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PRESSURE CONTACT TYPE SILICON POWER DIODE

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I. PREFACE

The semiconductor rectifier diode is simple and sturdy in construction, with highly stable characteristics.

As a result of research into application techniques, the reliability of the diode has been considerably enhanced and maintenance has become much easier, so that the diode has replaced the various types of rectifiers hitherto used. It is now employed in a wide range of applications, with utmost satisfactory results being now enjoyed. The silicon rectifier diode in particular has a higher reverse working voltage than that of the selenium, germanium-rectifier element, and can be safely used in a higher range of temperatures, so that it is suitable for higher power application. Thus, it has opened a range of applications impossible with existing rectifiers.

The silicon rectifier diode, used within permissible limits, was expected to suffer no substantial deterioration of characteristics and to have an almost permanent-life span. However, it may often be the case that if the conventional type of silicon rectifier element is used for rectifiers with particularly large fluctuations of load current, such as for dc welding, substations for dc electrification railways, locomotives and electric cars, cracking occurs in the brazed portion between the silicon element and the copper base, which worsens to finally make the unit unserviceable. In order to solve this problem many improvements have been made in the adhesion method of the silicon element. Fuji Electric has brought a fresh approach to the problem, completely changing the method of the conventional type of adhesion to the brazing method, and has succeeded in the application of the pressure contact mechanism. For the past two years Fuji Electric has been mass-producing this type of diode, which enjoys a superior record of actual performance.

II. PRESSURE CONTACT MECHANISM

1. Problems arising from Thermal Expansion of Material of Silicon Power Diode

There is a considerable difference in the thermal expansion coefficient between the silicon single crystal in the operating temperature range and the copper used as a base material, and yet the silicon single crystal wafer is comparatively weak.

It easily breaks or cracks due to bending stress, its characteristics easily changing.

For this reason, they cannot be directly joined, particularly in the case of large capacity silicon elements.

In the usual case, the silicon element is joined to a base plate such as molybdenum, tungsten, and cover of almost the same expansion coefficient, and this base plate is brazed to the copper base. This practice may solve the problem of cracking of the silicon element and the characteristics change. However, the problem of the difference in the expansion coefficient between the base plate and the copper base remains, thus influencing the method of the brazing. At least the following points should be borne in mind in determining the method of brazing :

1) As the diameter of the silicon element increases, the size difference increases, accordingly. Thus in the case of expansion or shrinkage, greater stress is applied to the junction (the problem remaining with the greater capacity element).
2) Full utilization the feature of the silicon element that it can resist high temperature (problem remaining with high current density).
3) In the case where a frequently repeated load is applied, destruction of the material at the junction due to fatigue should be taken into consideration (problem remaining with repeatedly applied load).

2. Fatigue of Brazing Material in Soft Soldered Diode

What is called "soft solder", mainly consisting of tin and lead has been used for adhesion of the base plate and the copper base, because of ease of manufacture. When soft solder is used, adhesion can be performed at a comparatively low temperature (between 180 and 250 °C), so that in the adhesion process there need be almost no concern about quality change of the p-n junction surface and reverse direction characteristics due to mechanical stress, Most of the stress caused by expansion and shrinkage during use of the element is absorbed at the portion of the soft solder, never extending directly to the silicon element, so that the diode can display its extremely high characteristics under continuously applied loads. However, the problem of intermittent loads remains. Because of the extremely low strength and adhesive properties of its material itself, soft solder tends to exceed the permissible stress limit with comparatively little temperature variation, resulting in plastic deformation and cracking, or detachment of adhered portions and diminishing of contact area. Even in the case of the deformation within the elasticity range due to stress which is permissible statically, should it be repeated numerous times, destruction may result. This is what is generally described as the phenomenon of fatigue. With respect to soft solder, fatigue tends to occur even at small values of stress, so that in the case of repeated loading of a large capacity element, the operating temperature of the element should be lowered.

Upon deterioration of the portion joined by soft soldering, the thermal resistance may increase between the element and the base, so that the rate of the temperature rise of the element accelerates, resulting in an over-reverse current or detachment of base plate rendering the diode unserviceable.

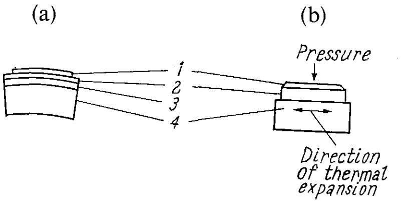
3. Problematic Points with Hard Soldered Diode

The first method considered to solve the problem of the fatigue of soft solder was adhesion by hard solder.

Hard solder has a considerably higher value of permissible stress and adhesion sturdiness than soft solder, and displays pure elastic deformation at the size of the present silicon diode and the operating temperature range. With its higher fatigue limit, it has almost unlimited durability with respect to temperature cycles. However, when performing adhesion by hard solder, the following technical problems inevitably arise:

1) Bimetal effect

When two materials of different expansion coefficient have been joined by a strong adhesive, deformation is inevitable due to the temperature variation involved. Also, during the period of cooling after brazing at high temperature, the materials of both sides bend as shown in *Fig. 1* (a). As the melting point of the hard solder increases, this bending becomes more acute, often resulting in cracking of the silicon element. In order to provide for this phenomenon, it is necessary to make the base plate thicker, so that even when the bottom surface undergoes elasticity deformation, the curve of the top surface negligibly small. By this practice, the thermal resistance between the p-n junction and the copper base increases. Consequently the allowable load current will become lower than that of soft soldered diode with same size.



(a) Bimetal effect of hard soldered diode
(b) Thermal expansion of pressure contact type diode

1: Semiconductor element
2: Base plate
3: Hard solder
} (small thermal expansion coefficient)
4: Base (large thermal expansion coefficient)

Fig. 1 Bimetal effect of hard soldered diode

2) Increase in defect ratio during the manufacturing process

When performing adhesion by hard solder, if a method is used involving an extensive period of heating in a vacuum furnace, copper and other metal, as well as other foreign material, diffuse into the single crystal of silicon, thus deteriorating the reverse direction characteristics. Even when high frequency induction heating is applied to perform the required adhesion locally in a short heating period, an excessive temperature rise at the junction is inevitable, so that the already formed junction undergoes a change which allows the reverse current to increase and the voltage insulation to deteriorate. For these reasons, the defect ratio is greater than with the soft soldered diode.

4. Solution by Employing Pressure Contact Type Silicon Power Diode

A silicon element adhered to a thin base plate is comparatively weak with respect to tensile and bending stress, but strongly resistant to vertical pressure to the base plate. Hence the possibility arises here that the adhesion between the base plate and the base, and between the element and the lead wire can be made a pressure contact type. In the case of the pressure contact type, the thermal expansion of each type of material can occur without any affect, and the bimetal-type deformation mentioned previously does not result [Refer to *Fig. 1* (b)].

The pressure contact method is quite often used in general electrical techniques, including, for instance, the fixing of the bus wire with screws, fuse holders, and switch contacts. These contacts, however, are intended mainly to allow the flow of electric current: provided that the electrical resistance at the portion of contact is not excessively large, the heat produced by the contact resistance is negligible, causing almost no problems in actual operation. In the case of the silicon element, it has the additional

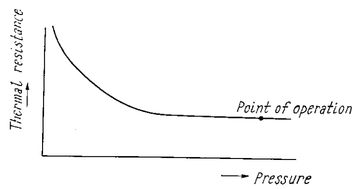


Fig. 2 Relationship between thermal resistance and mechanical pressure

Fig. 3 Pressure contact type power diode Si 250.3

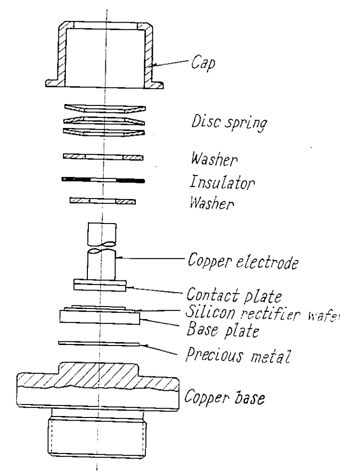


Fig. 4 Construction of Si 250.3

mission of transferring the thermal loss of the element to the base.

Compared to the minimization of the electrical resistance, minimizing the thermal resistance at the portion of the contact is far more difficult, so that the pressure contact type has never been given serious consideration for a silicon element.

For satisfactory thermal conduction, it is important to realize a plane contact or countless-point contact. These requirements may be achieved by selection of the correct hardness, roughness, degree of flatness, and pressure of the contact portions. If high-precision processing of the selected material is performed and sufficient pressure applied, it has been confirmed that the thermal resistance at the portion of the contact becomes almost zero (0), and that only the thermal resistance of the material between the measured points remains (Refer to *Fig. 2*).

When a frequent temperature cycle is repeated, if the expansion coefficient of the material at each side differ, tracing distortion results, so that the material of one or both sides is worn off by attrition. Arrangements should be made to avoid this. Further care should be taken so that when operation is performed for a long period of time at high temperatures, the contact material is not affected by the ambient gas, thus resulting in an increase in the thermal resistance. This should be prevented. The above points have been solved by fully selected materials and using inert gas inside the element.

III. PRESSURE CONTACT TYPE SILICON POWER DIODE Si 250.3

The pressure contact type mechanism was first applied to the large capacity high voltage silicon rectifier element Si 250.3 very extensively used for rolling stock and substations. Given below is an explanation concerning the construction as well as characteristics of the Si 250.3.

1. Construction

Fig. 3 shows the outer view and *Fig. 4* illustrates the interior construction of the pressure contact type silicon element Si 250.3. The rectifier element is constructed with a gold electrode welded onto the top section and aluminum foil onto the bottom section of the silicon single crystal plate through an alloying process. The bottom surface of the rectifier element contacts the copper base through the precious metal, through which both the current and the lost heat are flow. A copper electrode with the contact plate brazed by means of the hard solder, contacts the top surface, through which mainly current only flows. In order to apply the required pressure a disc spring is used, on which a cap is placed, with its flange fixed to the copper base. The disc spring is insulated from the copper electrode by means of an insulator. The operation of the pressure contacts at the side of the rectifier element is essentially different.

The copper electrode of the top surface is in contact with the silicon single crystal plate through a contact plate whose expansion coefficient is almost identical to that of the silicon single crystal, showing no deviation from the thermal expansion of the silicon single crystal plate.

Inserted between the base plate and the copper base is a precious metal plate, thus permitting the base plate to freely expand or shrink on the precious metal plate due to the temperature variation of the element.

In this case, there will be no attrition of the precious metal plate, but will be some extent of mutual interaction. According to experience so far obtained, this interaction permits closer surface contact, tending to improve slightly the electrical and thermal contact.

2. Characteristics

1) Rectification characteristics

The rectification characteristics are almost identical to that of the hard soldered element Si 250.1 which uses the same rectifier element, having the values shown in *Table 1*. The typical value of the reverse direction characteristics are identical to that of the Si 250.1. However, the defect ratio has been considerably reduced since there is no thermal stress in the course of the manufacturing process.

2) Continuously permissible temperature for the junction

Through the employment of the pressure contact type method, all the problems with respect to the temperature cycle have been solved and the overall reverse characteristics have been improved, so that the continuously permissible temperature of the junction can be raised by 10°C to the value of 160°C.

3) Thermal resistance and temperature rise

By employing the pressure contact type method, the thermal resistance is lowered and the dispersion minimized. As a result, the temperature rise of the element has become as shown in *Fig. 5*.

Table 1 **Ratings and Characteristics of Fuji Power Diode Si 250.1 and Si 250.3**

Item	Unit	Requirement	Si 250.1	Si 250.3
Peak Reverse Voltage	v (peak)	Surge Voltage	1500	1500
		Commercial frequency (1 sec)	1300	1300
		Commercial frequency (continuous)	1200	1200
Mean Forward Current	Amp (mean)	Air-cooled 6 m/s 50°C	200	280
Threshold Voltage	mv	20°C	830	830
Forward Differential Resistance	$\mu\Omega$	20°C	500	500
Forward Voltage Drop	mv	300 amp 20°C	980	980
		600 amp 20°C	1130	1130
Overcurrent	Amp (peak)	Commercial frequency (1 cycle)	6500	7500
		Commercial frequency (5 cycles)	3300	4000
		Commercial frequency (15 cycles)	2500	3200
Thermal Resistance between Junction and Case	°C/w		0.2	0.15
Allowable Continuous Junction Temperature	°C		150	160

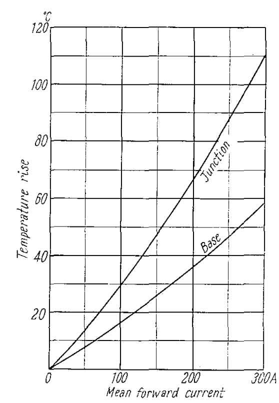


Fig. 5 **Junction and case temperature rise of Si 250.3 under condition of forced air cooling (6 m/s)**

The minimization of the thermal resistance and improvement of the permissible temperature of the junction resulted in the possibility of an increase of the rated current to 140% the present value.

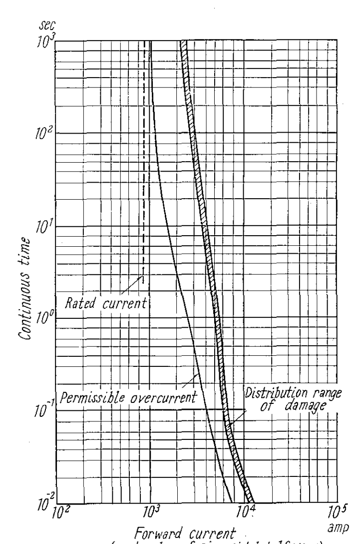
4) Overcurrent characteristics

As a result of the larger area of contact of the electrode which produces accurate contact performance, the tendency of local concentration of the overcurrent has been eliminated, thus increasing resistance to overcurrent.

Fig. 6 shows the results of the destruction test made with overcurrent applied for a certain period of time from the condition of the rated load application.

5) Result of temperature cycle test

In the method where the element is installed to a thermal plate, a large current is allowed to flow through the thermal plate for heating. The



Initial requirement: Temperature at each portion to be saturated under the rated current
Cooling: Air-cooled (6 m/s)
Ambient temperature: 50°C

Fig. 6 **Relationship between overcurrent and time**

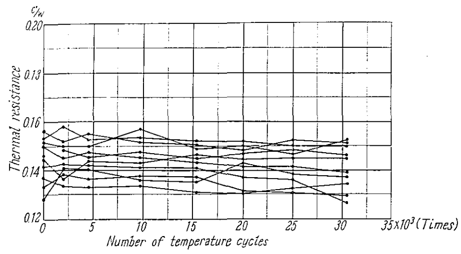


Fig. 7 Test results of thermal resistance for temperature cycles

thermal plate and the element are both cooled as soon as the current has been cut off and 4-minute temperature cycle with a range of variation of 80°C is applied to the element for testing the resultant variation of the thermal resistance between the junction and the base. The result is as shown in *Fig. 7.* The variation of the thermal resistance was extremely small, and it has been confirmed that there is no problem at all with respect to the temperature cycle, as was expected.

3. Silicon Rectifier using Si 250.3

The pressure contact type silicon element Si 250.3 was applied first to rolling stock and substations, and results were obtained just as expected.

Fig. 8 shows the master silicon rectifier for the New Tokaido Line; one set consists of two boxes, with dc output being 1660 v, 980 amp, 100 per cent continuous, 150 per cent 8 minutes).

A total of 160 (10 S × 4 P × 4 A) Si 250.3 are used in a single phase bridge connection. Available for substation applications is a rectifier (three phase, bridge connection 5 S · 8 P 6 A) 1500 v 3000 kw, 2000 amp (100 per cent continuous, 120 per cent 2 hours, 300 per cent 1 minute) constructed for the Japanese National Railway.

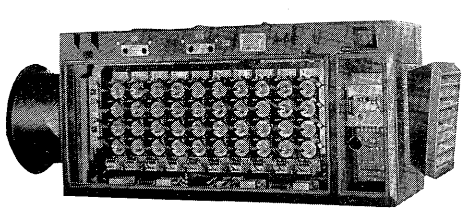


Fig. 8 Rectifier set of New Tokaido Line car

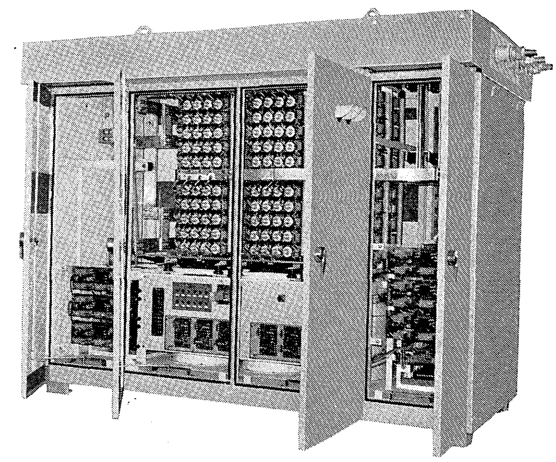


Fig. 9 1500 v 3000 kw silicon rectifier employing pressure contact type power diode Si 250.3

IV. CONCLUSION

A pressure contact mechanism is unprecedented in the construction of a silicon element. It has clearly solved the difficulties long involved in the existing brazing construction, and has allowed the silicon element higher reliability in practical operation and a wider range of applications.

Furthermore, ease of manufacture without affecting the characteristics of the element contributes to the improvement of production, so that this mechanism is not limited only to the large capacity element described above, but is extensively applied to both medium and small capacity elements, such as for welding machines and automobile-use ac generators. The construction of the silicon element in general use at the present is based on the prerequisite that the silicon element be brazed. Thus the adoption of the pressure contact mechanism quite likely represents a very basic step in the development of a new silicon element small in size and light in weight, providing even higher cooling efficiency and better space factor.