Effect of Rate of Voltage Rise on Reverse Breakdown of Silicon Diodes

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Significance
Part 5 –Monitoring instruments, laboratory measurements and test methods
Part 7 – Mitigation techniques

This declassified report is one of several prepared in the early sixties when industry was awakening to the sensitivity of semiconductors to transient overvoltages. One of the findings was that the so-called PIV rating of a diode did not reflect its transient withstand capability, hence the attention focused on that issue in this report. The finding of some upturn in the voltage breakdown confirmed the speculation that failure was a breakdown at the edge of the chip, while the PIV rating was related to the leakage across the bulk of the semiconductor.

With a 40-year perspective, It is now only of historical interest that at the time (pre-MOV era) the protection of semiconductors was attempted with gaps.

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SUMMARY

The possibility that the level of reverse voltage breakdown increases with increased rate of voltage rise was investigated for two silicon diodes, 1N679 and 4JA4.

The 1N679 samples were of the same lot with uniform PIV rating. The 4JA4 samples were from two lots with two distinct PIV ratings.

Conclusions

1. The voltage level at which failure occurs does increase with increased rate of voltage rise.

   a) This is significant for only very short spikes (less than 0.1 μs) with protection.

   b) This makes possible a coordination of surge suppressors and rectifier characteristics

2. There is little evidence that the reverse voltage breakdown level under transient conditions is increased for an increased PIV rating in the 4JA4 diode.

KEY WORDS

Transient overvoltages, surges, rectifier breakdown

INFORMATION PREPARED FOR Transient Overvoltages Pooled Program

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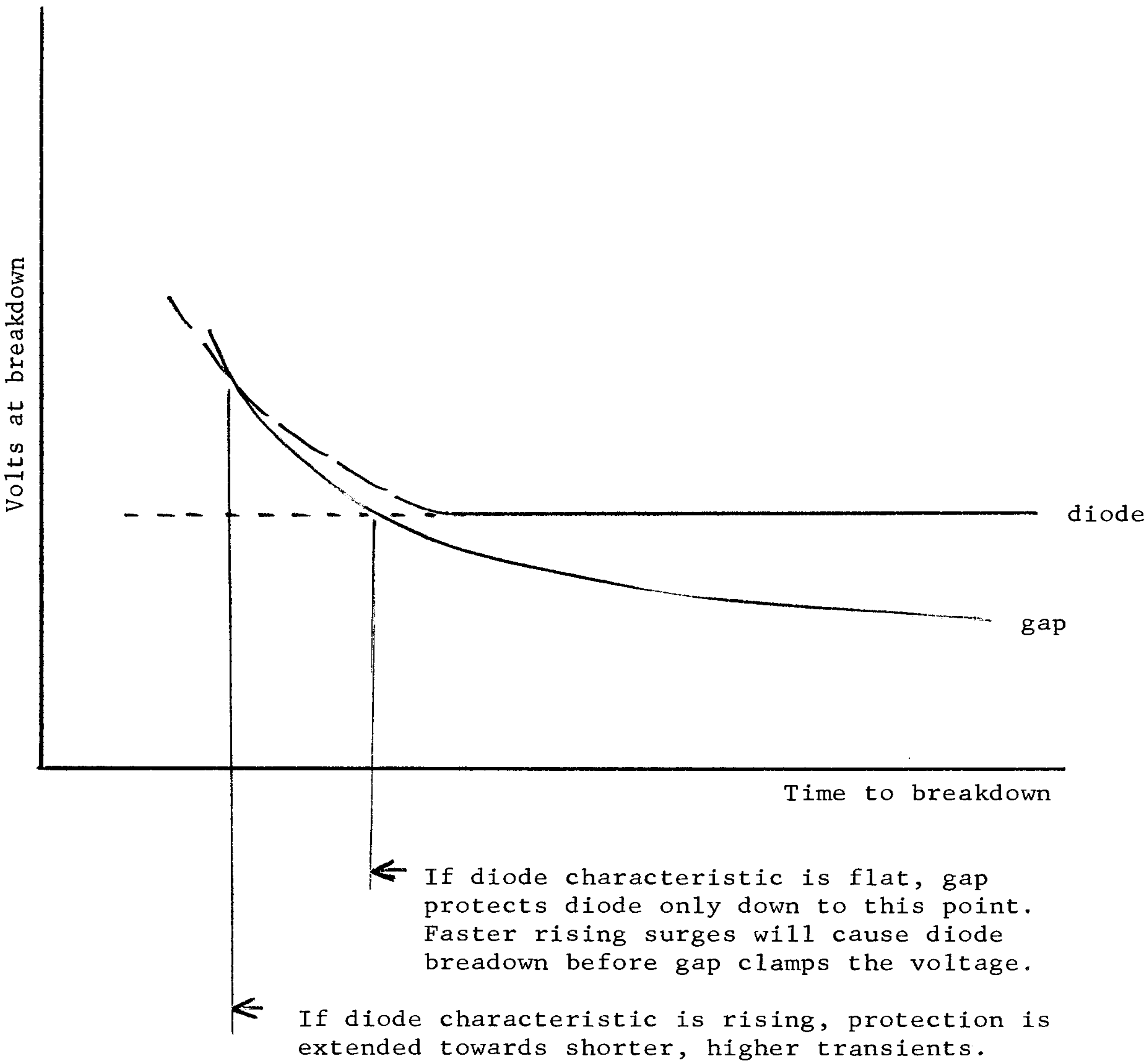


Coordination of gap and diode characteristics

Figure 1

EFFECT OF RATE OF VOLTAGE RISE ON REVERSE BREAKDOWN OF SILICON DIODES

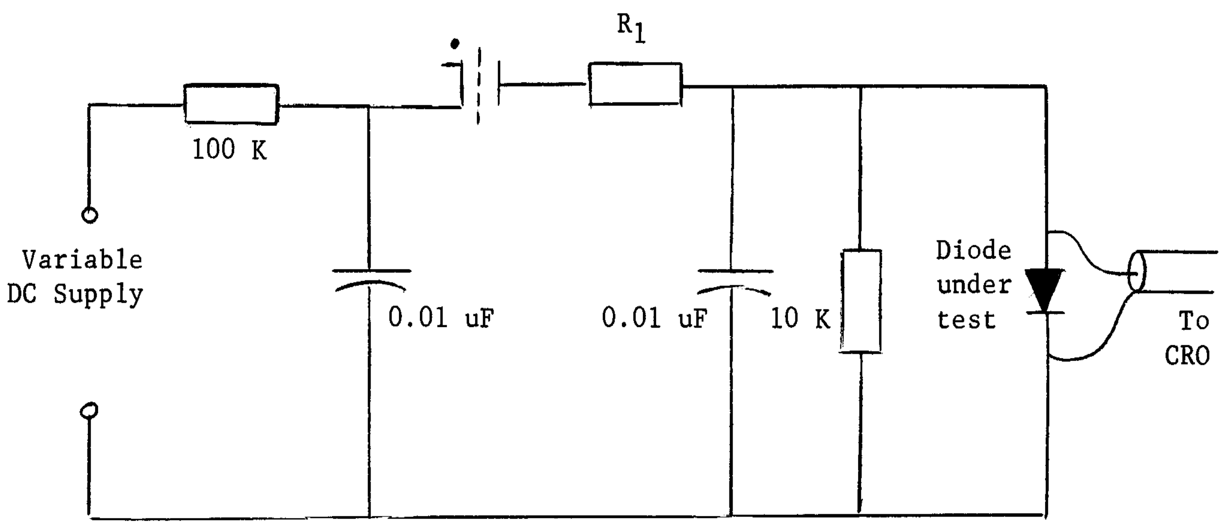
I. INTRODUCTION

Failure by reverse voltage transients in silicon rectifiers is believed to be caused by the breakdown of the junction surface. If this is true, we could expect their breakdown to show some of the characteristics of other insulation breakdown phenomena. In particular, there would be a rising volt-time characteristic, i.e., breakdown occurring at increasing voltage within a decreasing time as the rate of voltage rise increases.

Some surge suppressors, gaps, for instance, also exhibit a rising volt-time characteristic; this is to be expected as the suppressing action is obtained by breaking down the gas in the gap and releasing the energy in the resulting arc or in a series resistance. For this reason, gaps or other devices with rising volt-time characteristics are considered unsuitable for the protection of semiconductors against fast transients.

However, if the breakdown of the semiconductor junction surface also has a rising characteristic, protection is extended toward shorter transients, as shown in Figure 1. If on the other hand, the breakdown characteristic were flat, or worse, decrease (such as in the case of forward "dv/dt firing" of multi-junction devices), this would be a major restriction in the use of protectors with a rising volt time characteristic.

In order to show whether or not such a rising characteristic exists for silicon rectifiers, two diode types, one with a diffused junction (1N679) and one with an alloyed junction (4JA4) were subjected to reverse voltage impulse, with increasing rate of voltage rise.



R_1 adjusted from 25 ohms to 2,000 ohms to change time to crest (and thus rate of rise) of the impulse.

Test Circuit

Figure 2

II. TEST CIRCUIT AND PROCEDURE

A capacitor discharge surge generator was used to subject the diodes to an impulse voltage with controlled rate of voltage rise, and a long "tail". The impulse generator circuit is shown in Figure 2. The rate of voltage rise can be controlled by two factors: time to crest and crest voltage of the impulse wave. However, if failure occurs on the front of the wave, either or both factors can be varied to achieve the desired slope of the front of the wave.

The diodes were subjected to the impulse at room temperature, with no other current flowing in the junction and no other voltage applied across the junction prior to or during the impulse application.

The voltage across the diode was measured directly across the diode with a 551 Tektronix oscilloscope and P6913 high voltage probe. Oscillograms were taken for each shot, involving (48) 1N679 diodes and (32) 4JA4 diodes.

The 1N679 diodes were specially selected by the Rectifier Components Department for uniform PIV rating (400 volts) and were obtained from one manufacturing lot.

The 4JA4 diodes were also specially selected, for two uniform PIV ratings (200 and 600 volts) and were obtained from two manufacturing lots.

Typical oscillograms of the failure at various points are reproduced in Figures 4 and 5 at the end of the report, respectively for the 1N679 diode and the 4JA4 diode. These oscillograms show the sharp chopping of the voltage occuring during the rising portion of the wave, whith one exception at 700v/ μs where the failure occured on the tail.

III. TEST RESULTS

The complete test data are tabulated in the appendix. Only the average values are listed here.

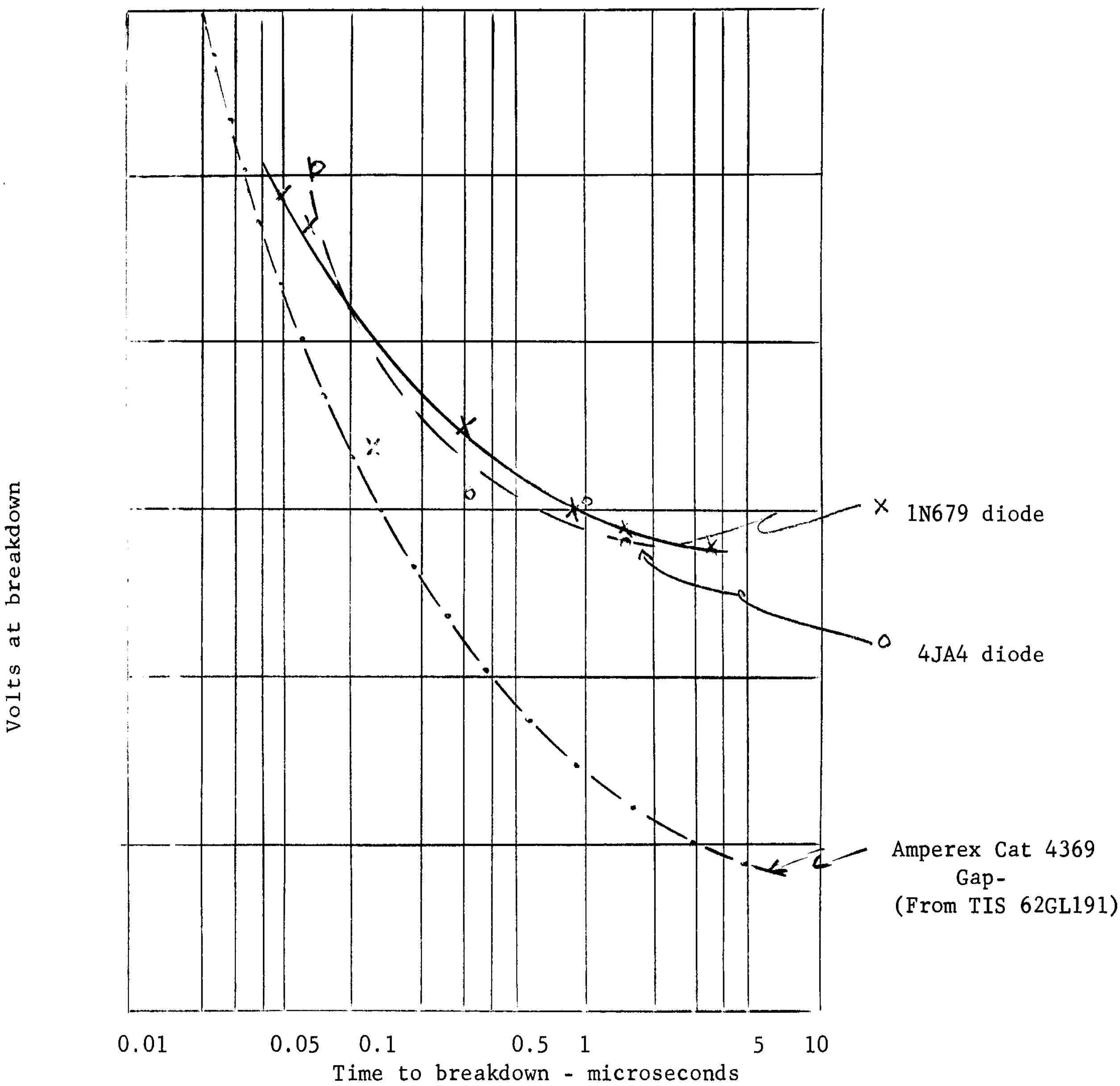
Average rate of rise Volts/μs	Average breakdown Volts	Average time to breakdown μs
700	1400	(not front of wave)
1000	1450	1.5
1500	1500	0.9
2000	1650	0.6
5000	1750	0.3
20000	1650	0.12
30000	2350	0.07
40000	2450	0.05

4JA4 Diode (all units from 2 lots and 2 PIV ratings)

Average rate of rise Volts/μs	Average breakdown Volts	Average time to breakdown μs
1000	1400	1.5
1500	1530	1.0
5000	1520	0.3
30000	2530	0.08

4JA Diode (at all voltage rise values)

Sample	Average breakdown, Volts	
200V PIV, Lot 1	1550	
200V PIV, Lot 2	1750	
200V PIV, Lots 1 and 2	1650	No strong statistical significance in the difference observed here
600V PIV, Lot 1	1840	
600V PIV, Lot 2	1770	
600V PIV, Lots 1 and 2	1800	



Actual coordination of gap and diode characteristics

Figure 3

IV. DISCUSSION OF THE RESULTS

Both diodes exhibit a rising characteristic (Figure 3), however, it rises very slowly until the time to breakdown decreases beyond 0.3 μs. This means that only extremely short spikes applied to diodes can reach a higher level without causing the breakdown of the diode.

When compared to the volt-time characteristic of typical gaps (Figure 3), however, it seems that the upturn of the characteristic occurs in the same time range, i.e. 0.5 μs. Therefore, there is a good possibility that gaps can be applied to the protection of rectifiers. Of course, this should not be a conclusion to be applied without the knowledge of both characteristics, gap and diode, if a specific diode is to be protected by a specific gap.

On the other hand, the results obtained with two different PIV ratings on the 4JA4 diode do not show strong statistical evidence that the 600 volt diode can withstand higher transient over-voltage than the 200 volt diode. At most, the gain is in the order of 8% for a three-fold increase in PIV.

There is no evidence of difference between manufacturing lots on the 4 JA4 diode.

V. CONCLUSIONS

1. The failure level of both diodes does indeed increase when the rate of voltage rise increases. However, this increase is only significant for spikes of less than 0.1 μs duration.
2. When surge suppressors are applied, the fact that they have a rising volt-time characteristic is not irrevocably objectionable since the diodes also have a rising characteristic. However, only careful matching of the characteristics would provide safe protection in specific applications.
3. For the alloyed junction diode, 4JA4, there is little evidence of increased surge withstand capability with increased PIV rating.

Appendix - Test Data

1N679 Diode Failure levels, standard deviations, and time to breakdown.

4 μs to crest wave		2 μs to crest wave	
700 V/μs	1000 V/μs	1500 V/μs	2000 V/μs
1300 V	1400 V	1300 V	1600 V
1400 V	1400 V	1400 V	1300 V
1350 V	1500 V	1700 V	1900 V
1500 V	1400 V	1400 V	1700 V
1350 V	1500 V	1700 V	1700 V
1450 V	1500 V	1500 V	1600 V
1400 V Avg.	1450 V Avg.	1500 V Avg.	1650 V Avg.
(Std. dev. 68 V)	(Std. dev. 60 V)	(Std. dev. 150 V)	(Std. dev. 175 V)
Breakdown in tail	Breakdown in 1.5 μs	Breakdown in 0.9 μs	Breakdown in 0.6 μs

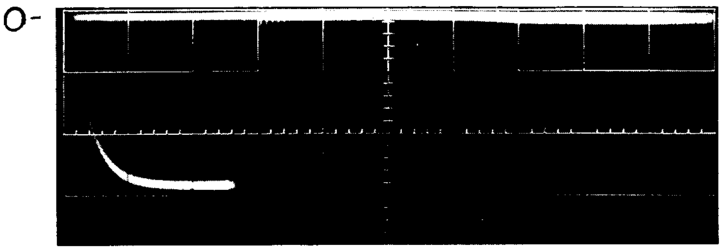
0.6 to crest wave	0.1 μs to crest wave		
5000 V/μs	20 KV/μs	30 KV/μs	40 KV/μs
1700 V	1350 V	2400 V	2800 V
1800 V	1750 V	2600 V	2400 V
1700 V	1850 V	2200 V	2300 V
1600 V	1800 V	2200 V	2500 V
1700 V	1550 V	2300 V	2400 V
1900 V	1800 V	2400 V	2300 V
1750 V Avg.	1675 V Avg.	2350 V Avg.	2450 V Avg.
(Std. dev. 120 V)	(Std. dev. 160 V)	(Std. dev. 140 V)	(Std. dev. 160 V)
Breakdown in 0.3 μs	Breakdown in 0.1 μs	Breakdown in 0.07 μs	Breakdown in 0.05 μs

NOTE: There is no significant difference from one level to the next except between 20 KV/μs and 30 KV/μs, however, a trend towards increasing levels from 700 V/μs to 20 KV/μs is apparent.

4JA4 Diode Failure levels, standard deviations, and time to breakdown.

	1000 V/μs	1500 V/μs	5000 V/μs	30000 V/μs	Avg.	
200 V Lot 1	1100 V	1100	1400	2400		
" "	1200 V	1500	1400	2400	1560	
200 V Lot 2	1300 V	1000	1200	2500		1650
" "	1500 V	2500	1500	2600	1750	
600 V Lot 1	1400 V	1600	1600	2500		
" "	1600 V	1500	1700	2700	1840	
600 V Lot 2	1600 V	1500	1300	2600		1800
" "	1400 V	1500	1700	2600	1770	
	1400 V Avg.	1530 V Avg.	1520 V Avg.	2530 V Avg.		
	(Std. dev. 170 V)	(Std. dev. 400 V)	(Std. dev. 140 V)	(Std. dev. 95 V)		
	Breakdown in 1.5 μs	Breakdown in 1 μs	Breakdown in 0.3 μs	Breakdown in 0.08 μs		

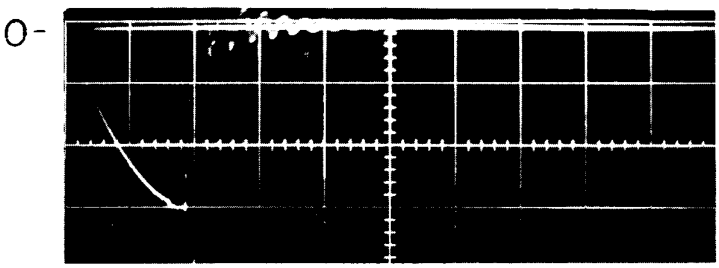
NOTE: The difference between Lots 1 and 2 at 200 volts is mostly due to one exceptional sample at 2500 volts, and is not significant.
The difference of 150 volts between the combined 200 and 600 volts Lots is barely significant and only represents an 8% increase for a 3 to 1 increase in PIV.



Time Scale 2 μs/div

Voltage Scale 500 V/div

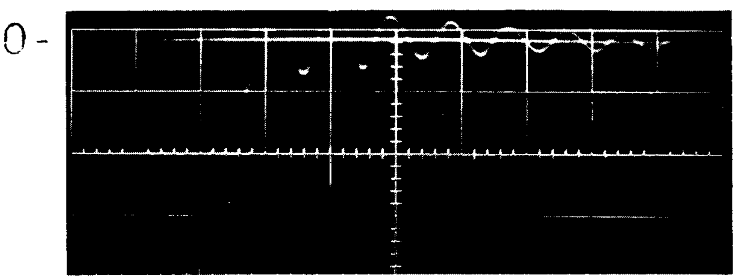
700 V/μs rate of rise



Time Scale 0.5 μs/div

Voltage Scale 500 V/div

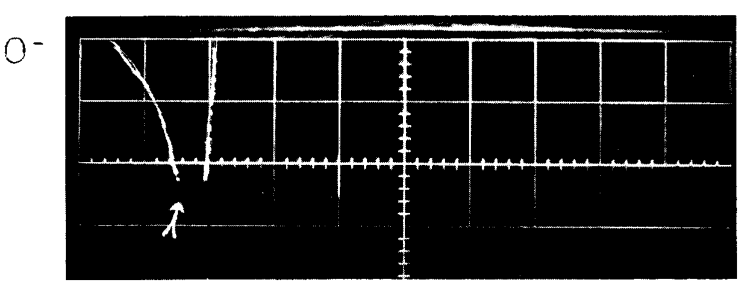
1,500 V/μs rate of rise



Time Scale 0.2 μs/div

Voltage Scale 500 V/div

5,000 V/μs rate of rise



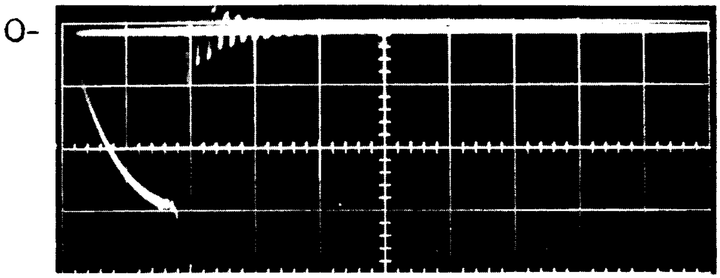
Time Scale 0.1 μs/div

Voltage Scale 1000 V/div
(trace reinforced for reproduction except at arrow showing the peak)

30,000 V/μs rate of rise

Breakdown of 1N679 diode at four different rates of voltage rise
Voltage measured across diode subjected to surge.

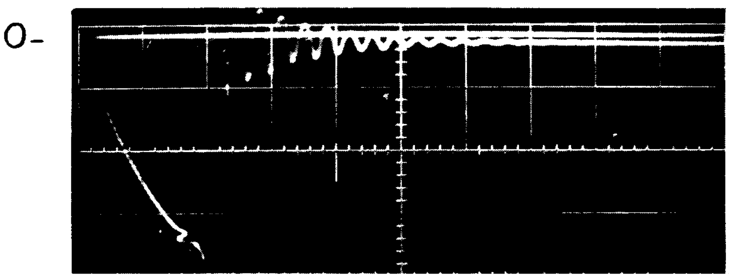
Figure 4



1,000 V/μs rate of rise

Time Scale 1 μs/div

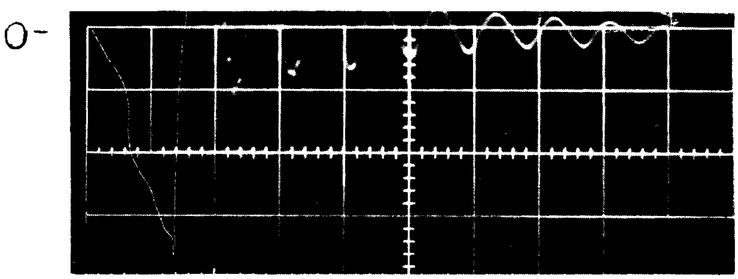
Voltage Scale 500 V/div



1,500 V/μs rate of rise

Time Scale 1 μs/div

Voltage Scale 500 V/div



5,000 V/μs rate of rise

Time Scale 0.2 μs/div

Voltage Scale 500 V/div
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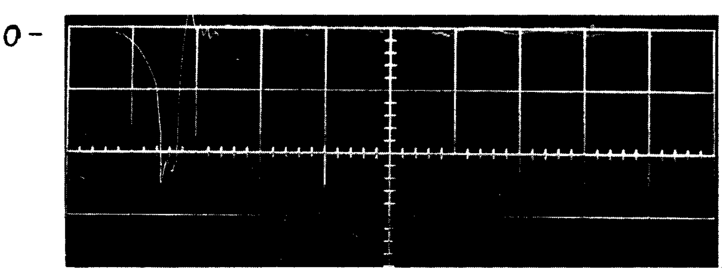

30,000 V/μs rate of rise

Time Scale 0.1 μs/div

Voltage Scale 1000 V/div
(trace reinforced for reproduction)

Breakdown of 4JA4 diode at four different rates of voltage rise
Voltage measured across diode subjected to surge.

Figure 5