A Low Firing Temperature Copper Conductor for use on an Aluminum Metal Compatible Dielectric in LED Thermal Substrate Applications

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Abstract

One of the most important contributing factors in the long life of LEDs (Light Emitting Diode) is keeping them cool, i.e., lowering the junction temperature, which can get as high as 150 °C. One way to accomplish this when building a circuit containing many LED packages is to use a thermal substrate. The majority of High Power/High Brightness (HP/HB) LED thermal circuits manufactured today are based on Metal Core Printed Circuit Board (MCPCB) technology. The MCPCB system consists of a copper foil, polymer dielectric layer and either an aluminum or copper base layer that are laminated together. The process of making MCPCB is a subtractive process, where most of the copper foil is removed. The copper foil is etched to create a circuit layer, the polymer dielectric provides the insulation between the copper foil and the metal base, and the aluminum or copper base provides thermal dissipation.

The thick film copper paste discussed in this document is processed using an additive process, like screening printing, where the copper conductor is deposited only in the chosen area. The copper thick film paste is screen printed to create a circuit design on top of a thick film dielectric (insulated area) layer which is also printed on a metal base layer. The selective deposition allows for less material usage, and potentially lower overall cost as well as improved thermal performance with inclusion of thermal vias.

This paper discusses the results of a newly developed lead (Pb) and cadmium (Cd) free low firing temperature (580-600ºC) copper thick film conductor paste on top of a low temperature firing dielectric paste. This study includes evaluations based on SEM photos, solderability, leach resistance, and initial and long term adhesions using SAC 305 solder and RMA flux. There are many different applications for HP/HB LED circuits, from general lighting to street lighting to automotive lighting and more. All of them have varying degrees of performance testing requirement. To try to cover as much of the reliability testing as possible we have included tests such as thermal aging (150°C), thermal cycling from -50 to+150°C, as well as 85°C/85% RH reliability testing under bias.

Key words: MCPCB, Thick film, Thermal Substrate Lead free solder, Copper Conductor, Nitrogen atmosphere

Introduction

LEDs (Light Emitting Diode) are used in an extensive range of lighting applications including, indoor and outdoor general lighting, backlighting for computers monitors and LCD TVs, and automotive lighting applications. One of the most important factors in the long life of LEDs is keeping them cool by lowering their junction temperature, which can reach as high as 150°C. For high power/high brightness LED lights, one way to accomplish this is to place the LED packages on a thermal substrate. The thermal conductivity of the material that the thermal substrate is made from directly affects the dissipation efficiency through conduction. Normally, the substrate used is aluminum, although copper may also be used. The most common thermal substrates are called Metal Core Printed Circuits Board (MCPCB), which are made using aluminum or copper as the base substrate and as a heat spreader, and a layer of an electrically insulating material. The MCPCB is used to allow the heat from the LEDs to dissipate through the substrate to keep the LEDs junction temperature cooler. The process of making MCPCB using copper as the circuit material is a subtractive process, were a copper foil is bonded to a polymer dielectric layer and then the desired conductor pattern is chemically etched to form the circuit. The structure is bonded to an aluminum or copper substrate to create a thermal substrate. This process of making MCPCBs is labor intensive, expensive, and there is material (copper foil) waist. MCPCBs can be made in various shapes and surface finish. Furthermore MCPCB can take advantage of incorporating a polymer dielectric layer with high thermal conductivity for lowering thermal resistance.

Heraeus Precious Metals has introduced the “Celcion” material system, a product line of low temperature firing pastes for insulated aluminum substrates. The Celcion™ system includes an isolating dielectric paste, silver conductor paste and a copper conductor paste, and a polymer cover coat ink. The dielectric has high thermal conductivity for lowering thermal resistance and the conductors are printed directly over the dielectric to form the circuit for the LEDs. The Celcion™ system is an additive system unlike MCPCB, whereby the pastes are printed in a variety of shapes, sizes and patterns to form a circuit on top of an aluminum substrate. The copper conductor was developed to provide similar properties as copper foil in MCPCB substrates. There are other reasons for using copper in place of silver, copper costs less than silver and it has better electrochemical migration behavior than silver which will be helpful in harsh environments. The firing temperature of the copper conductor is limited by the aluminum substrate since the aluminum substrate starts to distort when fired above 620°C. The printed substrates have to perform well under certain conditions depending on the application. For example, a substrate used in an automotive application might require strong performance in 85°C/85% RH, as well as during thermal cycle at -50/+150°C. However, a substrate used for an LCD displays might require less stringent testing. The copper conductor is applied on top of an electrically isolating dielectric layer on aluminum substrate to form the electrical circuit. For this paper the copper conductor was evaluated using SAC 305 solder at 250°C and RMA flux. This paper reports on the reliability of a 600°C firing copper conductor paste when fired on top of Celcion™ dielectric material in a nitrogen atmosphere, to form the electrical circuit. These substrates are subjected to thermal aging at 150ºC, thermal cycling at -50°C to +150°C and 1000 hours in an 85°C/85% relative humidity environment.

Experimental Procedure

The copper paste tested in this work is designated as CL81-10347. CL81-10347 copper conductor paste was printed on IP6075 dielectric which was printed on top of 3003 aluminum substrates, using a 280 mesh screen. The data presented in this paper is based on dielectric coated aluminum substrates first fired in air at 550°C and then CL81-10347 fired in nitrogen at 600°C. The aluminum substrates were prepared using three layers of IP6075 dielectric at a final fired thickness for 40-60 µm, and CL81-10347 paste printed to the recommended wet thickness of 38-42 µm. The parts were then dried at 125ºC for 10 minutes and fired at 600ºC in a belt furnace under a nitrogen blanket.

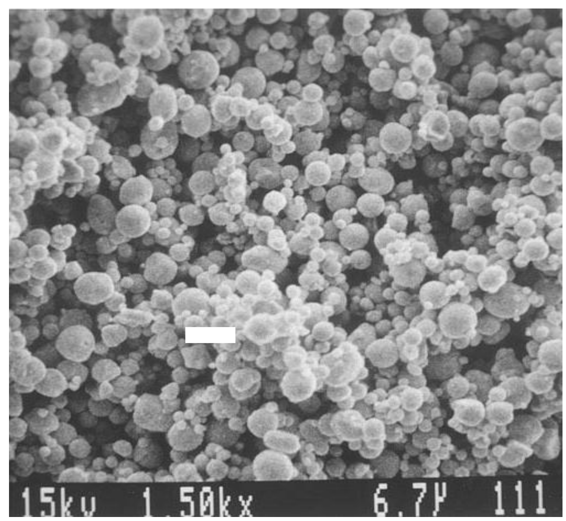
Nitrogen Firing

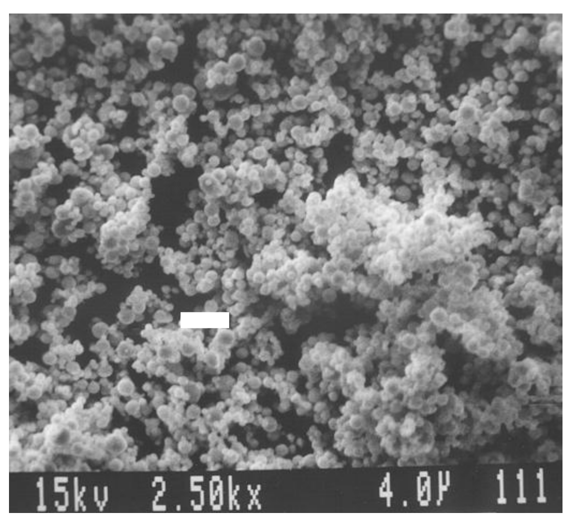
Firing substrates in a nitrogen atmosphere (N_2) is different than firing substrates in air. The following controls are needed when firing in the N_2 (inert atmosphere) belt furnace:

- Control total firing time to protect the copper film from gross oxidation.
- Introduce 1-20 ppm oxygen into the burnout section (zone) of the furnace to help with the organic binder burnout.
- Set profile to 600°C with +/- 10°C and 8-10 minutes at the peak.

Copper Powder Selection

Several copper powder sizes and types were evaluated in this study to help improve the fired film density and adhesion.





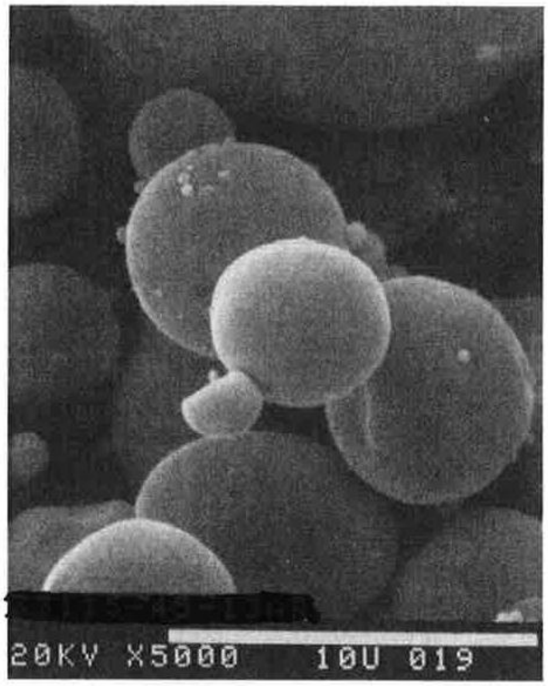


Figure 1: SEM Photo of Typical Copper Powders.

The photo in Figure 1 shows the SEM of three different sized of copper powder. Experiments were conducted using these powders to obtain the best fired film density and adhesion at a 600°C firing profile. Figure 4 shows the firing profile used for this study. It is also important to control the oxygen levels of the copper powder. The oxygen levels range from 3,500-15,000 ppm adsorbed on the copper powder.

Table 2: Typical Copper Powder Physical Data

Particle Shape	Sphere	Sphere	Sphere	Sphere
Particle Size (microns)	0.75-1.75	1.75-3.25	3.25-4.75	4.75-7.0
Surface Arae (m^2/g)	<1.5	<1.0	<0.5	<0.35
Tap Density (gm/cc)	>2.5	>2/5	>3.5	>3.5

Paste Experiment Set Up

The objective of the first stage was to find a copper powder that would provide a dense fired film and high conductivity. Several experiments were conducted using the copper powders listed in Table 2. It was discovered that the combination of the small and a large particle size powder produced the best fired film density. The next step was to find a glass powder, metal oxide combination to help achieve the optimum fired film adhesion when the conductor printed on top of IP6075 and fired at 600°C in a N_2 atmosphere.

The SEM photo in Figure 2 represents a cross section of CL81-10347 conductor and the SEM photo in Figure 3 represents the cross section of a copper foil in MCPCB. From the SEM photos it is clear that there is a difference in the structure of both films. The conductive layer of the MCPCB is made of a solid foil, whereas CL81-10347 is made from particles of copper powder and glass frit which are sintered together to form a conductive film. This paste was chosen as a conductor for dielectric on aluminum circuits because of the high reliability, good solder acceptance and leach resistance properties. The conductor was printed using a 280 mesh, 0.5 mil emulsion stainless steel screen. The screen printing parameters were adjusted to achieve the recommended fired film thickness. The test substrates were dried at 125°C for 10 minutes in a box oven and fired in a muffle-less belt furnace at 600°C ±5°C with a 5-7 minute peak dwell time for a total door-to-door cycle time of 90 minutes. Figure 4 shows the firing profile used for CL81-10347. All of the conductor test parts were printed to a fired film thickness range of 24-26 microns

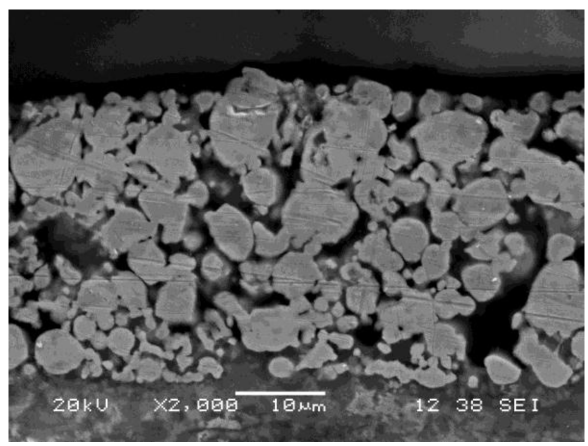


Figure 2: Cross-section SEM Photo of CL81-10347 Conductor.

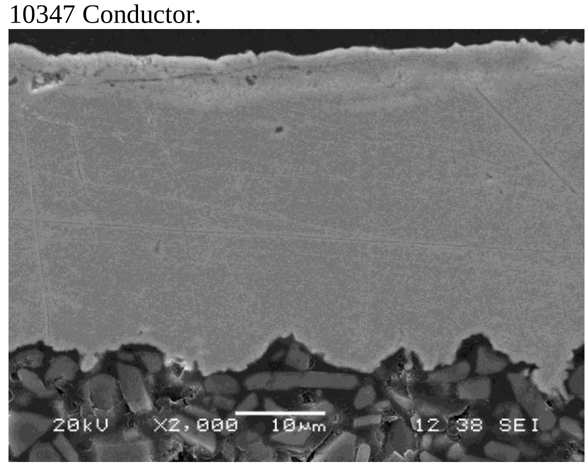


Figure 3: SEM cross-section photos of a MCPCB.

Test Procedure and Test Equipment

All solder performance testing was conducted using the Robotic Process Systems Automatic Solderability Tester Model 202TL. SAC305 solder at 250°C was used for solder acceptance, leach resistance and adhesion. The test coupon in Figure 6 was first clamped into the substrate holder. The coupon was then dipped in the flux for a prescribed amount of time at a set depth with a 5 second delay between flux dipping and immersion in the molten solder alloy. The test coupon was then immersed in the molten solder alloy at a prescribed depth and time depending on the test being conducted (i.e. solder acceptance, leach resistance or adhesion). After the elapsed dwell time, the coupon was raised from the molten solder alloy, allowed to cool and cleaned with acetone.

Figure 4: 600C firing profile.

Table 4 Robotic Process Systems Solderability Tester Parameters.

Flux Dwell	5 seconds
Flux Hold	1 second
Flux In	1 second
Flux Out	1 second
Solder Dwell	5 seconds (solder acceptance and adhesion testing) 10 seconds (leach resistance testing)
Solder In	1 second
Solder Out	1 second

Solder Acceptance

The test coupons (Figure 6) were dipped using the automatic solder dipper shown in Figure 5, at the dwell times listed in Table 4. Solder acceptance was determined by visual inspection under a microscope at 50x magnification. For leach resistance the pad dimensions were measured prior to and after dipping in the X and Y directions. Solder leach resistance was determined by dividing the post soldered area by the pre-soldered area to calculate the leach resistance.

Figure 5: Robotic Process Systems Automatic Solderability Tester Model 202TL.

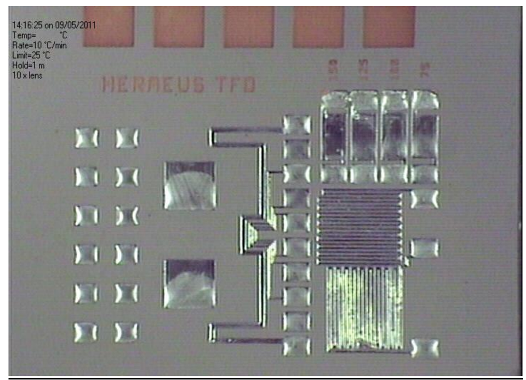


Figure 6: Solder acceptance of CL81-10347 with SAC 305 solder.

Solder acceptance and Leach resistance Results

The solder acceptance and leach resistance results of the copper conductor printed on top of IP6075 dielectric were evaluated with SAC 305 solder alloy. The results are listed in Table 5.

Table 5: Solder Acceptance and leach resistance of CL81-10347 with SAC 305 solder.

Solder acceptance and leach	
1 x 5 sec	<5%
2 x 5 sec	<5%
3 x 5 sec	<10%
Solderability	>95%

Adhesion Determination

Leads were positioned over 80x80 mil pads on the test coupon in Figure 7. The coupons were then placed in a fixture to hold the leads in place and inserted into the testing arm of the solder dipper. The test coupons were immersed in the flux followed by immersion in the various solder alloys (see Table 4 for immersion times). The test coupons were then cleaned with acetone and allowed to air dry for minimum of six hours. The hooks were cut off and the wires bent to a 90^o angle using a mechanical fixture to minimize any variation in the bend angle. Initial adhesion was determined after six hours. The remaining coupons were placed in a 150°C box oven for 1000 hrs as well as 1000 hrs. at 85°C/85%RH and thermal cycle adhesion at -50°C/+150°C for 1000 cycles.

Lead pull testing was used to determine the force needed to pull the individual leads from the printed conductor pad after soldering. Each lead was trimmed to two inches (flat). A Zwick Z2.5 Pull Tester was used to measure adhesion. The parts were then clamped into the Zwick's specimen grip. Each lead was pulled perpendicular to the substrate until separated from the printed conductor pad. The arm movement was set at a constant speed of 0.5 inches/minute. The grip separation was set at 1.25 inches.

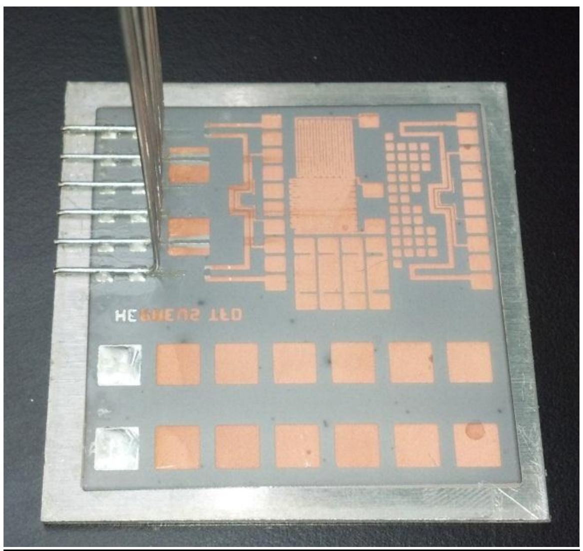


Figure 7: Adhesion Part with Lead Attachment and Hooks Removed.

Adhesion Results at 150ºC:

The following chart in Figure 9 shows the adhesion of the copper conductor on top of IP6075 dielectric fired at 600ºC with SAC 305 solder, both initially and after aging at 150 °C for up to 1000 hrs.

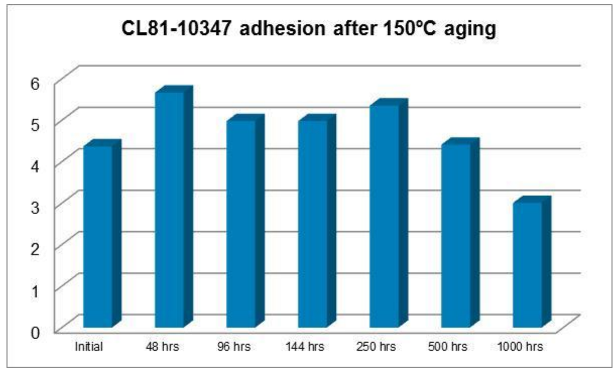


Figure 9: Adhesion Data with SAC 305 Solder After 150°C Aging.

Table 6 lists the adhesion failure mode of the CL81-10347 conductor. It is clear that as the conductor was aged at 150°C the percent of wire pulls out of the solder decreases and the amount of pad lifts increases.

Table 6: Adhesion Failure Mechanism of Aged Parts with SAC 305 Solder.

initial	100	wp		
48 hrs	85	wp	15	df
96 hrs	100	df		
144 hrs	100	df		
250 hsr	100	df		
500 hrs	20	wp	80	sf
1000 hrs	100	df		

wp - wire pull
df - dielectic failure
sf - solder failure
pl - pad lift

It appears that the failure mechanism up to 48 hrs. was the wire pulling out of the solder and then the mechanism changed to dielectric failure for the next 950 hrs.

Failure mechanism:

The following photos in Figure 8, 9, and 10 shows the failure mechanism described above.

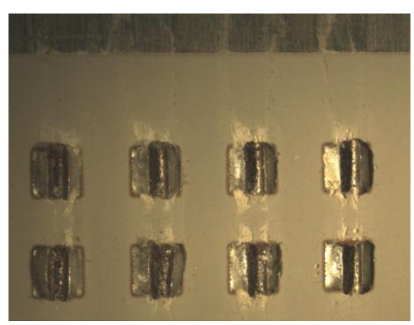


Figure 8: Wire Pull Failure Mechanism.

Figure 9: Pad Lift Failure Mechanism.

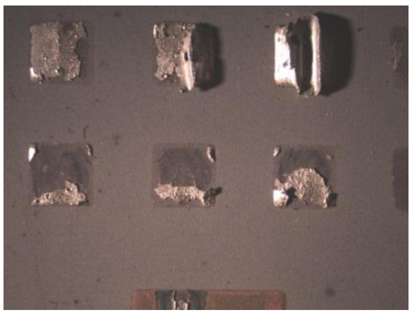


Figure 10: Dielectric Failure Mechanisms.

Thermal Cycle Adhesion:

The thermal cycle adhesion parts were tested at -50ºC/+150ºC for 1000 cycles, the parts were removed from the chamber in 100 cycle intervals. The adhesion data for CL81-10347 on IP6075 dielectric and the failure mechanism are recorded in Table 7. The parts were allowed to come to room temperature and equilibrate before testing adhesion.

Table 7: Thermal Cycle Adhesion Data with SAC 305 Solder.

Thermal Cycling	Lbs.	wp	df	sf	pl
50 Cycles	5.66	67	33		
100 Cycles	3.92		100		
200 Cycles	4.5		100		
300 Cycles	4.89		100		
400 Cycles	4.52		100		
500 Cycles	3.98				100
600 Cycles	2.53		100		
700 Cycles	3.99		50	50	
800 Cycles	4.89	33		67	
900 Cycles	4.44		67	33	
1000 Cycles	2.85		100		

While thermal cycling the failure mechanism becomes dielectric failure rather than conductor failure (wire pull or pad lift) compared to aging adhesion at 150°C.

Adhesion in 85°C/85%RH

The adhesion of CL81-10347 on top of IP6075 is shown in Figure 11. The chart shows the adhesion as well as the failure mechanism. The right axis represents % failure mechanism, while the left axis represents adhesion in Lbs.

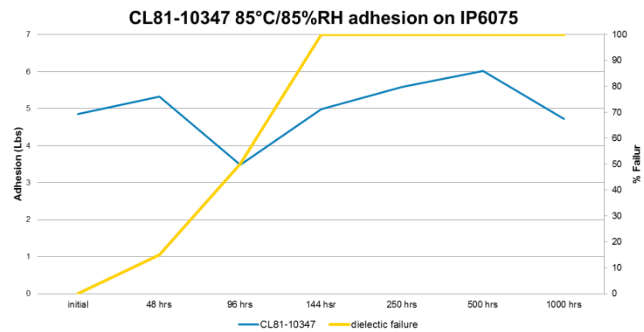


Figure 11: 85C/85%RH Adhesion Data with SAC 305 Solder.

Discussion

Dealing with nitrogen firing materials is a difficult task, due to the firing atmosphere. Organic systems have to be specifically chosen to burnout cleanly in an inert atmosphere, particle sizes of the powders have to be chosen and controlled to develop the appropriate microstructure. Then, you narrow your choices even further when the firing temperature has to be at 600°C or lower. There are processing steps involved when firing in a nitrogen atmosphere, the oxygen levels in the burnout zone of the furnace has to be set up to make sure that the organics are completely burned off before the sintering of the copper powder takes place. Selecting copper powders and an inorganic binder that works well at a low firing temperature as well as on top of a glassy dielectric layer has been a large part of this product development. Therefore the challenges in this product development were, how well the copper powders and the glass binder sinter on top of a dielectric to form a conductive layer with good physical properties. In some circumstances the adhesion on top of IP6075 seems low but after examining the failure mechanism it is clear that the conductor bonds well to the dielectric. The SAC 305 solder alloy used in this study is the recommended solder alloy for RoHS compliant products.

Conclusion

The combination of copper powder selection and lead free glass frit in this thick film copper conductor paste and SAC 305 solder alloy evaluated in this study provides information on how reliable the adhesion is at a given fired film thickness. Including results at 150°C, 85°C/85%RH and when thermal cycled for 1000 hours at-50/+150°C. This information can be useful to a hybrid circuit manufacturer when selecting a thick film conductor or a solder alloy for their application. Based on this study, we have successfully developed a lead and cadmium free thick film circuit conductor with acceptable performance using a lead free solder alloy. This material allows thick film manufacturers to build thermal substrates with copper conductors instead of silver conductors. The copper offers low cost possibilities due to its base metal nature and excellent reliability performance.

Acknowledgments

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