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The Induced Physical Effects on the Semiconductor Electronics under Electromagnetic Pulse

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***Abstract*—The response of the electronic devices subjected to the Electromagnetic Pulse (EMP) effect is a complex problem. The damage to the electronic device due to the EMP is one of the main failure mechanisms in the modern semiconductor electronic systems. The study of the induced physical effects on the semiconductor electronics in this particular aspect of damage is applicable not only to EMP problems but is also applicable when the high transient voltages appear in the circuits whether the pulse origin is EMP, or a transient transform within the system itself, which we will also address briefly.**

***Index Terms*—electromagnetic pulse, EMP sources, electronic system, damage, coupling mechanisms, susceptibility**

I. INTRODUCTION

In the recent years, the use of electronics, its components and assemblies has constantly increased. Evidently, there is a risk of generating the disturbing signals inside the electronic system by the injection of the external electromagnetic fields. The growing attention must also be paid to the threat posed by the Electromagnetic Pulse (EMP) radiation, which could couple into electronic devices intentionally or unintentionally due to the proximity to general environmental high frequency signal, usually in microwave range. A breakdown or destruction of the electronic systems would be inconceivable and devastating. The Electromagnetic (EM) radiation may cause permanent damage to the semiconductor devices [1]-[4]. This report discusses the EMP effects and damage mechanisms on the performance of the semiconductor electronics. Although some aspects of the electromagnetic radiation damage to semiconductor devices have been addressed in the prior publications [2]-[9], to the best of our knowledge the current report is the most comprehensive and novel in specifically addressing the analysis of different possible damaging factors of the Electromagnetic Pulse (EMP) effect in particular on the elements of the semiconductor electronics.

The paper is organized as follows (Fig. 1): the coupling mechanisms between the EMP device output and the target system are defined in Section 2. The induced effects on the target are discussed in Section 3. The main physical mechanisms of the EMP effects are discussed in Section 4.

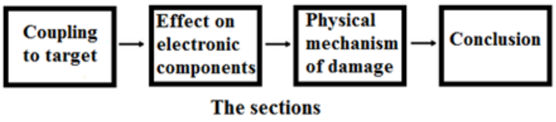

Figure 1. Paper’s structure.

II. THE COUPLING MECHANISMS

The damage to the electronic devices is determined by the amount of energy that is transferred while the electronic devices are coupled with electromagnetic environment. The electromagnetic coupling is a kind of mechanism where the microwave energy is delivered to equipment through a circuit line. An EMP typically contains energy at many frequencies from DC (zero Hz) to some upper limit depending on the source.

All electronic equipment is susceptible to the malfunctions and permanent damage under the electromagnetic radiation of the sufficient intensity. The intensity level for the system vulnerability is dependent upon the coupling from the external fields to the electrical circuits and their corresponding sensitivity characteristics.

A temporary malfunction (or upset) may occur when an electromagnetic field induces current(s) and voltage(s) in the operating system electronic circuits at levels that are comparable to the normal operating signals.

No matter what kind of the HF source is used or which power/frequency/ mode is applied, two principal coupling modes are recognized in the literature, assessing how much power is coupled into the target systems:

- Front Door Coupling, (FDC)
- Back Door Coupling, (BDC)

A. *Front Door Coupling*

The FDC is typically observed when the power radiated from the HF source is directly coupled into the electronic systems, which involves an antenna such as in communication equipment. The antenna subsystem is designed to couple power in and out of the equipment, and

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thus provides an efficient path for the power flow from the electromagnetic source to enter the equipment and cause damage.

B. Back Door Coupling

The BDC occurs when the electromagnetic field from the HF source produces the large transient currents (these currents are termed spikes, when they are produced by a transient source) or the electrical standing waves through the cracks, small apertures and via the fixed electrical wiring and cables, interconnecting the BDC equipment, or providing the connections to the power mains, or the telephone network (Fig. 2) [1], [5].

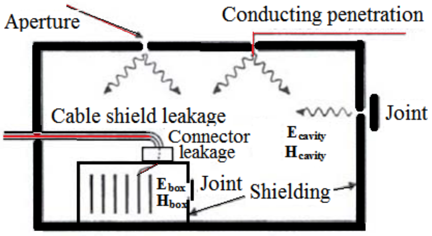

Figure 2. Back door coupling.

The BDC can generally be described as a wideband, but it may have the narrow-band characteristics because of the resonance effects (the coupling to cables for example).

The BDC creates the voltages on the traces and wires that superimpose with the normal signals and enter the device terminals. While the circuit traces and wires are not designed specifically to transmit and receive signals, they introduce the parasitic resonances in the systems that reduce the level of RF power required to stimulate the EMP effects. The microwave radiation from the EMP devices creates the high voltage standing waves on the fixed wiring infrastructure.

Since the impinging EMP field has a broad frequency spectrum and high field strength, the antenna response must be considered both in and out of the band. The inadvertent unintended antennas are the electrically penetrating conducting structures, power lines, communication cables and AC pipes that collect EMP energy and allow its entry into the enclosure.

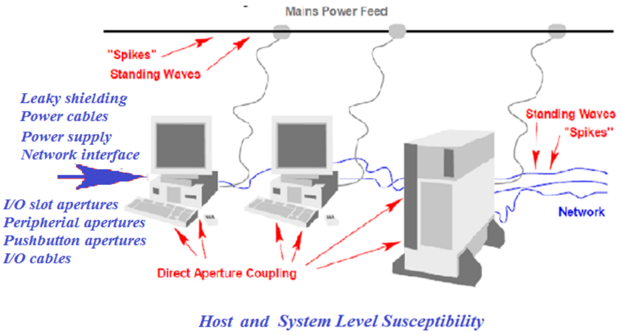

Figure 3. The coupling mechanism.

The cavity fields are other important aspects of EMP effects (Fig. 2). The EMP radiation will penetrate the enclosures such as computer cases and excite the field distributions according to the resonant modes of the structure. Predicting these field distributions deterministically is difficult due to the complexity of the EM boundary conditions that are typical of even the most basic electronic enclosure. Frequently, the dimensions of the enclosures and the corresponding EM boundaries are many times greater than the wavelength of the EMP radiation (Fig. 2, Fig. 3). Thus, these structures support numerous modes that are typically closely spaced in frequency. With EMP sources, the standing waves on the wiring which enters the equipment cavities may contribute to the excitation of the spatial resonances within the equipment cavity itself.

Further complicating the analysis of EM fields is the fact that the EM boundaries are rarely static. The small changes due to the motion, vibration, or temperature may substantially alter the field distribution. The form of the electromagnetic pulse in the cavity usually is a damped sinewave. A damped sinewave couple a relatively narrow frequency band.

The Openings like the doors, windows, utility lines / holes, improperly terminated cable shields and the poorly grounded cables can couple EMP energy directly into the shielded enclosure. The leakage through an aperture depends on its size, the type of the structure housing it and its location. The aperture responds to both the electric and magnetic fields.

The microwave radiation from EMP devices has the ability to directly couple into the shielded equipment cavities through the ventilation holes, and the poorly sealed panels (Fig. 2). The gaps or holes can behave as the slot radiators providing that they are comparable in size to the wavelength of the radiation. The panels which are not conductively sealed around their edges may also resonate when excited by the microwave radiation and directly couple the energy into the cavity. The spatial standing wave pattern will exhibit potentially large field strengths at its antinodes, and the semiconductor components exposed to such fields.

III. THE EFFECTS ON TARGETS

The equipment connected to exposed cables or wiring will experience either the high voltage transient spikes or the standing waves, which can damage the semiconductor devices (Table I).

TABLE I. SPIKES DAMAGE SEMICONDUCTOR DEVICES

Types of semiconductor devices	**Breakdown voltage range**
Silicon high frequency bipolar transistors	15V-65V
Gallium Arsenide Field Effect Transistors	10V
High density Dynamic Random Access Memories (DRAM)	7V
Generic CMOS logic	7V-15V
Microprocessors running off 3.3V or 5V power supplies	3.3V-5V

The HF source interactions with the system electronics can be categorized into four levels of destructive effect: upset, lock-up, latch-up, and burnout [5]-[9]. These four potential effects of the HF source on targets can be categorized into a hierarchy of damaging, each of which will require the increasing microwave emission on the target.

A. Soft-Kill

A soft kill is produced when the effects of the HF source cause the operation of the target equipment or system to be temporarily disrupted. The soft kill can occur in two forms:

a) Upset: The Upset is a temporary alteration of the electrical state of one or more nodes, in which the nodes no longer function normally. The Upset continues until the impressed radiation is terminated. Once the signal is removed, the affected system can be easily restored to its previous condition.

b) Lock-up: The Lock-up is similar to the upset: the electrical states of affected nodes are only temporarily altered, but the functionality of these nodes remains altered after the radiation is removed. The Lock-up produces a temporary alteration similar to the upset, but the electrical reset or shut off and restart can be necessary to regain the full functionality after the radiation is removed.

B. Hard-Kill

A hard kill is produced when the effects of the HF source cause permanent electrical damage to the target equipment or system, necessitating either the repair or the replacement of the equipment or system in question. The hard kill can be seen in two forms:

a) Latch-up: The latch-up is an extreme form of lockup in which the parasitic elements are excited and conduct the current in the relatively large amounts until either the node is permanently self-destroyed or the electrical power to the node is switched off.

b) Damage/Burnout: The damage/burnout is an electrical destruction of a node by some mechanism like the latch-up, metallization burnout, or junction burnout. One will often find the term “permanent damage” or “electrical burnout” used to describe the more catastrophic kinds of the damage. The damage/burnout occurs when the high-power microwave energy causes melting in the capacitors, resistors or conductors. The burnout mostly occurs in the junction region where multiple wires or the base collector or emitter of a transistor come together, and often it involves the electrical arcing. Consequently, the heating is localized to the junction region. The permanent damage can occur when these induced stresses are at the levels that produce the joule heating to the extent that thermal damage occurs (usually between 600 and 800 degrees Kelvin).

In this paper we have investigated the level of energy density that is necessary to induce the soft or hard kill on the various electronic systems. There is some data about the damage power density threshold of the electromagnetic pulse to destroy some electronic system (Fig. 4) [8]. The response of electronic devices under the EMP effect is a complex problem.

In [5] authors estimated the value of the damage power density threshold of the electromagnetic pulse to the response of the electronic devices under the EMP radiation. Their results (Table II) show that from the level about *0.01*—1(W/cm^2) and up the EM pulse produces the permanent electrical damage to the target equipment or system.

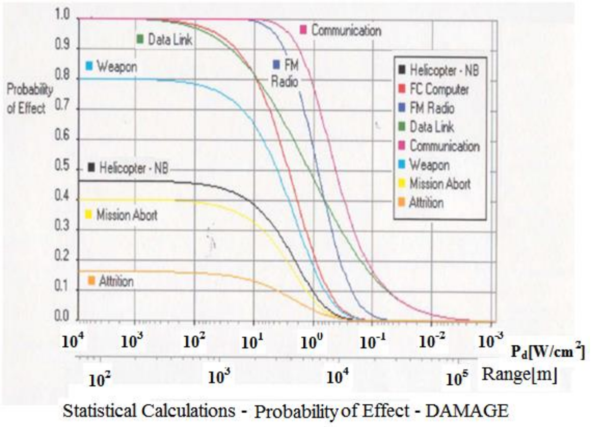

Figure 4. The threshold power density.

TABLE II. THE VALUE OF DAMAGE POWER DENSITY THRESHOLD

Power density level	Mutilate situation of the computer
0.01-1(μW/cm^2)	Produce false signals, node work will suffer disturbance
0.01-1(W/cm^2)	Computer chips will be mutilated
10-100(W/cm^2)	Computer components and logic circuit will be mutilate
1000-10000(W/cm^2)	The entire computer node will be mutilated

IV. THE PHYSICAL MECHANISMS OF DAMAGE

EMP is coming from the diverse sources and it can induce the transient electrical effects in the metallic or semiconductor materials. The damage to the sensitive components by the strong EMP-induced transients is a serious problem in the electronic systems. While many circuits can be protected from the **EMP** by the metal boxes, others require the connections to the wires that must pass out of these boxes. These wires act as antennas and channel the destructive pulses through the shield and into the electronics. Invariably, some of these penetrating wires connect directly to the sensitive electronic components (e.g., the signal diode in a communications system that must connect to an antenna wire). If the system is to survive, these components must be able to withstand the EMP induced transient with a minimal damage or degradation.

The solid-state electronic circuits contain many physical components (i.e., the resistors, capacitors, diodes, transistors, metal strips, etc.), all of which can be destroyed or degraded by an EMP. For example, a high voltage pulse can cause two closely spaced metal strips to short, or induce a conduction path through an insulator. Understanding the effects of EMP on the various circuit components is essential to be able to answer questions concerning the operability or survivability of a particular circuit or system in an EMP environment.

There are many different types of damage mechanisms that can occur in the electronic components. The semiconductors can experience the thermal and current mode second breakdown, surface breakdown, electromigration of impurity atoms, and many other high-field effects. The insulators can experience bulk or surface breakdown. The wires can be attracted towards each other to cause a shortening (or short circuit), or simply be burned off.

In our opinion there are four main physical factors of damage to semiconductor structures and their parameters due to the EMP radiation which we describe below.

A. The Induced Voltages and Currents

The current overshoot phenomenon appears in any diode structure because of the capacitance of the diode under the action from the high frequency electromagnetic field of the pulse in rise time. The current overshoot phenomenon may cause a significant transient current. If the rise time of the pulse is short enough, the transient current may interfere with the signal in the circuit or even may lead to the logical errors in the circuits and cause the failure of the electronic equipment.

The semiconductor devices can experience the serious failures and malfunctions caused by the over current and over voltage in cases when the reverse voltage is biased to the PN junction region (Fig. 5) of the thermal secondary breakdown induced by the high power microwaves, as the devices are mostly comprised of the integrated circuits and microelectronics, which are sensitive to the microwaves [3]-[7].

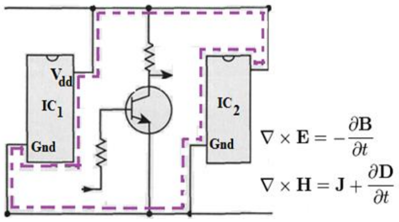

Figure 5. The large loop area enclosed by the faulty PCB layout scheme.

Another major EMP thermal problem affects the reliability of the electronic system. The high voltage transients, large current flow, etc., can exceed the designed levels of the thermal dissipation in the device and cause the thermal runaway till the melting point of silicon at 1688 K.

B. The Arcing (the Air and Dielectric Breakdown)

The Arcing is a very common event in the high-level pulsing of the circuits. The arcing can occur wherever the two conductors are close together, and there is a high voltage between the two (such as produced by a high level pulse entering the system) (Fig. 6). The arcing can also occur near the port entry point, or deeper within the system. Generally, it is better if the arcing is not deep within the system [8].

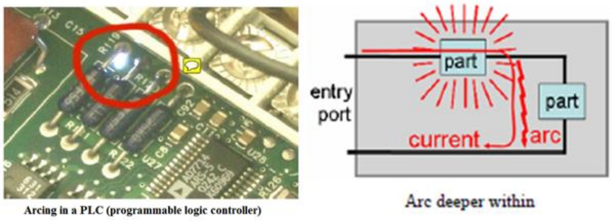

Figure 6. The arching occurring within the system.

The air breakdown occurs at the levels of about 1kV for a 1 millimeter of the air gap at the normal air pressure. The breakdown level may be affected by the water vapor, and the dust or debris that may have accumulated. The breakdown level can also be higher for very fast pulses – since some time is needed to initiate and close an arc.

C. A Latch-up

It is the inadvertent creation of a low-impedance path between the power supply rails of an electronic component, that is triggering the parasitic structure, which then acts as a short circuit, disrupting the proper functioning of the part and possibly even leading to its destruction due to the overcurrent.

All IC are made by combining the adjacent PNP type and NPN-type transistors. The paths other than those chosen to form the desired transistor can sometimes result in the so-called parasitic transistors, which, under the normal conditions, cannot be activated. The parasitic structure is usually an equivalent of a thyristor (or Silicon Controlled Rectifier, SRC), a PNPN structure which acts as a PNP and NPN transistor stacked next to each other (Fig. 7) [4], [7].

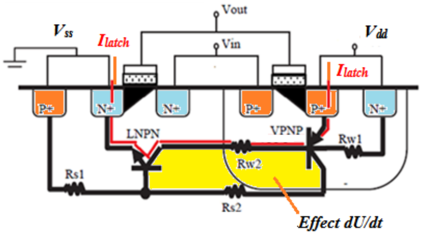

Figure 7. The parasitic PNPN bipolar component in the CMOS gate.

In a closed circuit that is produced between two bases and two collectors of a PNP and a NPN transistors, the EMP may produce the transient voltage that may be enough to open the p-n junctions collectors. During a latch-up, when one of the transistors is conducting, the other one begins conducting too. They both keep each other in saturation for as long as the structure is forward-biased and some current flows through it - which usually means until a power-down. The SCR parasitic structure is formed as a part of the totem-pole PMOS and NMOS transistor pair on the output drivers of the gates.

The latch-up is a phenomena where an impedance between the power supply and the ground becomes low, and when a vertical PNP (or NPN) transistor and lateral NPN (or PNP) transistor, which create a parasitic PNPN bipolar structure, simultaneously operate. When the latch-up occurs, a large amount of current $\boldsymbol{I_{latch}}$ suddenly flows between the V_{dd} and V_{ss}.

D. The Other Effects

In our earlier publications [10] we have discussed the increase of the recombination current induced under the strong electric field in the p-n- junction. The effect of the increase of the recombination current has been observed in the heterojunction bipolar transistor, but it is necessary to note that this effect takes place only at low level of the EMP power. The other effect is the excessive charge due to the electron-hole pair generation under the microwave interference when the temperature rises during the irradiation. [11], [12].

V. CONCLUSION

The main physical factors of the damage to the semiconductor structure and its parameters under EMP radiation are:

1) The over current and over voltage in a loop areas in the layout schemes;
2) The air and dielectric breakdown between the near placed conductors in the schemes;
3) A latch-up of the parasitic thyristor structure;
4) The induced EMI recombination currents.

The concrete mechanism depends on the distance to the target from the EMP source, its operating frequency, the burst rate and pulse duration, bandwidth, vulnerability of the target, coupled power level the EMP power, coupling mode or entry points. So a detailed study of these induced effects of microwaves on information electronic instruments is needed in each concrete case.

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