Application Oriented Testing of Power Semiconductors in Quality Control

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Abstract
Due to the development of power semiconductor and converter technology a partially new characterization of today's semiconductor devices is required which takes into account the particular features of the devices and their typical and possible applications. This paper exemplarily derives which data are needed for IGBTs; it shows test methods to obtain them. Furtherly test equipment recently developed to perform these tests on fast switching devices is presented; its operational principles are explained. The equipment has been introduced into IGBT production which is shown by presenting measurement results obtained in regular volume tests.

1 General

The recent test technology permits to optimize power semiconductor and converter industrie's product quality being a major factor of competitiveness. Testing is required for quality assurance in all phases of production. This paper gives an insight how to economically and reliably test power semiconductors. Furtherly the knowledge of test and characterization techniques is also helpful during product development verifying a new layout when the generalized information of specified data is transferred to a particular application. Thus this paper is also intended to faciliate understanding at the interface between manufacturers and users of power semiconductors with the aim of providing and assuring a characterization suitable for the state of the art applications.

The draft for an international standard [1] is related with the subject of this paper which points out new developments of tests and test equipment. It is not intended to repeat the contents of the standard. Instead the information given proceeds beyond the general knowledge which is used as a base — for example by applying mainly the standardized symbols.

For the sake of briefness the paper only deals with the characterization of the actual state of the power semiconductor component. Questions like long term reliability — for example power cycling —, long term influence of environmental conditions — for example high temperature and humidity — are not subject of the paper although big effort is spent in the areas of development and production to assure long term stability and quality of power semiconductor products satisfying any application.

2 Characterization for Recent Applications

Two major technical issues concerning the power semiconductors are considered during the design phase of converters: Reliable operation under regular conditions and a certain amount of intrinsic safety under fault conditions, both having to be characterized as explained in the following subsections:

2.1 Regular Operation

The power semiconductors must be properly sized for reliable operation according to the specification of the nominal load capability of the converter they are operated in. Their function is usually determined by parameters as maximum applicable voltage, current and power losses according to

$$T_{Jmax} \geq T_J = R_{thJA} \cdot \sum_i P_{Vi} + T_A \qquad (1)$$

with P_{Vi} being the conducting, blocking, turn on and turn off losses respectively. The calculation with the steady state value R_{thJA} may be replaced by taking into account a network of thermal capacities C_{thi} and resistances R_{thi} according to figure 1.

The stress of the power semiconductors thus can be estimated, calculated and simulated using the data as mentioned. The influence of intended or unintended parameter variations on the behaviour of the converter can be predicted up to a certain amount — such as a variation of an IGBT's gate resistor affects its switching losses according to equation 1. Depending on the topology of the converter and the version of power semiconductor device used, free wheeling diodes may have to be taken into account additionally.

The shape, value and duration of forward current, applied voltage and possibly heatsink temperature depends on the converter's particular topology, its layout and the load: these application specific parameters thus cannot be furtherly considered for power semiconductor characterization. However characterization data should fit to these operational conditions in a way all required values can be derived from specified values as exemplarily described in [2] and executed in [3].

2.2 Irregular Operation

Besides the regular operation as described in section 2.1 some irregular operation may occur: It may be caused by external events such as a short circuited output or by internal disturbances such as the control faultly turning on two switches of one phase leg at the same time and thus shorting the intermediate circuit. This kind of operation does not need to be considered for details in operational behaviour; it is however important to be able to estimate the consequences of a failure leading to irregular operation: Will the converter for example be seriously damaged or will it return to regular operation after the fault has been fixed?

The characterization of power semiconductor devices for irregular operation thus should specify which conditions the particular device will stand and exceeding what limits may lead to catastrophic failures.

3 Data for Generally Applicable Characterization

A system of comparable characteristics has been derived to obtain the necessary generalization of application specific data of the power semiconductors. It is briefly listed in the following; the examples used are intended to faciliate understanding of the general descriptions:

1. constants being generally valid

   This set of characteristics consists of constants like the maximum allowable junction temperature not to be exceeded as defined by chip design. Besides there are constants like the thermal resistance junction to heatsink R_{thJK} at specified mounting conditions, given by mechanical constants like mounting torque or force.

2. functions, usually of several variables, describing the behaviour for particular operational points

   There are four operational points to be considered:

   (a) blocking state

   A well known function used to describe blocking state gives leakage cur-

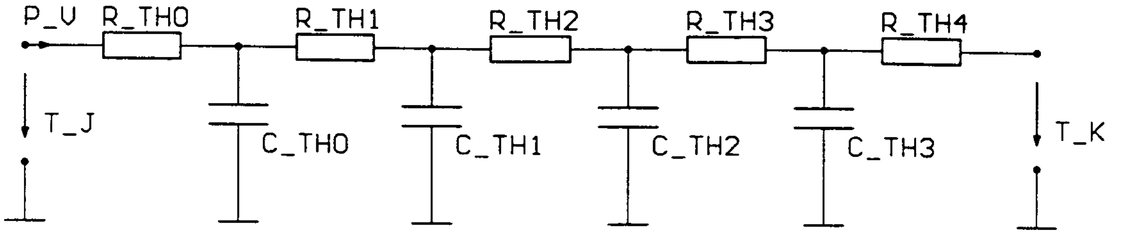

Figure 1: example for a thermal equivalent circuit junction to heatsink

rent according to:

$$I_{AK} = I_S \cdot \left(e^{\frac{e \cdot U_{AK}}{k \cdot T}} - 1\right) \qquad (2)$$

It is however mainly valid for the p-n junction of a diode while characteristics of an IGBT or other more complex devices cannot be calculated this easily. So the function of leakage current depending on blocking voltage often has to be specified with parameters like gate voltage and temperature. The knowledge of leakage permits to calculate blocking losses according to equation 1. Especially in case of diodes the thermal runaway as described in [4] can be critical because equations 1 and 2 describe a positive feedback.

(b) transient state of turn on

The most important characteristics are switching energy and times; they are mainly influenced by blocking voltage before turn on, current after turn on, the driver's voltage and resistance, the kind of load and temperature. In case of commutation from a free wheeling diode to a transistor the former strongly influences the turn on energy of the latter.

(c) conducting state

The conducting state is usually characterized by forward voltage in dependance of forward current with the parameters gate voltage and temperature. For power IGBTs are designed for switched mode the desaturation characteristic, expressed by threshold voltage, has to be considered.

(d) transient state of turn off

The characterization corresponds to the one for turning on as described in item 2b; the influence of a free wheeling diode however is less important.

3. maximum ratings for typical sequences of operational points

This specification is often given for non repetitive mode. The information provided is mainly needed for an estimation of irregular operation according to section 2.2.

A typical characterization of this type is short circuit: The device is turned on, shorts a voltage source in conducting state, and is turned off again. Usually the source voltage, the driver's voltage and resistance, the temperature and the duration of turn on are specified which the device will stand.

The most common characteristics are summed up in table 1, the left column giving the name and the center column the symbol and possible parameters. These comparable characteristics have been derived to obtain the necessary generalization of application specific data of the power semiconductors.

The remarks referring to the functions in the right column of table 1 refer to the execution of tests to obtain the respective characterization. Two types of tests can be distinguished:

1. static tests

Measurement times are significantly longer than the time constants of the device which means steady state operation is characterized. These tests usually are executed with either high voltage or high current to be applied to the device.

2. dynamic tests

   The transient intervals of switching on and off can be characterized by these tests. So the device changes state from high voltage and low current to low voltage and high current or the other way round.

   The characteristics for sequences in table 1 belong to this group, too, because the sequences are based on switching between different states, usually with the aim to finally turn the device off safely.

These different kinds of tests will be furtherly considered in the following:

4 Measurement Methods and Testers

4.1 Static Testing

As mentioned in section 3 static testing is usually executed with high voltage and low current or vice versa which means energy dissipation is quite small. A variety of automated test equipment is available for this purpose. The optimization between the contradictuous aims of short test times and high accuracy is an engineering task.

Static testing helps to detect faultly chips in early states of production process. So several static tests are executed beginning at the silicon wafers and ending with the power semiconductor components being completely assembled. The significance of the results of static measurements helps to assure an optimum quality level at relatively low expense.

However these state of the art test techniques shall not be furtherly considered in this paper being intended to describe new results.

4.2 Dynamic Testing

4.2.1 General

Dynamic tests incorporate high and low voltages and currents respectively in the same test sequence. This makes measurements difficult for several reasons: Resolution is determined by the high amplitudes and thus limits accuracy at low values. This is a severe problem determining switching energies — the standardized integration intervals are defined by full scale and 2 % voltage or current limits respectively. Furtherly the amount of energy stored in the test equipment is much higher. This would not be a problem executing some non repetitive tests with the purpose of characterization for datasheets in laboratory. If dynamic tests however are introduced in production as a means of quality control, the protection of operators and equipment must be adapted to the high number of pieces tested. Usually a limitation of energy dissipated in case of a failure of the device under test is required.

Two testers recently developed in particular for IGBTs and similar devices are presented in the following:

The schematic of a tester for general purpose dynamic testing can be seen in figure 2. The device under test on the right — the schematic shows a module in phase leg configuration — is controlled by two gate drivers Tr_1 and Tr_2. It is connected to an intermediate circuit. The ohmic or inductive load is connected to its positive or negative potential by the switches S_1 or S_2, depending on which transistor — T_2 or T_1 — is going to be tested. The switch T_T seperates most of buffer capacity in intermediate circuit in case of a failure of the device under test. Voltages and currents are monitored during the test sequence: afterwards the waveforms are analyzed by a computer. Values like the switching energies E_{on} and E_{off} — see table 1 — can be calculated. The operator obtains a bin classification of the device under test, at least a pass - fail information as needed for production purposes. Furtherly the measured and calculated values are logged for statistical interpretation

Table 1: list of characterization data with respect to application and testing

name	symbol	remarks
	constants	
mechanical	M_{mount}	for stability and thermal contact
thermal interface	R_{th}, C_{th}	under specific mounting conditions
max. junction temp.	T_{Jmax}	defined by chip design
	functions	
forward voltage	$U_{CEsat}(I_C, U_{GE}, T_J)$	high current, low voltage static test
threshold voltage	$U_{GEth}(I_C, T_J)$	low voltage static test
breakdown voltage	$BU_{CE}(I_C, T_J)$	high voltage, low current static test
leakage current	$I_{CES}(U_{CE}, T_J)$	high voltage, low current static test
turn on/off energy	$E_{on/off}(I_C, U_{CE}, U_{GE}, R_G, T_J, Load)$	high voltage and current switching test
turn on/off times	$t_{don/ri/doff/f}(I_C, U_{CE}, U_{GE}, R_G, T_J, Load)$	high voltage and current switching test
gate charge/capacity	$Q_G/C_{ies/oes/res}(U_{CE}, U_{GE}, f)$	switching test
	sequences	
RBSOA	U_{CE}, I_{CM} at U_{GE}, R_G, T_J	maximum non destructive values
short circuit	U_{CE} at t_{on}, U_{GE}, R_G, T_J	maximum non destructive values

in the process of permanent quality assurance. The tester is controlled by software which gives the opportunity to program a variety of test sequences and conditions. The programmer however must be aware of the high complexity of the system which requires a high amount of experience to create reliable test plans. The time invested here is saved during volume testing in production and the survey of production results.

The operational behaviour of a tester according to figure 2 may become unsatisfactory in case of test sequences to assure maximum non destructive values according to table 1. Due to its complex hardware and control it is sensitive to disturbances, for example oscillations, that may occur at potentially destructive tests. A development was carried out to overcome this problem by creating a very rugged short circuit tester according to figure 3. Its control renounces on a feedback. Any disturbance of the measurement by a series switch as T_T in figure 2 and the possible failure of this switch are avoided by simply limiting the energy stored in the capacitors C_1 or C_2 the device under test T_1 or T_2 respectively is connected to

$$W = \frac{1}{2} \cdot C \cdot U^2 \quad \text{with} \quad C = \frac{I_{max} \cdot T_{short,max}}{\Delta U_{max}} \tag{3}$$

where C is the capacity, I_{max} the maximum short circuit current to be expected for passing devices, $T_{short,max}$ the maximum short circuit time used and ΔU_{max} the maximum permitted voltage decay during short circuit time. The mechanical layout of power section with copper plates provides low inductance; thus the test conditions highly correspond to the ones in a converter the power semiconductor device is designed to operate in.

In the following some measurement results are presented: The waveforms explain the above statements and show the possibilities of the new dynamic IGBT testers as introduced. There are three subsections, each dealing with a particular type of power semiconductor component with its special requirements of testing to be covered.

4.2.2 Discrete Power Semiconductors

As figures 2 and 3 show the testers are usually designed for module testing which means the device under test consists of at least one IGBT and its free wheeling diode — T_1 and D_2 or T_2 and D_1 respectively. There are some discrete products of this type, for example IXSN35N120AU2/3 in Minibloc/SOT227 package, however the majority of discrete IGBT devices only consists of one switch, occasionally

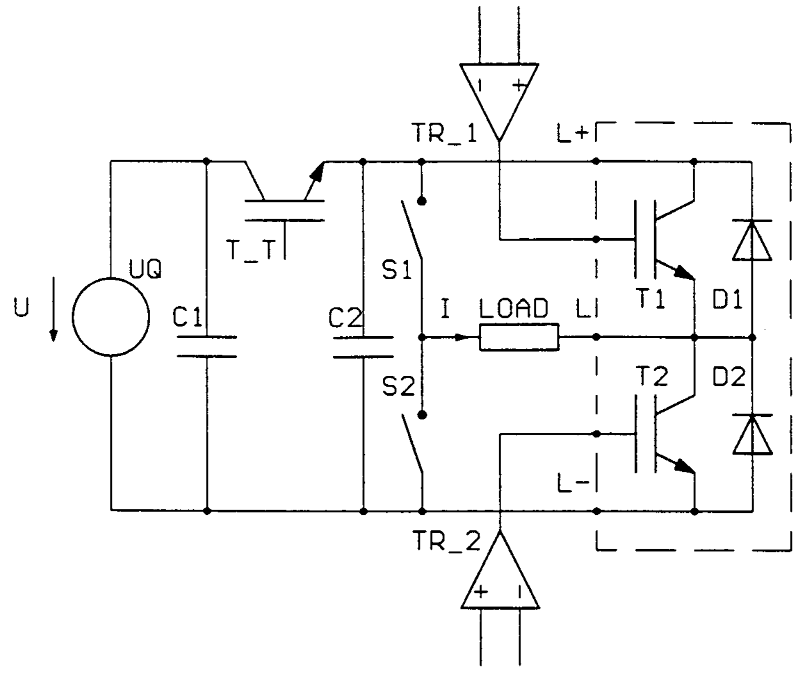

Figure 2: tester for resistive or inductive switching

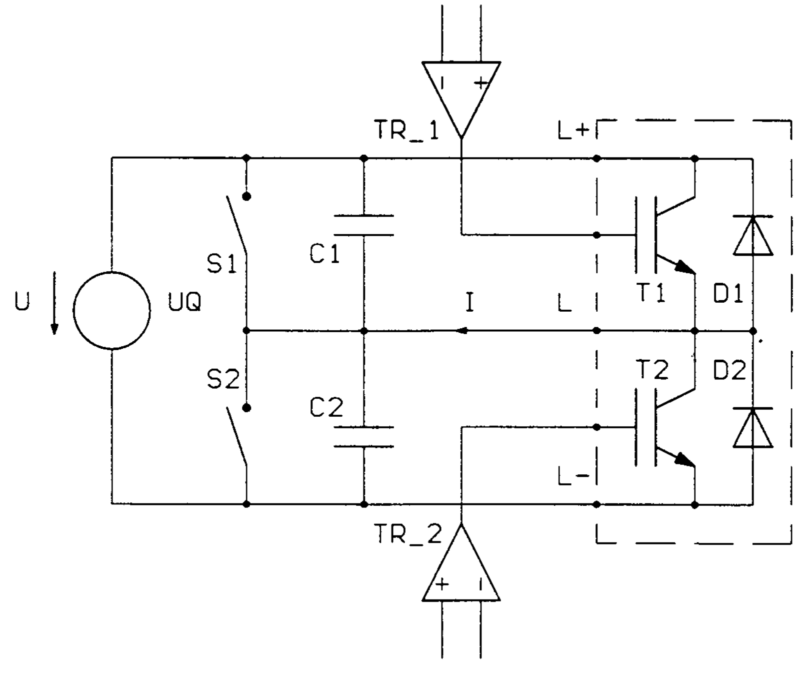

Figure 3: tester for short circuit test

of bidirectional type in case an anti-parallel free wheeling diode is implemented. This means the device under test is connected as T_1 or T_2 respectively to the tester and the free wheeling diode D_2 or D_1 of the appropriate type is added externally in the test fixture if needed.

Figure 4 shows the waveform obtained at a resistive switching test with a discrete IGBT using a general purpose dynamic tester as shown in figure 2. It is turned on at a voltage of intermediate circuit of $U_Z = 600\,V$ with a resistive load of $R_{load} = 20\Omega$ leading to a collector current flow of $I_C = 30A$ during the turn on interval of $t_{on} = 10\mu s$. Gate voltage is $U_{GE} = 15V$ in on state and $U_{GE} = 0V$ in off state respectively, thus ensuring passing devices' saturation and safe turn off.

4.2.3 Power Semiconductor Modules

As explained in section 4.2.2 dynamic testers are most commonly designed for use with modules containing IGBTs or similar switches and free wheeling diodes. The current to be switched by the device under test usually is higher in case of modules than in case of discrete components due to the formers' higher current capability.

Figure 5 shows the collector current waveform of an IGBT module with a nominal current of 200 A during short circuit test with a tester according to figure 3. The IGBT desaturates and thus limits short circuit current to almost $\hat{I}_C = 2000A$ peak and $I_C = 1750A$ continuous in the test interval of $t_{on} = 10\mu s$. With the gate voltage going back to $U_{GE} = 0V$ the IGBT safely turns off this huge current.

As a comparison figure 6 shows a similar waveform, however the device failing to turn off. Collector current quickly rises which proves it to be limited only by the device under test. The tester does not limit the current in this range, on the contrary the high rise rate of collector current $\frac{dI_C}{dt}$ shows tester circuit's inductance to be very low. The test conditions thus are adapted to the worst case in an application.

This design of a short circuit tester has proven a good operational behaviour in connection with a high reliability, testing passing and failing devices although the requirements are ambitious. Customers can be sure to obtain very rugged devices having passed the dynamic short circuit test in production.

4.2.4 Intelligent Power Semiconductor Modules

Intelligent power modules containing driver and possibly measurement circuits in addition to the power semiconductor chips have an increasing market share. This causes new requirements in testing because logic functions — for example reset inputs and fault outputs — and low voltage signals have to be checked additionally. The proceeding analyzing measured data also slightly differs dealing with intelligent modules instead of standard modules: Some parameters such as gate voltage U_{GE} according to table 1 cannot be influenced and thus are not given, instead other values as driver delay time or fault lockout time are of interest for the applications.

Figure 7 shows a simple example for a test of an intelligent power semiconductor module of IXYS VIE type. With double pulse inductive switching the function of the power semiconductor chips — IGBTs and diodes — and the driver circuitry controlled by a logic input signal can be checked.

5 Conclusion

Fast switching power semiconductors require partially new characterizations, test methods and testers. This paper has shown recent developments in this field. New measurement equipment has been introduced to adapt the characterization to the needs of the applications and to assure an optimum product quality. Further progress can be achieved by optimizing user friendlyness and reliability of characterization data, methods and testers in the course taken.

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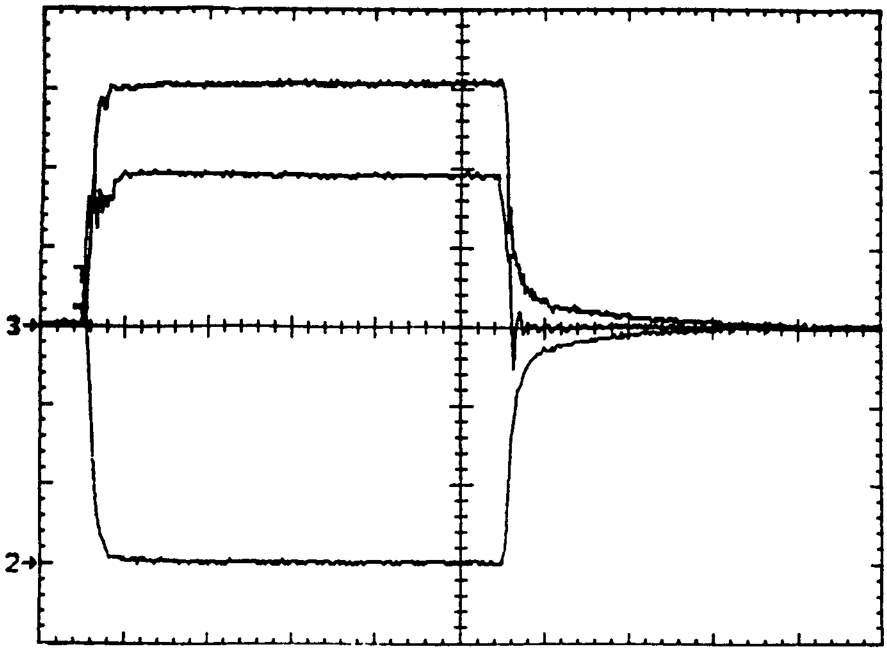

Figure 4: waveforms of resistive switching; top: I_C, $10\frac{A}{div}$; center: U_{GE}, $7.5\frac{V}{div}$; bottom: U_{CE}, $200\frac{V}{div}$; $2\frac{\mu s}{div}$

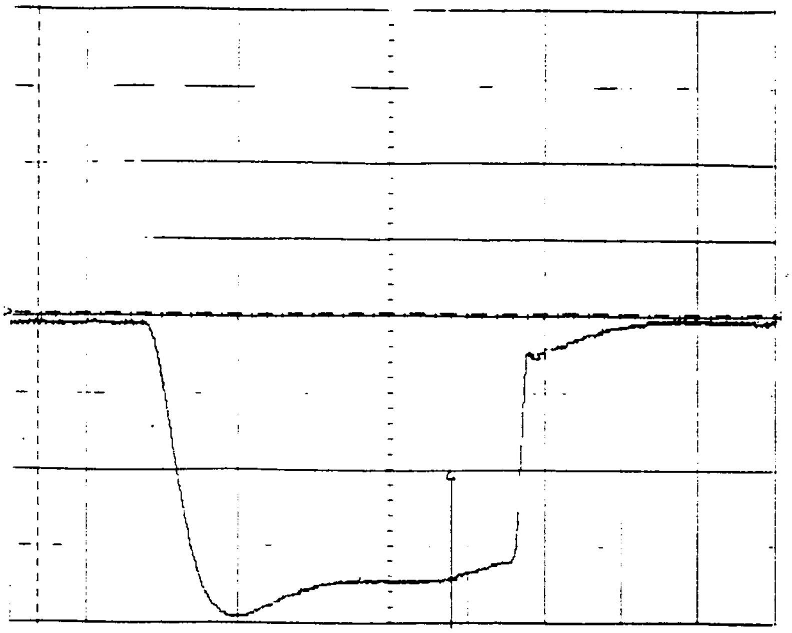

Figure 5: collector current waveform of a device passing short circuit test: $-I_C$, $500\frac{A}{div}$, $2\frac{\mu s}{div}$

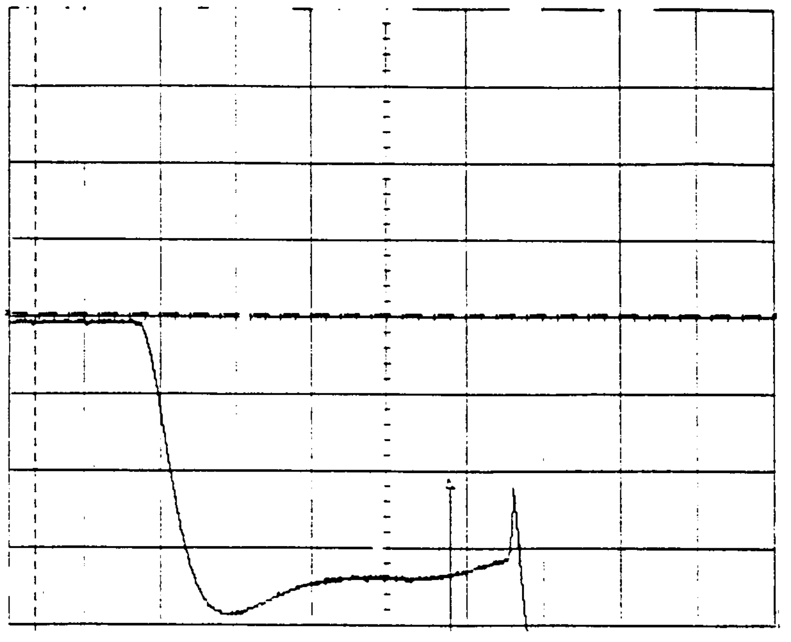

Figure 6: collector current waveform of a device failing short circuit test: $-I_C$, $500\frac{A}{div}$; $2\frac{\mu s}{div}$

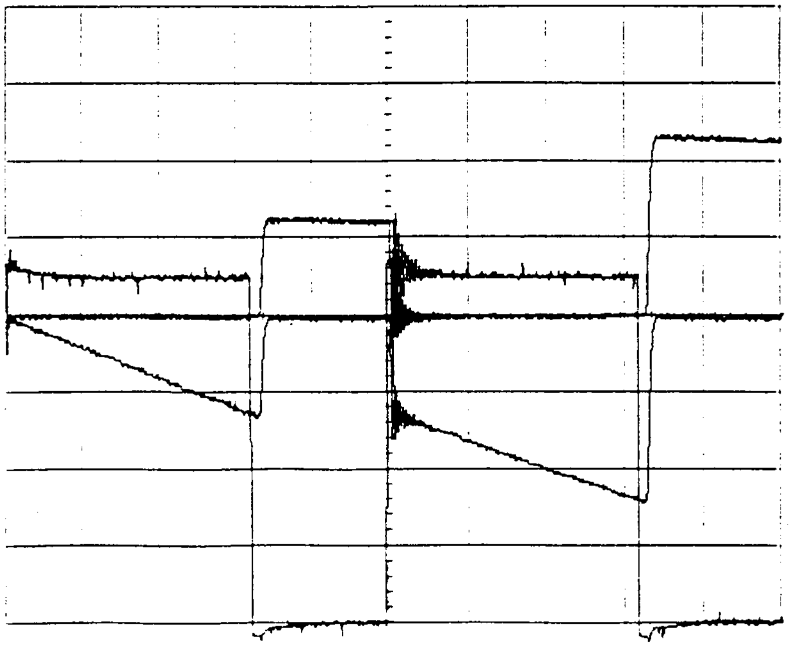

Figure 7: switching waveform of an intelligent module: $-I_{C2}$, $100\frac{A}{div}$ (triangular in center); I_{AK1}, $100\frac{A}{div}$ (rectangular in center); $U_{control2}$, $1\frac{V}{div}$ (bottom); $10\frac{\mu s}{div}$

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