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ELECTROMAGNETIC PULSE EFFECTS AND DAMAGE MECHANISM ON THE SEMICONDUCTOR ELECTRONICS

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Abstract. *In recent years, growing attention has been paid to the threat posed by high-power microwave electromagnetic interference, which can couple into semiconductor electronic devices intentionally from microwave sources or unintentionally due to the proximity to general environmental HF signals. This paper examines physical mechanism of malfunction and destruction of electronic devices by high power microwaves electromagnetic pulse.*

Key words: *electromagnetic pulse, EMP sources, electronic component, damage, coupling mechanisms, susceptibility*

1. INTRODUCTION

In 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 injection of the external electromagnetic fields. The growing attention must be paid also to the threat posed by the electromagnetic pulse 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 radiation may cause permanent damage to the semiconductor devices [1]-[8]. This report discusses the various electromagnetic pulse (EMP) effects and damage mechanisms on the performance of the semiconductor electronics. The authors used the results of own investigations and some literature dates.

The paper is organized as follows (Fig. 1). Section 1 presents the types and the main parameters of EMP sources. 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.

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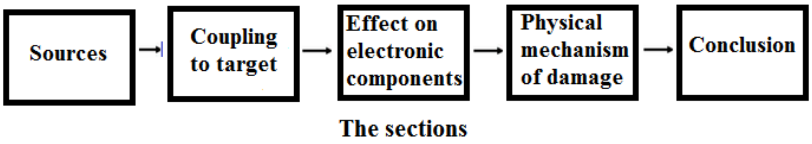


Fig. 1 Paper′s structure.

2. EMP SOURCES

It is well established now that sufficiently intense EMP in the frequency range of 200 MHz to 5 GHz can cause upset or damage in electronic systems [1], [4], [5], [8]. The reason to choose this range is extensively populated with the radars, television broadcasting, mobile communications, high power microwave (HPM) sources, etc. This induced effect in an electronic system is commonly referred to as intentional or unintentional electro-magnetic irradiation (EMI). Such EMI could be radiated or conducted [4].

An electromagnetic pulse, also sometimes called a transient electromagnetic disturbance, is a short burst of electromagnetic energy. The waveform of EM pulse describes how its instantaneous amplitude (of the field strength or current) changes over the time. The real pulses tend to be quite complicated, so the simplified models are often used in theoretical and experimental studies. Usually such models address a rectangular or "square" pulse.

Pulses are typically characterized by:

- The type of energy (radiated, electric, magnetic or conducted).
- The range or spectrum of frequencies present.
- Pulse waveform: shape, duration and amplitude

One way of classifying the EMI is based on the frequency content of their spectral densities as “narrowband” and “wideband”. The frequency spectrum and the pulse waveform are interrelated via the Fourier transform. An EMP typically contains energy at many frequencies from DC (zero Hz) to some upper limit depending on the source. The shortness of the pulse means that it will always be spread over a range of frequencies.

Types of EMP divide broadly into natural, man-made and weapons (Fig.2) [1], [4]. Nowadays, it is practicable to generate the transient wideband pulses (WB) with high amplitude and very short rise times. As a radiated electromagnetic field, these pulses have an effect on the function of modern electronics. The microwave interference is often considered to have a pulse width ranging from several to several hundreds of nanoseconds.

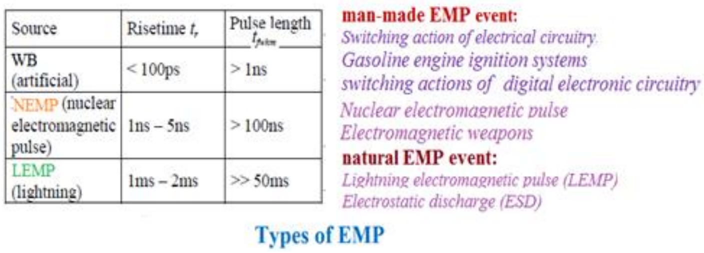


Fig.2 EMP characteristics.

3. The Coupling Mechanisms

The damage to 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 an equipment through a circuit line [1], [3], [7].

All electronic equipment is susceptible to the malfunctions and permanent damage under the electromagnetic radiation of sufficient intensity. The intensity level for 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) can 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 literature assessing how much power is coupled into target systems:

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

Front Door Coupling

The FDC is typically observed when the power radiated from the HF source is directly coupled into the electronic systems [6] (Fig. 3). But more often the antenna subsystem is designed to couple HF power in and out of the equipment, and thus provides an efficient path for the power flow from the electromagnetic source to enter the equipment and cause damage.

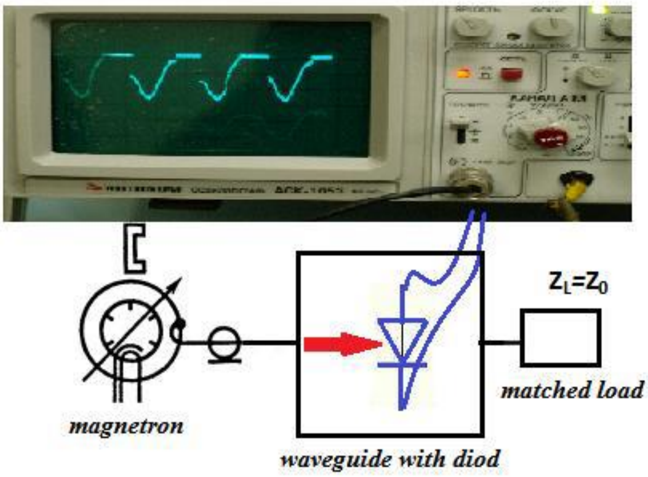


Fig. 3 Scheme of the experimental the research of the influence of microwave radiation on the diodes.

Back Door Coupling

The BDC occurs when the electromagnetic field from the HF source produces large transient currents (termed spikes, when 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 connections to the power mains, or the telephone network [1], [8] (Fig. 4). 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).

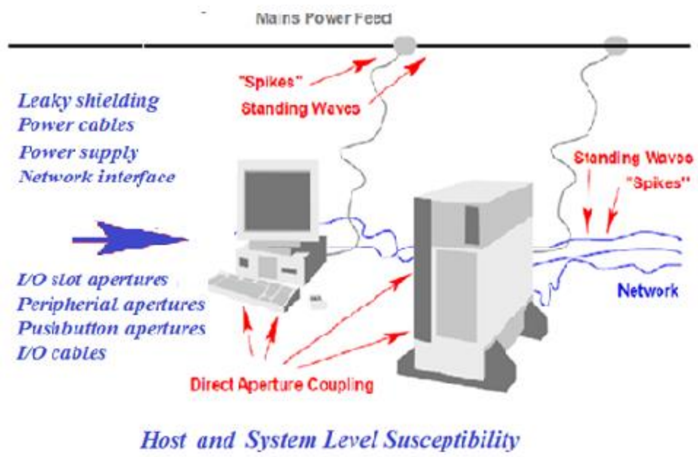


Fig. 4 The coupling mechanism.

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 HF power required to stimulate EMP effects. Microwave radiation from EMP devices creates the high voltage standing waves on the fixed wiring infrastructure. 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 1).

Table 1 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 3.3 V or 5 V power supplies	3.3V-5V

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

The Cavity fields are another important aspect of *EMP* effects. *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. It is often that the dimensions of the enclosures and the corresponding EM boundaries are many times greater than the wavelength of the EMP radiation. Thus, the 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 exciting 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 in to 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. 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.

In order to analyze the coupling process of electromagnetic pulses into the electronic systems the transversal electromagnetic (TEM) TEM-waveguides are used. The test area inside the TEM-waveguide is large enough to position a test setup of the electronic circuits. Combined with different pulse generators, the TEM-Waveguide allows to generatethe reproducible transient electromagnetic pulses with a defined field strength and pulse form.

4. THE EFFECTS ON TARGETS

The HF source interactions with the system electronics can be categorized into *four levels of destructive effect*: *upset, lock-up, latch-up, and burnout* [1,5,8,9]. 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.

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

4.2. Hard-Kill

A hard kill is produced when the effects of the HFsource 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 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. 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 electrical arcing. Consequently, the heating is localized to the junction region. 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).

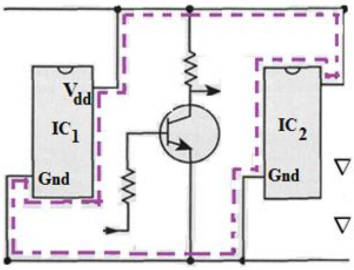
5. The Physical Mechanisms of Damage

In our opinion there are *four main physical factors of damage to semiconductor structure* sand their parameters under the EMP radiation.

5.1. The induced voltages and currents

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

Another EMP thermal problem lies in the major factor affecting 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 [2].



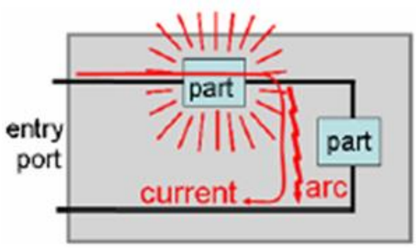
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

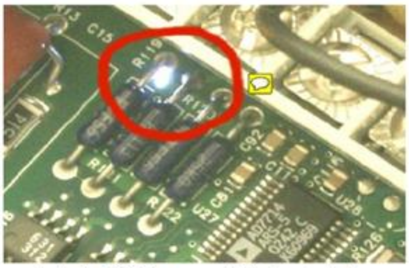
Fig. 5 The large loop area enclosed by faulty PCB layout scheme.

5.2. The arcing (the air and dielectric breakdown)

It is a very common 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 [7].



Arc deeper within



Arcing in a PLC (programmable logic controller)

Fig. 6 Arching occurring within the system.

The air breakdown occurs at the levels of about 1 kV for a 1 millimeter of the air gap at the normal air pressure. The breakdown level may be affected by the water vapor, and dust or debris that may have accumulated.

5.3. A latch-up

It is the inadvertent creation of a low-impedance path between the power supply rails of an electronic component, *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 adjacent p-type and n-type into 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 an NPN transistor stacked next to each other (Fig. 7) [4], [6].

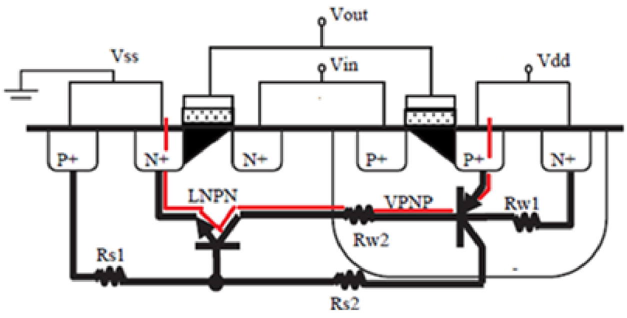


Fig. 7 The parasitic PNPN bipolar component in CMOS gate.

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.

Latch-up is a phenomena where impedance between the power supply and 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 latch-up occurs, a large amount of current suddenly flows between the V_{dd} and V_{ss}.

5.4. The induced EMI recombination currents

In our earlier publications [6,11] we have discussed the increase of the recombination current induced under the strong electric field in the p-n- junction (Fig. 8). The same effect of the increase of the recombination current has been in heterojunction bipolar transistor [10]. But it is necessaryto note that this effect take place only at low level EMP power.

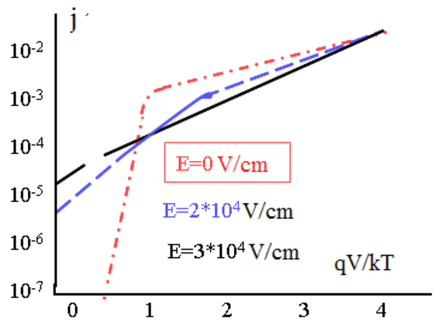


Fig. 8 The I-V characteristics of the p-n junction under microwave radiation.

6. Conclusion

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

- the over current and over voltage in a loop areas in the layout schemes;
- the air and dielectric breakdown between the near placed conductors in the schemes;
- a latch-up of the parasitic thyristor structure;
- 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.

Some protective measures are needed to exclude EMP effects on semiconductor electronics. From the classical protective measures - the grounding, the shielding and filtering, we may use only the shielding and the grounding because its allow to reduce any coupling.

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