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SUSCEPTIBILITY OF MICROCONTROLLER DEVICES DUE TO COUPLING EFFECTS UNDER NARROW-BAND HIGH POWER ELECTROMAGNETIC WAVES BY MAGNETRON

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Abstract—We investigated the malfunction and destruction characteristics of microcontroller devices under narrow-band high power electromagnetic (NB-HPEM) wave by magnetron. NB-HPEM wave was rated at a microwave output of 0 to 1000 W at a frequency of 2460 ± 50 MHz, and was radiated from an open-ended standard rectangular waveguide (WR-340) to free space. The influence of different reset, clock, data, and power supply line lengths was tested. The variation of the lines length was done with flat cables. The susceptibility of the tested microcontroller devices was in general, strongly influenced by clock, reset, and power supply line length, and was only slightly influenced by data line length. Furthermore, as the line length was increased, the malfunction threshold decreased as expected, because more energy was coupled to the devices. The surfaces of the destroyed microcontroller devices were removed and the chip conditions were investigated with a microscope. The microscopic analysis of the damaged devices showed component and bondwire destruction such as breakthroughs and melting due to thermal effects. Our results are expected to provide fundamental data for interpreting the combined mechanism of microcontroller devices in an intentional microwave environment.

1. INTRODUCTION

Modern electronic devices are very important for the function of traffic systems, security systems, and modern communications to name just a few applications. The electronic industry has developed remarkably along with modern digital and semiconductor technology. This has made possible the manufacture of high speed, broadband, lightweight, and miniaturized electronic devices that can be operated with low driving energy. So, electronic systems are sensitive to electromagnetic waves interference. Malfunction of such electronic devices in one of these areas could lead to casualties and economic disasters [1–4].

The electromagnetic environment can disturb electronic devices to object operate rightly. The electromagnetic environment can be divided into a natural electromagnetic environment and an artificial electromagnetic environment. A natural environment includes lighting electro-magnetic pulse (LEMP) at a frequency range from several tens to several hundred MHz. An artificial electromagnetic environment can include exposure to a nuclear bomb such as a high altitude electromagnetic pulse (HEMP) and also can include generate by intention to damage or upset electronic systems such as high power electromagnetic (HPEM), ultra wideband (UWB), and high power microwave (HPM). In particular, an invented intentional HPEM gives a shock to the input and output of systems, and as a result an affected electronic device is unable to display a function. As such, the susceptibility of electronic devices to electromagnetic fields such as HPEM, UWB, and HPM is a topic that has warranted much attention [1–7]. Many electronics devices generate strong electromagnetic waves, and researchers have investigated the mechanisms and solutions of the related problems that inevitably arise. However, these results have not provided sufficient information for electromagnetic environment standardization of electronic devices.

The damage of electronic system is determined by the amount of energy that is transferred while the electronic system is coupled by high power electromagnetic. Coupling is a kind of mechanism whereby electromagnetic energy is delivered to equipment under test (EUT) through a circuit line. Many electronic systems are located within a metal enclosure with apertures, slots and lines. Exterior HPEM may couple through apertures, slots and lines to the interior enclosure. Coupled voltage and current can cause a malfunction or destruction of electronic system. For such cases, the analysis of HPEM is therefore necessary [8–11].

The purpose of the present work is to measure the susceptibility of microcontroller devices by narrow-band high power electromagnetic (NB-HPEM) radiation. We used a magnetron with an output from 0 to 1 KW, and a narrow band operating frequency from 2460 ± 50 MHz as an intentional high power electromagnetic waves source. The narrow-band high power electromagnetic (NB-HPEM) wave was propagated into an open-ended standard rectangular waveguide (WR-340) to radiate through the free space for 5 s. The influence of different line lengths was also tested. Destroyed devices were opened to reveal the chip structures by a decaper and were analyzed using an optical microscope.

2. EXPERIMENTAL

Before and after the Second World War, the United States and Britain invented electromagnetic wave oscillators that were applied to radar systems which helped win the war. The klystron was invented in the 1938 by Varian and Varian in the United States, and the magnetron was invented in the 1939 by the British. Prior to 1940, the frequency and power of electromagnetic wave oscillators were several hundred MHz and several hundred KW. However, starting in the Second World War, the frequency and power of electromagnetic wave oscillators increased to several tens of GHz and several hundred MW based on development in the United States, Great Britain, France, Russia, and Japan. The magnetron was the high power electromagnetic wave oscillator which was used initially in early radar systems.

We used a magnetron as an intentional high power electromagnetic wave source because the output is easy to control, and because it can generate high frequency and high output power [5–8]. The output of the magnetron was controlled from 0 to 1 KW, and the operating frequency was narrow-band at 2460 ± 50 MHz. Narrow-band high power electromagnetic (NB-HPEM) wave was propagated into an open-ended standard rectangular waveguide (WR-340) to radiate through the free space (the air) for 5 s, as shown in Figure 1(a). Wherefore, we investigated the malfunction as well as the destruction effects of microcontroller devices and measured coupling effects easily. NB-HPEM wave was radiated not only into microcontroller devices directly, but also into a line which connected microcontroller devices, as shown in Figure 1(b). NB-HPEM wave was coupled at exposed lines that are clock, reset data, and power supply line from metal shield box respectively and permeated with microcontroller device in the box. Outside of the metal shield box adhered to the absorber so that NB-HPEM wave was radiated only lines or microcontroller devices. The variation of the lines were 3.06 cm, 6.12 cm, 12.24 cm and 24.48 cm respectively in base with NB-HPEM wave length as shown in Figure 1(c).

DUTs for the malfunction and destruction test setup were used for a LCD (16×2) circuit. LCDs were used as loads to observe the operating states of the devices. The features of the microcontroller devices used are shown in Table 1 and each device provides 4 ports in the package respectively. Consequently, for confirm against the damage or not the each ports simultaneously, microcontrollers were

Table 1. The features of the microcontroller devices.

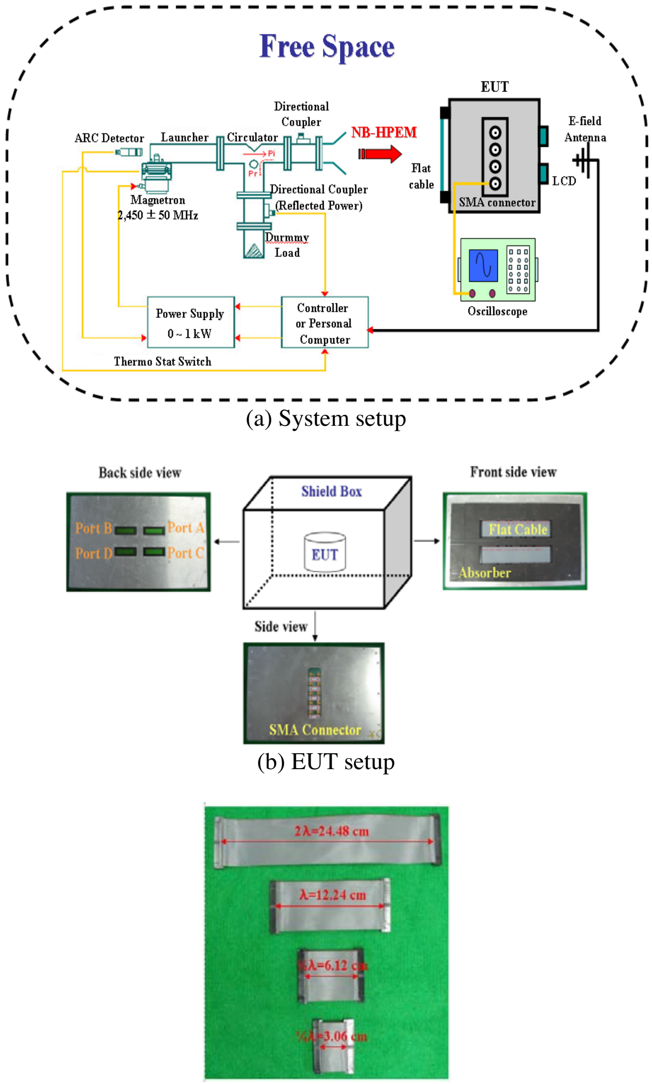
Features			
ATmega 8515	High-performance, Low-power AVR 8-bit microcontroller	ATmega 16	High-performance, Low-power AVR 8-bit microcontroller
	RISC (Reduced Instruction Set Computer) Architecture		Advanced RISC (Reduced Instruction Set Computer) Architecture
	Nonvolatile Program and Data Memories - 8K Bytes of In-System Self-Programmable Flash - 512 Bytes EEPROM - 512 Bytes Internal SRAM		Nonvolatile Program and Data Memories - 16K Bytes of In-System Self-Programmable Flash - 512 Bytes EEPROM - 1K Byte Internal SRAM
	I/O and Packages - 35 Programmable I/O Lines.. - 40-pin PDIP		I/O and Packages - 32 Programmable I/O Lines - 40-pin PDIP

programmed which it displayed LCD first line “HERE IS PORT (A∼D)” and LCD second line “INHA UNIVERSITY”. In case of the coupling energy permeated with microcontroller device, displayed characters of LCDs happened characters error or loss. Otherwise, displayed characters disappeared completely or flickered cursor moved left side of first line to become “clear display” states.

With above cases, if LCDs are going back into the function by reset button or off/on of power switch, we have decided for the malfunction. On the other hand, if LCDs are not going back into the function, in this case we have decided for the destruction. The surfaces of the destroyed microcontroller devices were removed (decapsulation), and the condition of the chips was analyzed using an optical microscope.

3. RESULTS AND DISCUSSION

Figure 2 shows the coupling voltage between the E-field polarization from the radiated NB-HPEM wave to the vertical or horizontal line. As the line length is increased, more energy is coupled to the line. In the case of the 3.06 cm line which coupled the lowest other lines, the coupling voltage between the E-field polarization from the radiated NB-HPEM wave to the vertical line was $1.84\,\mathrm{V}_{\min}$ to $3.027\,\mathrm{V}_{\max}$, and the horizontal line was more strongly coupled at $2.803\,\mathrm{V}_{\min}$ to $4.906\,\mathrm{V}_{\max}$. In the case of the 24.48 cm line which coupled the highest other lines, the coupling voltage between the E-field polarization from the radiated NB-HPEM wave to the vertical line was $2.54\,\mathrm{V}_{\min}$ to $4.378\,\mathrm{V}_{\max}$, and the horizontal line was more strongly coupled at $8.059\,\mathrm{V}_{\min}$ to $13.84\,\mathrm{V}_{\max}$. Therefore, we tested the case between the E-field polarization from the radiated NB-HPEM waves to the horizontal



(a) System setup

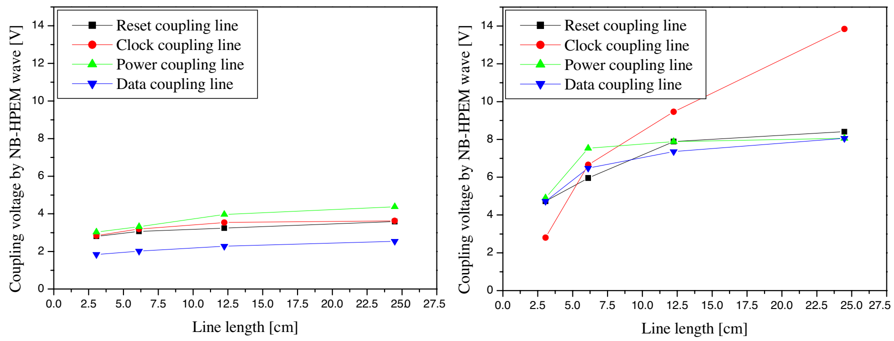
(b) EUT setup

(c) Variable line length

Figure 1. Test setup for the damage effects of microcontroller devices by NB-HPEM wave at free space.

line, in order to investigate damage effects of microcontroller devices by NB-HPEM waves easily.

The researchers in [1–4] defined the principle behavior of malfunction and destruction failure rates as shown in Figure 3. The



(a) Vertical (b) Horizontal

Figure 2. Coupling voltage between E-field (1.91 KV/m) polarization from the radiated NB-HPEM wave to the vertical and horizontal line.

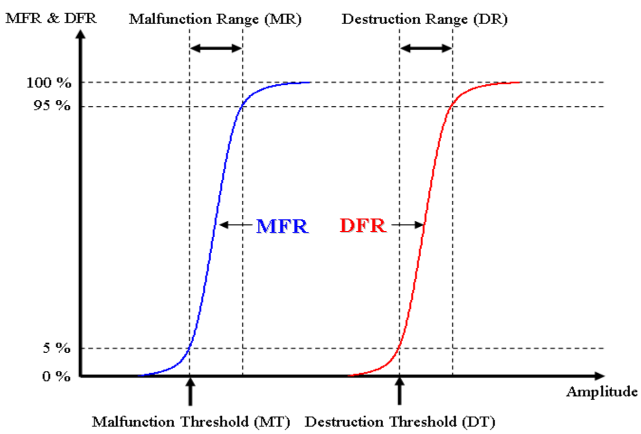


Figure 3. Definitions of malfunction failure rate and destruction failure rate.

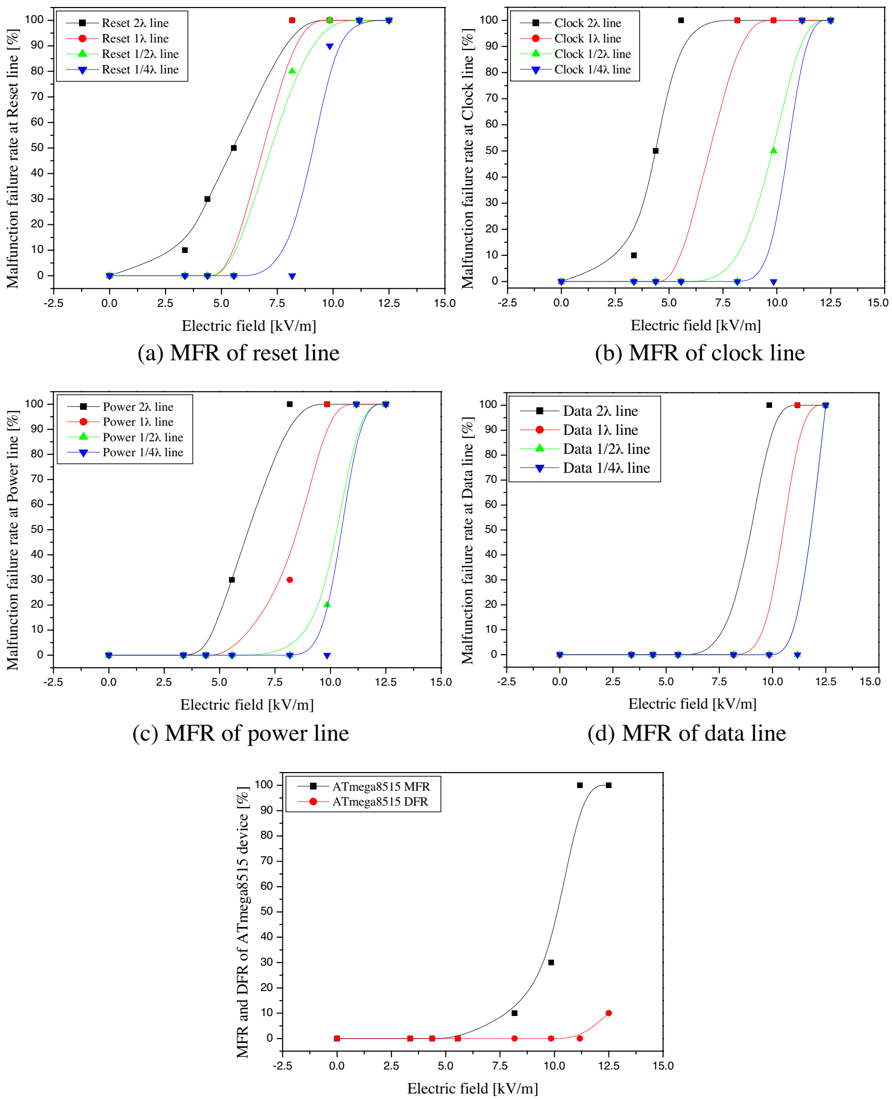
malfunction failure rate (MFR) has been defined as the number of malfunctions ($N_{\text{Malfunctions}}$) of a system divided by the number of tests (N_{Tests}) applied to the system. Here, a malfunction does not mean physical damage was incurred by the system. After a reset, the system returns to normal functioning. The destruction failure rate (DFR) of the device under test has been defined as the number of destructions ($N_{\text{Destructions}}$) divided by the number of tests (N_{Tests}) applied to the system. Destruction is defined as physical damage to the system such that the system will not recover without a hardware repair. The malfunction threshold (MT) specifies the value of the electrical field strength at which the MFR is 5% of the maximum value. The malfunction range (MR) is defined as the span of the electrical field strength within which the MFR changes from 5% to 95% of the maximum. Equivalent definitions were done for the destruction failure rate DFR. In here, MFR, DFR, MT, MR, DT and DR are useful parameters that are the possibility of knowing the sensitivity of the devices [1–4].

The susceptibility of difference lines, and the variations of line lengths were investigated a different as shown in Figures 4 and 5. The susceptibilities of the reset lines, clock lines and power supply lines were generally more significantly influenced than the data lines, but they are not happen destruction by NB-HPEM wave. Reset, clock, and power supply lines were shown a malfunction from 15 to 20 V coupled, and a data line was shown a malfunction of more than 30 V coupled.

The malfunction of microcontroller devices can be divided into two types to coupling effects by NB-HPEM wave. When microcontroller devices were operated normally, the first line of the LCD displayed “HERE IS PORT (A∼D)” and the second line of the LCD displayed “INHA UNIVERSITY”. When the microcontroller devices were made to a malfunction by applying NB-HPEM wave, the displayed LCD characters were modified and were a partial loss, such as “He&# I3 pOR$A” in the first line, and “In?@eRSIT\” in the second line. Otherwise, the displayed characters disappeared completely, or the cursor flickered and moved to the left side of the first line to become “clear display” states.

Microcontroller devices are read a sequence into instruction code for the system from flash memory, which is stored a program to instruction register in SRAM. In out experiment, the program was performed step by step to the clock signal and rate. A clock signal oscillated between a high and a low state, normally with a 50% duty cycle, and was usually in the form of a square wave. Circuits using the clock signal for synchronization could become active at either the rising edge, falling edge, or both edges of the clock cycle. If the coupling voltage was coupled at a clock line by NB-HPEM wave, the clock wave form could be distorted. Therefore, LCD characters can be modified or see a partial loss because microcontroller devices are unable to detect the clock signal edges.

When coupling lines were exposed to NB-HPEM wave, variations of coupling voltage between exposed coupling one-lines to unexposed coupling three-lines were measured. Before exposed at lines, reset, clock, data, and power supply lines of normal function voltage were 90–210 mV, 2–3 V, 1–2 V, and 3–4 V respectively. After exposed at lines, the reset, clock, data, and power supply lines of a malfunction of the start coupling voltage were 1.9-4.5 V, 18–25 V, 8–19 V, and 2.7–18.1 V respectively. As a result, the malfunction of microcontroller devices was increased coupling voltage because more energy couples to



(a) MFR of reset line

(b) MFR of clock line

(c) MFR of power line

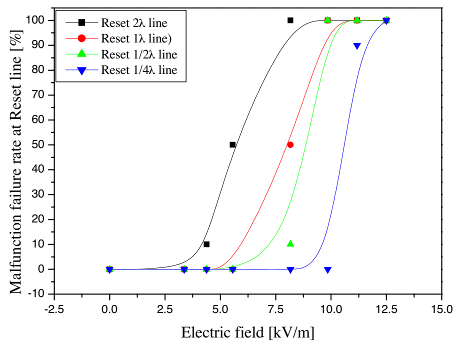
(d) MFR of data line

(e) MFR and DFR of MC

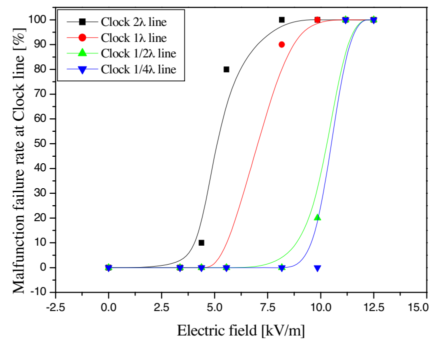
Figure 4. The damage effects on MFR and DFR of different line lengths for ATmega8515 by NB-HPEM wave.

the microcontroller devices, and clock wave form was distorted.

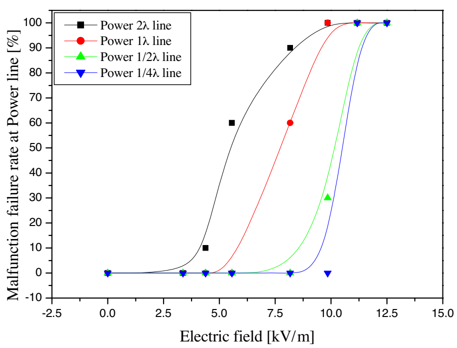
The microscopic analysis of the destroyed devices generally shows different damaging effects as shown in Figure 7. This is due to an increase in current flow at a particular point in the junction in order



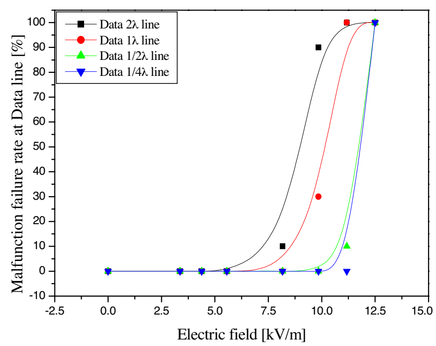
(a) MFR of reset line



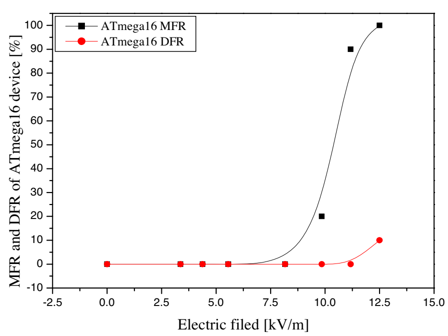
(b) MFR of clock line



(c) MFR of power line



(d) MFR of data line



(e) MFR and DFR of MC

Figure 5. The damage effects on MFR and DFR of different line lengths for ATmega16 by NB-HPEM wave.

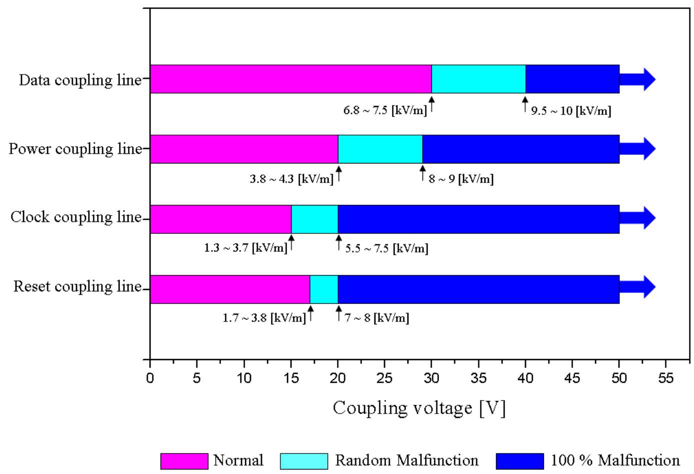


Figure 6. Malfunction coupling voltage of microcontroller (ATmega8515 and ATmega16) devices by NB-HPEM wave.

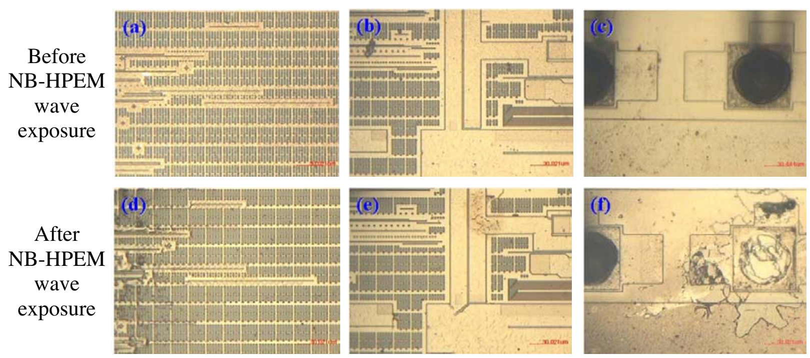


Figure 7. Destructive effects on microcontroller by NB-HPEM wave.

to accommodate the additional stress on the device. Consequently, the junction becomes hotter and encourages more current flow, which in turn heats the junction further. Once the melting point of silicon is reached, the junction short circuits, aluminum migrates down the molten silicon, and the metallization causes open circuits. Destruction was caused by short circuits between metal tracks which led to burnout. Latent damage can also occur, with microcracks remaining dormant until aggravated by NB-HPEM wave. If the E-field of NB-HPEM wave increases, bond wire and bond pads can be damaged, mostly due to thermal effects [12–14].

4. CONCLUSION

Investigation of the susceptibility of microcontroller devices by NB-HPEM wave has shown that the susceptibility of microcontroller devices varies between specific lines. The susceptibility of the reset lines, clock lines and power supply lines was more susceptible than data lines. Reset, clock, and power supply line has shown that a malfunction from 15 to 20 V coupled and data line was shown a malfunction more than 30 V coupled. When coupling lines was exposed to NB-HPEM wave, the variation of coupling voltage between exposed coupling one-lines to unexposed coupling three-lines was measured. Before exposed at lines, reset, clock, data, and power supply line normal function voltages were 90–210 mV, 2–3 V, 1–2 V, and 3–4 V respectively. After exposed at lines, reset, clock, data, and power supply line of a malfunction of start coupling voltage was 1.9–4.5 V, 18–25 V, 8–19 V, and 2.7–18.1 V respectively. As a result, the malfunction of microcontroller devices is due to increased coupling voltage because more energy couples to the microcontroller devices, and the clock wave form is distorted. Destructive effects were caused by short circuits between metal tracks which led to burn-out. Further increases in the amplitude led to additional bond wire and bond pad damage, mostly as a result of thermal effects.

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