New Encapsulated Piezo Actuators for High-Reliability Applications in the Semiconductor Industry

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Abstract:
The reliability of piezoelectric multilayer actuators is an important issue for industrial 24/7 applications. Two completely different load cases have to be distinguished when reliability parameters of these actuators are specified. One is the AC-driving were the actuators have to generate extreme accelerations. The other one is the pure DC-load which is typical for applications which are taking advantage of the ultrahigh resolution of closed loop piezoelectric positioning systems.

This paper explains DC- and AC-degradation mechanisms as well as the unique design of the PICMA® co-fired actuators which is properly adapted to both load cases. Besides some characteristics of the actuators results of DC- and AC-reliability investigations are presented.

Keywords: Clean room, piezo actuator, PZT, piezoelectric, multilayer, co-fired, reliability, lifetime, humidity

Introduction

There are several reasons why piezoelectric multilayer actuators are attractive for a steadily growing number of applications: low static power consumption, high stiffness, high induced forces, high component mechanical energy density, easy geometrical adaptation due to ceramic technology. But the most prominent properties are: almost unlimited resolution and extremely fast acceleration. While resolution is mainly important in nanopositioning equipment the rapid response is cruical for high-throuput applications from beam-steering, active optics and high-speed valves.

Besides lowering the prices extended knowledge of reliability parameters will promote the further spreading of the piezoactuator technology. There is a fundamental difference in the reliability issue between the “resolution”- and the “acceleration”-applications: a positioning device has often to stay at a defined position over long time. Hence a DC-type of driving signal is typical for such a purpose. On the contrary a switching AC-signal is characteristic for fuel injection systems. The paper explains the differences between DC- and AC-reliability matters.

The PI Ceramic co-fired multilayer actuators (PICMA®) were initially developed for positioning purposes [1]. Later on they were modified in a way that they can take the very high switching currents during high acceleration applications. In the second part of this paper we will describe why the PICMA®-design is well adapted for both types of applications and present some reliability results.

DC-degradation mechanisms

The degradation of dielectric components under DC-driving conditions is related to the size of the electric field, the temperature and the humidity. For multilayer actuators the field dependency of the lifetime is usually described by a power law with an exponent of -2.5 to -3 [2,3]. An Arrhenius equation is often applied for the lifetime-temperature-relation. The observed activation energies are in the order of 1 eV [2]. However, the most severe condition is the humidity which can easily lower the lifetime by some orders of magnitude [4].

Increased humidity is not unusual for actuator applications. Clean rooms in the semiconductor industry, one of the major application fields of nanopositioning equipment, have artificially humidified air to avoid electrostatic discharging. Another source of high humidity are the cooling liquids next to actuator based precise machining equipment.

Looking at the conventional actuator designs (Fig. 1) the high humidity–DC–signal combination is most critical for the open electrode configurations (Fig. 1a,b) were the internal electrodes are just separated by the active layer thickness and protected by a polymer coating.

The reliability problem is illustrated in Fig. 2 for an actuator with silver palladium internal electrodes.

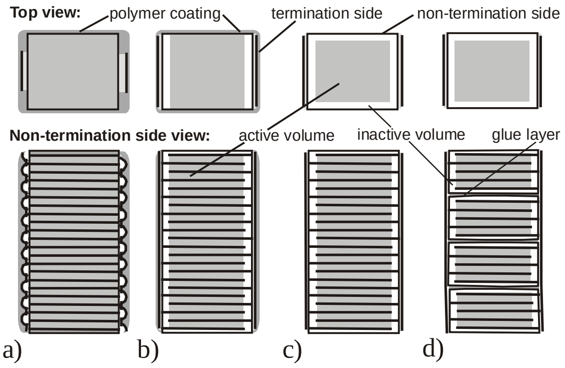

***Fig. 1:** Conventional multilayer actuator designs, a) co-fired all open electrode, b) co-fired open side electrode, c) co-fired buried electrode, d) glued chip buried electrode.*

Because no polymer coating is able to prevent moisture penetration [5,6], water is attracted by the field and ionized by electrolysis. Ag^+-ions move as Ag(OH) from the anode trough cracks, voids, dissolved secondary phases at the grain boundaries and, especially, on the surface to the cathode [7,8]. There it is reconverted into metallic silver. As a result silver dendrites grow from the cathode to the anode. First they lower the resistance later they can cause a breakdown. This phenomenon can be easily studied by putting a drop of water on an unprotected surface of an actuator at its nominal field. It takes just minutes to get a migration (Fig. 2b).

DC-humidity degradation is not just related to Ag/Pd-internal electrodes but also actuators with platinum electrodes tend to degrade at high fields [9]. Some authors just refer to dissolved "ions out of the ceramic" which cause the degradation [5,6].

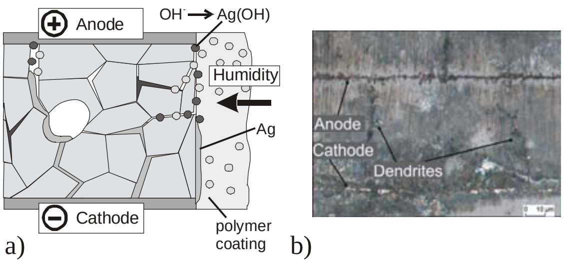

Fig. 2: *DC-degradation process in an open silver – palladium electrode actuator a) humidity driven degradation processes, b) water induced migration on an actuator surface without polymer protection.*

AC-degradation mechanisms

Besides material related AC-degradation phenomena [10] there are also design related issues. All actuator designs have inactive insulation volumes which are not field-accessed (Fig. 3). In these volumes tensile stresses are induced because the adjacent active regions expand along the actuator axis.

The higher the tensile stresses the higher is the probability to get uncontrolled cracks in axial direction which can either cause a dielectric breakdown or just separate an internal electrode from the termination. It can be shown that the tensile stresses increase when the actuator gets higher and the inactive volume gets longer (Fig. 3 c) as well as wider.

One possibility to limit this stress accumulation could be the segmentation of the actuator by just gluing chips together (Fig. 1 d). Then the stress would be released partially by the gluing layers. But this solution has principal drawbacks. Chips as well as actuators have no precise mechanical dimensions when they are fired. So either all the single chips have to be ground before gluing which is expensive and needs thick passive layers in the design, i.e. stress concentrations and loss of strain, or they are glued "as fired" which results in non-homogeneous gluing and termination layers.

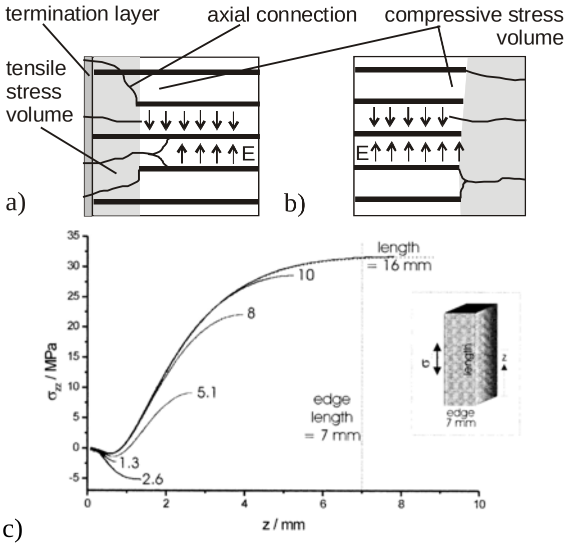

Fig. 3: *Tensile stresses in the inactive actuator volume a) cracking in the termination insulation plane, b) cracking in the buried electrode plane c) actuator length dependence of the maximum tensile stress in the inactive volume [11].*

PICMA-design

Fig. 4 shows the PICMA®-design. On the non-termination surface it has a thin ceramic protection layer [12] (Fig. 4 d). This inorganic coating can not be penetrated by the humidity, pretty much as the buried design (Fig. 1 c). The layer is pressed on the surface already in the green state. It is made of the same PZT ceramic material as the active layers. In contrast to the buried design where the insulation width has to be at least 200-300 µm for tolerance reasons, it has uniformly the same thickness as the active layers. Therefore it is partially accessed by the scattering field of the internal electrodes (Fig. 4 d) and, consequently, it is partly poled and expands during operation. Hence, the stress as well as the number of cracks are limited. Effects like significant stress accumulation in the non-termination insulation volume in the buried electrode design (Fig. 1 c) or stress concentration at the corners in the glued chip design [9] (Fig. 1 d) are avoided.

The second special feature is the slot segmentation of the stack to prevent stress accumulation in the termination insulation volume [12] (Fig. 4 a). In contrast to solutions were semi-controlled cracks are induced by poling these slots are already formed during sintering. The slot distance of about 2 mm is well adapted to the minimal stress optimum (Fig. 3c). The slot depth of 300-400 µm matches to the finding that poling cracks stop growing after 200 µm [13]. Moreover, the slot-layer has double the thickness as the other layers but it is active (Fig. 4 c). This prevents the slots from further growing.

The third feature is the special slot bypassing contact stripe layout [14] (Fig. 4 e). Usually the internal electrodes are contacted by a fired on Ag/Pdtermination layer. During operation this layer will be destroyed by cracking after 10^6-10^7 cycles [6], at least at the slots (Fig. 4 e). Therefore these cracks have to be electrically bypassed. In the PICMA®-design this is realized by a contact stripe which is soldered on by a controlled machine process. This contact stripe is not only flexible in terms of acting low forces to the solder layers by thin lamellas. It can also be easily adapted to the customer needs.

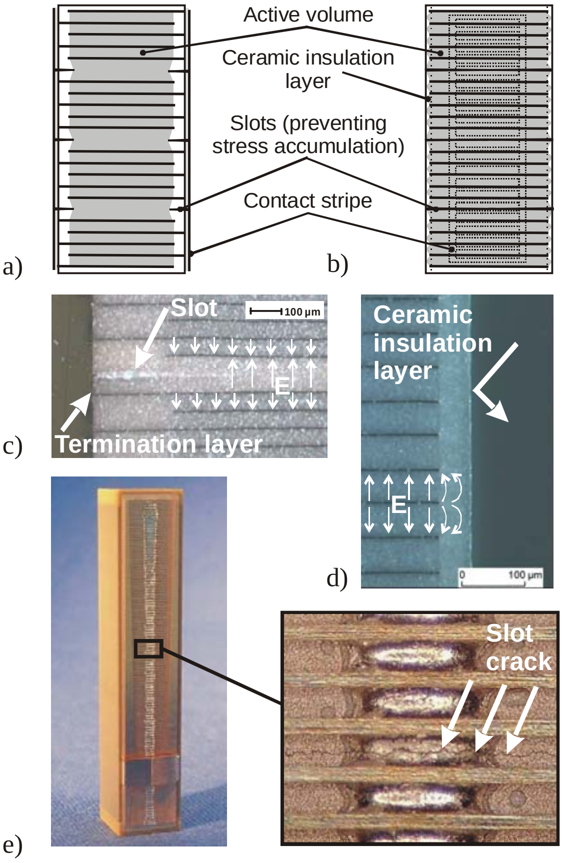

Fig. 4: PICMA®-design a) non-termination side view, b) termination side view, c) slot in the non-termination plane, d) insulation layer, e) Power-PICMA® with termination layer detail (electrical bypassing of the slot crack by the contact stripe).

Reliability results

The testing of component reliability is always accompanied by problems like testing for an abnormally long time or an unacceptable large sample number or finding accelerated test conditions which include the uncertainty of extrapolation to normal operating conditions afterwards.

Fig. 5 shows results of a long term DC-test were the PICMA®-actuators were compared to open electrode design actuators under severe conditions. Whereas all the comparative samples failed after 1,500 hrs. still 69 of the 80 PICMA® survived the 92 %-relative humidity test after 28,500 hrs. (3.25 years!). The current extrapolated characteristic lifetime is 700,000 hrs. In contrast to results reported elsewhere [9] failures occurred statistically distributed on the stack. We did not observe a local concentration at the corners which would indicate a systematic stress peak in the design.

The PICMA® suitability for high acceleration applications was tested by cycling the 7x7x36 mm^3-power-type (Fig. 4 e) at 150 V, 50 µm displacement, 150°C, 15 MPa pre-stress. Although the semi-rectangular rise times were as short as 80 µs and the resulting pulse currents were as high as 20 A PICMA® showed no degradation after $5\cdot10^9$ cycles.

Another indication of the PICMA®-reliability is the significant reduction in the failure rate of installed acutators. More than 100.000 PICMA®-actuators were used in different piezo positioning applications in the last four years. The failure rate was reduced by a factor of 10 to a very low value compared to the open electrode design actuators.

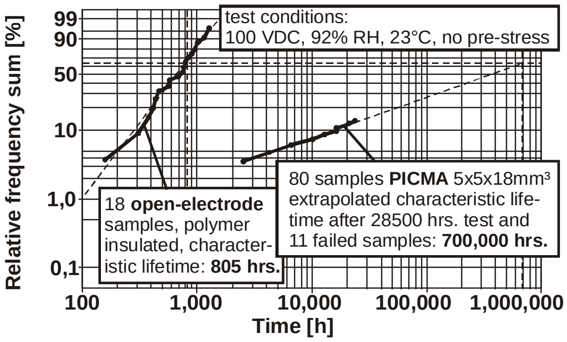

***Fig. 5:** DC-lifetime-test of PICMA actuators compared to conventional actuators with an open electrode design.*

Conclusions

The design of the co-fired PICMA actuators avoids the major reliability problems of stacked piezoceramic multilayer actuators for DC-drive under sever environmental conditions as well as dynamic pulse type AC-signals. This is ensured by three patented unique design features: 1) ceramic insulation layer protection, 2) slot segmentation and 3) slot bypassing contact stripe layout.

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