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Sputter-free and reproducible laser welding of electric or electronic copper contacts with a green laser

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Abstract

Today's commonly used IR-lasers suffer from two limitations: Firstly the process reproducibility can be quite low as copper is highly reflective at 1 µm wavelength, and secondly the process parameters used today typically result in splatters emerging from the welded region during the deep penetration welding process, leading to short circuits.
A newly developed purely green laser source meets all requirements of optimized process quality.
For a pulsed welding process at 0.5 µm wavelength, local power density distribution and pulse shape have been examined and optimized. The results have been compared to 1 µm wavelength.
The most precise method to detect splatters is the recording of the welding process by means of a high-speed camera. This allows to detect exactly which types of splatters exist and which process phase is responsible for their formation.
The time and the type of coupling of laser light into highly reflective materials can be determined as well.
By using green laser pulses no splatters occur from 0.1 mm to 0.8 mm penetration depth. Welding spots do not differ in size. Surface condition of copper has no influence on the welding. In addition to tests on overlap welding and butt welding of electric contacts, special attention has been turned to welding of DCB´s (Direct copper bondings in power electronic substrates).

green laser, copper, reproducibility, process quality, sputter-free, DCB, pulsed laser

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1. Introduction

Pulsed solid state lasers are used in electro technology, precision engineering, medical technology and automotive production, as well as in tool and mold production. They weld, cut, mark, drill and structure. They are also used for deposit welding and ablation. One application is the welding of copper materials of high conductivity for electronic and electrical contacts, including electronic switching devices or plug-in connectors. Although most running welding applications fulfill all requirements of solidity, conductivity and process stability, two questions are often asked:

(i) Can we reduce the amount of splatters from the welding process?

(ii) Can we stabilize the reproducibility of welding spots and reduce the influence of surface conditions?

These are important questions as (i) splatters can lead to failures of the work piece due to short circuits and (ii) often the surface has to be coated with tin or it has to be sandblasted prior to welding to ensure sufficient process reproducibility.

To answer these questions, laser parameters such as pulsed and continuous welding process, 1 µm and 0.5 µm wavelength, local power density distribution and temporal progression of the power have been examined and optimized. All tests have been performed with pure, oxygen free copper with low resistance (SE-Cu), which is generally used for electronic and electrical contacts.

1.1. Influence factors on the welding process of copper

Influence factors on the welding process can be put into three groups. In the first group is the surface tension and the viscosity of copper. They cannot be influenced by laser parameters (only by shielding gas). Both are smaller compared to steel and therefore the melt bath is more unstable. Furthermore loss of energy by heat conduction is a lot higher. So no matter which laser, copper will always differ in welding behavior from steel.

The second group includes those welding results that can be influenced by laser parameters like power density, power distribution and pulse shaping.

In the third group are those properties that are affected by the wavelength of the laser. Absorption is one of them, divided into the angle dependent absorption and the temperature dependent absorption and the state of matter dependent absorption. State of matter dependent absorption means, that there is a difference in absorption in vapor and fluid material depending on the wavelength. All three types of absorption affect the shape of the vapor channel and the roughness of the vapor channel surface. Therefore the wavelength does not only influence the beginning of the welding process. If the vapor channel is already existing, green and infrared still work differently.

1.2. Laser

In comparison to state of the art “TruPulse” lasers (infrared) a new laser source with a pulsed green laser beam was used for welding copper. Apart from the wavelength, the laser properties are similar.

PARAMETER	VALUE
Average power	400 W
Max. pulse power	4 kW
Max. pulse energy	40 J
Pulse duration	0,1 – 10 ms
Output	Fiber coupling, two outputs
LLK ø	100 µm

Fig. 1. Pulsed green laser

2. Reproducibility of Welding Spots

On sanded copper material of thickness 0.3 mm spots of nearly full penetration have been welded. With the green beam, the diameters of the spots are much more uniform. Also the surface condition does not matter. For green laser light it can be oxidized or rough, polished or etched with acid without changing the welding result. The reason is explained in chapter 4.

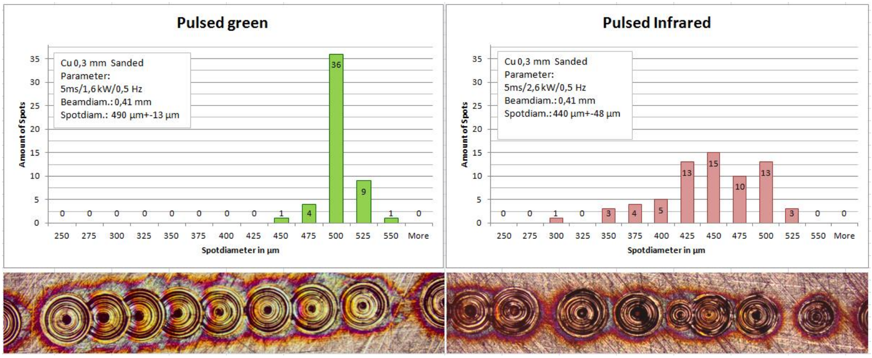


Fig. 2. (a) spot size, green (b) spot size, infrared

Fig. 3. Surface polished and sanded and etched with acid and oxidized, pulsed green laser

3. Incoupling efficiency

A nearly full penetration into a copper plate can be achieved with different combinations of pulse power and pulse duration. The higher the pulse power, the less pulse duration is needed. For long pulse durations a great amount of heat is lost by heat conduction which defines a minimum pulse power that is necessary to raise the temperature to melting temperature (for a given beam size). The incoupling efficiency of green light is much higher compared to infrared, thus the required pulse power is smaller. In Fig. 4 the minimum pulse power for infrared is 2.6 kW whereas the minimum green pulse power is only about 1.4 kW. In our experiments we noticed that higher intensity leads to more splatters. On the other hand, smaller beam size results in reduced difference of minimum pulse power between infrared and green, but also increased splatter generation. Furthermore the power density needed for melting the copper is not constant but also depends on the beam size.

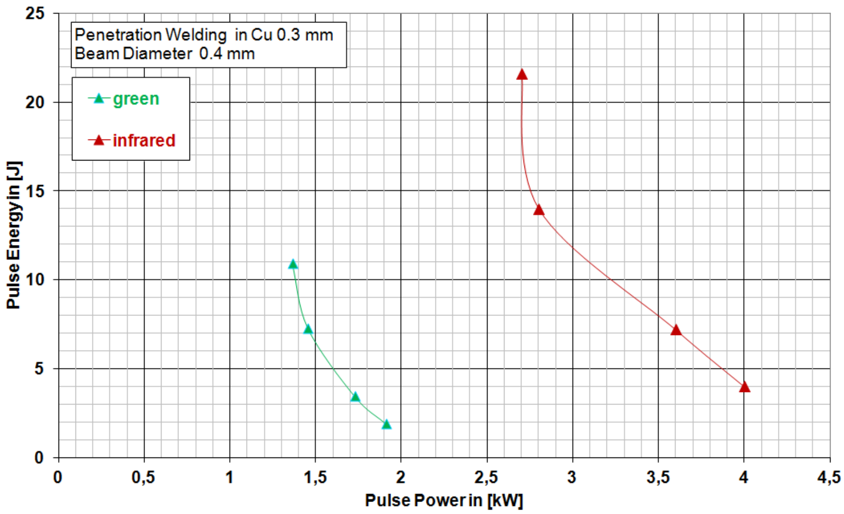


Fig. 4. Low sputter spot welding with different pulse duration and pulse power

4. High speed measurement of incoupling

Using a high speed camera, the welding process can be divided into defined process temperatures by inspection of the appearance of the weld.

- Room temperature: No melt
- Melting temperature: Flat surface of small melt bath
- Vaporization temperature: Vapor channel and vapor plume

With infrared and green pulses of the same diameter and the same pulse duration a spot welding into copper of 0.3 mm thickness was performed. The pulse power was adapted to achieve nearly a full penetration in both cases. After 5 ms both setups performed the same task. The infrared laser beam takes much longer to achieve melting temperature. Afterwards another 50 % of pulse duration is needed to raise the temperature to vaporization temperature. Not much welding depth is achieved until then. Most of the depth of penetration is performed at the pulse end, after the formation of the vapor channel and the multiple reflections therein. The time for achieving the melting temperature and vaporization temperature varies strongly. The part that does the welding (yellow, in Fig. 5) differs from spot to spot, leading to different sizes of spot diameter and different depth.
Using the green laser beam, the welding starts earlier and at exactly the same time for every pulse. In this example no vaporization temperature is needed, as the full welding depth is reached before. (But it will of course be needed for deeper penetrations)
The laser power input into copper is a lot more stable and uniform with green than with infrared. It is more stable, because it does not have a time jitter and it is more uniform, because the isotherms advance into the work piece steadily from the beginning of the pulse.

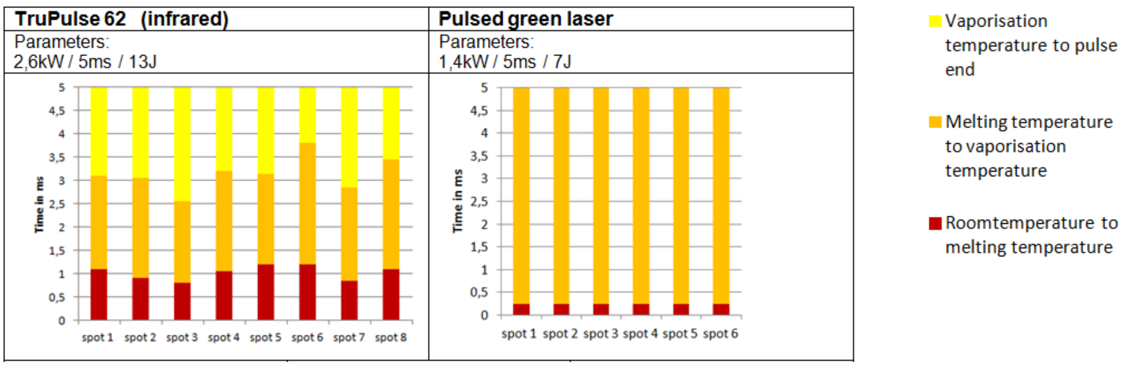


Fig. 5. Laser penetration time into copper 0.3 mm

5. Cover gas

Using cover gas (Argon or Nitrogen) while welding copper with infrared is not recommended. The loss by reflection is much higher and therefore more pulse power is needed to get the same spot size. The spot results are more unstable.
Doing the same with a green laser beam doesn´t affect the penetration depth much, but it has a positive

effect on the quality of the joint. The cross sections do have a better filling degree. Unfortunately, cover gas does not reduce splatters.

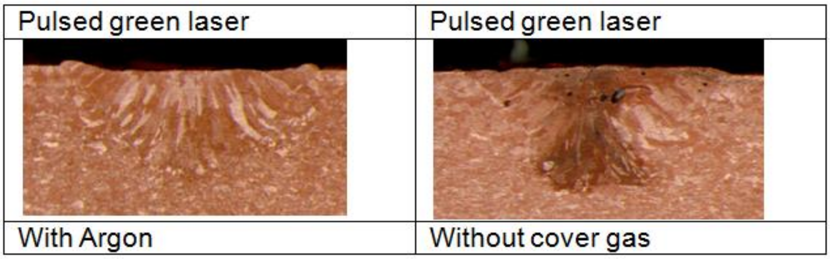


Fig. 6. Cross sections (a) with and (b) without cover gas

6. Welding depth with low sputtering

For a good quality of spot welding with low sputtering, an adaptation of spatial pulse power distribution and of pulse shaping over time is needed. Sputters are formed at different stages of the welding process. The sputters forming at the closing of the vapor channel can be easily avoided. A laser power ramp is enough to extinguish those.

It is more difficult to avoid the sputters that are generated during the last third of the welding time and originate from too much liquid melt in the pool without enough room to form a stable bath. The melt pool size is a good parameter to help here. Nevertheless, there is a limit to the stability of the melt ring around the vapor channel. The deeper the spot weld, the more melt volume is inside the ring around the channel. If the volume is too big, the surface tension of molten copper is not strong enough, to overcome the pressure from within the channel. Expulsions result. The maximum depth which can be welded with no visible sputters over 10 pulses with high speed films is 1 mm. At 1.3 mm depth some small sputters are emitted and at 1.6 mm expulsions get bigger.

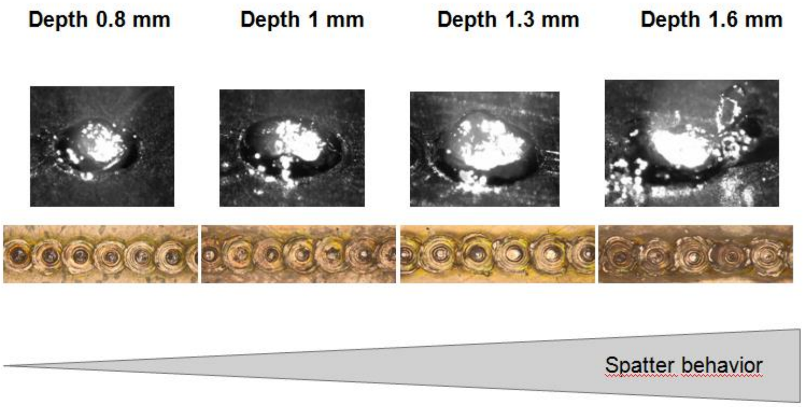
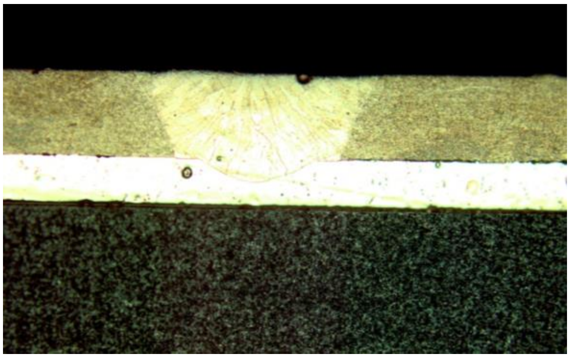


Fig. 7. Welding depth

7. Welding of DCB material

Direct copper bonding (DCB) is used in high power electrical devices. Those devices have a high thermal conduction combined with a good isolation and low thermal expansion. Often the top layer of copper is a printed circuit board, which is attached to a ceramics plate . The electrical connection from outside to the circuit board can be done by laser welding. As the thickness of the top layer of copper is very small, the welding depth has to be precise, so as not to destroy the ceramics. Tests have been done with a copper layer thickness of 0.2 mm. The thicker the connecting copper plate (to the outside), the smaller the setting range of parameters like pulse energy or focal distance. With a connecting copper plate thickness of 0.4 mm the margin is feasible. With a connecting copper plate thickness of 0.3 mm it is easy to achieve.



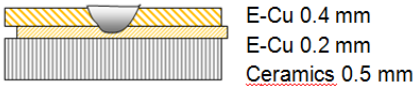


Fig. 8. Cross section of DCB welding

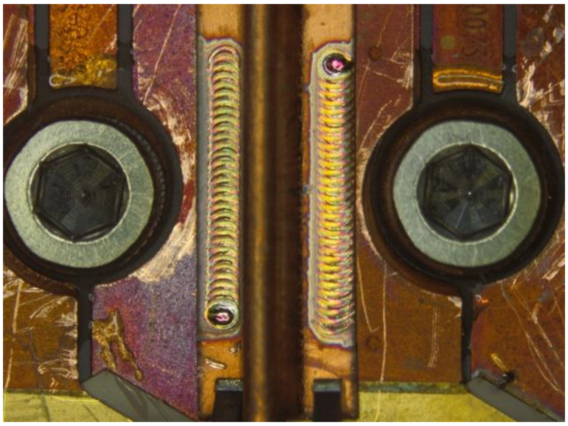


Fig. 9. Top side of DCB Welding

8. Summary

The pulsed green laser shows great potential for welding copper with low sputtering and with stable and uniform size of welding diameter and depth. The absorption of the laser beam is much higher and faster than with infrared, which results in a shifting of process mechanism from deep penetration welding to heat conduction welding. Therefore a highly improved weld quality and splatter-free welding has been achieved. There is no influence of surface condition any more on the welding process (see Fig 3).

Copper spot welding	Green	Infrared
Incoupling	+	-
Welding time	+	+
Sputters	+	-
Reproducibility	+	-

Fig. 10. Summary result

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