Acoustic emission testing of electrical stressed copper trace

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Abstract—**Copper becomes more and more important in the electronic industry. This metal is more resilient than conventional materials (like aluminium) due to the higher electrical and thermal conductivity. During several electrical stress pulses the copper changes. The surface can melt up and cracks and voids can develop inside the copper specimen.**

In this paper we use acoustic emission testing to analyse copper degradation especially of copper and copper traces. It is evaluated if an acoustic wave excited by a thermo-electrical stress pulse can be detected by a simple measurement setup and if a correlation between the acoustic signal and the degradation exists. The idea is that during the degradation, the behaviour of the material changes which in turn influences the emitted acoustic signal.

Keywords-acoustic emission testing, degradation copper wire and copper trace

I. INTRODUCTION

Copper is a fundamental metal in today's electronic industry. Its high electrical and thermal conductivity are relevant for it to withstand millions of electrical stress pulses. These electrical stress pulses however, cause voids and cracks inside the copper structure. Consequently, the electronic device can be partially or completely destructed.

How these voids and cracks occur and what the physical nature of these degradations is, cannot be easily explained and needs to be investigated. For this purpose, we introduced two hypotheses. Our first hypothesis is that these defects occur because of the thermal mismatch which causes thermo-mechanical stress leading to the partial failures within the copper structure. Another hypothesis is that the induced energy of the electrical stress pulse is sufficient to heat up locally the internal structure until it melts.

For the first experiment we use a simple model which consists of a copper wire with a diameter of 50 µm. This copper wire was electrically stressed by sub-millisecond current pulses with up to 80 ampere. Figure 1 shows the stressed copper wire. The surface has partially melted and copper nodes occur.

In the next step, we use copper traces for our investigation. The trace is manufactured by subtractive etching [1] of a thin copper film applied on an FR4 substrate. The copper trace is again electrically stressed by sub-millisecond current pulses in the range of 80 to 100 ampere. Figure 2 shows the test board with several copper traces. The copper traces have a length of 30 mm, a width of 0.2 mm and a thickness of 0.035 mm. The destructed part is marked by a rectangular box (burnt through). A piece of the test board is cut out for the focused ion beam (FIB) analysis.

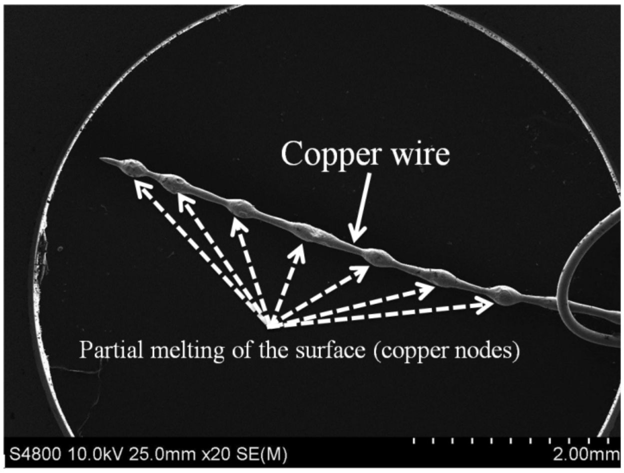

Figure 1. An electrical stressed copper wire with an exhibiting partial melting surface.

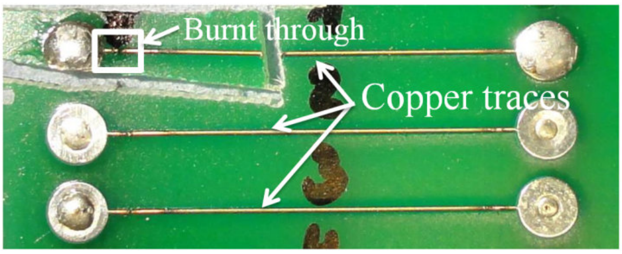

Figure 2. Test printed board with copper traces.

The FIB analysis shows that a trace has lifted off at the failure location where the trace is blown. Further, a split of the copper trace can be detected. The resulting scanning electron microscope image of the failure location is shown in Figure 3.

A non-destructive evaluation method is required to analyse the copper behaviour. Section II presents qualitative discussion why acoustic emission testing may be a viable method. Acoustic emission testing is a passive non-destructive testing method in contrast to ultrasound testing. Mechanical waves are generated by a stress pulse due to local heating and consequently a thermal expansion wave is generated which can be measured. Displacements on the order of picometers can be detected with an adaptable setup and equipment. Sources of acoustic emissions are, for example, growth of cracks, debonding and graduation of voids in metals or materials. Analysis, determination and detection of such a signal can provide useful information regarding the failure location in a material [2][3].

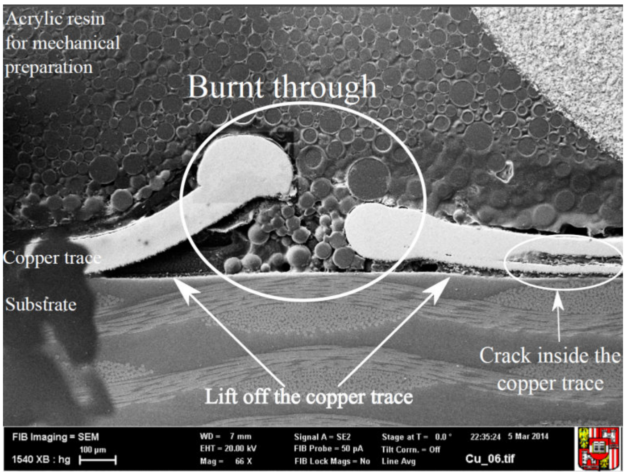

Figure 3. Scanning electron microscope image of a destructed copper trace.

In the literature a lot of examples exist how acoustic emission can be used for detecting small failures in different metals [4][5][6]. In this paper we use acoustic emission testing to analyse copper degradation especially of copper traces. It is investigated how the acoustic emission correlates to the copper deterioration.

This paper is organised as follows. In section II the mechanical consideration of the stressed copper trace is discussed based on the result of the FIB cut. The measurement setup is described in section III. The recording of the acoustic signal and evaluation of the copper trace is described in section VI.

II. MECHANICAL CONSIDERATIONS AND MATHEMATICAL MODELLING

A complete mathematical model which describes the full system behaviour from the stress current to the acoustic signal can be expected to be quite complex and is beyond the scope of this text. Nevertheless, we discuss some qualitative aspects to illustrate the motivations for our acoustic emission measurements. Consider a copper trace on a substrate like the ones shown in Figure 2. Without deterioration the trace is firmly attached to the substrate. The objective of the experiments is to detect deviations from this pristine state like cracks or debonding caused by repetitive current pulses.

When the pulses are short there is no significant heat conduction during the time of a pulse and the copper layer may be considered adiabatic during the pulse time. The different temperatures of the copper and the substrate as well as the different coefficients of thermal expansion cause mechanical stress to build up and that cause a bending of the substrate, like depicted in Figure 4. The amount of deflection depends on the temperatures as well as the Young's moduli and geometry of the different parts of the assembly. The deflection of the substrate and copper track is measured indirectly by recording their acoustic emissions.

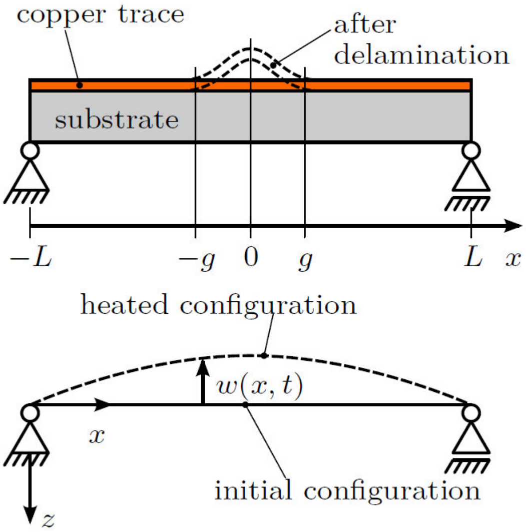

Figure 4. Side view drawing of a copper trace on a substrate. The composition of the different layers as well as a symmetric delamination of the copper layer of width g is shown in the upper part of the figure. The expected displacement of the arrangement due to thermal expansion of the copper layer is illustrated in the lower part.

Several effects may influence the deflection and thereby the acoustic emission:

- The Young's modulus of the copper depends on the temperature and when the copper layer melts locally, it must drop to zero at these locations. Therefore, the amount of bending caused by the thermal expansion should first rise with temperature and then drop once the copper softens.
- The Young's modulus may depend on the grain structure of the copper layer. It can be expected that repeated heating causes changes in the grain structure.
- Partial melting, debonding and changes in grain structure may change the geometry of the copper.
- A symmetric delamination around 0 is indicated in Figure 4. The delaminated part of the copper layer can only introduce smaller mechanical stresses, especially if it forms a loop like depicted in Figure 3 and Figure **4**. On the other hand, such a loop can move upwards quite freely when the copper trace expands with temperature. The loop movement is added to the substrate movement if the same emission of the deflection is measured.
- The delaminated loop has lower total heat conduction, because the thermal conductivity of air is lower than that of the substrate. If we drop the adiabatic assumption, it seems plausible that the delaminated loop will heat faster and cool slower than the laminated rest of the copper layer. Therefore, it can be expected that the movement of the loop is quite different from the rest of the beam.

III. MEASURMENT SETUP

Basically, the measurement setup (see Figure 5) consists of the following parts:

- Electrical stress system
- Trigger system
- Two power supplies
- 4-channel oscilloscope
- Workstation
- Device under test (DUT)
- Microphones

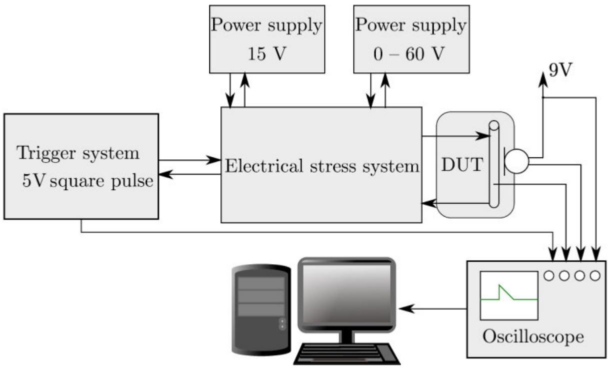

Figure 5. Schematic measurement setup.

The electrical stress system provides the current pulses for stressing the DUT. Each current pulse is triggered by a pulse signal generator. Electret microphones are used to record the acoustic signal of the stressed DUT. An oscilloscope records the voltage drop across the DUT, the current of the stress pulse and the microphone signal. The workstation is used for post processing the microphones signals.

A. *Preparation of the DUT*

The used DUT for the evaluation and analysis is a copper trace of printed circuits (see Figure 6).

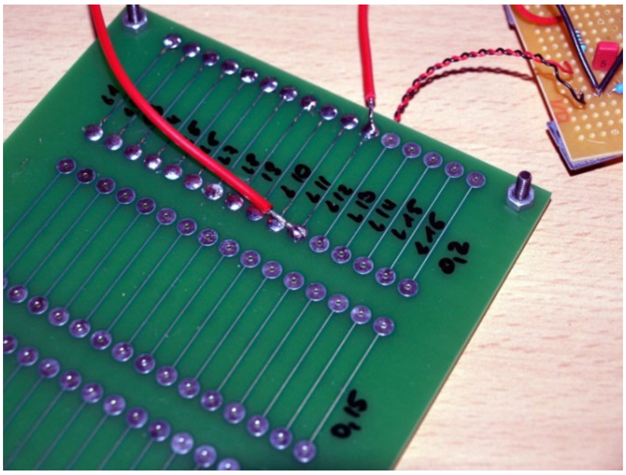

Figure 6. Copper trace with a length of 30 mm, a width of 0.2 mm and a thickness of 0.035 mm.

B. *Electrical stress system*

Figure 7 shows a schematic of the setup. The capacitor C is either charged through the charging resistor R_C or by a power supply with current limiting function. When the capacitor voltage u_C has reached a value close enough to u_0, the current pulse can be triggered by issuing a voltage pulse u_t to the silicon-controlled rectifiers *(SCR)* gate driver. The *SCR* gate driver drives the *SCR*'s gate according to its specifications, causing the *SCR* to conduct and shorting the capacitor through the DUT. The parasitic wire resistances and inductances are combined in R_p and L_p respectively. The current pulse is cut off, once the *SCR* current i swings below the *SCR*'s holding current.

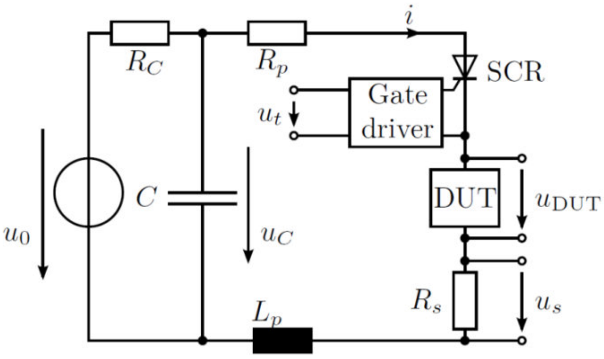

Figure 7. Schematic overview of the electrical stress system.

The shape and parameters of the current pulse are analysed by considering the circuit in the triggered state when the SCR is conducting. In this case u_0 and R_C can be neglected, because the charging current is much lower than the pulse current.

The resistance of the DUT, R_s and R_p can be combined to an effective series resistance R and the inductances of the DUT and L_p to an effective series inductance L. The conduction voltage drop u_{SCR} of the *SCR* is assumed to have a constant value. It is in fact a function of at least i and the temperature, but this is neglected to simplify the analysis.

This results in an R, L, C series circuit which is described by the ordinary differential equation (6)

$$LC\ddot{u}_c(t) + RC\dot{u}_c(t) + u_c(t) = u_{SCR} \quad (4)$$

from which the sought current

$$i(t) = -C\dot{u}_C(t) \quad (5)$$

can be derived and $\ddot{u}_c(t)$, $\dot{u}_c(t)$ denote the first and second derivative with respect to time. The solution can have an oscillating, critically or overcritically damped behaviour, of which only the last one has been observed. If the component values had allowed an oscillating behaviour, the calculation would have been more complicated, because the nonlinear behaviour of the SCR, which does not allow $i(t) < 0$, would have to be taken into account. The initial conditions $i(0) = 0$ and

$u_C(0) = u_0$ lead to the solution

$$i(t) = \frac{u'_0\left(e^{\lambda_1 t} - e^{\lambda_2 t}\right)}{\sqrt{R^2 - \frac{4L}{C}}}$$

where λ_1 and λ_2 are the eigenvalues

$$\lambda_{1,2} = -\frac{R}{2L} \pm \sqrt{\frac{R^2}{4L^2} - \frac{1}{LC}} \qquad (7)$$

of the system, $u'_0 = u_0 - u_{SCR}$ and the positive sign of the root must be used for λ_1.

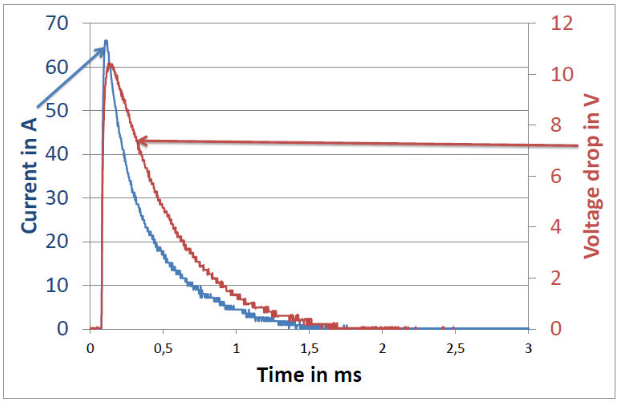

Figure 8. Typical electrical stress pulse used for stressing the copper trace.

Figure 8 shows a typical electrical stress pulse. The stress pulse has a peak amplitude of 75 A. The voltage drop over the copper wire is 9 V.

IV. MEASUREMENT RESULTS

The copper trace is electrically stressed which generates an acoustic wave. The focus lies on the evaluation and analysis of changes inside the copper trace and its crystal structure. Our hypothesis is that due to the stress pulse, voids and cracks occur and thus the characteristic acoustic emission changes over time.

In the first measurement, the printed circuit board with 48 copper traces with a length of 30 mm, a width of 0.2 mm and a thickness of 0.035 mm is used. A single copper trace (see Figure 6) is stressed at a time. The microphone is placed over the centre of the copper trace (15 mm). The copper trace is electrically stressed until it fails. One stress pulse is triggered every 15 s. The waveforms were saved in packets of 100 stress pulses. The typical number of stress pulses to destroy a trace of the given geometry is 230. In Figure 9 the recorded microphone signals of the 1st, 50th, 100th, 150th and 200th are illustrated. One can observe gradual changes in the maximum amplitude and in a decline in the centre frequency.

Next, we investigate the temporal progress of the acoustic signal. It should be analysed if and how the acoustic signal changes over the stress cycles. We only recorded the microphone signals, thus we use the signal energy as parameter how the signal changes over the cycle. For the discrete signal the following equation can be used

$$E = \sum_{n=-\infty}^{\infty} |x(n)|^2 \qquad (8)$$

where x[n] is the microphone signal. We know that we cannot describe the physical behaviour with this computation. We are only analysing if there is a significant change in the signal. In Figure 10 the signal energy over the cycles are plotted. It can be seen that the signal energy of the microphone signal is increasing significantly with the cycles (increase of 48% from the beginning to the destruction). This implies that the acoustic emission increases too.

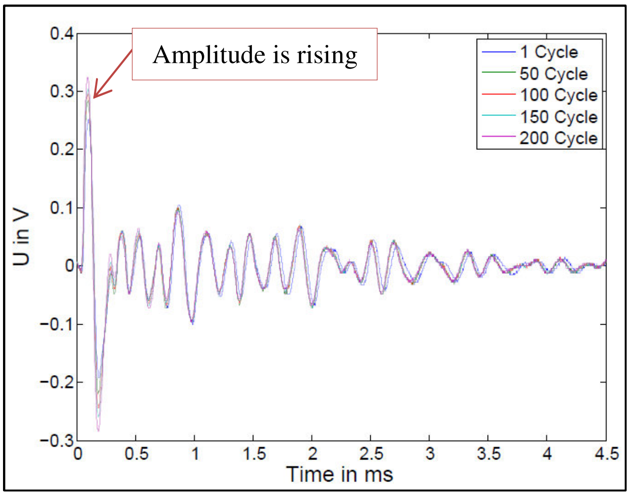

Figure 9. Microphone signal of a stressed copper trace.

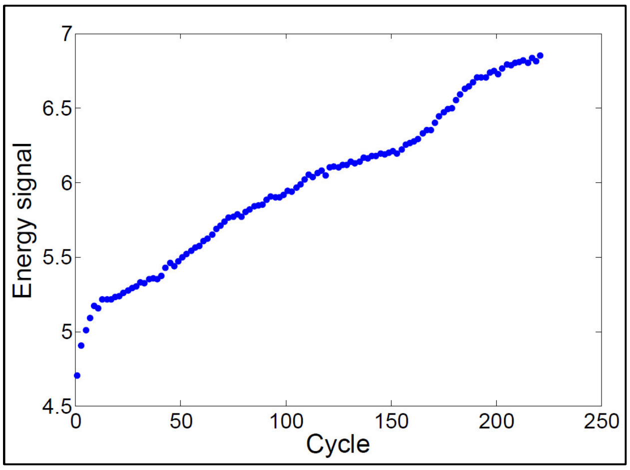

Figure 10. Energy signal over the cycle.

In a next step the amplitude spectrum is analysed. Internal failures of the material would be expected to change the emission spectrum. However, the evaluation showed that no major changes in the spectrum can be detected (see Figure 11).

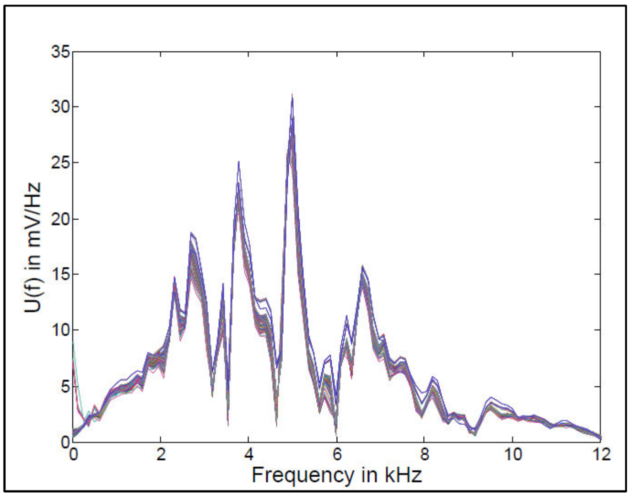

Figure 11. Amplitude spectrum of the microphone signal for all 250 cycles. A major change in the spectrum would be expected.

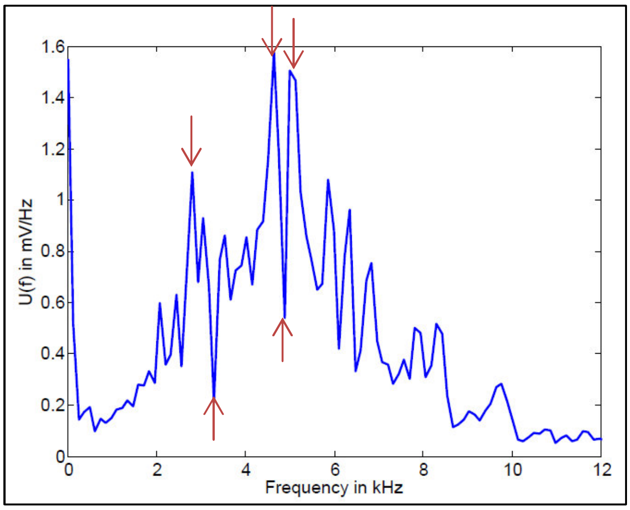

Figure 12. Standard deviation of the frequency over all 250 cycles to determine the major changes in the spectrum.

In a further step the mean and standard deviation of all frequencies are computed to determine exhibiting significant changes over load cycles (see Figure 12). An analysis of frequencies with the biggest change (2.8 kHz, 3.2 kHz, 4.6 kHz, 4.8 kHz, 5.2 kHz) shows that they are increasing over load cycles and one of them (4.8 kHz) decreases (see Figure 13), hinting that some of them might be indicative of the ageing structure changes presumed.

The major challenge is that the change of the copper trace is in the range of some millimetres or smaller. However, the whole printed circuit board influences the propagation of the acoustic emission significantly. Currently, a clear classification of the change of the emission spectrum is not possible. Which of them come from the lift off of the copper trace and which of them are artefacts from the printed circuit board cannot be exactly distinguished. This process requires further investigations. One investigation will be to use a printed circuit board with only a single copper trace on it to stress.

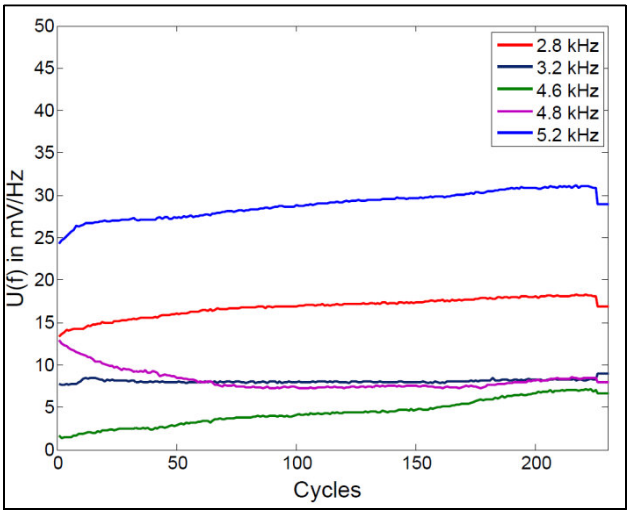

Figure 13. Analysis of selected frequencies over the stress cycles. No major change can be detected.

V. CONCLUSION

In this paper we show a procedure for electrically stressing a copper trace and measuring the acoustic emission. We propose a simple mechanical model which addresses the acoustic emission to the thermally induced bending of the copper trace and substrate under the thermal stresses caused by the electrical stress pulses. The hypothesis is that the degradation of the copper trace changes the system dynamics and therefore the sound emission.

In the measurement setup, the DUT consists of a printed circuit board containing several copper traces. The copper trace is electrically stressed and the acoustic signal is detected via a nearby microphone. The maximum amplitude changes over the stress cycles. However, there are a lot of artefacts which require further analysis. One challenge is that this signal is damped due to the whole printed circuit board. Additional measurements will be necessary to clarify the correlation between location of the failures and other artefacts.

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