

AUTOMATION OF CAPACITANCE MEASUREMENTS FOR POWER SEMICONDUCTOR MODULES

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ABSTRACT

This paper presents an overview of questions related to the increase in accuracy of measurements of capacitance parameters of power semiconductor modules when developing a device for automated measurements. The paper addresses the matters of circuit engineering of primary components, technical characteristics and software of a meter designed to automate the process of testing of capacitance parameters of power modules based on insulated gate bipolar transistors and fast recovery diodes. Unit testing results that prove the efficiency of the proposed method of the technical implementation are provided. Software implementation is described; ways to improve software-hardware solution are proposed. The paper is of value for developers and users of equipment for automated testing of electric parameters of semiconductor devices.

Keywords: automated test equipment (ATE), capacitance parameters, IGBT, FRD, power semiconductor modules, MATLAB.

INTRODUCTION

The national standard [1] and programs for in-process and final control of electrical parameters provide for measurements of input and output capacitance of insulated gate bipolar transistors (IGBT) and the total capacitance of fast recovery diodes (FRD) in the course of manufacturing of IGBT- and FRD-based semiconductor modules. That said, the desired measurement range of capacitance is usually 50 pF – 50 nF; while frequency of the current used for measurements shall be 1 MHz.

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High frequency and wide measurement range make it rather difficult to control capacitance parameters of power modules. The situation turns to the worse during the automation of the control process because it is impossible to connect a product under test directly to a meter. Also, it is required to use additional contacting devices to ensure quick replacement of IGBT/FRD modules under test. Usage of the contacting device substantially increases the distance between contacts of the module under test and the meter. Interconnecting conductors considerably reduce the level of interference immunity of the meter and distort measurement results, while the screening adds stray capacitance to the measuring circuit. For example, the value of stray capacitance for a 50 Ohm coaxial cable is approximately 100 pF/m.

In the general case, it is possible to produce the measurement results considering the stray capacitance of interconnecting conductors which is an additional constituent part of the measurement result and can be disposed of during calibration. However, it is difficult to ensure high accuracy of results in case of measuring relatively small values of capacitance. Therefore, development of the method to "remotely" measure capacitance parameters of power modules and technical implementation of such method constitute an important task today.

The second series of questions which arise in the course of the creation of automated testing and measuring equipment pertains to tasks related to the development of software which can ensure both the ease of use of the meter and the excellent metrological characteristics.

The diversity of software, development frameworks, and mathematical methods for processing the experimental data presents a developer with a challenge to choose the optimum tools which are best suited for resolution of the task at hand. For this research, the main criteria were development speed; availability and support of conventional hardware interfaces; presence of comprehensive mathematical tools in the form of a set of ready functions used for statistical processing and solution of differential equations; possibility of building a measuring system with the developed hardware; and possibility of implementation of a friendly graphical user interface. According to the above-mentioned requirements, the below development environments were considered as possible alternatives.

LabVIEW [2] product simplifies the development of measuring systems and considerably facilitates the process of obtaining required measurement data by means of integrating the NI data acquisition equipment or third-party hardware. An important advantage is the possibility to check and control the hardware component through the visual representation of the connected equipment. It is possible to flexibly automate a measuring system to suit specific tasks by means of a graphical approach which substantially increases the efficiency of

software development and reduces the number of errors. The major disadvantage, in the context of this research, appeared to be the significant complexity of using LabVIEW with the original equipment which was not developed by National Instruments Corporation. In order to use the original equipment, it is required to master the technology and independently develop the necessary drivers that implement interoperability application protocols.

MATLAB [3] is promoted by the developer as the language of technical computing. It is used for machine learning, signal processing, image processing, computer vision, communications, computational finance, control design, robotics, and much more. The MATLAB platform is optimized for solving engineering and scientific problems. The matrix-based MATLAB language is a convenient way to express computational mathematics. Built-in graphics make it easy to visualize and gain insights from data. A vast library of pre-built toolboxes makes it possible to get immediately started with algorithms essential to a specific application domain. The environment allows operating large data sets. MATLAB code can be integrated with other languages, enabling deployment of algorithms and applications within web, enterprises, and automated systems. In addition to the above-mentioned features, there are a vast community of users and function libraries that are generally available for the developer of software products in MATLAB language.

Test Executive And Development Studio – ATEasy [4] is a product intended to create and control automated test systems. It is designed to develop applications for functional test, ATE, data acquisition, process control, and instrumentation systems. ATEasy provides necessary tools to develop, deploy, and maintain software components, including instrument drivers, test programs, and user interfaces, as well as features to fully describe a testing procedure. It is designed to support and simplify ATE system applications with long product life cycles by offering easier maintenance of such applications. The open architecture of ATEasy provides easy-to-use access to many industry standard hardware and software interfaces including GPIB, VXI, PCI/PXI, USB, LXI/TCP-IP, Serial Communication, DLLs, ActiveX, .NET assemblies, HTML, VXI Plug&Play Function Panel drivers, IVI drivers, LabView VIs, C Header files and others. ATEasy is oriented towards a rather complex multi-level model of measurements as part of the common logic of testing. Under different conditions, this factor would be an undeniable advantage; however, the limited statement of the problem made it impractical to use the offered procedures.

The above-mentioned development environments were analyzed in the context of this research which implies the development of original open hardware and top level software. For the purpose of testing process control, MATLAB was selected as the product which has no

shortcomings, as compared to peers, within the framework of this application-oriented measurement task.

MATERIALS AND METHODS

Hardware implementation

In order to eliminate problems which arise during the "remote" measurements of capacitance parameters of power modules, a method similar to [5] is proposed here. The essence of this method is clarified by the circuit diagram (Fig. 1) using measurements of FRD total capacitance as an example.

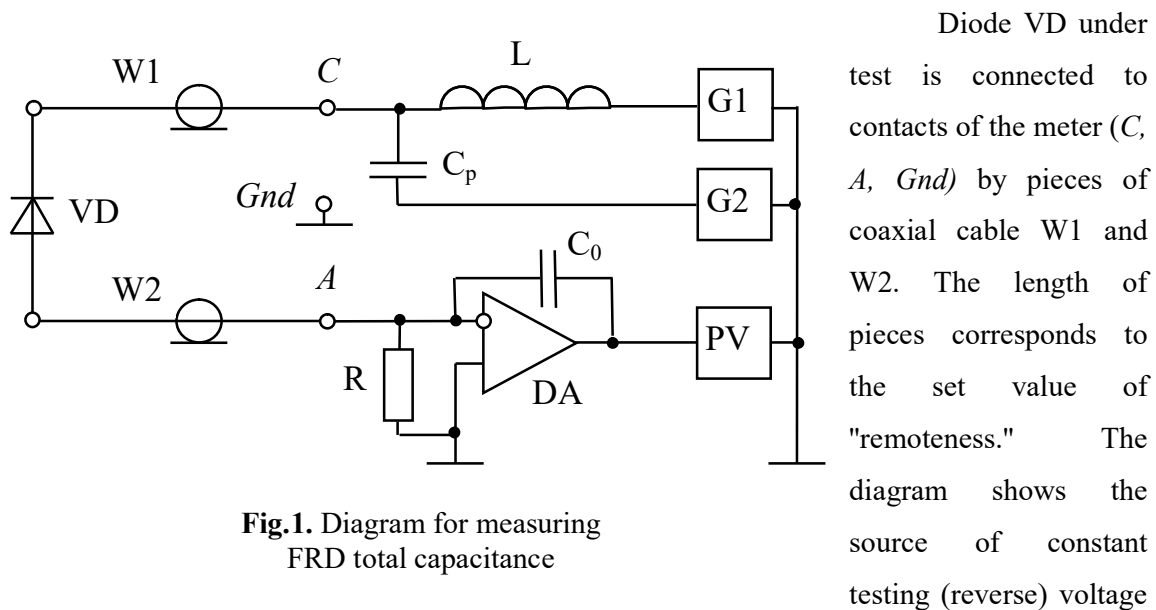


Fig.1. Diagram for measuring FRD total capacitance

G1, generator of sine-wave voltage with frequency 1 MHz and stabilized amplitude G2, broad-band operating amplifier (op amp) DA, converter of the amplitude of output voltage of the operating amplifier into the measuring signal (analog or digital) PV.

The sine-wave voltage of generator G2 causes current to flow through coupling capacitor C_p of sufficiently large capacity, cable W1, diode under test VD, cable W2, reference capacitor C_0 , and amplifier DA. At that, the op amp maintains the potential of the inverting terminal and of the cable W2 conductor at the value close to zero, which almost excludes the impact of the cable W2 self-capacitance on the magnitude of the current.

Cable W1 capacitance is shunted by fairly small values of output resistance of generator G2 and also has no impact on the magnitude of current. Thus, the amplitude of output voltage of amplifier DA is in proportion to the product of the amplitude of voltage of generator G2 by the capacitance of diode, and is in inverse proportion to the capacitance of reference capacitor

C_0 . In case of the constant amplitude of voltage of generator G2, the measurement range of capacitance is determined by the selection of C_0 .

In order to measure the IGBT input capacitance, the reviewed diagram shall be transformed as shown in Fig. 2.

Transistor VT under test is connected to contacts of the meter (C, G, E, Gnd) by pieces of coaxial cable W1, W2, and W3. The sine-wave voltage of generator G2 causes current to flow through the input circuit of the transistor. Voltage source G1 sets the required constant collector-to-emitter voltage, while capacitor C_p of appropriate capacitance closes the output circuit of the transistor based on the alternating-current component

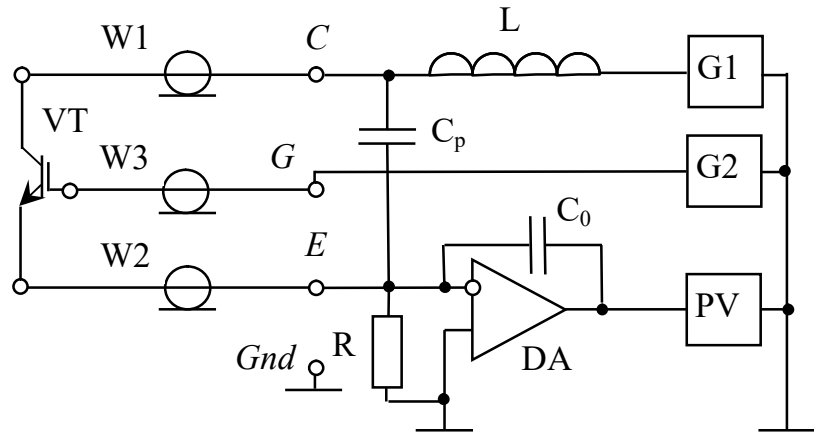


Fig.2. Diagram for measuring IGBT input capacitance

and ensures almost zero impedance at 1 MHz frequency.

In this circuit, the capacitance of cable W1 does not impact the measuring signal, capacitance of cable W3 is shunted by fairly small values of output resistance of generator G2, and the potential of the cable W2 conductor is close to zero owing to op amp DA.

In order to measure the IGBT output capacitance, the diagram shall be transformed as shown in Fig. 3. This diagram differs from the diagram for measuring FRD capacitance by the presence of a switching element which connects an output of the IGBT gate with an output of the emitter in the process of measurements.

The switching element can be built into the contacting device but it is more expedient to integrate it into the meter.

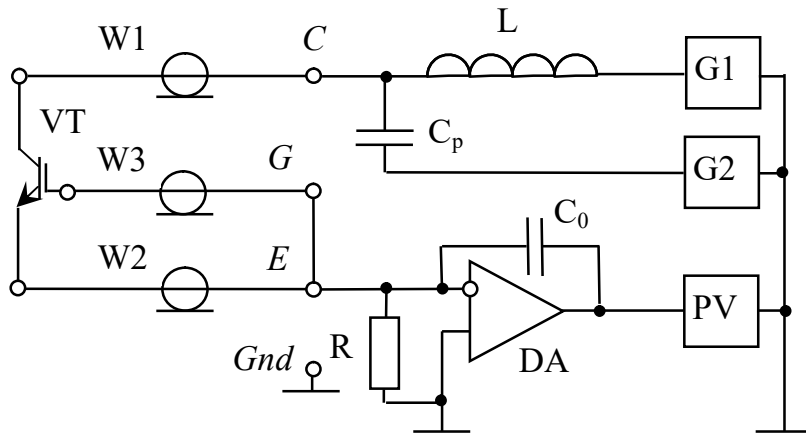


Fig.3. Diagram for measuring IGBT output capacitance

The proposed method for measuring capacitance parameters of IGBT and FRD (Fig. 1-3) was implemented in the capacitance parameters measuring unit which is controlled by the external computer system. Also, this unit functions as a part of the equipment for automated parameter

testing of the IGBT- and FRD-based power semiconductor modules.

The functional diagram of the unit (Fig. 4) features a converter of the mains AC voltage of $\approx 220V$ into the intermediate DC voltage of 12 V (AC/DC), a generator of sine-wave voltage with frequency 1 MHz (G_1MHz), a generator of constant testing voltage of 25 V with galvanic isolation and of power voltages ± 5 V and +5 V for analog and digital devices respectively (DC/VS), a measuring converter of capacitance into an analog signal (C_meter), and a microprocessor device (Controller) that maintains the operation mode, selects the sub-range of measurements, generates the results, and communicates with the external computer system (RS485 interface).

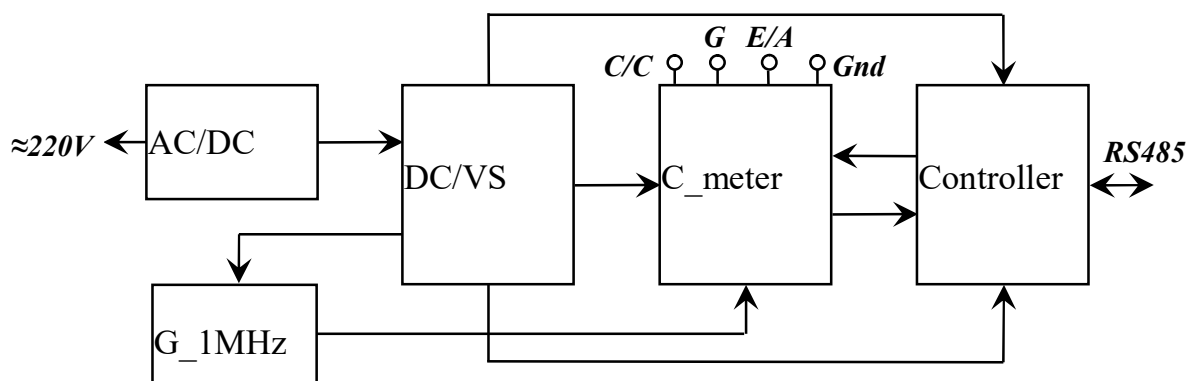


Fig.4. Functional structure of the capacitance parameters measuring unit

When measuring the total capacitance, FRD is connected to contacts C/C (cathode) and E/A (anode) by pieces of a coaxial cable (Fig. 1). Reverse voltage of 25 V is supplied to FRD. The

generator creates the high-frequency sine-wave current with the amplitude which is proportionate to the diode capacitance. The measuring converter converts current into voltage, detects and scales it. An analog-to-digital converter, being the part of the controller, helps to generate results of the capacitance measurements.

When measuring the input or output capacitance, the IGBT is connected to contacts *C/C* (collector), *G* (gate), and *E/A* (emitter) by pieces of a coaxial cable, and schemes shown in Fig. 2 or Fig. 3 are implemented.

The transistor capacitance measurement results are generated similarly to those generated for the diode.

Measuring converter *C_meter* implements some circuits shown in Fig. 1-3 and contains an op amp (DA), a set of reference capacitors (C_0), coupling capacitor (C_p), choke (L), signal converter (PV), and a series of additional elements. Signal converter PV is designed as an operational precision rectifier using signal Schottky diodes [6], RC low pass filter, and conditioning op amp.

The circuit of measuring converter *C_meter* employs integrated op-amps OPA656U (Texas Instruments) featuring gain min 110 dB at 1 MHz, input currents ± 2 pA, and offset voltage max ± 0.25 mV. It ensures the required accuracy during the generation of a measuring signal while the capacitance of the cable W2 piece (Fig. 1-3) is almost completely balanced out.

High-frequency reed relays SIL05-1A72-74L (MEDER electronic) are used to set the range of capacitance measurements (by switching capacitor C_0) and to select the measured parameter for IGBT (input or output capacitance).

Generator of the sine-wave voltage $G_{1\text{MHz}}$ includes a square waveform generator providing for crystal frequency control (1 MHz). Owing to the high-quality rejection filter, the voltage main harmonic is singled out and comes on the input of an amplifier with automatic gain control (AGC), which stabilizes the amplitude of the source output voltage at 0.2 V. The AGC circuit includes [6] a full wave precision rectifier in feed to the op amp, a reference voltage source (-2.5 V), an integral voltage regulator, and a regulating element (field-effect transistor).

The proposed circuit engineering and application of integral op amps OPA656U provide for the relatively low output impedance of the sine wave generator and, hence, almost completely balance out the capacitance of the cable W1 piece (Fig. 1, 3) or the cable W3 piece (Fig. 2).

The STM32F4DISCOVERY kit [7] featuring 32-bit ARM microcontroller is the base for the controller of the capacitance parameters measuring unit. The result of capacitance

measurements is generated by means of the 12-bit analog-to-digital converter being a part of the microcontroller.

In order to communicate with the external computer system, the controller has interface converter RS485/UART with galvanic isolation based on ADM2483 (Analog Devices) circuit.

In order to use the capacitance parameters measuring unit as a part of the automated testing equipment within the local information network, an individual address for the controller can be assigned by means of microswitches.

In terms of design, the capacitance meter was executed as a unified device and contains functional nodes in the form of printed modules as shown in the diagram (Fig. 4). Serial converter AC/DC of Hengfu Corporation 25W Open Frame Switching Power Supply HF25W-SPL-12 [8] was used as a converter of the mains AC voltage into the intermediate DC voltage. The authors developed and made the remaining modules.

The unit provides for the measurements of capacitance from 50 pF to 50 nF in the below three sub-ranges: 50 – 500 pF, 500 – 5000 pF, and 5 – 50 nF. The sub-range used for the generation of the final result is selected automatically. An intrinsic error of capacitance measurements C_x does not exceed $\pm (0.1C_x + 2 \text{ pF})$.

When measuring the IGBT input and output capacitance or the FRD total capacitance, the "collector-emitter" or "cathode-anode" constant voltage (25 V) is maintained with an error $\max \pm 0.7 \text{ V}$.

When measuring the IGBT input capacitance, the amplitude of the AC component of the "collector-emitter" voltage with the frequency of 1 MHz does not exceed 5 mV.

When measuring the IGBT output capacitance, the gate connects to the emitter through relay contact in such a way as the constant "gate-emitter" voltage does not exceed 10 mV.

The program of capacitance measurements executed by the unit controller is activated by the high level control program installed at the external PC. The control program is implemented in MATLAB system which provides enough tools to program and design graphic interface, facilitates mathematical processing of the measurements results, and makes it possible to program interoperability with external devices through a serial interface using Modbus RTU protocol.

The program loop provides for measurements of input and output capacitance regardless of the object under test (IGBT or FRD). In case of FRD, the value of the measured input capacitance is zero, while output capacitance is understood as its total capacitance.

In order to compensate for a random component of the measurement error, the control program provides for the possibility to carry out multiple measurements and to perform statistical processing of the obtained results.

Software implementation - low level

The capacitance meter runs under the high level (PC software). Serial interface RS-485 with galvanic isolation and power supply from the high level is physically implemented to communicate with the computer. This interface supports the shared bus topology.

Addresses and formats of transmitted information comply with Modbus RTU standard. The capacitance meter has a unique address in the Modbus network, i.e. an identifier assigned in the range of 1 to 127 by means of microswitches on the processor board. The unit has 16-bit parameter registers for recording (6 (0x06) – Preset Single Register) and information registers for reading (Modbus 3 (0x03) – Read Holding Registers) of the measurement results or data on the measuring process, error codes, etc. All registers are writable and readable; data of information registers is updated by the firmware of the built-in controller.

The software is developed under BSD license approved by the Open Source Initiative for distribution of the open-source software. The software is implemented in C language; CoIDE is the development environment[9].

Software implementation - high level

In a particular case, the national standard [10] is used to define parameters of field-effect transistors. According to Para 3.1 of the standard "An error of measurements of parameters of field-effect transistors (as per normal law of distribution of error components) is determined by the following formula

$$= \pm \sqrt{\delta_1^2 + (\delta_2)^2 + (\delta_3)^2 + (\delta_4)^2 + (\delta_5)^2 + \delta_6^2}, \quad (1)$$

where δ_1 is an intrinsic error of measuring equipment; δ_2 , δ_3 , δ_4 are respectively errors of mode setting for voltage, current, and frequency of measurements, ambient temperature, determined with consideration of the confidence coefficient of 0.997; δ_5 , δ_6 are coefficients of the influence of voltage, current, frequency, and temperature over the value of a measured parameter; δ_6 is an error component related to "remote measurements."

The above formula lists main factors that determine the measurement mode and significantly influence the measurement results.

The technical solutions described above make it possible to obtain accuracy figures of measurements of the FRD and IGBT capacitance parameters as shown in Fig. 5. As the above technical solution ensures an acceptable accuracy by compensating only one component of the measurement error out of several, and specifically the remote component as part of an *instrument* error, it is possible to further increase the accuracy of measurements by:

- a) statistical processing of the measurement results, thus, minimizing a *random* error;
- b) taking into account physical processes in the semiconductor devices and influence of the environmental factors, thus, minimizing an *additional* error;
- c) providing access to a software model and an algorithm of measurements execution to allow a user make adjustments into the measuring system in operation, thus, minimizing a *procedural* error;
- d) automating of measurements, thus, minimizing a *human* error;
- e) calibrating and making regular inspections of the magnitude of measurement error, thus, minimizing a *systematic* error.

Within the measuring system under discussion, the components of the measurement error (a – e) [11] are accounted for and compensated using PC software on the high level and microcontroller software on the low level.

Consider the problems which arise during implementation of the measuring system software and the relevant solutions.

When carrying out a series of experiments (from 10 to 100) with each IGBT/FRD, the microcontroller runs a program to minimize a random error. Then, the results of experiments are processed, first, by disposing of minimum and maximum values, and, second, by calculating the mean value of remaining measurement results.

Additional and systematic errors are minimized using a behavioral model of the studied semiconductor device, which was developed by the authors of this paper based on the researches of multiphysics and SPICE models of power semiconductor devices. Studies of these models fall outside the scope of this paper. However, it should be noted that the usage of such models is fully justified when taking an integrated approach to the problem of increasing the accuracy of measurements. The results of measurements of the parameters of technical objects are actually used to build a certain model, which adequately reflects characteristics, properties, and functional structure of the studied object. Thus, a lot of models of measuring objects exist in metrology. A normative model, an analytical models (ideal and realistic), and an experimental model can be considered to be the most applicable ones.

The normative model is developed at the design stage and is executed in the form of technical documentation (a drawing, a technical description, and specifications contain the standard values of product's parameters, etc.) The model serves to create and ensure follow-up control over parameters of an object and contains all relevant sets of the object definitions. If such model is used for measurement control of an object and for the development of the parameter measurement procedures for a created object, then the metrological normative model fully matches the general normative model. The realistic model of an object is obtained in the course of analytical studies of possible external influencing factors. The experimental model is built based on the experimental values of the parameters of a controlled object. Therefore, the control over characteristics of any technical object, including power semiconductor modules IGBT/FRD, necessarily implies the building of an experimental model and its comparison with the normative model in order to make a decision about the compatibility of such models.

The above-listed models materialize in the usage of the behavioral approach, which makes it possible to effectively and accurately take into account the change in characteristics of the controlled items in different modes when the number and the range of models decrease. That said, the behavioral approach makes it possible to build models that require much fewer inputs of computing resources if compared with mathematical modeling and circuit simulation. For further information about the behavioral approach refer to [12].

Lists of the MATLAB functions used to control the measurements are given in the appendices hereto. These lists are relevant for the capacitance parameters measuring unit with the functional structure as shown in Fig. 4.

RESULTS

Field testing of the unit developed by the authors was carried out to confirm the efficiency of the proposed method for measuring capacitance parameters and the viability of its technical implementation.

When processing a measurement signal, the possibility of the remote measurement of small capacitance without compensating for the fraction of capacitance of interconnecting conductors was assessed by measuring the capacitance of a capacitor with the nominal value of 27 pF, although this figure falls out of the set range. Measurements were carried out while connecting the capacitor to the unit contacts *C/C* and *E/A* (simulation of measurements of the IGBT output capacitance or the FRD capacitance) directly or by means of the 20 cm long pieces of cable RG 174 A/U (92 pF/m). In the similar way, the capacitor was connected to

contacts G and E/A (simulation of measurements of the IGBT input capacitance). Table 1 contains the measurement results obtained after statistical processing.

Table 1.

Output capacitance (pF)		Input capacitance (pF)	
C/C – EA	Over distance	G – EA	Over distance
27.2	27.3	27.8	28.0

Testing of the capacitance parameters measuring unit indicated that it is necessary to perform a phase correction of the frequency characteristic of the op amp OPA656U in the circuit of the measuring converter (DA, Fig. 1-3) to ensure stability of operation within measurement ranges 500 – 5000 pF and 5 – 50 pF.

The preliminary assessment of metrological characteristics of the unit was performed by measuring the capacitance of the reference elements. Thermally stable ceramic capacitors, which were chosen for this purpose, were connected to the unit by the 20 cm long pieces of coaxial cable. Experiments were performed for capacitance values evenly distributed throughout the entire measurement range (21 values within the range of 50 pF – 50 pF). Readings of RLC parameter meter APPA 703 [13] were accepted as an actual value of capacitance of the capacitors when they were directly connected to contacts of the meter. Values of the reference capacitance were assigned, among other things, by the parallel connection of capacitors.

Figure 5 illustrates the experiment results which characterize the relative error in the measurement modes of both IGBT input and output capacitance.

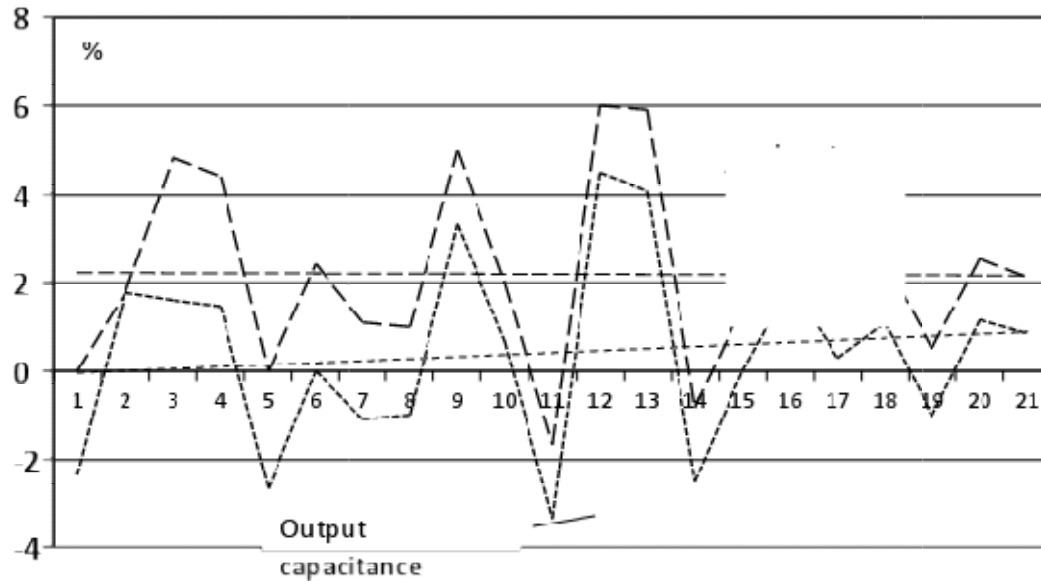


Fig.5. Relative measurement error

Using the described capacitance parameters measuring unit, a series of experiments was carried out, which involved the performance of 100 measurements of FRD capacitance, IGBT input capacitance, and IGBT output capacitance each. The measurement results are shown in Fig. 6-11. A dotted line indicates direct results of the capacitance measurements, while a continuous line shows smoothed values using the 3rd degree polynomial.

The experiments were conducted at a constant ambient temperature for two reference power IGBT modules (IGBT-1, IGBT-2) with FRD-1 and FRD-2 forming part of the modules.

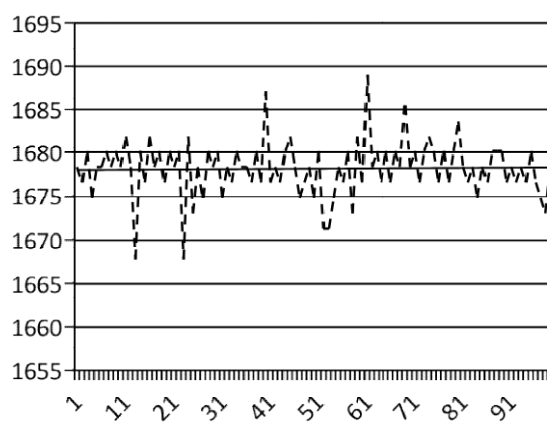


Fig.6. FRD-1 capacitance (pF)

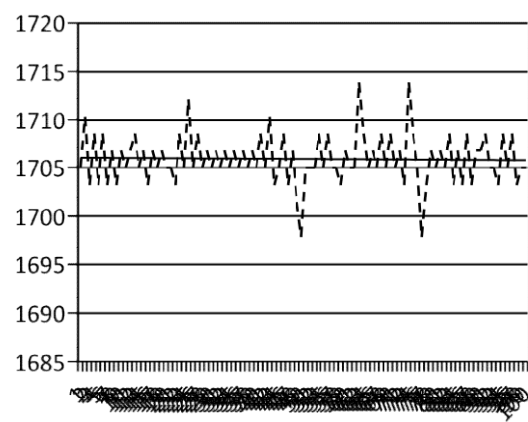


Fig.7. FRD-2 capacitance (pF)

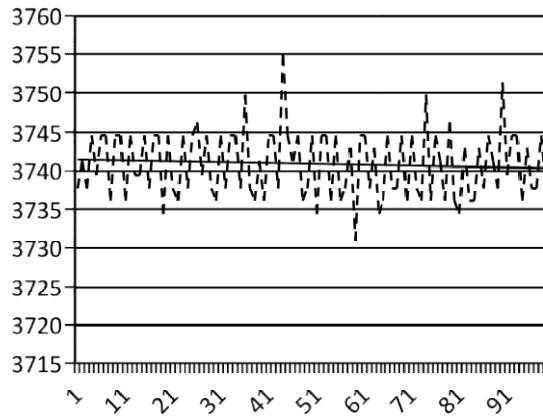


Fig.8. IGBT-1 output capacitance (pF)

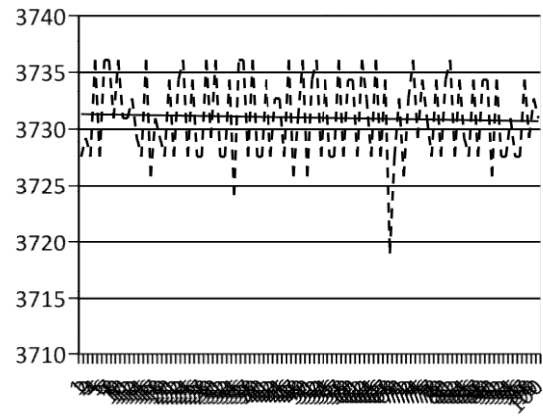


Fig.9. IGBT-2 output capacitance (pF)

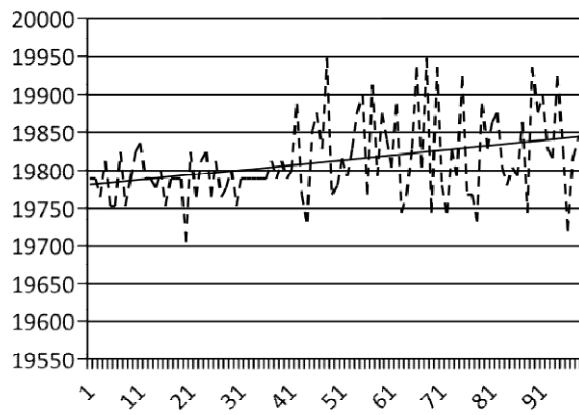


Fig.10. IGBT-1 input capacitance (pF)

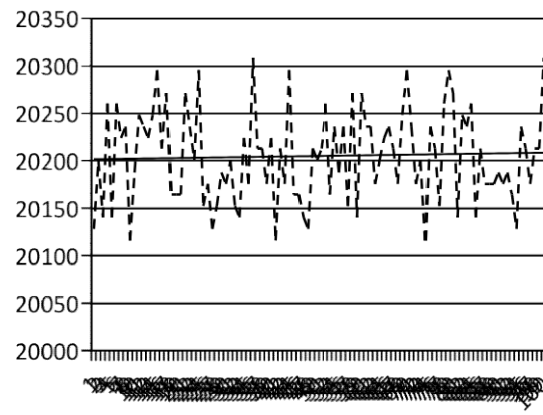


Fig.11. IGBT-2 input capacitance (pF)

An additional experiment was carried out, which included 100 measurements of the FRD-2 capacitance, as well as the IGBT-2 input and output capacitance, during the process of temperature heating from 25°C up to 50°C. Figures 12-14 illustrate the obtained measurement results.

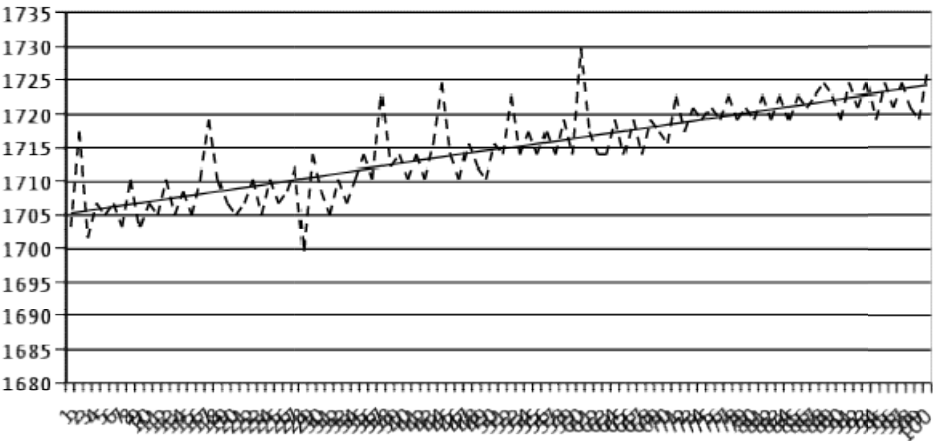


Fig.12. FRD-2 capacitance (pF) when heated from 25 up to 50 °C

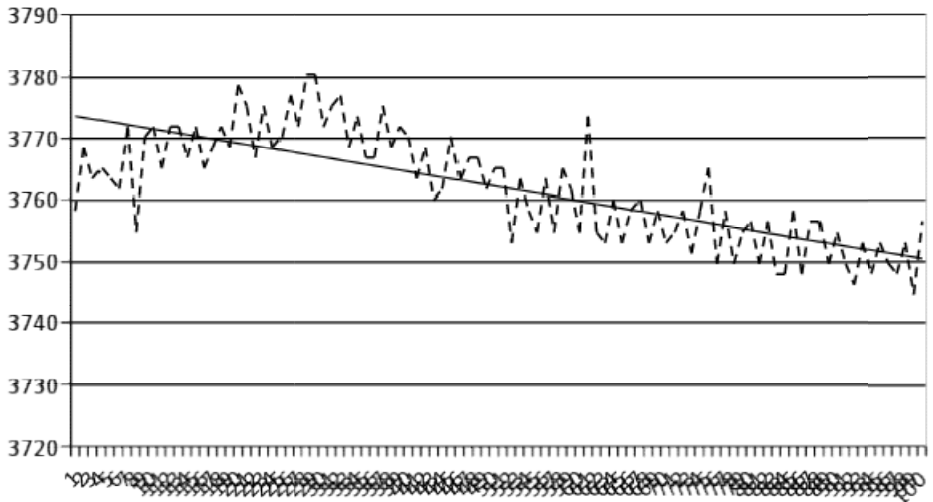


Fig.13. IGBT-2 output capacitance (pF) when heated from 25 up to 50 °C

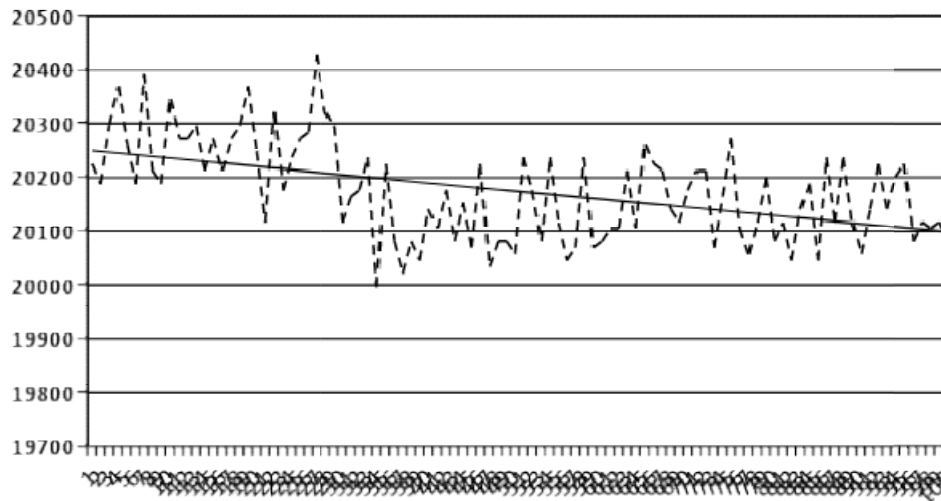


Fig.14. IGBT-2 input capacitance (pF) when heated from 25 up to 50 °C

DISCUSSION

Experiments showed that in the measuring converter circuit (Fig. 1-3) a phase correction of the frequency characteristic of the op amp should be performed to ensure the stability of operation within measurement sub-ranges 500 – 5000 pF and 5 – 50 pF. These findings do not fully conform to the results of the device modeling in NI Multisim 12.0 environment [14].

It was experimentally proved that it is possible to perform such correction by connecting a low-ohmic resistor in series with the reference capacitor C_0 (Fig. 1-3). That said, the total circuit resistance on the frequency of 1 MHz does not basically change, which facilitates the process of calibration of the meter.

The testing result provided in Table 1 is indicative of the efficiency of the proposed method of remote measurement of the IGBT/FRD capacitance parameters in case of small values of the measured capacitance and relatively big distance between the meter and IGBT/FRD.

Figure 5 shows charts of the relative error of the meter, which were obtained after calibration of the meter for central values of each of the sub-ranges in the mode of output capacitance measurement. It is indicative of the acceptable metrological characteristics of a measurement path.

A moderate increase of the relative error may be associated with the difference in the frequency of the measuring current: 100 kHz for a reference device [13], 1 MHz for the meter of IGBT/FRD capacitance.

An insignificant difference in measurement errors observed in the modes of input and output capacitance measurements (Fig. 5) can be explained by the influence of the stray capacitance

in the circuit of constant voltage source G1 (Fig. 3). Some part of the current created by generator G2 is bifurcated to such stray capacitance, thus, leading to the decrease of measurement values.

In case of more stringent requirements for the measurement accuracy of parameters of the power semiconductor IGBT modules, it is expedient to perform separate calibration for the modes of input and output capacitance measurements in each of three sub-ranges 50 – 500 pF, 500 – 5000 pF, and 5 – 50 nF.

Based on the results of experiments shown in Fig. 12-14, it may be concluded that there is a non-linear temperature dependence of the measurement results of IGBT/FRD capacitance. In this regard, the measurement accuracy of capacitance parameters can be increased by taking into account the influence of the ambient temperature through the use of the behavioral model which links the change in values of the IGBT/FRD electrical parameters with the measurement mode according to formula (1): voltage collector-emitter, collector current, frequency, temperature. This approach is based on the results of researches carried out in [15–22].

In the case at hand, the usage of the behavioral model, which includes temperature dependent measurement results and is built on experimental data, makes it possible to practically exclude the influence of the temperature component of an error on the measurement results. This dependence is functional and can be easily approximated by any means, for example, by application of fuzzy logic systems or neural networks acting as the universal approximators.

CONCLUSION

The proposed method of remote measurement of capacitance parameters can be applied not only in the automation systems to test parameters of semiconductor devices but also in other spheres, for example, during the development of capacitance sensors.

The results obtained speak to the fact that it is possible to use behavioral models based on experimental data in automated test systems because little attention is given to temperature dependent effects of capacitance parameters in the available theoretical models.

The study is relevant and important because the task of automation of the testing of electrical parameters of power semiconductor modules at the manufacturing stage is very common today. The article is of practical value for a wide range of developers of equipment for automated testing of electronic products.

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