

Highly Flexible Die Attach Adhesives for MEMS packages

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Abstract

Die attach materials for most MEMS packages must be highly flexible as temperature changes during the assembly process and application may lead to thermo-mechanical stress as a consequence of dissimilar coefficients of thermal expansion of substrate, chip and adhesive. Thermo-mechanical stress results in a distortion of the signal characteristics of the extremely stress-sensitive MEMS device. Within the scope of this paper, highly flexible heat-curing adhesives with a Young's modulus down to 5 MPa (0.725 ksi) at room temperature were developed. DMTA measurements show that temperature storage at +120 °C (+248 °F) does not cause the adhesive to embrittle, which would have a negative effect on the MEMS package's reliability. After storage at +120 °C (+248 °F) for up to 1000 h, no increase in Young's modulus can be observed. The adhesives cure at extremely low temperatures down to +100 °C (+212 °F), which reduces stress development during the assembly process. In addition, the adhesives have very process-friendly properties. Processing times of more than one week can be achieved. The option of dual curing enables preliminary light fixation of the chip within just seconds.

Keywords

Adhesives, MEMS packaging, stress, die attach, adhesive bonding

Introduction

Microelectromechanical systems (MEMS) are sensors and actuators with micromechanical structures produced using semiconductor technology. In the past 10 years MEMS components have been finding increasing use in various tasks. Many application areas can no longer be imagined without them. Examples for such application areas include mobile phones, where MEMS microphones and inertial MEMS sensors are broadly used. Despite their wide dissemination in a great variety of applications, packaging of these MEMS elements is still challenging. During the packaging process and in operation, it is important to minimize the stress input into the MEMS chip, which leads to a warpage of the micromechanical structures, and therefore to a change of the signal characteristics of the piezo-resistive or capacitive elements in the MEMS sensor [1,2,3,4,5]. One key factor of stress-free packaging is the die attach adhesive which bonds the MEMS chip to the substrate [6]. Within the scope of this paper, innovative MEMS die attach adhesives on the basis of acrylates and the patented mCD (modified polycarbamin acid derivate) chemistry were developed. These products show outstanding properties appropriate for MEMS die attach applications. They are able to minimize tensions to a great extent thanks to their high flexibility. In addition, they provide further advantages beneficial for MEMS packaging, including high die shear strength and curing at low temperatures.

Requirements on MEMS die attach adhesives

Both, during curing and in operation, temperature changes in combination with the thermal mismatch of MEMS chip and substrate (thermal mismatch = dissimilar coefficients of expansion of the materials) can cause stress in the piezo-resistive and capacitive structures. As a consequence, the adhesive must be extremely flexible in order to compensate the stress input during temperature changes. Various studies have already been conducted on this issue. They consistently show that the stress input during the packaging process and in operation is clearly minimized by using highly flexible adhesives, such as silicones. Wilde et al. [1,2] investigated the influence of thermo-mechanical loads on the function of pressure sensors. Both, the simulation and the experimental verification show a significantly lower change in the signal characteristics during temperature changes if flexible adhesives are used. The influence of the flexibility of die attach adhesives on the stress input in MEMS packaging was also characterized by Waldwackari et al. [7] by bending

dummy chips as an indicator for stress. In this experiment, a larger stress input was observed during the curing process, compared with that during temperature changes in operation. Another fundamental requirement on the adhesive is the retention of flexibility upon repeated temperature stress avoiding a reduced decoupling effect of the adhesive in operation. The retention of flexibility is a special challenge, particularly for highly flexible adhesives on the basis of epoxies. Stress during the assembly process creates a zero offset, which however can be corrected. In contrast, stress in the MEMS chip caused by embrittlement of the adhesive as a consequence of repeated temperature change stress is irreversible and leads to malfunctions of the MEMS element. Therefore, for the reliable function of the MEMS component, it is essential that the die attach adhesive retains its flexibility at temperature storage. It is impossible to correct a shift of the signal at temperature changes in operation caused by stress input as a result of reduced flexibility.

Adhesives

For die attach applications, adhesives on the basis of epoxies are predominantly used due to their excellent bond strength, resistance and reliability. However, conventional epoxies have a high Young's modulus or low flexibility in general. Therefore, they are only conditionally suitable for MEMS die attach applications requiring high flexibility to minimize stress. Highly flexible silicones with a Young's modulus value in the range of 1 MPa (0.145 ksi) are used for MEMS die attach as a standard, but they give lower bond strength than epoxies or acrylates. The goal in the adhesive development was to create MEMS die attach adhesives on the basis of mCDs or acrylates, which combine high flexibility and high bond strength. The retention of the adhesives' flexibility upon temperature stress was a key emphasis in order to ensure the reliable function of the MEMS component. Another focus in adhesive modification was on low-temperature curing to minimize the stress input during packaging, and on a glass transition temperature outside the usual temperature range of use in the consumer industry to prevent strong changes of the mechanical properties at temperature changes in operation. Owing to the desired property profile, the mCD chemistry patented by DELO and the acrylate chemistry were used as basic chemistries for development. These chemistries provide great modification potential for flexibility and curing at low temperatures. In addition, the acrylate chemistry offers the possibility of preliminary fixation by light (dual curing) which can facilitate the die attach process.

Experimental

The flexibility of the adhesives was characterized with the help of DMTA (dynamic mechanical thermo analysis) as this method allows a very precise determination of a material's elastic properties. During the measurement, a sinusoidal oscillating force is applied to the material specimen and the resulting deformation of the material is measured. The amplitude and the phase displacement of deformation against the applied force are determined. From the measured values, the visco-elastic properties of a specimen can be determined as a function of time and temperature. Besides the storage modulus E' as an indicator for the elastic properties, the loss modulus E'' , the glass transition temperature T_G and the mechanical loss factor $\tan \delta$ of the material can be determined. To characterize the flexibility of the adhesives, adhesive films were measured under tensile stress. This measuring mode delivers the most reliable values, especially of highly flexible adhesives. The parameters listed in table 1 were used to determine the elastic properties of the specimen.

Table 1: Parameters for the characterization of the flexibility by means of DMTA measurement

Mode	Tensile mode
Specimen geometry	0.5 x 5 x 14 mm ³ (0.02 x 0.2 x 0.55 in ³)
Start temperature	-100 °C (-148 °F)
End temperature	+150 °C (+302 °F)
Heating rate	2 K/min
Amplitude	30 µm
Frequency	1 Hz

The die shear strength was characterized with a die shear tester Series 4000PX of company Dage Semiconductor. The parameters listed in table 2 were used to determine the die shear strength.

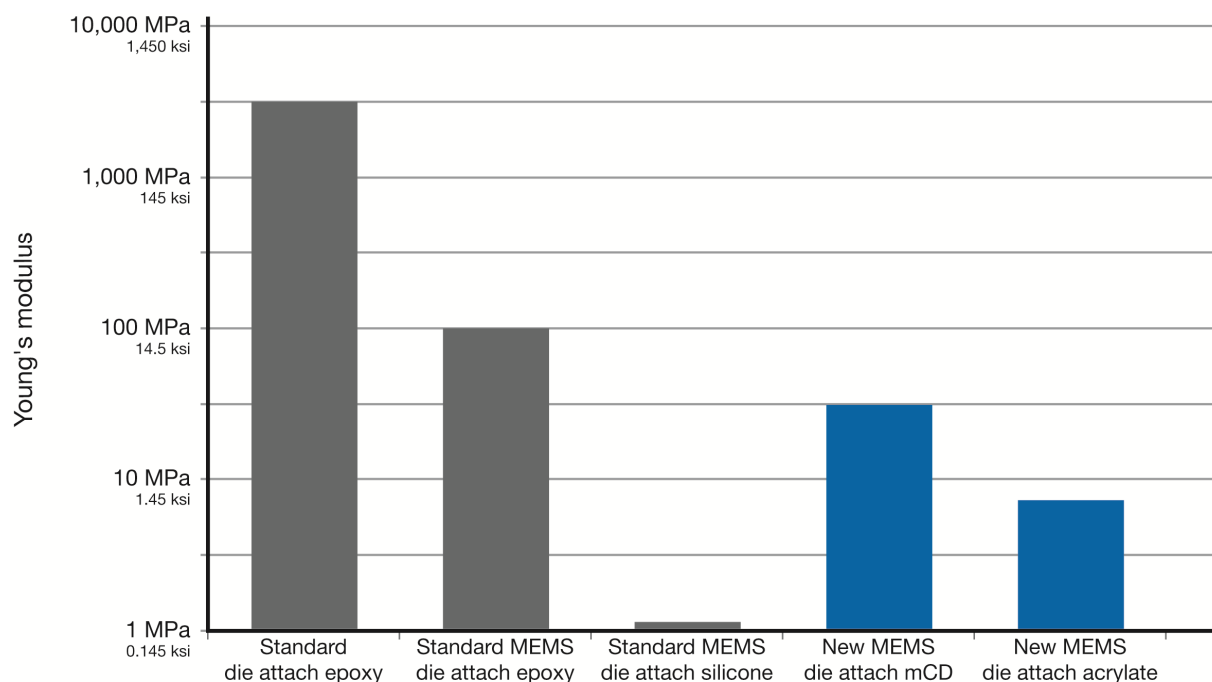
Table 2: Parameters for the determination of the die shear strength

Chip size	2 x 2 mm ² (0.08 x 0.08 in ²)
Substrate	FR4
Shear height	40 µm
Shear speed	500 µm/s

Results and discussion

Flexibility

As described above, the most fundamental requirement on die attach adhesives for the MEMS application area is high flexibility in order to minimize stress input in the capacitive and piezo-resistive sensor elements during packaging as well as in operation. For MEMS die attach processes, highly flexible silicones with a Young's modulus in the range of 1 MPa (0.145 ksi) are usually used. Besides silicones, flexible epoxies are also used due to their better adhesion. However, these epoxies are significantly less flexible and have a Young's modulus in the range of 100 MPa (14.5 ksi). The goal in the adhesive development was to create die attach adhesives with a balanced property combination of high flexibility and high die shear strength. Figure 1 shows the Young's modulus of the newly developed adhesives as an indicator for flexibility compared to the silicones and epoxies usually used in this application area.

Figure 1: Comparison of the newly developed MEMS die attach adhesives and conventional die attach adhesives

The newly developed adhesives on the basis of acrylates and the mCD chemistry have a Young's modulus of 5 MPa (0.725 ksi) res. 25 MPa (3.626 ksi). Thus, they provide a clearly higher flexibility than the epoxies used in the field of MEMS and are only slightly stiffer than the usually used silicones. As a result, the newly developed adhesives are more beneficial in terms of stress minimization than conventional MEMS die attach epoxies. The fundamental challenges for the reliable function of a MEMS component include the retention of flexibility of the die attach adhesive upon temperature stress.

Embrittlement of the adhesive caused by temperature stress in operation would lead to an increased stress input at temperature change, and consequently to a disturbance of the signal characteristics. Therefore, the influence of permanent temperature stress on the flexibility was investigated with the help of DMTA measurements. Figure 2 and 3 show the Young's modulus as a function of the temperature after various temperature storages of the die attach adhesive on the basis of the mCD chemistry (figure 2) and the die attach adhesive on the basis of acrylate chemistry (figure 3). It provides a detailed picture of the Young's modulus of the adhesives before and after temperature storage.

Figure 2: Young’s modulus as a function of the temperature (DMTA) after various temperature storages of MEMS die attach adhesives on the basis of mCDs

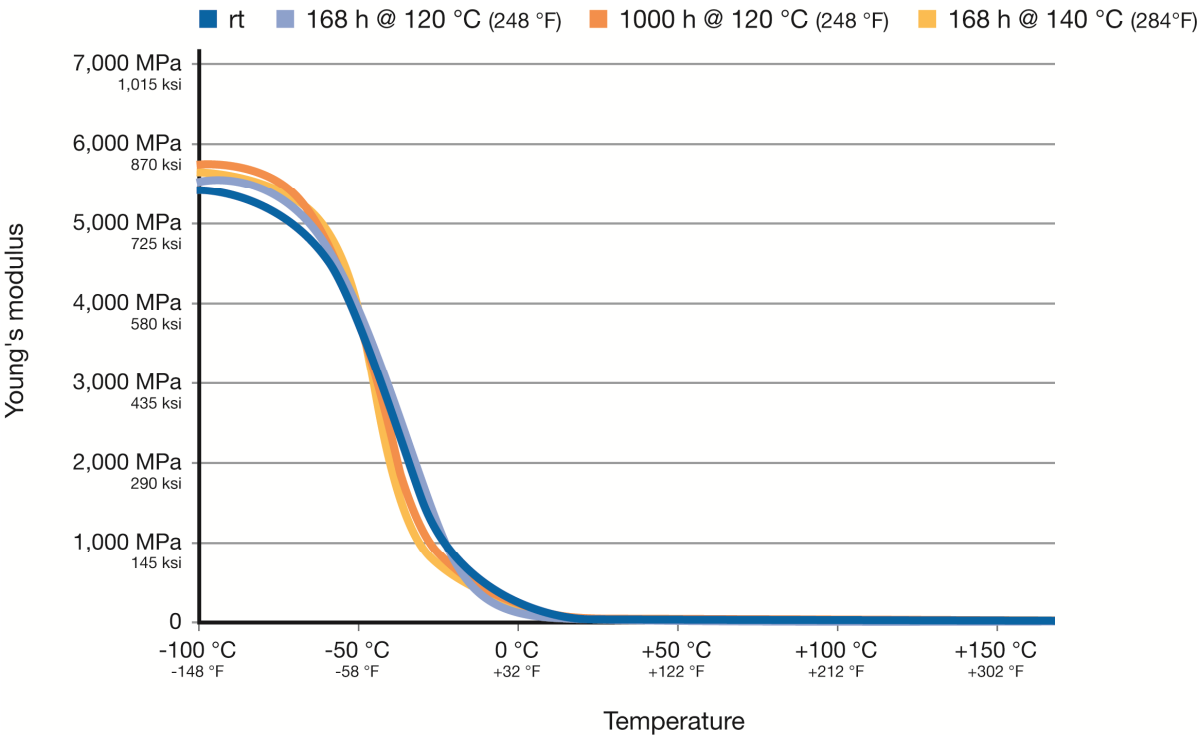
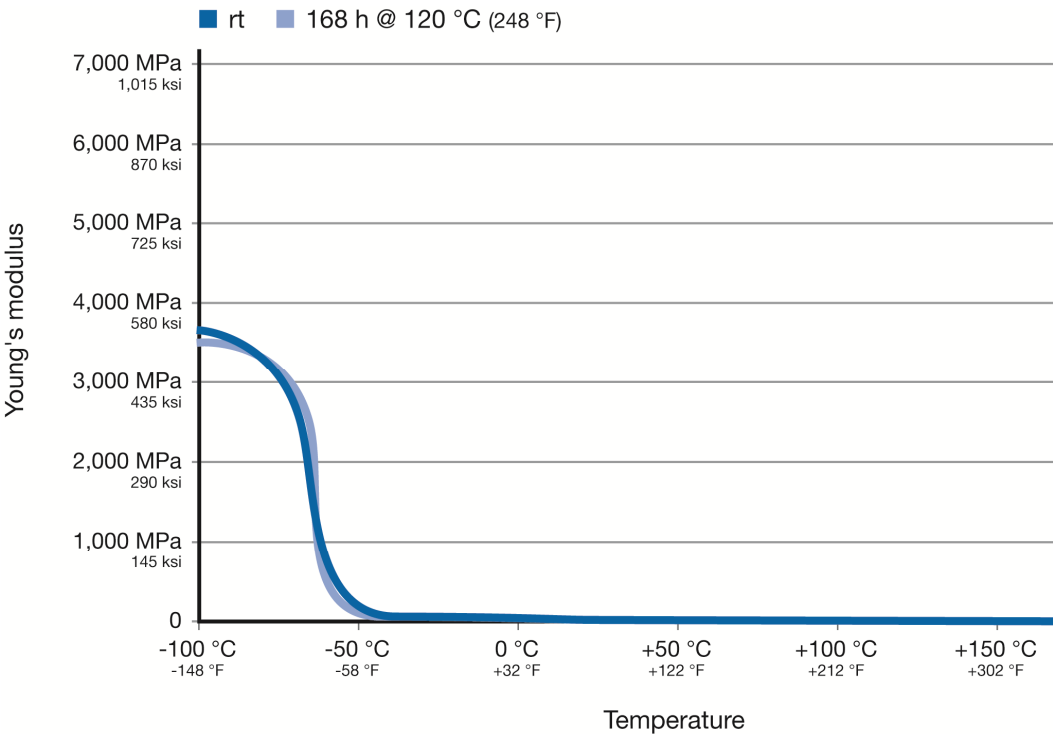


Figure 3: Young’s modulus as a function of the temperature (DMTA) after various temperature storages of MEMS die attach adhesives on the basis of acrylates



The figure shows the typical progress of a DMTA curve with a significant decrease in Young's modulus in the glass transition range. The DMTA measurements of the adhesive based on acrylate chemistry show a glass transition (turning point of Young's modulus curve) of approx. -60 °C (-76 °F). The adhesive based on mCD chemistry has a glass transition of -40 °C (-40 °F). Thus, the glass transition of both adhesives is outside the common temperature range in the consumer industry. Thus, a significant change of the mechanical properties and the thermal coefficient of expansion at temperature changes in operation are prevented. In addition, both adhesives give an extremely high stability to embrittlement at temperature storage. A change of the mechanical properties or embrittlement caused by permanent temperature stress would shift the glass transition to higher temperatures in most cases, which is shown as a parallel displacement of the DMTA curve along the temperature axis. As regards the adhesive on the basis of the patented mCD chemistry (figure 2), no displacement of the DMTA curve can be observed after storage at +140 °C (+284 °F) for 168 h. The adhesives on the basis of acrylates (figure 3) are resistant to embrittlement for 168 h at +120 °C (+248 °F). In table 3, the Young's moduli at rt of both adhesives before and after temperature storage (168 h @ 120 °C) are compared as an indicator for flexibility.

Table 3: Comparison of the Young's moduli of both adhesives before and after temperature storage (168 h @ 120 °C)

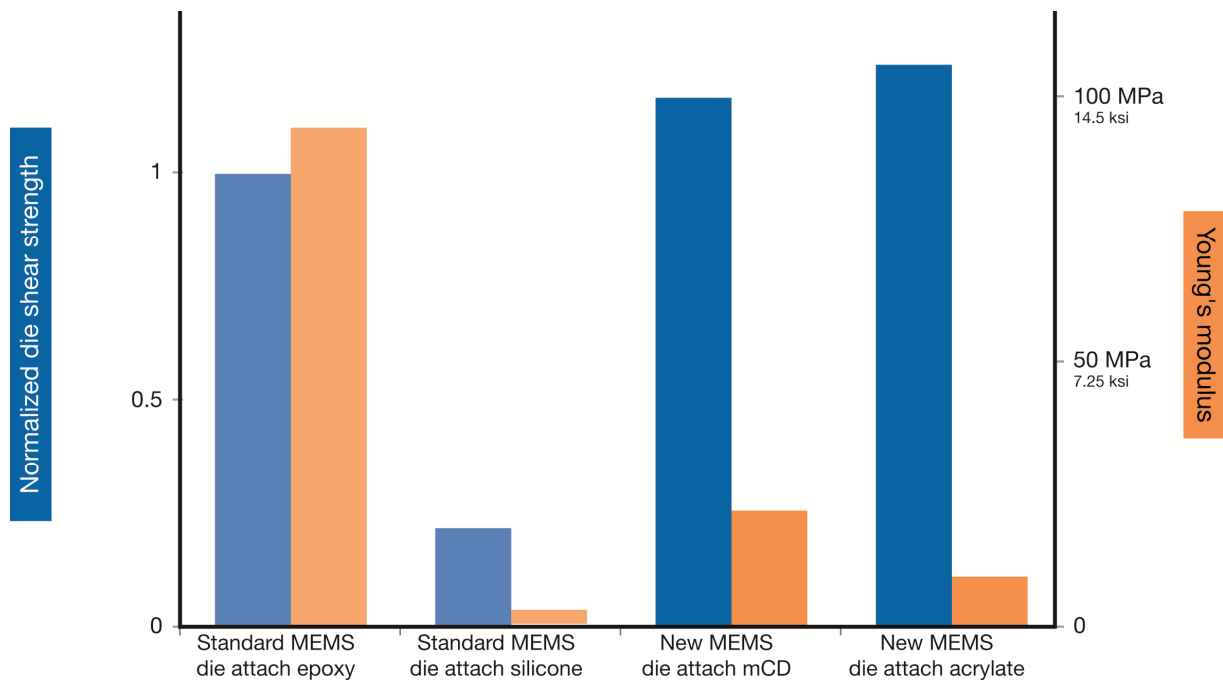
Chemistry	MEMS DIE attach	
	mCD	Acrylate
Young's modulus, initial value	25 MPa (3.626 ksi)	5 MPa (0.725 ksi)
Young's modulus after 168 h @ +120 °C (+248 °F)	30 MPa (4.351 ksi)	8 MPa (1.16 ksi)

The adhesives show an only slight increase in Young's modulus, which does not have any influence on the reliable function of the MEMS elements as verified after first characterizations in operation (MEMS microphones). All in all, a very high flexibility which is consistently high even after permanent temperature stress in the consumer application area is ensured for both newly developed MEMS die attach adhesives. This is essential for the reliable function of the MEMS in operation.

Die shear strength

The adhesives' high flexibility mostly involves low bond strength. In particular, the standard silicones used for MEMS die attach applications give clearly lower die shear strengths than epoxies. The goal in the adhesive development was a balanced relation between high flexibility and high die shear strength. Figure 4 compares the flexibility and the normalized die shear strength of both newly developed die attach adhesives with these of the silicones and epoxies usually used in this field.

Figure 4: Die shear strength and flexibility of the newly developed MEMS die attach adhesives compared to standard MEMS die attach adhesives



The newly developed adhesive on the basis of mCDs and acrylates are less flexible than standard silicones. However, the die shear strength is more than three times higher. Compared to the epoxies normally used in the MEMS application area, the flexibility is significantly higher despite comparable die shear strength. Thus, the newly developed adhesive provide an outstanding combination of high flexibility and high die shear strength, giving them a competitive edge over the currently used MEMS die attach adhesives.

Low-temperature curing

Another focus of development was curing at low temperatures in order to reduce tensions during curing as a consequence of dissimilar coefficients of expansion of substrate and chip. Table 4 illustrates the minimum curing temperatures of the newly developed adhesives compared to silicones and epoxies usually conventionally used for MEMS die attach.

Table 4: Minimum curing temperatures of the newly developed adhesives compared to standard MEMS die attach adhesives

	Standard MEMS die attach	New MEMS die attach
Curing temperature	+150 °C (+302 °F)	+100 °C (+212 °F)
Curing time	~ 60 min	30 min

The new MEMS die attach adhesives on the basis of the patented mCD chemistry and the acrylate chemistry can be cured at +100 °C (+212 °F), which is a significantly lower curing temperature than that of usually used MEMS die attach adhesives with a recommended curing temperature of +150 °C (+302 °F). This enables low-stress curing. In addition, the required curing time of approx. 30 min (depending on the geometry and the process) is clearly shorter compared to the curing times of standard adhesives amounting to approx. 60 min. This can offer an advantage in terms of the process time or uph.

Processing properties

The dispensing capability of the adhesive was tested and improved in accordance with the dispensing methods common in the field of MEMS die attach. Special importance was attached to the prevention of tailing. The adhesives show an excellent performance using the pressure/time dispensing method, which is a standard in the field of MEMS die attach. Both, adhesives on the basis of mCD and adhesives on the basis of acrylates can be dispensed through needles or shower heads down to a nozzle diameter of 150 μm .

Reliability

Besides the previously reviewed properties flexibility, die shear strength and low-temperature curing, a high reliability in operation in terms of temperature and humidity stress is a fundamental requirement. The adhesives were subjected to the common reliability tests in the consumer area:

- Thermal shock: $-40\text{ }^{\circ}\text{C}$ ($-40\text{ }^{\circ}\text{F}$)/ $+125\text{ }^{\circ}\text{C}$,
- High temperature storage: 336 h @ $+105\text{ }^{\circ}\text{C}$ ($+221\text{ }^{\circ}\text{F}$)
- Low temperature storage: 336 h @ $-40\text{ }^{\circ}\text{C}$ ($-40\text{ }^{\circ}\text{F}$)
- Humidity storage: 336 h @ $+85\text{ }^{\circ}\text{C}$ ($+185\text{ }^{\circ}\text{F}$)/ 85 % r. h.
- Reflow: 5x $+260\text{ }^{\circ}\text{C}$ ($+500\text{ }^{\circ}\text{F}$)

After temperature stress or exposure to humidity, the die shear strength of the MEMS element and the function of the whole package were verified. Both adhesive chemistries were successfully tested.

Summary

Die attach adhesives on the basis of epoxies and acrylates were developed, which offer a unique property profile for MEMS applications:

- High flexibility res. Young's modulus of 5 MPa (0.725 ksi)
- No embrittlement after temperature storage up to $+140\text{ }^{\circ}\text{C}$ ($+284\text{ }^{\circ}\text{F}$) for 168 h
- Glass transition temperature below the temperature range of use
- Low-temperature curing at $+100\text{ }^{\circ}\text{C}$ ($+212\text{ }^{\circ}\text{F}$)
- Outstanding die shear strength compared to standard MEMS die attach adhesives

The high flexibility, which is in the range of silicones, reduces the stress input into the piezo-resistive or capacitive elements at temperature changes in operation. Thanks to a glass transition temperature of $-40\text{ }^{\circ}\text{C}$ ($-40\text{ }^{\circ}\text{F}$) res. $-60\text{ }^{\circ}\text{C}$ ($-76\text{ }^{\circ}\text{F}$), which is outside the temperature range of use, sudden changes of the mechanical properties and a non-linear expansion at temperature changes in operation are prevented. Low-temperature curing allows a minimization of stress during the assembly process. Despite the high flexibility, the adhesives have excellent die shear strength. Table 5 summarizes the key properties of the newly developed adhesives on the basis of the patented mCD chemistry and acrylate chemistry.

Table 5: Key properties of the newly developed adhesives

	MEMS die attach	
Chemistry	mCD	Acrylate
Young's modulus	25 MPa (3.626 ksi)	5 MPa (0.725 ksi)
No embrittlement after temperature storage	168 h @ $+140\text{ }^{\circ}\text{C}$ ($+284\text{ }^{\circ}\text{F}$)	168 h @ $+120\text{ }^{\circ}\text{C}$ ($+248\text{ }^{\circ}\text{F}$)
Glass transition temperature	$-40\text{ }^{\circ}\text{C}$ ($-40\text{ }^{\circ}\text{F}$)	$-60\text{ }^{\circ}\text{C}$ ($-76\text{ }^{\circ}\text{F}$)
Minimum curing temperature	$+100\text{ }^{\circ}\text{C}$ ($+212\text{ }^{\circ}\text{F}$)	

Compared to standard MEMS die attach adhesive, the new adhesives offer an enhanced property profile. Die attach adhesives on the basis of silicones usually used for MEMS die attach are slightly more flexibly, but give clearly lower bond strength. Flexible epoxies also used in this field have similar bond strength, but clearly lower flexibility than the newly developed adhesives. In addition, both, silicones and epoxies are cured at significantly higher temperatures. Thus, the newly developed MEMS die attach adhesives provide a unique property profile which is beneficial in many ways as regards stress minimization in the MEMS chip, reliable function of the MEMS component and management of the assembly process.

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