Required by the application - Optimized joining technologies in IGBT modules increases the lifetime of hybrid bus inverters

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Abstract

Target of the research project presented in this paper is to find an appropriate solution to increase the ruggedness/reliability of the system soldering in a power module and the implementation in an existing design. Accelerated reliability tests, passive thermal cycling (TC) and thermal shock tests (TST) are performed to estimate the reliability of the improved solder connections. The differences in the aging of the layers depending on the load applied and the influence on the failure mechanism will be shown. The results are compared by analyzing Scanning Acoustic Microscopy (SAM) images. The focus is on reliability and how the improved joining technology employed in the device will increase the system lifetime of an inverter in a hybrid bus. The lifetime calculation is based on a real traction cycle, measured for a series hybrid drive city bus inverter with a liquid cooling system.

1 Introduction

The electric propulsion system of a series hybrid drive city bus will significantly reduce the fuel consumption and the CO_2 emission. The basic topology and the main components of such a system are shown in **Fig. 1** [1].

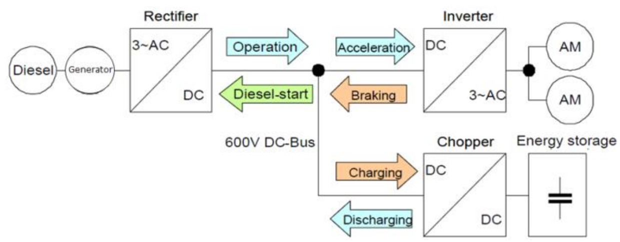

Fig. 1 Basic topology of a series hybrid drive

Compared to passenger cars, higher power ratings are demanded, leading to higher DC link voltages. Usually, adapted industrial 1200V IGBT power modules and additional industrial components are used in this application. The power losses of the IGBT module are generated in the inverter as a result of the load profile of the hybrid city bus in the application. The arrows in Fig. 1 indicate the energy flow depending on the bus operation conditions. If the bus is in normal operation the energy is flowing from the Diesel via the rectifier, the inverter and the electric machine (AM) to the wheel. If the bus is in acceleration the energy storage supports the drive and it will be discharged. In case of braking the energy is flowing via the inverter and the chopper into the energy storage.

The following investigations are focused exemplary on the inverter. In case of driving or acceleration the energy in the inverter is conducted mainly by the IGBTs. If the bus is breaking, the energy will be conducted mainly by the freewheeling diodes (FWD) of the inverter. An example of a traction cycle for a 12m city bus is shown in **Fig. 2** [1].

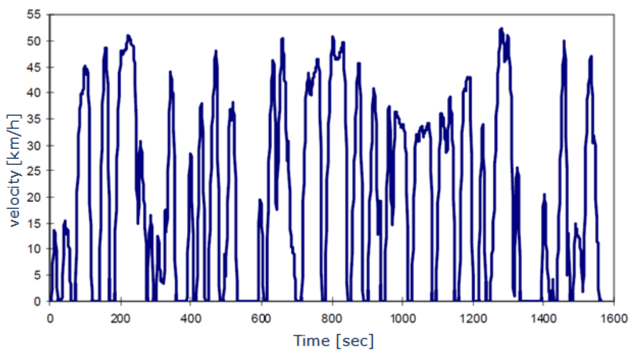

Fig. 2 Exemplary traction cycle for a city bus

With a given load profile and the module operation conditions while the inverter is working, the lifetime of the power semiconductor in terms of wear out effects for the joining layers can be estimated as described in [2].
Nevertheless, the inverters – and especially all the components in the power electronics of the inverter – have to withstand high electrical, mechanical and enormous thermal loads in day-to-day-today-operation of the city bus. Furthermore, all of the equipment has to operate without any failure for up to 60,000 hours to fulfill the economic requirements of a commercial vehicle (CAV). This is considerably higher than for passenger car applications.

2 Power Modules

The long term reliability, respectively the lifetime of the power device, is very often defined by the thermal stress

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of the dies and the case temperature. As published in [3, 4], both temperatures are the result of the mission profile in combination with the thermal transfer path between the chip and the cooling system.

The IGBT power module is a core device in the power electronics of the inverter. The general internal structure of a power module is shown in **Fig. 3**.

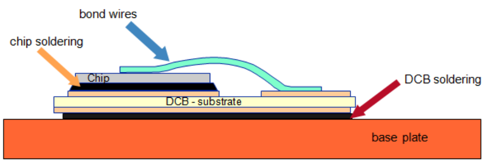

Fig. 3 General structure of a power module

The chips, IGBT and free-wheeling diodes (FWD), are soldered onto a substrate. The substrate material, aluminum oxide (Al_2O_3), is a ceramic, metalized on both sides. Copper is used as state-of-the-art metallization material (DCB substrates). For standard industrial modules, the DCB substrates are soldered onto a 3mm thick copper baseplate using a lead-free soft soldering process. These layers represent transient and steady-state thermal impedance. The baseplate also enables thermal conduction in the horizontal axis at the same time. An FEM simulation is used to calculate the active thermal area of power modules with and without baseplate. The results of the comparison are shown in Fig. 4. The module with the baseplate provides a larger heat spreading which increases the thermal area.

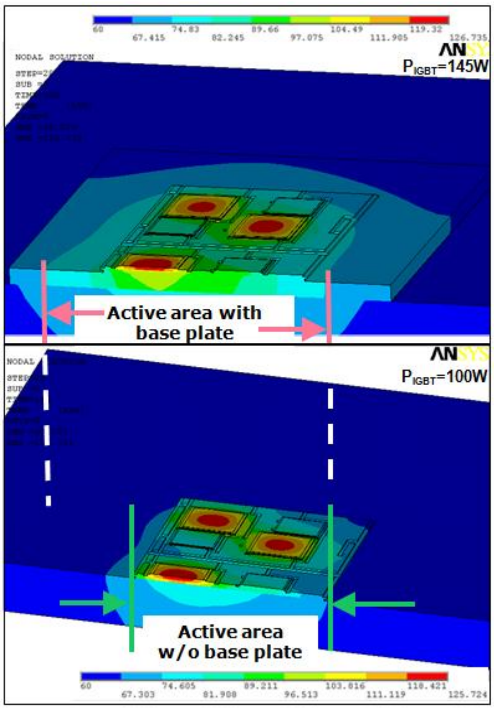

Fig. 4 Simulation results of heat spreading of power modules with and without baseplate.

2.1 The Effects of Power Cycling and Thermal Cycling on Power Modules

The larger heat spreading in case of a module with baseplate will also have an enormous impact on the resulting absolute junction temperature, and even more on the junction temperature ripple ΔT_j. Both directly influence the thermal mechanical strain on the chip soldering and the aluminum bond wire connection on top of the dies [5]. The simulated junction temperatures (T_j) of the power modules with and without baseplate are compared in Fig. 5. The results for dynamic load cycles indicate a significantly lower junction temperature swing for the module with baseplate.

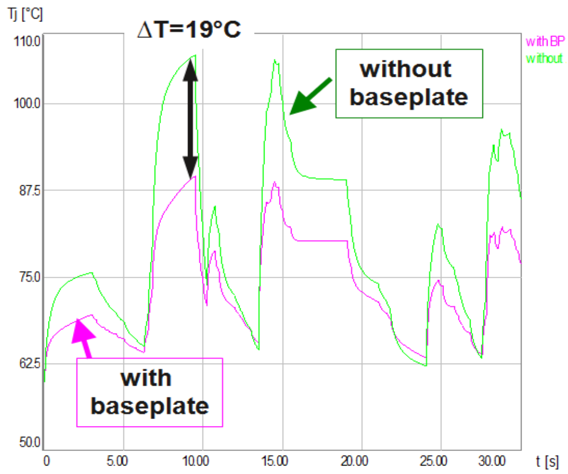

Fig. 5 Simulated IGBT junction temperature of power modules with and without baseplate.

Since the power cycling (PC) failure mechanism of bond wire detachment is directly related to the junction temperature swing ΔT_j, a reduced ripple of the junction temperature is desirable, and therefore modules with baseplate are preferred. The detailed results are discussed in [3] and [4]. Further, the power modules being considered already provide the state-of-the-art 1200V IGBT4 technology, along with the state-of-the-art power cycling capability from Infineon [6, 7].

Based on the advantages of the power cycling reliability results previously explained for modules equipped with a baseplate, the DCB solder layer is consequentially improved with respect to delamination. The joined materials have different coefficients of thermal expansion (CTE). The dynamic thermal loads generated in the application and the different CTE cause a thermal load on this connection. This load results in a thermo-mechanical strain inside the DCB's solder layers of the device. Solder fatigue caused by the periodic straining of the connections will ultimately result in a propagation of cracks within the solder volume [8]. The ability to withstand the highly dynamic thermal loads depends, among other factors, on the ruggedness of the connection layers within these semiconductor modules.

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2.2 Adapted Power Module

Increasing demands regarding robustness leads to a steady striving for even more rugged joining techniques in industrial IGBT modules, to fulfill the technical and the economical requirements of commercial hybrid city bus application. Based on the existing Elfa® 2[1][1], an inverter design for hybrid bus application, the EconoDUAL™ 3 is selected for further investigations to improve the DCB system soldering. The specimens provide an adapted DCB soldering. This new joining technology can be regarded as a selective fetch ahead from Infineon's upcoming set of .XT joining technologies [10]. The typical appearance of this package selected as the basis for further investigations is shown in **Fig. 6**.

Fig. 6 Typical appearance of the EconoDUAL™ 3

3 Test Configuration and Results

To evaluate the reliability of the DCB system soldering, accelerated testing is a common practice. The acceleration factor is used for conversion of test time at test conditions to equivalent operating time under target operating conditions. The most important aspect in an accelerated test is that no changes in the failure mechanism are observed. The passive thermal shock test (TST), acc. to IEC60068-2-14 and the passive thermal cycling (TC) test, according to Infineon QRP for product qualification are selected to evaluate the system solder fatigue. By applying different time intervals (Δt) and different temperature gradients (ΔT) both tests induce thermal mechanical strain in the solder layer of the device under test (DUT).

3.1 Thermal Shock Test

The thermal shock test is a fast test to induce a high thermo-mechanical strain, not only in the DCB solder layer but also in all components of the power semiconductor module. Two chambers with different temperature levels are used. The modules stay in these chambers for a well-defined time to ensure that a steady-state temperature is reached. The DUT is placed in the first chamber with a lower limit temperature of T_{min}=-40°C for a typical time of $t_{storage}$=1h. After this time, the device is then transported to the second chamber using a lift system with $t_{transport}$<30s. The DUT again stays in this chamber for 1h at the upper temperature of T_{max}=125°C. The DUT is then moved back into the first chamber for the same length of time. The total duration of times at T_{min} and T_{max} (2 hours) is one cycle of the TST. In this thermal shock test, the device has to withstand an enormous temperature difference of ΔT=165K. The cycle quantity for standard industrial medium power components is N_{cyc}=50 cycles. The power components pass the test if the electrical parameters and the thermal conductivity junction to the device case remain within the limits of the test specification.

3.1.1 Thermal Shock Test Results

In a first step, the prototypes with the improved system soldering were tested up to N_{cyc}=1000 cycles according to the Infineon automotive qualification standard with an intermediate read-out step after 500 cycles. SAM images of the specimen, system and chip soldering layer, at N_{cyc}=0, N_{cyc}=500 and N_{cyc}=1000 cycles are shown in Fig. 7. In these SAM pictures, almost no delamination is visible. Further, the plastic housing of the module with its injected molded metal parts are w/o any damages despite of the applied big thermal stress. But for all the electrical parameters and especially the thermal conductivity junction to the case are well within the limits of the test specification. The prototypes therefore passed the TST test with N_{cyc}=1000 cycles.

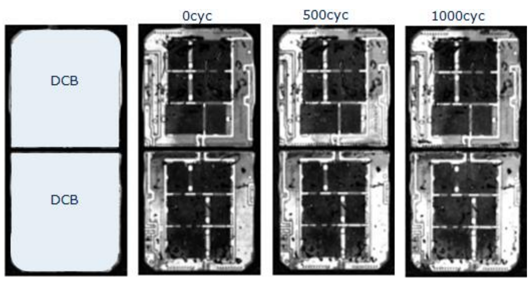

Fig. 7 SAM images of the DCB prototype soldering after N_{cyc}= 0, N_{cyc}= 500 and N_{cyc}= 1000 cycles of TST.

Based on these very promising results, the TST was continued up to N_{cyc}=2000 cycles, with values read-out at N_{cyc}=1500, N_{cyc}=1750 and finally at N_{cyc}=2000 cycles with the investigation focus on the delamination of the improved DCB soldering layer. In Fig. 8 the DCB soldering after N_{cyc}=1000 and N_{cyc}=2000 cycles are presented. When continuing up to 2000 cycles resulted in a slight delaminating of the system soldering at the usual positions between the two DCBs and at the DCB corners [8], shown using the circles in Fig. 8. Nevertheless, the delamination is very small, and did not influence the area underneath the chip.

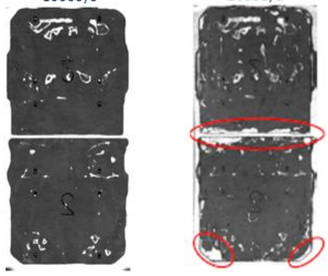

Fig. 8 SAM images of the DCB prototype soldering after N_{cyc}=1000 and N_{cyc}=2000 cycles of TST.

[1] Elfa® 2 is a Registered Trademark of Siemens AG

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3.2 Thermal Cycling Test

Additional prototypes were investigated in a passive thermal cycling test (TC). In this investigation the test is continued until the end of life (EOL) of the DUT. Initial lifetime estimation for the DCB soldering can be deduced taking the EOL results and the mission profile of the application into account.

The TC test is performed in a passive external heating and external cooling setup. In this passive setup, the DUT is mounted on a heating/cooling plate and the thermal load is induced evenly via the baseplate to the system solder by this external plate. The evenly applied temperature cycle starts at T_{c_min}=25°C and applies ΔT_c=80K up to T_{c_max}=105°C baseplate temperature. The setup is then allowed to cool down to T_{c_min}=25°C. The complete cycle takes approximately t_{cyc}=6min. The power module passes the TC test if the electrical parameters and the thermal conductivity between the junction and case remain within the limits of the test specification. The SAM images of the chip and DCB solder layer are shown in Fig. 9. The first SAM images displays the initial status at N_{cyc}=0 cycles; values are read out every N_{cyc}=5k and are shown up to N_{cyc}=40k cycles. The examinations are covering both solder layer´s, chip and DCB, but with predominate focus on the delamination of the adapted DCB soldering layer.

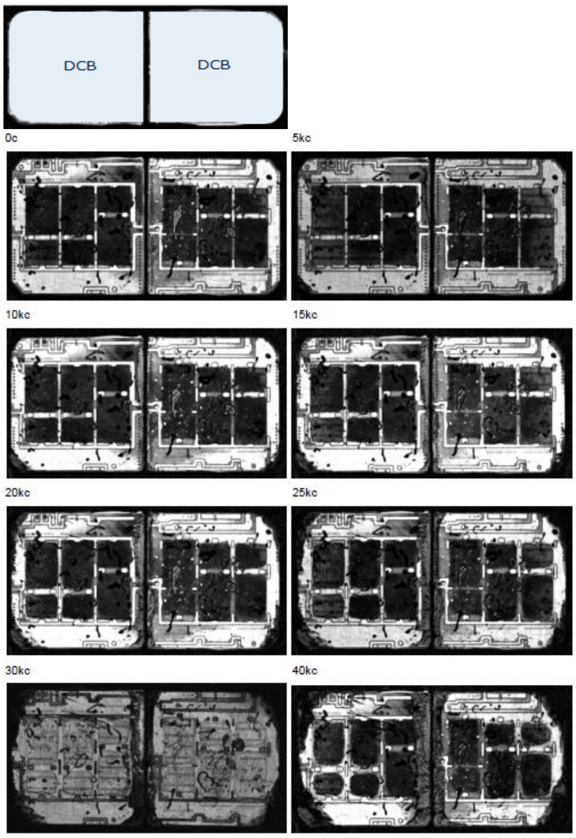

Fig. 9 SAM images of the soldering at N_{cyc}= 0 cycles and every N_{cyc}= 5k cycles up to N_{cyc}= 40k cycles of TC.

The delamination of the DCB soldering layer started at the DCB edges. However, it did not reach the chips until N_{cyc}=25k cycles. After 25k cycles, the delamination just reached the chip edges – and even after 30k cycles the delaminated chip area is negligible. The delaminated area grows with increasing number cycles. The examination of the results after 40k cycles show that the sum of the delamination in the system solder and the chip solder layer will affect the thermal conductivity between the junction and case. The sum of the delamination is close to EOL of the device, based on the test specification. The test is stopped as the EOL of the module is approached. Finally, the prototypes passed the passive thermal cycling test for up to N_{cyc}=30k cycles. Furthermore, the thermal resistance R_{thjc} after 30k cycles was investigated in order to determine the influence of the delamination below the chip area. The result was very good, and all values are well below the specified limits.

As the temperature was evenly induced over the complete baseplate area, the thermo-mechanical stress level is higher for the passive TC compared to the active TC (active TC is comparable to the PC test but with cycle times in a minute range), where the stress is induced locally by the chips themselves. The active thermal cycle capability for the standard industrial EconoDUAL™ 3 is specified with Ncyc=12k cycles at Tc_min=25°C, ΔTc=80K, and is shown in **Fig. 10** [9].

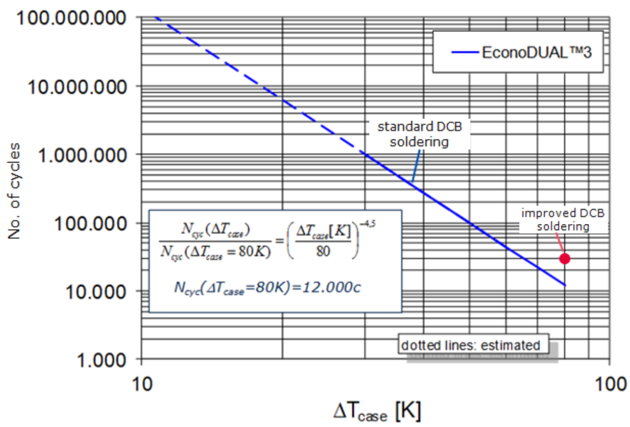

Fig. 10 Thermal cycling capability for the standard EconoDUAL™ 3 modules

The module with the improved system soldering shows a significantly increased passive TC reliability concerning delamination underneath the chip area.

For the improved power module, as a first conservative assumption, this first result of the TC cycle improvement at N_{cyc}=30k for ΔT_{case}=80K is used in a linear approximation, comparable to the given standard DCB soldering diagram in Fig. 10, for the complete ΔT_{case} range to perform the lifetime estimation and comparison.

A final extended thermal cycling (TC) specification will be released by Infineon after the complete implementation of the new solder joint technology.

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4 Lifetime Estimation

The requirements to operate the inverters claims up to 60,000 hours in 15 years, leading to approx. 11 hours operation per day. This operation time results in a driven distance of 1,000,000 km for the vehicle [1].

To obtain realistic lifetime estimation for the usage of an inverter as shown in Fig. 1, the following calculation is based on a measured load cycle for an inverter of a series hybrid bus application.

Typically, the IGBT of the module used in an inverter for a traction application is more stressed than the freewheeling diodes of the same module. Hence, the lifetime estimation focuses on the IGBT respectively the DCB soldering when the inverter is in normal operation.

The real profile involves a trip duration of $t_{driving}$=4800s. The resulting temperatures of the power devices and the solder layer are calculated based on the inverter operating conditions.

The junction temperature for the IGBT switch (T_{jIGBT}), for the FWD (T_{jdiode}) and for the DCB system soldering (T_{solder}) are shown as a function of time T=f(t) in Fig. 11.

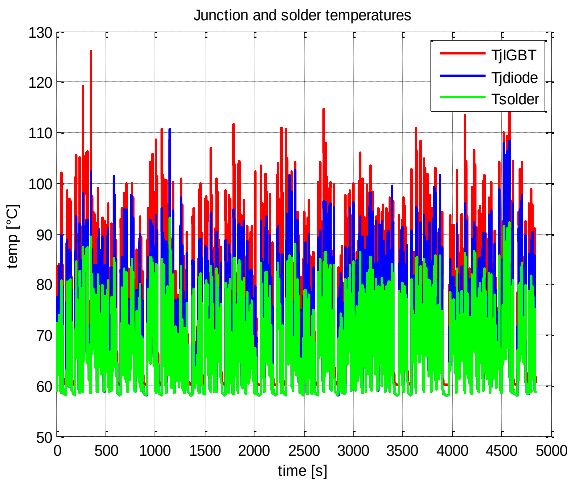

Fig. 11 Calculated temperatures based on a cycle at inverter operating conditions

Based on the Rainflow-Algorithm the calculated temperatures for the EconoDUAL™ 3 in Fig. 11 are separated and counted, depending on the temperature ripple for the solder layer (ΔT_{solder}). The results are shown in Fig. **12.**

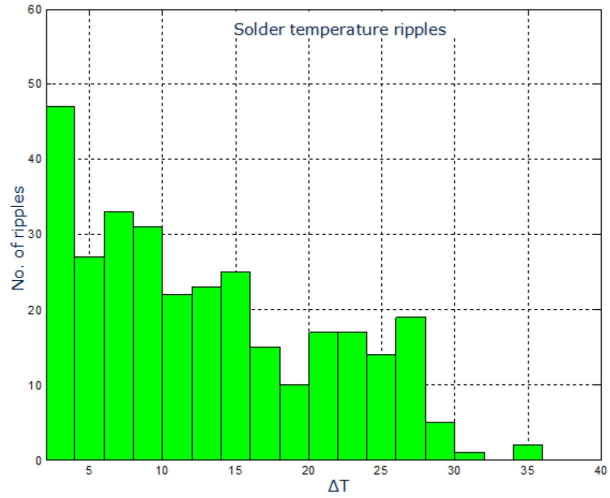

Fig. 12 Temperature change of the solder layer based on the traction cycle.

In combination with the TC capability for the EconoDUAL™ 3, the estimated solder lifetime is listed in **table 1**. The results of the lifetime estimation for the standard module shows, that this module can be used in the measured traction cycle for 11 hours of operation per day for approx. 8.4 years. Compared to the requirements this is a limitation. In reality measures would be necessary to guarantee the full lifetime e.g. derating. But this measures lead to disadvantages for the drive.

Operation hours per day	1.35	6	**11**
Possible years	67	14.9	**8.4**

Table 1 Approximation of the DCB solder lifetime in the standard EconoDUAL^{TM} 3

The improved EconoDUAL™ 3 module provides a significantly higher ruggedness of the solder connections. The lifetime depending on operating hours per day is shown in table 2. The module with the improved soldering system fulfills the requirement of 60,000 hours. 11 hours of operation per day for almost 21 years can be achieved. Even with an increase of up to 15 hours of operation per day, the 15 years lifetime target can be achieved.

Operation hours per day	1.35	**11**	15
Possible years	167.5	**20.9**	15.2

Table 2 Approximation of the DCB solder lifetime in the improved EconoDUAL^{TM} 3

Consequently, the lifetime of the power module is more than doubled by employing a novel solder material and

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the associated processes instead of the traditional solder technique.

5 Summary and Outlook

This paper presents a novel solution to increase the ruggedness of the DCB to baseplate connection. Accelerated reliability tests such as passive thermal cycling and thermal shock tests were performed to estimate the reliability of the improved connection. The crack formation in the solder layer during the test has been significantly reduced by using a different solder material and the associated processes.

The lifetime estimation revealed that the lifetime can be significantly extended by more than a factor of 2. For the existing inverter design, the adapted DCB soldering provides a significant advantage when it comes to complying with the comprehensive requirements of an inverter used in a city bus hybrid drive.

Based on the improvements discussed, this high reliable soldering will be implemented as a further standard in the EconoDUAL™ 3 power modules designed for commercial vehicle applications with increased lifetime requirements.

The implementation of this new joining technology can be regarded as a selective fetch ahead from Infineon's upcoming set of .XT joining technologies [10].

Furthermore, the new EconoDUAL™3 will be qualified according the Infineon automotive standard for IGBT modules.

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