

Failure Analysis and Quality Control of Microwave Devices

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Abstract. Microwave devices have been widely used in the communication and navigation and navigation fields. The reliability level of microwave devices is an important factor to affect the reliability of electronic equipment. The statistical analysis for the failure of sixty microwave devices was presented and the main causes of failure were given. The failure is mainly analyzed from three aspects below, the surface failure mechanism, the interior failure mechanism and the failure mechanism of electrode system and encapsulation. The surface failure mechanism is analyzed from four aspects, ionic contamination on the surface, silicon dioxide layer defect, the influence of interface states between silicon and silicon dioxide, radiation ionization trap. The interior failure mechanism is analyzed from two aspects, failure caused by thermal breakdown and failure due to latch-up effect of integrated circuit. The failure mechanism of electrode system and encapsulation is analyzed from two aspects, failure mechanism of metallization system and failure mechanism of metallization system of bonding. Meanwhile, the results showed that operation, process, adjustment, components and using problems were the main causes of failure. The valuable statistical data and analysis results were provided for the quality control of microwave devices.

1. Introduction

Communication and navigation products play an important role in civilian life and military equipment nowadays. Microwave device is the critical component of electronic system in communication and navigation products [1]. A variety of microwave devices develop rapidly. Integrated circuit is representative in microwave devices, and its design and manufacture technology develops rapidly to the direction of larger scale, faster rates, and higher level of integration [2]. To improve the reliability of communication and navigation products, we must improve the reliability of microwave devices firstly. Failure of microwave devices may occur due to various factors in its production process or service environment, so understanding about the failure mechanism of microwave devices is the premise to improve the reliability in communication and navigation products application.

From the statistical analysis for the failure of sixty microwave devices, we can summarize that failure modes of microwave devices are as follows [3], the failure which is obtained by appearance observation and electric characteristics test such as flaking of oil paint, looseness of outer lead, inverse current leakage and short circuit, the failure which is due to the defect in interior of the device such as serious injury of inner lead, extraneous matter on the chip and crack of chip. Meanwhile, the failure mechanism of microwave devices is summarized from the follow three respects, and it can illustrate the reason of why the failure occurs.

2. The surface failure mechanism



2.1. Ionic contamination on the surface

With the stained moisture or conductive material on the surface of chip and ionizing radiation or electrostatic charge accumulation, positive ions and negative ions appear on the surface of oxide layer. These ions can move along the surface under the effect of bias voltage, inducing that positive ions accumulate around the negative electrode and negative ions gather around the positive electrode. When the contamination is serious, silicon surface barrier alters considerably. The accumulation of moving electric charge on the surface reduces the surface conductance, and induces surface leakage and breakdown creep. Ionic contamination on the surface can also induces corrosion of metal, and further induces rust and fracture of the electrode and packaging system of the device [4].

2.2. Silicon dioxide layer defect

Surface passivation technology defect which induces surface degradation is an important failure mode. According to its degradation parameters and mechanism, electric conduction of Si-SiO₂ boundary layer results in reverse voltage degradation of p + n junction and change of threshold voltage V_{TH} of MOS device. Recombination of surface carrier induces degradation of current amplifier factor of transistor or deterioration of the low frequency noise. Reasons of surface degradation are as follows.

- 1) Swimming ion of encapsulation materials invades the passivation membrane on Si surface.
- 2) Interface charge on interface between Silicon and passivation membrane.
- 3) The pinhole, island caused by defects of passivation membrane on Silicon surface.
- 4) Leakage of the surface passivation membrane caused by electric field.

2.3. The influence of interface states between silicon and silicon dioxide on device performance

Interface states between silicon and silicon dioxide is different from electronic state in internal silicon wafer. It can give free electrons to internal silicon wafer and the positive charge at the interface form on the interface. Meanwhile, it can also give electron-hole to internal silicon slice, and the negative charge at the interface form on the interface. Due to the existence of interface states charge, space charge region with opposite charge forms on silicon wafer near the interface, and it induces that electron-hole concentration near silicon wafer surface is different from the interior. Exhausted and inversion layer forms on silicon wafer surface owing to electrostatic induction effect, and it will effect reverse characteristic of the device, and it will also make h_{FE} decline.

2.4. Radiation ionization trap

When Si-SiO₂ system is irradiated by gamma rays, X rays, the trap density in Silicon dioxide layer increases, meanwhile, electron-hole pairs form. These surplus electron-hole pairs will induce ionization damage. With transition of electron from valence band to conduction band, electrical properties, chemical properties and physical and mechanical properties of microwave devices will be influenced seriously, and finally the reliability and stability of the device will be influenced [5].

3. The interior failure mechanism

The interior failure mechanisms mainly include failure caused by thermal breakdown and failure due to latch-up effect of integrated circuit[6].

3.1. Radiation ionization trap

Thermal breakdown is a typical interior failure, and it seriously threatens secure use of power transistor and high inverse voltage. After the p-n junction reaching first breakdown point, and when the voltage increases continually, the electric current will increase to a critical value. After that, the voltage between the two-terminal of device decreases suddenly and the electric current increases sharply, which shows the negative resistance phenomenon. The phenomenon is called secondary breakdown. When operating point moves to low voltage and large current meanwhile, the device will be burned without protect. Secondary breakdown is a thermal breakdown, and its destructive effect is irreversible. The first breakdown and secondary breakdown is shown in figure 1.

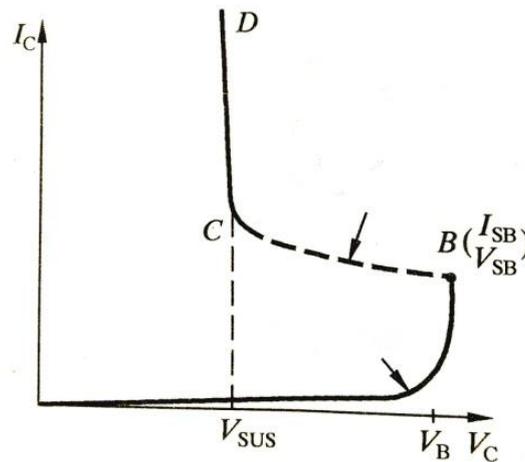


Figure 1. Current-voltage characteristic curve.

There is intrinsic difference between first breakdown and secondary breakdown. The first breakdown is an electric breakdown, and device can still be back to normality when reverse voltage decreases, so the first breakdown is nondestructive and reversible. But secondary breakdown is a thermal breakdown, and it is destructive and irreversible. When the secondary breakdown occurs, device will be burned due to the excessive current through the p-n junction. There is no exact theory to perfectly explain the secondary breakdown now, and suppositional theories include thermal model and current mode [7].

3.2. Failure due to latch-up effect of integrated circuit

CMOS integrated circuit has the characteristics of low power dissipation, fast speed, big noise tolerable limitation, high output impedance and wide voltage range, so it plays an important role on the large scale and very large scale integrated circuit. But input impedance of CMOS integrated circuit is high, so there is a special failure mechanism, latch-up effect except Electrostatic discharge damage (ESD). Owing to existence of silicon controlled rectifier in circuit construction, when the triggered conduction condition forms, low resistance high current between the power and ground will occur. When integration density is higher and the size of the device is smaller, latch-up effect will be more sensitive. Failure due to latch-up effect seriously influences reliability of CMOS integrated circuit [8].

4. Failure mechanism of electrode system and encapsulation

Electrode system of microwave devices includes metallized layer, wire bonding, ohmic contact between the chip and the base, and they play the role of transmitting power. Electrode system on the device reliability is very important. According to pertinent data, Failure due to metallized layer is the most common in electrode system, and it accounts for 26% of device failure [9]. And the second factor is the wire bonding and chip bonding.

4.1. Failure mechanism of metallization system

1) Mechanical injury

The metallized aluminum layer of device consists of strips of aluminum, and it combines the active region of the device with soldered joint. The aluminum is easy to scratch owing to its softy and poor mechanical strength. For example, slide of measuring probe, scratch of metal tweezers and scribing can make aluminum film of the chip scratch, and they seriously affect the yield of product. Scratch should be eliminated before encapsulation through strict microscopy.

2) Electro migration

The metallized aluminum layer of device combines the active region of the device with soldered joint, or metallized aluminum layer connect several active regions. When there is enough high current passing through the aluminum bar, the aluminum ions in energized aluminum strip transfer along the

electron source direction. The transmission is obvious under the condition of high temperature and large current. The aluminum ions accumulate topically in metallic membrane and finally induce short circuit. Cavity will occur in aluminum strip after a long time, which will induce open circuit. The phenomenon is called electro migration. Electro migration is sensitive to current density and temperature, and it can lead to open circuit, short circuit and parameter degeneration of the device. Rational design, increasing the cooling, decrease of the current density, reduction of temperature and strict control on the process are measures to improve migration resistance of the aluminum layer system.

3) Discontinuity of metallic membrane on the oxidation layer stair

Aluminum membrane on the silicon dioxide stair is usually very thin for planar device. So the aluminum membrane on the oxidation layer stair especially around ohmic contact is very likely to be fractured.

Discontinuity of aluminum membrane on the oxidation layer stair is due to the masking effect of the aluminum membrane in evaporation process. Incident particles can't reach the stair surface, and it induces the blind angle, and then aluminum membrane gap occurs. Meanwhile, the evaporation aluminum grains are relatively coarse, and they grow up slowly in the flank inducing that low atom density area forms around the corner. Existence of low atom density area decreases strength of aluminum membrane, and it is the essential reason for the discontinuity of metallic membrane.

In order to reduce the failure phenomenon, zero angle of θ in sputtering process, multisource evaporation, rotation of substrate when evaporating and increasing the temperature of the substrate can be adopted [10].

4.2. Failure mechanism of bonding

About a quarter to a third of failure on microwave devices is caused by the bonding, so it has a great influence on the quality of the device.

1) Failure caused by error in process

In the failure of bonding, a part is caused by error in process. For example, if the lead is too long, it is easy to touch the bare chip and burn device. Overweight pressure welding can damage lead, and finally induce breaking. Too light pressure welding or too dirty aluminum surface make the pressing point easy to fall off. Oblique pressure welding is likely to cause a short circuit.

2) Cracked silicon filament caused by glue in encapsulation process

Low temperature performance of glue layer is poor, and it will crack seriously after long-term low temperature test. With thicker glue layer, lower temperature and longer time, the damage will be greater, and finally silicon filament may be snapped. If the glue is excessive in encapsulation process, it will be piled into the interior and jointed with the lead, and finally silicon filament is snapped.

3) Failure of encapsulation system

As for the production process of microwave devices, lead quality and encapsulation process are also very important on reliability of microwave devices. For any device, if the chip is fine but without good encapsulation to protect the chip, tube core will be affected by external high and low temperature, moisture, salt fog, low air pressure, vibration, impact and centrifugal effect, so the quality of the device cannot be assured.

Due to the simple process, low cost of plastic encapsulation plus device and significantly improvement of purification technology, reliability of plastic encapsulation device is improved, so a large number of civilian devices generally use plastic package. However, because of poor moisture resistance, big effect by harmful impurities in the resin and poor thermal shock resistance, performance of plastic encapsulation device decreases, meanwhile, corrosion occurs in the electrodes and wiring. Due to above defects in plastic encapsulation device, reliability of plastic encapsulation device is lower than device of hermetically metal sealing, plastic encapsulation device is generally used in civil products which are in good environmental conditions. Epoxy resin adhesive piece is also usually used in integrated circuit encapsulation. Failure caused by epoxy resin adhesive piece is as follow. Due to its poor heat dispersion, catalysis on epoxy resin occurs above 200 °C, and it induces

that the chip is easy to fall off. For using silver paste or epoxy resin as die bonding material, thermal fatigue occurs in thermal cycle of the device caused by thermal change and different expansion coefficient between chip and tube socket, and it results in failure because of increase of contact resistance.

4) Failure caused by rust and fracture of the base pin

Corrosion of base pin in microwave devices includes chemical corrosion and stress corrosion. The most general material of base pin is Kovar alloy which is sensitive to corrosion, so it seriously influences the reliability of the device. Reasons of corrosion and fracture on base pin include two aspects, internal cause and external cause [11]. Internal causes are as follows.

- a. Kovar alloy lead is sintered badly resulting in boundary oxidation.
- b. Kovar alloy grains are coarse.
- c. Electrodeposited coating is unsound or it has pinhole defect.
- d. Excessive sulfur content in the plating brightener.
- e. There is residual corrosion substance before and after the plating.

External causes are as follows.

- a. Soldering paste and flux remain on base pin
- b. Cartons for filling device contain acidic material.
- c. In the process of shipping process, base pin suffers damage from mechanical stress.

Excessive humidity or corrosive gas exists in storage or work environment of the device, and it induces corrosion failure of base pin.

5. The main failure causes and quality control methods of microwave devices

Statistical analysis for the failure of sixty microwave devices showed that operation problems, process problems, adjustment problems, components problems and using problems were the main causes of failure. Based on the failure causes and statistical analysis, we can summarize that main failure causes in using aspect are unsuitable operation and electrical-over-stress. Main failure causes in the quality of its components and module were lead bonding, ruggedized protection glue, chip defect, chip bonding, coil separation and so on. The respective percentage of the above causes was 27%, 13%, 13%, 10%, 10%. Ruggedized protection glue and coil separation are specific failure cause. Statistical data of components and modules is relatively consistent with Rome Air Development Center, but the failure rate of domestic components caused by chip bonding is much higher than the foreign components and modules. It is worth of attention for the manufacturer. Process improvement which is based on the main failure causes of microwave devices can improve the quality and reliability for the manufacturer. Meanwhile, quality evaluation and then eliminating defective devices through specific inspection and analysis methods before the actual service can reduce the failure rate in the microwave components' service and improve the system reliability.

6. Conclusion

Failure of microwave devices affects the work reliability of communication and navigation products. From the statistical analysis for the failure of sixty microwave devices, the failure mechanism was summarized. Failure mechanism of microwave devices includes the surface failure mechanism, the interior failure mechanism and the failure mechanism of electrode system and encapsulation. The surface failure mechanism includes ionic contamination on the surface, silicon dioxide layer defect, the influence of interface states between silicon and silicon dioxide, radiation ionization trap. The interior failure mechanism includes failure caused by thermal breakdown and failure due to latch-up effect of integrated circuit. The failure mechanism of electrode system and encapsulation includes failure mechanism of metallization system and failure mechanism of metallization system of bonding. Being familiar with failure mechanism of microwave devices is beneficial to radically reduce failure factor and improve the application reliability. Meanwhile, operation problems, process problems, adjustment problems, components problems and using problems are the main causes of failure. Quality control methods are mentioned briefly at last.

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