«On-line» neutron fluence registration by silicon bipolar transistor

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Abstract. An efficient practical method of bipolar transistor application for neutron fluence registration is presented. The method is focused on the neutron fluences damage effect correlation for various sources to reference source. The bipolar transistor connection diagram and an example of device realization based on STM32 microcontroller are described. STM32 is used for providing test signals and parameter registration used for gain factor calculation of the bipolar transistors monitor (BTM). The proposed approach allows to consider the features of BTM that is pre-irradiated at reference source and their application as the neutron fluence monitors. These connection diagram and constructive solutions provide "on-line" neutron fluence registration for different sources in terms of the reference source as required for the verification of radiation test results.

1. Introduction and overview

The neutron irradiation test is performed to determine the susceptibility of semiconductor devices to degradation in the neutron environment [1]. Devices under test (DUT) are to detect and measure the degradation of critical semiconductor device parameters as a function of neutron fluence and to determine whether the specified semiconductor device parameters are within the specified limits after exposure to a specified level of neutron fluence. Typically, a specific parameter, such as minority-carrier lifetime or current gain factor is measured as a function of particle fluence, and the rate of parameter degradation is determined for specific measurement conditions. The degradation rate has been referred to in literature as the damage factor.

The neutron fluence used for device irradiation can be obtained by measuring the amount of radioactivity induced in a fast-neutron threshold activation foil such as $^{32}$S, $^{54}$Fe, or $^{58}$Ni, irradiated simultaneously with the device. The conversion of the foil radioactivity into neutron fluence requires knowledge of the neutron spectrum incident on the foil. If the spectrum is undefined, it can be determined by using the following E720-E722 DoD adopted ASTM standards or their equivalent.

In ASTM standard E722 [2], the neutron fluence is described in terms of the monitor response to the equivalent monoenergetic neutron fluence per unit. The monitor foil is used to predict the equivalent monoenergetic neutron fluence, which is only valid in case of a constant energy spectrum.

Neutron exposure of a sample is commonly given in terms of the neutron fluence, n/cm². However, the amount of displacement damage from neutrons in a given material depends on neutron energy. Therefore, in order to allow meaningful comparisons between experiments using different neutron
energy spectra, neutron fluences are often determined in terms of ("normalized to") an equivalent 1-MeV neutron fluence, which is the fluence of 1-MeV neutrons that produces the same electronic effect as the neutron spectrum used in a particular study [3].

The radiation response of many types of devices (e.g., bipolar transistors, solar cells, focal-plane arrays, and other detectors) can be predicted reasonably well based on calculations of the amount of displacement damage energy imparted to the primary knock-on atoms [4, 5].

The Messenger-Spratt equation [6] was used to describe the radiation response of the common emitter dc current gain factor of a bipolar transistor:

\[
\frac{1}{H_{21E}(F_n)} = \frac{1}{H_{21E}(0)} + K_N \cdot F_n,
\]

where \(H_{21E}(0)\) and \(H_{21E}(F_n)\) are the initial gain and final gain respectively, \(K_N\) is the particle- and energy-dependent displacement damage factor, and \(F_n\) is the particle fluence. The damage factor is determined experimentally by gain factor measurements of the DUT (for a particular set of device operating conditions) after incremental exposures at a given particle energy.

To compare the results of the radiation test for different neutron energy spectra, one uses a comparison method for neutron fluences \(F_n\) in terms of the equivalent to the reference reactor, neutron fluence \(F_{ref}\), which produces the same damage effect [7-9].

The connection diagram of the bipolar transistor and the device based on the STM32 microcontroller are proposed by the authors to allow carrying out the active mode measurements with a minimum quantity of additional lines.

2. Background information

There is a well-known function of \(\delta(E)\) dependence for Si [2, 5, 6], which can be used to estimate the damage effect \(D_n\) of neutron radiation with a spectral distribution \(\varphi(E)\):

\[
D_n = \int \varphi(E) \cdot \delta(E) \cdot dE
\]

An alternative method of determining the effectiveness of neutron radiation is a method to compare the results of the irradiation of silicon structures to the results for the reference source by using the bipolar transistor monitors (BTM). The gain factor dependence \((H_{21E})\) on the neutron fluence can be described by the Messenger-Spratt equation.

Types of bipolar transistors (planned to be used as BTM) are determined by the range of neutron fluence values.

Using the results of gain factor \(H_{21E}\) at a fixed value of emitter current (the stage we called “calibration”), one can calculate values of \(K_N\).

3. The algorithm of neutron fluence measurement using BTM

We propose using the following sequence of operations for radiation tests:

1. The voltage \(V_{cc}\) should be set at the programmable power supply output.

2. The Data acquisition/switch unit measures the current consumption for each of the BTMs (as a sum of collector and base current for each transistor).

3. The gain factor value \(H_{21E}\) for BTM is calculated using equation:

\[
H_{21E} = \frac{I_{Collector}}{I_{Base}} = \frac{I_{Emitter} \cdot R_{Base}}{V_{cc} \cdot V_{BE}} - 1
\]

where \(V_{BE}\) – voltage decrease at emitter junction, V;

\(V_{cc}\) – voltage value at output of programmable power supply, V;

\(R_{Base}\) – resistance in transistor base line, Ohm.

4. The neutron fluence value corresponding to the neutron fluence of the reference reactor is calculated in the final step.
Base current must be kept constant during the radiation tests. Thus, it is needed to take into account the coefficient correlating the dependence of the damage factor of the transistors and the injection level of the minority carriers in the base of the BTM.

Figure 1. Dependence of damage constant \( K_N \) on emitter current (\( I_E \)) for high frequency (VT1) and low frequency (VT2) BTMs.

The executed research resulted in the following dependence for the constant \( K_N \) (see Fig.1):

\[
K_N(I_{X}) = K_N(I_{\text{emitter}}) \cdot \left( \frac{I_X}{I_{\text{emitter}}} \right)^\beta
\]

where \( K_N(I_{\text{emitter}}) \) and \( K_N(I_{X}) \) are values of the damage constant for emitter current of BTM at the “calibration” \( (I_{\text{emitter}}) \) stage and at the “measurements” \( (I_X) \) stage, respectively, and \( \beta \) is the exponential function index.

The values of the constants of damage \( K_N \) for several values of \( I \) and \( \beta \) are determined during the calibration process.

4. The bipolar transistors connection

Fig.2 shows a connection diagram of the BTM: for each BTM there is only one additional line of communication, which is essential for multi-point measurements. The attenuator at the output of BTM is used for reducing BTM output voltage to the ADC range measurement.

Figure 2. The BTM connection diagram for «on-line» registration.

The irradiation of BTM is carried out in active mode. The values of \( I_C \) and \( I_B \) are measured remotely.
The value of the coefficient $H_{21E}$ of BTM can be determined using the results of measurements as in (3).

5. The device for results processing
The multi-channel registration of BTM parameters can be developed using modern microcontroller devices [10]. It allows simplifying the processing of measurement results. Besides, the autonomy of the portable microcontroller-based devices is their certain advantage.

The key item of a developed device is microcontroller STM32 [10, 11]. It digitalizes the analog signal coming from BTM1 to BTM4, records the digital signals in the microcontroller data register, calculates the current values of BTM informative parameter ($H_{21E}$), and transforms the data in a code combination. This code comes to LED indicator through the parallel input/output port of the microcontroller.

Fig.3 presents the "calibration" stage: the linearly increasing voltage is formed at DAC-output of the STM32 microcontroller and comes to transistor base of BTM.

![Figure 3. Schematic diagram for BTM at "calibration" stage](image)

BTM is opened by DAC output voltage. When the value of this voltage gets to a previously determined level (for example, 100 mV or 1.0 V for emitter current properly 1.0 mA or 10 mA), the device fixes the voltage value at DAC-output, measures the BTM-transistor base voltage, calculates BTM gain factor ($H_{21E}$) and indicates its value. Each of the transistors is connected separately at the “calibration” stage for the measurement of parameters.

At the “measurements” stage, the code signals are formed at ADC-inputs ADC1 to ADC4, each of which corresponds to voltage value at resistor loads BTM1 to BTM4. Afterwards, gain factor ($H_{21E}$) for each of the BTM1 to BTM4 transistors is calculated. The result of calculation of BTM value of $H_{21E}$ is indicated on the LED display.

6. The proposed device architecture
The developed device for neutron fluence effective value registration is based on the 32-bit STM32F407VGT6 microcontroller with ARM Cortex-M4F core, consisting of:

– 12-bit DAC;
– 2x12-bit ADC, which can be expanded to 16 channel;
– interface for parallel data output on the indicator;
– open-source hardware and software.

The proposed architecture of STM32 allows organizing the process of multichannel BTM-parameter measurements with ±1.0 mV precision, primary information processing and indicating the measurement results.

For software development, we used STM32Cube [12, 13] (“STMicroelectronics”). The STM32Cube HAL library consists of in-line HAL-abstraction software for STM32, providing the maximum of code translation inside the STM32 series. The set of built-in software components (RTOS, USB, FatFS, TCP/IP, Graphics) was configured for their combined action.

We have developed the driver program for the STM32 microcontroller, which realizes the previously described algorithm. The program was debugged and the microcontroller was programmed for the device prototype.
7. Experimental setup for device prototype testing
The device prototype during the experiments of 2T312B bipolar transistors was irradiated under the fields of two types of sources (RISI and IPPE, Russia).

The set of 8 transistors was pre-irradiated at the "calibration" stage at reference source BARS-4 (RISI). The measurement results of gain factor $H_{31E}$ for each of the transistors were used for further calculation of the $K_N$ and $\beta$ parameters (for values of emitter current equal to 1.0 and 10.0 mA before and after irradiation).

Then we repeated the irradiation of four transistors of the set at the same fluence and measured the gain factor $H_{31E}$ for each of the 2T312B transistors. The uncertainty of the calculated values of neutron fluence from the standard detectors registrations was less than 10%.

The remaining set of four transistors was placed in a FS-1M (IPPE) source, the spectral-energy characteristics of the neutron radiation of which differ significantly from the reference reactor. Comparing the results of the irradiation, we see the differences between the neutron fluence of more than 0.1 MeV energy (that were obtained from the results of "on-line" measurements of the gain factor $H_{31E}$ for each of the four transistors) and standard detectors registrations is less than 10%.

A novel device architecture has been proposed for the processing of the results of research experiments. Thus, we used two different algorithm variants for device realization – both for calibration and measurement – each of which was implemented as a separate program stored in the microcontroller before testing.

8. Conclusion
The practical method for bipolar transistor application for “on-line” neutron fluence registration is described. This method is focused on the neutron fluence damage effect correlation of various sources to reference source.

The proposed method is based on the application of pre-irradiated bipolar transistors monitors (BTM) and the SMT32 device as a self-contained unit.

The developed device prototype was used in radiation tests of two types of neutron sources (RISI and IPPE, Russia). Comparing the results of the irradiation, the uncertainties of the neutron fluence of more than 0.1 MeV energy from the standard detectors registrations was determined to be less than 10%.

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