Assembly technologies and connection methods for 3D-MID

Dr. Christian Goth and Guido Schatz

The assembly of the electronic components follows the manufacture of a mechanical molded part with defined structuring and metallization. HARTING AG Mitronics has qualified various connection methods in place for mechanical fixation and electrical contacting of SMT components and silicon chips. In addition, corresponding 3D assembly technologies for placing the components and for applying the connecting medium have been developed.

1 Special issues in MID technology

Unlike purely planar substrates in conventional PCB manufacturing, the MID substrate is a 3D body that usually also calls for 3D packaging. The application of the connecting medium and assembly of the components are therefore very specific to the application and depend on the particular geometry of the interconnect device.

The connection method and selection of the connecting medium are essentially determined by the substrate material and the subsequent utilization conditions. Most thermoplastics employed in MID technology exhibit a coefficient of thermal expansion (CTE) that is higher than that of standard materials in electronics production and that additionally is direction-dependent. Moreover, there are significant differences in the plastics that are suitable for MIDs. The right selection of material and process is therefore critical for long term reliability. Silicon's CTE is in the range of 2.5 to 3 ppm/K, while that of ceramic (Al₂O₃) is 6 to 8 ppm/K and that of PCB material (FR4) is approximately 15 to 18 ppm/K. MID materials have values of, e.g., approximately 12/30 ppm/K (LCP) (parallel/perpendicular to the injection molding direction) or 30/50 ppm/K (PA6/6T). Consequently, if the material is not selected in line with the requirements, tensile, pressure and/or shearing loads arise in the interfaces between the substrate material and the conductor path, conductor path and connecting medium, and connecting medium and component.

Figure 1: Different coefficients of thermomechanical expansion between the individual join partners lead to tensions in the composite (on the basis of [6]).
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2 Media application

For flat components in standard electronic production, the connecting medium is applied by means of screen printing. For three-dimensional interconnect devices with a number of process surfaces, this technique can be employed, but with certain limitations. MID technology consequently requires alternative application procedures, such as dispensing. Further application methods that are fundamentally suitable for 3D-MID are jetting, as well as pin transfer or pad printing. At present, however, these methods are still of only secondary importance. All of these methods can apply soldering paste, solder resist and also various adhesive systems.

2.1 Dispensing

In dispensing, the connecting medium is applied directly onto the appropriate position of the substrate metallization with a special metering valve (Figure 2). The media volume can be metered with a compressed air dispenser (time-pressure method) and with a screw dispenser. The screw dispenser makes more precise volume control and reproducible process conditions possible, particularly for increasing miniaturization. Because of the sequential application and the additional process times caused by the need to move the substrate and/or dispenser head in space during the dispensing procedure, more time is required than with screen printing. The dispensing method consequently reaches a high level of flexibility with regard to layout changes, metering volumes and 3D capability.

Figure 2: Dispensing on 3D-MID to apply soldering paste, adhesive and solder resist

2.2 Screen printing

In screen printing, a stainless steel or plastic blade is used to roll the connecting medium over the stainless steel screen that is aligned with the substrate by means of registration marks and to press the medium through the openings. A high level of productivity is achieved here because all solder or adhesive depots are printed in one process step. Utilization in MID technology is conditionally possible if the interconnect device has only one process surface and no geometric form elements prevent the screen from lying in place.
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2.3 Jet procedure
In the jet procedure, as in the known ink jet printing, the connecting medium is applied onto the substrate without contact. Here, a time-controlled plunger movement is used to force the quantity of material out of the media chamber and consequently to define the corresponding volumes on the contact points. Special media are required. The jet procedure is only conditionally applicable for high-viscosity materials.

2.4 Pin transfer/pad printing
In a pin transfer, the connecting medium (soldering paste, adhesive, solder resist) is not applied to the substrate with a metering head. Instead, the connecting medium is held in a stamping tool (pin, pad) in a dispensing station and guided to the connection point (transfer). The application of a defined quantity of material in a certain form can essentially be influenced by the geometry of the stamping tool, the viscosity of the medium and the layer thickness in the depot.

2.5 Solder resist
The utilization of solder resist is standard in PCB technology. The surfaces covered with solder resist are not moistened during the soldering process, which prevents a short circuit. The result is additional insulation protection and protection against external chemical and mechanical influences. The classic application methods (e.g., screen printing, photolithographic processes) for solder resist masks are not suitable for MiDs. Solder resist is comparably burdensome to apply. For this reason, various MID applications do without a solder resist mask and apply solder resist only at critical points. This makes it possible to prevent large-scale wetting and consequently a negative effect on the reliability caused by inhomogeneous solder points. In MID technology, the solder resist can be applied by means of pad printing or dispensing, for example. The latter is the currently predominating method. A smooth transition between conductor path and component pad should be ensured in components without solder stop in order to reduce the extent that the melting solder paste flows towards the conductor path due to capillary action. [9]

3 Component assembly
When laying out the interconnect device, a product concept that is both based on the function and suitable for production should be ensured (design for manufacturing). Particularly the step in which the components are packaged must be taken into consideration early in the development in order to check and appropriately develop the equipment requirements. During component assembly, the process surfaces must be aligned so that they are orthogonal to the joining direction, which is why the assembly systems must offer more degrees of freedom than required for purely planar processing (Figure 3).
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Figure 3: Planar (left) and spatial (right) MID packaging, implemented at HARTING Mitronics in cooperation with Infotech AG

Conventional standard assembly systems must be adapted for three-dimensional applications with multiple process areas. Due to the diversity of the task definitions, application-specific solutions are often necessary. HARTING develops these in close cooperation with the system manufacturers and the particular customer. There are two fundamental approaches here that have been scientifically examined [1] and implemented in industry. The workpiece can be fixed in place while the placement head can move freely in space in order to place the component in the appropriate position. On the other hand, if the interconnect device moves in space, the placement head carries out purely Cartesian movements. The systems available on the market offer the appropriate flexibility depending on the production run by means of a modular construction with integrated dispensing and soldering systems. High throughput is possible thanks to fully automatic lines with separate processing stations.

4 Connection procedures

The connection procedures that are important in MID technology are two mass soldering processes (convection soldering and condensation soldering) and conductive gluing. Selective soldering procedures such as laser soldering and hot bar soldering and press-in technology can partially supplement these basic procedures.

The soldering paste as a connecting medium is a mixture of metal powder and flux. The flux improves the wetting properties and removes already-existing oxide layers. The metal powder melts during the soldering process, wets the substrate and component metallization, and forms the solder point. Due to a change in the structural conditions in the edge area, an adhesive joint results between the join partners (solder/substrate metallization or solder/component metallization). Due to the reciprocal diffusion of the atoms of the solder and the base material, a homogenous chemical joint results that has different intermetallic phases. These areas are usually brittle and can have a negative effect on the component's long-term reliability. The application of a nickel diffusion barrier in the Cu-Ni-Au MID coating system reduces the nickel's dissolution and diffusion processes.
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Figure 4 3D-MID with soldered SMD components

The switch from solder pastes that contain lead to lead-free pastes has resulted in a significant rise in the peak temperatures during soldering. Unleaded solder pastes have a melting point that is much higher than that of leaded ones (e.g., unleaded SAC solder from around 217° C to 224° C, leaded SnPb alloys from 179° C). This requirement is relatively uncritical for duroplastic materials, but the thermal characteristic of the LDS thermoplastics must be taken into consideration when selecting the MID materials. However, there are appropriate materials (e.g., LCP, various PA types, LDS duroplastics) that are suitable for processing the standard unleaded solder materials. When materials with lower temperature resistance (e.g., PET) are opted for, it is also possible to use low melting solder alloys, e.g., SnBi with a liquidus temperature of 138° C. HARTING Mitronics has already tested standard alloys as well as low melting soldering pastes.

4.1 Convection and condensation soldering

These two soldering methods are soft-soldering processes (i.e., liquidus temperature less than 450° C) and primarily differ with regard to the heat transfer. Unlike selective soldering methods, these mass soldering methods involve heating the entire component, and not just selectively heating the areas to be soldered.

Convection soldering

Convection soldering is the standard connecting procedure in flat module manufacturing for the assembly of SMD components. In convection soldering, the heat transfer is brought about with a turbulently flowing gas (air and/or nitrogen). A selective airflow guides the heated air to the module using corresponding nozzle systems. For forced convection, the heat-transfer coefficient (30 to 120 Wm⁻²K⁻¹) is less than that with condensation (400 to 700 Wm⁻²K⁻¹). [5] This means that a reliable soldering process requires a median temperature of up to 265° C, which is considerably more than the liquidus temperature. This soldering method presents a risk of shadowing, especially with complex three-dimensional 3D-MIDs. [3]

Condensation soldering (vapor phase)

In vapor phase soldering, saturated, chemically inert vapor condenses on the colder module. Due to the direct transfer of the condensation heat released during the phase change, the steam temperature is quickly reached. Perfluoropolyethers (PFPE), which are available with different boiling temperatures, are used as the heat-
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transfer media [5]. Condensation soldering is the established procedure in MID technology. In standard electronics production it is only opted for around ten percent of the time.

In condensation soldering, the boiling temperatures of 230°C for standard alloys (e.g., SnAgCu) or 155°C for low melting solder materials (e.g., SnBi) mean a lower temperature load than in convection soldering without the risk of shadowing. In addition, homogenous surface temperatures with a difference of a few Kelvin (condensation 0 to 5 K, convection up to 20 K) result during vapor phase soldering. The result is very easily reproducible process conditions. The 3D-MID’s geometric design should avoid closed blind cavity structures if possible, because obstruction of the condensation escape leads to a reduction in the heat transfer and consequently a more irregular heat distribution. [3]

Figure 5: Specially adapted workpiece carrier for simultaneously holding 20 3D-MIDs

Special workpiece carriers are required to process MIDs in a convection or condensation soldering process (Figure 5). When designing the carrier systems, the module’s geometry must be kept in mind and the thermal mass should be as low as possible. Manufacturing in multiple cuts is called for in order to increase the throughput. Running the vapor phase medium out of the soldering system through blind cavity structures in the carrier should be avoided [5]

4.2 Conductive adhesive bonding

Conductive adhesive bonding is an alternative to mass soldering. The temperature load on the substrate material is significantly less than the process temperatures during soldering, particularly with SnAgCu solder, due to the lower hardening temperatures. This results in high long-term reliability due to the availability of hard and soft adhesives. The latter can be optimally adapted to the connection method and used for long terms at temperatures in the range from 150 to 170°C. Because the adhesives do not have any wetting characteristics, there is no need for solder resist during the gluing. [3]

The electrical conductivity for isotropic conductive adhesives is realized through the three-dimensional network of electrically conductive particles. 20 to 30 volume percent of these are embedded in the polymer matrix made
of base polymer and hardener. The thermal hardening helps produce the mechanical strength of the connection points. The hardening temperature here depends on the materials that are employed and is usually in the range from 80 to 150° C, which also makes it possible to use economical thermoplastics. Conductive adhesive costs significantly more than soldering paste. [6]

4.3 Laser soldering

In laser soldering, the energy needed to heat the solder is introduced directly into the joining position with the focused laser beam. This melts the solder and wets the component and the substrate. The temperature load on the joint partners is limited because the temperature is introduced only locally in the connection point and the laser beam is only present for a short time. This also makes it possible to use thermoplastic substrate materials with lower heat distortion resistance. Due to the sequential processing, however, it is only suitable for applications with few solder points, and possible shadowing caused by the component or the 3D interconnect device must be kept in mind.

4.4 Hot bar soldering

Hot bar soldering is also a soldering procedure that works sequentially. In this case, a heated stamp or bar is used to press the connections into the connection point and melt the solder. The stamp is adapted to fit the shape of the element that is to be joined for the specific product (e.g., component, stranded wire, flat conductor) and then is not removed again until the solder has solidified. The heat is generated by a tool (thermode) through which current is flowing. The rise in temperature and the soldering and cooling times can be adapted to the solder material. Hot bar soldering requires good access to the solder points.

4.5 Press-in technology

In press-in technology, the electric contacting is brought about by pressing a metal pin into a through-metallized hole. According to DIN EN 60352, a gas-tight connection must result between the press-in pin and the metallized feedthrough. The flexible press-in pin has numerous advantages over the rigid press-in pin and has established itself on the market. [3] The viscoelastic behavior of the thermoplastic materials and the layer thicknesses of the metallization (subsequent galvanic reinforcement may be necessary) must be taken into consideration during the MID part design in order to obtain a connection with long-term reliability. One possible variant of press-in technology uses pins that are pressed into a non-metallized hole and then soldered to the conductor path.

5 Chip assembly techniques

Chip assembly can be used to significantly increase the miniaturization potential of MID technology. Here the MID is not only the chip carrier, it also serves as the interface to the overall system or takes over the housing function or other mechanical functions. [4] The possibility to align sensor modules at defined angles to one another and position them exactly makes it possible to implement completely new configuration concepts, particularly in the area of sensor technology. Figure 6 shows example sensor applications from HARTING Mitronics.
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For chip assembly on thermoplastic, injection-molded, 3D-interconnect devices, HARTING Mitronics develops processes for MID applications in the industrial environment based on the technologies for planar components. Here, wire bond or flip chip (FC) technology is employed to mechanically fix the unprotected silicon (Si) chip in place on the interconnect device and then electrically contact it (Figure 7), while additionally offering some first protection against environmental influences.

The essential factors that distinguish between wire bond and flip chip are the process sequence, the stability requirements and the space requirements. [4]

Wire bonding is an established and widespread connection technology that is very cost efficient in spite of the sequentially running process. The movable electric wire connections provide good stability. Because of the outwardly running wires and the glob top, more space is occupied than in FC technology, but on the other hand there is also a certain flexibility in the substrate layout. FC assembly has the advantage that all connections can be contacted in one step, regardless of the number of inputs and outputs. The space requirements are minimal because the terminals lie under the chip surface. Moreover, the functionality can be stepped up by means of an increased number of contact points while maintaining outstanding electrical properties.
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5.1 Wire bonding

In COB (Chip-on-Board) technology, first the pre-fabricated and detached silicon chip is attached to the substrate (chip bonding). The mechanical fixation usually is performed with an adhesive, with conductive adhesive frequently being used for better heat dissipation into the substrate or for an electrical connection to the mass contact. Electrical connection by means of wire bonding is done with local welding of very fine metal wires to the metallization of the chip terminal pad or the substrate metallization. The energy required for this is generated by means of ultrasonic vibrations in the bonding tool (ultrasonic US wedge-wedge bonding) or by means of introducing additional heat (thermosonic (TS) ball-wedge bonding). The Al wire can be bonded purely with ultrasound at room temperature. On the other hand, as a rule, temperatures over 100°C and special surface finishes (e.g., thick gold or Ni-Pd-Au) are required for Au wires. Therefore, HARTING Mitronics prefers to use the US method, because the surface requirements can be satisfied by the standard coating system with Cu-Ni-Au.

The bond connection quality is fundamentally supported by a good application of ultrasound, sufficient layer thicknesses for the metallization (particularly Ni or Ni/Pd), and a low level of surface roughness. Good ultrasound application requires a hard bond tool support, which is classically provided by the substrate or the metal layer. The rigidity and strength of thermoplastic substrates are less than with ceramic or fiber glass-reinforced, duroplastic substrates. In addition, the layer thicknesses of the usually purely chemical metallization are normally slight. To compensate for the unfavorable characteristics of the soft substrate material, the metallization should therefore not fall below a minimum layer thickness (e.g., for LCP: 10 µm Cu, 10 µm Ni). With the Ni/Pd/Au finish surface and galvanically reinforced conductor paths, it is possible to improve the bonding properties with a smoother and harder surface.
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Particularly with laser direct structured substrates, the surface is strongly roughened by the laser process in order to achieve optimal adhesion of the metallization. This requires an adjustment in the process parameters. The roughness of the structures must be optimized with respect to both the bonding strength and the bondability. The bonding process can be better performed at a low level of roughness; the values of the mean surface roughness ($R_a$) should preferably not exceed 1.8 µm and those of the mean roughness depth ($R_z$) should preferably not exceed 10 µm with slight nodule formation. A reduction in the surface roughness is possible chemically, mechanically with a stamp or by means of CO$_2$ snow jet. [3] [7]

With two-component injection molding (2-shot method), on the other hand, the metallizable plastic is activated and metallized in a purely chemical way, as a result of which the bondability of the metallized substrates tends to be a given due to the lower levels of roughness. With the 2-shot method, the etching and deoxidation steps are essential for the roughness. If there is a solid frictional connection between the two plastic components and the bonding direction is parallel to the conductor path, it is additionally possible to avoid possible oscillations in the substrate. [3]

The sensitive Si chips and the wire bond connections are protected against environmental influences (e.g., corrosive media, moisture and mechanical load) with a potting compound (glob top) (Figure 9, left). By placing the chip in a cavity that can easily be produced in injection molding, the space requirements of the glob top are...
5.2 Flip chip technologies

With flip chip technology, the chip is turned or flipped so that the functional side of the chip with electrical terminals points towards the substrate (Figure 10). In this case, the substrate must reflect the chip layout. The mechanical mounting takes place in the same area as the electrical contacting. In the case of soldering and conductive adhesive bonding with isotropic adhesives (ICA, Isotropic Conductive Adhesive) these are two separate steps; in the case of adhesive bonding with non-conductive (NCA) and anisotropic conductive adhesives (ACA) the two steps are carried out simultaneously. The Si chip must be given so-called bumps: solder bumps during the soldering process and bond wire bumps (e.g., Au stud bumps) during gluing. The solder bumps can be applied with various wafer bumping technologies (e.g., with screen printing, electroplating, jetting). Au stud bumps can be made with Au wire bond processes. If the capillaries of the bonding tool do not cut the stud bumps at the same level, a further process step can be used to get the lengths to a uniform level (coining). Due to the design freedom of the injection molding process, MID technology also has the possibility of integrating small bumps on the substrate for the chip assembly. [2] [8]

Figure 10: 3D-MID magnetic field sensor with exactly aligned silicon chips.

Flip chip soldering

In flip chip soldering, first the soldering paste is applied to the substrate metallization, and then the chip is assembled and soldered. In a further process step, underfill is applied for mechanical stabilization. The underfill here is dispensed on one or two sides of the chip. It then flows under the chip and fills all the empty spaces between the chip and substrate.

Flip chip adhesive bonding

Isotropic conductive adhesive (ICA)
During chip assembly with isotropic conductive adhesive, first the electrical connection is made by applying and hardening conductive adhesive. As with FC soldering the mechanical stabilization is implemented with a separate application of underfill. This process is particularly suited for components that are sensitive to pressure and/or temperature.

**Non-conductive adhesive (NCA)**

In the case of flip chip adhesive bonding with NCA, non-conductive adhesion, electrical contacting, and mechanical fixation take place in one process step. The separate application of underfill is not necessary because the entire area under the chip is filled with adhesive (Figure 9, right). During the hardening under temperature, a constant contact force must be applied in order to prevent the chip from lifting and consequently in order to ensure a direct connection between the bond wire bumps and the substrate metallization.

**Anisotropic conductive adhesive (ACA)**

With anisotropic conductive adhesion, the adhesive is given conductive particles (metal, metal-sheathed polymer) that are trapped between the stud bump and substrate and that consequently lead to an electrical connection. This requires that a relatively high pressure be exerted that leads to compaction of the conductive particles in the z direction. In the x-y direction, the adhesive remains non-conductive due to the low concentration of conductive particles. As with the NCA process, here again the entire area under the chip is filled with adhesive.

### 6 MID on PCB

The MID can be electrically contacted to the PCB in a manner similar to that for an SMD component (Figure 11). In this case the depicted connection methods can fundamentally be used. At HARTING Mitronics, conductive adhesive bonding or soldering are currently opted for. MIDs that have already been assembled must comply with a corresponding assembly hierarchy. During the packaging, the MID parts can be fed in a tape for a high degree of automation depending on the geometry, as with the SMD components. Here, MID technology offers the possibility of integrating metallized plastic bumps, which allows comparatively space-saving mountings.
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Authors

Dr.-Ing. Christian Goth is active at HARTING Mitronics as Strategic Technology Manager. He earned his doctorate at the Universität Erlangen-Nürnberg with a paper on the topic “Analysis and Optimization of the Development and Reliability of Spatial Electronic Interconnect Devices (3D-MID)” under the direction of Prof. Franke in the professorship for manufacturing automation and production systems. From 2007 to 2011 he was executive director of Forschungsvereinigung Räumliche Elektronische Baugruppen 3-D MID e.V.

Guido Schatz works at HARTING Mitronics as an industrial engineer for the manufacturing steps automatic optical inspection and AVT / electronic assembly. He received his mechanical engineering degree in industrial engineering and management from the Universität Siegen.

Bibliography


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Glossary

List of abbreviations

Ag Silver
Al Aluminum
Au Gold
Bi Bismuth
Cu Copper
I/O Input / Output
LCP Liquid Crystal Polymer
P Phosphorus
PA Polyamide
Pd Palladium
PFPE Perfluoropolyether
ppm Parts per million
Si Silicon
Sn Tin
TS Thermosonic
US Ultrasound

Formulas and units

Al2O3 Aluminum oxide
CO2 Carbon dioxide
K Kelvin
Wm⁻²K⁻¹ Heat-transfer coefficient


# Assembly technologies and connection methods for 3D-MID

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<thead>
<tr>
<th>Abbreviation</th>
<th>Term</th>
<th>Explanation</th>
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<tr>
<td>Liquidus temperature</td>
<td>If the temperature of an alloy falls below this value, the homogenous liquid phase begins to solidify</td>
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<td>ACA</td>
<td>Anisotropic Conductive Adhesive</td>
<td>Anisotropic conductive adhesive that is weakly filled with small conductive particles of equal size.</td>
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<td>COB</td>
<td>Chip-on-Board</td>
<td>Technology for mounting bare semiconductor chips directly on the interconnect device</td>
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<tr>
<td>CTE</td>
<td>Coefficient of Thermal Expansion</td>
<td>Parameter that describes the behavior of a substance with regard to changes in its dimensions when there are temperature changes</td>
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<tr>
<td>FC</td>
<td>Flip chip</td>
<td>Bare semiconductor chip (usually silicon) that is mounted with the contacting side facing the substrate (flipped)</td>
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<tr>
<td>FR4</td>
<td>Flame Retardant 4</td>
<td>Standard material for PCBs made of epoxide resin with fiber glass reinforcement</td>
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<tr>
<td>ICA</td>
<td>Isotropic Conductive Adhesive</td>
<td>Isotropic (direction-independent) conductive adhesive</td>
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<tr>
<td>MID</td>
<td>Molded Interconnect Device</td>
<td>Injection-molded part with integrated conductive structure and components (optional)</td>
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<tr>
<td>NCA</td>
<td>Non-conductive adhesive</td>
<td>Non-conductive adhesive</td>
</tr>
<tr>
<td>RA</td>
<td>Average roughness</td>
<td>The arithmetic mean of all deviations of the roughness profile from the median line (reference line) within the measurement section</td>
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<tr>
<td>RZ</td>
<td>Mean roughness depth</td>
<td>The arithmetic mean of the individual roughness depths of five equidistant adjacent individual measurement sections</td>
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<tr>
<td>SMD</td>
<td>Surface Mount Devices</td>
<td>SMD components are soldered directly on to the PCB by means of solderable connecting faces.</td>
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<tr>
<td>SMT</td>
<td>Surface Mount Technology</td>
<td>Name for the technology for surface mounting of components</td>
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