Application of Thick-Film Substrate Technology in High Voltage HRC Fuses

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Abstract: High voltage HRC fuses manufactured today typically comprise wire or strip fuse-elements wound round a non-conductive support element (star-core). This paper presents a unique design of a high voltage HRC fuse, utilising thick-film substrate technology. In contrast to conventional wire or strip designs, and a known design of HV fuses utilising thick-film technology, wherein helical fuse-elements are supported on a glass tube [4], the design presented in this paper embodies fuse-elements of a unique design screen-printed on to flat non-conductive substrates. The design of the fuse-elements, arrangement of the fuse-elements on the supporting substrates and, finally, the layout of the substrates inside the fuse housing of standard dimensions contribute to generating adequate arc voltage and achieving high rupturing capacity sufficient for high voltage applications.

Keywords: (high voltage fuse, HRC fuse, substrate fuse)

1. Introduction

This paper presents a unique design of an HV substrate fuse. The design was developed and successfully tested in accordance with the IEC 282-1 standard on full-size prototypes. From HV test results it is evident that thick-film substrate technology is applicable for HV fuses. The main advantages of the fuse design presented in this paper are: high resistance to vibrations, highly accurate and reproducible film deposition technology and, hence, low scatter of I:t characteristics and other parameters, very low switching voltage. Due to the exceptional design the manufacturing process can be substantially automated.

2. Design of the HV substrate fuse

2.1 Materials and deposition technology

Various techniques exist for laying down conductive fuse-elements on to non-conductive substrates; starting with every kind of thin-film deposition technique (sputtering using glow discharge technology), vapour deposition (gas-phase chemical process) or electroplating (liquid-phase chemical formation); at the other end of the spectrum there is thick-film technology with the screen-printing process. To achieve small power losses, which are directly related to the resistance of the printed metal layer, printing thick-film conductive layers is necessary. The various film deposition technologies carry different price tags and, hence, only some of the available techniques could be used for an economically viable HV fuse design. Consequently, thick-film screen-printing was chosen as the conductive film deposition method. This printing method is mature, easily obtainable and inexpensive [1-2].

As for the substrate material, different material classes like ceramics, glasses or glass-ceramics are available [5]. The following substrate materials were investigated: alumina, aluminium nitrite, beryllia, Robax, Borosilicate glass and other special glasses.

The preferred conductive layer material is silver paste, due to its good solderability, good adhesion and good electrical and thermal properties. Depending on the substrate material and firing conditions different silver pastes were used. The recommended firing profile varies slightly for the different pastes used. The common phase is a drying step at approx. 120°C and a peak temperature between 400°C and 800°C (depending on the type of paste used). The peak time is 15 minutes. Firing of all samples was carried out in a box furnace.

The accuracy of the printed silver layer structure is one of the most important issues. The quality of the constrictions (e.g. width tolerance) depends on the quality of the printing mask and on the physical properties of the silver paste and substrate material used. The main concern is the surface tension of the paste. To obtain adequate printed geometry the paste should show good wetting behaviour during the printing process. The substrate material has a significant influence on the quality of the printed layer as, depending on the substrate's surface free energy, the printed layer demonstrates better or worse wetting properties. After the firing process is complete the printed layer must have good adhesion to the substrate [3].

A number of different substrate fuse samples were produced using a semi-automatic screen printer. After printing the quality of the printed film was verified using high-magnification video, SEM and optical laser techniques, Fig. 1 and Fig. 2.

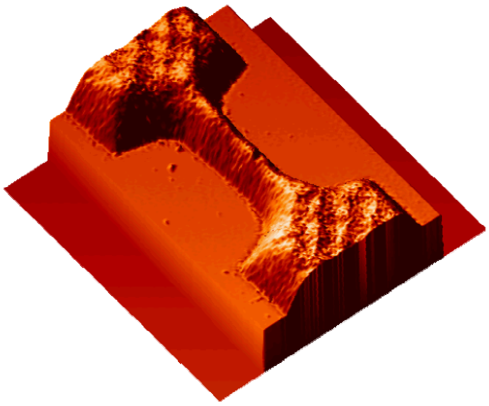

Fig. 1: Screen-printing: 3D SEM image of fuse-element constriction.

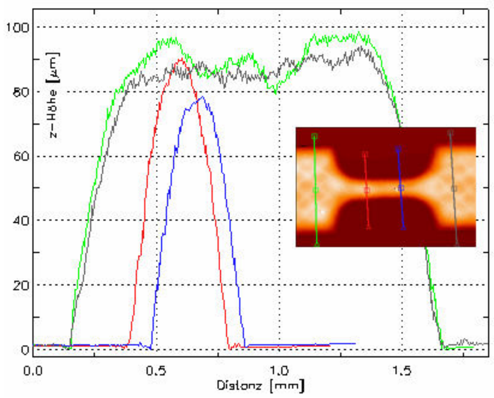

Fig. 2: Screen-printing: profile of the printed layer.

To obtain comparable results for different substrate thicknesses the table height of the screen printer is adjusted. By doing so the distance from the sieve to the substrate is kept constant. When changing the printing paste, which also requires a new sieve or at least thorough cleaning of the previously used sieve, critical printing parameters such as mesh size, squeegee speed, pressure etc. are adjusted for the specific physical properties of the paste (e.g. different viscosity).

2.2 Fuse-element design

The fuse embodies a number of substrates with thick-film fuse-elements screen-printed on to them. To accommodate the required fuse-element length on the available length of the substrate - which is limited by the standard length of fuse housing - the fuse-element zigzags between the two connection areas located at shorter ends of the substrate, Fig. 3.

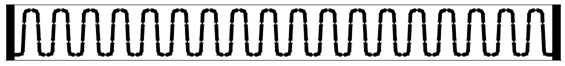

Fig. 3: Fuse-element and substrate geometry.

A number of constrictions are located along the length of the fuse-element to facilitate multiple arc ignitions and to generate sufficient arc voltage to interrupt the fault current. The constrictions are normally located in the vertices of the zigzag. One or more constrictions may also be located in the straight segments linking the vertices, Fig. 4.

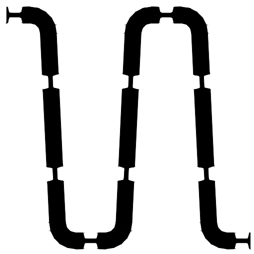

Fig. 4: Location of constrictions along fuse-element length.

The amplitude of the zigzag, its shape, location and number of constrictions differ depending on the required voltage rating, an example of fuse-element design rated at 7 kV is shown in Fig. 5.

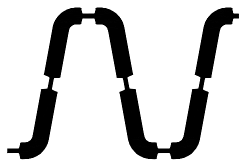

Fig. 5: Example of fuse-element design rated at 7 kV.

In order to ensure sufficient dielectric clearance after interruption is complete the number of zigzags, the cycle and amplitude of an individual zigzag and the angle between the straight segments linking the vertices are selected for a given voltage rating. The geometry and cycle of the zigzag are also so selected as to ensure that the arc can only develop along the fuse-element length. Excessive reduction in the cycle of the zigzag would result in individual arcs merging in an uncontrollable fashion thus shortening the total arc length and, consequently, in an unacceptable reduction in total arc voltage. This in most cases would lead to unsuccessful interruption and possible fuse explosion. On the other hand the cycle cannot be freely expanded due to standardised - and limited - fuse dimensions. Finding the golden optimum proved to be one the most important issues.

The fuse-element may be laid on one side of the substrate (referred to henceforth as ‘single sided’ printing or substrate) or both sides of the substrate (referred to henceforth as 'double sided' printing or substrate) – the latter permits doubling of the number of parallel fuse-elements (hence nearly twofold increase in the nominal current rating and improvement of switching characteristics) without increasing the cost of the substrates and space used. For the highest current ratings double sided printing is practically the only feasible solution.

2.3 Arrangement of substrates in fuse housing

Depending on the required fuse current rating one or more substrates - hence one or more parallel fuse-elements - may be arranged inside the housing. Current ratings for which up to 6 parallel fuse-elements are sufficient are realised using 3 double sided substrates positioned in a 'triangular arrangement' (the substrates are so arranged that their cross-section resembles an equilateral triangle), Fig. 6.

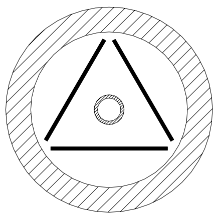

Fig. 6: Triangular arrangement of substrates.

Current ratings for which more than six parallel fuse-elements are needed are realised using from 4 to 8 single- or double sided substrates (hence from 8 to 16 parallel fuse-elements) positioned in a 'star-shaped arrangement' (the substrates are so arranged that their cross-section resembles a star), Fig. 7. Conventional striker wire is situated inside the insulating tube located along the symmetry axis of the fuse.

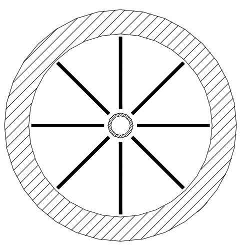

Fig. 7: Star-shaped arrangement of substrates.

2.4 Test results

2.4.1 Electro-mechanical cycling tests

Long-term stability of the printed silver layer laid on the substrate was examined. Fatigue, for example de-bonding of the metal layer from the substrate, would cause unacceptable changes in the tripping and interruption behaviour of the fuse, which might lead to a malfunction [5]. During the firing process, all organic solvents are completely oxidised. At higher temperatures special glass-particles embedded in the silver paste melt and create a liquid phase between the conductive layer and the substrate. After the firing process is complete interfacial adhesion between the conductive layer and the substrate is provided by the glass layer.

It is known that different substrates show different adhesion properties to glass and metal layers. Good adhesion between the conductive layer and the substrate must be ensured during the entire lifetime of the fuse, during which the fuse is normally subjected to long periods of electro-thermal cycling. Consequently, to ensure long-term stability of the fuse electro-mechanical cycling tests were performed in a climatic chamber on several different substrate materials. The temperature profile used for the test is shown in Fig. 8.

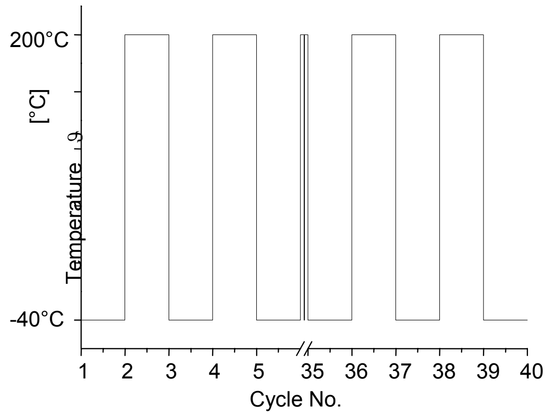

Fig. 8: Thermal cycling profile in a climate chamber.

All samples survived the harsh test without failure. No film de-bonding or breakdown of the substrate or conductive layer was observed. Initially this was very surprising for the aluminium-nitrite substrate, as this material needs special glasses for good adhesion at standard firing process. The reason for such an unexpected - but positive - result might be the slightly decreased cooling rate after firing during the batch process compared to a continuous process. The slower glass cooling process probably helped to reduce the internal and interfacial stresses and, hence, created good conditions for strong adhesion.

The disadvantage of the above test is that the conditions of thermal cycling in the climate chamber are not completely comparable with real electro-mechanical cycling conditions found in service. In the climate chamber the temperature of the whole fuse-element and the substrate is increased in an almost uniform manner. In the real world the fuse-element is the heat source, in particular the constrictions, which results in non-uniform temperature distribution in the fuse-elements and the substrate. Due to different mechanical properties of the conductive film and the non-conductive substrate both materials are subjected to high internal stresses. Thermal expansion coefficient and modulus of elasticity have the greatest effect on the magnitude of the stress [5].

To identify any potential problems related to long-term stability of the fuse under real operating conditions and to compare the behaviour of different substrate materials under current cycling conditions additional tests were performed. Loading current was set to the nominal (rated) current of the substrate fuses used, Fig. 9.

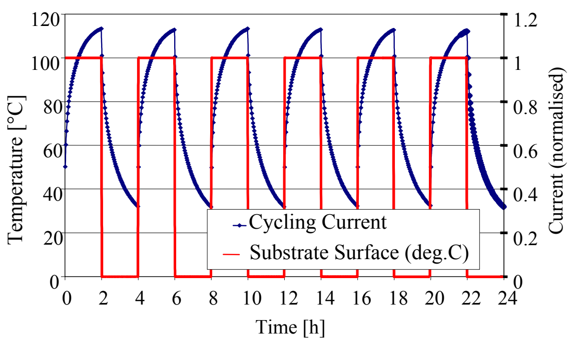

Fig. 9: Cycling current and temperature profiles.

Both the ON and OFF times were set to 2 hours. Voltage across fuse terminals and temperatures in the geometrical centre of each sample were measured and recorded using computerised data acquisition system. The electro-mechanical current cycling test ran over a period of four weeks. All tested fuse samples successfully passed the test: no perceptible change in measured temperature or resistance was observed.

2.4.2 Dielectric tests

The dielectric behaviour of a fuse is one of the key issues. Although capability to interrupt a fault current is the main functionality of the fuse, its capability to withstand recovery and nominal voltage of the electrical system are essential. The dielectric strength of the fuse is related to the dielectric strength of an individual zigzag. For the purpose of the dielectric strength test the worst case condition was simulated, with no arc-quenching material present in the fuse. Initially one notch per each parallel fuse-element was tripped, and afterwards PD-inception voltage was measured in an HV-circuit, Fig. 10.

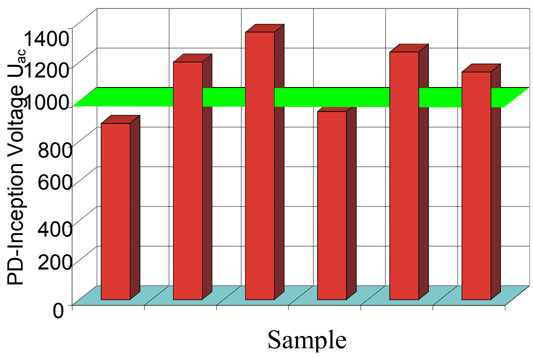

Fig. 10: PD-inception voltage for tripped substrate fuses without arc-quenching material.

The average PD-inception voltage was found to be approximately 1000 V. It can be concluded that the dielectric strength of the design is adequate. If necessary, dielectric strength could be increased further by application of special arc-quenching materials.

2.4.3 Current interruption

HV short-circuit and overcurrent tests (TD1, TD2 and TD3 test duties) were carried out on full-scale prototypes of the substrate fuse design presented in this paper. The fuses successfully passed short-circuit and overcurrent tests. Fig. 11 shows fulgurite formed at progressive stages of current interruption at 7 kV TRV.

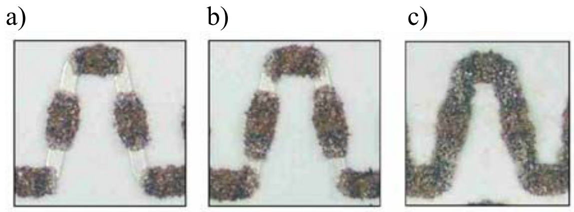

Fig. 11: Fulgurite formed at progressive stages of current interruption (a, b, c).

Fig. 12 shows fulgurite formed on a different fuse-element design printed on borosilicate glass after successful short-circuit current interruption at 12 kV TRV.

Fig. 12: Fulgurite formed after successful short-circuit current interruption at 12 kV TRV.

Typical current and voltage traces recorded during short-circuit interruption are shown in Fig. 13.

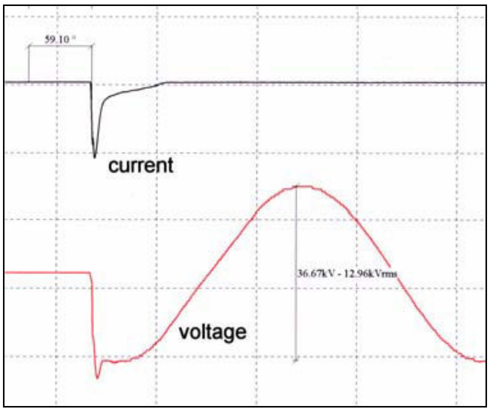

Fig. 13: Current and voltage traces recorded during short-circuit interruption.

It is noteworthy that during interruption the fuse generates very low switching voltages. This characteristic makes the design and technology particularly suitable for HV fuses for the protection of power electronic devices.

3. Conclusions

The paper presents a novel design of an HV substrate fuse. From the electro-mechanical current cycling tests performed to verify long-term behaviour of the new design it is clear that the design and materials show negligible degradation – no cracking, film de-bonding from the substrate or perceptible change in fuse-element resistance could be observed. The design was successfully tested on full-size prototypes under HV conditions, which ultimately proves that thick-film screen-printing technology is suitable for commercial HV fuse-protection applications.

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