DEPENDENCE OF CURRENT INTERRUPTION PERFORMANCE ON THE ELEMENT PATTERNS OF ETCHED FUSES

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Abstract: **This paper is about fuses for the protection of semiconductors. The pattern of their current- interruption area is composed of chemically etched copper plated on a ceramic substrate. Interruption tests revealed that the I^2t characteristics of these fuses are greatly influenced by the numbers *P* and *S* of parallel and series interruption points. The I^2t value of a *6S-32P* fuse is 72 % that of a *6S-8P* fuse, and the I^2t value of a *24S-8P* fuse is 24 % that of a *6S-8P* fuse. The synergy of these P and S effects reduces the I^2t value of a *24S-32P* fuse to only 8.6 % that of a *6S-8P* fuse.**

Keywords: **etched fuse, current-interruption, P effect, S effect.**

1. Introduction

Etched fuses in which the fuse element is attached to ceramic substrate not only have excellent current-interruption performance but are durable and heat resistant. They have therefore been used ever since the first low-voltage semiconductor protection fuse composed of chemically etched copper plated on a ceramic substrate was presented in 1991 at the 4th ICEFA [1].

Semiconductor devices are increasingly being used in power control systems, and their operating voltages are getting higher. This trend is driving the development of fuses applicable to high- voltage semiconductors [2], and etched fuses are potentially able to provide the kind of protection that high-voltage semiconductors require [3-5].

We recently found experimentally that the current-interruption performance of etched fuses can be improved by making the element patterns smaller and that the I^2t value of a fuselink can be decreased by increasing the number of parallel interruption points [4]. In the work we report here we investigated the dependence of current-interruption performance on the number of parallel interruption points, which is called the parallel effect (P effect), as well as the dependence of current-interruption performance on the number of interruption points arranged in series, which is called the series effect (S effect). We did this by experimentally evaluating the performance obtained with various numbers of parallel and series interruption points.

In these experiments we also investigated the effect of giving a fuse element three-dimensional structure, which means putting additional plating on the heat-radiating parts of the element while leaving the thickness of current-interruption parts as originally plated. This added structure reduces the resistance of the element, thereby increasing the current rating.

2. Fuse element for the tests

2-1. Interruption unit patterns

We used the two types of interruption unit patterns shown in Fig. 1.

We used the square type to clarify the effects of *P* and *S* on the current-interruption performance because the width b of the seed of an arc remains constant as the arc grows. After an arc forms where part of the narrow point melts, the width of the arc remains constant as the arc expands in the H direction.

Because the round type of pattern is likely to be used in actual fuses, we used this pattern for testing the rated current.

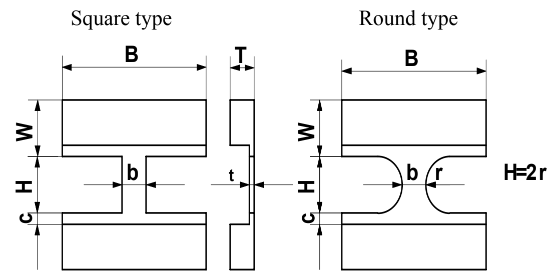

Fig. 1: Interruption unit patterns.

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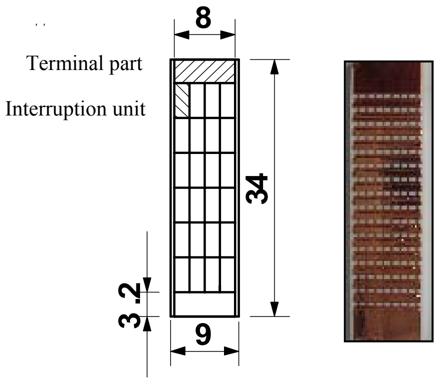
2-2. Test fuses

Test fuses were constructed by connecting the interruption units as shown in Fig. 2, with *S* units in series and *P* units in parallel.



6S-4P 16S-8P

Fig. 2: Fuse structure (units in mm).

Interruption units were formed on ceramic substrates of 34 mm long, 9 mm wide, and 1 mm thick. Three-dimensional structure was formed by leaving the thickness t of the current-interrupting part 0.015 mm and increasing the thickness T of the heat-radiating part to 0.1 mm. In each fuse the sum of the lengths of two terminal parts was 6.4 mm and the sum of all the lengths designated W in Fig. 1 was 20.4 mm.

The sum of the widths b in the test fuses for the P- effect tests, for which the series number *S* was 6, was 3 mm. The dimensions of each part of the P effect test fuses, for which the target resistance was 3.62 mΩ, are listed in Table 1.

The sum of the lengths H in the test fuses for the S effect test, for which the parallel number *P* was either 8 or 32, was 7.2 mm. The dimensions of each part of the S effect test fuses, for which the target resistance was 5 mΩ, are listed in Table 2 (for *P*=8), and Table 3 (for *P*=32).

Table 1. Element dimensions (mm) of P effect test fuses

Type	b	Σb	H	ΣH	c
6S-4P	0.750	3.0	1.2	7.2	0.2
6S-8P	0.375	3.0	1.2	7.2	0.2
6S-16P	0.188	3.0	1.2	7.2	0.2
6S-32P	0.094	3.0	1.2	7.2	0.2

Table 2. Element dimensions (mm) of S effect test fuses with *P*=8

Type	b	Σb	H	ΣH	c
4S-8P	0.25	2	1.8	7.2	0.2
8S-8P	0.25	2	0.9	7.2	0.2
12S-8P	0.25	2	0.6	7.2	0.2
16S-8P	0.25	2	0.45	7.2	0.2
24S-8P	0.25	2	0.3	7.2	0.2

Table 3. Element dimensions (mm) of S effect test fuses with *P*=32

Type	b	Σb	H	ΣH	c
4S-32P	0.0625	2	1.8	7.2	0.2
8S-32P	0.0625	2	0.9	7.2	0.2
12S-32P	0.0625	2	0.6	7.2	0.2
16S-32P	0.0625	2	0.45	7.2	0.2
24S-32P	0.0625	2	0.3	7.2	0.2

3. The interruption test circuit

The principal part of the interruption test circuit (Fig. 3) is a resonance circuit having a 10 kV 14,000 μF capacitor and an air-core inductor. The voltage in the resonance circuit is stepped down through the inductor. The test was done under conditions assuring a maximum resonance current of 100 kA (50 Hz) and a recovery voltage higher than 850 V.

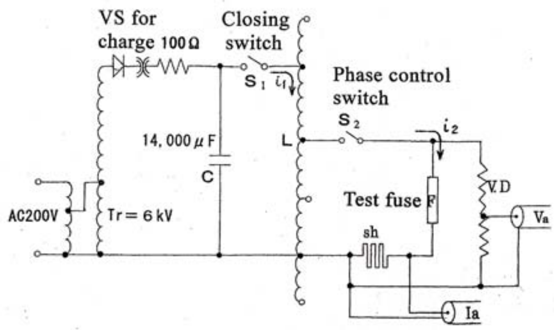


Fig. 3: Interruption test circuit.

4. Oscillograms of interruption tests

The S effect is demonstrated by the results shown in Fig. 4, which were obtained with of 8*S*, 16*S*, and 24*S* 8*P* fuses having square type interruptions. Note that the cut-off currents are approximately 2,000 A, while the maximum arc voltages became higher and the I^2t values became lower than the expected values inversely proportional to the increase of *S*.

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The test results obtained with a 24*S*-32*P* fuse are shown in Fig. 5. Note that increasing *P* from 8 to 32 decreased the cut-off current from more than 1,500 A to about 1,300 A and decreased I^2t from 224 A^2s to 79 A^2s. From Figs. 4 and 5, we might think that before the current cut-off point P effect is more effective than the S effect in keeping the cut-off current low and that after the current cut-off point the S effect is more effective than the P effect in keeping the I^2t value low.

5. Experiment results on the P effect

The P effect test results obtained with 4*P*, 8*P*, 16*P*, and 32*P* 6*S* fuses with square type interruption units are summarized in Table 4.

Table 4. P effect test results for 6*S* fuses

Type	I^2t[A^2s] (Resistance[mΩ])			
	Sample 1	Sample 2	Sample 3	Average
6S-4P	1,770 (4.2)	1,172 (4.9)	1,466 (4.6)	1,469 (4.6)
6S-8P	1,652 (3.9)	1,197 (4.5)	1,133 (4.6)	1,327 (4.3)
6S-16P	1,374 (3.8)	768 (4.7)	831 (4.6)	991 (4.4)
6S-32P	1,288 (4.2)	713 (5.1)	863 (5.1)	955 (4.8)

Analysis of variance was applied to evaluate their significance because the data in Table 1 showed much dispersion. It is confirmed that more than 95 % of data is accurate. The average I^2t values listed in Table 4 are plotted in Fig. 6.

When the P effect is normalized by setting the I^2t value for the 6*S*-8*P* point in Fig. 6 to 100 %, the parameter *r* (the resistance of the fuse) is eliminated and the P effect without the influence of *r* can be expressed by the percentage change. The normalized P effect is shown in Fig. 7, which shows that the I^2t for a 6S-32P fuse is only 72 % that for a 6*S*-8*P* fuse.

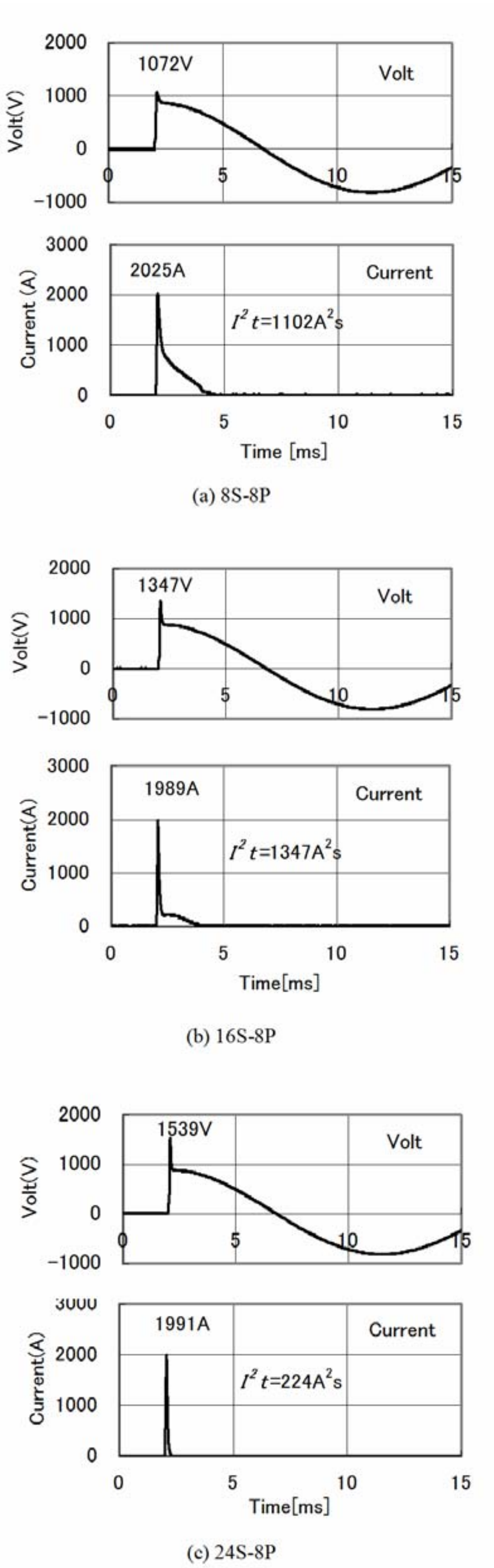

Fig. 4: Oscillograms of interruption tests obtained with 8*P* fuses.

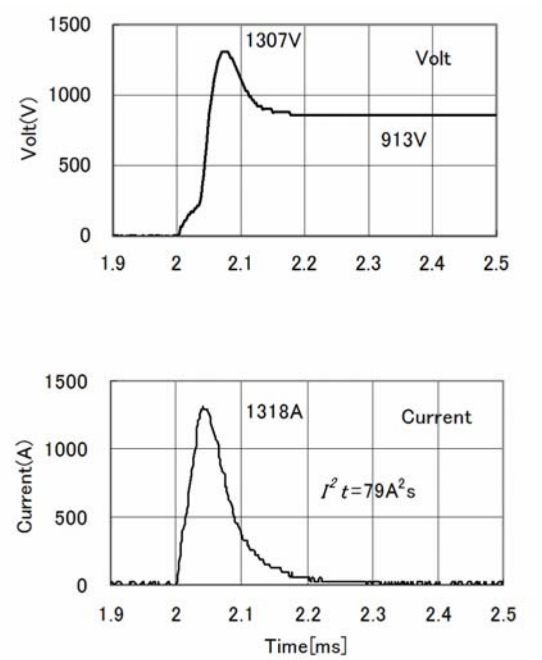

Fig. 5: Oscillograms of interruption tests of 24*S*-32*P*.

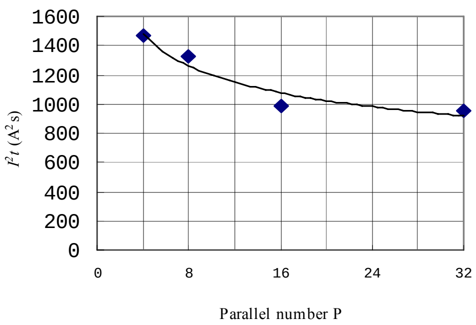

Fig. 6: Parallel number *P* - I^2t characteristic (6*S* series).

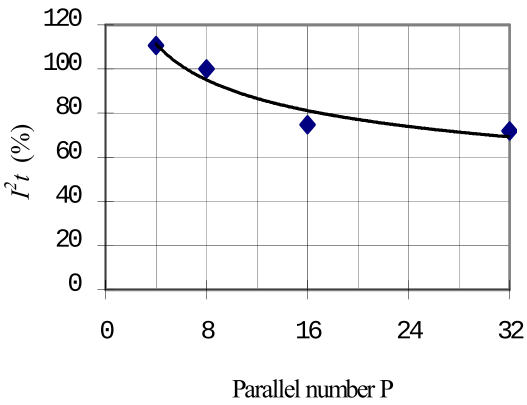

Fig. 7: Normalized P effect.

Increasing the number of parallel interruption points in a fuse element divides an arc into smaller ones, and thus makes the pre-arcing time shorter and the cutoff current smaller. This is why I^2t initially decreases with increasing *P*. As shown in Fig. 7, however, when there are too many parallel interruption points the likelihood of interaction between adjacent arcs and thus of restriking increases and limits the decrease in I^2t. To obtain further improvement of current-interruption performance, we need to arrange the interruption points in a pattern that prevents restriking. One way to do this is to adjust the number of interruption points arranged in series.

6. Experiment results on the S effect

6-1. Test fuse element patterns

The test fuses for the S-effect tests were 4*S*, 8*S*, 12*S*, 16*S*, and 24*S* 8*P* and 32*P* fuses with t×∑b □ 0.03 mm□.

6-2. Results of experiments with the 8*P* series

The experimental results and estimated I^2t values are listed in Table 5.

To evaluate the dependence of I^2t on parameters such as the series number *S*, we need to take into account the relation between I^2t and resistance. As we can see from the data listed in Table 5, resistance increases with increasing *S*. The corresponding I^2t values for fuses with the target resistance were estimated as follows. The I^2t values calculated from the test result listed in Table 5 were plotted on log–log paper as shown in Fig. 8. Then straight lines having a slope inversely proportional to the square of resistance were drawn through the points plotted for each value of *S*. According to our experiments I^2t values were inversely proportional to the square to the 2.5th power of resistance. In this experiment former relation was applied.

Table 5. S effect test results for 8*P* fuses

Type	Test result		Presumed value
	Resistance(mΩ)	I^2t(A^{2}s)	I^2t(A^{2}s) at 5 mΩ
4S-8P	4.3	4,604	3,405
8S-8P	5.0	1,012	1,012
12S-8P	5.4	403	470
16S-8P	5.8	329	443
24S-8P	6.6	224	390

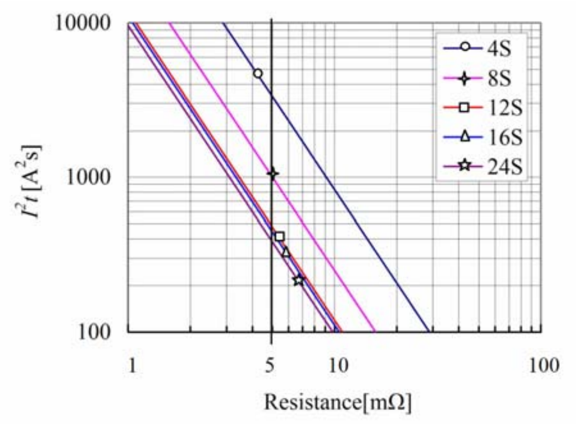

Fig. 8: Resistance - I^2t characteristics (8P series).

The I^2t values at the intersections of the 5 mΩ line in Fig. 8 and each of the straight lines we drew in that figure give are listed in Table 5 as presumed values and are plotted in Fig. 9, showing the S effect at 5 mΩ. From Fig. 9 the I^2t value for a 6S-8P fuse is estimate to be 1650 A^{2}s. The I^2t value of the 24S-8P fuse (390 A^{2}s) is thus only about 24 % that of the 6S-8P fuse.

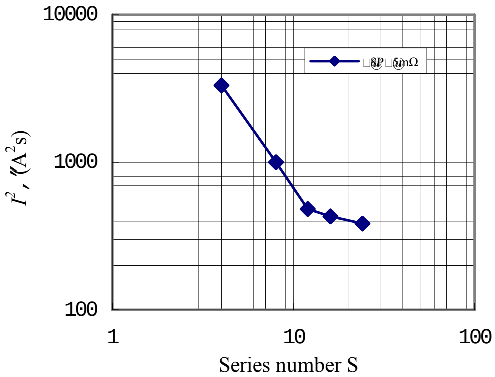

Fig. 9: S - I^2t characteristics (for the 8P series).

The total arc voltage of a fuse element can be calculated as the product of the arc voltage of one interruption point and the series number S, because the arc voltage of each arc is almost the same. Since increasing the series number S makes the arc voltage of the fuse higher. It decreases I^2t as shown in Fig. 9. When S is too large, however, isolated arcs between terminals can degrade current-interruption performance. For the element pattern used in the present experiments, currents were successfully interrupted by fuses with S numbers as large as 32 (described in the next subsection). Additional plating between interruption points might block the expansion of an arc and prevent arcs from unifying.

6-3. Results of experiments with the 32*P* series

The experimental results and presumed I^2t values are listed in Table 6. Presumed I^2t values were obtained by the same process described in subsection 6.2. The relation between presumed I^2t values at 5 mΩ and series number S is shown in Fig. 10, where one sees that the decrease of I^2t with increasing S is greater than that seen in Fig. 9. This may be due to synergy of the P and S effects.

Table 6. S effect test results and presumed I^2t values at 5mΩ for 32P fuses

type	Test result		Presumed value
	Resistance(mΩ)	I^2t(A^{2}s)	I^2t(A^{2}s)
4S-32P	4.4	4,166	3,226
8S-32P	5.6	538	675
12S-32P	6.1	167	249
16S-32P	5.8	123	166
24S-32P	6.0	79	114

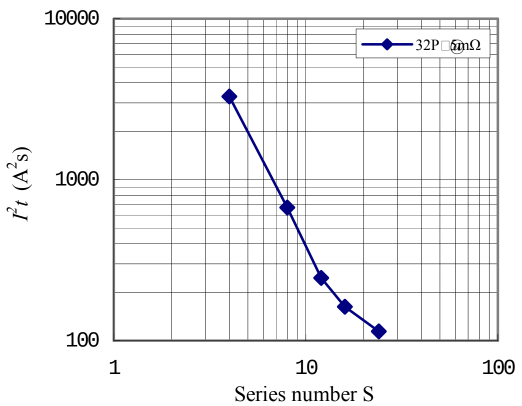

Fig. 10: S - I^2t characteristics (for the 32P series).

7. Synergy of S and P effects

The characteristic curves shown in Figs. 9 and 10 are plotted together in Fig. 11 for comparison. The I^2t value for the 24S-8P fuse is 390 A^{2}s (Table 5 and Fig. 9). If the S and P effects were independent of each other, we can see from Fig. 7 that the P-effect would reduce the I^2t value for the 24S-32P fuse by about 28 %, or from 390 to 280.8 A^{2}s. The experimental results obtained with the 24S-32P fuse, however, showed that its I^2t was actually 114 A^{2}s, or only 8.6% that of the 24S-8P fuse. This much smaller value than expected decrease in the I^2t value reflects the synergy of the S and P effects.

The cause of this synergy is not clear, but it could be that current-interruption performance deteriorates because the P effect becomes ineffective when the parallel number P is greater than 16. If this deterioration were due to the restriking of arcs and the S effect suppressed this restriking, the current-interruption performance would be improved much

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more than expected from P and S effects independently. Identifying the cause of this synergistic effect will require further experimental investigation.

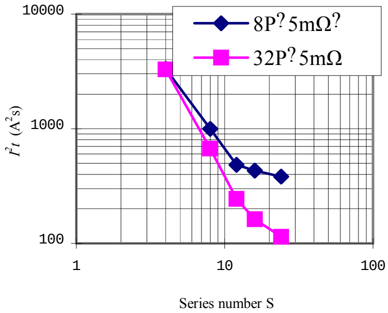

Fig. 11: *S* - I^2t characteristics for 8*P* and 32*P* series.

8. Rated current test

We carried out a temperature-rise test on a 16*S*-16*P* fuse having the round type of interruption units and a resistance of 4.9 m Ω. The test yielded a rated current of 45 A.

9. Conclusion

An advantage of etched fuses is that the patterns of their interruption units can easily be made extremely small, so their numbers *S* and *P* of series and parallel interruption points can be large. This is important because the I^2t value for a 24*S*-32*P* fuse, with a resistance of 4.9 mΩ, is only 8.6% that of a 6*S*-8*P* fuse.

Highly serial and parallel fuses for practical use cannot be made without reducing the cost of their production and the decreasing the resistance of their elements, but we think that the low I^2t values of these fuses justifies their higher production cost. We also think that because the patterns in these fuses are so small, it will be necessary to repeatedly carry out such reliability tests as tests of deterioration due to oxidization, repeated overload tests, and continued turning-on -off- electricity tests.

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