PROTON-ELECTROTEX
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Application Note
Power Semiconductors

Contents

1 Introduction

This document describes semiconductor products made by PROTON-ELECTROTEX JSC, as well as their manufacturing technology and recommendations regarding their usage.

If you have any other technical questions, please contact the technical support of PROTON ELECTROTEX, JSC by phone +7 (4862) 44-04-95 or feedback form on the www.proton-electrotex.com website.

2 Power Diodes

2.1 Definition

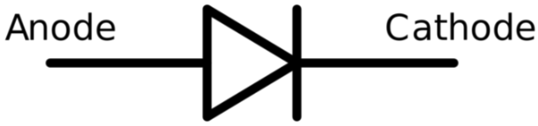


Figure 1. Symbolic designation of a diode.

A diode is the simplest semiconductor device based on a p-n junction. It is an electronic component with two electrodes. Its electrical resistance strongly depends on the polarity of applied voltage and has an asymmetric current-voltage curve depending on the direction of the current.

A diode mainly functions as an uncontrolled current rectifier – when "forward" voltage is applied (with a more positive potential at the anode) the diode switches to a high conductivity state capable of conducting high "forward" current (in the direction from the anode to the cathode). When "reverse" voltage is applied (with a more positive potential at the cathode) the diode switches to a low conductivity state capable of blocking the high "reverse" voltage by conducting minimal reverse leakage current.

2.2 Design

The most common type of diode in power electronics is the p-n junction diode. A typical cross-section of its semiconductor structure is shown in Figure 2.

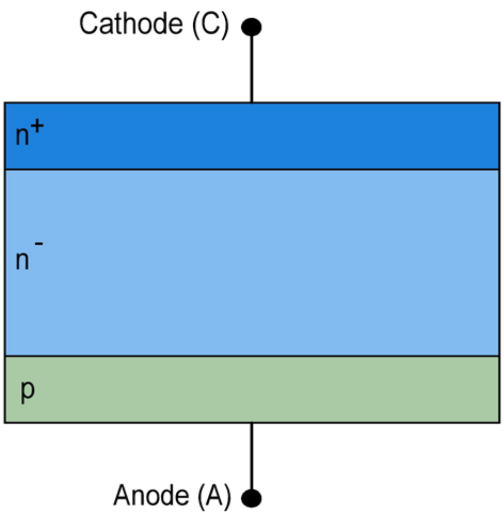


Figure 2. Typical cross-section of the semiconductor structure of a power diode with p-n junction.

A special trait of a power diode is the presence of at least one lightly doped (high-resistance) layer between the p-n junction and the anodic and cathodic surfaces of the structure. It is marked as the "n-" layer in Figure 2 that illustrates the most common type of diodes, i.e. it is an n-type conduction layer with a relatively low concentration of donor dopant (having relatively high resistivity).

The near-surface layers of the semiconductor structure in a diode with p-n junction are low-resistance (heavily doped with acceptor (for anode) and donor (for cathode) impurities). This is necessary to obtain ohmic (non-rectifying) contact with the surface metallization and achieve low contact resistance.

The p-n junction of a diode's semiconductor element comes out to the surface at its periphery creating a danger of surface breakdown when high reverse voltage is applied. To avoid the surface breakdown, it is necessary to decrease the electric field strength in the region where the p-n junction emerges on the structure surface. The most frequent method to reduce the electric field in this area is profiling, or creating a certain geometric shape of the semiconductor chip surface at the exit point of the p-n junction. Usually the required shape of the surface is achieved by grinding the edge of the silicon wafer at a certain angle, i.e. by forming a so-called bevel (Figure 3).

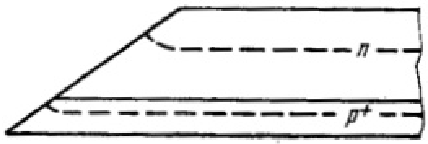


Figure 3. Edge bevel of a diode semiconductor element.

2.3 Primary Electrical Parameters and Properties of Diodes

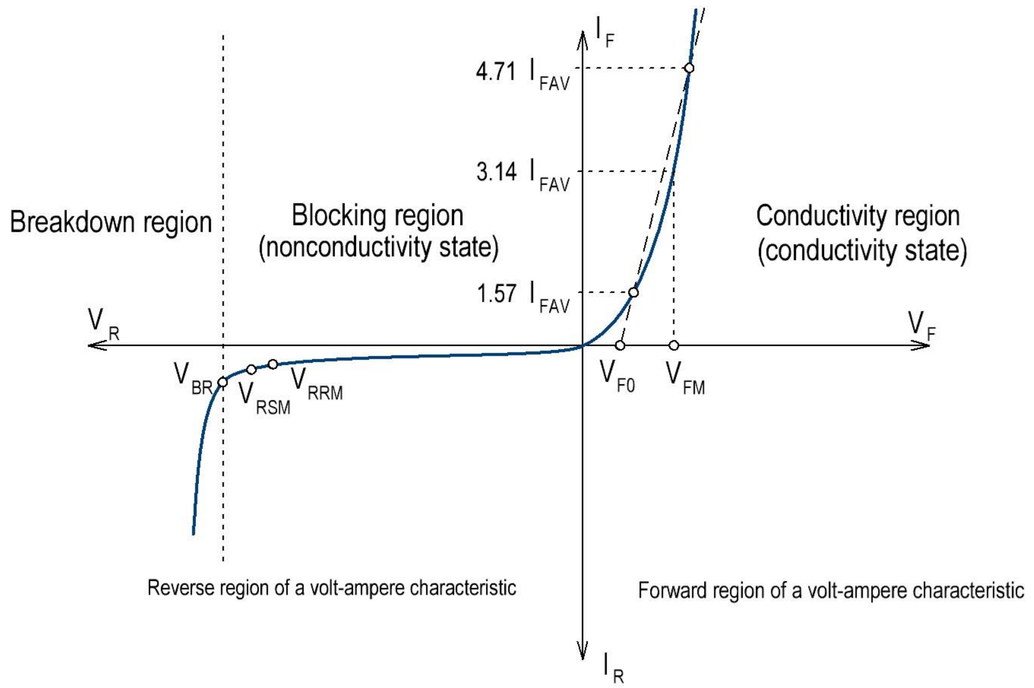


Figure 4. Typical current-voltage curve of a diode.

2.3.1 Non-conducting State

The main parameters of a diode in the non-conducting state are:

V_{RRM}, Repetitive Peak Reverse Voltage [V] is the highest instant voltage that can be applied to the diode in the reverse direction, including all repetitive voltages. V_{RRM} divided by 100 is the device's voltage class. V_{RRM} is the main criterion of the maximum allowed operating mode in the non-conducting state: peak values of the reverse voltage during operation of the diode in normal operating modes should not exceed this value.

V_{RSM}, Non-repetitive Peak Reverse Voltage [V] is the maximum allowed non-repetitive peak reverse voltage that can be applied to a diode. V_{RSM} is always greater than V_{RRM}.

V_{BR}, Breakdown Voltage [V] is the voltage at which the avalanche breakdown of the diode semiconductor structure begins.

$V_{BR} \geq V_{RSM}$, therefore V_{BR} is not a parameter applicable to operating conditions of regular diodes. The V_{BR} value is determined by testing and serves as one of the reference points used to assign a reverse voltage class to the diode (i.e. to determine the V_{RRM}) after adding a certain technological margin. The exception is avalanche diodes that allow short-term operation in the avalanche breakdown mode. Datasheets for such diodes indicate V_{BR} as the minimal value of this parameter for a particular type of diode at certain values of junction temperature and reverse current.

I_{RRM}, Repetitive Peak Reverse Current [mA] is the maximum instant value of the reverse current when a reverse voltage pulse with an amplitude equal to V_{RRM} is applied to the diode. The actual I_{RRM} values on the devices are usually measured by the manufacturer at the maximal allowed temperature of the diode junction during the acceptance tests.

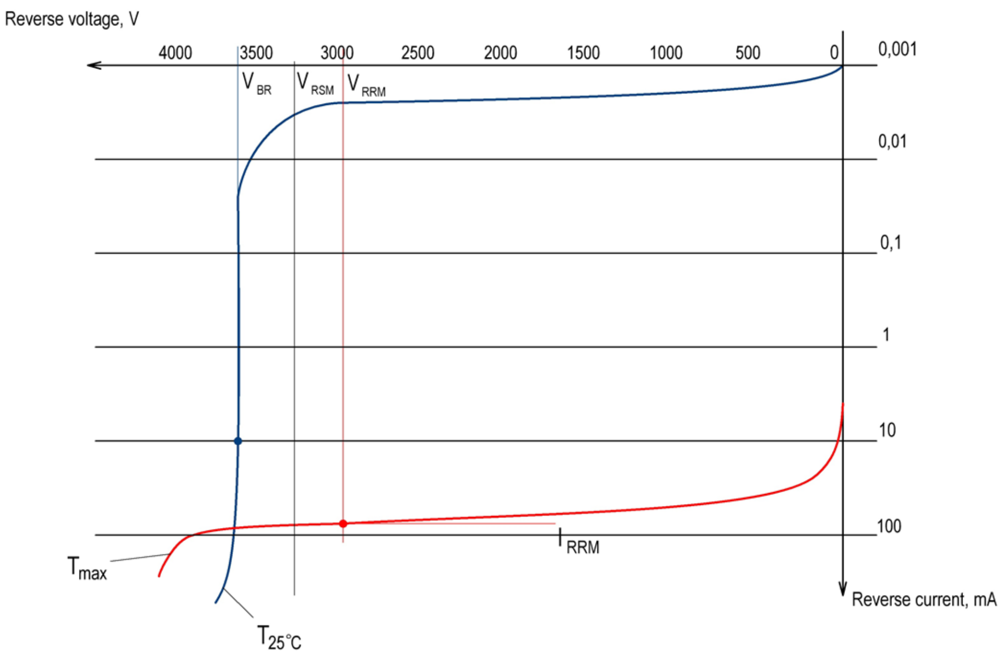


Figure 5. Typical current-voltage curve in logarithm scale.

Temperature changes in the reverse current-voltage dependence (I-V curve) of a diode are shown in Figure 5. The most common silicon-based power diodes have the following trends:

- Strong increase of the reverse current at higher temperature. The reverse current of silicon power diodes is less than 0.1 mA at the room temperature, while at the maximum operating temperature (125-190°C for various types of devices) the range varies from single digits to 200-300 mA. The current grows approximately exponentially along with the temperature increase, doubling every 7-10°C.
- The tendency for V_{BR} to increase at higher temperature. For typical silicon diodes, V_{BR} changes by 10-15% with a temperature change of 100°C.

2.3.2 Conducting State

PROTON-ELECTROTEX JSC follows the standards of measuring parameters in conducting state as shown in Figure 6.

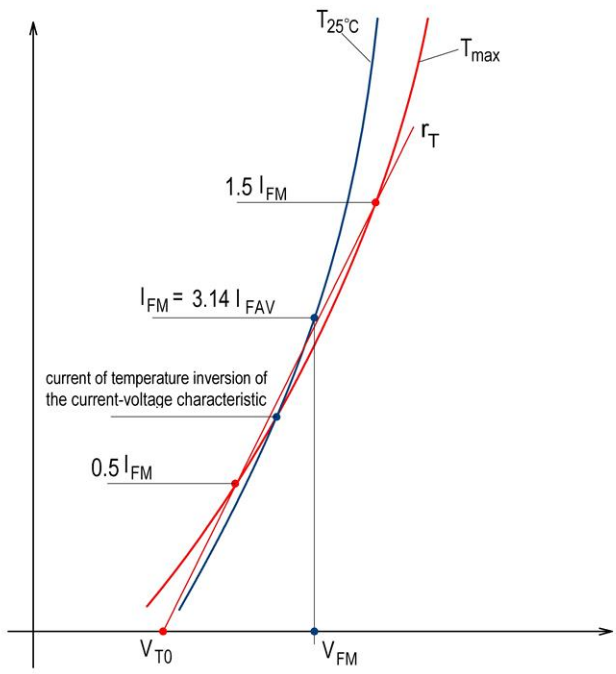


Figure 6. Typical forward current-voltage curve of a power diode.

The primary parameters of a diode in conducting state are:

I_{FAV}, Average Forward Current [A] is the average value of rectified pulsing current over a time period. I_{FAV} is assumed to be the maximum allowed average value of the forward current flowing through the diode for continuous time. Usually the I_{FAV} values are provided for rectified sine current, where the peak value of the current I_{FM} = 3.14 * I_{FAV} corresponds to the peak forward voltage (V_{FM}), i.e. the instantaneous value of the forward voltage.

I_{FRMS}, RMS Forward Current [A] is the maximum allowed RMS value of a diode's rectified pulsing current at the specified pulse shape and cooling conditions.

V_{FM}, Peak Forward Voltage [V] is the maximum instant value of forward voltage at specified peak forward current and junction temperature.

Elements of a piecewise linear approximation of the I-V curve (threshold voltage **$V_{F(T0)}$** and dynamic resistance **rT**) are introduced for the convenience of calculating losses in the conducting state. The meaning of these parameters is clarified in Figure 6. To determine them, a line is drawn through the I-V curve points corresponding to the current values of 0.5*I_{FAV} and 1.5*I_{FAV}. The slope of this line corresponds to r_T, and the segment cut off on the voltage axis is $V_{F(T0)}$.

Having the elements of the piecewise linear approximation of the I-V curve (**V_{T0}** and **r_T**), it is possible to calculate the power loss of the diode at the selected value of the forward current:

$$P = V_{T0} * I_{FAV} + r_T * I_{FRMS}^2$$

Datasheets provided by PROTON-ELECTROTEX JSC include a more precise approximation of the I-V straight:

$$V_{FM} = A + B * I_{FM} + C * \ln(I_{FM} + 1) + D\sqrt{I_{FM}}$$

where A, B, C, D are constants.

Using this approximation makes it possible to calculate the power dissipation more precisely, but requires to use numerical methods.

Influence of temperature on the forward I–V curve of silicon-based power diodes is shown Figure 6. The nature of the change in the forward voltage depends on the current: if it is less than the so-called temperature inversion current of the I-V curve then the voltage decreases along with increasing temperature, if it is higher, it increases.

It is desirable to select such modes of diode operation that the range of operating currents mostly lies above the temperature inversion current of the I-V curve. Power diodes, as a rule, have a large area of semiconductor chip; therefore, an uneven distribution of current density over the chip area may occur at current densities below the temperature inversion point that may lead to local overheating.

The I_{FAV} and I_{FRMS} values can be calculated in a similar way to the I_{TAV} and I_{TRMS} values for thyristors (Section 3.3.3). The shape factor (kF) for a diode will always be 1.41 for a rectangular current waveform and 1.57 for a sinusoidal current waveform.

2.3.3 Transition State

The process of a diode's transition from conducting state when forward voltage is applied to non-conducting state when reverse voltage is applied is called reverse recovery.

Figure 7 illustrates the current and voltage at the diode during the process of its reverse recovery when operating on an active-inductive load. If the diode recovers with an active-inductive load which is typical for the main applications of power devices, the value of its negative current increases linearly, reaches a certain value of I_{rrM} depending on its design, and then drops to zero. In accordance with the standard GOST 24461-80 the main parameters of reverse recovery for diodes made by PROTON-ELECTROTEX JSC are measured as follows: at the drop of the reverse recovery current, a chord is drawn from $0.9*I_{rrM}$ to $0.25*I_{rrM}$. The time interval between the current crossing the 0 value and the point where the chord crosses the time axis determines the reverse recovery time t_{rr}.

The V_{rrM} value corresponds to the maximum value of surge voltage during diode switching.

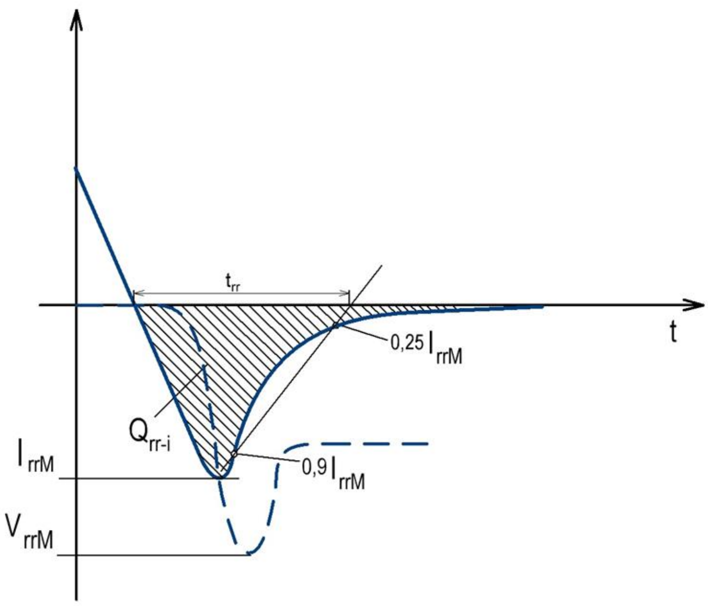


Figure 7. Reverse recovery of a diode with p-n junction.

The main parameters of diode reverse recovery are:

I_{rrM}, Reverse Recovery Current [A] is the maximum reverse current conducted by the diode during reverse recovery (Figure 7).

V_{rrM}, Reverse Recovery Voltage [V] is the maximum reverse voltage during the reverse recovery of the diode.

t_{rr}, Reverse recovery time [µs] is the duration of the transient recovery process, i.e. the period when the reverse current flowing through the device is significantly higher than the reverse leakage current.

Q_{rr}, Reverse Recovery Charge [µC]

Usually the following formula is used to estimate the value of Q_{rr}:

$$Q_{rr} = \frac{I_{rrM} * t_{rr}}{2}$$

i.e. the reverse recovery current is approximately triangle-shaped.

The Q_{rr} value depends on the amount of excess electron-hole pairs accumulated in the semiconductor structure of the diode when the forward current is applied and conditions of reverse recovery – the rate of fall of the forward current, and reverse voltage of the source.

A more accurate estimate is achieved by the numerical integration of the reverse recovery current epure; in this case, index “i” is usually added to the designation of the reverse recovery charge:

$$Q_{rr-i} = -\int_{t_0}^{t_i} idt$$

Where:

t_0 – moment when the anode current passes zero value,
t_i – moment when integrating ends.

Typically, t_i is chosen as the moment when the reverse current reaches a certain low value, for example, 2% of the I_{rrM} value.

The Q_{rr} value depends on the amount of excess electron-hole pairs accumulated in the diode’s semiconductor structure when forward current is applied, as well as on the reverse recovery conditions – the rate of fall of forward current, and reverse voltage of the source.

"Removal" of the excess electron-hole pairs during reverse recovery depends on two processes: their outflow from the semiconductor structure that causes a reverse current pulse, and recombination in the semiconductor structure that does not cause any "external" current. The recombination rate is characterized by the lifetime of charge carriers (τ) – the average lifetime of an excess electron or hole in the semiconductor structure before the recombination event.

The entire process of reverse recovery from the beginning of the forward current fall to the end of the reverse current fall becomes very short – less than τ – at high values of the current decay rate. Therefore, recombination has little effect on the decrease in the number of excess electron-hole pairs, the removed charge of which (Q_{rr}) depends only on the amount initially accumulated during the flow of the forward current.

However contribution of recombination becomes significant at low values of the current fall rate, when the time interval from the beginning of the decay of the forward current to its transition through zero value exceeds 3τ. In this case, the device “forgets” the initial value of the forward current before the recovery process – Q_{rr} at low di/dt of the fall barely depends on the value of the forward current.

Thus, Q_{rr} highly depends on the forward current and weakly depends on di/dt at high value of falloff di/dt, while the opposite is true at low fall-off di/dt.

Q_{rr} increases as the reverse voltage grows higher, which is explained by expansion of the space charge region of the reverse biased p-n junction and an increase in the number of electrons and holes removed from the semiconductor structure. The total number of removed charge carriers, however, cannot be higher than the number of electron-hole pairs remaining in the structure when the current crosses zero value; therefore the Q_{rr} (V_R) dependence also aims for saturation with increasing V_R.

E_{RQ}, Reverse Recovery Energy [J] – this parameter is not listed in datasheets by PROTON-ELECTROTEX JSC, but it must be mentioned in these notes. E_{RQ} is the time integral of the power loss (product of anode current and voltage) in the transient process of reverse recovery. The value of the reverse recovery energy is very important when the diode operates at increased frequency. Experience shows that even at several kHz the fraction of the total power lost at the diode due to reverse recovery can become comparable or even exceed the loss power dissipated in the conducting state. The reverse recovery energy and the reverse recovery charge of the diode are related. If reverse recovery occurs in a circuit with a fully inductive load, the diode is not protected by RC circuits that damp the voltage surges and changes in the source voltage during t_{rr} can be neglected, then the following formula is valid:

$$E_{RQ} = Q_{rr-i} * V_R$$

where V_R is the source voltage.

2.4 Types of Power Diodes manufactured by PROTON-ELECTROTEX JSC

PROTON-ELECTROTEX JSC produces the following types of power diodes:

- Power rectifying diodes (**D**)
- Fast recovery diodes (**DF**)
- Avalanche diodes (**DA**)
- Fast recovery avalanche diodes (**DFA**)
- Welding diodes (**D0**)

Power rectifying diode is a diode designed for operation in rectifying units operating at relatively low frequencies (usually at an industrial frequency of 50 or 60 Hz, sometimes at frequencies up to 500 Hz). The main focus for these devices is minimizing the power loss in conducting state while providing the needed reverse voltage. The Q_{rr} and E_{RQ} values for such diodes can be quite high, preventing use at increased frequency and in pulse-frequency modes.

A **fast-recovery diode** is a device with reduced t_{rr}, Q_{rr}, E_{RQ} values designed to operate at higher frequencies or in pulse-frequency modes.

An **avalanche diode** is a diode that can operate in avalanche breakdown mode. Typically this device is characterized by the value of breakdown voltage V_{BR} that describes the minimum value of the start of avalanche breakdown, as well as the energy properties of the breakdown: the maximum permitted peak power dissipation (P_{RSM}) and/or the energy loss during avalanche breakdown.

Fast recovery avalanche diodes are avalanche diodes with reduced recovery time.

Welding diodes are diodes designed for use in industrial welding equipment. Welding equipment features rather low voltage at the diode, so alloyed semiconductor elements of minimum thickness are used there to ensure high power and high current density in welding diodes. Besides, the low thickness of the welding diodes housing ensures low thermal resistance R_{th}.

3 Power Thyristors

3.1 Definition

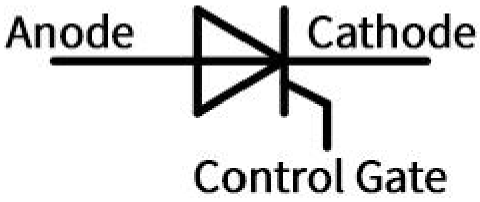


Figure 8. Symbolic designation of a thyristor.

Thyristor is a semiconductor switch with three electrodes (anode, cathode, control gate).

A thyristor can be characterized by three main states:

- closed state – the thyristor is in a state of low conductivity when forward voltage is applied (with a more positive potential at the anode);
- non-conducting state – the thyristor is in a state of low conductivity when reverse voltage is applied (with a more positive potential at the cathode);
- conducting state – the thyristor is in a state of high conductivity when forward voltage is applied (with a more positive potential at the anode) and conducts current in the anode-cathode circuit.

A thyristor is a semi-controlled switch. It can be in both a low-conductivity state and a high-conductivity state with forward voltage in the anode-cathode circuit. The thyristor switches on (transitions from a state of low conductivity to a state of high conductivity) when current flows in the gate-cathode circuit. If the thyristor starts conducting current in the anode-cathode circuit after switching on the gate current can be removed and the thyristor will remain in a state of high conductivity, i.e. the thyristor can be turned on by a short current pulse in the gate circuit.

A conventional power thyristor can only be turned on using the control circuit. To turn it off, one must stop the current in the anode-cathode circuit or reduce it below a certain value called the holding current. Then, after a certain period called the turn-off time, the thyristor will go from the conducting state to the closed state.

Unlike a diode, the semiconductor structure of a thyristor has four layers with different types of conductivity: n-emitter, p-base, n-base, p-emitter. These layers are separated by three p-n junctions:

- cathode emitter p-n junction between n-emitter and p-base
- anode emitter p-n junction between p-emitter and n-base
- collector p-n junction between p- and n-bases

The cross section of the semiconductor structure is shown in Figure 9.

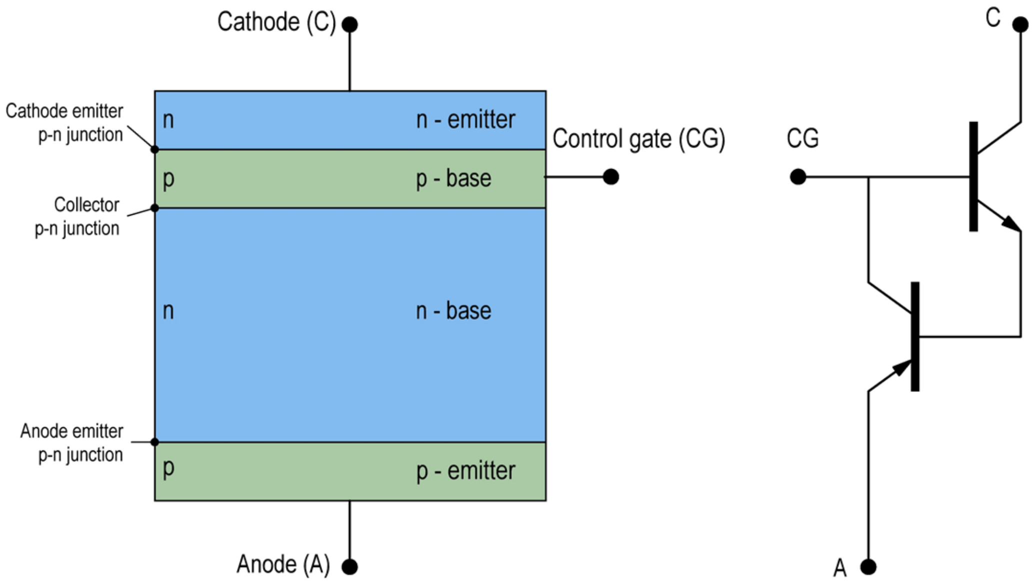


Figure 9. Cross-section of a thyristor's semiconductor structure and its circuit diagram.

Due to the physics of this semiconductor structure, application of a more positive potential to the anode than the cathode causes a volt-ampere curve with a section of negative differential resistance (Figure 10). This negative section of the I-V curve can be explained as follows. A four-layer thyristor structure (Figure 9) can be represented as two functionally combined three-layer transistor structures n-p-n and p-n-p, and since the collector p-n junction is common for both of these transistor "components" the collector of each of them is connected to the base of the other. Since transistors have amplifying properties, this layout creates positive current feedback, resulting in a I-V section with a negative differential resistance.

When forward voltage is applied to the thyristor (positive bias at the anode), the total anode-cathode voltage is applied mainly to the collector p-n junction since the emitter junctions are forward-biased. The section with negative resistance appears only when the sum of the differential current gains (in a circuit with a common base) of the "component" transistors is greater than one. The gains coefficients of the transistors are not constant, and they increase at higher current in the range of the collector current from zero to a certain value. At the initial section of the I-V curve (Figure 10) the sum of the gains at low total collector current is less than 1, therefore the I-V curve has positive differential resistance. As the collector current increases (in the absence of gate current, due to an increase in the leakage current of the reverse-biased collector p-n junction with increasing voltage), the sum of these coefficients increases and at a certain voltage value (switching voltage) becomes equal to 1, and the differential resistance of the I-V curve is equal to zero.

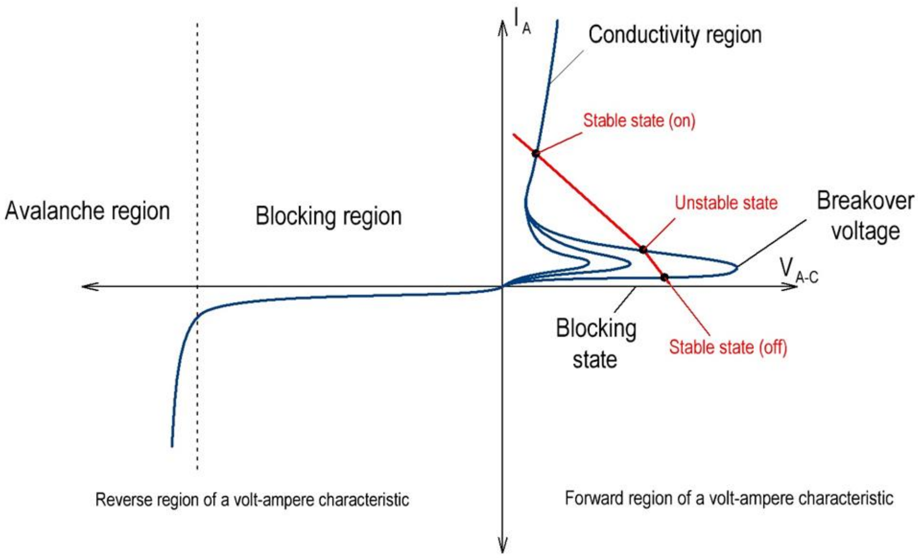


Figure 10. Typical current-voltage curve of a thyristor.

Usually a thyristor operates on a load with equivalent resistance less than the absolute value of the negative resistance of its current-voltage curve. For this reason there is an “abrupt” change in the current and voltage of the thyristor after reaching the switching voltage: it switches from a “stable” state with relatively low current and relatively high voltage (off state) to another “stable” state with relatively low voltage and relatively high current (on state). In this case, the "component" transistors reach saturation, that is, the collector p-n junction becomes forward-biased (like the emitter ones).

Positive gate current that causes an increase in the collector current of the corresponding "component" transistor leads to a decrease in switching voltage. At a certain value of the gate current (the so-called gate current of the I-V curve "rectification") the negative section of the I-V curve does not appear at all, i.e. the thyristor stays in the on-state at any values of the positive anode voltage.

When reverse voltage is applied to the thyristor (the bias at the anode is negative), the emitter p-n junctions get locked, while the collector junction has forward bias: both "component" transistors operate in the "inverse" mode. In this case there is no positive current feedback; therefore, the reverse branch of the I-V curve is generally similar to that of a diode. However, the leakage current of the reverse biased emitter p-n junctions will be amplified by the "component" transistors, in the inverse state too.

Thus, a thyristor can be described by two static states – “off” and “on”, and two dynamic processes – transition “from off to on” and “from on to off”. Physical processes that determine the properties of a power thyristor in static states are in many ways similar to those of a power diode. Dynamic processes in the thyristor have a number of special features that require to introduce a number of additional elements into the semiconductor structure of the thyristor.

3.2 Design

Cross-section of a semiconductor structure and its topology for a typical power thyristor are shown in Figure 11 и Figure 12. It is based on a four-layer structure similar to that shown на Figure 9. The least doped (high-resistance) layer in a modern power thyristor is the n-base. Space charge regions (SCR) of high-voltage collector and anode p-n junctions expand into this n-base layer when forward and reverse voltages are applied in the off state (blocking voltages). The gate electrode is usually connected to the p-base and is located on the cathode side of the semiconductor structure. To achieve this, an n+ emitter layer is not formed on a part of the cathode surface. These p-type regions emerging onto the surface are called p-control regions. Design of a thyristor has the following important additional elements:

Cathode emitter shunting. The shunt elements are made as local p-type regions that come out to the cathode surface and have common metallization with the n+ emitter. Shunts are introduced to ensure a decrease in the gain of the n-p-n "component" transistor, which is necessary to ensure high thyristor switching voltage (especially at the maximum operating temperature), as well as to increase noise immunity and improve some dynamic characteristics.

Branched control electrode. Initially the gate current turns a thyristor on only in a relatively narrow (100-500 μm wide) region topologically adjacent to the edge of the control p-region and the control electrode. It is caused by the finite value of the "lateral" propagation of the gate current in the semiconductor structure. Then the on-state spreads over the entire area of the thyristor structure with a certain finite speed that depends on parameters of the structure layers, shunting, as well as amplitude and rate of rise of the switched anode current pulse and no longer depends on the gate current. The speed of propagation of the on-state can be from several microns to several hundred microns per microsecond.

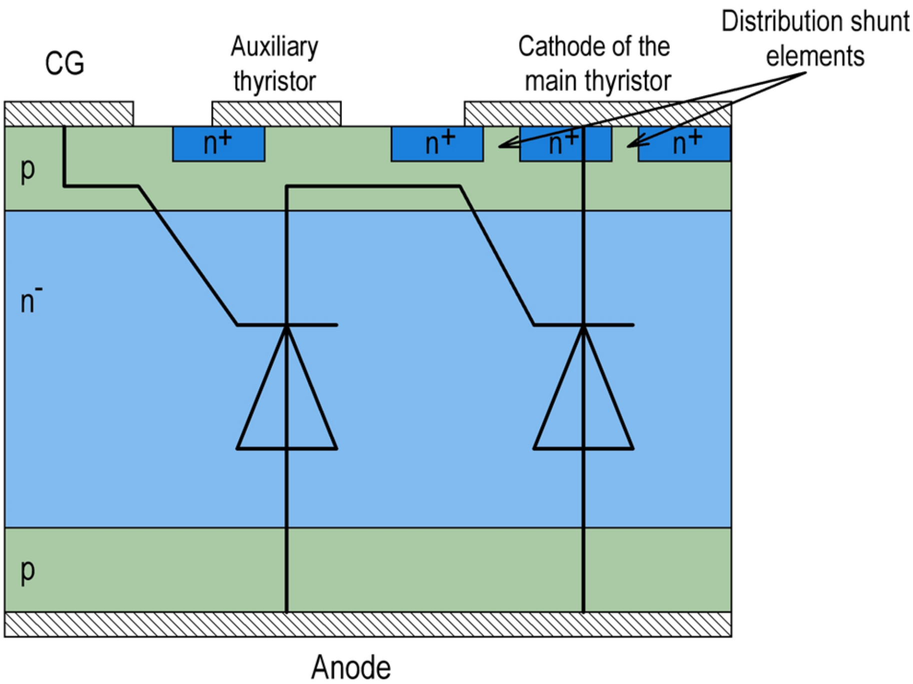


Figure 11. Cross-section of a thyristor's semiconductor structure.

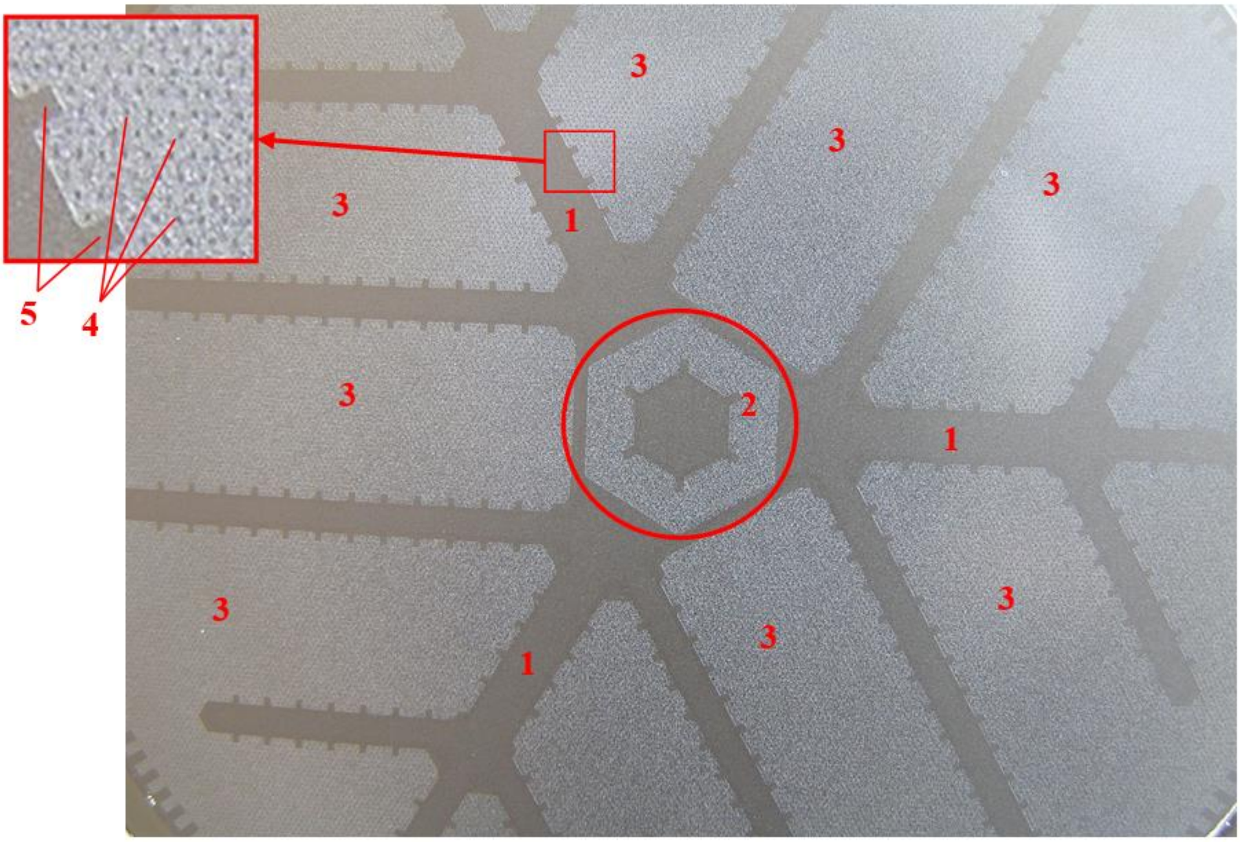


Figure 12. Topology of a semiconductor structure of a modern thyristor (with removed cathode metallization): 1. - branched p-gate region, 2 - auxiliary thyristor, 3 - cathode region of the main thyristor, 4 - p-region of distributed shunt elements, 5 - p-region of edge shunt elements of a branched gate electrode.

Since the area of semiconductor structure can be very large (up to several hundred square centimeters), it can be problematic to turn on the entire area of the thyristor in acceptably short time. This problem is solved by a branched gate electrode with a topology (plan view) selected to reduce the time of the on-state propagation over the entire area to a reasonable value. So-called "edge" shunting elements are often placed along the perimeter of the branched gate area to perform a role similar to that discussed above for distributed shunting, and also contribute to a more uniform distribution of the gate current along the perimeter of the branched area that can reach tens and even hundreds of centimeters.

Auxiliary (amplifying) thyristor. Having the branched gate electrode in the semiconductor structure requires to increase the drive current. Typical gate current required to turn on the thyristor structure evenly along the entire length of the perimeter of the control electrode is about 1 A per 1 cm of the length of the gate electrode perimeter. Thus, to turn on a thyristor with a branched gate electrode, it may be necessary to control current pulses with an amplitude of tens or even hundreds of amperes, which greatly complicates the control unit of the device. To avoid this, an additional auxiliary thyristor structure is introduced. This auxiliary thyristor is integrated into the common four-layer structure (Figure 11) and has a common anode with the main thyristor but independent gate, and its cathode is connected to the metallization of the branched gate of the main thyristor. The total cathode area and the perimeter of the gate electrode of the auxiliary thyristor are significantly smaller than those of the main thyristor. The “external” terminal of the control electrode of the entire thyristor is connected to the metallization of the gate electrode of the auxiliary thyristor, so this element gets turned on first and high gate current is not required. The anode current of the switched-on auxiliary thyristor is supplied to the branched control electrode of the main thyristor and leads to the switching on of the main structure. Since the current flowing through the auxiliary thyristor also passes through the p-n junction "branched gate electrode – cathode of the main thyristor", the flow of this current is accompanied by a voltage drop greater than when current flows through the main thyristor. Therefore, some time after turning on the main thyristor the auxiliary structure is usually turned off.

The **region of the semiconductor element's periphery**. Profiling of the edge bevel is often used to prevent surface breakdown of high-voltage p-n-junctions of a thyristor in a similar manner to power diodes. Since the thyristor has two high voltage p-n junctions, the bevel profile is more complex than that of a diode (Figure 13). Direct and reverse bevels are distinguished in semiconductor structures with asymmetric p-n junctions depending on whether the smaller part has greater or lower dopant concentration, respectively. The bevel is straight for the collector p-n junction of the structure shown in Figure 13, and reverse for the anode one. Effective protection against surface breakdown for straight and reverse bevels is achieved at different values of the angle α: for a straight bevel this angle should be as small as possible, while for a reverse bevel values less than 40-50° are enough. Therefore, in order to minimize the size of the peripheral area, the bevel for thyristor structures usually has two steps: the angle α_1 is 20-40°, and the angle α_2 is 1-3°.

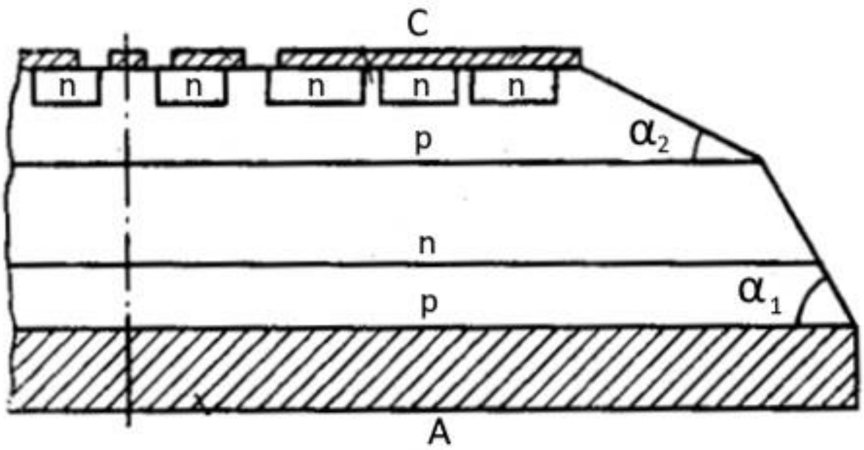


Figure 13. Typical profile of a power thyristor's semiconductor element.

3.3 Primary Electrical Parameters and Properties of Thyristors

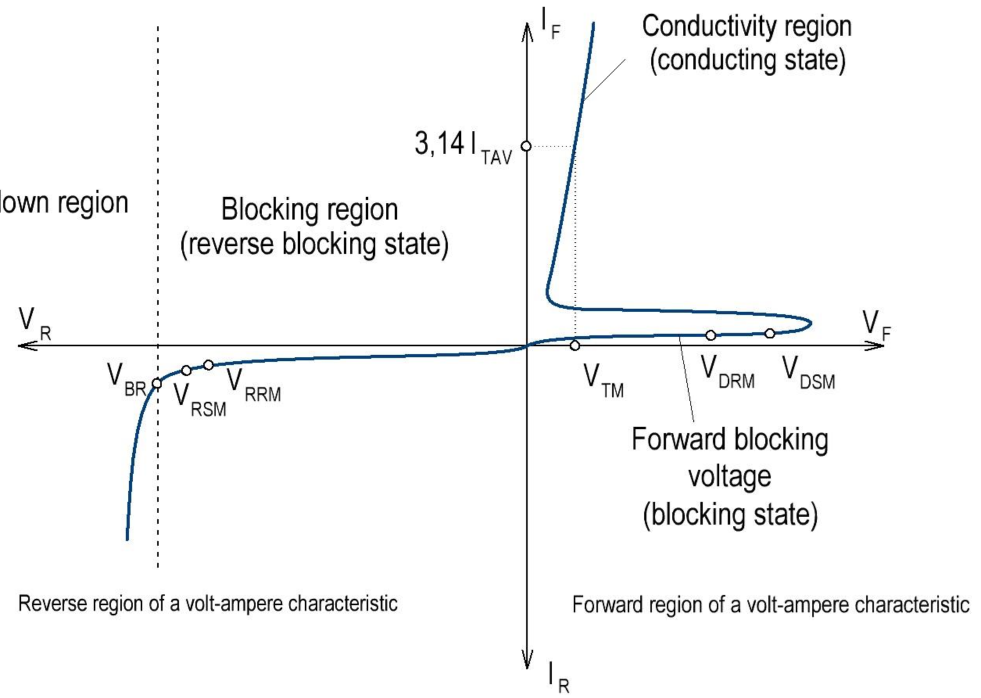


Figure 14. Voltage-current curve of a thyristor.

3.3.1 Closed State

Modern thyristors are designed to make their I-V curve in closed state similar to I-V curve of a reverse-biased collector p-n junction: shunting of the cathode emitter and life time of charge carriers are selected so that current amplification ratio of “component” transistors at typical leak current density was low. Switching without applying gate current in this case is only possible with avalanche breakdown of the collector p-n junction at a current significantly higher than the allowed leak current, and usually causes a failure of the device.

Thus, the "operating" section of a thyristor’s I-V curve in the closed state in its general appearance, characteristic sections, relation to temperature changes etc., is similar to the reverse I-V curve of a diode, reviewed in section 2.3 on *page 6*.

An important property of the closed state of a thyristor describing its noise immunity is its resistance to a rapid rise in the anode voltage (dv/dt resistance).

As a rule, forward anode voltage applied to a closed thyristor is not constant and can have sharp surges. At the same time a current pulse passes through it due to overcharging of the barrier capacitance of the collector p-n junction that can have an amplitude much greater than the leakage current. If the anode voltage increases during the surge, this current has a "forward" direction and can lead to "abnormal" switching of the thyristor.

The main method to remove this negative effect is to reduce the effective shunting resistance of the cathode emitter. Exploring the physics of thyristor switching at short impulses showed that it can be described by so-called "critical charge" (Q_{crit}). If the current pulse through the collector p-n junction under any action is very short (in the limit it has the form of a δ-function), then to turn on the thyristor the integral of this current over time must be greater than a certain value called critical charge. In this case, the value of Q_{crit} is approximately inversely proportional to the effective cathode shunting resistance, making it possible to achieve the dv/dt resistance values required for an acceptable noise immunity.

The main properties of a thyristor in the closed state are:

V_{DSM}, non-repetitive off-state surge voltage [V] is the highest instantaneous value of any non-repetitive off-state transient voltage.

V_{DRM}, repetitive off-state voltage [V] is the highest instantaneous off-state voltage applied to the thyristor, including any repetitive transient voltages.

I_{DRM}, repetitive off-state Impulse current [mA] is the off-state impulse current caused by repetitive off-state impulse voltage.

$(dv_D/dt)_{crit}$, critical rate of rise of off-state voltage [V/μs] – this parameter indicates the maximum allowed rate of rise of the off-state voltage when an exponential voltage is applied to the switched-off thyristor. The dv/dt_{crit} value is determined in accordance with Figure 15.

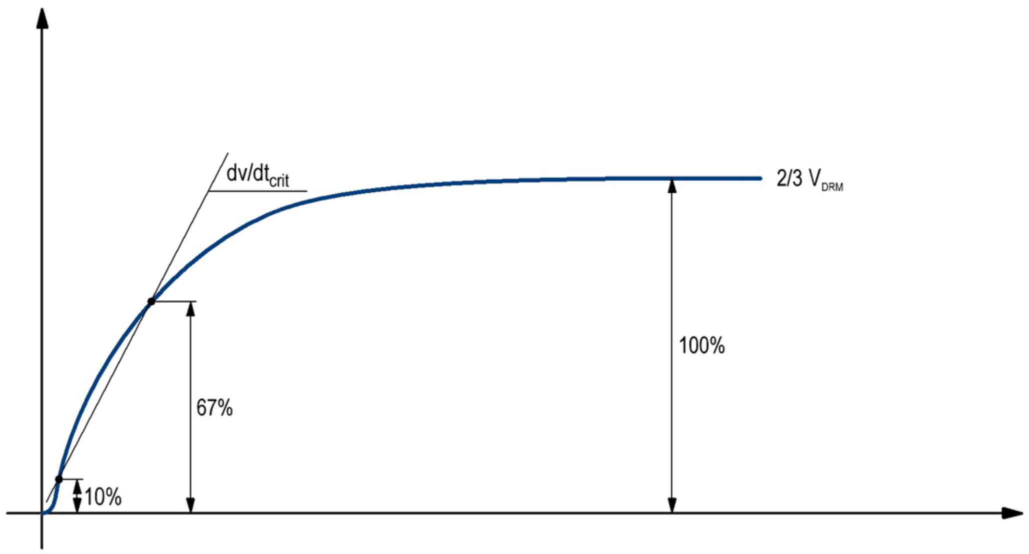


Figure 15. Determining dv/dt

3.3.2 Reverse Non-conducting State

The I–V curve of a thyristor in the reverse state is close to the I–V curve of a reverse-biased high-voltage emitter p-n junction (anode emitter p-n junction) for the same reasons as described above for the forward I–V characteristic in the closed state.

The main parameters and properties of a thyristor in the reverse non-conducting state are:

V_{RSM}, Non-Repetitive Pulse Reverse Voltage [V] is the highest instantaneous value of the non-repetitive transient reverse voltage applied to the thyristor.

V_{RRM}, Repetitive Pulse Reverse Voltage [V] is the highest instantaneous value of the reverse voltage, including only repetitive transient voltages.

I_{RRM}, Repetitive Pulse Reverse Current [mA] is the thyristor's reverse current caused by a repetitive pulse reverse voltage.

$V_{(BR)}$, Reverse Breakdown Voltage [V] is the thyristor's reverse voltage, at which an avalanche breakdown of the thyristor semiconductor structure begins.

3.3.3 Open State

Typical "operating" density of a thyristor's anode current is 100-300 A/cm^2. The n-base and most of the p-base of the thyristor are "flooded" with excess electron-hole pairs at such current densities (i.e., the concentration of excess electrons and holes there is much higher than the concentration of equilibrium ones).

This is why the I–V curve of an open thyristor in the range of "operating" currents in its general form and response to temperature changes is similar to the I–V curve of a diode considered above. The elements of the piecewise-linear approximation of the I-V curve and the values of the maximum permissible average and effective currents are determined in a similar way.

An important parameter that describes operation of a thyristor at low anode currents is its holding current. If you reduce the anode current of a switched-on thyristor (without applying current to the gate circuit), then the equilibrium state point will "descend" along the I-V curve (Figure 10) to the lowest possible equilibrium state, and then abruptly jump (through the range of unstable states) to a new equilibrium state, this time corresponding to a turned-off thyristor. The minimum anode current that allows to keep the thyristor switched on without current in the gate circuit is called holding current. As the anode current approaches the holding current value, the switched-on state contracts into a narrow "cord" up to a hundred microns wide. Location of this cord is not fixed by any prominent points of the structure, but is instead determined by the "weakest" point with the lowest anode current density at which the thyristor can still maintain the on-state due to uncontrolled technological deviations. Any further decrease in the current leads to turning off (interruption of the current) precisely in this cord.

A decrease in the anode current below a certain limit in a power thyristor with a significant cathode area leads to a decrease in the area of the structure in the on-state, i.e. it is a process opposite to the propagation of the on-state when the device is turned on.

The main parameters and properties of a thyristor in the open state are:

I_{TAV}, average on-state current [A] is the highest allowed period-average on-state current at the specified pulse shape and cooling conditions.

I_{TRMS}, RMS on-state current [A] is the highest allowed RMS on-state current at specified pulse shape and cooling conditions.

V_{TM}, impulse voltage in the open state [V] is the highest instantaneous value of the voltage in the open state due to the impulse current of a given value.

I_H, holding current [mA] is the lowest anode current required to keep the thyristor open.

Properties of I-V curve piecewise linear approximation ($V_{T(T0)}$ and r_T) are introduced for thyristors in a similar fashion to diodes.

$V_{T(T0)}$, threshold voltage [V] is the voltage value determined by the point of intersection of the line of straight-line approximation of the I-V curve of the open state with the voltage axis.

r_T, dynamic resistance in the open state [mOhm] is the resistance determined by the slope of the straight line approximating the I-V curve in the open state.

I_{TAV} and I_{TRMS} values can be calculated based on housing temperature and current waveform.

The allowed housing temperature is set to a certain value based on the cooling conditions. Values of the currents I_{TAV} and I_{TRMS} in this case correspond to maximum values of the sinusoidal current measured for one half-wave at which the junction temperature reaches the maximum allowed value. These data indicate the approximate value of operating current used by a customer to select the device. They are mainly used to compare various types of products according to their on-state properties. Please bear in mind when comparing devices that their housing temperature can vary depending on their application, heavily affecting their current ratings.

The customer can independently calculate the current I_{TAVM} depending on the required temperature or conduction angle using the following formula:

$$I_{TAVM} = \frac{\sqrt{V_{T(T0)}^2 + 4 * k_F^2 * r_T \dfrac{T_{jmax} - T_a}{R_{thjc}}} - V_{T(T0)}}{2 * k_F^2 * r_T}$$

where k_Φ is a shape factor that is used to calculate various current shapes. This coefficient for a sinusoidal current waveform can be calculated using formula:

$$k_F = \frac{\sqrt{\frac{(\frac{\alpha}{2} - \frac{\sin(2\alpha)}{4}) * 1}{2\pi}}}{\frac{-1}{2\pi} *}$$

where α is angle of conductivity in radians.

For rectangular current, the shape factor is calculated as follows:

$$k_{FDC} = \sqrt{\frac{2\pi}{\alpha}}$$

The table below shows values of shape factor for various conduction angles for sinusoidal current and rectangular current.

Table 1. Current shape factor for various angles of conductivity.

α (grad)	30°C	60°C	90°C	120°C	180°C
k_F	3.98	2.78	2.22	1.88	1.57
$k_{F\ DC}$	3.46	2.45	2.00	1.73	1.41

The consumer can use the shape factor values from Table 1 for calculations. To calculate $k_ф$ for any other angles of conductivity, it is necessary to use the formulas described above.

I_{TRMS} is calculated from I_{TAVM} using the following formula for a sinusoidal current waveform:

$$I_{TRMS} = I_{TAVM}\frac{\pi}{2}$$

3.3.4 Gate Parameters

Gate circuit of a thyristor is usually described by three groups of properties:

1. Properties describing the minimum conditions sufficient to turn the thyristor on. These include direct current and gate voltage, i.e. the minimum value of the direct control current and the corresponding gate voltage required to turn on the thyristor (in the specified test modes).

2. Properties describing the maximum allowed amplitude of the gate current pulses, corresponding gate voltage and pulse power losses in the control circuit that do not cause damage to the thyristor structure. Values of the maximum impulse current and voltage are also useful for selection or development of a gate circuit (driver), since they provide information on the required open circuit voltage and short-circuit current at the output of this circuit.

3. Properties of noise immunity along the gate circuit: the maximum allowed values of the amplitude of the current and control voltage pulses that do not turn the thyristor on.

The main parameters and properties of a thyristor's gate circuit include:

I_{GT}, **Gate Trigger Direct Current [mA]** is the lowest DC gate current required to turn on the thyristor.

V_{GT}, **Gate Trigger Direct Voltage [V]** is the constant gate voltage corresponding to the gate trigger direct current.

I_{FGM}, **Maximum Forward Gate Current [A]** is the maximum forward current for the thyristor's gate circuit. The value of I_{FGM} is limited by the power loss in gate circuit P_G.

V_{FGM}, **Maximum Forward Control Voltage [V]** is the maximum forward voltage allowed for the thyristor gate circuit that corresponds to the maximum forward control current of I_{FGM}.

I_{GD}, **Non-triggering Direct Gate Current [mA]** is the highest DC gate current that will not trigger the thyristor.

V_{GD}, **Non-trigger Direct Gate Voltage [V]** is the highest constant control voltage corresponding to the I_{GD} current, which does not cause the thyristor to turn on.

3.3.5 Turning the Thyristor On

The dynamics of transition from the off-to-on state is described by the thyristor's turn-on time counted from the beginning of the gate current pulse till the anode current reaching a certain value (or till the moment when the anode voltage drops to a specified low value). In this case, the turn-on time is usually divided into two phases: the turn-on delay time and the rise time.

There are no big changes in the anode current and voltage during the delay time. If the gate current has a sharp leading edge (i.e. the gate action on the thyristor can be considered pulsed) then the delay time is approximately equal to the time when the charge of excess electron-hole pairs equal to Q_{crit} accumulates in the lightly doped layers of structure, plus the time of electrons and holes travel through heavily doped layers.

During the rise time the thyristor transitions to the on-state, thus the thyristor becomes "closed". As a rule power thyristors are used in circuits with an active-inductive load, where the current rise time after the thyristor switch "closes" is determined by the load inductance. Therefore, the end point of the thyristor turn-on process is usually defined not by the moment when the anode current rises to a specified value, but by the moment when the anode voltage across the thyristor falls to a specified value that is much lower than the source voltage, i.e. the moment when the thyristor switch can be conventionally considered "closed".

It should be noted that the "end" moment of the turning on usually is not the same as "physical" turning on over the entire area of the thyristor. The on-state propagation process is longer and can take up to several milliseconds, while the thyristor turn-on time measured as described above takes only a few microseconds.

The concept of di/dt resistance is used to describe the limitations imposed by the finite speed of propagation of the on-state in a thyristor. The current density conducted by the thyristor structure in the process of "physical" switching on depends on two factors: the rate of rise of the anode current that is determined by the external circuit, and the propagation rate of the switched-on state that is determined mainly by the design and technological parameters of the thyristor structure. If the rate of rise of the anode current increases and reaches a certain value, a local increase in the current density in the conducting sections of the structure will cause power losses and overheating. If they reach and exceed a critical value the thyristor will fail. Such rate of rise of the anode current is called critical – $(di/dt)_{crit}$. A thyristor may not operate in modes where an increase in current with a rate higher than $(di/dt)_{crit}$ can occur when the thyristor is turned on.

The $(di/dt)_{crit}$ limit is only relevant in the transient process of switching the thyristor on. If the process of on-state propagation has already ended and the structure is switched on over its entire area, a rapid rise in the anode current is safe even if its rate exceeds $(di/dt)_{crit}$.

If the anode current first decreases to a value close to the holding current and then rises sharply without supplying current to the gate circuit, it can result in a thyristor failure even with the anode current rising slower than $(di/dt)_{crit}$. The reason is that the switched-on area of the thyristor at the initial current decrease is pulled together into a "cord", the area of which can be much smaller than the area of the initial switch-on at the "regular" switch-on by the control current pulse.

If a thyristor is turned on with a rate of rise of the anode current lower than $(di/dt)_{crit}$, operation of the thyristor is still possible, but please remember that until the structure of the thyristor is fully turned on across its entire area, the power of local losses in the turned on region will exceed the losses calculated from the “static” I-V curve for a fully turned-on thyristor. To take this factor into account, the “turn-on loss energy” parameter is used.

To increase $(di/dt)_{crit}$ and reduce the energy losses during turn-on to the required values, a branched gate electrode is used in the thyristor. Its longer perimeter allows to increase the initially turned-on area of the main thyristor structure and to reduce the on-state propagation time.

The main parameters and properties of the thyristor during switching on include:

I_L, turn-on current [mA] is the lowest forward thyristor current required to maintain the thyristor in the conducting state immediately after the end of the control current pulse when the thyristor turns on. If the forward current of the thyristor is less than the turn-on current when the control current pulse is removed it will drop to zero and the thyristor will switch to the closed state.

t_{gd}, turn-on delay time [µs] is the time interval between the beginning of the control current pulse and the moment when the main voltage drops to a given value close to the initial one (for example, 0.9 from the initial).

t_{gt}, turn-on time [µs] is the time interval needed to turn the thyristor on by a pulse of the gate current. This time interval is measured from the moment at the beginning of the control current pulse to the moment when the anode current rises to a given value.

$(diT/dt)_{crit}$, critical rate of rise of the on-state current [A/µs] is the highest value of the rate of rise of the current in the open state at which the thyristor can operate.

3.3.6 Turning the Thyristor Off

The dynamics of the transition from the on-state to the off-state is described by two physical processes: recovery of reverse and direct blocking capacities.

Recovery of the reverse blocking capacity (reverse recovery) of a thyristor is generally similar to the reverse recovery of a diode and is described by similar parameters. In case of a thyristor, the reverse recovery of its high-voltage emitter p-n junction (usually an anode p-emitter) is accompanied by expansion of its space charge region and partial removal of excess electrons and holes accumulated in the lightly doped layers. Since a thyristor conducting anode current of "operation" density has its base layers "flooded" with excess electron-hole pairs of n- and p- and has a similar state to a diode, the reverse voltage delay phase during its reverse recovery is very close in terms of the ongoing processes to that in the diode. A part of the p-base is freed from excess electron-hole pairs at the end of this phase. It creates an obstacle for the removal of electrons into the n+ emitter, and the forward-biased collector p-n junction begins to inject holes into the n-base. Due to this "transistor" effect there is a slight increase in current and reverse recovery charge in the thyristor as compared to a similar diode structure. However, this effect usually becomes significant only at the end of the reverse recovery current decay phase, leading to more notable reverse recovery tail current than in diodes.

This "transistor" phase of the reverse current flow persists after the reverse voltage across the thyristor reaches the source voltage. The removal of excess electrons from the n-base is greatly reduced, and the flow of excess holes leaving through the reverse-biased anode emitter p-n junction is compensated by the flow of holes injected by the forward-biased collector p-n junction. As a result, the number of excess electron-hole pairs in the n-base decreases mainly due to their recombination.

After the reverse blocking ability gets restored (reverse voltage is applied to the thyristor) a significant charge of excess electron-hole pairs is still stored in the n-base. If the polarity of the voltage applied to the thyristor changes, then the process of reverse recovery of the collector p-n junction will occur (since it will be under reverse bias). A pulse of recovery current in this p-n junction can lead to a repeated switching on of the thyristor structure, i.e. the direct blocking capacity has not yet been restored.

In order to prevent the thyristor structure from switching the reverse recovery charge of the collector p-n junction should be less than Q_{crit}. This charge is proportional to the charge of the excess electron-hole pairs at the moment of voltage polarity reversal. Since the charge of excess electron-hole pairs in the n-base gradually decreases due to recombination, at some point this condition will be satisfied. The shortest time interval between the moment the direction of the anode current changes during reverse recovery and the moment when the polarity of the anode voltage changes when the thyristor does not switch is called the turn-off time – t_q, Figure 16.

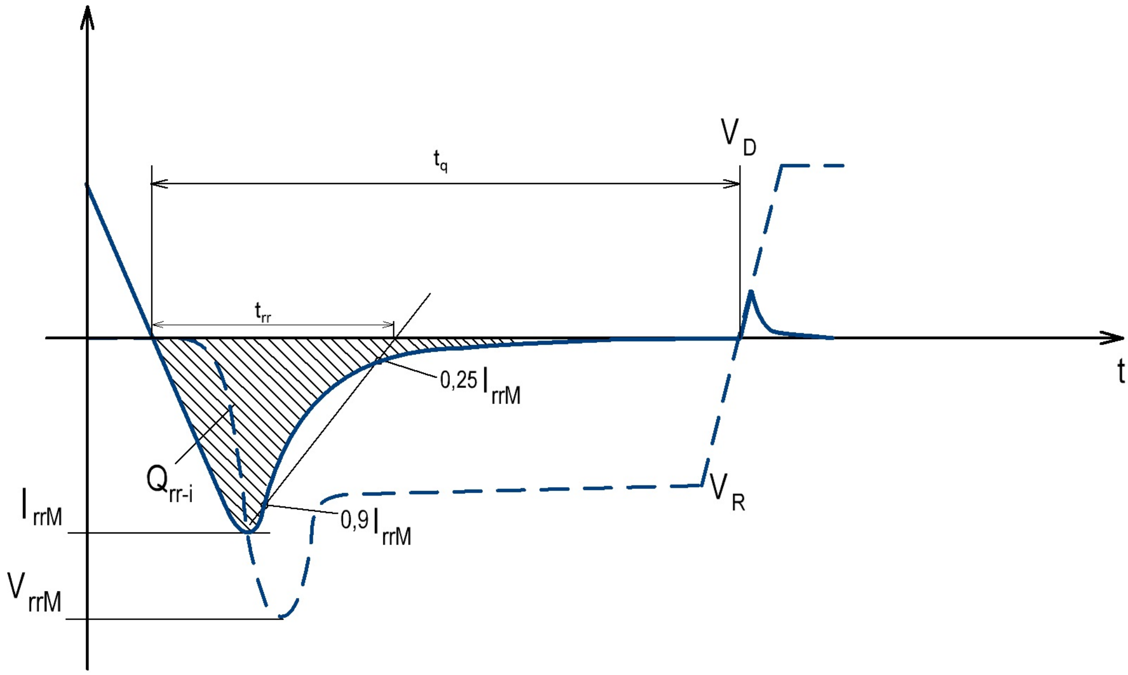


Figure 16. Reverse recovery and turn-off process of a thyristor.

Since the charge of excess electron-hole pairs in the n-base decreases due to recombination, that is, exponentially with a constant of decay time equal to the effective lifetime of excess electron-hole pairs τ, the following formula is valid for the thyristor turn-off time:

$$t_q = t_{rr} + \tau * \ln$$

where:

Q_1 is the charge of excess electron-hole pairs in the n-base of the thyristor at the end of the reverse recovery process,

K_{eff} is the proportionality coefficient between the charge of the excess electron-hole pairs in the n-base of the thyristor and the charge of reverse recovery of the collector p-n junction when the voltage polarity changes.

The main parameters and properties of a thyristor during turning off (reverse recovery) include:

t_q, Turn-off Time [µs] is the shortest time interval between the moment when the main current has dropped to zero after switching off the main circuits externally, and the moment when the thyristor is able to withstand the voltage in the off state at a certain rate of growth.

Q_{rr}, Reverse Recovery Charge [µC] is measured in the same way as for diodes – along the chord between points 0.9*I_{rrM} and 0.25*I_{rrM}.

t_{rr}, Reverse Recovery Time [µs] is the time interval between the moment when the main current passes through the zero value changing its direction from forward to reverse, and the moment when the reverse current decreases from its peak value to a given value, or when the extrapolated reverse current reaches zero.

I_{rrM}, Reverse Recovery Current [A] is the maximum reverse current flowing through the thyristor during reverse recovery.

3.4 Types of Power Thyristors Made by PROTON-ELECTORTEX JSC

The PROTON-ELECTROTEX JSC company manufactures the following types of power thyristors:

- Phase control thyristors (**T**)
- Fast thyristors (**TF**)
- Fast impulse thyristors (**TFI**)
- Fast high-frequency thyristors (**TFIS**)
- Avalanche thyristors (**TA**)

Phase control thyristors. Such thyristors are designed for use in equipment operating at a relatively low frequency (usually at industry-standard frequency of 50 or 60 Hz, less often at frequencies up to 500 Hz): controlled rectifiers, soft starters for electric motors, current inverters, etc. The main focus for these devices is minimizing power losses in conducting state and providing the specified forward and reverse blocking voltage. These devices are often used in converters for voltages of 6-10 kV and higher, where a series connection of individual thyristors is required. Therefore, it is important to increase the allowed blocking voltages and to ensure synchronous switching on and reverse recovery for such thyristors. The Q_{rr} and E_{RQ} values for a thyristor used at industrial frequency can be quite high, usually making it impossible to use them at increased frequency and in pulse-frequency modes. Turn-off times are typically 80 to 1000 µs depending on average current and thyristor class.

Fast thyristors are devices with reduced t_q, t_{rr}, Q_{rr}, E_{RQ} values designed to operate at higher frequencies or in pulse-frequency modes. The thyristor parameters of V_{TM}, t_q, Q_{rr} are interconnected, so a decrease in the value of t_q and Q_{rr} leads to an increase in V_{TM}. Similarly with fast-recovering diodes, to optimize the combination of V_{TM}, t_q and Q_{rr} various technological methods are used that enable controlled reduction of τ in layers of the semiconductor structure: alloying with atoms of heavy metals (gold, platinum, etc.), irradiation with high-energy particles (γ-quanta, electrons, protons, alpha particles, etc). Methods to control the p-emitter injection coefficient are also used. To reduce t_q, a more efficient distributed cathode emitter shunt is also used (with smaller shunt spacings than for phase-control thyristors). Frequency range for TF-series thyristors is up to 10kHz.

Since operation at higher frequencies is often accompanied by an increased speed at the front of the anode current pulses, fast thyristors must often meet requirements imposed on pulsed thyristors, such as increased di/dt-resistance and short turn-on time.

Fast impulse thyristors are thyristors with additionally normalized reverse recovery charge Q_{rr}. Besides, these devices are adapted for switching current pulses with a high rate of rise at the front and high amplitude. The optimal frequency range for TFI is the same as for TF, up to 10 kHz.

Fast high-frequency thyristors are thyristors that are used at higher frequencies up to 30 kHz. A special feature of such thyristors is their highly branched control electrode that ensures short propagation time of the on-state.

Avalanche thyristors are thyristors that can operate in avalanche breakdown mode.

4 Design Types

4.1 Semiconductor Element

Power devices produced by PROTON-ELECTROTEX JSC are based on diode (Figure 17) or thyristor semiconductor elements (Figure 18). Designs of the semiconductor elements are described in Sections 2.2 and 3.2. The semiconductor elements that determine properties of the device are placed inside a housing (disc, stud or module) to protect it from the environment. The housing ensures sealing and mechanical strength of the entire structure.

Figure 17. Diode semiconductor element.

A distinctive feature of a thyristor semiconductor element is the presence of a gate area located "above" the cathode surface of the device. For fast thyristors and thyristors of large diameters, the gate area has branches spreading from the center to the periphery of the element. As it was mentioned above, this is necessary for uniform switching on of the device over its entire area.

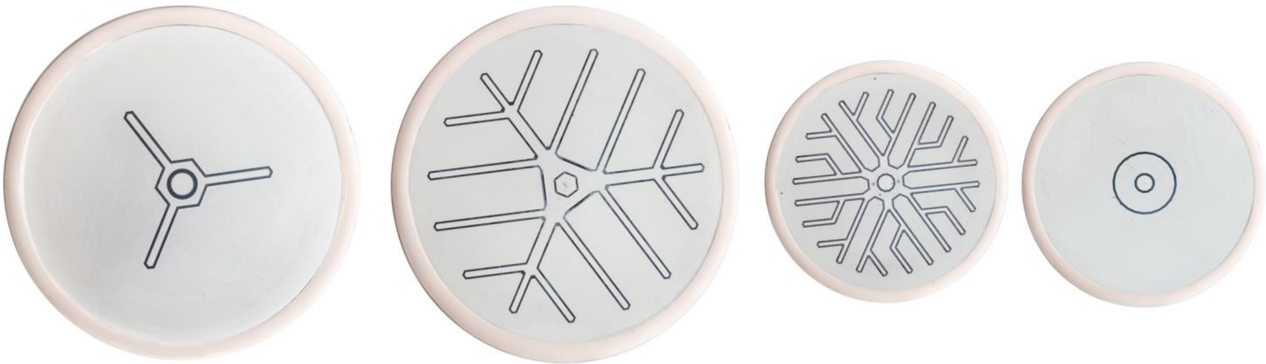


Figure 18. Thyristor semiconductor element.

4.2 Disc Devices

Disc devices are an assembly of a thyristor or diode semiconductor element with a housing consisting of two copper bases separated by an insulating ceramic insert with fins (Figure 19). Thyristors also have a control electrode and an additional cathode lead on the device housing. PROTON-ELECTROTEX JSC produces disc devices with a diameter of contact surface equal to 19 to 100 mm. Details of the overall dimensions of various housings are available in the catalog posted on the company's website.

Figure 19. Disc devices.

The disc pressure contact design of a power semiconductor device serves to increase its resistance to thermal cycling, since it does not have soldered or welded joints with the semiconductor element. This feature allows parts with different temperature expansion coefficients to move independently of each other. The mass, dimensions and their symmetry of disc devices make it possible to reduce the dimensions of conversion equipment and simplify its design. However, if the power semiconductor device is in an unclamped state, this design does not provide a reliable electrical connection between the internal elements, perhaps it is even a complete absence of contact. Testing and operation of disc-type power semiconductors is not allowed without devices ensuring external clamping force. Any electricity applied to the device when it is not clamped can destroy the semiconductor element or cause damage significantly reducing its life. Value of the axial compressive force is one of the key parameters of a power semiconductor device. The most suitable device to provide the required clamping force is a standard heatsink. Its design provides even distribution of force across the entire surface of the semiconductor’s electrodes and does not create distortions. Besides, design of disc devices allows for two-sided heat dissipation, additionally improving cycling resistance and reliability of the devices.

4.3 Stud Devices

Figure 20. Stud devices.

Stud-type power semiconductor devices (Figure 20) have a copper baseplate with a threaded bolt to provide electrical and thermal contact with the heatsink. Devices with a flat baseplate have a copper flange to clamp the device to the heatsink. Housing covers for both of these types are made of ceramic metal. The upper power terminal can be produced as a metal (copper) braided harness (flexible terminal). Stud devices manufactured by PROTON-ELECTROTEX JSC have pressure contact design of their semiconductor element, similar to disc ones. Clamping inside the housing is provided by the elements of the housing itself.

4.4 Module Devices

Figure 21. Module Devices.

Modular power semiconductor devices (Figure 21) are hybrid integrated devices normally containing two semiconductor elements. Housing of a module is designed to meet the customer's requirements as much as it is possible. The choice varies from miniature F to a large D housing, with A, B, C and E types in-between. PROTON-ELECTROTEX JSC manufactures modules with the following schemes of connecting the two chips: anti-parallel, with a common cathode and with a common anode. More details, internal connection diagrams and dimension drawings are available in the catalog posted on the company's website. Same as the disc and stud devices, modules manufactured by PTORON-ELECTROTEX, JSC have pressure contact designs. Clamping of the semiconductor element inside the module is provided by the module structure elements. Modular devices have an insulated baseplate that allows to mount multiple devices on a single heatsink.

All types of modules have industry-standard overall and mounting dimensions to simplify their installation and replacement of counterparts in existing convertors.

4.5 Housingless Devices

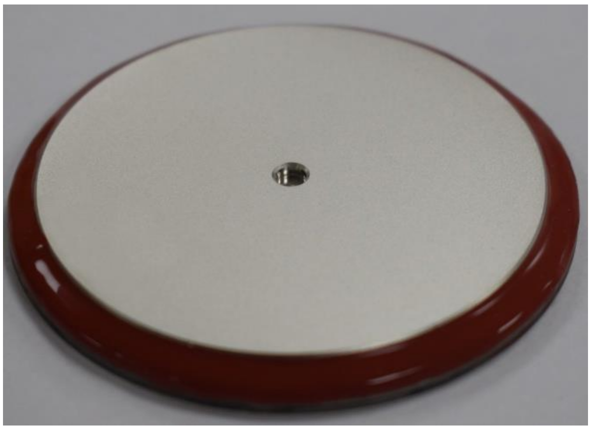


Figure 22. Housingless welding diodes.

Housingless welding diodes are designed with a reduced number of thermal contacts for minimal thermal resistance (Figure 22). The cathode side of a silicon chip in such diodes is connected to a copper electrode serving as a mechanical damper, while the anode side is fused with a molybdenum thermal compensator which is also the diode shell. Although housingless welding diodes are more susceptible to external impacts, they have some undeniable advantages like higher current density, lower weight and smaller dimensions compared to housed welding diodes.

A standard welding diode can operate at frequencies up to 7 kHz, however their optimum frequency range is up to 2 kHz.

Since housingless devices do not have a protective "shell", please follow handling recommendations specified in section 12.4, *Page* ***Ошибка! Закладка не определена.***.

5 Thermal Parameters of the Devices

5.1 Temperatures

T_{stg}, storage temperature [ºC] is the range of allowed storage temperatures for devices manufactured by PROTON-ELECTROTEX JSC according to their datasheets – for devices in metal-ceramic housings from -60ºC to +50ºC; for devices in plastic cases from -40°C to +50°C.

T_j, temperature of p-n junction [ºC] is the range of allowed operating temperatures for the semiconductor element inside the device housing. It is one of the main parameters affecting the reliability of the device. For thyristors and diodes manufactured by PROTON-ELECTROTEX JSC the lower temperature limit starts from -60°C (-40°C for module design), and the upper limit varies from 125°C to 190°C depending on the device type (the allowed range is indicated in the datasheet or passport of the device).

The lower temperature limit (T_{j_min}) is based on the loss of the mechanical and electrical properties of several materials used in the structure of the device, for example, the dielectric compound used in casting of the modules and protective coating of the semiconductor element's bevel.

The upper limit of the junction temperature (T_{j_max}) is based on the maximum permissible level of the leakage current in the closed state, which is determined according to the criterion of the guaranteed inadmissibility of a thermal breakdown in long-term operation.

5.2 Thermal Resistance

R_{thjc}, thermal resistance of the p-n junction to case [ºC/W] is the thermal resistance of the junction-case determined by the area of the semiconductor element, quality of contact connections and the housing design. This parameter is the ratio of the difference between the p-n junction temperature (T_j) and the case temperature (T_C) to the total power dissipation (P_{tot}):

$$R_{thjc} = \frac{T_j - T_C}{P_{tot}}$$

Thermal resistance depends on the internal design of the device. Datasheets provide several values of thermal resistance:

- **R_{thjc}** – for one-sided cooling for module and stud devices;
- **R_{thjc}** – for double-sided cooling (only for disc devices);
- **$R_{thjc\text{-}A}$** – for cooling from the anode side;
- **$R_{thjc\text{-}K}$** – for cooling from the cathode side.

Since R_{thjc} mostly depends on the design of the device, it is established during qualification tests and is also confirmed on randomly selected samples of devices during periodic testing.

R_{thch}, thermal resistance case to heatsink [ºC/W] is the ratio of the difference between the temperature of the contact surface (case) of the device (T_C) and the temperature of the heatsink (T_h) to the total power dissipation (P_{tot}):

$$R_{thch} = \frac{T_C - T_H}{P_{tot}}$$

The indicated values of this parameter are given for steady-state conditions and are valid only if the requirements for the heatsink surface specified in the recommendations for operation in the passport for a specific type of device are met.

Z_{thcj}, transient thermal resistance [K/W] is a parameter that describes the process of changing thermal resistance over time, usually provided in datasheets as a graph (Figure 23). The graph shows 3 curves: ASC, CSC and DSC – for cooling from the cathode side, anode side and double-sided cooling, respectively.

The Z_{thjc} parameter for various durations of the current pulse is calculated using the analytical dependence:

$$Z_{thjc} = \sum_{i=1}^{n} R_i(1 - e^{\frac{-1}{\tau_i}})$$

where:
i = from 1 to n, where n is the number of added elements.
t = duration of the pulse heating in seconds.
R_i, t_i – calculated coefficients provided in datasheets for the device

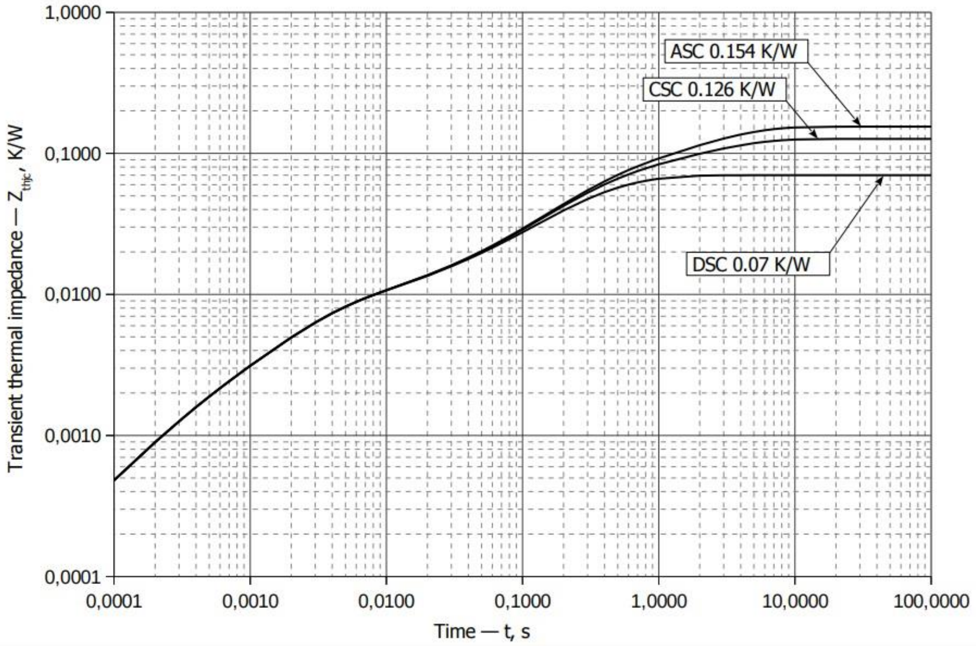


Figure 23. Time dependence of transient thermal resistance.

6 Overload Parameters

Converters based on power semiconductor devices often include high-speed protection circuits that prevent voltage from applying to the circuit elements when they get triggered. When the thyristor structure is subjected to abnormal current impulses, it can withstand a short-term exposure to a temperature significantly exceeding the maximum allowed operating temperature and then remains operational after cooling down to the operating temperature. To assess the ability of semiconductor device to withstand abnormal currents, the value of open state surge current is used. All formulas given in this section are relevant for a half-sine current waveform.

$I_{FSM/TSM}$, surge current [kA] is the highest forward impulse current that causes exceeding the maximum permissible junction temperature, but does not lead to a failure or deterioration of the device's properties after cooling. It is assumed that cases of surge current during the device lifetime will be rare with a limited number of repetitions.

Datasheets by PROTON-ELECTROTEX JSC provide the surge current amplitudes with a shape of sine half-wave with a duration of 10 and 8,3 ms (half a period for AC with a frequency of 50 and 60 Hz, respectively). The numerical values of the surge current provided in the parameter section of datasheets by PROTON-ELECTROTEX JSC are assumed for exposure without applying a reverse voltage.

Surge current is usually caused by a short circuit in the load connected to the semiconductor device. In this case, it is assumed that the converter's protection device triggers by the time the pulse ends and the mains supply gets turned off.

The surge current values provided for all types of devices manufactured by PROTON-ELECTROTEX JSC are confirmed experimentally in qualification tests by exposing the tested device to 10 surge current pulses of a given amplitude.

I^2t, protective factor [A^2c*10^3] is the maximum load of the device when exposed to abnormal currents characterized by a Joule integral, defined as $\int I_{F/T}^2 dt$ or the I^2t factor. For a sinusoidal current waveform, this value can be determined from the $I_{FSM/TSM}$ surge current value using the following formula:

$$I^2t = \int_0^{t_0} I_{F/T}^2(t)dt = \frac{I_{FSM/TSM}^2 * t_p}{2}$$

The I^2t value for the fuse protecting the device must be lower than the maximum I^2t value for the protected device.

To determine the surge current and protective factor for subsequent application of reverse voltage V_{rm} = 0.67 * V_{RRM} at $T_j = T_{j\_max}$, special graphs are given in the datasheets. Figure 24 shows an example graph of relation between I_{TSM} / I^2t and the pulse duration t_p for the T123-250 thyristor. Besides, datasheets also contain a graph of relation between I_{TSM} / I^2t and the number of pulses n_p.

Once again, it should be mentioned that such overloads exceed the maximum allowed value of the junction temperature. Therefore, overloads are only allowed a limited number of times for the entire service life of the device as a result of abnormal operating modes of the converters, such as a malfunction.

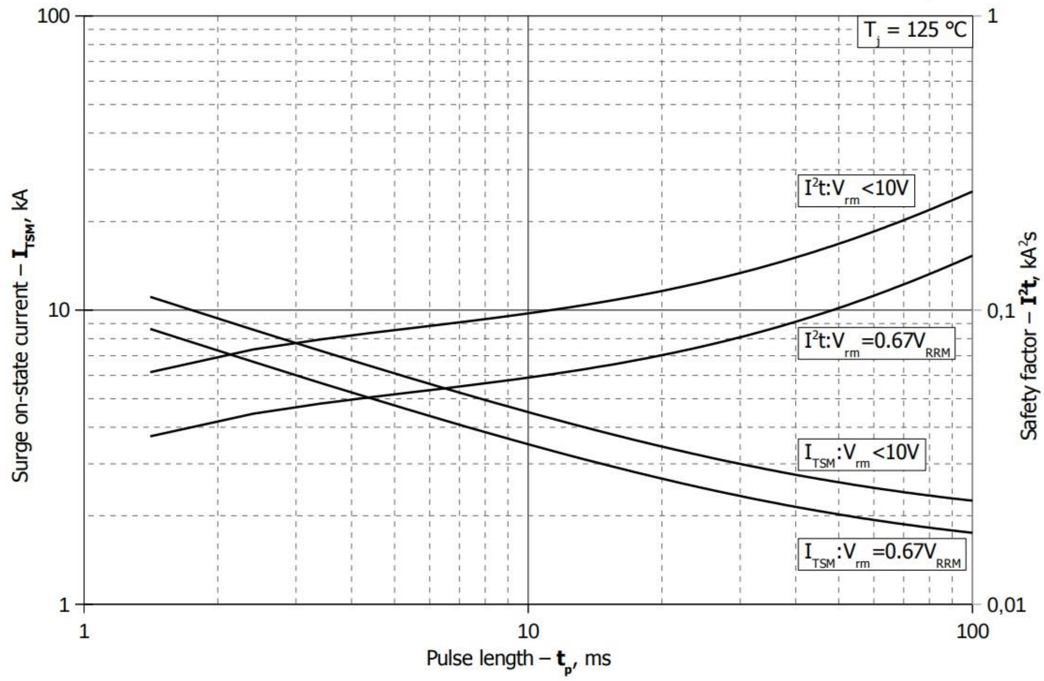


Figure 24. Relation between the maximal amplitude of surge current in open state I_{TSM}, protective factor I^2t and impulse duration t_p.

P_{RSM}, Surge Reverse Power Dissipation (W) is the main parameter describing the overload capacity of avalanche devices. The P_{RSM} value is normalized at the threshold temperature ($T_j = T_{j\_max}$) and duration of the reverse voltage pulse t_p = 100 μs.

7 Mechanical and Geometry Parameters

Mechanical and geometry parameters listed in datasheets for semiconductor devices include the following:

F, mounting force [kN] is defined as the value of mounting force required to ensure the needed thermal and electrical contact.

This parameter is reviewed in more detail below in Section 7.1 for disc and stud devices and in Section 7.2 for modules.

a, acceleration [m/s²] is defined as the allowed amount of acceleration in any direction, provided that the nominal mounting force is applied to the device.

w, mass [g] denotes the mass of the entire semiconductor device.

D_S, surface creepage distance [mm] denotes the total distance between the anode flange and the gate contact, defined as the shortest path across the ceramic surface of the housing (Figure 25).

D_a, air creepage distance [mm] denotes the straightened distance, defined as the shortest direct path between the anode flange and the gate contact (Figure 25).

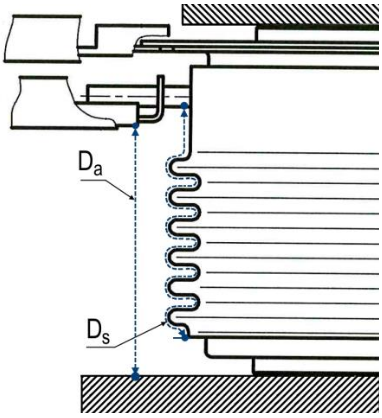


Figure 25. Total and straightened distances between the anode and the gate electrode of a disc thyristor.

7.1 Clamping Force

The specified clamping force must be observed for all disc devices to ensure reliable electrical and thermal contact. The required clamping force is provided in passports and datasheets for each type of device. It is very important to observe the recommended clamping force, otherwise if the clamping force is insufficient the device may fail due to overheating, while excessive clamping force may lead to cracking of the semiconductor element.

The clamping force for disc devices depends on the housing diameter. Table 2 and **Ошибка! Источник ссылки не найден.** show the nominal clamping force ranges for various types of disc devices. Actual clamping force should be within these specified ranges.

It is important to provide the clamping force within the specified range of values for all operating conditions, including worst case scenarios. Insufficient mounting force leads to higher thermal resistance and to a possible device failure due to overheating. At the same time excessive mounting force leads to higher mechanical load on the silicon wafer, so the service life of the device gets reduced due to premature wear of its elements, especially under cyclic loads. In addition, it is important to ensure even distribution of the compression force over the entire area of the device.

Stud devices in the SA1 type housing (type T(D)x61) should be mounted on a heatsink with a torque of 20 to 30 N*m.

Stud devices in the SB1, SB2 type housings (type T(D)x71) should be mounted on a heatsink with a torque of 25 to 35 N*m.

Stud devices in SB3 type housing (type Dx75 - flanged) should be mounted on a heatsink with an clamping force of 1.5 to 2.5 kN.

Table 2. Clamping force for welding diodes.

Diameter of contact surface	Housing	Clamping force
44.4 mm	D.Q1	From 30000 to 36000 N
50 mm	housingless	From 45000 to 50000 N
57 mm	D.W1	From 60000 to 70000 N
58 mm	housingless	From 60000 to 70000 N

Table 3. Relation between clamping force and diameter of contact surface for disc thyristors.*

Diameter of contact surface	Housing	Clamping force
19 mm	T.A1	From 5000 to 7000 N
25 mm	T.B2	From 9000 to 11000 N
32 mm	T.B3	
34 mm	T.C3	From 14000 to 16000 N
38 mm	T.C1; T.C2	
50 mm	T.D3; T.D5	From 24000 to 28000 N
51 mm	T.D1; T.D2	
63 mm	T.E3; T.E4	From 33000 to 40000 N
75 mm	T.F2; T.F5	From 40000 to 50000 N
80 mm	T.F1	
	T.H1; T.H2	From 60000 to 70000 N
100 mm	T.G5; T.G6	From 70000 to 90000 N

* Clamping forces for disc diodes are identical to thyristors in the same housings.

7.2 Tightening the Screws

Module-type devices are mounted using fastening screws. The table below shows the tightening torque that should be applied to the fastening screws for each type of modules produced by PROTON-ELECTROTEX

JSC. It is important to observe the tightening torques provided in the datasheets to ensure reliable thermal contact and to avoid overheating and failure of the device.

Table 4. Tightening torque for screws in pressure contact modules in various housings.

Housing	Tightening torque for baseplate screws	Tightening torque for power lead screws	Mounting dimensions (w*l*h)
A2	6 N*m (±15%)	12 N*m (±15%)	60x149x52
B0	6 N*m (±15%)	12 N*m (±15%)	50x101x52
C1	6 N*m (±15%)	9 N*m (±15%)	50*115*52
D	9 N*m (±15%)	18 N*m (±15%)	77*180*84
E	6 N*m (±15%)	18 N*m (±15%)	70*176*90
F	6 N*m (±15%)	6 N*m (±15%)	34*94*30

7.3 Climate Category

PROTON-ELECTROTEX JSC manufactures devices of various climate categories. The type of climate category is indicated on the device:

N – temperate and cold climate (for modules -60 ... + 40°C, for disc and stud devices -40 ... + 40°C);
T – tropical climate (for disc and stud devices +1 ... +55°C);
Climate category of the devices complies with the Russian standards GOST 15150 and GOST 15543.1, as well as DIN IEC 60721.

7.4 Resistance to Mechanical Impacts

Stud and disc devices are tested in accordance with the Russian standard GOST 17516.1. They are mechanically strong and retain their parameters after mechanical impacts within the limits required by the GOST M25 group: sinusoidal vibration 0.5-100 Hz; acceleration amplitude 10 m/s^2 (1g) and single shocks with a pulse duration of 50ms and acceleration of 40 m/s^2 (4g).

Module devices are tested in accordance with the Russian standard GOST 20.57.406 (method 103-1.6). They are mechanically strong and retain their parameters after exposure to sinusoidal vibration at a frequency of 50±2 Hz with a maximum acceleration amplitude of 50 m/s^2 (5g) and single shocks with a pulse duration of 50 ms and acceleration of 40 m/s^2 (4g).

8 Applications of Power Semiconductor Devices

The range of applications for power semiconductor devices is very wide. Power semiconductor diodes and thyristors can be used in power converters, DC and AC circuits of various power units. Various types of devices can be used in rectifiers, excitation systems of high-power turbine generators and synchronous compensators, in low-voltage rectifiers for welding and galvanic equipment, in converters for DC power lines, non-contact switching and control equipment and other devices.

Below is a list of industries using equipment with power semiconductor devices manufactured by PROTON-ELECTROTEX JSC:

Induction heating and melting of metals • High power (above 1 MW) inverters	**Drives for oil & gas industry** • Pump control stations	**Welding equipment** • Rectifiers for resistive welding equipment
Nuclear power • Inverters • Rectifying charger units	**Power units for various applications** • Rectifiers • AC switches • Impulse assemblies	**General purpose drives** • Soft starters • DC drives • Frequency converters
Pulse charge systems • Magnetizers • NDT equipment • Laser pumping systems • Crowbars • Seismic location	**Power supply and storage systems** • UPS • Energy storage systems • Rectifiers for galvanizing and electrolysis • Auxiliary power sources	**Railroad and underground** • Charging-discharging devices • Traction drives • Traction substations • Auxiliary converters for electric stock
Quarry and mining equipment • AC traction drives for quarry trucks • Control drive for excavator bucket • DC traction drives for quarry trucks • Drives of moving parts (lifting equipment, conveyor lines) • Pump station controls (mining automation)	**Generation and transfer of electric power** • Static compensators • Equipment for DC links • Emergency reserve switch units • Thyristor-controlled shunt reactors • Static thyristor compensators • Voltage sag compensators • Generator excitation systems	**Converters for medical equipment and testing equipment** • Pulsed generators • Power sources

9 Manufacturing Technologies

PROTON-ELECTROTEX JSC has implemented a full production cycle of bipolar semiconductor devices from silicon grinding to labeling and shipments of finished products.

The entire cycle of manufacturing a power semiconductor device can be divided into 5 main stages:

1. Production of silicon wafers – forming a round bevel, grinding, cleaning.
2. Production of diffusion plates – forming layers and topology of a semiconductor element.
3. Production of the semiconductor element – fusion of silicon wafers with a molybdenum thermal compensator, sputtering of contact metallization, forming the peripheral areas (bevels).
4. Testing the semiconductor element – measuring a set of parameters at room and maximum temperatures.
5. Assembly of a semiconductor element in a disc, module or stud housing and making power assemblies with heatsinks – assembly operations, acceptance tests, labeling and packaging.

Figure 26 shows a block diagram showing the entire process of manufacturing a power semiconductor thyristor at PROTON-ELECTROTEX JSC.

An ERP system is used to optimize lead times and loading of our production areas with a large number of technical transitions. The proprietary logic of the ERP system allows to solve specific tasks needed in manufacturing process of PROTON-ELECTROTEX JSC, increases the "transparency" of production processes and optimizes interaction with suppliers of components. All this allows us to predict the date of shipment of finished products with very high accuracy.

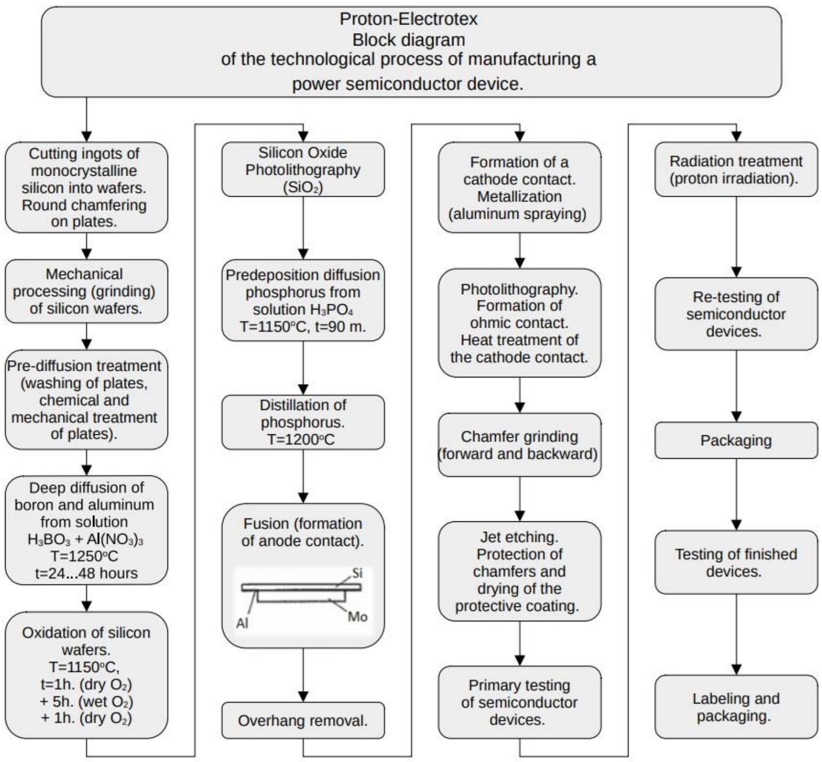


Figure 26. Block diagram of the manufacturing process for a power semiconductor thyristor.

Product Customization

PROTON-ELECTROTEX JSC offers its customers an opportunity to order power semiconductors based on their **custom requirements**. The choice of possible options is extensive and includes shipments of devices with non-standard terminals and precise grouping of batches by parameters.

Other options include:

- selection by Q_{rr} (to ensure serial connection);
- selection by V_T/V_F, including measurements in non-standard mode;
- selection by t_q;
- modifications to thyristors' housing and/or control leads;
- special labeling.

Such additional requirements are quite common, so to provide our customers with products adapted to their custom needs PROTON-ELECTROTEX JSC has a special procedure to review and register these requirements to guarantee their fulfillment at all appropriate stages of production, including testing.

In general, custom products are manufactured under the following procedure:

1. The customer provides a list of requirements to products.
2. PROTON-ELECTROTEX analyzes and confirms the possibility of manufacturing the required device.
3. Planning of a production route and preparation of technical documentation for the products (passports, datasheets, design documents, etc).
4. Assigning a unique product structure code.
5. Preparing the production plan and product release.

PROTON-ELECTROTEX JSC aims to protect the customer's interests and if for some reason the request review indicates a too low yield percentage value or some other problems arise in production of custom devices, all possible solutions to problems are discussed with the customer.

10 Testing

To ensure continuous quality control of manufactured devices and compliance of their parameters with those stated in the technical specifications, PROTON-ELECTROTEX JSC tests its semiconductors at each stage of production.

PROTON-ELECTROTEX JSC has developed several types of measuring systems with a wide range of functions:

- Power semiconductors measurement complex

This complex is designed to measure various parameters of power semiconductor devices. It is a modular system. Modularity allows to assemble the required system configuration for specific measuring tasks. This approach makes it easier to organize the measurement process since there is no need to purchase a universal laboratory meter, and one can use the equipment strictly corresponding to the required task.

Figure 27. Power semiconductors measurement complex

More details about the power semiconductors measurement complex are available in the [Measuring Equipment] section of our website.

- Automated complex for measurements of power semiconductor modules (ATSM)

The automated complex for measurements of power semiconductor modules (ATSM) is a multi-component robotic system designed to measure such parameters as: dielectric strength of insulation; blocking voltage; gate parameter; $V_{TM/FM}$ at minimum and maximum temperatures. ATSM can measure modular devices in various housings and is compatible with all types of the semiconductor element connection schemes inside the modules.

Figure 28. Automated complex for measurements of power semiconductor modules

Measurements are taken at room and maximum operating temperatures. The modules are transported into the complex by a robotic arm.

More information about ATSM is available in the article ATSM: Robot measures modules on the company's website.

Such automated measurement systems make it possible to minimize human factor in the process of measuring parameters, reduce the number of errors and rejects, and improve the quality of products.

Tests of semiconductors are carried out in accordance with the Russian standards, following methods required by GOST and TU.

1. Qualification tests

Qualification tests are carried out for the pilot batch of devices or for the first production batch according to the control program and plan of periodic tests.

2. Reliability tests

Reliability of thyristors is confirmed by testing for fail-free operation, lifetime, expected life and storability time. Types and frequency of reliability tests are as following:

- Test for fail-free operation – once every 3 years
- Lifetime – once a year, processing of feedback from operation.

- Useful life – once a year, processing of feedback from operation.
- Storability time – during qualification tests.

3. Acceptance tests

Acceptance tests for all manufactured products are carried out in accordance with a two-stage control plan. The list of acceptance tests is provided in the technical specifications (TU) for each specific type of device, since the list of measured parameters may vary for different types of devices.

4. Periodic tests

Periodic tests are carried out according to a two-stage sampling plan depending on the type of device.

5. UL certification

All module devices manufactured by PROTON-ELECTROTEX JSC are certified according to the UL-1557 standard. This certification allows to use the semiconductors in equipment shipped to the United States. Information on certified products can be found on the UL official website, UL section number E255404.

11 Reading Datasheets

All letter designations of thyristors and diodes comply with the following standards:

- IEC 60747-1 - General (letters and terms)
- GOST25529-82 (IEC 60747-2) - Diodes
- GOST20332-84 (IEC 60747-6) - Thyristors
- Labeling of devices is made in accordance with GOST 20859.1-89.

The first table in a datasheet contains the primary parameters used by designers to select a semiconductor: average forward current, impulse voltage, turn-off time (for thyristors), a list of possible voltage classes and range of operating temperatures.

High power cycling capability
Low on-state and switching losses
Designed for traction and industrial applications

Phase Control Thyristor
Type T353-1600-18

Mean on-state current	I_{TAV}	1600 A
Repetitive peak off-state voltage	V_{DRM}	1000 ÷ 1800 V
Repetitive peak reverse voltage	V_{RRM}	
Turn-off time	t_q	160, 200, 250, 320, 400, 500 μs

V_{DRM}, V_{RRM}, V	1000	1100	1200	1300	1400	1500	1600	1800
Voltage code	10	11	12	13	14	15	16	18
T_j, °C	-60 ÷ 125							

Figure 29. General information in a datasheet

All the primary parameters of each device are encoded in its designation (label). Legend for semiconductors designations is shown below.

For example:

Designations of disc thyristors

T[1][2][3]-[4]-[5]-[6][7]-[8]

[T] – designation of the device type according to GOST 20859.1 (T — thyristor, TF — fast thyristor, etc.)
[1] – serial number of the design modification
[2] – designation of the maximum housing diameter according to GOST 20859.1
[3] – designation of the housing design according to GOST 20859.1
[4] – maximum allowed average forward current
[5] – class according to GOST 20856.1
[6] – group by the critical rate of voltage rise in closed state $(dv_D/dt)_{crit}$
[7] – group by turn-off time t_q
[8] – climate category according to GOST 15150

Designations of modules

MT[1]-[2]-[3]-[4]-[5]

[MT] – designation of the module type (MT — thyristor module, MD — diode module, MT/D — thyristor-diode module, MD/T – diode-thyristor module)
[1] – designation of the connection type according to GOST 30617
[2] – maximum allowed average current
[3] – class of the module according to GOST 30617
[4] – module modification (A2, C1, D, etc.)
[5] – climate category according to GOST 15150

Designations of disc diodes

D[1][2][3]-[4]-[5]-[6]
[D] – designation of the device type according to GOST 20859.1 (D — diode, DA – avalanche diode, etc.)
[1] – serial number of the design modification
[2] – designation of the maximum housing diameter according to GOST 20859.1
[3] – designation of the housing design according to GOST 20859.1
[4] – maximum allowed average forward current
[5] – class according to GOST 20856.1 (*for D0 series: class 2 (V_{RRM} = 200, V_{RSM} = 300); class 4 (V_{RRM} = 400, V_{RSM} = 500))
[6] – climate category according to GOST 15150

For phase-control thyristors, designation elements no. 6 and no. 7 are optional and may or may not be included in the device labeling at the customer's request.

Specific designations of devices are provided in the corresponding datasheets.

Datasheets for module devices also list possible options for the internal topology. There are 4 main options for connection diagrams in dual-component modules (A2, C1, D and F), namely:

- thyristor-thyristor
- diode-diode
- thyristor-diode
- diode-thyristor

Possible combinations of thyristor and diode elements are shown in Figure 30.

Besides, the product range of PROTON-ELECTROTEX JSC includes single-component modules E1 and B0.

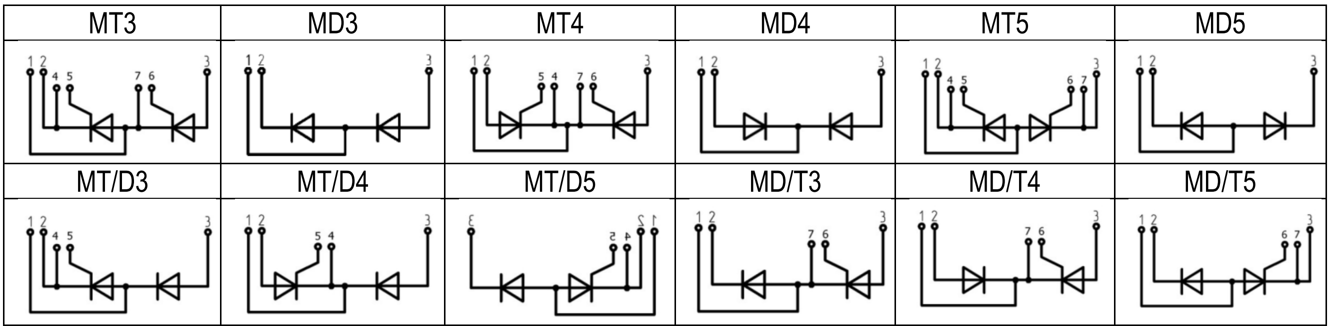


Figure 30. Diagrams of bipolar modules' internal topology.

Below are designations of the device classes, as well as various groups of parameters (for thyristors).

Legend for device classes:

Voltage class	1	2	3	4	…	15	16	18	…	52	54	56	58	60	65
V_{DRM} V_{RRM}, [V]	100	200	300	400	…	1500	1600	1800	…	5200	5400	5600	5800	6000	6500

Groups by critical rate of voltage rise in closed state **$(dv_D/dt)_{crit}$**:

Group designation	0	P3	E3	A3	P2	K2	E2	A2	T1	P1	M1	K1	H1	E1	C1	B1
	0	1	2	3	4	5	6	7	8	-	9	-	-	-	-	-
$(dv_D/dt)_{crit}$ [V/µs]	not regulated	20	50	100	200	320	500	1000	1600	2000	2500	3200	4000	5000	6300	8000

Groups by turn-off times **t_q** for phase-control thyristors:

Group designation	0	B2	C2	E2	H2	K2	M2	P2	T2	X2	A3	B3
	0	-	-	1	-	-	2	-	3	-	4	-
t_q, µs	not regulated	800	630	500	400	320	250	200	160	125	100	80

Groups by turn-off times **t_q** for TF, TFI and TFIS:

Group designation	C3	E3	H3	K3	M3	P3	T3	X3	A4	B4	C4	E4
	1	2	3	4	5	6	7	8	-	9	-	-
t_q, µs	63	50	40	32	25	20	16	12.5	10	8	6.3	5

Groups by reverse recovery times **(t_{rr})**:

Group designation	0	T3	X3	A4	B4	C4	E4	H4	K4	M4	P4	T4	X4	A5	B5	C5	E5	H5
	0	-	-	-	-	-	1	2	3	4	5	6	-	7	-	8	-	9
t_{rr}, µs	not regulated	16	12.5	10	8	6.3	5	4	3.2	2.5	2	1.6	1.25	1	0.8	0.63	0.5	0.4

For example, a T143-500 thyristor of class 16, the 7th group by critical rate of voltage rise in the closed state (A2), 3rd group by turn-off time (T2), climate category N may have the following designation in the order and other product documentation:

- Thyristor T143-500-16-A2T2-N
- Thyristor T143-500-16-73-N

All further data for disc, stud or module thyristors and diodes list the maximum allowed values of various parameters of devices.

Maximum Allowed Values of Parameters

The maximum values of parameters indicated in the datasheets represent the threshold values of the allowed electrical, thermal and mechanical loads that cause no risk of the device's destruction. At the same time, any component is subject to aging effects even when operating at or below the rated parameters. All parameter values are determined under conditions strictly regulated by standards. These conditions are listed next to each parameter in the column "measurement conditions". Exceeding even one value from the section of maximum allowed parameters can lead to failure of the device.

Characteristics

The characteristics section lists the properties of devices measured under certain conditions. As a rule, the conditions used to obtain these characteristics depend on the device type. Usually the characteristics are provided at 25°C and $T_j = T_{j\_max}$. The actual measurement conditions are indicated in the "measurement conditions" column.

PROTON-ELECTROTEX JSC is constantly improving the quality of its datasheets, releases datasheets for new devices, updates existing datasheets, creates extended sheets with a larger set of relation graphs.

12 Mounting

A key condition for a long and trouble-free operation of the devices is their correct mounting. Fulfilling all requirements to installation ensures reliable electrical and thermal contact and prolongs the service life of the devices.

12.1 Disc Devices

To ensure reliability and durability of disc-type devices, we recommend to provide their cooling using heatsinks designed and manufactured by PROTON-ELECTROTEX JSC. These heatsinks take into account all the specifics of the semiconductor devices and can be supplied together with thyristors or diodes as ready-to-use assemblies.

To ensure reliable thermal and electrical contact, the following must be taken into account during installation of semiconductor devices:

- The contact surfaces of devices and heatsinks as well as the insulating material of the control wires must not have any damage or foreign inclusions.
- The contact surface of the heatsink must have:
  - roughness of no more than 1.6 microns, and
  - deviation from flatness of no more than 0.03 mm
- If necessary, the contact surfaces of heatsinks and devices must be polished.
- The coating of the contact surfaces must not be damaged to avoid corrosion. Contact surfaces should be cleaned with ethanol and a soft lint-free cloth prior to assembly. The assembly of devices with a heatsink must be carried out in clean environment. The surfaces of the semiconductors and heatsink must be kept clean during assembly. Do not touch the contact surfaces with bare hands when installing the devices. It is recommended to carry out the installation wearing cloth gloves.
- Installation and operation of devices without heat-conducting material is allowed.
- The contact surface of the heatsink should not be smaller than the contact surface of the mounted device.
- Use aligning pins when installing the devices. The pins must have correct dimensions since the devices are made of soft material and an excessively long pin can push the device housing during tightening and destroy the semiconductor element inside.
- To prevent tilting of the device and uneven distribution of the clamping force during installation (or removal), the mounting bolts of the tightening device should be tightened alternately crosswise, gradually increasing the tightening torque on each of them.
- Insufficient clamping force causes higher thermal resistance and lower allowed current load on the device and deteriorates resistance to thermal cycling.
- Clamping force must be within the recommended range provided in the datasheet and the certificate for the device.
- Excessive clamping force can damage the metallization of the semiconductor element's cathode layer, push through the gate area or destroy the element.

- The clamping device where the devices are mounted must ensure uniform distribution of the clamping force. Uneven force distribution leads to deformation of the housing and internal stresses inside the housing, which will ultimately cause premature failure.
- The clamping force should be applied in the central point of the device, and the distance from this point to the contact surface of the device should ensure an even distribution of the force over the entire contact surface of the device.
- The design of the clamping device must be able to withstand any amount of forces caused by the thermal expansion and contraction of the devices during thermal cycles. The clamping device must allow temperature expansion and contraction of the semiconductor devices without significant changes in the compression force and its distribution over the contact surface of the device.
- To prevent displacement of the semiconductor device, it must be fully clamped before the power bus is attached to it.

Devices with forced air or water cooled heatsinks can be mounted in any position provided that the volume of cooling air or liquid is sufficient to remove the generated heat.

In case of natural air cooling the heatsink fins must be vertical to allow the air to pass through. In order to avoid mutual heating of nearby devices, heatsinks for natural cooling should be located at sufficient distance from each other.

Since heatsinks have electrical potential, they must be located at a sufficient distance from the ground and other equipment, or have adequate insulation.

If the semiconductor devices are additionally heated by other nearby equipment or components (for example, power resistors, transformers or fuses), then the load on the devices must be reduced in accordance with the temperature.

If several devices are combined into an assembly, the following points must be considered:

- Design of a clamping device with a serial connection of the semiconductor devices may achieve a voltage that is multiples of the blocking voltage of each individual device.
- Design of a clamping device with a parallel connection must include a separate clamping device for each individual semiconductor device, since the height tolerances of the devices make it difficult to design a single clamping device providing an even distribution of force.

Connection of the power buses must be made with reference to the additional thermal expansion of devices and other components of the power circuit over the entire temperature range.

The terminals must not get damaged when connecting the control wires.

The control wires must be securely connected to prevent accidental disconnection of the control circuit, for example due to vibration.

Control wires should not be placed near the power part of the circuit and must be securely protected from electromagnetic interference.

After the installation is complete, all fixing devices must be additionally protected against corrosion. Such anti-corrosion lubricants as CIATIM-221 (GOST 9433) or VNII NP-207 (GOST 19774) are recommended for this.

A thin layer of grease on the contact surfaces may be used to ensure long-term chemical resistance and to reduce environmental corrosive effects, but such grease should not impair electrical and thermal contact.

12.2 Stud Devices

To ensure reliable thermal and electrical contact, the following must be taken into account during installation of semiconductor devices:

- The contact surfaces of devices and heatsinks, as well as the insulating material of the control wires must not have any damage or foreign inclusions.
- Installation and operation of devices without heat-conducting material is allowed.
- The contact surface of the heatsink should not be smaller than the contact surface of the device to be mounted.
- Insufficient torque applied to the device leads to higher thermal resistance and lower allowed current load on the device and deteriorates resistance to thermal cycling.

Additionally, follow the recommendations listed below:

Stud-type devices must be mounted on the heatsink using a torque wrench. The range of torque values for stud-type devices is indicated in the datasheet and the passport for the device.

It is not acceptable to install the devices on heatsinks with holes of insufficient depth or with damaged thread. This can lead to reaching the required torque without ensuring a complete contact between the surface of the device and the heatsink, resulting in thermal overload of the device.

The points of contact between heatsinks and devices should not have any damage, traces of corrosion or foreign inclusions.

The roughness of the contact surface of the heatsink should not exceed 3.2 μm

Installation of devices without the use of heat-conducting material is allowed.

The recommendations for heatsink positioning are identical to those for disc devices.

Any damage to the flexible power terminal and its insulation during installation are not acceptable.

In case of flanged semiconductors the clamping device must be tightened in the same way as for disc models. The mounting bolts are tightened alternately crosswise with a gradual increase in tightening torque. The clamping force for flanged devices is provided in the datasheets and the passport for the device.

12.3 Module Devices

To ensure reliable thermal and electrical contact, the following must be taken into account during installation of semiconductor devices:

- The contact surfaces of devices and heatsinks, as well as the insulating material of the control wires must not have any damage or foreign inclusions.
- If necessary, the contact surfaces of heatsinks and devices must be polished
- The coating of the contact surfaces must not be damaged to avoid corrosion. Contact surfaces should be cleaned with ethanol and a soft lint-free cloth prior to assembly. The assembly of devices with a heatsink must be carried out in clean environment. The surfaces of the semiconductors and heatsink must be kept clean during assembly. Do not touch the contact surfaces with bare hands when installing the devices. It is recommended to carry out installation wearing cloth gloves.

Additionally, follow the recommendations listed below:

Power modules must be mounted on heatsinks or on any surfaces of devices capable of providing optimal thermal conditions. The contact surface of the heatsink should have roughness below 10 microns and deviation from flatness below 50 microns.

Prior to installing power modules, a heat-conducting material must be applied to the surface of the heatsink or to the baseplate of the module (For more information on heat-conducting materials, see section 14.4 on *page* ***Ошибка! Закладка не определена.***). The required thickness of the material layer is 75 ± 25 μm.

All fastening bolts should be tightened crosswise, with a gradual increase in torque to the required value specified in the datasheet and the passport for the device.

If several modules are connected in series on the same heatsink, the total voltage may exceed the isolation voltage of the device. PROTON-ELECTROTEX JSC does not recommend installing modules in serial connection on a single heatsink.

When connecting the power buses, the terminals of the power modules must not be subjected to torsional or fracture loads.

12.4 Housingless Devices

General requirements to mounting housingless devices are similar to those for disc devices. Additionally, follow the recommendations described below:

It is allowed to cover the surface of the heatsink with a thin layer of silver-nickel, pure silver, gold or nickel. The galvanized coating of the heatsink's contact surface prevents electrical erosion of the contact surfaces and ensures reliable thermal contact.

Since housingless devices do not have a "shell" protecting them, the following handling recommendations should be observed:

- It is recommended to use an O-ring around the device (between the surfaces of the anode and cathode heatsinks) to protect it from the environment. The O-ring must be made of materials resistant to chemicals and high temperatures.
- To reduce the environmental impact, it is also recommended to keep the devices in vacuum package until they are installed in the equipment.

The anode of housingless devices does not have a centering hole. Centering is carried out by the outer boundaries or only by the cathode centering hole.

Housingless diodes are vulnerable to damage caused by particles such as small chips that get onto the surface of the diode during installation. Precautions must be taken when mounting the diodes to avoid the ingress of solid particles onto the contact surfaces of the device.

13 Operation

13.1 Control

A thyristor is a current-controlled bipolar semiconductor, so a signal of a certain amplitude, duration and polarity must be applied to its gate electrode. In this case, the amplitude and duration of the control pulse is limited by a number of requirements. Below are the requirements for the most common thyristor applications. In case of special applications it is recommended to contact the support of PROTON-ELECTROTEX JSC for advice.

Typical current and voltage waveforms of the gate circuit are shown in Figure 31.

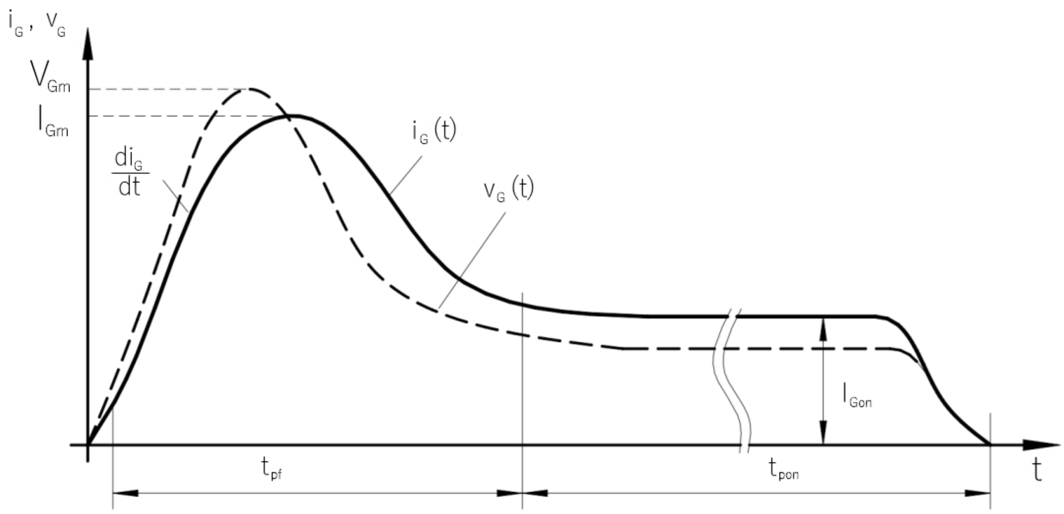


Figure 31. Diagram of current and voltage in gate circuit.

I_{Gon} – seed current; $I_{Gon} = (3÷5)*I_{GT}$;

where I_{GT} is the gate trigger direct current (this parameter is listed for the minimal operating temperature that the thyristor will be operated at).

I_{GM} is the amplitude of forcing impulse; $I_{GM} = (10÷12)*I_{GT}$

di_G/dt is the rate of rise of the gate current; $di_G/dt \geq 1$ A/µs; there is no upper limit for the di_G/dt value.

t_{pf} is the duration of the gate forcing impulse; $t_{pf} = (2÷3)*t_{gd} \approx 10$ µs ÷20 µs;

where t_{gd} is delay time;

t_{gt} is turn-on time, depends on the device's connection diagram.

The duration of t_{pon} is determined by the nature of the load and the operating conditions of the circuit where the thyristor is located. The current acts as insurance for the thyristor during the t_{pon} time if there is a possibility of anode current decreasing to the trigger current value.

To minimize the influence of the control conductors' inductance on the rate of rise of control current, it is necessary that the open circuit voltage of the gate driver is within 15 ÷ 30 V.

The peak reverse gate voltage should be below 5 V to increase the thyristor's noise immunity level (the gate electrode is negative with respect to the cathode).

The operating point of the load of the gate electrode must be located in the zone of optimal control, i.e. it must not go beyond the curve corresponding to the maximum allowed power losses in the gate electrode at the adopted duration and duty cycle of control pulses, and must not fall into the zone of non-guaranteed turn-on of the thyristor. The I-V curve of the gate electrode is provided in the datasheet for each thyristor.

It is not allowed to apply control pulses to the thyristor when reverse voltage is applied to it. In this case the transistor effect appears and additional thyristor leak current is generated, so higher reverse voltage applied at this moment leads to higher leakage current (it can reach several amperes or more), and this current flows through the cathode region adjacent to the gate electrode, i.e. it is localized, so high power is released in small volume, which can lead to current filamentation and breakdown.

Twisted pair should be used for control wires and placed away from sources of electromagnetic interference. One can increase the number of wire twists to reduce the interference effect. It is possible not only for the thyristor control wires, but also other wires of the gate electrode circuit. Besides, the length of the control wires should be reduced to the required minimum to reduce the interference. Do not allow the control wires to come in contact with surfaces having a high electrical potential.

13.2 Serial and Parallel Connection

The maximum values of currents and blocking voltages of various power semiconductors are limited, so the same type of semiconductors often needs to be connected in groups to increase the total power. The main types of connections are as follows:

- Serial – used when it is necessary to increase the maximum blocking voltage;
- Parallel – used when it is necessary to increase the maximum current;
- Mixed – parallel + serial.

Serial Connection

Serial connection of power semiconductors requires to ensure equal distribution of the blocking (forward and/or reverse) voltage both in static and dynamic modes, i.e. when the thyristors are turned on and when the blocking properties are recovered when the thyristor or diode is turned off. There are several possible reasons for the uneven distribution of blocking voltages:

- Different leakage in serial devices due to natural technological variation and/or different operating temperatures caused by, for example, different cooling conditions (on average, a temperature change of 8°C leads to a twofold change in leakage). Overvoltage then occurs in devices with a lower leakage current.

- Varying turn-on time of individual thyristors serially connected in branches leads to redistribution of voltage between the thyristors that were turned on earlier and turned on with a delay. Overvoltage then occurs on thyristors that switched on with a delay.
- The spread in the values of reverse recovery charge in series-connected devices causes them to receive reverse voltage at various times during recovery. Overvoltage occurs in thyristors with lower reverse recovery charge.

The following measures are recommended to equalize the distribution of blocking voltages:

- Shunting high-ohm resistors are used in parallel to each semiconductor device (diode or thyristor) to reduce the effect of non-uniform leakage currents of series-connected power semiconductors. Lower resistance values of the shunt resistors are used at higher requirements to equalization of the voltage in this mode;
- To reduce the uneven distribution of blocking voltages due to various values of the reverse recovery charges of the semiconductor, snubber RC-circuits are used in parallel to each semiconductor device. The higher the value of the snubber capacitance connected in parallel with the device, the more uniform distribution of blocking voltages is. However, increasing the capacity is not always a rational way, therefore it is necessary to select devices for serial connection according to their reverse recovery charge. As a rule, the spread of charges is accepted of no more than 5% or 10%.
- High-power control pulses with a steep edge are used to reduce the spread in the turn-on time of the semiconductors, causing a decrease in the thyristor turn-on delay time and minimizing the influence of this effect on the voltage distribution. The presence of RC snubber circuits in parallel to each device has a positive effect since a certain forward voltage was applied to the thyristors before the moment of turning on, when the snubber capacitors are also charged. This voltage is initially applied to it after the thyristor is turned on, ensuring uniform voltage distribution.

Parallel Connection

In case of parallel connection of power semiconductor devices it is critical to ensure even distribution of the load current across the devices. The following measures are needed to achieve this:

- the average current of the most loaded semiconductor should not exceed its allowed $I_{TAV}/_{FAV}$ value;
- the distribution of loads in case of abnormal current flow must ensure that the current flowing through any semiconductor does not exceed the permitted value of $I_{TSM/FSM}$;
- in case of open circuit fault or disconnection of one or several semiconductors in the circuit, the current distribution between the devices remaining in operation should not be significantly disturbed.

To solve these tasks, it is necessary to ensure identical operating conditions of all semiconductors and a low scatter of elements used to make piecewise linear approximation of the I-V curve taking into account normal technological spread of the semiconductors' parameters. To solve this problem, the following recommendations must be observed:

- Install inductive or ohmic current dividers in series with each semiconductor device;
- Select semiconductor devices by static losses at the operating point (by the $V_{TM/FM}$ value at the operating current). It should be noted that there is always a certain technological spread of the semiconductor's parameters.
- Select operating currents above the inversion point of the semiconductor's I–V curve. In this case, the equalization of currents in parallel branches will occur automatically due to the negative feedback in the region of I-V curve above the inversion point. That is, as the temperature of the p-n junction increases, its

resistance increases and the forward current decreases, which leads to a decrease in temperature of p-n junction (Figure 32);

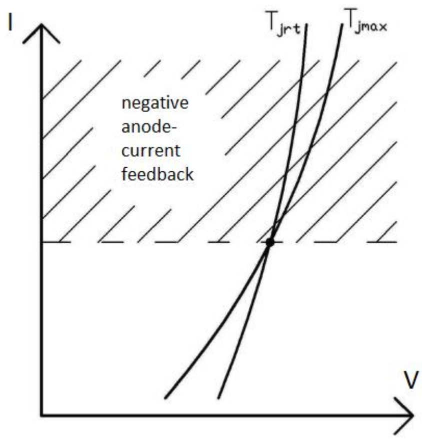


Figure 32. Point of temperature inversion and negative feedback zone.

- Apply high-power control pulses with a steep front. It results in a decrease of the thyristor turn-on delay time and minimized influence of this effect on the initial current distribution;
- Pay special attention to the propagation time of the thyristor on-state in circuits with high-power high-voltage thyristors or thyristors based on chips of large diameters (more than 56 mm), or in case of high inductances in the power section that limit the rate of change of the power current. The reason is that the high-power thyristors are initially switched on in a limited area near the control electrode, then a longitudinal propagation of the on-state occurs in a limited time;
- Structural arrangement of parallel branches should ensure equal resistances of current-carrying buses, including fuses;
- The cooling conditions must be the same for all devices in a parallel connection.

14 Cooling

14.1 General Requirements to Heatsinks

General requirements to heatsinks are determined primarily by the technical and economic parameters of the power semiconductors and converters based on them, i.e. their type and design features, the amount of generated heat, expected operation conditions, and technological specifics of production. Based on all of the above, it can be concluded that the general technical requirement to a heatsink is its ability to provide an adequate thermal mode of operation for the semiconductor devices under specified conditions with minimal consumption of materials, energy and funds.

To achieve all of the above, one needs to:

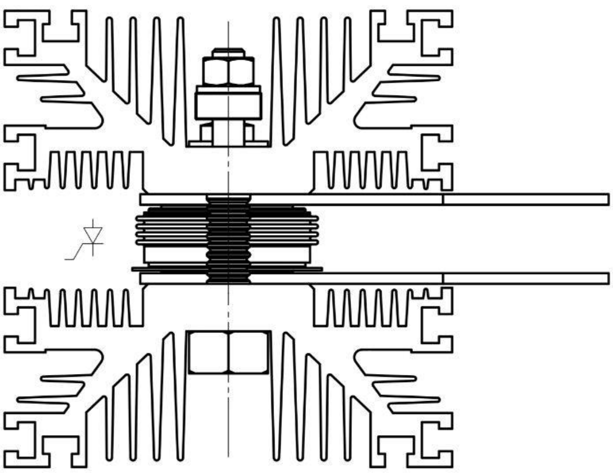
- optimize the weight, size and cost parameters of the heatsinks at the given parameter values;
- stabilize the thermal contact resistance between the semiconductor and heatsink ($R_{th\ (c\text{-}h)}$), which is mainly achieved by high-quality processing of the contact surfaces.

The contact surfaces of the heatsinks must ensure reliable metal-to-metal contact, which in turn ensures good thermal and electrical conduction through the entire life cycle of the equipment. Besides, heatsinks must withstand thermal cycling loads and environmental effects.

PROTON-ELECTROTEX JSC recommends to use heatsinks with silver or nickel coating. It is not recommended to use copper or aluminum heatsinks without protective coatings as their contact surfaces can quickly deteriorate due to corrosion caused by current flow.

There are several types of heatsinks, the most common of them are air and liquid. PROTON-ELECTROTEX JSC produces air heatsinks for standard use.

14.2 Air Cooling



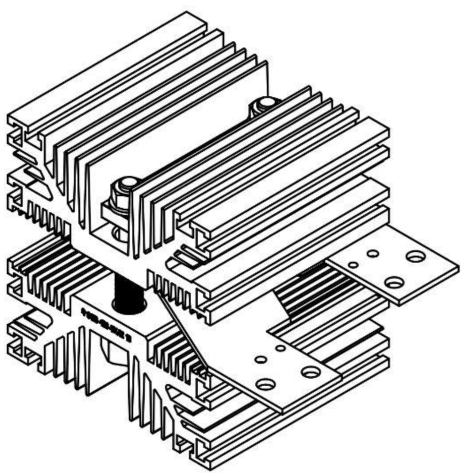


Figure 33. An assembly example for a disc thyristor and a heatsink.

The most common type of heatsinks used for air cooling of power semiconductor devices is aluminum, less often copper with ribbed surface (Figure 33). The fins of heatsinks significantly increase their surface area, thereby increasing the area of convection and thermal radiation, distributing the heat flux and reducing transient thermal processes.

Air cooling can be divided into two types: natural (convection) and forced.

Classic finned heatsinks are suitable both for cooling by convection (removal of thermal energy by natural air flows due to rising heated air) and for forced air cooling (air movement provided by a fan). Each type of heatsink can be designed and optimized for a specific type of air cooling.

The fins of heatsinks designed for convection air cooling should be as high as possible. This increases the surface area dissipating the heat. In this case, the distance between the ribs should not impede the natural circulation of the air flow between them.

If the heatsinks are positioned vertically one above another, remember that the air reaching the upper heatsinks with natural cooling will be already heated. In this case, it is recommended to install the heatsinks at an angle of about 30° to divert the air flow to a side.

Forced air cooling is used to dissipate more heat energy. The air passing through the heatsink with forced air cooling heats up less. In this case, the air flow can circulate through several vertically arranged heatsinks without compromising its efficiency. However, the large number of heatsinks creates significant resistance to air flow, reducing the fan efficiency. The value of thermal resistance $R_{th(h-a)}$ is highly dependent on the speed of the air directed through the heatsink.

When the air flow passes through the fins of the heatsinks it becomes turbulent, increasing the efficiency of heat transfer from the fins to the air stream.

The heatsink radiator can be roughly divided into two parts:

- the base of the radiator, where the device is mounted and where the heat energy is distributed, and
- radiator fins that provide the main heat removal by means of radiation and convection.

The value of thermal resistance of a heatsink is not constant since it depends on the difference between the temperature of the heatsink itself and the ambient temperature. "Better" heating of the heatsink occurs at higher dissipation power, thereby increasing the effective heat exchange area.

PROTON-ELECTROTEX JSC offers standard air heatsinks for the majority of its disc and stud devices that meet all the requirements described above.

14.3 Liquid Cooling

Liquid cooling of power semiconductors is used in cases where forced air cooling is not sufficient. Liquid cooling allows to remove more heat energy from the semiconductors than air cooling. Normally, the heat carrier in systems with liquid cooling is water or a mixture of water and antifreeze (eg ethylene glycol), more rarely oil.

When using heatsinks for liquid cooling, it is necessary to ensure the uniformity of the semiconductor's contact surface. A single water channel running through the center of the heatsink, or using a simple direct cooling path with laminar flow may not be sufficient for high power applications. The use of heatsinks with turbulent water ducts is preferred.

Distilled or deionized water must be used to prevent the build-up of deposits in the coolant passages. This will extend the life of the heatsink. Besides, such water has high ohmic resistance and reduces parasitic leakage currents.

Additionally, to avoid electrochemical corrosion in the liquid cooling system, it is possible to install a sacrificial anode that will oxidize instead of the coolant. Such electrode must be replaced after a certain time.

Heatsinks must be able to withstand the rated mechanical force applied to the devices without deformation.

14.4 Thermal Interface Materials

Thermal interface materials (TIM) are generally used for modules that have an insulated baseplate. If TIM is intended for use with a pressure-contact device (for example, a disc thyristor), such material must be electrically conductive. Otherwise it is better to avoid using TIM, as this does not always lead to an improvement in the thermal performance of the semiconductor-heatsink system.

The amount of heat that the semiconductor-heatsink system is able to dissipate is determined by its total thermal resistance. A significant contribution to this resistance is made by the thermal interface material applied between the module baseplate and the heatsink. Any material used as a thermal interface has its own thermal resistance R_{th} higher than that of aluminum or copper used to make the heatsink and the module baseplate. TIM compensates for irregularities, cavities and voids caused by imperfect surfaces. Air filling these irregularities interferes with normal heat transfer since it has low thermal conductivity.

Currently, there are many available varieties of thermal interface materials, with the following most common types:

- thermal greases;
- thermal pads;
- PCM, or phase-change materials.

There are the following general requirements to applying thermal paste:

- thermal paste must not contain solid particles;

- thermal paste must retain its properties throughout the entire operation of the device;
- the maximum temperature of the paste must not be lower than the maximum temperature of the semiconductor device under load (with a temperature margin of at least 10%).

The surfaces of the semiconductor and the heatsink must be cleaned and degreased before applying the thermal paste. It is recommended to use lint-free cloth and wear gloves. Avoid getting paste into the threaded holes as it can result in insufficient tightening torque.

Thickness of the paste layer can be measured with a special comb ("wet film comb", see Figure 34). The thickness of the paste is defined as the average value of the largest “coated” (or “wet”) tooth and the smallest “uncoated” (or “dry”) tooth.

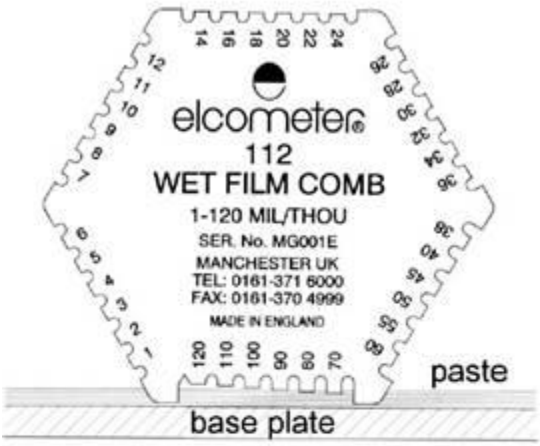


Figure 34. Wet film comb used to measure the thickness of thermal paste.

It is recommended to replace silicone thermal paste during every maintenance of the semiconductors.

There are no special requirements for thermal pads, including graphite ones.

When using PCM as the heat-conducting material, it is necessary to allow the material to spread evenly between the contact surface of the semiconductor device and the heatsink, therefore it is not recommended to carry out the first start-up of the unit at the rated power. In this case, the temperature of the module baseplate must be higher than the PCM’s temperature of the phase transition (usually 45°C). After the material distributes (2-3 thermal cycles), the unit can be started at rated power.

15 Storage and Transportation

All devices manufactured by PROTON-ELECTROTEX JSC are shipped in two types of package – external (transport) and internal. Shipping package complies with the Russian standards GOST 20859.1 and GOST 23216.

Figure 35. Cardboard transportation packaging containing semiconductors in internal packaging.

The internal packaging contains cardboard inserts that hold the devices and prevent damage during transportation.

Figure 36. Modules in internal packaging

Packaging of large diameter disc thyristors contains a plastic ring (Figure 37) that prevents the device from rotating inside the package when exposed to vibrations during transportation.

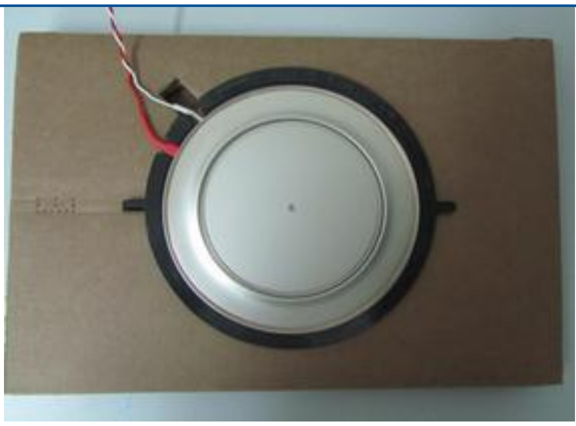


Figure 37. Disc thyristor in internal packaging.

It is allowed to transport the devices by all types of transport (land, air, sea) satisfying requirements of the storage group 4(Zh2) according to the Russian standard GOST 15150. If the devices need to be transported without packaging for some reason, the following requirements must be observed:

- avoid direct sunlight;
- avoid atmospheric precipitation, wind, sand or dust;
- avoid condensation.

The manufacturer is not responsible for damage to the devices during transportation without shipping packaging.

The ambient temperature during transportation must not drop below the minimum allowed storage temperature specified in the datasheet for the corresponding type of semiconductor device (for example, when transporting in unpressurized aircraft compartments). The lower limit of storage temperature for most devices is -60°C (-40°C for modules). For more detailed information refer to the datasheet or the passport for the related device.

All packaging is tested for vibration and shock loads during transportation in accordance with Russian standards:

- GOST 23216 (transportation conditions Zh)

75g – 2 000 impacts, 15g – 20 000 impacts, 10g – 88 000 impacts

- GOST 20.57.406 method 103-1.6 (without electrical load)

Frequency f = (50 ± 2) Hz

Acceleration a = 50 m/s^2 (5g) for tests in two mutually perpendicular directions and a = 100 m/s^2 (10g) for tests in three mutually perpendicular directions

The total test duration is 6 hours – 2 and 3 hours for two and three directions, respectively.

- GOST 18425

The devices must be stored in conditions meeting the requirements of GOST 15150 (group 4(Zh2)). The group 4(Zh2) allows to store the devices under cover or in rooms where fluctuations in temperature and humidity are similar to fluctuations in the open air (for example, in tents, metal containers without thermal insulation, etc.) located in macroclimatic regions with moderate or cold climate in the atmosphere of the first type.

In case of long-term storage, the devices must be packed in inner and transportation packaging. If it is impossible to store the devices in the packaging in which they were delivered for some reason, observe the same requirements as in the case of transporting the devices without packaging.

During storage, it is allowed to increase the values of the repetitive pulse current in the closed state and the repetitive pulse reverse current by 50%, and the pulse voltage in the open state by 20%.

PROTON-ELECTROTEX
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