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Low temperature optodic bonding for integration of micro optoelectronic components in polymer optronic systems

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Abstract

Large area, planar optronic systems based on flexible polymer substrates allow a reel-to-reel mass production, which is widely adopted in modern manufacturing. Polymer optronic systems are fully integrated with micro optical and optoelectronic components as light sources, detectors and sensors to establish highly functional sensor networks. To achieve economical production, low-cost polymer sheets are employed. Since they are mostly thermally sensitive, this requires a restricted thermal loading during processing. Furthermore, a short process time improves production efficiency, which plays a key role in manufacturing processes. Thus, in this contribution we introduce a new bare chip bonding technique using light instead of heat to meet both requirements. The technique is based on the conventional flip-chip die bonding process. Ultraviolet radiation curing adhesives are applied as bonding material, accordingly a sideway ultraviolet radiation source, a so-called optode, is designed. Before implementing the concept, the light distribution in the contact spot is simulated to examine the feasibility of the solution. Besides, we investigate two different UV lamps regarding induced thermal influence on polymer substrate to choose one to be employed in the optode. Process factors, irradiation intensity and irradiation time are studied. Based on these results, the mechanical and electrical reliability of the integrated components is finally evaluated.

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Keywords: Flip-chip; die bonding; UV-curing adhesives; optoelectronic; component integration; low-temperature

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1. Introduction

With rapid development of modern information technology the demands of sensor systems for more reliability of signal detection and conversion, higher speed of data transmission, more flexibility of carrier materials, and lower cost of mass production are increasingly growing. Fully integrated, large area optronic systems based on planar polymer substrates are the innovative solution. Optronics implies the employing of optical or optoelectronic components as light sources, detectors or sensors as well as optical waveguides as transmission medium to create a fully optical system that is well-established for sensing, processing of signals and transmission of data. Polymer films with a thickness of a hundred micro meters as carrier substrate offer high flexibility so that the optronic systems allow a reel-to-reel mass production, which facilitates a highly efficient manufacturing process. Besides, polymer films can mostly be purchased on a low budget, which makes the production of optronic systems more economical.

To realize such polymer based planar optronic systems, one key focus is on the integration of optical or optoelectronic components into the thin polymer sheets. We employ the optical or optoelectronic components in form of bare chips. Given the fact that most polymer products are thermally sensitive because of their low glass transition temperature Tg, e.g. PMMA with Tg 105 °C, PET 70 °C and PVC 80 °C, the thermal loading on polymer sheets must be restricted during processing [1]. Another particular aspect is the requirement of the high positioning accuracy of the bare optoelectronic chips. As shown in Fig. 1 left, a small tilt of the bonded laser diode may cause a great loss of light transmission into the waveguide [2].

According to the state of the art in the field of chip mounting technology, there are two bonding methods available to accomplish the electric connections: wire bonding and flip-chip die bonding. In wire bonding technology, the chips are mounted face up, and the wires are used to build interconnections between the pads of chip and external [3]. Flip-chip die bonding is referred to as a mounting technology, in which the functional side of bare chip is faced down, and the pads on chip are aligned directly with the external circuit [4]. By this way, the electric connection is completed simultaneously with the mechanical mounting, which makes the whole bonding process much more efficient and cost-effective. Regarding the fact that optronic systems are built on a large area, flexible polymer substrate, wire bonding technology is excluded, since thin wire interconnections cannot withstand a variety of environmental disturbances. Thus, flip-chip die bonding technology is preferred.

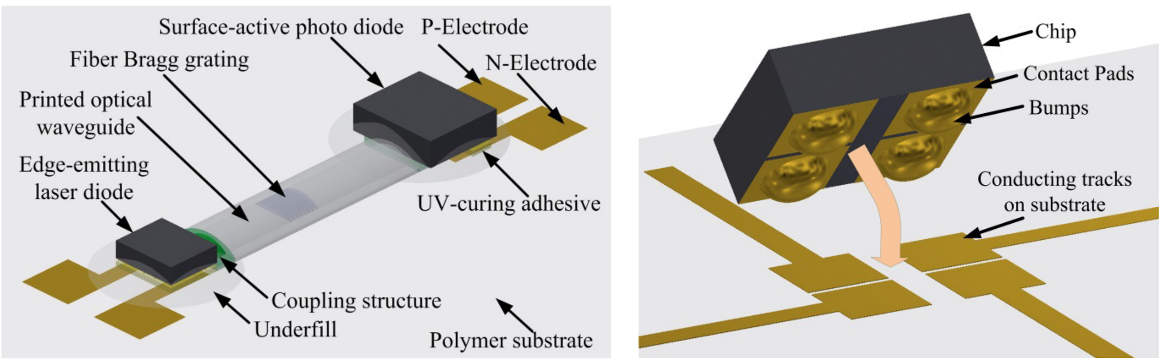

Fig. 1. Left: Planar optronic system based on conventional semiconductor optoelectronic components; right: Flip-chip technology.

In most applications of flip-chip technology, thermal effects are utilized, typically using solder bumps combined with hot air reflow or heat curing adhesives [5]. However, as already mentioned, thermal loading has to be avoided in polymer optronic systems to protect the polymer substrate from damage. With above considerations, we developed a new bonding method based on flip-chip technology using light instead of heat to realize the integration of bare optoelectronic chips into polymer optronic systems. Using light means applying ultraviolet curing adhesives (abbreviated as UV curing adhesive) as bonding material and getting it cured by UV irradiation. In order to enforce a stable UV irradiation during the curing process, a reliable UV radiation source is necessary.

2. Optodic Bonding

The development focus of this new bonding method lies on the design and realization of the UV radiation source, the so-called optode [6]. In this context, the new bonding method was called “optodic bonding”.

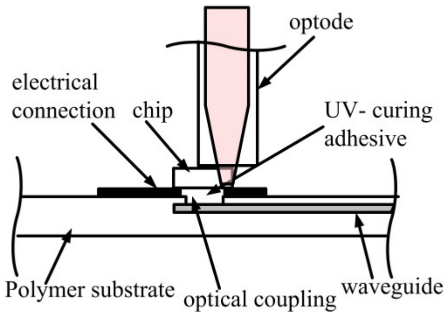

Fig. 2. Schematic illustration of chip integration in optronic system using optodic bonding (Krühn T, 2012).

Fig. 2 illustrates the principle of how optoelectronic chips are integrated in the optronic system. The chip is flipped down to make a direct contact with the pads on the circuit while it is mounted on the polymer substrate. UV-curing adhesives serve hereon as bonding material mainly to assure the mechanical connection. Furthermore, some UV-curing adhesives contribute to electric contacting as well, e.g. isotropic conductive adhesive (ICA) and anisotropic conductive adhesive (ACA) [7]. Because of the danger leading to an electrical short of circuit, the ICA UV-curing adhesives are out of choice. ACA UV-curing adhesives are also excluded for the moment due to the shortage of the sorts on the market and the high cost of purchase. Therefore, in this work we employ non-conductive UV-curing adhesives. By triggering the optode, the UV rays are getting started to irradiate and will be guided in the direction of the spot of the adhesive. While getting the adhesive cured, the chip is getting mounted mechanically on the polymer films and electrically interconnected with the circuit.

2.1 Optode for sideway irradiation

On the basis of the concept shown in Fig. 2, an optode serving as sideway irradiation was designed and is illustrated in Fig. 3.

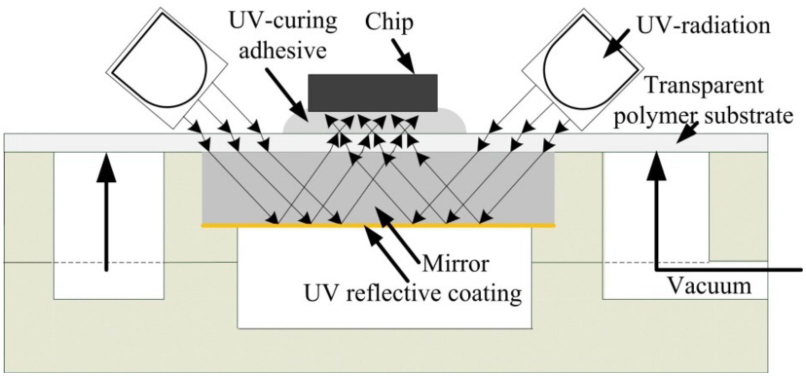

Fig. 3. Schematic illustration of optode for sideway irradiation.

A manual flip-chip die bonding assembly system named *Fineplacer*® is used which is equipped with a heat plate as thermode for a conventional bonding process. To realize the optode illustrated in Fig. 3, the heat plate has to be replaced by a newly constructed underplate. As a result, the vacuum configuration attached within the heat plate was eliminated as well, leaving the polymer films unfixed. This gives rise to unwished moving of the polymer films during processing. Even a tiny shifting can cause great positioning faults. Given this effect, we built a vacuum channel in form of a circle, which consists of many small holes around the bonding spot on the surface of the underplate.

The transparent polymer substrate lay on the underplate must have a sufficient transmission grade of UV irradiation. Fig. 4 shows the property of the transmission, reflection and absorption of the light in the UV range from 350 nm to 400 nm for the polymer substrates PET with a thickness of 200 µm and the PMMA with a thickness of 175 µm.

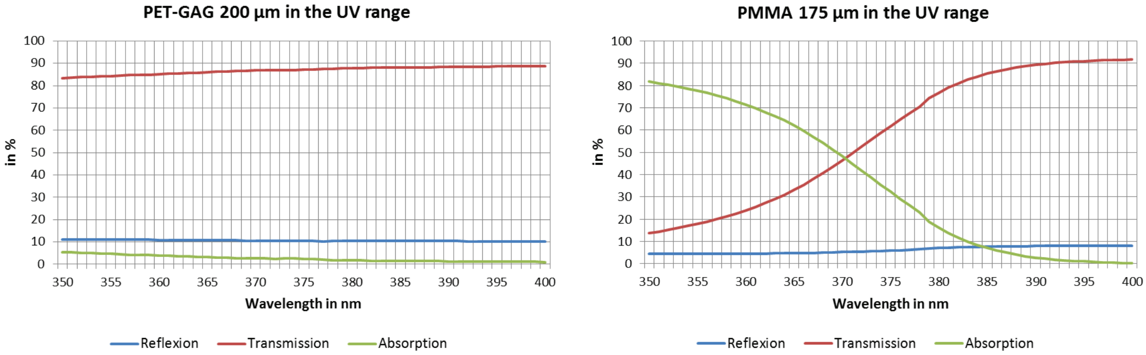

Fig. 4. Light transmission, reflection and absorption in the UV range. left: PET 200 µm; right: PMMA 175 µm.

Polymer substrate PET-GAG has a sufficient UV transmission grade for the range from 350 µm to 400 µm. In contrast, for PMMA a UV transmission grade of about 80% starts only from the wavelength of 380 µm. This optical property of polymer substrates has a significant effect on choosing UV-radiation source.

The chip is placed face-down, aligned with the conducting track on the polymer substrate after the UV-curing adhesive is dispensed on this contact spot. To accomplish the junction between chip and substrate, the key is the curing of the adhesive. However, because of the ultrathin thickness of the adhesive layer barely adequate UV rays can reach there to get the adhesive cured. To solve this problem, we place a mirror under the contact spot utilizing the principle of light reflection to collect sufficient UV irradiation.

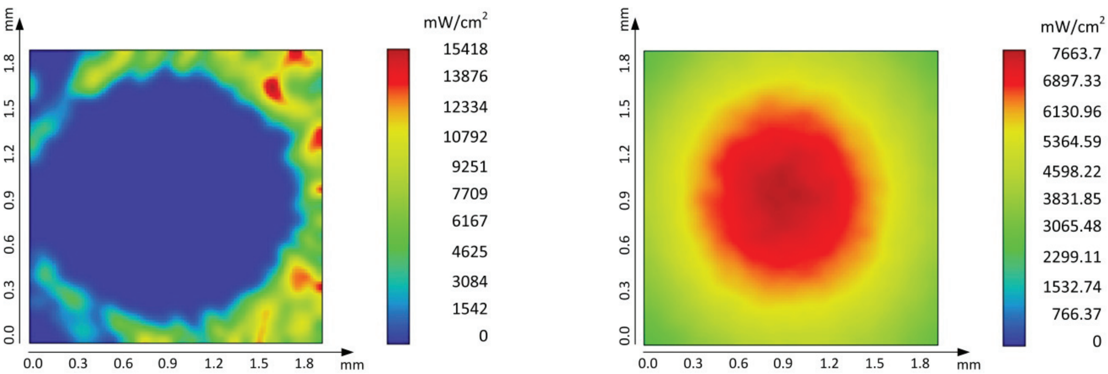

Fig. 5. Simulation of the intensity distribution of UV irradiation on the contact spot from sideway optode. left: without mirror; right: with mirror.

As a first step, the feasibility of this solution was to be examined. For this purpose, we conducted a simulation of an optode with and without mirror. As simulation tool the software Zemax was applied. Aim of the simulation was to find out whether and how much UV irradiation reaches the contact spot. The question can be answered by investigating the intensity distribution of UV irradiation on the contact spot. The result presented in Fig. 5 shows a clear contrast between the simulation with and without mirror. The number in the figure has the unit mW/cm^2. In the left figure for the simulation without mirror, a blue circle can be seen that stands for an intensity of nearly 0 mW/cm^2, i.e. no UV irradiation at all. In contrast, a red circle in the right figure that describes the simulation with mirror indicates an intensity of 7663.70 mW/cm^2, i.e. sufficient UV irradiation. Therefore, the simulation with mirror verified the feasibility of a sideway optode.

As shown in Fig. 3, the UV ray is emitted by a UV lamp, passes through the thin transparent polymer substrate, reaches the coated surface of the mirror and then is reflected to the contact spot, where the adhesive lies. The employed mirror has a thickness of 5 mm. If the coated surface of the mirror faces upwards, the adhesive can hardly be irradiated. Due to the low thickness of the substrate, the propagation path of the UV rays is too short to create a sufficiently horizontal shifting distance between incident light and emerging light, so that the UV rays reach the adhesive. They will only be reflected once and then emitted away immediately. By flipping the mirror faced down the coated surface lies far away from the polymer substrate by the thickness of the mirror itself. Thus, the propagation path of the UV rays is extended. It results in a larger horizontal shifting distance between incident light and emerging light. In this way, the UV irradiation will reach the contact spot to get the adhesive cured.

In addition, the position of the UV lamp and the angle of incidence of UV rays play a large role in the curing process as well. Thus, when designing the optode, both factors were taken into account, trying to make them adjustable. By adjusting the angles and axes, an optimum position is to be found out, in which the adhesive is maximally irradiated and cured by UV rays. It must be subsequently fixed before starting the bonding process.

Due to the spatial restriction of *Fineplacer®*, only the left UV radiation can be realized.

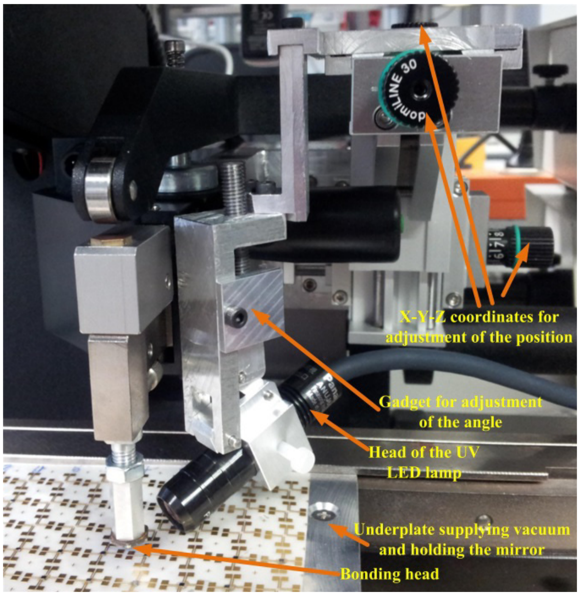

Fig. 6. Photo of realized sideway optode (only the right side of UV irradiation).

2.1. Choice of UV lamp

Fig. 6 shows an irradiation head, which is the head of a LED UV lamp. An appropriate lamp can prevent the polymer substrate from thermal damage, if it induces no or very few heat loading. Furthermore, it can facilitate a shortening of the process time, which improves production efficiency. As investigated, there are mainly two types of UV lamps on the market: the conventional UV lamp based on plasma physics and the LED UV lamp based on semiconductor technology. The table below shows a brief comparison of these two different lamps considering the items that are relevant to optodic bonding.

Table 1. Comparison of the different types of UV lamps.

	conventional UV technology	UV-LED technology
Functional principle	Built on plasma physics and optics	Built on semiconductor technology and optics
Spectrum	Continuous UV spectrum between 200 and 450 nm	Quasi-monochromatic radiation at defined wavelength, e.g. 365 nm, 385 nm
Lifetime	1000- 5000 h	>10000 h
Advantages & disadvantages	Warm-up period necessary	No warm-up period, instant on and off
	Heat portion	No heat loading of substrate

In order to find out the different effects that these two UV lamps have on polymer substrate, we conducted a test, where the UV head was installed in the optode, enabling it radiating directly towards the polymer sheet without adhesives. According to the right graph from fig. 4 we chose a head of the UV LED lamp with a wavelength of 385 nm, at which the UV transmission grade of PMMA is around 85%. Both UV irradiations lasted for 40 seconds with a maximal intensity of 10100 mW/cm^2. As test material we employed PMMA. Fig. 6 shows the different changes between the samples after irradiation by conventional UV lamp and LED UV lamp.

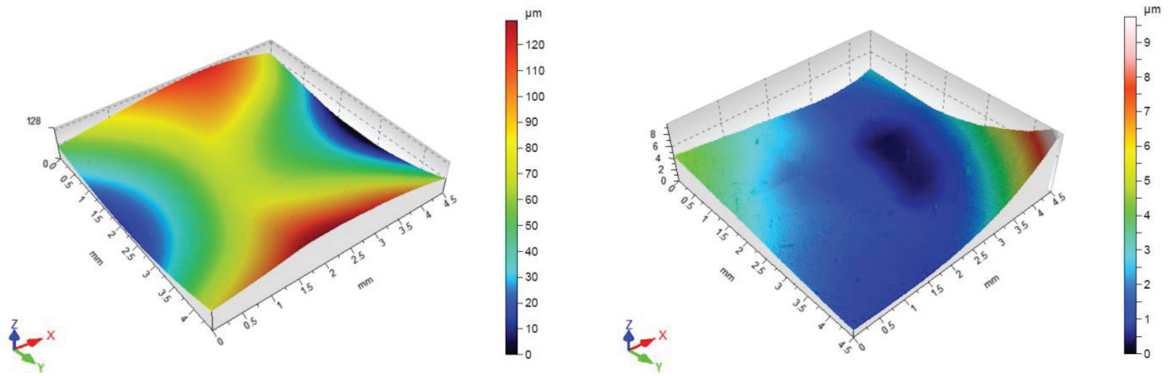

Fig. 7. Photos of polymer films. left: irradiated by conventional lamp; right: irradiated by LED lamp.

For the film that is irradiated by a conventional lamp, an obvious deformation is observed, which is caused by the heat portion of the irradiation. The maximum deformation is about 120 µm. In contrast, the film irradiated by a LED lamp remains nearly unchanged and was not damaged. Only a tiny deformation of 9 µm round the corner can be observed.

The explanations can be founded in table 1. In UV LED technology, the common warm-up period for on and off is eliminated, thus improving the process efficiency. In addition, very barely or even no heat loading will be induced over the whole irradiation. This is exactly what was expected as the goal of this research.

3. Analysis of process parameters

In order to achieve a reliable integration of optoelectronic bare chips into polymer substrates to establish a high functional sensor network, it is necessary to investigate the process parameters in optodic bonding. Only by mastering the influences of these parameters, the process can be controlled and improvements made to meet all requirements. Based on the concept and on the realized optode, mainly two parameters are considered: irradiation intensity and irradiation time.

To investigate the influence of both process parameters, bare chips of 1 mm x 1 mm size were used. The contact pads have an area of 80 µm x 80 µm, which is similar to most optoelectronic chips. Some pairs of adjacent pads on the chip are designed as two nested daisy chains, so that the electric conductivity can be measured. For the following tests, 4 daisy-chain pairs of each chip are applied [8].

3.1. Irradiation time

Generally, process time is one of the most relevant parameters in manufacturing engineering. Here the irradiation time is part of the entire process time, taking up a great portion. Thus, shortening irradiation time means shortening process time, which is of great significance for improving production efficiency. Prepared as specimens, the chips were integrated on polymer substrate by optodic bonding under the same conditions but different irradiation time. The intensity was adjusted to 7070 mW/cm^2. By checking the electric conductivity between adjacent contacts, we affirmed whether the chip had been bonded successfully. Meanwhile, we measured the electric resistance to conform with the conductivity quantitatively, when the chip was bonded successfully.

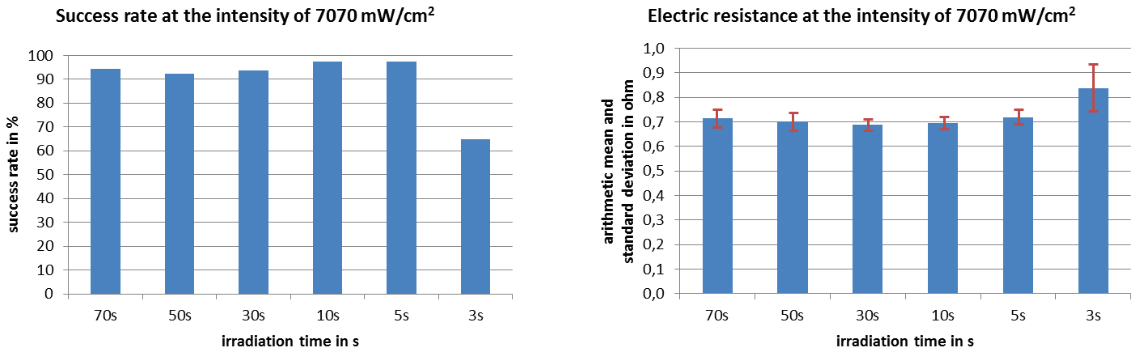

Fig. 8. Success rate (left) of optodic bonded chips and their electric resistance (right) in dependence on irradiation time.

After starting cautiously at 70 seconds, time was reduced always by 20 seconds till 10 seconds. Shorter than 10 seconds, tests were made at 5 seconds and 3 seconds. For every time stage, 10 chips, altogether 40 pairs of adjacent pads, were connected using optodic bonding technology. We observe in Fig. 8, the success rate from 70 seconds to 5 seconds remains approximately around 95%, which is nearly constant. At 3 seconds, it is strongly decreased. This means, 5 seconds UV irradiation time is sufficient to cure the adhesive successfully. Shorter than 5 seconds, here at 3 seconds, it can clearly be seen that the possibility to fail increases. A similar phenomenon can be observed in the electric resistance measuring. The arithmetic mean and standard deviation of the adjacent junctions stay around 0.7 ohm ±0.3 ohm from 70 seconds to 5 seconds. At 3 seconds, the value is evidently greater than others, which stands for a worse electric conductivity.

It is noted that in this work the chips were always bonded manually using optodic bonding technique. Thus, a success rate of 95% can be a sufficient result. For the automatic process about 100% should be reachable.

Furthermore, we conducted a shear test on these specimens to investigate the mechanical strength of the connections that are joined by optodic bonding. The result is shown in the following figure:

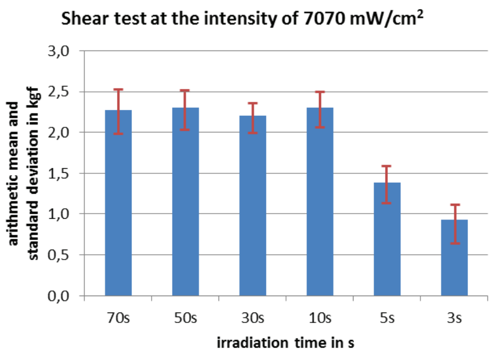

Fig. 9. Shear force of optodic bonded chips in dependence on irradiation time.

It can be recognized, that the mean shear forces for irradiation time from 70 seconds to 10 seconds are practically the same, staying around 2.25 kgf, which is nearly 22.5 N. According to the size of chips for 1 mm^2, the mean mechanical strength is calculated to about 22.5 N/mm^2. At 5 seconds, the shear force declines strongly to less than 1.4 kgf, and it keeps falling to 0.9 kgf at 3 seconds. The irradiation time has no significant effects on standard deviation.

Synthesizing the results above, an irradiation time of 5 seconds is sufficient for realizing the electric contacting between the optoelectronic chips and circuit in optronic system. However, considering the aspect of mechanical strength, the irradiation time of 5 seconds does not achieve the best result the UV adhesive can reach. An irradiation time of 10 seconds is still a time that is short enough for the whole production process.

3.2. Irradiation intensity

The intensity of irradiated UV rays affects the curing degree of the basis resin of NCA adhesives. The demanded minimum intensity for curing differs in dependence on adhesives. Analogously to investigating the irradiation time, we prepared the specimens in the same way. This time only the irradiation intensity was changed and all other conditions remained identical. The irradiation time was set to 5 seconds, with which a good success rate can be achieved. Afterwards we examined the electric conductivity and measured the electric resistance.

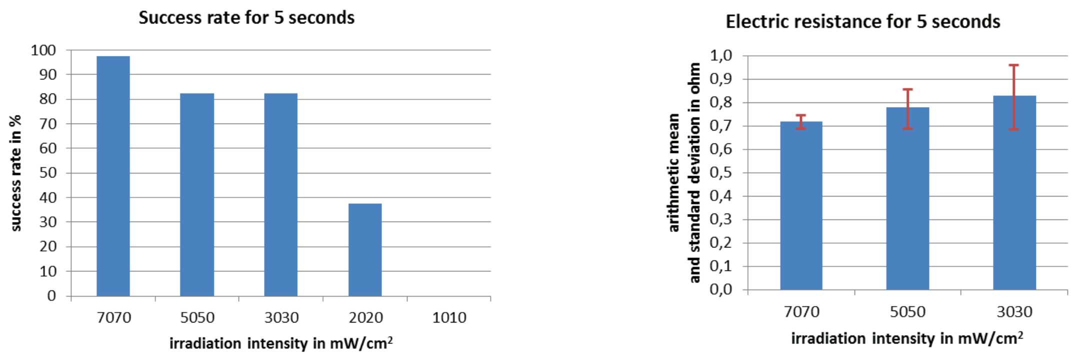

Fig. 10. Success rate (left) of optodic bonded chips and their electric resistance (right) in dependence on irradiation intensity.

It was started with an intensity of 7070 mW/cm^2 which was then reduced by 2020 mW/cm^2 till 1010 mW/cm^2. For every intensity stage, 10 chips, altogether 40 pairs of adjacent contacts, were produced using optodic bonding technology. The results in Fig. 10 show that the adjacent pads irradiated by the intensity from 7070 mW/cm^2 till 3030 mW/cm^2 are most successfully bonded with a rate above 80%. At the intensity of 2020 mW/cm^2, the success rate sinks dramatically to less than 40% and even zero at the intensity of 1010 mW/cm^2. On the right side of Fig. 10, we see the results of the electric resistance measuring. Because of the low success rate, it makes only sense to analyze the specimens which were bonded with the intensity from 7070 mW/cm^2 to 3030 mW/cm^2. It is evident that the electric conductivity is getting worse with reduced intensity, not only from the aspect of the arithmetic mean value but also as far as the standard deviation is concerned.

To investigate the influence of the irradiation intensity on mechanical strength, shear tests were carried out. Due to the low success rate, the specimens produced from the intensity of 2020 mW/cm^2 and 1010 mW/cm^2 were not tested. Fig. 11 shows that the shear force decreases appreciably along with the reduced intensity, i.e. the mechanical strength is proportional to the applied intensity.

Summarizing from the resistance measuring and shear tests, the irradiation time and irradiation intensity have significant effects on the performance of bonded chips, which are integrated by means of optodic bonding. Long irradiation time ensures good conductivity and high mechanical strength; nevertheless, it must not last longer than necessary. No improvements are achieved by a longer lasting irradiation, if the demanded time has been reached. So even with short irradiation time, production quality can be guaranteed. In this way, higher production efficiency can be achieved. Regarding the influences of irradiation intensity, higher intensity provides better electric conductivity and stronger mechanical connection.

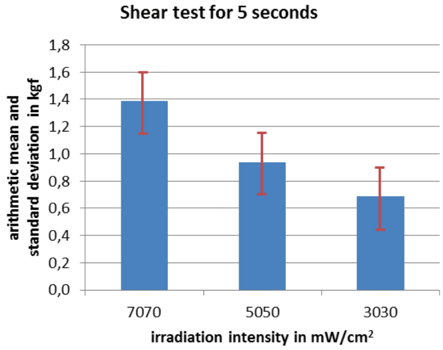

Fig. 11. Shear force of optodic bonded chips in dependence on irradiation intensity.

4. Conclusion and outlook

In this work, we introduced a new flip-chip bonding process, the so-called optodic bonding, to integrate optoelectronic bare chips in polymer optronic systems. To avoid damaging of thermal sensitive polymers, we applied UV curing adhesives as bonding material instead of commonly used heat curing adhesives. The use of an optode was highlighted functioning as a sideway UV source to achieve a higher performance of the curing process. The feasibility of the concept was confirmed through simulations and subsequently realized. In selecting UV lamp we investigated two types and applied one of them to minimize the thermal loading possibly induced by UV irradiation. A high success rate of the integrated chips from manual operation under appropriate settings of process parameters verified the optodic bonding process. Two relevant process factors, irradiation time and irradiation intensity, were investigated by evaluating the electrical and mechanical reliability. The results imply that the optodic bonding process can be an appropriately qualified integration technique for establishing polymer-based flexible and highly functional sensor networks. It is emphasized that the optodic bonding technique allows short curing time, i.e. short process time, which has an important impact on mass production.

Future research work will focus on the investigation of further process parameters, such as applied bonding force and positioning accuracy. An optimization of process parameters must be implemented. In addition, besides the sideway optode, a new configuration of optodes, e.g. with UV irradiation from the bottom side, will be attempted. The ultimate aim is to realize a stable, reproducible integration process of optoelectronic chips in polymer optronic systems.

Acknowledgements

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