Piezo actuators with copper electrodes for fuel injection systems

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Enhanced performance and durability

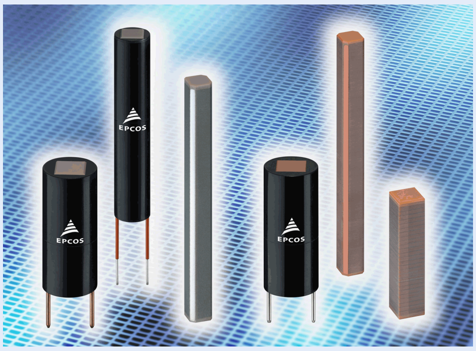
Piezo fuel injection systems have become firmly established as the state of the art in passenger vehicles, in particular in diesel and increasingly in gasoline powered cars. Since their market debut in the year 2000 more than ten million cars worldwide have been equipped with fuel injection systems that are based on multilayer piezo actuators. As the world market leader in piezo actuators for fuel injection systems, EPCOS has now introduced a new generation of actuators based on an innovative ceramic technology with copper inner electrodes that offer unrivalled performance and durability. EPCOS is the only manufacturer able to mass produce piezo actuators with copper inner electrodes.

Piezo-based systems offer clear advantages over other fuel injection technologies such as the conventional electromagnetic (solenoid) injectors. Although solenoids are still somewhat less expensive, piezo-based injectors offer faster response and a much more precise control of fuel injection volumes, which in turn results in greater fuel efficiency and reduced emissions as well as increased engine power. Moreover, for fuel injection valves, the specific displacement and force properties of piezo actuators enable system architectures with a substantially reduced number of mechanical elements.

Billions of cycles without failure

Piezo actuators consist of up to hundreds of stacked layers of piezo-ceramic material – lead zirconate titanate or PZT – each approximately 80 µm thick, which are then sintered in a complex process at temperatures of between 900 and 1100 °C. EPCOS' portfolio of customer-specific actuators includes components ranging in length from 5 to 80 mm and featuring from 100 to 1000 layers. Depending on their length, these actuators can achieve displacements of between 5 and 130 µm. These high-performance devices are designed to operate billions of cycles without failure.

FIGURE 1: EPCOS' NEW PIEZO ACTUATORS WITH COPPER ELECTRODES



Piezo actuator designs can range from 5 to 80 mm in height and supply up to 10 kN force and 130 µm displacement.

Because of their technological superiority piezo injectors have become a standard feature in many upper mid-range and premium cars. In order to make piezo fuel injection systems viable for a much broader range of commercial vehicles and lower priced cars, EPCOS has developed a new generation of actuators. They reduce material costs and free users from fluctuating noble metal costs without sacrificing performance. Moreover, the durability of the actuators was increased substantially.

Innovative materials

The development of the latest generation was based on EPCOS' piezo-ceramic technology with copper inner electrodes. Noble metals were traditionally the material of choice for electrodes in piezo ceramics because, unlike base metals, they do not oxidize during sintering under pure air or oxygen at around 1000 °C. In addition, conventional electrodes are made of silver with up to 30 percent palladium added to keep the melting point of the inner electrode well above the sintering temperature of the ceramics. Copper was made a viable inner electrode material by running all of the high-temperature processes in the fabrication of the piezo stacks under a reducing atmosphere: no oxidation can occur in the absence of oxygen. This innovation however requires a deep understanding of the material and precise control of all thermal processes because the process window is extremely narrow compared to the silver-palladium process.

EPCOS' first generation of copper piezo technology, which was introduced in 2003, already helped to cut material costs. Nevertheless, it lagged somewhat behind silver-palladium technology in terms of performance. The new copper technology has not only caught up to, but actually surpassed, silver-palladium technology.

Increased performance

The performance of ceramic materials is determined by two characteristic figures of merit: piezoelectric coupling, which describes the ability of the material to convert electrical energy into mechanical energy, and energy efficiency.

TABLE 1: KEY PERFORMANCE PARAMETERS OF PIEZO TECHNOLOGIES

	Established silver-palladium technology	First generation copper technology	**Second generation copper technology**
Curie temperature [°C]	340	340	**340**
Piezoelectric coupling	0.68	0.62	**0.71**
Energy efficiency	0.51	0.51	**0.52**

$$\text{Piezo Coupling}^2 = \frac{\text{Mechanical Energy}}{\text{Electrical Energy}} = \frac{\text{Stroke . Force}}{\text{Voltage . Charge}}$$

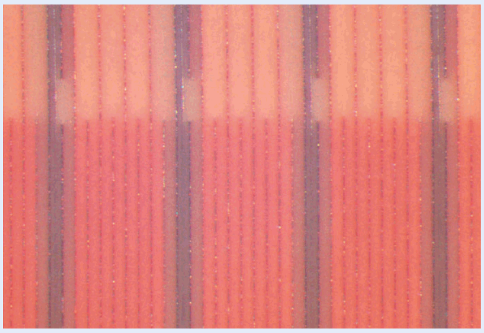
$$\text{Efficiency} = 1 - \frac{\text{Loss Energy}}{\text{Electrical Energy}}$$

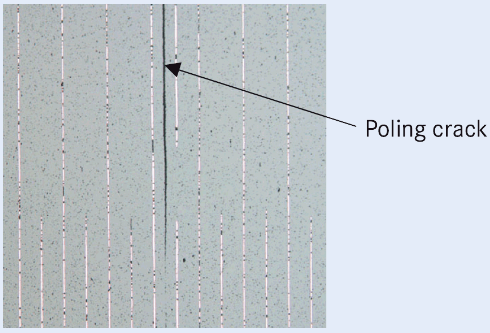
With the first generation copper technology EPCOS was able to achieve the same level of efficiency and approximately 90 percent of the coupling of silver-palladium. The second product generation now features superior coupling and efficiency, making the actuators viable for the full range of piezo fuel injection applications in nearly all diesel and gasoline engines.

Improved durability

As a mechatronic device, a piezo actuator must satisfy rigorous mechanical and electrical durability demands. EPCOS was able to increase the robustness of the new copper-based piezo actuators to a level beyond that of the established silver-palladium technology, which is well proven under automotive conditions.

FIGURE 2: COPPER TECHNOLOGY WITH CRACK MANAGEMENT

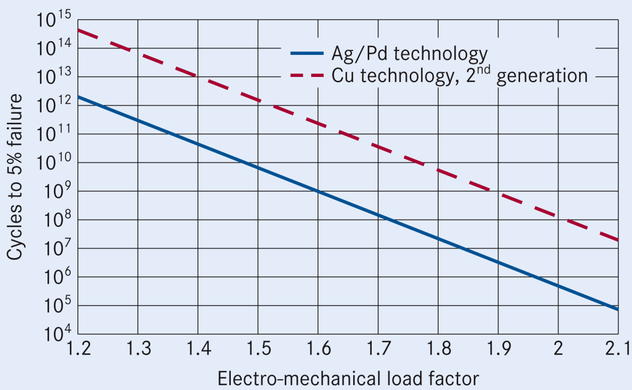




Polished section of the new generation copper actuator (left) showing the stacked design of the active and dielectric layers. Even under very high loads, poling cracks that naturally occur in piezo actuators are only able to propagate in a predetermined direction. The enlarged section on the right shows a poling crack in a breaking layer.

Active crack management that successfully prevents mechanical failures even at very high load levels is one of the most important design features employed to accomplish this goal (Fig. 2). Mechanical failures in piezo actuators usually occur in the form of cracks or damage to the contacts and can be caused by high mechanical stress to the component. In particular, cracks that run perpendicular to the inner electrodes can create a short circuit in the component.

FIGURE 3: TIME TO FAILURE FOR SILVER-PALLADIUM AND COPPER TECHNOLOGIES



At constant load level the time to five percent failures of the novel copper technology is almost 3 orders of magnitude greater than the established silver palladium technology.

A newly developed multilayer design guarantees that cracks develop only in certain predetermined planes of the device during poling and operation. With this concept EPCOS has been able to improve the robustness of piezo stacks by several orders of magnitude. The Wöhler diagram shown in Fig. 3 compares the time to failure of a typical piezo stack in silver-palladium technology and in the second generation copper technology. Thanks to this advanced crack management of the latest generation of piezo actuators with copper electrodes, the time to failure is almost three orders of magnitude greater than for the standard technology, which is well proven in robustness for 1 billion cycles under automotive conditions. With this improvement, EPCOS has not only increased the performance of piezo stacks for existing applications in automobiles, but satisfied a key entry criteria for commercial vehicle applications. Here, motors typically must run reliably in excess of 2 million kilometers over the course of their lifetimes.

Alternatively, the increased durability of the second generation copper technology enables downscaled actuator designs that can operate at a higher energy density, while delivering a performance and robustness comparable to that of silver-palladium technology.