Evaluation Of Physical Processes In The Management Of Technical Systems And Complexes Under The Influence Of Destructive Electromagnetic Radiation

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Summary
The article analyzes the possible physical effects and processes that can occur in semiconductor and microprocessor radio-electronic equipment when exposed to powerful electromagnetic radiation of ultrashort duration, of different origin.
The primary and secondary effects in semiconductor elements under the influence of pulsed microwave noise are considered.
Experimental studies of the destructive effect on computing technology are analyzed with an example of a personal computer based on a 286 processor (8-12 MHz), which included a system unit in a metal case, a keyboard and a monitor. For BBS with a spectrum width of f = 0.5–2 GHz, the processor hangs up. BBS duration is 3… 5 ns, rise time is 0.5 ns.

Keywords:
radio electronic means, electromagnetic radiation, ultrashort pulse duration, broadband signals.

1. Introduction

Modern radiolocation media have the ability to generate GW power pulses, with a duration shorter than ns, in order to solve the problems of transmitting useful information over long distances.
For example, the use of broadband signals (BBS) in radiolocation or communications is considered in terms of protection of useful information.
The need to transmit information over long distances requires an increase in strength, which may lead to a breakdown in the atmosphere, which preconditions the study of the space-energy and spatiotemporal characteristics which are generated [1, 6, 13-16].
The aim of the article is to analyze the origin of possible destructive phenomena in semiconductor and microprocessor element bases in radio electronic equipment when exposed to powerful electromagnetic radiation.

2. Theoretical Consideration

As a result of the interaction of impulse noise with elements and assemblies of electronic equipment, two main effects can be observed, leading to a temporary or catastrophic failure in the operation of objects. The first of them is associated with aiming at structural elements (leads of semiconductor elements, strips of printed circuit boards, etc.) of microwave power, which in turn leads to electrical overloads ("antenna effect"). The second mechanism is associated with the direct interaction of the pulse with the structure of the semiconductor element.
The values of the amplitudes of electrical signals induced in the circuits of circuits, which can be considered as antennas, are mainly determined by the following factors:
- signal parameters (power P, filling frequency f, pulse duration τ_i);
- geometric dimensions and design features of elements, their mutual orientation;
- electrical operation of the circuits;
- constructive arrangement of mounting circuits relative to the equipment case, etc.

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antenna-feeder devices and interconnections can have a significant impact on the performance of the elements.
For powerful signals of ultrashort duration, the most vulnerable are the elements of the transmit-receive path of radio electronic equipment (limiters, low-noise amplifiers, mixers, etc.).

Note that along with electrical overloads in devices using semiconductor devices, one should take into account the effects associated directly with the interaction of the signal with the electronic subsystem of the semiconductor. In this case, one should take into account the change in the parameters of deep energy levels in the semiconductor, which lead to a change in the generation-recombination processes.

These effects lead to degradation of the current-voltage characteristics of pn-junctions of semiconductor devices and a change in the operating mode of the radioelement.
The most critical effects in semiconductor structures exposed to an electromagnetic pulse are instabilities of the current distribution over the cross-section of the regions of the semiconductor element and the processes of avalanche multiplication of carriers. In this case, any fluctuations (inhomogeneities in the distribution of dopants, connecting contacts, defects on the surface and in the bulk of the structure, etc.) can serve as a region of increased current density. These physical effects in some cases are the cause of changes in the electrical and functional characteristics of semiconductor elements (failures, switching, the appearance of false or distortion of useful signals) when exposed to electromagnetic radiation, with the subsequent restoration of operating characteristics. This is due to processes when the pulse energy is insufficient for the development of electrical and thermal processes in the circuit elements, leading to catastrophic breakdowns. From the point of view of constructing models of the behavior of semiconductor elements, when exposed to powerful ultrashort signals in the literature, the main attention is focused on the primary effects associated with avalanche and tunneling breakdown, as well as the breakdown of the gate dielectric. Moreover, among the secondary effects, catastrophic damage is in most cases the result of thermal secondary breakdown.
The primary effects in semiconductor elements when exposed to pulsed microwave noise are in most cases determined by the mechanisms of avalanche and tunneling breakdown. Secondary effects include thermal flashback, current flashback, and latching effects.

Thermal secondary breakdown. Due to the variety of failure mechanisms of semiconductor devices, determining the exact value of the energy (power) of damage to electronic equipment is associated with significant difficulties. However, it is possible to assess the damage power level by analyzing thermal processes in the devices.
The main reason leading to damage to semiconductor elements in the presence of currents and voltages due to the effect of pulsed electromagnetic radiation is the release of significant thermal power in active volumes in a short period of time.

Current secondary breakdown. Planar epitaxial transistors are characterized by a current form of breakdown. This mechanism takes place in high-frequency transistors with an epitaxial layer in the collector and is associated with avalanche injection in the space charge layer of the collector.

Electrical snap-in (dU / dt effect). The formation of active elements in the volume of a conducting substrate leads in some cases to the appearance of parasitic 4-layer structures, which can turn on like a thyristor when exposed to electrical pulse signals. A typical manifestation is a sharp increase in current in the supply circuit, input or output circuits. A sharp increase in voltage (at a rate of 0.1-10 V / ns) can cause “latching”, even if the maximum exposure voltage does not exceed the allowable one according to the passport (dU / dt effect). Such an effect can be not only a consequence of interference created by external influences, but also induced signals from neighboring elements along the power circuit.

The performance of the radioelement when the effect occurs is disrupted and is not restored after the end of the exposure. Disconnecting the power sometimes clears the latching. Due to the flow of high currents, burnout of metallization or thermal breakdown of internal semiconductor structures can occur.
For the analysis of resistance to the effect of dU / dt, the same parameters are usually used as for the analysis of latching of thyristors, which determine the characteristic points of the S-shaped current-voltage characteristic:
$I_{ак}, U_{ак}$ – activation current and voltage;
$I_{уд}, U_{уд}$ – holding current and voltage;
$I_{з}, U_{з}$ – residual current and voltage after latching;
$E_{кр} = dU / dt$ – critical rate of rise or fall of the impulse.

The dominant mechanisms of failures in semiconductor devices under the influence of short-pulse electromagnetic radiation are analyzed. The influence of signal characteristics on the degradation of diode structures, bipolar transistors, field-effect transistors with a Schottky gate, integrated analog and digital microcircuits is considered. Due to the rapidly developing digital computing technology, digital microcircuits are of particular interest for use in weapons.

Formed on the basis of CMOS technology, there are two main failure mechanisms when exposed to ultrashort pulses.

The first of them is associated with the breakdown of the gate dielectric in the case when the voltage at the gate reaches a value determined by the electrical strength of the oxide material. The critical power level depends on a number of technological parameters of the process of growing the gate oxide and its thickness, as well as on the duration of the acting pulse. Despite the use of various gate protection methods in CMOS microcircuits, this type of breakdown cannot be ignored.

The second of the possible failure mechanisms under the action of short pulses in CMOS microcircuits is the activation of a parasitic four-layer structure at a high slew rate of the influencing signal (dU / dt effect), which has an S-shaped characteristic of the current-voltage characteristic characteristic of thyristors.

Thus, the analysis performed allows us to draw the following main conclusions:

- semiconductor structures are the most sensitive to the action of ultrashort pulsed fields - the main physical mechanisms in a semiconductor structure that determine the temporary loss of operability of a semiconductor device are: an increase in the temperature of carriers to deep levels of the interface, as well as the detection of microwave power at rectifying junctions;
- the cause of catastrophic irreversible failures in most cases is thermal secondary breakdown, as well as current pinching, leading to the melting of the structure and destruction of metallization and local areas. The effects associated with thermal secondary breakdown in the first approximation can be estimated using the Wunsch-Bell-Task model;
- a significant influence on the critical level of pulsed microwave power is exerted by the design and technological features of microcircuits (circuit technology, type of housing, seat, interconnections, etc.).

Experimental studies of the destructive effect of powerful electromagnetic radiation on electronic equipment using ultra-wideband signals

A review of the literature on the potential for the destructive effect of powerful electromagnetic radiation from radio electronic equipment using ultra-wideband signals shows that theoretical research in this area is limited. The reason for this, apparently, is the large number and variety of types and types of radio electronic equipment, their design and technical features: bandwidth, operating frequency, etc. At the same time, there are quite a lot of publications devoted to experimental studies of the destructive effect of powerful electromagnetic radiation on individual elements of the existing electronic equipment. In particular, the rapidly developing area of creating "smart", ie., with in its composition onboard computers or special computers, weapon systems for ground, surface, air, underground, underwater basing arouses the practical interest of researchers regarding the possibility of their incapacitation using ultra-wideband signals.

For example, in many scientific works [2-5,15-17], the results of studies of functional failures of a personal computer when exposed to ultrashort electromagnetic pulses are presented. It is noted that the action of the fields of ultra-wideband signals, even at levels of significantly lower levels of degradation of the hardware element base, is manifested in the blocking effect of interference and violations of varying degrees of complexity in the technological operations performed. In analog devices, it is associated with the appearance in sensitive circuits of a specific non-linear response - states of dynamic "chaos".

Since in the active mode of operation, the chaotic state is formed by the device itself, the duration of the blocking action of external excitatory factors, i.e. the time of loss of performance, corresponds to the relaxation time of the equipment. In studies on the response of microwave receiving modules for various purposes, it was shown that the state of chaos and, accordingly, the duration of blocking of analog equipment can be hundreds - thousands of times longer than the duration of the exposure signal. At the same time, despite the existing experience in determining and quantifying the parameters of electromagnetic resistance under the action of ultra-wideband signals for analog equipment, there are only some data on similar indicators for digital devices. This situation is due to the difficulties in choosing the criteria for the blocking action of interference, which is associated with a large number of dimensional resonances arising in various types of digital devices, when an interference signal enters the object, bypassing intra-block and network protection devices (the so-called "back-door").

Experimental data show that the criterion parameter under conditions of exposure to electromagnetic signals of ultrashort duration with different spectral characteristics is the value of the spectral power density or field strength of the ultra-wideband signal in the range of characteristic frequencies of the object's sensitivity.

The object of the study was a personal computer based on a 286 processor (8 - 12 MHz), which included a system unit in a metal case, a keyboard and a monitor. The computer under test was located in the working area at a distance of 0.2 - 2 m from the antenna (radiation field strength: 0.1 - 20 kV / m). Irradiation was carried out in a series of single or packs of 5 - 50 ultra-wideband signals, following with a frequency of 0.5 - 20 Hz.

Table 1. Parameters of generators and characteristics of ultra-wideband signals

Radiation source	A type antennas	t_i/t_f,ns	Mode work	U_{out}, кV	$E_r(t)$, (L=2 m) кV/m	E_r (f), (f=0.5-2 GHz) V/m Hz
1. Spark pulse generator on piezoelectric effect	Spark channel	3-5/0,5	Series of 2-5 pulses	13-18	0,6-1	0,02-0,2
2. Fast recovery diode modulator	Waveguide horn P6-23, loop	10-20/0,3	Single/ periodic, 20-100 Hz	0,8-1	1-3	0,5-1,5
3. Coaxial forming line	horn	70/1,0	Single/ periodic, 1-30 Hz	6-14	4-6	0,3-3
4. Five-stage pulse generator	Waveguard horn P6-23	15/0,7	Single/ periodic, 10-20 Hz	45-50	15	0,5-4

A Hertz dipole 4 sm long and a standard pyramidal horn P6-23A (frequency band 1 - 8 GHz) were used as receiving ultra-wideband antennas. The recording of the responses of the receiving antennas was carried out with a C7-19 oscilloscope with a frequency band of 0 - 5 GHz.
The amplitude and spectral parameters of the ultra-wideband signal were calculated based on oscillographic data and antenna calibration characteristics (Table 1).

As a result of irradiation with ultra-wideband signals of a working computer, various effects were observed: from distortions on the monitor screen to functional failures and "freezing" (Table 2).
Any of the failures was associated with the need to restart the PC. As can be seen from the table, various functional elements of the PC had a different response and the degree of failures depending on the amplitude and time parameters of the pulse generator.

Almost in each of the series, blocking of the computer keyboard was achieved with a minimum pulse power of ultra-wideband signals. Interference with video signals and monitor sweep signals was also determined by the shielding conditions of the video controller and the monitor case.

Table 2. Functional failures of a personal computer when exposed to ultra-wideband signals with different threshold levels of spectral field strength

The nature of PC failures	Generator	E (f), V/m Hz (f=0,5-2 GHz)
Failure of the keyboard due to interference on the interface cable. The manifestation is similar to pressing a set of both function and symbol keys. There is no reaction to pressing the keys until the pulse generator is turned off and the PC / keyboard is restarted.	1 – 4	≥ 0,025
Distortion of the horizontal scan of the monitor. Distortion range 10-25%. Increase in distortion proportional to field strength	2 – 4	≥ 0,8
When the case of the system unit is open - a fatal error (BIOS message): no access to the hard disk. In some cases, DOS generates a disk read failure message. Strong distortion of the horizontal scan of the monitor. Distortion area 50-100% of the screen.	2 – 4	≥ 1,0
Failure (fatal) in the video system when continuing or stopping work. In text mode, a frame sync failure occurs due to graphical image shuffling.	3, 4	≥ 1,5

The processor "freeze" was observed at peak values of the radiation field strength: $E_{max}(t) = 10\text{-}15$ kV/m in a series of single or multiple ultra-wideband signals, following with a small interval. This blocking level could decrease as the repetition rate increased. The low repetition rate of the pulse generator triggering at a lower field strength did not allow achieving the effect of a processor failure during each burst of ultra-wideband signals, which is apparently due to the low probability of coincidence of the impact pulses with the working pulses of the computer.

The result of PC tests was the presence of a complex dependence of the degree of failure on the field strength, polarization and spectral composition of the ultra-wideband signal, which indicates the existence of multiple resonances in the response function of the device. Spectral processing of ultra-wideband signals from various sources showed a direct dependence of the effects of computer failure on the spectral density of the field strength in the frequency range of 0.5 - 2 GHz at values E(f)=1 – 10 V/m.

An analysis of experimental studies of the destructive effect of powerful electromagnetic radiation on computers using the example of a personal computer based on a 286 processor (8 - 12 MHz), which included: a system unit made in a metal case, a keyboard and a monitor, shows that for an ultra-wideband signal with with a spectrum width f = 0.5 - 2 GHz and a spectral field density E (f) = 1 - 10 V / m, the processor "hangs". The duration of the ultra-wideband signal is 3 ... 5 ns, the rise time is 0.5 ns.

Conclusions

Experimental studies of the destructive effect on computing technology are analyzed with an example of a personal computer based on a 286 processor (8-12 MHz), which included a system unit in a metal case, a keyboard and a monitor. For BBS with a spectrum width of f = 0.5–2 GHz, the processor hangs up. BBS duration is 3… 5 ns, rise time is 0.5 ns.

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