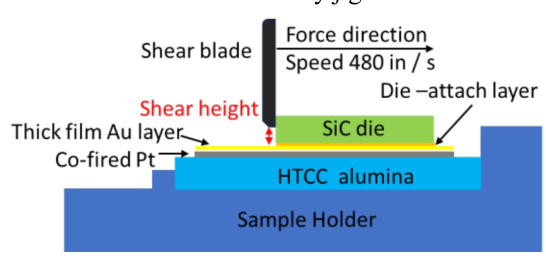

Figure 3. Illustration of die shear test and the shear tool height on Au/Pt/HTCC substrate.

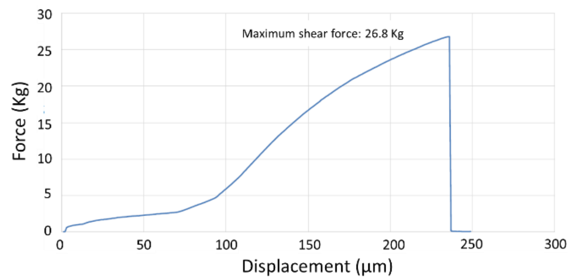

Figure 4. Die shear test data of shear force vs. die shear tool displacement indicating the maximum shear force of 26.8 kg at the steep drop of the force.

calibrated weights. The substrate of the test assembly was horizontally mounted, and a shear tool moved horizontally in an approximate displacement rate of ~ 480 in/min to shear the die, as illustrated in Figure 3. The die shear tool height illustrated in Fig. 3 was set at ~ 95 μm above the top of Pt or the thick-film Au layer. The data of shear force vs. the shear tool displacement was recorded. A sudden steep drop of the shear force with respect to the shear tool displacement increase indicated a shear failure of the die-attach. An example data chart of shear force vs shear tool displacement including the shear failure point is shown in Figure 4. The maximum shear force measured before the breaking point is the shear strength.

Optical pictures of both the backside of the die and the substrates after shearing were recorded for shear failure analysis and counting the number of effectively attached hexagonal pads on the SiC die. The metal patterns shown on die back side and the substrate indicate the sheared / failed layer or the interface(s).

3. RESULTS and ANALYSIS

3.1 Pt/HTCC Substrate Results

Twelve die shear samples of SiC die attached to Pt/HTCC alumina substrates were tested. Table 1 shows the sample information and shear test results of each sample.

Column 1 is the sample ID, column 2 shows measured die shear strength in unit of kg, column 3 shows the number of hexagon metal pads on the SiC die that was effectively attached. The number of pads attached was obtained by visually examining the sheared die and substrate. Column 4 shows the maximum shear stress / shear strength of unit pad area of the die from the second and third columns and the area of the hexagon pad, in unit of kg/mm^2. The 2.0 x die shear strength of MIL-STD 833 for 5 mm x 5 mm die is 5.0 kg, so all the samples pass the die shear standard. The die shear strengths of unit area (small area) all satisfy 1.25 x MIL-STD 833 requirement for 1 mm^2, some of these test results are above 2.0 x MIL-STD 833 requirement [8]. The mean die shear strength is 13.64 kg, exceeding 2.0 x MIL-STD 833, with standard deviation of 2.94 kg.

Table 1. Die shear test results of 12 SiC die with patterned $TaSi_2$/Pt/Ir/Pt metallization attached to Pt/HTCC alumina substrate with DuPont 5063D paste fired at 600 °C for 3 hours.

Sample	Die shear (kg)	Number of hexagon pads	Max.-shear stress (kg/mm^2)
P1	9.03	13	0.80
P2	11.84	12.5	1.09
P3	11.02	13	0.98
P4	17.22	13	1.53
P5	9.61	13	0.85
P6	11.91	13	1.06
P7	16.92	13	1.50
P8	13.38	11.5	1.34
P9	15.7	11.5	1.58
P10	14.31	12.5	1.32
P11	18.56	13.5	1.59
P12	14.2	14.0	1.17

The test results shown in Table 1 are plotted in a histogram as shown in Figure 5. The data are divided into four bins with width of 4 kg of each. A Gaussian distribution curve in red is plotted with the mean value and standard deviation discussed above. The number of total and averaged Pt pads for each bin are specified. Averaged maximum shear stress (strength) of each bin is calculated using the total force and total pad numbers (pad area) in the bin, is labeled on top of each bin in the figure.

Figure 6 shows the optical pictures of SiC die on left and the substrate of sample P8 on right after shearing. These pictures clearly indicate the primary failure at the interface between the co-fired Pt and die-attach Au layer. This is unexpected since the co-fired Pt surfaces are relatively rough compared with the smoother thin-film Pt surface on the SiC pads. A rougher surface usually provides more effective bonding surface area. It is speculated that the relatively weaker bonding between Au (paste) particles and co-fired Pt surface

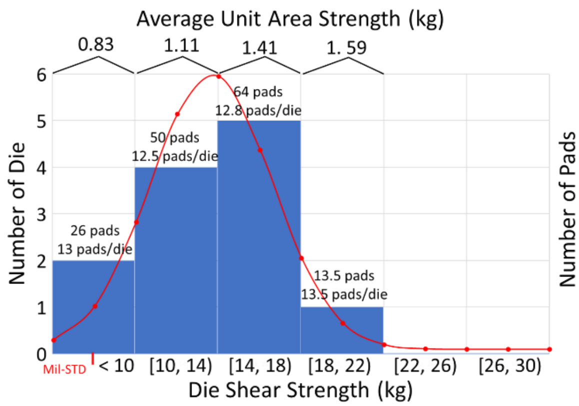

Figure 5. Histogram plot of die shear test results of 12 SiC die with patterned hexagon $TaSi_2$/Pt/Ir/Pt metallization attached to Pt/HTCC alumina substrate with DuPont 5063D paste fired at 600 °C for 3 hours.

might be due to the crystal structures of surface Pt co-fired at very high temperature.

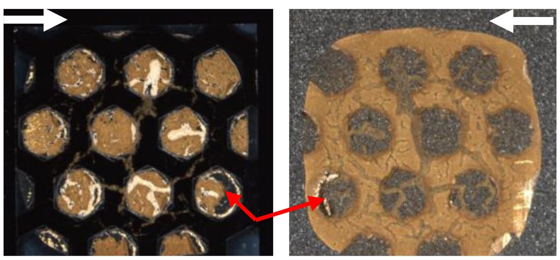

Figure 6. Optical pictures of the die (left) and substrate (right) of sample P8 after shearing from the substrate. The white arrows show the shearing direction. The red arrows indicate possible void due to the shrinkage of Au paste during drying process.

The pictures of neither die nor substrate show much Au attach layer in the area indicated by the red arrows in Figure 6. This might possibly be due to void forming during the Au paste drying process with physical shrinkage of the paste, but the void is not significant in most die Pt bond pad areas.

3.2 Au/Pt/HTCC Substrate Results

The results of shear tests of SiC die attached to Pt/HTCC substrates in Section 3.1 indicate that the shear failure interface is mainly between the Au attaching layer and the co-fired Pt on the substrate. This observation revealed a possibility to improve the shear strength by coating an Au layer fired at 850 °C onto co-fired Pt surface. Twelve die shear samples of SiC die attached to Au/Pt/HTCC alumina substrates using DuPont 5036D were tested. Table 2 shows the sample information and shear test results of each sample.

Column 1 is the sample ID, column 2 shows measured die shear strength in unit of kg, column 3 shows the number of hexagon pads on the SiC die that was effectively attached. The number of pads attached was again obtained by visually examining the sheared die and substrates. Column 4 shows the maximum shear stress / shear strength of unit metallization area of the die, in unit of kg/mm^2. All the samples pass the die shear standard of MIL-STD 833 for 5 mm x 5 mm die (5 kg). The die shear strengths of of a unit area (small area) all satisfy 2.0 x MIL-STD 833 requirement for 1 mm^2 requirement. The mean die shear strength is 18.99 kg, exceeding 2.0 x MIL-STD 833, with a standard deviation of 3.88 kg. The mean shear strength, comapred with the mean shear strength of samples with Pt/HTCC substrates, is improved by 39%.

The test results of Table 2 are plotted in histogram as shown in Figure 7. The data are divided into four bins with width of 4 kg of each. The Gaussian distribution in red is plotted with the mean value and standard deviation discussed above. The number of total and averaged Pt pads for each bin are specified. Averaged maximum shear stress (strength) of each bin is calculated using the total force and total pad numbers (pad area) in the bin, and is labeled on top of each bin in the figure.

Table 2. Die shear test results of 12 SiC die with patterned TaSi2/Pt/Ir/Pt metallization attached to Au/Pt/HTCC alumina substrate with DuPont 5063D paste fired at 600 °C for 3 hours.

Sample	Die shear (kg)	Number of hexagon pads	Max.-shear stress (kg/mm^2)
A1	16.0	12.5	1.48
A2	18.0	11	1.89
A3	14.22	12	1.37
A4	18.42	12	1.77
A5	14.10	10.5	1.55
A6	25.28	13.5	2.16
A7	21.11	13.5	1.81
A8	19.24	12	1.85
A9	26.80	13	2.38
A10	20.45	12	1.97
A11	19.37	12	1.86
A12	14.92	12	1.44

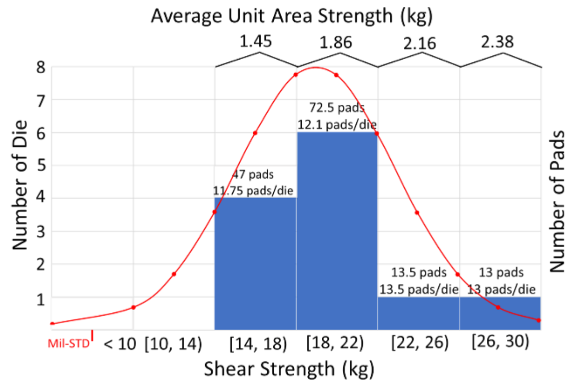

Figure 7. Histogram plot of die shear test results of 12 SiC die with patterned hexagon $TaSi_2$/Pt/Ir/Pt metallization attached to Au/Pt/HTCC alumina substrate with DuPont 5063D paste fired at 600 °C for 3 hours.

Figure 8 shows the optical pictures of SiC die (a) and the substrate (b) of sample A4 after shearing. The pictures indicate clearly following shear failures labeled 1-3: 1) Partial detach of $TaSi_2$/Pt/Ir/Pt metallization stack from SiC substrate, SiC wafer is semitransparent, the dark background color becomes visible. 2) Detach of Au die-attach layer from Pt surface of HTCC substrate. The Au attach layer left on die looks dark yellow indicating detaching from the relatively rough Pt surface. The corresponding areas on the substrate show Pt surface. 3) Failure of Au attaching layer since Au attaching layer material is shown on both die and the substrate in the corresponding areas. The shining golden area labeled by "4" indicates the scratched front edge by the shear tool after the die was sheared off. The scratched area was under the die before shearing. The scratched front edge on metallized pad on the substrate indicates that the HTCC substrate likely buckled under high shear force. This substrate buckling was observed on several sheared substrates.

4. DISCUSSION

Over 39% improvement of shear strength by Au thick film coating on co-fired Pt/HTCC alumina substrate and multiple failure mechanisms observed from sheared die and substrate with Au/Pt/HTCC substrates indicate that the Au thick film layer, fired at 850 °C, forms a solid bonding to co-fired Pt/HTCC surface. The measurements likewise indicate that Au-Au bonding achieved at 600 °C is stronger than Au-Pt/HTCC bonding achieved at the same temperature. Compared with the Pt thin film surface on SiC die backside, co-fired Pt surfaces are more crystalized.

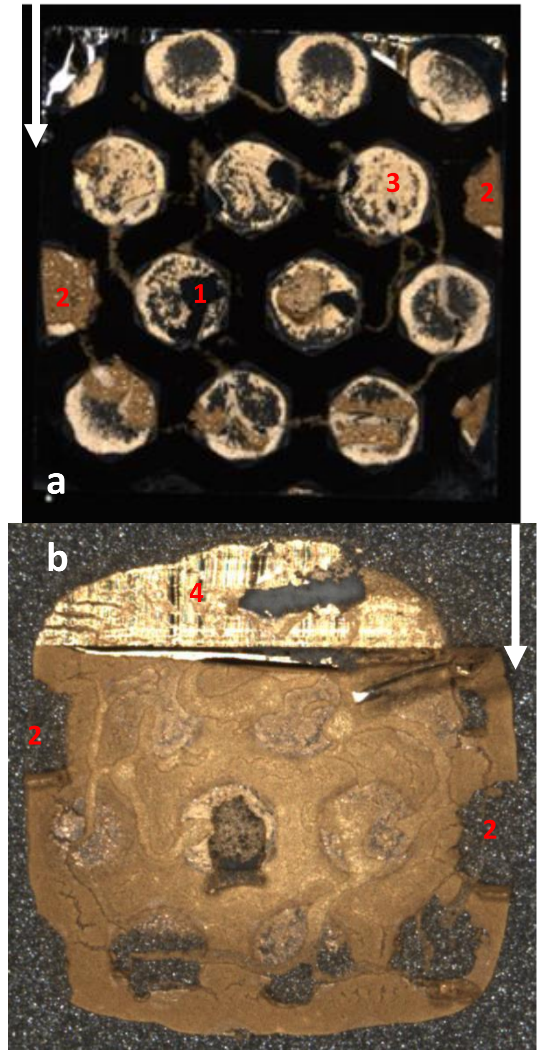

Figure 8. Optical pictures of the die (a) and substrate (b) of sample A4 after shearing test. The white arrows show the shearing direction. The red numbers indicate different failure mechanisms (see main text). SiC die measures 5 mm x 5 mm x 350 µm (thick).

Diffusion bonding between Au particles (of the dried paste) and crystalline Pt surface formed at 600 °C may not be as strong as the bonding between Au particles and amorphous Pt on SiC die formed at the same temperature.

For Au/Pt/HTCC substrates, the observations that shear failures are distributed among different interfaces/layer is evidence that the thin film stack $TaSi_2$/Pt/Ir/Pt (die metallization) and thick-film stack Au/Au/Pt (die attach Au layer and substrate metallization) demonstrated reasonable bonding strength at these interfaces such that the material system stack might be approaching its optimized mechanical strength.

Both histograms show deviations of the experimental die shear data from the ideal Gaussian distribution with the mean and standard deviation derived from the data. More testing results are needed to achieve more precise statistical results beyond the preliminary results reported in this paper. In addition to room temperature shear data, shear strength data after long term high temperature exposure as well as high temperature in situ shear test are planned for future.

In addition to measuring the mechanical strength of the revised die-attach scheme, these die shear results also establish feasibility for the co-fired Pt/HTCC extreme environment packaging system to adopt the conventional electronic packaging sequence. The shear strength of Au thick-film fired at 600 °C on Au/Pt/HTCC substrate for 1 mm^2 area derived from (pad number) weighted average unit area shear strength shown in Fig. 7 is 1.8 kg/mm^2. For the 16-pad HTCC package (measured 26.7 mm x 14.5 mm x 3 mm) with two round-shape Au/Pt mounting pad with radius of 3 mm and sixteen 1.27 mm x 1.27 mm Au/Pt I/O pads [9], the total metallization area is about 79 mm^2. The estimated shear strength of 16-pad package attached to a circuit board with matching pads is over 70 kg considering 50% effective bonding area (40 mm^2). This example indicates that chip-level HTCC packages with Au/Pt metallization pads can be attached to Au/Pt/HTCC circuit board with DuPont 5036D paste and fired at 600 °C to achieve acceptable bonding strength, demonstrating the first feasible component attachment process for (Au)Pt/HTCC alumina packaging system using Au paste at acceptable lower temperature that won't damage the SiC ICs and bonding wires. This is critical towards realizing the conventional electronics manufacturing sequence for extreme-temperature durable electronics wherein individual IC packaging is the first step, then packaged ICs and other discrete components are integrated onto circuit boards.

5. SUMMARY

The measured average die-shear strength of 5 mm x 5 mm SiC chips with 50% patterned $TaSi_2$/Pt/Ir/Pt metallization attached to Pt/HTCC substrate using DuPont 5036D paste fired at 600 °C was about 13.6 kg (>$6x10^5$g). The die-attach assemblies with Au/Pt/HTCC alumina substrates showed ~ 39% shear strength improvement compared with those with Pt/HTCC alumina substrates exceeding 2.0 x MIL-STD 833 requirements for large die. This die shear strength validates the room temperature mechanical performance of the Au thick-film DuPont 5063D based die-attach scheme for Au or Pt terminated IC die on (Au)/Pt/HTCC substrates. More shear tests after long term high temperature exposure of test samples as well as high temperature in situ shear tests need to follow these preliminary test results.

The unit area shear strength of DuPont 5063D fired on Au/Pt/HTCC substrate at 600 °C revealed the feasibility of an Au thick-film paste based scheme to attach Au/Pt/HTCC chip-level packages to HTCC circuit boards with same Au/Pt metallization at an acceptable temperature to SiC ICs. This component attachment allows users to test and select individually packaged high-temperature IC units for subsequent integration onto their circuit boards.

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