

ALTERNATE CURRENT TRANSISTOR

Inventor: Ákos KUN, Electrical Engineer

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The a.c. transistor embodied in the invention is a semi-conductor element of bipolar character; owing to its symmetrical junction structure, the transistor is suitable for continuous regulating alternating electrical quantities without pulse shape distortion, as well as for switching such quantities at a high degree of efficiency.

In order to meet the ever increasing requirements of the industry, novel types of semi-conductor element are developed in quick succession by the electronic branch. The main driving power behind the very high rate of development is that the users' requirements in electronics are at all times higher than the actual level of manufacturing techniques.

After many different types of transistors have been developed and mass-produced for d.c. systems, demand shifted to the field of semi-conductor based a.c. control and switching elements.

The first achievement of the developing process was a four-layer diode /Fig. 1/, which was followed in quick succession by many more sophisticated designs based on it: two-way thyristor diode /diac/ cathode-control thyristor, anode-control thyristor, avalanche-type thyristor, photo-activated thyristor, two-way thyristor diode /triac/, thyristor diode closable by control electrode, thyristor tetrode and a number of other, less developed designs. Following from their fundamental characteristic, the multi-layer diodes of different designs function in a different manner than transistors, thus requiring an absolutely different circuitry as well for being used as control elements. The basic difference between the two types of semi-conductor element is that while pass-through capacity of transistors is infinitely variable from closed condition to saturation, the multi-layer diodes can only assume two conditions of operation: fully open or fully closed, thus being in this respect similar to the traditional diodes. This fundamental difference in operation has necessarily resulted in a variety of circuit layouts in multi-layer diode engineering. Such a special circuit includes a control unit as its main component, by means of

which two-way multi-layer diodes can be used not only as controllable switching elements, but also as control elements. Since the multi-layer diodes retain their diode character in any circuit, their control necessitated the development of various special circuits which control the angle of flow of the electric quantity passing through a multi-layer diode, instead of its amplitude. Consequently, in a.c. circuits there alternating electric quantities are continuously controlled as follows: the multi-layer diode is switched on by the control unit only in a specified phase of the electric quantity passing through the diode, and the novel electric quantity regulated in this manner is produced by the periodical addition of the split phases, i.e. by their effective value.

Continuous control of alternatic current is the simplest through a one-way thyristor diode; a practical solution is shown on Fig. 2, where loadability is max. 5 A, and range of continuous control Zero to 220 V. As apparent from the characteristic curves shown under the Figure, the simple cathode-control thyristor controls alternating current by two steps: first, the rectifying unit transforms alternating current to pulsating rec-

tified current, then - after phase-split control has been completed by the thyristor - the rectifier reforms the regulated electric quantity to alternating one. By means of the latest thyristor triodes /triacs/ developed from the former types of thyristor diodes it is significantly more simple to solve such tasks, since they render the transformation of alternating current to pulsating rectified current unnecessary, being suitable for working both ways through their composite junction structure.

Although the multi-layer diode control system is being accepted in ever widening fields, it has several disadvantages which hinder its further spread. Among others, these diodes are highly sensitive to overvoltage and overcurrent, as a result of which they are liable to be damaged due to careless operation. The rather complicated junction structure only enhances their sensitivity, and also significantly increases production costs.

All disadvantages mentioned before have been effectively eliminated by the a.c. transistor embodied in the invention, since in linear mode of operation no control circuit is necessary, as against the use of the multi-layer diodes. Owing to the fact that the method of control is amplitude

reduction instead of phase splitting, the voltage produced by the invention in linear mode of operation is free of transient peak voltages and pulse shape distortion alike. Since physical functioning of the junction structure of a.c. transistors is the same as that of the traditional transistors, let us first take a look at the functioning of bipolar junction transistors generally used in d.c. circuits.

Let us apply external forward voltage on the pnp-type transistor illustrated on Fig. 3. Since under a forward bias the emitter - base layer of any bipolar junction transistor is loaded in forward direction, and its collector - base layer in reverse direction, the junction transistor can be divided to two sections. The first of these is the base - emitter layer, loaded in forward direction; as regards functioning, the first section can be regarded as an asymmetrically doped diode. Since this type of doping plays a very important role in the transistor effect, let us first take a closer look at the junction structure of the traditional semi-conductor diodes.

As is known, in dead condition of any diode a mutual compensation process occurs between the

two semi-conductor layers of opposite charge carrier content, under the effect of which neutral character of the junction is terminated, the "p" side getting under negative potential, and the "n" side under positive potential. Owing to the fact that the above-mentioned diffusion process is self-limiting, after some time equilibrium occurs between the majority charge carriers of the two layers, while diffusion potential arises in the junction. If differential concentration is the same for the minority and majority charge carriers in the two layers, symmetrical diffusion occurs in the junction, i.e. diffusion voltage is evenly divided between the two semi-conductor layers of different charges but identical concentration level. If the levels of concentration are different, i.e. when differential concentration of the minority and majority charge carriers within one of the layers is lower, an offset asymmetrical diffusion occurs in the junction, i.e. under the effect of diffusion the discharged layer occurring in the junction is shifted off to the layer of lower concentration level to a degree which corresponds to the difference between the concentration levels of the two layers.

Assuming that the two layers are symmetrically doped, let us now apply an external forward voltage controllable down to zero on the diode. By gradually increasing external voltage above a certain level, conductance is started between the two semi-conductor layers in accordance with the known forward-oriented characteristic of the diode. Termed as threshold voltage, that voltage level permits gradual diffusion of charge carriers into each other by overcoming the potential wall established in the junction by diffusion voltage. With external voltage increased, also the number of charge carriers flowing through the junction increases, thus raising the forward current intensity of the diode. If this quickly increasing rate of charge carrier stream is not checked, a further increase of forward voltage results in a thermal breakdown between the two semi-conductor layers, ruining the diode. In order to prevent thermal breakdown, a series resistor need to inserted in the path of forward voltage, for maintaining the flow of charge carriers at an appropriate level.

Let us now see what happens in the diode if concentration levels of the two semi-conductor layers differ from each other. As apparent from

what has been stated so far, in this case an asymmetrical diffusion field occurs in the junction, shifting off to the layer of lower concentration level to a degree which corresponds to the difference in doping.

Reverting to the asymmetrically doped emitter - base layer shown on Fig. 3/a, the so-called diode effect occurs there as well under external forward voltage, but in a slightly different manner than mentioned before. This is so because in this case - owing to the offset diffusion field - the majority charge carriers in the emitter layer need overcome a much lower resistance than the charge carriers in the base layer for getting recombined with the negative electrons of the base layer. For in order to pass over into the junction, the not very numerous charge carriers of the base layer must first overcome the relatively very high diffusion voltage shifted over into the base layer, so as to be able to recombine thereafter with the majority emitter charge carriers streaming into the junction. In accordance with these asymmetrical conditions, only a single stream of differential rate can occur between the two semiconductor layers, resulting in an emitter current

intensity which significantly exceeds the base current intensity produced by the majority charge carriers of the base layer. As regards the transistor this means that the large number of majority charge carriers coming from the emitter are prevented from getting recombined in the junction by the low number of base layer charge carriers, whereas their bulk remain stacked up at the edge of the discharged layer. Flowing out of the base layer, the not very numerous recombined charge carriers actually are the base current of the transistor.

Before following the further role of the emitter majority charge carriers accumulated in front of the discharged layer, let us take a look at the things occurring in the collector layer.

As it has become apparent before, a diffusion process involving mutual compensation occurs between the two semi-conductor layers in dead condition of the circuit. However, the process occurs in this case not only between the two semi-conductor layers of opposite potentials, but also between the p-type collector layer and the n-type /metallic/ collector armature. In view of the metallic character of the armature, the level of concentration is

almost infinitely higher there than that in the semi-conductor layer, as a result of which a significantly offset asymmetrical diffusion field is generated in the junction. That diffusion field then sucks almost all majority charge carriers off the collector layer, thus electrically neutralizing the section of collector semi-conductor layer falling outside the diffusion field. On applying external reverse voltage on the metallic - semi-conductor layer, the rest diffusion voltage significantly increases, as it occurs with semi-conductors in general. Since that effect narrows down the diffusion field in the junction, the risk of puncture is not enhanced by the increase of external voltage. The avalanche effect triggered off by field emission is, however, still there, likely to ruin the junction transistor in case of external voltage exceeds a certain level.

The case is slightly different from the former if an n-type semi-conductor layer is coupled to the metallic armature of the collector /n-p-n-type transistor/. Since the presently homogenous majority charge carriers prevent the occurrence of a spontaneous diffusion in the junction in dead condition, the layer of the opposite potential

necessary for reverse-oriented diffusion is produced in npn-type transistors by external reverse voltage. This is so because a metallic conductor can be charged to either potential to a very high potential level, this occurring for positive potential in the form of an apparent discharge of electrons. Since the very powerful diffusion voltage generated by reverse voltage in the collector junction is always of the opposite potential level than the majority charge carriers coming from the emitter, the advanced diffusion field applied such a strong suction effect on the emitter majority charge carriers accumulated in ~~the base~~ the discharged base - emitter layer, and being incapable recombine, that they pass through the base - emitter junction at a very high speed, getting made on the collector armature. Fast travel of the majority charge carriers from emitter to collector is also facilitated by the phenomenon mentioned before, according to which once diffusion equilibrium has been established, the areas falling outside the charge range become electrically neutral. Accordingly, in our case the emitter charge carriers need not overcome the repulsive effect of the majority charge carriers of identical polarity in the

collector layer. ~~_____~~

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~~_____~~ Consequently, functioning of the bipolar junction transistor can be regarded as an asymmetrically doped diode, supplemented with a metallic - semi-conductor contact.

Let us now return to the base - emitter layer of the pnp-type transistor, located under forward bias and illustrated on Fig. 3/a. As follows from the particulars of functioning described before, once forward voltage has reached the base - emitter threshold, the charge carriers start streaming in the transistor in the main and auxiliary directions alike. Let us now gradually increase the value of U_{EB} up to the supply voltage coupled to collector load resistor. With the forward voltage gradually increased, the rate of flow of main and auxiliary charge carriers quickly increases, in accordance with the known forward-oriented characteristic of diodes and the output characteristic curve of transistors. This sudden increase of transistor effect is rendered physically feasible by the fact that - as against the reverse-oriented load - the

forward-oriented potential gradually decreases the diffusion potential that occurred between the semiconductor layers. Thus in the present case, the potential barrier separating the two layers is getting lower with the decrease of the diffusion potential of the emitter - base - layer, requiring less and less power for letting the charge carriers accumulated at both sides of the junction recombine with each other in the discharged layer. Although various losses result in gradually cutting the efficiency of the transistor, thus linearizing the supposedly ideal output characteristic after a while the ratio of minority and majority charge carriers remains basically the same. That advantageous ratio according to which for maintaining the stream of charge carriers in the main direction it is sufficient to use only a fraction of control current which, in turn, depends on the current amplification factor of the transistor, remains in force until the transistor is regulated to saturation voltage by the increase of forward voltage. With voltage U_{EB} further increased, the transistor effect gradually ceases, and the diode-like function of the base - emitter layer comes to the fore. As soon as the base potential /which is much in excess

of collector potential/ reaches the level of breakdown voltage for the base - emitter layer, an extremely high field emission occurs through the diffusion field which has been almost completely decomposed by now, and under the effect of the process the valance electrons are released from their bonds. That avalanche-like process goes on until the transistor is ruined by a thermal breakdown caused by the very powerful emitter - base current.

Let us now cut supply voltage to the level permitted for maximal reverse voltage of the emitter - base layer /Fig. 3/b./. Let us increase the forward voltage of T1 as described before from $U_{EB} = U_{CE}$ up to the supply voltage coupled to the collector load. From that point onwards, the transistor dealt with here gradually turns from a controllable semi-conductor element into a low-capacity diode, at least as regards its physical functioning. The majority charge carriers leaving the emitter chose the line of least resistance in an increasing number, instead of streaming towards the collector load, thus making on the base armature having a higher potential level. From then on, the transistor will function in this range of operation as a rectifying diode, with base current limiting

resistor R_b gradually taking over the role of the load of the emitter - base diode, thus relieving the transistor which has controlled so far through its control current.

Let us now measure the first range of operation on the set-up illustrated on Fig. 3/b. By gradually increasing forward voltage U_{EB} , the transistor effect described before is induced, i.e. the majority charge carriers starts streaming from emitter to base, this requiring only a minimum of base current consumption. As the following step, let us bridge over the base current limiting resistor, by directly coupling the base armature to the collector armature. Since in the present case supply voltage is not higher than maximal reverse voltage permitted for the base - emitter layer of the transistor, the avalanche effect described before will not occur at that point either. Instead of this, the transistor fully opens, functioning as a diode with increased capacity. As regards its physical parameters, that diode is the same as the one represented by the base - emitter layer of the transistor, with the difference that the output of the collector semi-conductor layer is transferred to the base layer having a much lower capacity.

Since the rate of that process depends on the rating of resistor R_b , the transistor will function over the entire range of operation as a high - capacity diode continuously controllable through external control voltage.

The a.c. transistor - embodied in the invention - dealt with here actually operates on the principle described before. Since the traditional transistors can be used in d.c. circuits in both normal and inverse modes of operation, although with a lower efficiency in the latter, nothing prevents our transistor from being subjected to a.c. load as well, this actually consisting of periodically repeated normal and inverse loads. However, in order to render the continuously controllable power diode shown on Fig. 3/a be capable of functioning in both d.c. and a.c. circuits, its junction structure must be made symmetrical. This is absolutely necessary because alternating current has no definite polarity, as a consequence of which an a.c. transistor must be loadable at both the collector end and the emitter end. Failing to meet that fundamental condition, the traditional transistors can be used for a.c. control only in a one-way circuit. This is so because on being used in a two-way circuit. This is

the very big difference obtained between the normal and inverse efficiencies would result in a very high wave shape distortion. Another characteristic which also hinders the application of traditional transistors in two-way circuits is their low emitter - base reverse voltage, practically inhibiting their use in circuits having a potential in excess of 5 to 7 V.

Consequently, the most important condition of the design of the a.c. transistor embodied in the invention is to ensure identical doping of the collector and emitter layers, for maintaining the symmetry of the set-up. This represents no major technological problem, but in order to facilitate the use of a.c. transistors at higher voltages as well, reverse voltage must be increased at both ends. This requirement, in turn, clashes with the lowest possible forward voltage deemed desirable for semi-conductors in general, thus also contrasting with efficiency, since with the increase of doping the reverse voltage tolerance of junctions decreases.

For solving the problem, a.c. transistors are made by means of the so-called epitaxial layer process, similar to the one adopted for making p-n-type

diodes. The method essentially consists of applying a thin layer of slight doping but of a crystal orientation similar to the neighbouring layers between the highly doped layers and the control layer by the epitaxial process. Function of the slightly doped layers is then to ensure appropriate break-down voltage towards the control layer. Since the a.c.

transistors, abbreviated ACTs, can be put to use both ways by means of resistors $R_1 - R_2$, and their two main electrodes each can be interchanged at like owing to the symmetry of the design, in the present case it would be senseless to adhere to the words emitter layer and collector layer any longer. It is, therefore, recommended that these layers be called work layers from now on.

Similarly to the d.c. diodes treated before, passage capacity of ACTs can be continuously controlled by means of resistor $R_1 - R_2$ /Fig. 4/a/. The highest passage capacity is obtained at zero control resistance, i.e. with the control electrode short-circuited on one of the work current and current amplification factor, just like in the traditional transistors, the gradual decrease of control voltage producing control current duly results in gradually closing the ACT. Zero level, i.e.

cut-off state, is achieved when control voltage just layer being subjected to forward voltage.

Since the reverse voltages of the control and work layers of the ACT are completely symmetrical, their level being never lower than the maximum of the a.c. voltage to be controlled, ACTs can be very well used as high-capacity switching elements, similarly to the multi-layer diodes of traditional design. The difference, however, is that control is feasible not only from an a.c. supply mains, but - by means of a low-capacity galvanic separation a.c. transistor - also from d.c. supply. Quickness of control is also enhanced by the fact that while the traditional thyristors could be switched off after ignition only by breaking the main circuit, ACTs can be switched off in any phase of a.c. supply by simply cutting the control circuit.

As apparent from the time curves on Fig. 4/a, the present design of ACTs can pass and control only one of the half periods of a.c. voltage. Consequently, the set-up shown here need by extended with a full-wave bridge rectifier scheme /Fig.2/ in order to be capable of controlling both period halves. Although the ACT embodied in the invention could be made suitable for controlling both half

periods also without the use of a full-wave bridge rectifier scheme, but only at the price of installing a relatively complicated control unit, the function of which is to couple the control electrode alternately to one or the other work electrode, in accordance of the alternating frequency of a.c. voltage supply. In view of the fact that the ACT embodied in the invention actually controls itself through resistors R1 and R2, it need not be provided with a separate control circuit, as against the multi-layer diodes. As apparent from Fig. 4/a, the ACT controls through amplitude reduction instead of phase splitting, as a result of which the costly R-L-C filter elements absolutely necessary in multi-layer diode engineering can be disposed of in this mode of operation. Moreover, ACTs can be produced not only in the npn-design, but also in the pnp-design /Fig. 5/. Also the symbols deemed practical for marking the circuit elements are shown on Fig. 5. Following from the symmetrical layout, the traditional polarity signal taken over from transistor engineering has no real meaning here, and its application on one of the work layers only serves for clearly marking the work electrode to which the control electrode should be coupled

for using the ACT in positive or negative sense.

Similarly to the two-way thyristor triodes, the ACT embodied in the invention is suitable for controlling ripple voltages and periodically alternating voltages alike /Fig. 4/b/. Actually made up of two ACTs and having a composite junction structure, the control element features the advantage over the triac that it can automatically control itself, and since the amplitude reduction control system causes no wave-shape distortion at all, the circuit illustrated on Fig. 4/b can be regarded as a continuously controllable electronic transformer as well. The small voltage step visible on the zero line of the transmission characteristic curve is caused by the threshold voltage of ACT, its value being max. 1 V. The basic circuits and practical symbols of the electronic transformer are shown on Fig. 6. Although the production techniques of the complemented ACT /CACT/ are more sophisticated and costly than those of the equivalent variant /EACT/, the former entails the advantage of being suitable for continuous control by means of not only a pair of tandem potmeters, but also a plain rheostat coupled in between the two control electrodes.

If appropriately designed, the composite junction structure ACTs can be used also as voltage stabilizers with a.c. supply units /transformers/. The ACT embodied in the invention can, however, be used not only for controlling periodically changing quantities, but also as a controllable rectifier element. Illustrated on Fig. 7, the electronic transformer and rectifier circuit is based on the afore-mentioned principle. The set-up supplies not only controlled mains voltage, but also a two-way rectified one. Similarly to the single-capsule Graetz cubes, the circuit can be manufactured as an enclosed six-pole element, for a specified a.c. voltage input and maximal output current intensity. By replacing the external resistors marked R1 and R2 with a low-capacity a.c. transistor each, and controlling the control electrodes of the transistors by means of a plain potential supervisory circuit located in the output circuit, the invention electronic transformer and rectifier circuit can be easily transformed to a d.c. stabilizer. Since the fully electronic circuit shown on Fig. 7 is incapable of acting as a resistive coupling, appropriate care is necessary to couple it in the right phase position. In view of the reversability

of mains plugs, this problem must be solved mainly with portable instruments; if external insulation is adequate, it is sufficient to ensure the right phase position only on servicing the instrument. The lack of resistive coupling represents no problem with industrial equipment, since phase - zero position can be permanently set on stationary instruments.

Since the invention electronic transformer and rectifier circuit shown on Fig. 7 has been set to produce positive output voltage, for producing negative potential, the circuit elements need be reversed to provide adequate shock-protection.

Efficiency of the ACT embodied in the invention is the higher the smaller the difference between input voltage and output voltage. This is so because thermal losses of the ACT increase with the increase of transmission ratio, and it would render operation uneconomical in linear mode of operation, under strong control. Consequently, under an efficiency level of 60 or 70 per cent, linear control should be reversed to switching-type control, similar to the one used with multi-layer diodes. Operating on the phase splitting principle, the latter facilitates operation at a

fair degree of efficiency even at high transmission ratios. Since in that mode of operation, ACTs are self-controlled by means of a zero to 180 degree phase shift circuit, it is more simple to establish control circuits with them than is customary with the impulse-operated control circuits generally used in multi-layer diode engineering.

ACTs should possibly be made out of silicon as starting material, and although the symmetrical design requires certain modifications in the manufacturing process, the latter is essentially the same as the epitaxial - planar method. Thus ACTs can be produced for different reverse voltages and work currents in both low-capacity and high-capacity variants.


CLAIMS OF PATENT:

- 1/ Alternating current transistor, characterized by a bipolar symmetrical junction structure /1/ and a practical system of symbols /2/.
- 2/ Alternating current transistor, as claimed under Para. 1, and characterized by an npn-type symmetrical junction structure /1/ and a practical system of symbols /2/.
- 3/ Alternating current transistor, as claimed under para. 1, and as illustrated on Fig 5/a,

characterized by a pnp-type symmetrical junction structure /1/, and a practical system of symbols /2/.

- 4/ Alternating current transistor, as claimed under Para. 2. and as illustrated on Fig. 6/a, characterized by an npn-type composite junction structure /1/, and a practical system of symbols /2/.
- 5/ Alternating current transistor, as claimed under Para. 3, and as illustrated on Fig. 6/b. characterized by a pnp-type composite junction structure /1/ and a practical system of symbols /2/
- 6/ Alternating current transistor, as claimed under Para. 2, and 3, and as illustrated on Fig 6/c, characterized by a complement-type composite junction structure /1/ and a practical system of symbols /2/.
- 7/ Controllable rectifying diode, as illustrated on Fig. 4/a, and characterized by an alternating current transistor /1/ as claimed under Para. 2 and 3, and resistors R1 and R2 /3/ and /4/, by means of which it is suitable for single-way rectification of a.c. voltage, and controlling such voltage without any wave-shape distortion.

- 8/ Electronic transformer, as illustrated on Fig. 4/b, and characterized by an alternating current transistor /1/ as claimed under Para. 4, 5 and 6, and resistors R1 and R2 /3/ and /4/, by means of which it is suitable for controlling a.c. voltage without any wave-shape distortion.
- 9/ Electronic transformer and rectifier circuit, as illustrated on Fig. 7, and characterized by an alternating current transistor as claimed under Para. 2 and 3 /5/ and /6/, as well as diodes D1 and D2 /7/ and /8/, by means of which it is suitable for rectifying a.c. voltage in a controlled manner.

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Ákos KUN

SUMMARY

The a.c. transistor embodied in the invention is a semi-conductor element of bipolar character, suitable for controlling alternating electrical quantities without continuous pulse shape distortion, as well as for switching such quantities at a high degree of efficiency. Following from its simple junction structure, the ACT is free of all drawbacks characteristic of the thyristors and triacs used in multi-layer diode engineering. Owing to its special advantages, the invention ACT can also be used as a rectifying diode and electronic transformer.