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Failure Analysis Methods for Reliability Improvement of Electronic Sensors

Swajeeth Pilot. Panchangam, V. N. A. Naikan

***Abstract**: This paper has documented the common failure modes of electronic sensors. The effects of failure modes are studied in detail and these are classified based on their criticality and probability of occurrence. Methods for taking corrective actions for eliminating the occurrence of various failure modes are also proposed. The paper also addresses FRACAS method and its effectiveness for reliability studies of sensors based on the real failure modes observed in practice. It is understood that the designer has an important role in elimination of the failure modes at the design stage itself. This is expected to result in reliability growth of sensor systems used in many critical systems such as space applications, nuclear power plants, and chemical industries etc.*

***Index Terms**: Sensor reliability, FMEA, FRACAS, reliability growth analysis, sensor failure modes.*

I. INTRODUCTION

Sensors are very crucial feedback elements in critical systems for timely assessment of their health and to take appropriate measures to prevent any catastrophic failures. High reliability assurance of sensors requires the complete knowledge of their physical failure modes. This paper focuses on predicting and listing out all the catastrophic & major failure modes possible in any type of sensor. If failure occurs due to any one of the failure modes, the designer has to redesign the sensor system to eliminate the failure mode. This type of modeling can be useful in reliability growth of a sensor. Sensor reliability is highly important in applications such as propulsion systems of a satellite, nuclear power plants, aircraft systems etc. Such systems require continuous reliable monitoring sensor system to avoid unexpected failures which might result in huge economic loses apart from ill effects on environment, health & safety of human beings and other species. Instead of spending huge amounts on replacement/repair of industrial systems due to unreliable sensors it may be better to have a high reliable sensor system with adequate redundancies. An attempt is made in this paper to identify and develop corrective measures for eliminating the failure modes that may occur in sensor system operating under various environmental & loading conditions.

The rest of the paper is organized as follows:

In Section-2, the problem statement and brief introduction to failure mode effect analysis are presented. In Section-3, the possible failure modes and corresponding corrective measures which are common to all types of sensors are presented. In section- 4, FMEA analysis is carried out for a sensor based on the data given in MIL-217+ Hand Book and other useful & realistic reliability analysis methods are presented. Conclusions are presented in section- 5, followed by selected references.

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II. RELIABILITY GROWTH OF SENSORS THROUGH FMEA

A. Problem statement

Reliability of sensors used for monitoring various parameters of critical systems is very important for timely assessment of their health and to take appropriate measures for fault diagnosis at incipient stages in order to prevent any catastrophic failures. Reliability growth [8] of a sensor can be achieved through eliminating its failure modes. Failure modes are eliminated by redesigning the sensor system. All possible failure modes due to which sensor fails need to be identified. Since 1980s, several studies have been devoted to the problem of FMEA analysis [1], [9] for electronic components and many papers have been published on this particular topic.

This paper is focused on two aspects of this important problem. First research objective is to list all major & critical failure modes which are common to all types of sensors. Second objective of this work is to recommend the proper & necessary corrective action to be followed for failure modes.

B. Failure mode effect analysis (FMEA)

FMEA [2] influences design by identifying failure modes, assessing their probability of occurrence and their effect/impact on the system. This tool helps to isolate their causes, and determines corrective action. It provides a design tool that measures progress toward the reliability goals and indicates areas for redesign. This program is initiated early in the design phase [7].

III. COMMON FAILURE MODES OF SENSORS

The failure cause distribution of electronics systems (like sensors) given in MIL-217+ Hand Book are as shown in the fig.1. The various parameters responsible in causing failure to electronic systems are given in fig.1. As sensor is also an electronic component, some of the major failure modes possible in sensors are identified and their corrective measures are suggested in this section.

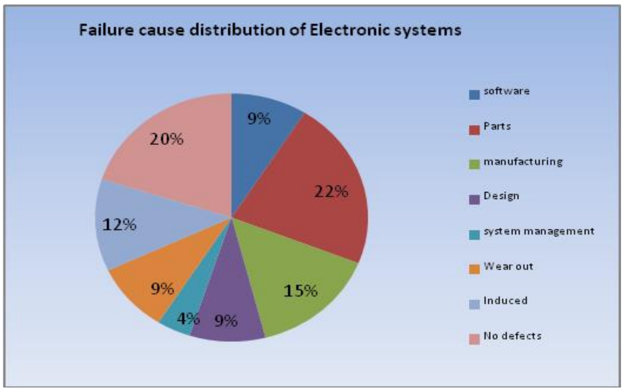

Fig.1. Failure cause distribution of electronic systems

Senor failure: Unless otherwise specified sensor failure is the occurrence of any condition which renders the sensor system incapable of operating within its specified performance parameter limits.

Mostly the sensors are built on CMOS technology [3, 4]; the following major failure modes are responsible for sensor failure. Major failure modes, their effects and possible corrective actions for their elimination are briefly discussed in this section.

3.1. Latch-up:

A CMOS structure is a pair of parasitic bipolar transistors. The collector of each BJT is connected to the base of the other transistor in a positive feedback structure as shown in fig.2. A phenomenon called latch-up can occur when both BJT's conduct, creating a low resistance path between power rail (V_{dd} and *GND*) and also the product of the gains of the two transistors in the feedback loop, will be greater than one. The result of latch-up is at the minimum a circuit malfunction, and in the worst case, the destruction of the sensor.

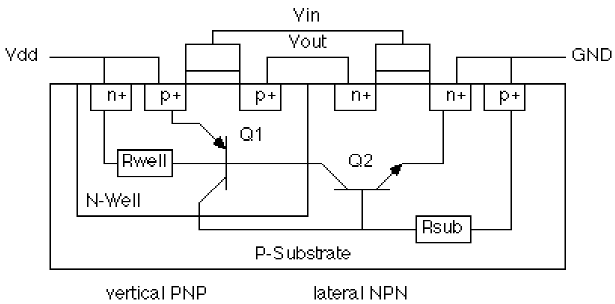

Fig.2. cross section of parasitic transistors in CMOS

Corrective measures:

a) Higher substrate doping level reduces *Rsub*.
b) Reduce *Rwell* by making low resistance contact to *GND*.
c) Guard rings around p- and/or n-well, with frequent contacts to the rings, reduces the parasitic resistances.
d) Move n-well and n+ source/drain farther apart increases width of the base of Q_2, reduces gain β_2 and also reduces circuit density.
e) Buried n+ layer in well reduce gain of Q_1.

3.2. Resistance heating:

There are three distinct sensor resistive heating modes:

a) Increased resistance of conductors can occur when a path is designed with low resistance to carry current has an elevated resistance and current continues to flow through the path.
b) Decreased resistance of insulation can occur when insulating material with normally high resistance intended to impede the flow of current has a lowered resistance, allowing current through the path. For example, a dielectric breakdown may create a low resistance path within insulation.
c) Excess power can occur when a resistive component on the PCB in the sensor cannot dissipate heat properly that is generated by the current flowing through the component.

Corrective measures*:*

a) Avoid poor electrical connections.
b) Remove failed components.
c) Avoid underrated components.

3.3. Bridging faults:

One of the major failure modes of a sensor is bridging faults. It is a non desired connection between two or more nodes within an integrated circuit of a sensor [5]. Detecting bridging faults in sensors is very important to achieve high reliability. Bridging faults can be detected by the following methods [5]:

a) I_{DDQ} testing
b) Conventional voltage testing
c) Pseudo random pattern testing

As an example consider the following figure to understand bridging faults in digital circuits (reference from [5]).

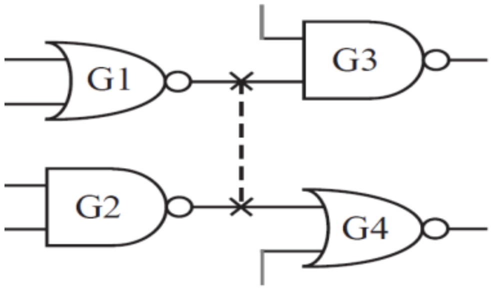

Fig.3. Gate level bridging faults model

Corrective measure:

Test point insertion: to improve testability of sensor for bridging faults with functionality of a sensor remains unchanged. Also refer [5] for details of eliminating bridging faults occurred in digital circuit shown in fig.3.

3.4. Dielectric breakdown:

The oxide layer of a sensor CMOS acts as a dielectric to the flow of charge form gate. When excess rated voltage is applied, the oxide layer may get shorted. This implies the dielectric breakdown occurred and which leads to the integrated circuit inside a sensor fails. Oxide shorts in a sensor CMOS are classified in to two clauses:

a) Due to electrical over stress or static discharge
b) Time dependent breakdowns which occur during operation within rated temperature, and power dissipation [1].

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Corrective measures:

a) Using silicon- gate process instead of metal-gate process. Latter option has higher gate oxide failures compared to silicon-gate process.
b) Proper formation and etching of oxide layers should be done with utmost care.

3.5. Hot- carrier:

CMOS is a combination of PMOS & NMOS transistors. In saturation region, NMOS transistor has high electric field in drain depletion region. When electrons flow from source to drain due to this high electric field impact ionization occurs. Due to impact ionization the electrons in the drain region gains high drift velocity and scattered randomly. These appear as substrate current and some fraction of electrons enter into silicon dioxide barrier. These electrons are called as hot-carriers which degrades the performance of a sensor. Oxide shorting may occur due to hot-carriers. Hot-carrier is a type of sensor device wear-out.

Corrective measure:
Hot-carrier effect is reduced by derating operation of a sensor.

3.6. Contamination:

Contaminants on a sensor's integrated circuit may provide resistive and conductive paths between conductors, causing failures, and can possibly cause conditions for propagating integrated circuit faults to form. Contaminants are introduced during manufacturing, assembly, storage, and use. Contaminants can range from dirt, dust, solder beads, and solder flux or other process residues. Flux residues after soldering may be melted by the operating temperatures which in turn provide a high conductive path between two nodes. These contaminants disturb the normal insulating properties obeyed by electronic circuitry of a sensor.

Corrective measures:

a) Standards set by IPC for cleanliness verification and cleaning process should be followed stringently.
b) Implementing the specifications set by IPC-610D to the acceptance criteria for solder beads.

3.7. Internal components failure mode:

The crucial electronic components of any sensor are resistors, electrolytic capacitors, ceramic capacitors, metal film capacitors, Metal oxide varistors, power MOSFETs, diodes, and other discrete active devices. Failure of these components leads to sensors failure which in turn causes catastrophic problems when these sensors used in critical application. Sudden component failure generates enough heat due to fault current to damage and carbonize the sensor's insulating material. This carbonization can lead to conduction between traces at different potentials and may cause sensor to fail.

Corrective measures:

a) Robust design for environmental stresses is needed.
b) Components that generate heat should be placed away from fault sensitive parts such as the power supply or input.
c) Components that may fail exothermically, such as power FETs or Metal oxide varistors, can be strategically placed such that a failure does not propagate beyond the component.
d) Placing components properly can help limit damage to the sensors when components fail thermally or heat due to large amounts of power dissipation.

3.8. Corrosion:

Most of the sensor internal electronic circuit built on PCB. PCB contains insulating materials between copper conducting tracks. When flux residues/ environmental humidity exists on PCB, the water molecules gets accumulated on the conducting copper tracks. This condition leads to corrosion of tracks, which is one of the critical failure modes for a sensor operating for critical applications.

Corrective measures:

a) Implementing the specifications set by IPC-610D to the acceptance criteria for solder beads.
b) Proper management of sensor against humidity accumulation is to be done.

3.9. Vibration:

This mode is very often in sensors measuring parameters like vibration and pressure of any critical system. All the electronic components inside a sensor are sensitive to stresses applied on it. Due to exposure to vibrations from critical systems, the components get aged or wear-out soon. Mechanical components of sensor like knurl-ring, connectors, bobbin, electrical connectors, O ring, sensing element etc, are highly prone to wear-out. Any of these electronic or mechanical component wear-outs highly degrades the performance of the sensor.

Corrective measures:

a) Derating
b) Preventive maintenance
c) Replacement of the operating sensor with new sensor periodically (mean life) to prevent catastrophic damages due to sensor failure.

3.10. Electromigration failure mode:

Electro migration failures occur if a void is created at a point where the flux of the outgoing ions exceeds the incoming flux. This leads to cause an open in the metal line. Conversely, a short to the adjacent or overhead metal runs is caused when aluminum atoms are piled up at a point where the incoming ion flux exceeds the outgoing flux. Any devices that use polycrystalline aluminum metallization are susceptible to electro migration failure [6]. Down scaling of the feature dimensions into sub-micron regions, and with operating frequencies reaching into hundreds of MHz, reliability of the sensor's CMOS devices is majorly impacted by electro migration, so that very concrete steps are required to manage this failure mechanism.

Corrective measures:

a) Use of package and heat sinks.
b) Proper care should be taken at design stage to control current density.

3.11. Electrostatic discharge failure mode:

Human body contains static charge. Improper handling of sensor circuitry by manufacturer during its development stage leads to static discharge in to internal circuitry. This phenomenon disturbs the electrical properties of CMOS circuitry inside a sensor. Finally, sensor gets failed due to improper shielding from static charge.

Corrective measure:

Proper shielding during fabrication should be done.

3.12. Electromagnetic interference failure mode:

Electromagnetic radiation emitted by external source creates disturbance that interrupts, obstructs or degrades the performance of sensors.

Corrective measure:

Sensor, control device, and digital cable shields (i.e., shielded twisted pairs) are rarely terminated at the cabinet entry. Instead, they are terminated inside on a terminal strip via pigtails and jumpered to the cabinet frame. This allows radiation from cable shields to take place inside the cabinet, which compromises its shielding effectiveness.

IV. FMEA ANALYSIS AND REALISTIC RELIABILITY ANALYSIS METHODS FOR SENSORS

FMEA analysis report on important failure modes is presented in table I. The failure modes are classified in to various groups such as catastrophic, critical & marginal failure modes based on its severity. The table also shows the probability of occurrence of failure modes and methods for corrective actions. These failure modes need to be eliminated or at least their effects need to be minimized for ensuring better reliability.

TABLE I FMEA OF A SENSOR

Failure mode	Failure effect	Severity	Probability of occurrence	Corrective measure
Latch up	Power rails short circuit	catastrophic	0.01≤ p <0.01 (occasional)	Reduce Rsub and Rwell
Resistance heating	Insulation disturbances	Critical	0.1≤ p <0.2 (probable)	Remove failed components & avoid underrated components
Bridging faults	High current flow	catastrophic	0.001≤ p <0.01 (Remote)	Insert Test points
Dielectric breakdown	Insulation disturbances	Critical	0.01≤ p <0.01 (occasional)	Derating
Hot-carrier	Insulation disturbances	Marginal	0.001≤ p <0.01 (Remote)	Derating
Contamination	Insulation disturbances	catastrophic	p < 0.001 (Extremely unlikely)	Follow IPC standards
Internal components failure	Heat dissipation	critical	0.01≤ p <0.01 (occasional)	Placing components properly in order to limit damages
Corrosion	Degrading PCB in a sensor	critical	0.001≤ p <0.01 (Remote)	Clean flux residues & protection from humidity
EMI	Sensor components becomes in-active	catastrophic	0.1≤ p <0.2 (probable)	EMI effect nullifying circuit is to used
Vibration	Wear out	critical	P ≥ 0.2 (frequent)	Derating & preventive maintenance

FMEA analysis for electronic sensors shown in table I also may not be sufficient for realistic and useful reliability analysis of a sensor design. To perform useful reliability analysis for sensors, its potential stresses along with their influences on sensor failure modes (as listed in above) has to be investigated. This realistic approach helps in further design improvements. Physics of failure is generally used for this purpose. In this approach, the failure modes with high probability of occurrence will be extensively analyzed, perform design up gradation, and tested to ensure that the impact of the failure mode on system is almost negligible.

FRACAS (Failure Reporting and Corrective Action System), is most widely used physics of failure method for useful reliability analysis. FRACAS system performs investigation on the system as follows:

- What failed
- Where it failed
- When it failed
- Under what operational/stress conditions it failed.

The difference between FMEA & FRACAS is that, in FMEA the failure modes are listed based on possibility and estimation, however, in FRACAS the failure modes of product are observed under real operating conditions and with real users. Therefore, the feedback from FRACAS is much delayed compared to FMEA. Also, FMEA is performed during design stage of sensor and FRACAS is done during sensor in operation under real stress vs strength margins. Sensor FMEA analysis supports FRACAS to extensively focus and eliminate the critical failure modes listed in FMEA analysis, which results in reduction of potential failure modes of an sensor. FRACAS system not only realize reliable data used comprehensively and effectively, but also may achieve closed-loop failure through FRACAS unique flow. The popular reliability methods for product design analysis are as shown in table II [9], [10]. FRACAS is having high normalized score with 88.3. These scores are obtained by conducting a survey on various techniques used by industries for reliability improvement and failure analysis [10]. This score indicates the percentage of industries using each o these techniques. It can be seen that FRACAS is in the top of the list used by most industries.

TABLE II POPULAR RELIABILITY METHODS

Rank	Method	Normalized score
1	FRACAS	88.3
2	Design reviews	83.8
3	Subcontractor/Vendor control	72.1
4	Parts control	71.2
5	Reliability qualification test.	70.3
6	FMEA	68.5
7	Prediction	62.2
8	TAAF	59.5
9	Thermal analysis	58.6

Steps for design up gradation to achieve high reliability of sensors are briefly discussed below:

- For initial design of a sensor for specific application, conduct FMEA on sensor by estimating all possible failure modes based on previous sensor designs.
- Suggest corrective actions for all the sensor failure modes listed. Designer has an important role in considering the corrective measures and preventing the failure modes from occurring in a sensor.
- Once the sensor design is put in to operation with appropriate stress and strength margins, conduct FRACAS by observing the failure modes in real test scenario. Update the database of failure modes correspondingly. The real test feedback given by FRACAS helps the designer for further sensor design improvement to have negligible impact of potential failure modes on the sensor.

V. CONCLUSIONS

In this paper major failure modes of sensors are identified and their effects on sensor performance are studied. The corrective measures for all documented catastrophic, critical & marginal failure modes are also presented. Reliability growth of sensors can be achieved by the designer through effectively eliminating the failure modes. The documented failure modes of sensors in this paper can be used in reliability growth analysis of sensor network systems installed for various critical applications such as: space applications, nuclear power plants, and chemical industries etc. This paper also addressed the realistic and useful reliability method called FRACAS. FRACAS for sensors may contain all potential failure modes listed in FMEA and some new failure modes observed during testing and operation. Each potential failure mode is extensively investigated in FRACAS. Therefore, for further stages of sensor design improvement designer should consider the feedback from FRACAS.

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