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[50] Field of Search.....317/234/41.1.  
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[54] **CONTROLLED RECTIFIER HAVING AUXILIARY  
 CATHODE AND SLOTTED MAIN CATHODE**  
**4 Claims, 10 Drawing Figs.**  
 [52] U.S. Cl..... 317/235 R,  
 317/235 AB, 317/235 AE  
 [51] Int. Cl..... H01J 11/10

**ABSTRACT:** The main cathode of a controlled electrode is slotted with at least five teeth, each of which extend across the main emitter junction and adjacent an auxiliary cathode. The regions between the teeth on the main cathode serve the effect of a plurality of local points for carrier injection.

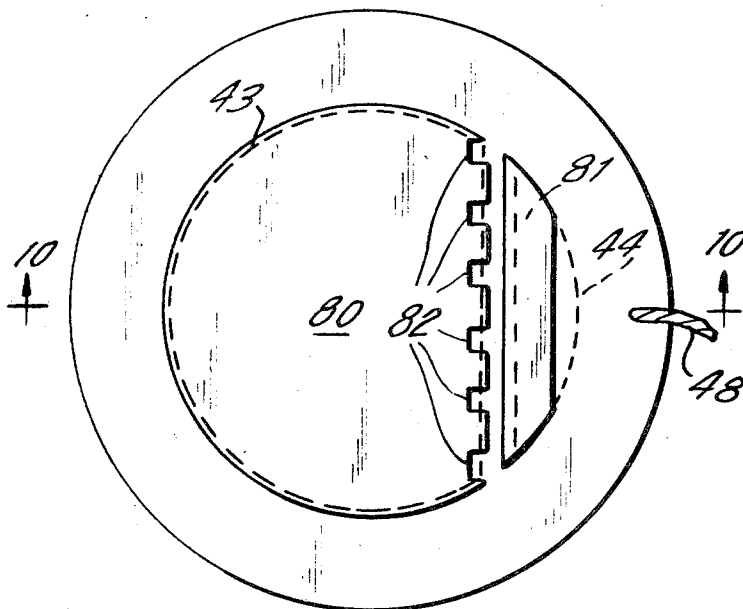


FIG. 1.

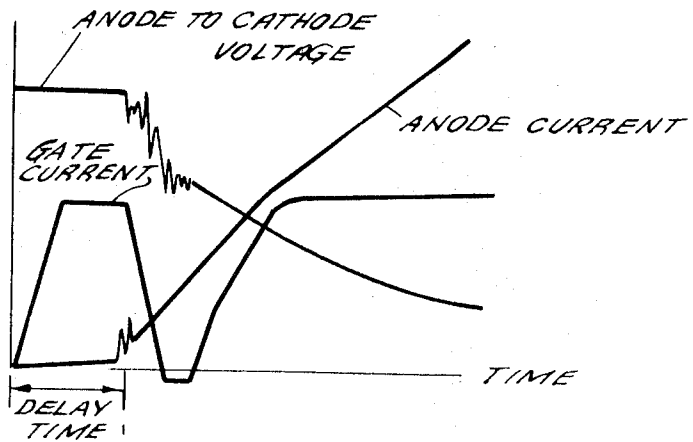


FIG. 2.

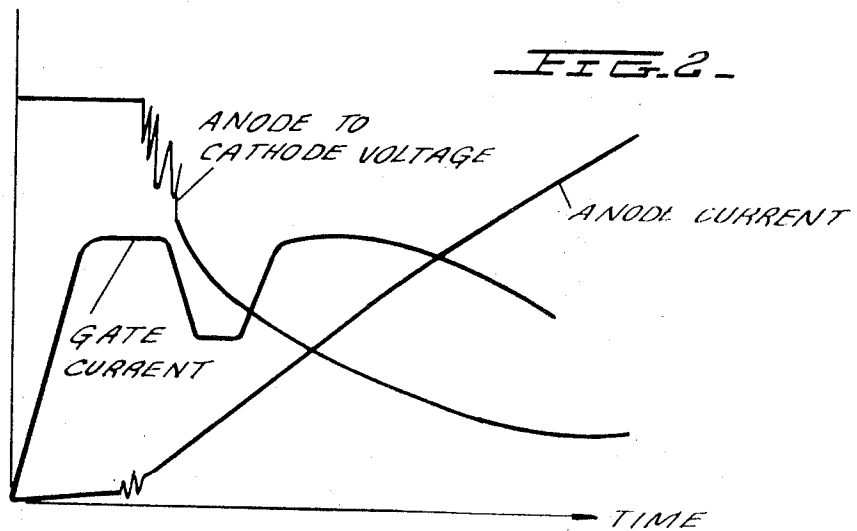
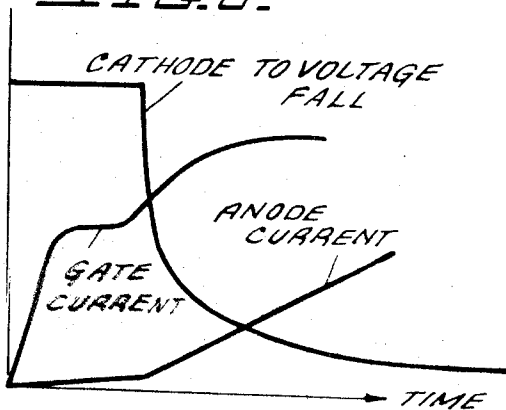


FIG. 3.



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FIG. 4.

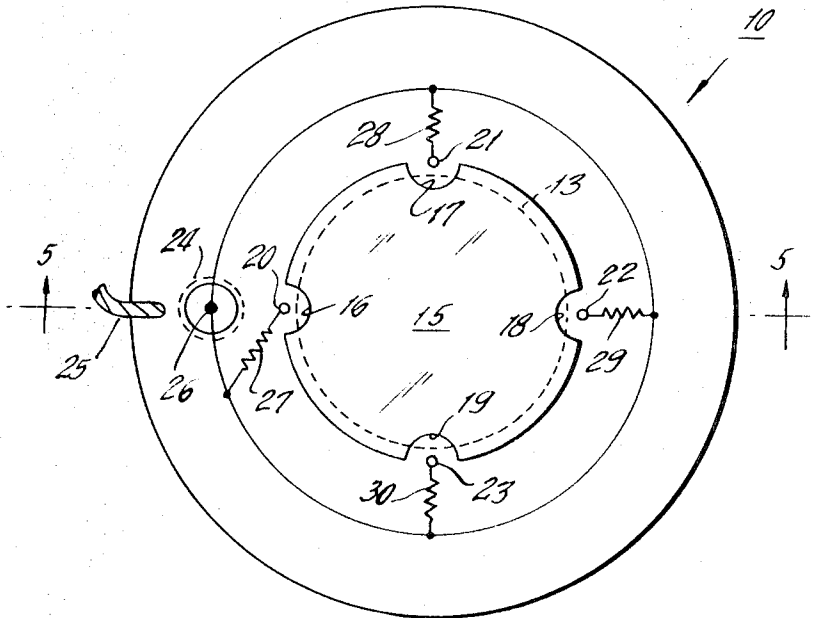
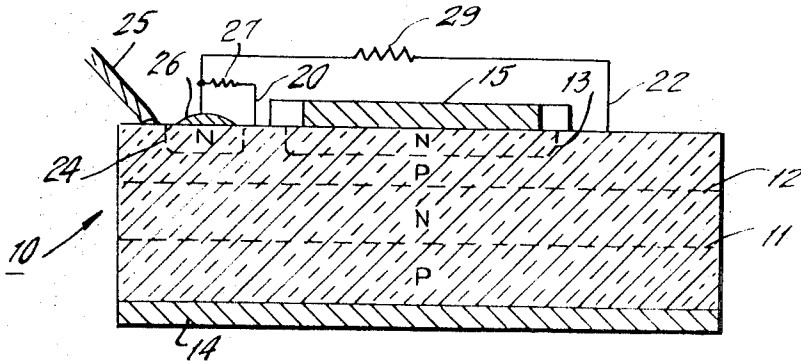


FIG. 5.



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# CONTROLLED RECTIFIER HAVING AUXILIARY CATHODE AND SLOTTED MAIN CATHODE

## RELATED APPLICATIONS

This application is an improvement of the apparatus shown in copending application Ser. No. 761,603, filed Sept. 23, 1968, entitled "Controlled Rectifier Having High Rate-of-Rise of Current Capability and Low Firing Gate Current," in the name of David Cooper, now abandoned and copending application Ser. No. 761,587, filed Sept. 23, 1968, entitled "Controlled Rectifier Having High Rate-of-Rise of Current Capability and Low Firing Gate Current," in the name of David Cooper and Harold Weinstein, each of which are assigned to the assignee of the present invention.

## BRIEF DESCRIPTION OF INVENTION

This invention relates to controlled rectifiers, and more particularly relates to a controlled rectifier using an auxiliary cathode configuration with a slotted main cathode so that the device has good characteristics for both rate of rise of current and has improved characteristics for withstanding high rates of rise of voltage without unintentional firing. Two of the most important characteristics which must be controlled in the construction of a controlled rectifier are rate of rise of voltage characteristics ( $dv/dt$ ) and the rate of rise of current ( $di/dt$ ) which the device is capable of withstanding. The  $dv/dt$  rating of a controlled rectifier is related to its ability to withstand fast rising anode-to-cathode voltages without being fired or turned on. The  $di/dt$  rating for the device permits its operation under fast rising currents without causing localized hot spots which would burn out the device.

In order to achieve good  $dv/dt$  characteristics, the common practice is to use a shorted emitter. In order to obtain good  $di/dt$  characteristics, and low gate current for firing the device, an auxiliary cathode is connected to a plurality of auxiliary gates located adjacent the main cathode area. These auxiliary gates which are driven from a substantial current source then insure the creation of a plurality of parallel initial conducting plasmas, thereby avoiding the localized hot spots of only one or two initial plasmas which could destroy the device under high rates of rise of current.

In accordance with the present invention, a device using an auxiliary cathode and which is of the type described in application Ser. Nos. 761,603 and 761,587, noted above, is modified so that the lateral edge of the main cathode area is slotted or serrated, with the slotted portions extending across the emitter junction which faces the continuous gate electrode formed by an extension of the auxiliary cathode contact. Thus, the slotted cathode construction provides a shorted emitter at a plurality of points along the emitter junction, whereas the portions of the slotted cathode which do not cross the emitter serve as effective localized points for initiating a plurality of parallel conduction plasmas before the device is fired.

It is now possible for the designer to control the parameters of any device as to  $dv/dt$  and  $di/dt$  simply by controlling the slot configuration, for example, by increasing the number of slots or by making the width of the slots wider or smaller. It is, however, important that at least about five slots be used to provide a minimum number of initial conducting plasmas while also providing at least five shorted regions over the emitter for  $dv/dt$  control. In other words, with the novel construction of the invention the slotted ohmic contact allows carrier injection from many points along its length to the auxiliary cathode, thus avoiding hot spots and giving good  $dv/dt$  characteristics. The emitter is shorted close to all these points, thereby restoring the shorting effect that is lost in conventional construction. The width of the slots can be varied in order to give dominance to the parameter which must stand out in any particular application.

## BRIEF DESCRIPTION OF DRAWINGS

FIG. 1 is a graph which shows the gate current, cathode current and anode-to-cathode voltage characteristics of a stan-

dard controlled rectifier having a single gate for a high rate of rise of anode current.

FIG. 2 displays the same parameters as in FIG. 1, for a standard controlled rectifier having a plurality of gates.

FIG. 3 shows the improved electrical characteristics obtained with a controlled rectifier having an auxiliary cathode.

FIG. 4 is a top view of a controlled rectifier semiconductor wafer having an auxiliary cathode.

FIG. 5 is a cross-sectional view taken across the section line 5-5 in FIG. 4.

FIG. 6 shows a top view of a second embodiment of a structure having an auxiliary cathode.

FIG. 7 is a cross-sectional view taken across the section 7-7 in FIG. 6.

FIG. 8 is a top view of a third embodiment of a device having an auxiliary cathode.

FIG. 9 is a top view of a wafer constructed in accordance with the invention.

FIG. 10 is a cross-sectional view of FIG. 9 taken across the section line 10-10 in FIG. 9.

Referring now first to FIG. 1, there are shown wave shapes of the anode current, gate current, and anode-to-cathode voltage during turn-on conditions, for a typical controlled rectifier having a single gate.

After a short initial delay time, considerable noise (i.e., oscillations) appears in the anode-to-cathode voltage, and sometimes in the anode current rise characteristic. More significantly, the gate current is forced toward zero after the delay time by an internally generated back voltage. This internal voltage is to the high internal sheet resistance of the semiconductor material (such as silicon) in the gate-cathode region. It has been found that when the gate current is forced to zero, or below zero as shown in FIG. 1, the device may fail in a mode known as  $di/dt$  failure due to the small turn-on area, as discussed above.

To overcome this type of failure, many devices are built with more than one gate electrode. Such devices have the somewhat improved gate current characteristics shown in FIG. 2. Deep gate starvation nonetheless occurs so that such devices have limited usefulness in high  $di/dt$  applications. Moreover, the use of multiple gates requires the injection of a considerable gate current, usually of from 1 to 5 amperes with a very fast rise time.

A controlled rectifier structure having an auxiliary cathode eliminates the gate-starvation conditions shown in FIGS. 1 and 2, and produces the superior characteristics shown in FIG. 3 which will be described later. One embodiment of this type structure is shown in FIGS. 4 and 5 whose size, especially in thickness, is exaggerated for purposes of clarity.

A semiconductor wafer 10 is illustrated, which may be of monocrystalline silicon. Wafer 10 may have a diameter, for example, of three-fourths inch and a thickness of about 10 mils, it being understood that these dimensions can vary depending on the desired power rating of the device. The wafer 10 has PN junctions 11, 12 and 13 therein, in a manner typical for any controlled rectifier structure, which separate the various P and N layers identified in FIG. 5. These layers may be formed by any of the well-known junction-forming techniques such as diffusion, alloying, epitaxial deposition; or the like.

An anode contact electrode 14 is then suitably affixed to the bottom P-layer of wafer 10, and an upper cathode electrode 15 is secured above junction 13, in a well known manner. Note that cathode electrode 15 overlaps planar junction 13 to form a so-called "shorted emitter" connection. Electrode 15 has a plurality of notches 16 to 19 symmetrically disposed about its periphery, and a plurality of auxiliary gate leads 20 to 23 are disposed adjacent notches 16 to 19, respectively. Gate leads 20 to 23 can be made in any desired manner and could, for example, be formed of aluminum lead wires which are ultrasonically bonded to the upper P-type surface of wafer 10 and in surrounding relationship to cathode 15.

As previously described, in one prior art-type configuration, the various gates 20 to 23 are connected to a common source

of firing current such that, when anode 14 is positive and cathode 15 is negative so that junction 12 is reverse-biased, the application of a positive potential to the gate leads with respect to cathode 15 will cause firing of the device. By using a plurality of gate leads, a plurality of initial conducting plasmas will be created from anode 14 to cathode 15, so that the device can turn on with a relatively high rate of rise of current. However, this heretofore required a relatively high gate current source, since the source must provide the gate currents required for each of gates 20 to 23.

The standard wafer configuration, which has been described to this point, is then changed by the addition of an auxiliary cathode region defined by the N-type region above an additional PN junction 24 and by the addition of an adjacent main gate lead 25 which cooperates therewith. An auxiliary conductive cathode electrode 26 is then connected atop the N-type region above junction 24, and electrode 26 is then connected to each of the auxiliary gates 20 to 23 which surround the main cathode 15 by suitable leads. Gate lead 25 may again be of an aluminum wire which is ultrasonically bonded to the upper P-type region of wafer 10 adjacent junction 24. In order to insure proper current sharing of the various gates 20 to 23, the leads to the gates 20 to 23 may be provided with parallel connected resistors 27 to 30, respectively. If gate sensitivity were properly balanced, the balancing resistors 27 to 30 could be eliminated.

The device shown in FIGS. 4 and 5 operates in the following manner. Assuming that anode 14 is positive with respect to cathode 15, the N-type region above junction 24 will inject electrons into the lower P-type region, thereby causing an initial conduction plasma on the left-hand side of the device in FIG. 5 from anode 14 to auxiliary cathode electrode 26. This initial firing, obtained by a relatively low current from cathode 26 (which is internally generated by the initial anode current causing back e.m.f. due to silicon sheet resistance), is then directed through the various balancing resistors to the individual gates 20 to 23, thereby firing the main portion of the controlled rectifier with a high rate of rise of current.

The electrical characteristics of the device of FIGS. 4 and 5 are shown in FIG. 3 where it is seen that, at the end of the delay period, and as the anode-to-cathode voltage begins to decrease, there is a continuing rise in gate current, rather than a decrease as in FIGS. 1 and 2. This rise in gate current is a function of the accompanying rise in anode current which in turn generates the voltage which excites the auxiliary cathode. This enhances the  $di/dt$  characteristics of the main cathode and reduces the danger of  $di/dt$  failure of the device. Moreover, the magnitude and rise time of current into the main gate lead 25 no longer determine the  $di/dt$  capability of the device.

It will be apparent to those skilled in the art that the wafer of FIGS. 4 and 5 can be contained within any suitable type of housing. Similarly, it will be understood that the specific conductivity-type sequences shown in FIGS. 4 and 5 could be reversed.

FIGS. 6 and 7 show a second arrangement, wherein the individual gates 20 to 23 of FIGS. 4 and 5 are replaced by a single electrode plate which extends over the edge of the additional junction 24 in FIGS. 4 and 5.

Referring to FIGS. 6 and 7, a silicon wafer 40 contains the usual junctions 41, 42 and 43, where, however junction 43 has the generally semicircular shape shown in FIG. 6. An auxiliary junction 44 having the shape shown in FIG. 6 replaces the junction 24 of FIGS. 4 and 5. An anode electrode 45 is affixed to the bottom of wafer 40 and semicircular aluminum contact 46 is connected to the top of wafer 40, overlapping the right-hand portion of junction 43 which terminates on the surface of wafer 40. An aluminum bar 47 is then applied across the junction 44 to serve as the auxiliary cathode contact and as a continuous auxiliary gate electrode for the main cathode region underlying cathode contact 46. A main gate 48, which is similar to gate 25 of FIGS. 4 and 5 is then placed adjacent junction 44. A suitable spacing of the adjacent sides of con-

tacts 46 and 47 and the left edge of junction 43 is such that dimensions "A," "B," and "C" of FIG. 6 are each about 0.015 inches for a wafer having the size of the wafer described in connection with FIGS. 4 and 5.

A device of the type shown in FIGS. 6 and 7 was tested in a standard  $di/dt$  switching test with a case temperature of about 65° C. an anode-to-cathode voltage of about 700 volts and at frequencies which varied from 400 to 5,000 cycles per second. The device was also tested at a repetition rate of 75 Hz. under higher  $di/dt$  conditions. It withstood rates of rise of current up to 1400 amperes per microsecond.

FIG. 8 shows a modification of the arrangement of FIGS. 6 and 7 where components similar to those of FIGS. 6 and 7 have identical identifying numerals. In FIG. 8, the main cathode 60 has a greater area than cathode 46 of FIG. 6 by the use of projecting fingers 61, 62 and 63 for cathode electrode 60. Electrode 64, which replaces electrode 47 of FIG. 6 then has extending fingers 65 and 66 which are interleaved with fingers 61, 62 and 63. Note that junction 67 which replaces junction 44 of FIG. 6 has a shape which follows the periphery of the right-hand side of electrode 64. As shown in FIG. 8, the interleaving arrangement permits the use of more cathode area for a given size of silicon wafer than the design of FIGS. 6 and 7. Thus the device can have a higher current rating.

Referring to FIGS. 9 and 10, there is illustrated therein a controlled rectifier configuration constructed in accordance with the present invention. Elements of FIGS. 9 and 10 similar to those of FIGS. 6 and 7 are given similar identifying numerals. In FIGS. 9 and 10, a main cathode contact 80 cooperates with auxiliary cathode contact 81, where the auxiliary cathode contact 81 is similar to that of FIGS. 6 and 7. That is, the edge of auxiliary cathode contact 81 facing the main contact cathode 80 is straight. The auxiliary cathode contact 81 covers the auxiliary N region 44, as in FIGS. 6 and 7, while the main contact 80 is disposed atop the main N region also as in FIGS. 6 and 7. In FIGS. 9 and 10 and in accordance with the present invention, the portion of the cathode contact 80 facing auxiliary cathode 81 is provided with a plurality of slots, shown as the six slots 82. Each of these slots form adjacent teeth which extend across the edge of junction 43 in the manner shown in FIGS. 9 and 10.

In the particular example of FIGS. 9 and 10, the slot width may be 0.025 inches and the tooth width may be 0.050 inches. The length of each of the teeth and thus the depth of the slots may be 0.035 inches. The diameter of the complete wafer may be 0.700 inches. The lateral dimensions of the devices, and in a direction running along the section line 10 of FIG. 9, for example, junctions 43 and 44 may be contained within a circle having a diameter of 0.425 inches and may be spaced from one another by a gap of 0.030 inches. Auxiliary cathode contact 81 overlaps the left-hand straight edge of junction 44 by 0.010 inches, while the teeth of the slotted contact 80 overlap the right-hand edge of junction 43 by 0.005 inches.

Where the  $di/dt$  of the device is to be improved at the expense of its ability to withstand forward  $dv/dt$ , a larger slot width can be used. Where the  $dv/dt$  characteristic is to be improved at the expense of the  $di/dt$  characteristic, the number of slots may be increased or the slot width may be decreased.

Although this invention has been described with respect to particular embodiments, it should be understood that many variations and modifications will now be obvious to those skilled in the art. Therefore, the scope of this invention is limited not by the specific disclosure herein, but only by the appended claims.

We claim:

1. A controlled rectifier having adjusted  $di/dt$  and  $dv/dt$  characteristics, and being capable of being fired with a relatively low gate current; said controlled rectifier comprising: a wafer of monocrystalline semiconductor material having first and second parallel surfaces; first, second and third spaced PN junctions sequentially disposed therein; at least a portion of said third PN junction terminating along said first surface of said wafer and dividing said first surface into a first surface re-

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gion extending atop said third PN junction and into a second surface region; a first main electrode connected to said first surface region of said first surface; a second main electrode connected to said second surface of said wafer; a fourth PN junction disposed beneath said second surface region of said first surface and above said second PN junction; an auxiliary electrode connected to said second surface region atop said fourth junction; a main gate electrode connected to said second surface region adjacent said auxiliary electrode; and an auxiliary gate electrode connected to said auxiliary electrode and to said second surface region of said wafer adjacent to said first main electrode; said auxiliary electrode and said auxiliary gate electrode comprising a common conductive electrode extending across said fourth PN junction; said first main electrode having an edge portion adjacent one edge of said common conductive electrode; said edge portion being slotted; the teeth of said slot extending across said third junction thereby to form a shorted emitter connection; said edge of said common conductive electrode being straight.

2. The device of claim 1 wherein said common conductive electrode and said main electrode are spaced segments of a common metallic disc.

3. A controlled rectifier having adjusted  $di/dt$  and  $dv/dt$  characteristics, and being capable of being fired with a relatively low gate current; said controlled rectifier comprising: a wafer of monocrystalline semiconductor material having first and second parallel surfaces; first, second and third spaced PN

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junctions sequentially disposed therein; at least a portion of said third PN junction terminating along said first surface of said wafer and dividing said first surface into a first surface region extending atop said third PN junction and into a second surface region; a first main electrode connected to said first surface region of said first surface; a second main electrode connected to said second surface of said wafer; a fourth PN junction disposed beneath said second surface region of said first surface and above said second PN junction; an auxiliary electrode connected to said second surface region atop said fourth junction; a main gate electrode connected to said second surface region adjacent said auxiliary electrode; and an auxiliary gate electrode connected to said auxiliary electrode and to said second surface region of said wafer adjacent to said first main electrode; said auxiliary electrode and said auxiliary gate electrode comprising a common conductive electrode extending across said fourth PN junction; said first main electrode having an edge portion adjacent one edge of said common conductive electrode; said edge portion being slotted; the teeth of said slot extending across said third junction thereby to form a shorted emitter connection; said edge portion having at least five slots therein.

4. The device of claim 3 wherein said common conductive electrode and said main electrode are spaced segments of a common metallic disc.

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