1 Introduction

1.1 Motivation

The European Commission has established a long-term target of achieving at least a 55 % reduction in greenhouse gas emissions by 2030 in comparison to 1990 levels [EUR21]. Additionally, the European Union (EU) aims to become climate-neutral by 2050, which would entail balancing the overall carbon emissions by removing an equivalent amount of greenhouse gases from the atmosphere [EUR20]. To achieve these targets, the EU presented the European Green Deal program, which requires action by all economic sectors to transition to a sustainable and low-carbon economy. Decarbonization of the energy sector, for example, can be achieved by increasing the renewable energy portion and substituting combustion engine vehicles with electric vehicles. This should reduce greenhouse gas emissions [EUR19].

Integrating renewable energy sources and advancing electrification of mobility requires high-performing power electronics with improved efficiency and power conversion capabilities. The advancements in power electronics enable the efficient integration of renewable energy sources into the grid, maximizing the utilization of clean energy and reducing reliance on fossil fuels. Power electronics drive the electrification of transportation, enabling the design of electric vehicles with extended range, fast charging capabilities, and efficient motor drive systems. Therefore, the market forecast for power electronics shows strong growth until 2030 (Figure 1) [MAR23].

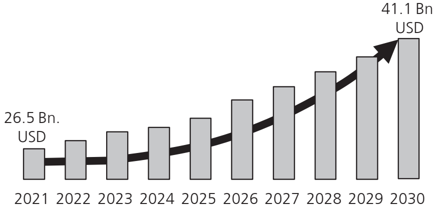

Figure 1:
Market forecast for the power electronic components until year 2030 [MAR23]

As the demand for power electronics continues to grow, the electronic packaging of semiconductor components should be improved to meet the increasing performance requirements. Consequently, insulated-gate bipolar transistors (IGBT) and metal-oxide-semiconductor field-effect transistors (MOSFET) require larger current-carrying cross-sections and high-temperature stable joints with operational temperatures up to 225°C [GOT15]. However, conventional packaging technologies, such as wire bonding and soldering processes are limited to fulfill these requirements [BWO15]. In terms of soldering, the required operation temperature for electronic packaging is higher than the melting temperature of the joint [HNH03]. The high pressure during wire bonding can damage the substrate, particularly when bonding a thick wire to the chip. Additionally, the combination of materials and surface conditions represents the limitations of the wire bonding process [ZHO11].

Conversely, the laser beam welding process can fulfill the anticipated demand for electronic packaging. The weld joint created by a laser beam has temperature stability that extends to the melting temperature of the base material. Furthermore, the use of an interconnector with a large cross-section enables the creation of a large joint area. Moreover, the laser beam welding process is not constrained by the material combination and surface conditions. Nevertheless, the induced thermal stress during the laser beam welding process represents a challenge due to the low heat tolerance of the thermally sensitive substrate situated beneath the metalization. Despite the ability to precisely regulate the energy input during the laser beam welding process, this technology has not yet been widely adopted as a packaging solution for electronic components.

To overcome the limitations of the conventional laser beam welding process among the established electronic packaging technologies, [BWO15] proposed a novel process termed "Laser Impulse Metal Bonding" (LIMBO). The LIMBO process is a laser-based welding process that enables direct welding of the thick interconnector to the thin metalization on the thermally sensitive substrate. Both joining partners are spatially separated with a defined gap. This outgoing position allows a differentiation between the melting and joining procedures. Consequently, the underlying chip surface is only subjected to thermal stress during the joining procedure. A schematic representation of the LIMBO process and three process stages are shown in Figure 2.

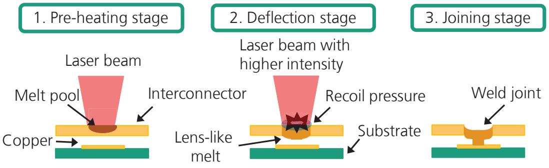

Figure 2: Schematic representation of the LIMBO process [BWO15]

During the pre-heating stage, the laser beam shines on the upper joining partner to locally generate a melt pool, which melts the entire thickness of the upper joining partner. As two joining partners are separated with a gap, the heat required for melting the upper joining partner has a negligible thermal influence on the lower joining partner. The pre-heating stage continues until the melt pool has reached the bottom side of the upper joining partner. This stage should be performed with the heat conduction welding regime to maximize the melt volume for the subsequent stage. At the deflection stage, the laser beam with higher intensity shines on the melt surface to rapidly vaporize the melt surface. As a consequence, a metal plume recoil pressure is generated at the melt surface. This outflowing metal vapor pressure pushes the melt towards the lower joining partner, which bridges the gap. The subsequent joining stage starts as soon as the melt contacts the lower joining partner surface. This thermal link allows heat conduction between gap-bridging melt and the underlying substrate. The stored heat in the melt heats the metalization surface. After the joining stage, the gap-bridging melt, and the metalization solidifies to form a weld joint.

A single LIMBO process results in the formation of a single circular-shaped weld joint area. However, considering the functionality of the weld joint for electrical interconnection, this single weld joint is limited to its current-carrying area and mechanical stability. The motivation of this thesis is therefore to further develop the described LIMBO process aimed at the electric packaging demand. The increased weld joint area is expected to improve the electrical and mechanical properties. However, the boundary condition for the electric packaging such as a limited surface area for the welding process and a low thermal threshold of the substrate should be considered.

1.2 Aim of the thesis

The total weld joint area can be increased by applying multiple spot-welds on a chip surface with a sufficient distance (pitch) between them. In this way, an array of welds can be applied on a chip surface. However, the pitch limits the spatial utilization of the chip surface with a limited area. The spatial utilization can be defined as a geometrical ratio between the total weld joint area A_w and the available chip surface area A_c denoted by ζ_c (Figure 2). When the chip surface area is limited, the aforementioned ratio is increased when each weld joint is placed in closer proximity to one another. By reducing the pitch, the spatial utilization increases on a chip surface. The ideal case would be a gapless continuation of the spot welds. However, the subsequent welding process will be influenced by the previous weld.

The aim of this thesis is therefore to investigate the impact of the thermal influence on a thermally sensitive substrate during the subsequent welding process. In contrast to the initial LIMBO process, where the joining partners are spatially separated, both joining partners are already connected through the previous weld joint. The existing connection thus permits heat conduction throughout the entire subsequent welding process. To date, no investigation has been conducted to investigate the influence of pitch on the subsequent LIMBO process. Figure 3 shows the schematic representation of the starting position (LIMBO) and the aim of this thesis, which concerns the spatial utilization value ζ_c.

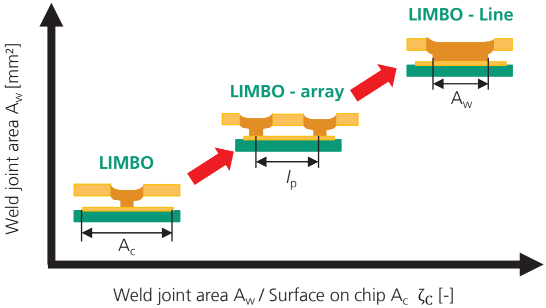

Figure 3:
Schematic representation of the aim of the thesis

l_p: Pitch

ζ_c: Geometrical ratio between weld joint area A_w and surface on chip for welding A_c

The hypothesis of this thesis is that the total weld joint area can be maximized on a limited chip surface by reducing the pitch. As a result, the weld joint properties will improve. The induced thermal load should not exceed the substrate threshold despite the reduced distance and multiple welds on a chip. Three research questions have been defined to address the hypothesis of this thesis and to be answered:

1. Which process variables influence the heat distribution through the gap-bridging melt during the LIMBO process?
2. What are the effects of the existing weld joint on the subsequent LIMBO process concerning the thermal load on the substrate?
3. Which factors influence the electric contact quality and the mechanical stability of a joint area over the gap?

The increased weld joint area is targeted to benefit the function-oriented electrical and mechanical properties. Therefore, three target parameters for this thesis are defined below to evaluate the hypothesis of this thesis:

- Extension of the circular-shaped weld joint to a continuous linear weld joint with a length $l \geq 1$ mm ($A_w = 0.2$ mm²) on a sensitive substrate,
- Improvement of the electric contact quality k_c value lower than 1.5,
- Improvement of the maximum shearing force F_{shear} value higher than 150 N to compensate the thermal expansion.

The increased weld joint area of the LIMBO process should at least have a comparable current-carrying cross-section to a thick copper wire. The current-carrying cross-section of a 0.5 mm thick copper wire has a current fusing value of 50 A [HER17]. The linear-shaped weld joint area should therefore target to achieve a comparable current-carrying cross-section ($A = 0.196\ mm^2$) from a 0.5 mm thick copper wire. A long-term stability criterion from the medium-voltage system [BÖH05, P. 107] is benchmarked for the electrical property. The thermally induced mechanical property is considered based on the expected thermal expansion of the interconnector during the operation at $T = 200°C$.