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HIGH CURRENT SEMICONDUCTOR DEVICES

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I. INTRODUCTION

Power semiconductor devices in these years have undergone great advancement and improvements in performance ratings and characteristics, thereby making high voltage and high power devices actually applicable for various application.

Regarding power thyristors, devices of a level of 2,500 V, 400 A have been used sucessfully in power supply equipment for rolling mills. Regarding rectifier diodes, devices of a level of 2,500~3,000 V, 800 A are widely used in power supply equipment (converters) for railway substations, and aluminium refinery.

As the capacities of converters become larger and larger, it is desirable to reduce the number of parallel-connected cells from the viewpoints of reliability and economy. To attain this desirable end, stronger requirements have become to be placed on higher current semiconductor devices.

On the other hand, due to advancement in the monocrystal technology, silicon monocrystals of larger diameters have become available. Devices which have as large current ratings as twice of those available in the past have become possible. On the other hand, advancement in the semiconductor device cooling technique also has supported developments of high current semiconductor devices. Basing on the above background, the Fuji Electric has recently developed and put on the market two types of high current semiconductor devices—one is EGR 01-25 thyristor of a level of 2,500 V, 1,000 A and the other is ERR 01–25 diode of a level of 2,500 V, 1,600 A. This article will introduce manufacturing techniques and characteristics of the FGR 01 thyristor and ERR 01 diode.

II. MANUFACTURING TECHNIQUES

As diameters of silicon devices have become larger, such problems in manufacturing procedures have been encountered; those are how to treat flawlessly the silicon single-crystals, how to control the life time of carriers, and how to prevent warping of the element caused by heat expansion difference between silicon element and its supporting parts. These problems were not conspicuous for small-diameter silicone devices. Solving these problems, the Fuji succeeded in developing an entirely new series of semiconductor devices.

1. Forward Voltage Drop

As the diameter of the silicon semiconductor element becomes larger, the forward voltage drop is apt to increase since the quality of the single-crystal itself is degraded and in addition, various factors which may cause shortening of the life time of the silicon device may be introduced in the manufacturing process. As a countermeasure against this, the Fuji employed an improved diffusion process and heat treatment method. As a result, devices with as small forward voltage drop at the same current density as those of the conventional all-diffused devices ERP 01 (3,000 V, 800 A diode) and EGP 04 (2,500 V, 500 A thyristor) have become available. *Fig. 1* illustrates forward voltage drop distribution of EGR 01 tyristors. These devices are made of dislocation-free crystal in order to obtain a uniform junction-front, and they are manufactured in the processes in which the lineage and other crystal defects are not introduced. Therefore, the starting perfect

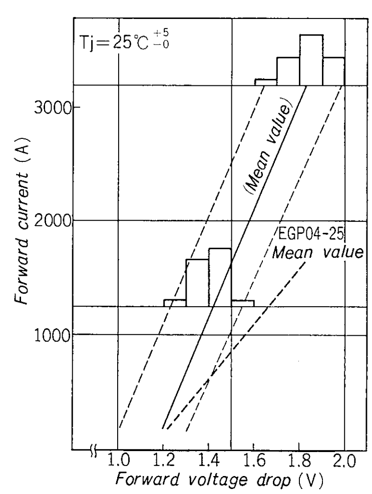


Fig. 1 Distribution of forward voltage drop (EGR 01-25)

material are maintained throughout the manufacturing processes.

2. Thermal Resistance

One of the major problems encountered in manufacturing large diameter semiconductor devices is that distortion of the device becomes larger due to large difference in thermal expansion coefficient between silicon element itself and its supporter. This difference in expansion coefficient does not cause any serious problem for small diameter semiconductor devices. To solve the above problem, studies on supporting plate materials were made in order to minimize the distortion, and a new packaging method were developed.

Distribution of thermal resistance between junction and the reference point of cooling fin of EGR 01-25 thyristor is shown in *Fig. 2*. Although the current capacity of a semiconductor device is affected by the overall cooling system, the intended thermal resistance as calculated basing on appropriate case temperature and generation loss is 0.025°C/W. The figure shows that the device has a sufficient allowance with respect to the intended characteristic.

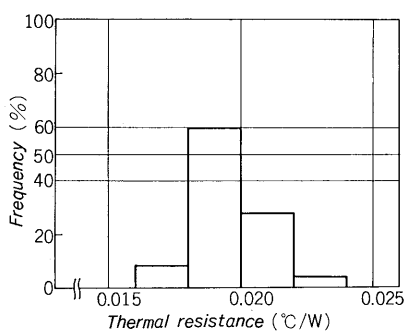


Fig. 2 **Distribution of thermal resistance between junction and reference point of cooling fin (EGR 01-25)**

External dimensions of the thyristor are shown in *Fig. 3*. The upper and lower electrodes, the internal contact plate, and the element can slide within the case, and the stresses which would be produced during heat cycle are relieved.

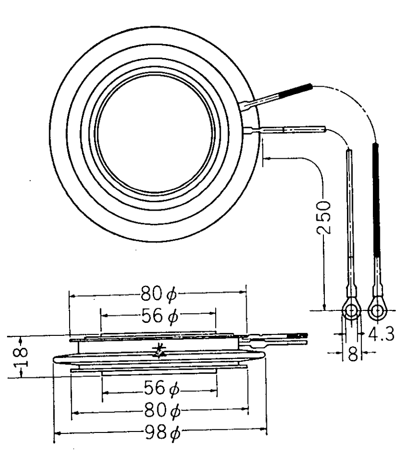


Fig. 3 **Size of the thyristor (EGR 01-25)**

3. Voltage Blocking Capability

For these new devices also, the voltage blocking junction is formed in a double diffusion method. Therefore, both internal breakdown voltage and surface blocking capability are kept sufficiently high and stable. The increase of diameters will cause such unfavorable effects on the voltage blocking capability as the higher radial gradient of resistivity, the increase of length of the junction surface, and the increase of leakage current due to under junction area. These drawbacks, however, can be fully covered by stringent grade control of wafers, by improvements in machining accuracy and surface forming technique, and the carrier life time by maintaining at a high level.

4. Switching Characteristics

The *dv/dt* capabitity is apt to be degraded when the element diameter is increased because the capability is closely related to the uniformity (flatness) of the emitter junction front. For these new semiconductor devices, a high *dv/dt* capacity is maintained by obtaining uniform junction front as a result of adoption of the all diffusion technique and emitter junction structure which minimizes the emitter injection efficiency. On the other hand, a structure which improves the *dv/dt* capability is apt to have a trend to degrade the spreading of the conduction area. Attention has been paid to this point also and optimum characteristics are selected.

Regarding the *di/dt* capability, the construction between gate and cathode are so arranged that the current injected through the gate will cause formation of a wide initial conducting area. The high *di/dt* capability is obtained by employing precise machining technique and the required structure is reliably maintained.

III. RATINGS AND CHARACTERISTICS

1. Current Rating

To obtain a high current rating, the forward voltage drop and thermal impedance of the device must be small. Forward voltage drop characteristics of EGR 01 thyristor and ERR 01 diode are shown in *Figs. 4* and *5*. The thermal impedance between junction and reference point is 0.025°C/W for both thyristor and diode. In the flat packaged cells of a compression contact strtcture, the electrical contact resistance and thermal contact resistance are dependent on the mounting force. Dependences of forward valtage drop and of thermal resistance on the mounting force are shown in *Figs. 6* and *7*, respectively. The standard mount ing force is selected at 2,000 kg.

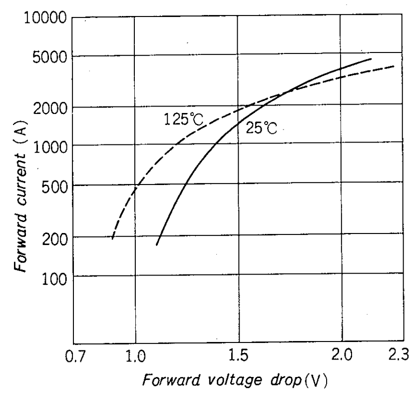


Fig. 4 **Forward characteristics (EGR 01 thyristor)**

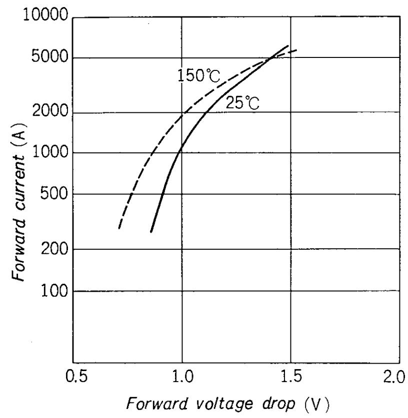


Fig. 5 **Forward characteristics (ERR 01 diode)**

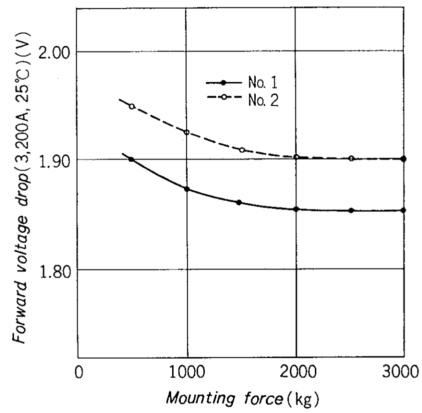


Fig. 6 **Mounting force vs. forward voltage drop (EGR 01 thyristor)**

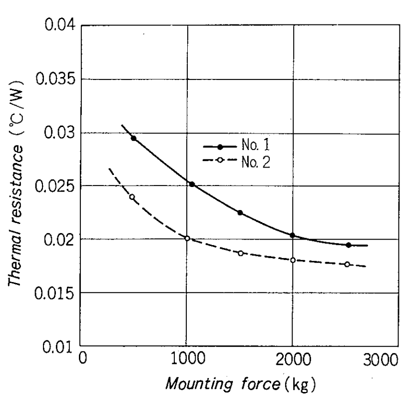


Fig. 7 **Mounting force vs. thermal resistance (EFR 01 thyristor)**

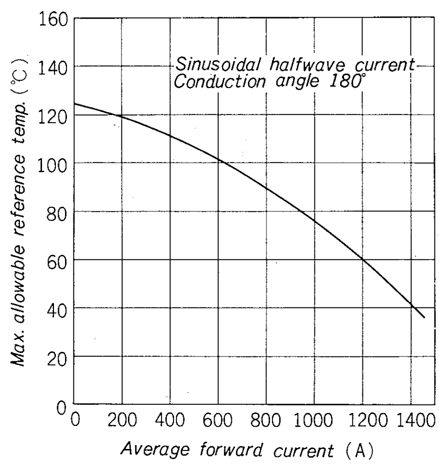


Fig. 8 **Average forward current vs. maximum allowable reference temperature (EGR 01 thyristor)**

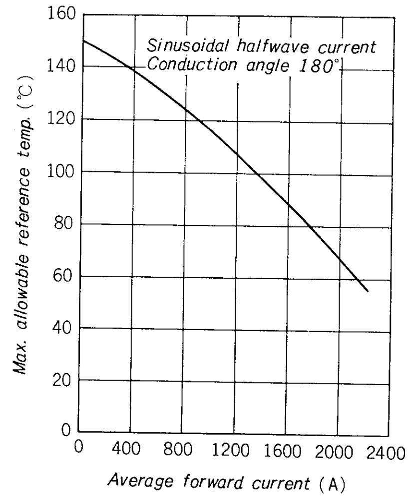


Fig. 9 **Average forward current vs. maximum allowable reference temperature (ERR 01 diode)**

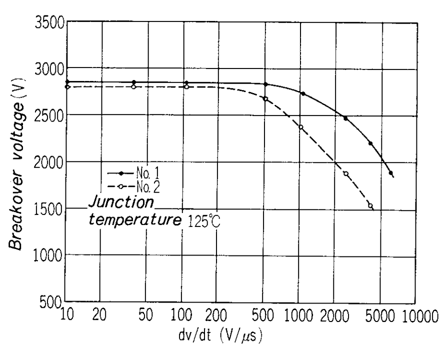
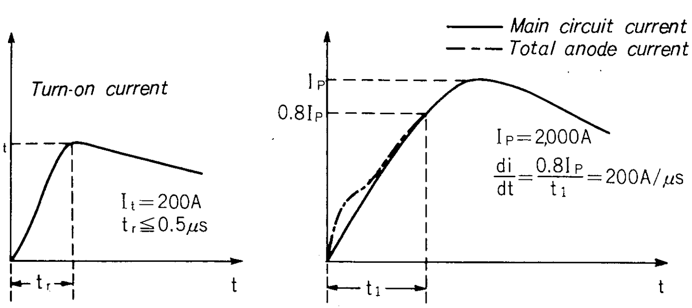


Fig. 10 **Forward break-over voltage vs. *dv/dt* (EGR 01-25)**



Anode voltage before turn-on: 1,300 V
Gate drive condition: ig=1.0 A, dig/dt=1.0 A/μs
Junction temperature: 125°C

Fig. 11 **Test condition of *di/dt* test (EGR 01-25 thyristor)**

Current ratings, of the thyristor and diode as obtained basing on the evaluation of the forward voltage drop and thermal resistance are shown in *Figs. 8* and *9*.

2. Critical Rate of Rise of Forward Blocking Voltage (*dv/dt*)

Fig. 10 illustrates the relationship of forward breakover voltage v.s. *dv/dt*. The *dv/dt* capability of the EGR 01 thyristor is 2,000 V/μs or over at junction temperature 125°C and peak voltage 1/2 PFV.

3. Critical Rate of Rise of Forward Current (*di/df*)

Fig. 11 illustrates the *di/dt* test condition for EGR 01 thyristor. The turn-on current flows from the accessory RC snubber circuit. Since the circuit is virtually non-inductive, the rise characteristics depends only on the turn-on characteristic of the thyristor and, therefore, is very steep. It has been proven that the thyristor can withstand a composite current duty of a combination of a main circuit current having a rise rate of 200A/μs and a peak turn-on current of 200 A.

4. Reverse Recovery Characteristics

Fig. 12 illustrates the *di/dt* v.s. reverse recovery current of the EGR 01 thyristor. This characteristics are especially important for determination of the accessory snubber circuit constants for suppression of the initial reverse voltage produced in the reverse recovery period.

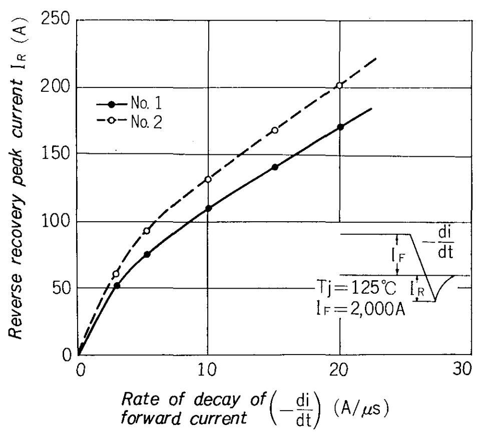


Fig. 12 *di/dt* vs. reverse recovery current (I_R) (EGR 01 thyristor)

5. General Ratings and Characteristics

General ratings and characteristics of the EGR 01 thyristor and ERR 01 diode are shown in *Tables 1* and *2*, respectively.

IV. RELIABILITY

Power semiconductor devices in these days are often used as components of large systems. In such applications, the reliability of the semiconductor devices is of the prime importance. The results of tests of semiconductor devices primarily for reliability are described in this section.

1. High Temperature Storage Test

This test was performed to ensure the stability of the junction surface and inner contact surface. Of both EGR 01 thyristor and ERR 01 diode, there were no noticeable degradation of blocking capability, forward voltage drop and thermal resisiance.

2. High Temperature Blocking Test

Both thyristor and diode indicated no trace of degradation after being subjected for a long period to the rated blocking voltage at the rated maximum junction temperature.

Table 1 Ratings and characteristics of EGR 01 thyristor

Item	EGR 01	
	20	25
Repetitive peak reverse voltage	2,000 V	2,500 V
Repetitive peak forward blocking voltage	2,000 V	2,500 V
Non-repetitive peak reverse voltage	2,200 V	2,700 V
Critical rate of rise of forward blocking voltage (*dv/dt*)	2,000 V/μS (1/2 V_{DRM})	
Maximum forward voltage drop	2.0 V (25°C, 3,200 A)	
Rated average forward current	1,000A (Sinusoidal waveform, 180° conduction, reference temperature 76°C)	
Critical rate of rise of forward current (*dt/dt*)	200 A/μS, (switching voltage 1/2 V_{DRM} T_j=125°C)	
Peak turn-on current	200 A (switching voltage 1/2 V_{DRM} T_j=125°C)	
Peak one cycle surge forward current	18,000A(50Hz sinusoidal half wave current)	
Maximum holding current	400 mA (T_j=25°C)	
Maximum reverse leakage current	60 mA (at repetitive peak reverse voltage)	
Maximum forward leakage current	60 mA (at repetitive forward blocking voltage)	
Operating temperature	−40°C to 125°C	
Storage temperature	−40°C to 125°C	
Maximum thermal resistance	0.025 deg/W (junction to reference point)	
Maximum gate trigger current	300 mA$_{DC}$ (T_j=25°C)	
Maximum gate trigger voltage	3.0 V$_{DC}$ (T_j=25°C)	
Minimum gate trigger voltage	3.0 mA$_{DC}$ (T_j=125°C)	
Maximum gate nontrigger voltage	0.2 V$_{DC}$ (T_j=125°C)	
Allowable average gate power dissipation	5 W	
Allowable peak gate power dissipation	70 W (pulse width≦100 μS)	
Allowable negative gate voltage	5 V	
Maximum turn-on time	6.0 μS	
Maximum turn-off time	400 μS (T_j=125°C)	
Standard mounting force	2,000 kg	
Weight of element	480 g	

3. Continuous Current Conduction Test

If the junction surface is contaminated, ions attached on the surface are activated and will cause surface deterioration. The results of a current conduction test with a low source voltage and of a equivalent load test proved that both thyristor and diode are free of deterioration and are very stable.

4. Thermal Fatigue Test

High current semiconductor devices uses silicon pellets and other components of larger diameters. Therefore, they are subject to larger thermal stresses caused by intermittent load. From this viewpoint,

Table 2 Ratings and characteristics of ERR 01 diode

Item	ERR01	
	20	25
Repetitive peak reverse voltage	2,000 V	2,500 V
Non-repetitive peak reverse voltage	2,200 V	2,750 V
Maximum forward voltage drop	1.50 V (25°C 5,000A)	
Rated average forward current	1,600A (sinusoidal waveform, 180° conduction, reference temperature 83°C)	
Peak one cycle surge forward current	28,000 A(50Hz sinusoidal halfwave current)	
Maximum reverse leakage current	50 mA (at repetitive peak reverse voltage)	
Operating junction temperature	−40°C～+150°C	
Storage temperature	−40°C～+150°C	
Maximum thermal resistance	0.025 deg/W (junction to reference point)	
Standard mounting force	2,000 kg	
Weight of element	480 gr	

Table 3 Reliability tests of EGR 01 thyrister and ERR 01 diode

No.	Item	No.	Item
1	High temperature storage test	8	Temperature cycling test
2	High temperature blocking test	9	High temperature and high humidity test
3	Equivalent load test	10	Salt atmosphere test
4	Conduction test with low sorce voltage	11	Vibration test
5	**di/dt* life test	12	Shock test
6	*Gate power life test	13	Mounting force test
7	Thermal fatigue test	14	*Gate terminal strength test

* These tests were perfomed on only EGR01 thyristors.

for reliability evaluation, the highest importance was attached to a thermal fatigue test with intermittent load. A current higher than the rated average forward current was intermittently applied to the specimen for 60,000 cycles or over under condition that the temperature variation of the junction was 80°C or over for the thyristor or 110°C or over for the diode. The test proved that both EGR 01 thyristor and ERR 01 diode sustained no degradation in forward voltage, thermal resistance, or blocking capability. None of the tested specimens was deteriorated. *Fig. 13* illustrates an example of thermal fatigue test.

5. di/dt Life Test

Semiconductor devices were subjected to a switching duty equivalent to that of the above mentioned *di/dt* capability test at an averaged junction temperature 125°C for 5,000 hours. No specimens turned out to be deteriorated. The *di/dt* values mentioned

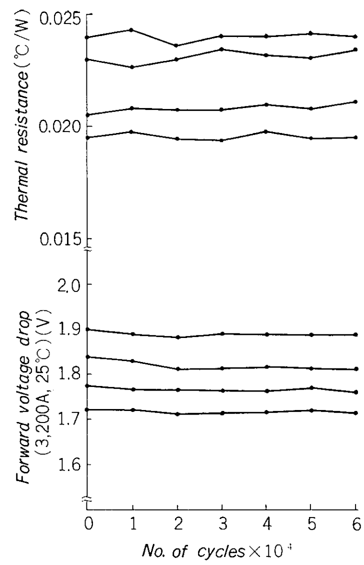


Fig. 13 Example of thermal fatigue test (EGR 01-25)

in the table of ratings can be fully warranted from the viewpoint of long-run reliability also.

6. Others

Other items of reliability test performed on the EGR 01 thyristor and ERR 01 diode are shown in *Table 3*. The above tests proved that the new semiconductor devices have equal or better reliability as compared with the power semiconductor devices hitherto been used.

V. HEAT SINK

The high power semiconductor devices introduced in the above produces heat loss of a range of 1,000～2,000 W. An efficient cooling is essential for them. The most commonly practiced cooling methods are water cooling, air cooling, and boiling liquid cooling

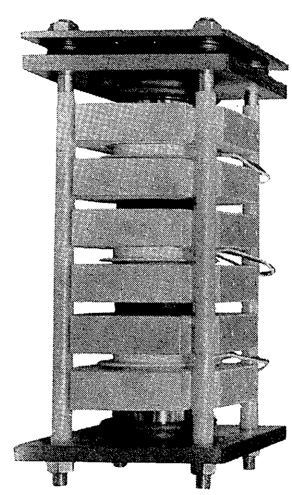


Fig. 14 Thyristor stack (EGR 01-25)

method using chemical liquid. An example of EGR 01–25 thyristors mounted on a oil cooling stack is shown in *Fig. 14*. Two of these stacks will constitute a 3-phase bridge which can deliver 2,500 A DC continuously.

Specification of the thyristor stack

Thyristors:	EGR 01-25
Construction:	1S1P3 arm (three cells)
Cooling method:	Forced oil cooling (cooling oil speed: 1 m/sec)
Cooling fins:	Copper (CuP1–1/2H) 130 × 29 t Two fins are used as a pair.
Mounting force:	2,000 kg ± 10%

This oil-cooling stack can be also fabricated with ERR 01 diodes to make up a 3 phase pure bridge rectifier circuit which will deliver 4,000 A DC continuously.

VI. CONCLUDING REMARKS

This article has introduced manufacturing techniques, ratings and characteristics, and reliability of new high power thyristors of a power level of 2,500 V, 1,000 A and diodes of a level of 2,500 V, 1,600 A.

These semiconductor are of the highest level in the world today. However, to make the best use of these high power semiconductors, further developments are required in the application peripheral techniques such as cooling system, protection against overcurrent and overvoltage. When these techniques are fully developed, the new high power semiconductors will find wide application in various industries including electric railways, steel manufacturing and electrochemical plants.