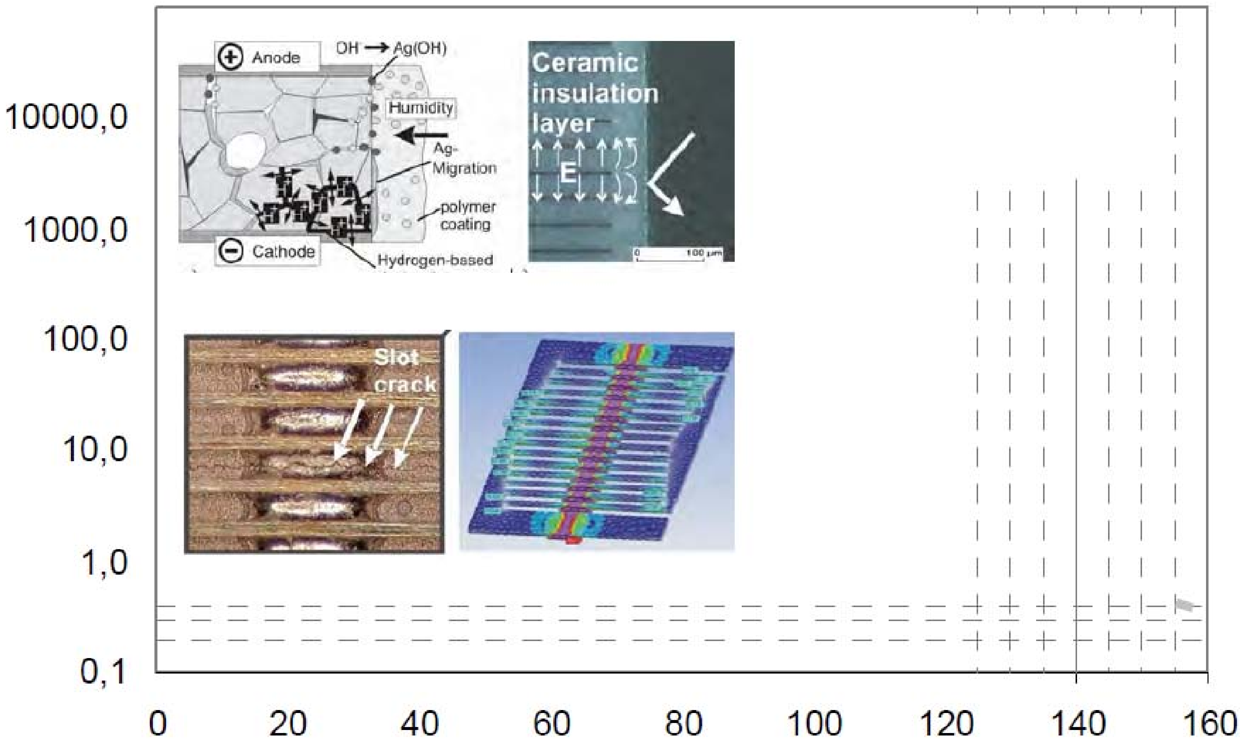
Piezotechnology

Development of Highly Reliable Piezo Multilayer Actuators and Lifetime Tests under DC and AC Operating Conditions



Development of Highly Reliable Piezo Multilayer Actuators and Lifetime Tests under DC and AC Operating Conditions

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Abstract:
Piezoelectric multilayer actuators are the driving force behind the most challenging nanopositioning applications. These types of actuators have been in use for about two decades and have reached maturity several years ago. Continuous improvements are based on long term tests and exact knowledge of the environmental operating conditions and failure modes allows to push the limits of this technology even further.
The paper presents the results of an extensive study involving up to four environmental chambers and more than 1,000 actuator samples to develop a grid of 13 humidity and temperature conditions. Weibull-analysis is used at every condition to determine the DC-voltage dependent lifetime of the co-fired PICMA® multilayer actuators. In addition to the (most critical for precision positioning applications) DC tests, behavior under large-signal AC-conditions with up to 10^{10} cycles for different functions as well as temperature-conditions was also evaluated. Three patented design features of the latest actuator generation are based on the findings.

Keywords: Lifetime, reliability failure mode, piezo actuator, nanopositioning, PZT, piezoelectric, multilayer, co-fired, DC-lifetime, humidity, AC-signal long-term test.

Background

Piezoelectric multilayer actuators hold a distinguished position among solid state actuators. They have proven their versatility and maturity in a multitude of applications adapting to largely different requirements from laser research to automotive applications. When a new technology becomes state of the art lifetime improvements will be a prominent content of the development activities of the manufacturers.
The reliability specifications of piezoelectric multilayer actuators have to be separated into those for prevailing DC-signals and those for predominant AC-loads. Whereas the first ones are typical for high resolution oriented positioning applications and are given in hours, the second ones are specified in cycles and are mostly used in high acceleration types of functioning like fuel injection or ink jet printing.
The following paper first describes the principal degradation mechanisms of piezoelectric actuators and the related protective design features of PI Ceramic multilayer actuators (PICMA®) (Fig. 1) and afterwards PICMA® reliability data for both kinds of applications.

Ceramic encapsulation to prevent DC-degradation

The reliability of piezoceramic actuators under large DC-signals is influenced by the size of the electric field, the temperature and the environmental humidity. Especially the humidity is promoting the different degradation phenomena.
When water molecules get into contact with the inner electrodes of the multilayer actuators, electrolysis occurs under large electric fields:

$$2\,H_2O \rightarrow 2\,H_2 + O_2$$

Cathode: $2\,H_2O + 2\,e^- \rightarrow H_2 + 2\,OH^-$

Anode: $6\,H_2O \rightarrow O_2 + 4\,H_3O^+ + 4\,e^-$.

Then silver ions Ag+ move as Ag(OH) from the anode trough cracks, voids, dissolved secondary phases at the grain boundaries and, especially, along the surface to the cathode [2,3,4,5,6]. There it is reconverted into metallic

Fig. 1: *4th generation design of PICMA® multilayer piezo actuators (cross sections 2x3mm² to 10x10mm²) [1].*

silver. As a result silver dendrites grow from the cathode to the anode and can result in electric breakdowns and short cuts (Fig. 2a).
Another degradation mechanism is the destructional effect of the hydrogen from the electrolysis. It can lead to semiconductive behavior because of reductive processes as well as to embrittlement and complete destruction of the ceramic compound because of internal stresses [7,8,9,10] (Fig. 2a).
Humidity based degradation of piezoceramic actuators at high DC-fields, especially caused by the described protonic effect, is a serious problem for actuators which just have a polymer protection on their inner electrodes. This is because there is no polymer which is really dens for humidity.
In contrast the patented PICMA® design has an inorganic ceramic insulation layer which reliably prevents water penetration and, therefore, the described destruction effects (Fig. 2 b) [11]. This layer is made of the same PZT ceramic material and has uniformly the same thickness of 60 µm as the active layers. That's why it is partially accessed by the scattering field of the internal electrodes and, consequently, it is partly poled and expands during operation. Hence, the stress as well as the number of cracks are limited [12].

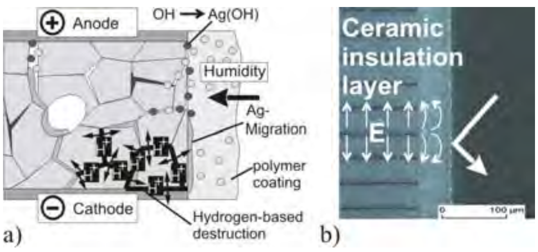

Fig. 2: *a) DC-signal failure mode of polymer coated actuators: water electrolysis induced metal migration and hydrogen degradation; b) PICMA®-design with an inorganic ceramic layer reliably prevents these effects.*

Improved AC reliability with slot segmentation and crack bypassing

Under permanent large signal AC-operation, water based destruction is not the dominating degradation effect of the actuators, because usually self heating due to dielectric losses prevents the local humidity effect. Then the internal mechanical stresses and the related cracking in the passive actuator volume are more pronounced.

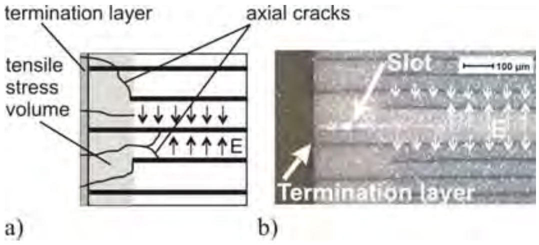

Fig. 3: *a) AC-signal destruction mechanisms of co-fired multilayer actuators; b) PICMA®-design: artificial slot crack in the non-termination plane prevents stress accumulation.*

Especially the passive volume, which separates the outer termination from the inner counter electrodes, has to be considered (Fig. 3a). In this volume tensile stress accumulation [13] can lead to high energy cracking. When these cracks get an axial component they can connect two adjacent electrodes (Fig. 3a). Because the actuator itself is a huge dielectric energy source an induced dielectric breakdown will usually have fatal consequences.
In the PICMA®-design the patented slot segmentation prevents this stress accumulation and improves the AC-reliability [11,12] (Fig. 3b). These artificial cracks are already formed during sintering. The slot distance of about 2 mm is well adapted to the minimal stress optimum [13] (Fig. 3c). The slot depth of 300-400 µm matches to the finding that poling cracks stop growing after 200 µm [14]. Moreover, the slot-layer has double the thickness as the other layers but it is active (Fig. 4 c). This additionally prevents the slots from further growing.

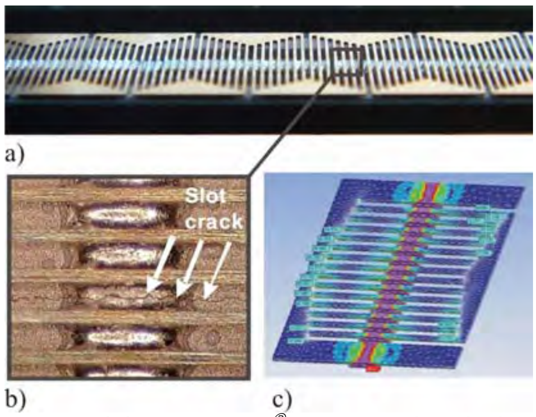

Fig. 4: *a) latest PICMA®-contact stripe design; b) detail of a bypassed slot crack; c) FEM-optimization of the mechanical stresses during the design phase.*

The third feature is the special slot bypassing contact stripe layout [15] (Fig. 4). Usually the internal electrodes are contacted by a fired on

Ag/Pd-termination layer. During operation this layer will be destroyed by cracking after 10^6-10^7 cycles [16], at least at the slots. Therefore these cracks have to be electrically bypassed. In the PICMA®-design this is realized by a contact stripe which is soldered on by an automated process. Lately a new meandric design was implemented which can take up to 20 A peak currents and therefore allows the PICMA to be driven in a ultrahigh dynamic mode with slew rates as low as 50 µs (Fig. 4).
Knowing about the destruction mechanisms, all PI Ceramic co-fired multilayer actuator components which are driven at large fields have a ceramic protection as well as a slot design if necessary.

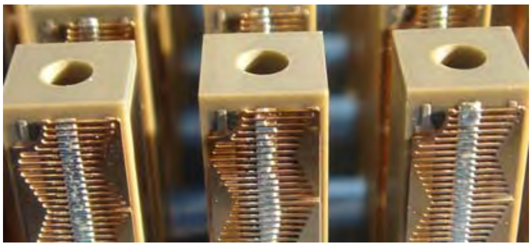

Fig. 5: *Co-fired actuators with through hole. 5x5 mm cross section 2 mm aperture. Outer and inner surfaces are ceramic protected and separated by a slot design.*

Fig. 5 shows a PICMA® actuator with a cross section of 5x5 mm² and a free aperture of 2 mm diameter. Outer and inner surfaces are ceramic protected and separated by a slot design. Some lateral bending and contraction actuators with free contours are exemplified in Fig. 6. All the elements in the picture are fully ceramic protected by insulation layers at top and bottom as well as inner and outer contour insulation borders.

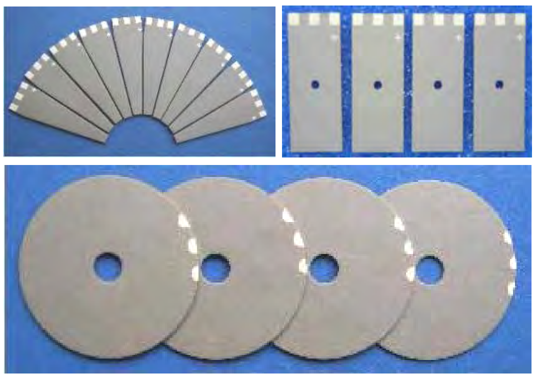

Fig. 6: *Monolithic lateral bending and contraction piezo actuators with free contours and full ceramic protection.*

DC-Reliability investigation

The superior DC-signal reliability of PICMA® actuators was demonstrated in a 3 year-test at elevated humidity of 92% r.h., room temperature and 100 V DC, were PICMA® 5x5x18 mm³ (P-885.50) actuators showed an extrapolated lifetime of about 80 years whereas conventional polymer coated products survived just one month [12].
Afterwards, there was a strong request from the market for a tool which allows the customer to calculate the PICMA®-DC-lifetime for different voltage, temperature and humidity conditions. Therefore a comprehensive lifetime investigation was started, were PICMA® 5x5x18 mm³ actuators were tested at 13 different climatic conditions (Fig. 7).

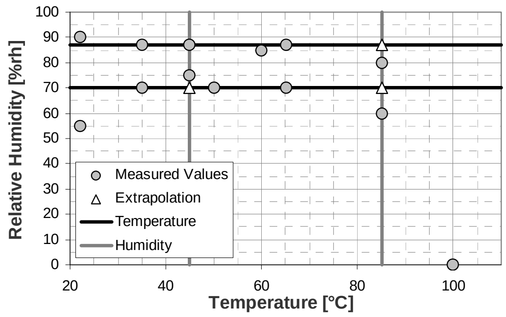

Fig. 7: *Tested climatic conditions of the comprehensive PICMA® DC-lifetime investigation and interpolated temperature and humidity functions for the deduction of the lifetime calculation tool.*

Five different voltages with 8 samples each were tested at every climatic condition. With some pre-tests and tests on other actuator geometries more than 1,000 PICMA®-samples and up to 4 climatic chambers in parallel were operated. The leakage current was used as the failure indicator.
Weibull-analysis was carried out for the determination of the single experiment mean time to failures (MTTF's). The mean value of the Weibull form factor Beta was 1.4.
Afterwards interpolations were performed to get individual relations for the lifetime versus the three determining factors. A power law was utilized for the voltage, an Arrhenius type of equation for the temperature and an exponential law for the relative humidity. Finally, the different interpolation equations were averaged and the time factors were implemented to get the PICMA®-DC-lifetime calculation tool (Fig. 8).

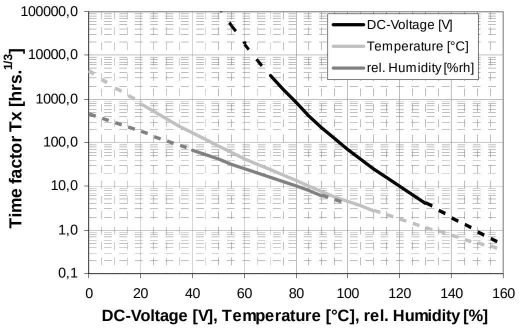

Fig. 8: *PICMA®-DC-lifetime calculation tool: the three time factors for the relevant DC-voltage, temperature and relative humidity condition have to be determined and multiplied to get the PICMA® DC-MTTF.*

The tool can be used in a very simple way: just determine and multiply the time factors for the three application conditions DC-voltage, temperature and relative humidity to get the PICMA® DC-MTTF.

Especially the voltage has a very distinct influence on the lifetime as can be seen from the steepest slope of the graph in the logarithmic scale diagram in Fig. 8. The following example supports this observation: for the conditions 150 V, 80% relative humidity and 40°C a MTTF of 1 x 10 x 130 hours = 1,300 hours or 2 month can be calculated. If, however, the voltage of 150 V, which is above the rated nominal voltage of 120 V, is reduced to 100 V, then the MTTF is increased to 70 x 10 x 130 hours = 91,000 hours or more than 10 years!

The PICMA®-DC-lifetime calculation tool in Fig. 8 is very helpful in the challenging process to match the customer request for high displacement or rather voltage at specified driving and environmental conditions with the requirement to deliver a very reliable system.

PICMA® AC - reliability results

AC-reliability is specified in cycles. Hence, the testing frequency has to be high to get a considerable number of cycles in a short time. For large voltages, like in most actuator applications, the self heating of the actuator due to dielectric losses limits the maximum driving frequency.

Table 1 show the frequency limits for a PICMA® 5x5x36 mm³ with the new contact stripes (Fig. 4), which have very good cooling properties. The measurements were done with a PI E-618.00 high power amplifier with 3.2 kW peak power.

Tab. 1: *Frequencies, where a PICMA 5x5x36 mm³ with the new contact stripe design (Fig. 4), reached it's specified operating temperature limit of 150°C for different large signal driving conditions and cooling measures (pre-stress 15 MPa, two spherical end pieces, the rectangular signal had a slew rate of 60 µs; *150 V is above the specified nominal voltage).*

Signal	Voltage [V]	Frequency limit [Hz] @ 150°C (surface, center)			
		Encapsu-lation	Free convection	Air cooling (3,5l/min)	Air cooling (25,5l/min)
Sine	0...150*	235	350	485	900 (140°C)
	0...120	355	535	750	
	0...100	510	765	1020	
	-15...105	300	428	560	
Rectang. (60 µs)	0...150*	100	154	190	460
	0...120	125	193	240	745
	0...100	160	250	317	1060
	-15...105	130	201	265	735

With the knowledge about the self heating limits, a test was run with 5 PICMA® 5x5x36 mm³ at 0…120 V unipolar sine wave, 15 MPa pre-stress with forced air cooling (high flow rate of 25 l/min) at 1.16 kHz. This very high large signal frequency allowed the test for 10^{10} cycles to be finished within 100 days because 10^8 cycles were realized per day.

Further results of extreme tests with voltages above the rated nominal voltage comprise:

- 3 samples of PICMA® 7x7x36 mm³ at 0…150 V unipolar, rectangular signal with 80 µs slew rate and 50 µm displacement at 150°C to $5x10^9$ cycles;
- 10 samples of PICMA® 2x3x18 mm³ at 0...200 V unipolar, triangular signal, 464 Hz, -30°C, silicone oil, no pre-stress, $1x10^9$ cycles.

All tests were successful in a way that no actuator lost more than 10% of its initial displacement.

Another interesting test is run by a customer with a PICMA®-Chip actuator PL022.30 2x2x2 mm³ at 20 V_{pp} bipolar sine wave, 100 kHz, to $1x10^{12}$ cycles [17].

These examples show the possibilities of piezoelectric actuators to reliably operate AC-applications with very high cycling numbers. Currently we plan to start a more comprehensive test program to find the AC-driving limits with the voltage and the time function as parameters.

Conclusions

The reliability discussion of piezoelectric multilayer actuators requires to differentiate between two separate different load cases and degradation mechanisms.

Large DC-signals in humid environments can lead to phenomena such as metallic migration and hydrogen degradation. For continuous pulse type AC-signals (switching), however, internal mechanical stresses in passive actuator volumes and resulting axial cracks are limiting the actuator lifetime.

Three patented design features of PICMA® actuators counteract these phenomena and ensure superior reliability in both load cases: 1) ceramic insulation layer protection, 2) slot segmentation and 3) crack bypassing contact stripe layout.
As a result of an extensive study a graphical tool for calculating the PICMA® DC lifetime was developed. During the design phase of a new actuator application, focus should be on the voltage dependency, when lifetime is a critical system parameter. Furthermore results of some tests with extreme AC signals are presented to demonstrate piezoelectric actuator reliability under severe conditions.

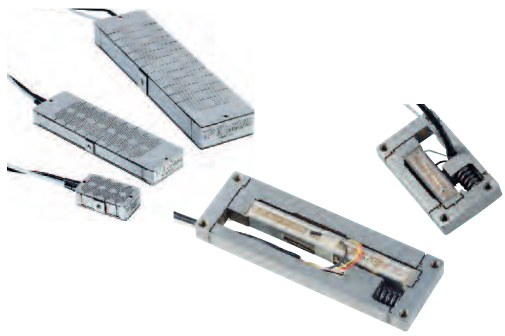

Fig. 9 *PICMA®-actuator integrated in flexure acutator. Lever amplfier provides extended travel to 1 mm.*

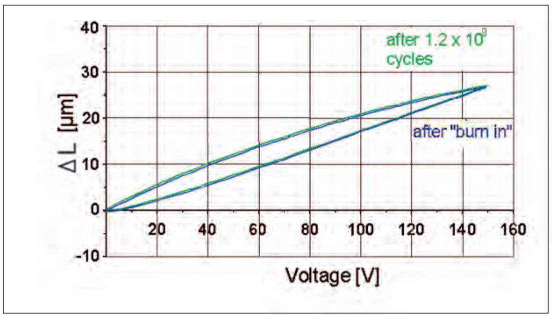

Fig. 10: *Dynamic test series with eight PICMAÈ actuators 5 x 5 x 18 mm: Total number of cycles 4.0 x 10exp9 cycles; 116 Hz sinewave, 100 V unipolar operating voltage, 15 MPa preloading. Control measurements after each series of 10exp9 cycles. Only insignificant decrease in the displacement.*

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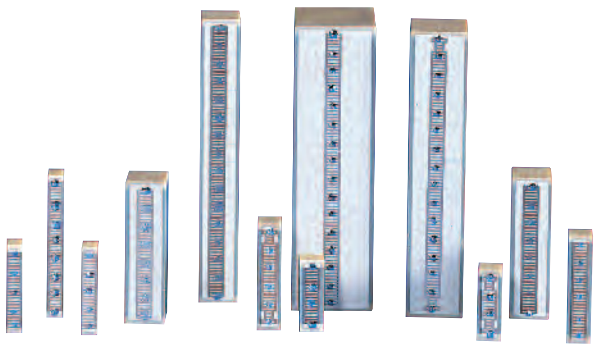
PICMA® Multilayer Piezo Stack Actuators

Ceramic-Insulated Actuators



hermetic encapsulation with inert gas filling for permanently high humidity or splash water

Technical Data

Order numbers*	Dimensions A x B x L [mm]	Nominal displacement [µm] (0 – 100 V)	Max. displacement [µm] (0 – 120 V)	Blocking force [N] (0 – 120 V)	Stiffness [N/µm]	Electrical capacitance [µF] ±20 %	Resonant frequency [kHz] ±20 %
P-882.11	2 x 3 x 9	6.5 ±20 %	8 ±20 %	190	24	0.15	135
P-882.31	2 x 3 x 13.5	11 ±20 %	13 ±20 %	210	16	0.22	90
P-882.51	2 x 3 x 18	15 ±10 %	18 ±10 %	210	12	0.31	70
P-883.11	3 x 3 x 9	6.5 ±20 %	8 ±20 %	290	36	0.21	135
P-883.31	3 x 3 x 13.5	11 ±20 %	13 ±20 %	310	24	0.35	90
P-883.51	3 x 3 x 18	15 ±10 %	18 ±10 %	310	18	0.48	70
P-885.11	5 x 5 x 9	6.5 ±20 %	8 ±20 %	800	100	0.6	135
P-885.31	5 x 5 x 13.5	11 ±20 %	13 ±20 %	870	67	1.1	90
P-885.51	5 x 5 x 18	15 ±10 %	18 ±10 %	900	50	1.5	70
P-885.91	5 x 5 x 36	32 ±10 %	38 ±10 %	950	25	3.1	40
P-887.31	7 x 7 x 13.5	11 ±20 %	13 ±20 %	1700	130	2.2	90
P-887.51	7 x 7 x 18	15 ±10 %	18 ±10 %	1750	100	3.1	70
P-887.91	7 x 7 x 36	32 ±10 %	38 ±10 %	1850	50	6.4	40
P-888.31	10 x 10 x 13.5	11 ±20 %	13 ±20 %	3500	267	4.3	90
P-888.51	10 x 10 x 18	15 ±10 %	18 ±10 %	3600	200	6.0	70
P-888.91	10 x 10 x 36	32 ±10 %	38 ±10 %	3800	100	13.0	40

Standard piezo ceramic type: 252
Standard connection types: 100 mm pigtail
* For optional solderable contacts, change order number extension to .x0 (e.g. P-882.10)
Recommended preload for dynamic operation: 15 MPa
Maximum preload for constant force: 30 MPa
Resonant frequency at 1 V_{pp}, unloaded, free at both sides. The value is halved for unilateral clamping
Capacitance at 1 V_{pp}, 1 kHz
Operating voltage: -30 to +130 V; the lifetime depends on the voltage applied.
Operating temperature range: -40 to +150 °C
Standard mechanical interfaces: Ceramics
Available options: strain gauge sensors, special mechanical interfaces, etc.
Other specifications on request.

