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Electrical Noise and Semiconductor Reliability

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Abstract

Low-frequency electrical noise is a sensitive measure of defects in semiconductor devices because the noise has an impact, directly or indirectly, on the performance and reliability of the device. Its measurement is particularly important to characterize noise in semiconductor devices.

Keywords: noise, magnetic, holes, filament, experimental, surface, bias, recombination, semiconductors, lifepath, magnetic field, transit time, electrical noise, system technical, side arms, single crystal, noise voltage

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Introduction

A long-standing and abiding desire of electronic engineers has been to find a practical method for estimating the life expectancy of a transistor by correlating low-frequency noise and reliability.

Radiation has been shown to increase low-frequency noise levels in linear bipolar devices, while it tends to cause latch-up in CMOS ICs; X-rays affect MOS devices to a greater extent than they affect bipolar ICs, due to the development of positive charges in the oxide layer, causing a change in threshold voltage.

GaAs devices being majority charge carriers - are relatively radiation resistant compared to silicon devices [19].

For many failure causes, a method allows to achieve functional reliability with a short flicker noise measurement period and allows to eliminate unreliable specimens.

Spontaneous fluctuations (noise) are the most surprising phenomena, ubiquitous in all physical as well as biological processes.

Although noise has always been considered as an undesirable parameter and a limiting factor in the performance of electronic components and circuits, in recent years, it has become an interesting area of research in many different fields, from nanotechnology to radio astronomy, particle physics, semiconductor physics, optics, medicine, wire communications, etc.

In general, the main cause of these fluctuations is related to faults within the electronic component.

The study of noise is a powerful means of characterising certain physical properties of electronic components, allowing us to assess their reliability.

We distinguish three main categories of physical noise sources:

- diffusion noise;
- junction noise;
- excess noise.

Noise: a random time signal with zero mean value, whose values have a Gaussian distribution. Noise is characterised by its frequency (power spectral density) or statistical (standard deviation) properties.

In addition to the bias conditions, the transistor has another noise factor — the base resistance $R_{bb'}$. It can reach important values of several kΩ.

If the thickness of the base decreases, this will lead to an increase in the resistance $R_{bb'}$, which is expressed as a function of the thickness of the active base ZB. Its value is:

$$R_{bb'} = K / ZB$$

where K is a coefficient, in which several other basic characteristics are expressed, such as doping level, width, etc.

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The objective is therefore to decrease the thickness of the base without increasing its own strength; the most obvious solution is to dope the doping level of the base.

The resulting negative effect is to decrease the gain of the transistor.

The electrical noise is defined "as the set of all unwanted disturbances which superimpose themselves on the useful signal and tend to mask its contents" (*IEEE Dictionary 97*).

Depending on its origin, noise in electronic systems can be divided into two broad categories:

1. Noise coming from outside the system (stray signals or disturbances):
2. Noise originating from within the system (electrical noise); its main origin is the discrete nature of the charge carriers. Noise depends on these random fluctuations [Vasilescu 2005] and refers to noise sources generated by compounds in electronic circuits.

As with diseases, noise is never eliminated, only prevented, cured, or endured, depending on its nature, seriousness, and the cost/difficulty ratio of treatment.

In the past, much work has been done to study the different types of noise sources (low-frequency, excess) encountered in planar silicon transistors used in monolithic integrated circuits.

Some examples of such noise sources are given below.

The sound of buzzing:

- in metal-semiconductor diodes, in pn junctions and in low injection transistors.
- in leakage currents of FET devices.
- in the light emission of light emitting diodes and lasers.
- Noise due to recombination and generation, in the space charge junction region. It is due to high-level injection effects (including noise in photodiodes, avalanche diodes and particle detector diodes).
- Thermal noise and gate-induced noise in FETs.
- Generation-recombination noise in FETs and transistors at low temperatures.
- Noise due to recombination centres in the space charge region of the FET and noise in the space charge limited region of solid-state diodes.
- 1/f electronic flicker-noise in solid-state devices; it translates the fluctuation of trap occupancy at the oxide surface.
- Contact or low frequency noise.
- Burst noise (popcorn noise, burst noise, rattling noises) in diode and transistor junctions and trap kinetics, at the oxide surface.
- Micro-plasma noise.
- Random noise.
- Flicker noise in diode junctions, transistors, Gunn diodes and FETs.
- High injection noise.
- Excess low frequency noise.
- Bistable noise, in operational amplifiers.
- Pink noise.

The theory of low-frequency noise in bipolar transistor junctions dates back many years and has remained - in concept - essentially unchanged.

Unlike other sources of noise, burst noise is due to manufacturing defects and can be eliminated by improving the manufacturing process.

Thus, for example, X-ray examination of transistor wafers has shown that the total number of defects increases with the incidence of implantation energy.

Typically, the noise consists of random pulses of varying length and equal amplitude, but sometimes the random pulses appear to be superimposed on each other (Figure 1).

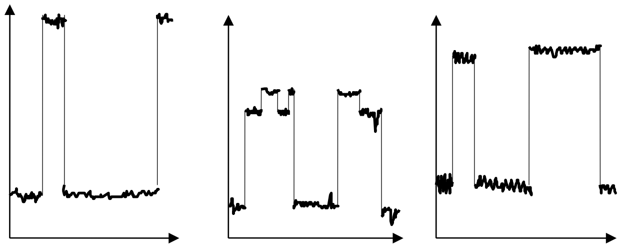

Figure 1 Typical burst noise observed at the collector of a transistor [16].

This noise is caused by a defect in the semiconductor junction (usually, a metallic impurity). The width of the noise pulses varies from microseconds to seconds. He pulses repetition rate — which is not periodic — ranges from several hundred pulses per second to less than one pulse per minute.

However, for any particular sample of the device, the amplitude is fixed because it depends on the characteristics of the junction defect.

Typically, the amplitude is 2...100 times that of thermal noise. The power density of the burst noise has a characteristic $1/f_{1\ldots2}$.

Since noise is a current-dependent phenomenon, the voltage of the burst noise is highest in a high-impedance circuit — e.g., the input circuit of an operational amplifier.

The source of the burst noise is not very clear so far, but it seems to be associated with — heavily doped — junctions at the emitter surface. The appearance and disappearance of the pulses is thought to be associated with a single trap in the space charge region.

A long-standing and abiding desire of electronics engineers has been to find a practical method to predict the expected lifetime of a transistor, correlating low-frequency noise and reliability.

For many causes of failures, a method allows us to obtain in-service reliability by measuring the short period of burst noise for a low load, which allows us to eliminate unreliable specimens.

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Excess noise and reliability

Extensive studies on silicon bipolar transistors [1]-[4] have shown that noise phenomena can be subdivided into two categories: normal noise and excess noise.

The former includes thermal noise and burst noise; the latter includes scintillation noise (flicker or 1/f), micro-plasma noise, generation-recombination noise and excess noise (burst noise). It has long been assumed (and the assumption has been verified, in part [5]-[7]) that excess noise can provide information about the reliability of electronic devices.

One example — with respect to useful information obtained from intermittency studies — is that the superposition theorem is not valid in certain cases — when dealing with multilevel burst noise. It has been found that [11] — sometimes — the presence of one level of burst noise in a device excludes the presence of another.

Popcorn burst noise

Burst noise (popcorn noise or burst noise) was first discovered in semiconductor diodes and — recently — has been rediscovered in integrated circuits [8]-[11].

If we amplify the burst noise and listen to it in a loudspeaker, it is similar to the sound emitted when popcorn is made (hence the English words "popcorn" and popcorn noise, respectively).

It is a curious, unwanted phenomenon that disturbs the normal operation of a pn junction device. This burst noise is characterised by fluctuations in collector current, generally having the appearance of a telegraphic wave, but sometimes different levels of current pulses can be observed. It may occur or disappear spontaneously (or under particular stress conditions); it does not occur on all devices manufactured from the same wafer, nor does it occur on all wafers[1] of a given production batch.

Burst noise was first discovered in the early 709-type operational amplifiers. Essentially, it is a steep voltage (or steep current) offset that lasts a few milliseconds and has an amplitude ranging from less than one microvolt to several hundred microvolts. The occurrence of noise of this type is quite random. An amplifier may exhibit a few pops per second during an observation period and then remain without pops for several minutes.

Worst-case conditions typically occur at low temperatures with high values of source resistance Rs. In this regard, some operational amplifier designs and the products of some manufacturers are particularly inadequate in this regard.

Regarding the mechanism of the explosion noise, several theories have been developed.

In [2] and [4], the authors conclude that the burst phenomenon is localized near the surface of the emitter-base junction.

In 1969, Leonard and Jaskowlski [23] stated that the random appearance and disappearance of micro-plasmas in the collector-base junctions of the reverse-biased transistor would produce step changes in the collector current.

However, Knott [24] argued, in 1970, that burst noise was the result of a mechanism occurring in the emitter-base junction, and not in the collector-base junction.

In 1971, Oren [22] said that it would be premature, without further study, to use the models mentioned above. Indeed, a closer look shows that several mechanisms are at play (e.g., modulation of leakage current flowing through faults located in the emitter-base spatial region, surface problems, metallic precipitation, dislocations) and no single answer is yet available.

Roedel and Viswanathan [12] found, in the 741 operational amplifier, a close correlation between the intensity of the burst noise and the density of dislocations in the emitter-base junction.

Martin and Blasquez [14] concluded that noise is a good means for characterizing surface parameters (if surface effects are predominant in the degradation process), but blast noise is not as good an indicator as flicker noise.

In [25], it was shown that low-frequency excess noise has two components: 1/f noise and flicker noise.

Although there are various theories on the popcorn mechanism, it is known that devices with surface contamination of the semiconductor chip will be particularly bad poppers.

It is claimed that there are no operational amplifiers that are completely free of pop noise. Some state-of-the-art detector circuits have been developed to select devices having low amplitude pops, but 100 % assurance is impossible as it would require an infinite test time.

Some studies showed that spot noise measurements at 10 Hz and at 100 Hz select units that have much higher noise than typical noise, the measurements being an effective selection for potentially high pop noise units. Screening can be performed, but it should be noted that the confidence level of the selection is only 60 %.

Burst noise was observed in planar, germanium and silicon diodes and transistors. It is believed that a pulse is caused by a single lattice centre in the charge space region. The proportion of transistors affected by burst noise (popcorn noise) varies between 25 % and 70 % [12], depending on the type.

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[1] Radiation showed to increase low-frequency noise levels in linear bipolar devices, while it tends to cause a latching effect in CMOS ICs; X-rays have been found to affect MOS circuits to a greater extent than bipolar ICs as a result of the development of positive charges in the oxide layer, causing a shift in the threshold voltage. As GaAs devices are majority carrier devices, they are relatively radiation resistant compared to silicon devices [37]. We checked the percentage of the explosion noise incidence, by correlating it with the position of the units on the wafer (located towards the centre and/or towards the periphery of the wafer); the results show a higher incidence rate for devices located at the periphery of the wafer.

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The physical origin of pop noise was said to be fluctuations generated in the vicinity of macroscopic crystal defects or dislocations in the surface region of the emitter-base junction [13], but there is still controversy about the mechanism and origin of pop noise [14].

Several experiments showed that burst noise is a large-scale, intermittent recombination; its rate of occurrence depends on mechanical stresses.

Moving dislocations — acting as centres of a large-scale recombination — explain the characteristics of burst noise. In one experiment, the cause of the moving dislocations appears to be the emitter current transfer time [15], [16].

Measurements showed that the percentage of transistors with popping noise depends on the implantation energy. X-ray examination of these transistor wafers showed that the total number of defects increases with the incident implantation energy.

From the experimental results [17], it can be deduced that defects induced by ion implantation cause popping noise.

Due to stress, estimating and predicting the reliability of an electronic device has become more dependent on variations in device characteristics.

The stresses that increase component degradation are: temperature, humidity, pressure, vibration, shock and electrical polarisation. It is widely believed that explosion noise tends to decrease when temperature increases[2].

The observation of distinct burst noise in a high proportion of transistors in the same sample revealed poor semiconductor crystal or oxide layer quality and, as a result, an inadequate manufacturing process. Clearly, a variation over time of the excess noise amplitude indicates an evolutionary defect.

Flicker noise

All solid-state devices have a noise component with a spectrum $1/f_n$, where $n \geq 1$.

This type of noise is known as flicker noise or 1/f noise. It was showed that the spectrum of this 1/f noise is maintained at extremely low frequencies; Firle and Winston [15] measured 1/f noise at 6.10^{-5} Hz.

Experiments made by Plumb and Chenette [21] indicated that flicker noise in transistors could be represented by an if_1 current generator in parallel with the emitter junction. Theoretically, a current generator, partially correlated with the i_{f2} current generator, could be used in parallel with the collector junction. Carefully conducted experiments showed that its effect was so small that it could be neglected.

Under normal operating conditions, excess noise consists — essentially in the low frequency range — of flicker noise and burst noise. These two noises can be represented by two equivalent current generators connected to the input terminals of the transistor (Figure 2).

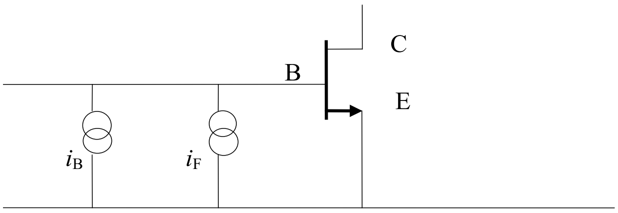

Figure 2 Equivalent current generators

About the origin of scintillation noise

There is a sufficient evidence to support that 1/f noise is generated by a time-varying element R(t).

Hence, the 1/f law. mathematically, means that the square of the modulus of the Fourier transform of R(t) contains a factor 1/f.

The mystery — which underlies the 1/f noise phenomenon — is related to the origin of the time-varying element with resistance R(t).

There are two schools of thought about the origin of this noise:

1. One of them argues that the noise must result from a universal phenomenon. Work on a theory — which brings in the principles of wave mechanics — has recently encountered great difficulties.
2. The other school of thought states that several mechanisms intervene to produce noise 1/f and that it is advisable to consider the devices that produce it individually.

The noise produced by devices with oxide surface layers, for example, is due to these surface states — says McWhorter's theory. The surface states generate these electrical charges, which are released from the oxide surfaces in the mass of the device, thus contributing to its conductivity. The latter is therefore modulated to achieve a 1/f law and the surface states must release their charge over periods of time ranging from microseconds to several hours (or even longer).

All these states must obey a well-defined law.

Slow states assume the existence of surface layers in the oxide; the theory cannot therefore apply to devices without oxide layers. Furthermore, in practice, it has been shown that only fast states can be correlated with 1/f noise.

A theory recently proposed by the *University of Exeter* (UK) overcomes these difficulties and allows the theory of surface states to be applied to all such devices.

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[2] In [11], it was found that - in order to reduce explosion noise - one or more of the following steps must be performed: *(a)* removing or neutralizing recombination-generation centres; *(b)* removing atoms from the crystal or at least preventing their precipitation at the junction; *(c)* reducing or eliminating dislocations from the junction surface. In the meantime, point *(a)* was abandoned, due to the impossibility of removing all surface and volume centres of entanglement.

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According to the new theory, it is sufficient to have fast states; and these are found on all surfaces, in various concentrations.

McWhorter's theory failed to analyse the problem of the redistribution of charges of surface states.

In order to solve the problem, the classical laws that apply to diffusion are used.

Solving the diffusion equation for pulses — or for short charge pulses caused by fast states — shows that the carrier population density near the surface of a semiconductor is modulated so as to produce the 1/f noise characteristic.

There is no need to have an oxide surface, as there is no need to have slow states. In fact, it can be shown that slow states cause a deviation from the 1/f law, which has been observed by several researchers.

Recent experiments have shown that 1/f noise was produced by a universal phenomenon — that of diffusion. Excitation therefore resides in fast surface states and the 1/f law results from a diffusion phenomenon.

Noise measurement

Typically, noise measurements are made at the output of the circuit or amplifier for two reasons:

1. the output noise is larger and, therefore, easier to read on the measuring instrument;
2. the possibility of the noise measuring instrument affecting the shielding, grounding, or balance of the input circuit of the measured device is avoided.

In order to make, comparatively, the excess noise predominant, the HTRB step stress test (one week storage; initial, starting temperature: +150 °C; +25 °C/threshold) followed by 24 hours of stabilization at normal ambient temperature with shorted junctions was used. This allows the selection of high reliability transistors to be performed on a previous noise measurement [3].

The selection principles are:

(a) only transistors with a low level of flicker noise are accepted;
(b) all batches that have a high proportion of burst noise elements are rejected;
(c) batches that have a high mean value of the spectral denoising of flicker noise are rejected (Figure 3).

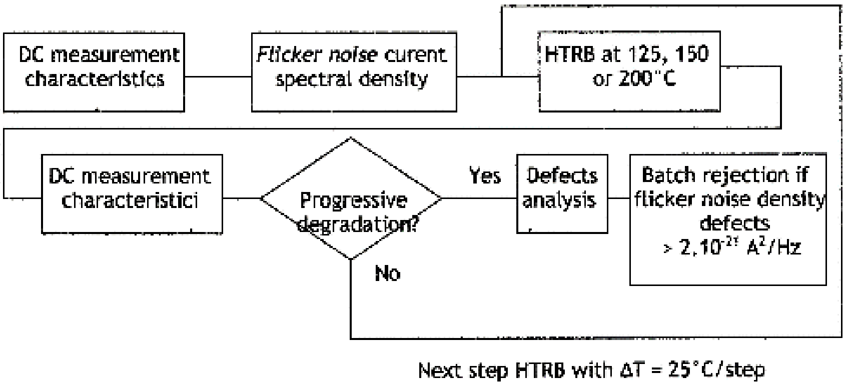

Figure 3. Sequence of the proposed test programme for batch reliability acceptance

Low noise, long life

The conclusion of our reliability tests:

By measuring excess noise, it is possible to make a reasonable prediction of the expected lifetime of devices, using non-destructive testing.

A significant increase in excess noise occurs shortly before failure. Units with low initial values of noise current have a longer lifetime when artificially aged.

Some findings on perfect crystal device technology — perfect crystal device technology (PCT) for reducing flicker noise in bipolar transistors [25]:

i. Flicker noise can be drastically reduced, by eliminating various crystal defects — such as dislocations and precipitates — and by achieving a low Si/SiO_2 density of state, using P/As mixed with doped oxide diffusion technique. It is worth mentioning the disappearance of explosion noise if PCT technology is used.
ii. The degree of generation-dislocation during the diffusion process depends on the grown-in dislocation density; the lower the better.
iii. The diffusion-induced dislocation density depends on the crystal orientation. Orientation (111) was found to be the best — from the dislocation point of view.

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[3] If 50% of the transistors have a DC gain 50% greater than the original gain, a sample test is stopped, and a fault analysis is performed. The transistor under test must be biased by a large external base resistance and the measurement is made at 30 Hz. For a valid comparison, the emitter voltage should be kept at the same value and the noise should be measured with a constant base current [15].

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Noise figure

Noise figure, NF, is the logarithm of the ratio of signal-to-noise at the input to signal-to-noise at the output.

$$NF = 10 \log [(S/Z)in / (S/Z)out] \quad (1)$$

where S and Z are power or (voltage) levels.

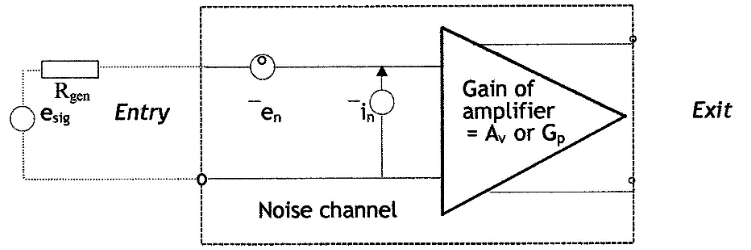

Figure 4. Noise characterization of an operational amplifier [26]

This is measured by determining S/Z at the input in the absence of the amplifier and then dividing by S/Z at the output in the presence of the signal source.

The values of R_{gen} and any X_{gen} as well as the frequency must be known in order to express NF correctly in terms that are understandable.

We want to have as high a S/Z ratio as possible; any noisy channel or amplifier can be specified, in terms of noise, using two noise generators en and in (as shown in Figure 4).

The main points to be observed when selecting low noise amplifiers are as follows:

Avoid applications that require high gain (>60 dB), as amplified noise (2 μV) can get into the audio domain.

For high-reliability systems, all components with blast noise should be rejected; likewise, all batches with a large proportion of components that have 1/f noise or blast noise should be rejected.

Only components with a low noise level shall be accepted. Avoid using too high resistors in your circuits, minimise external sources of noise.

Noise spectroscopy [38]-[41] gives information on the noise of parameters located in the gap layer of the pn junction.

The forward noise reliability indicator is defined as the ratio of the maximum value of the noise spectral density (measured on a load resistor) to the thermal noise spectral density.

As an indicator of noise reliability in reverse bias operation, the ratio of the breakdown voltage for the ideal junction to the reverse soft breakdown voltage has been introduced [41].

Burst noise is used as a third reliability indicator.

Signal quality improvements in digital networks

Substantial improvements in signal quality [47] — both at the component and system level — can be achieved by properly balancing the reactive design of digital, digital networks.

In 50 MHz...200 MHz networks, cancellation of component, configuration and technology noise has been demonstrated using appropriate cancellation criteria, CAE tools and design verification.

In [47], it was shown that, except for device loading, reactive mismatch is the dominant source of signal degradation in many digital networks designed today.

Principles for reactive compensation and location criteria are developed and explained in the context of digital, high-speed operation.

It is shown that, unlike resistive adaptation, reactive compensation does not produce any penalty on the signal, except for the possible change in propagation delay.

Guidelines have been developed for reactive noise cancellation in digital systems, operating with rise times ranging from a few ns to 50 ps.

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He received his engineering training from the Polytechnic Institute of Bucharest.

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R&D Experience: design and manufacture of experimental equipment for Romanian Army Research Institute and for air defence system.

He joined "Brown Boveri" (today: "Asea Brown Boveri") of Baden (Switzerland) in 1969, as a research and development engineer.

R&D *Experience*: design and manufacture of new industrial equipment for telecommunications.

In 1974, he joined "Hasler Limited" (today: "Ascom") of Berne as a Reliability Manager (recruitment by competitive examination).

Experience: set up QRA and R&M teams.

He developed policies, procedures and training.

He managed QRA and R&M programmes as QRA Manager monitoring and reporting on production quality and in-service reliability.

As a Switzerland official, he contributed to development of new ITU and IEC standards.

In 1981, he joined "Messtechnik und Optoelektronik" (Neuchâtel, Switzerland, and Haar, West Germany), a subsidiary of "Messerschmitt-Bölkow-Blohm" (MBB) of Munich, as a Quality and Reliability Manager (recruitment by competitive examination).

Experience: Product Assurance Manager of "intelligent cables".

He managed the applied research on reliability (electronic components, system analysis methods, test methods, etc.).

Since 1985, he has worked as an independent consultant and international expert on engineering management, telecommunications, reliability, quality, and safety.

He is a university professor and has written many articles and communications on modern telecommunications, and on quality and reliability engineering and management.

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He is the author of many technical books, published in English, French, German, or Romanian languages.

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From 1991, he won many Awards and Distinctions, presented by the Romanian Academy, Romanian Society for Quality, Romanian Engineers Association, etc. for his contribution to the reliability science and technology.

Recently, he received the honorific titles of *Doctor Honoris Causa* from the *Romanian Military Academy* and from *Technical University of the Republic of Moldova*.

In 2013, he received, together with prof. Marius Bâzu (head of the Reliability Laboratory of the Romanian Research Institute for Micro and Nanotechnologies (IMT) the *Romanian Academy "Tudor Tănăsescu" prize* for the book *Failure Analysis*, published by John Wiley & Sons.

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