國家原子能科技研究院

委託研究計畫研究報告

半導體元件耐輻射可靠度之關聯性研究

Development of Radiation Reliability Test Platform for Key Electronics Components

計畫編號：112A009

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計畫中文摘要

全球金融、電信、交通、氣象、國防、航空和許多其他應用都越來越依賴衛星服務。 隨著這些應用的不斷擴展，衛星的數量正迅速增加，其成本必須降低。因此，為數眾多的小型衛星正在使用更多的商業級現有電子元件。商業現成的（COTS）電子元件通常對輻射影響更敏感。另外，對於小型衛星，屏蔽電子元件的結構厚度較小。隨著 IC 製程演進和更薄的氧化層，元件對總游離劑量效應(TID)輻射效應的敏感性會降低，TID 限值也會提高。另一方面，單事件效應(SEEs)發生機率隨著 IC 製程的縮小而增加。產生 SET 和 SEU 所需的閾值能量更少。 本計畫的主要目的為對商業級現有電子元件的輻射可靠性評估。

今天的航太業者要在體積小、功率低的和成本低的小型衛星中使用商業級現有電子元件來滿足高水準的性能。關鍵問題是確定可靠度和成本之間的適當平衡。要求的測試越多，單位成本就越高。 衛星

工業和電子設備製造商目前面臨的挑戰是為太空應用中使用的商業級現有電子元件確定最佳測試水準與成本。

在計畫的第一年，我們將探討關鍵電子元件輻射導致的各種失效機制，以幫助本土產業進入太空市場。這些元件是衛星運行的關鍵，也更容易受到輻射的影響。確保測試期間的輻射源品質也是關鍵，包含對劑量計的選擇。

計畫英文摘要

Global finance, telecommunications, transportation, weather, national defense, aviation, and many other sectors rely heavily on satellite services today. With increasing expansion on the above-mentioned, the number of satellites are increasing rapidly, but the cost of these satellites must be reduced. Therefore, such high volume, small satellite constellations are using more commercial grade plastic components. Commercial off-the-shelf (COTS) devices generally tend to be more sensitive to radiation effects. Also with small satellite, there is less structural mass shielding the electronics. With finer IC geometries and thinner oxides, the sensitivity to TID radiation effects is reduced, and the TID tolerance is improved. On the other hand, SEEs increase with reduced IC scaling. Less energy is required to produce SET and SEU. Radiation reliability evaluation of these COTS become essential, and this is the main purpose of this project.

Spacecraft designers today are being pressed to use commercial devices to meet high levels of performance in increasingly smaller, lower power, and lower cost spacecraft. The key issue is determining the proper balance between reliability and cost. The more screening required, the

higher the unit cost. The current challenge for the satellite industry and for electronic devices manufacturers is to define the optimum screening level vs. cost point for commercial devices used in space level applications.

In the first year of the project, we will develop an understanding of the various failure mechanisms of key electronics components due to radiation. In particular, power discrete electronic devices which are key to the operation of satellites and yet they are more susceptible to radiation will be chosen. Ensuring radiation quality during testing is also key so that our reliability evaluation results are credible, and selection of dosimeters will be included in the study.

壹、計畫緣起與目的

Satellite services is by far the largest segment and continues to be a key driver for the overall satellite industry. So, what has a satellite done for you lately? I believe most people would be surprised at just how much modern life depends on satellites services. If the large number of satellites currently in operation happen to shut down, modern life would be significantly disrupted. Global finance, telecommunications, transportation, weather, national defense, aviation, and many other sectors rely heavily on satellite services. There are three primary segments in the satellite services market: satellite navigation, satellite communications, and Earth observation. Navigation satellites are used for the global distribution of navigation signals and data in order to provide positioning, location, and timing services. Examples of available services are traffic management, surveying and mapping, fleet and asset management, and autonomous driving technology—driverless cars and trucks are expected to be the next big thing. Telecommunication satellites or SATCOM examples are television, telephone, broadband internet, and satellite radio. These systems can provide uninterrupted communications services in the event of disasters that damage ground-based telecommunication networks. Both business and commercial aircraft in-flight internet and mobile entertainment are growing segments of the market. Earth observation satellites are used for the transmission of environmental data. Space-based observations of the Earth promote sustainable agriculture and aid in the response to climate change, land and wildlife management, and energy resources management. Earth observation satellites aid in the safeguard of water resources and improve weather forecasts, so there is a very wide and growing range of satellite services.

There are a lot of electronics in satellites, including five electronic basic subsystems that support the payload: the telemetry subsystem, tracking and command subsystems, the electric power and distribution subsystem, the thermal control subsystem, and the attitude and velocity control subsystem. The payload would include antennas, transmitters and receivers, low noise amplifiers, mixers and local oscillators, demodulators and modulators, and power amplifiers. Earth observation payloads would include microwave and infrared sounding instruments for weather forecasting, visible infrared imaging radiometers, ozone mapping instruments, visible and infrared cameras, and sensors.

The radiation effects on electronic devices are a primary concern for space level applications. Outside the protective cover of the Earth’s atmosphere, the solar system is filled with radiation. The natural space radiation environment can damage electronic devices and the effects range from a degradation in parametric performance to a complete functional failure. These effects can result in reduced mission lifetimes and major satellite system failures. There are two primary ways that radiation can effect satellite electronics: total ionizing dose (TID) and single event effects (SEEs). TID is a long-term failure mechanism vs. SEE, which is an instantaneous failure mechanism. SEE is expressed in terms of a random failure rate, whereas TID is a failure rate that can be described by a mean time to failure.

With the rapid expansion of Internet of things and cloud computing, the % of world population that can access to the internet must be large, and companies are planning to deploy large constellations of small, low-cost satellites circling the Earth that will enable access to a worldwide communication network. Consequently, spacecraft designers are being pressed to use commercial devices in order to meet high levels of performance in increasingly smaller, lower power, and lower cost spacecraft. Commercial off-the-shelf (COTS) devices generally tend to be more sensitive to radiation effects. Also with small satellite, there is less structural mass shielding the electronics. With finer IC geometries and thinner oxides, the sensitivity to TID radiation effects is reduced, and the TID tolerance is improved. On the other hand, SEEs increase with reduced IC scaling. Less energy is required to produce SET and SEU. With higher frequency devices, SETs can turn into more SEUs, increasing the number of SEFIs.

Therefore, the space market is an emerging market for the electronic industry. Since the electronic industry is a key to Taiwan's economy, and the strength of electronics is also very high in Taiwan, and with the Taiwan Government pushing the space industry, a rigorous reliability evaluation of electronics devices and circuits for space applications must be established, and this is indeed the purpose of this program in INER.

貳、研究方法與過程

Owing to the limited resources and timelines, we will focus on a few key semiconductor components to start with. As the circuits in integrated circuits are generally unknown, we start with the key discrete power components. Gamma radiation is used first, and circuit board is designed to mount these components with them biased under reverse bias of junction to accelerate the degradation. After the printed circuit board is fabricated, gamma testing is performed. The electrical parameters of each component were measured before and after radiation to examine the degradation. Detail analysis of the degraded parameters can help to pinpoint some failure mechanisms which will then be confirmed through failure analysis tools.

Table 1 shows the components under test. Figures 1-4 shows the schematic circuits designed for the testing of the components under gamma irradiation.

Table 1 Specifications of the discrete components under radiation test

	PART NUMBER	DESCRIPTION	TYPE	COMPANY
C1	EEE-FK1E100R	CAP ALUM 10UF 20% 25V SMD	Aluminum electrolytic capacitor	Panasonic Electronic Component

C2	16TQC10M	CAP TANT POLY 10UF 16V 1411	Tantalum-Polymer Capacitors	Panasonic Electronic Component
C3	CC1210ZKY5V8BB106	CAP CER 10UF 25V Y5V 1210	Ceramic capacitors	YAGEO
C4	C1206C106M3PAC7800	CAP CER 10UF 25V X5R 1206	Ceramic capacitors	KEMET
C5	T521B106M016ATE100	CAP TANT POLY 10UF 16V 1411	Tantalum-Polymer Capacitors	KEMET
D1	HS1MFL	DIODE GEN PURP 1KV 1A SOD123F	Rectifier diode (Glass passivated)	TAIWAN SEMICONDUCTOR CORPORATION
D2	BAS2103WE6327HTSA1	DIODE GP 200V 250MA SOD323-2	Rectifier single diode	INFINEON TECHNOLOGIES
D3	1N4007G	DIODE GEN PURP 1KV 1A DO204AL	Rectifier diode (Glass passivated)	TAIWAN SEMICONDUCTOR CORPORATION
D5	STTH10LCD06FP	DIODE GP 600V 10A TO220FPAC	Rectifier single diode	STMicroelectronics
R1	ERJ-P06J103V	RES SMD 10K OHM 5% 1/2W 0805	Chip Resistors - Surface Mount	Panasonic Electronic Component
R2	ESR18EZPF1002	RES SMD 10K OHM 1% 1/2W 1206	Chip Resistors - Surface Mount	ROHM ELECTRONICS
Q1	2N7002KT1G	MOSFET N-CH 60V 320MA SOT23-3	ROHM ELECTRONICS	ONSEMI
Q2	IRLHS6242TRPBF	MOSFET N-CH 20V 10A/12A 6PQFN	MOSFET N-CH 20V 10A	INFINEON TECHNOLOGIES
Q3	TSM052NB03CR RLG	MOSFET N-CH 30V 17A/90A 8PDFN	N Channel 30 V 17A	TAIWAN SEMICONDUCTOR CORPORATION
Q4	2N7002H6327XTSA2	MOSFET N-CH 60V 300MA SOT23-3	N channel 60 V 300mA	INFINEON TECHNOLOGIES

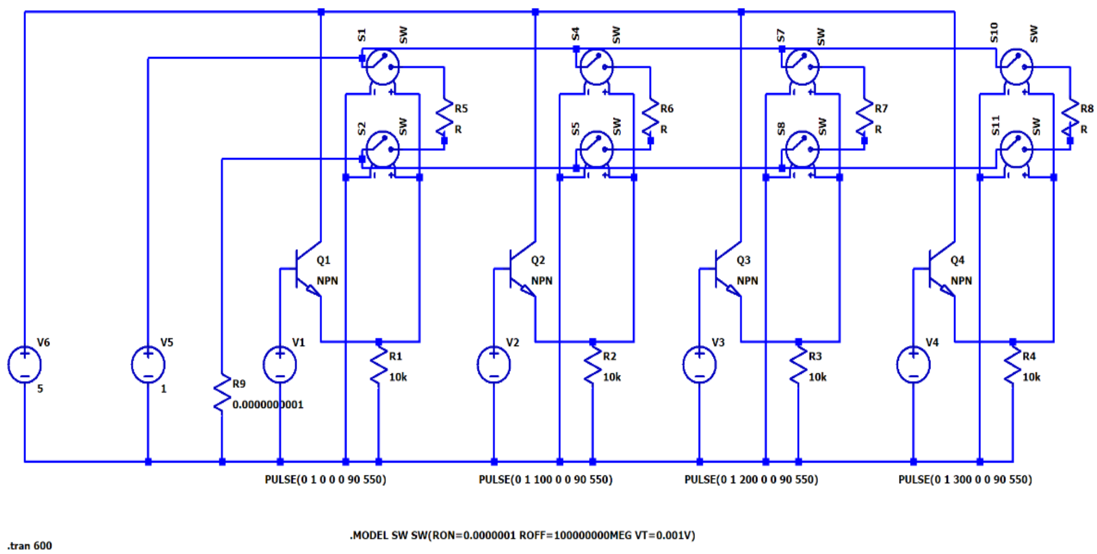


Figure 1 Biasing circuit for resistors testing

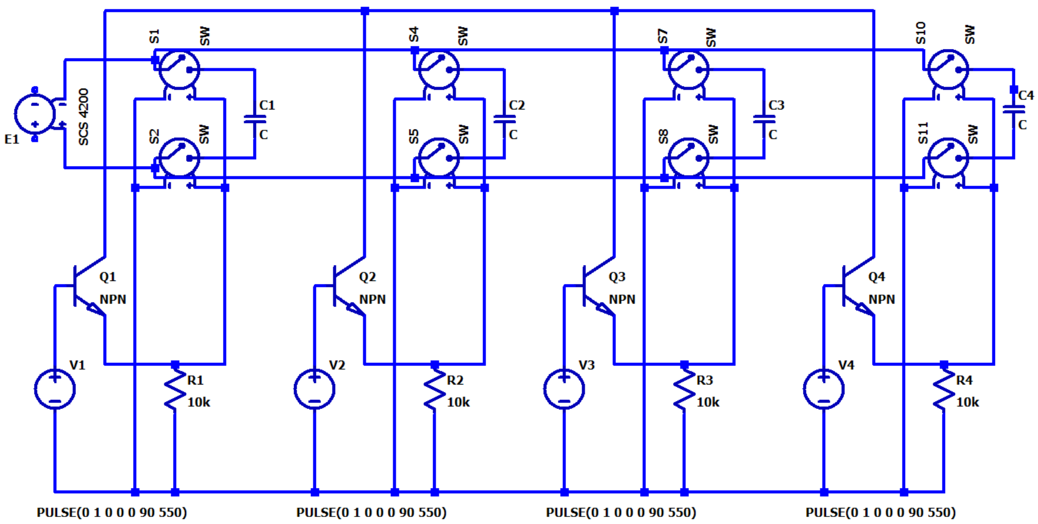


Figure 2 Capacitors test circuit

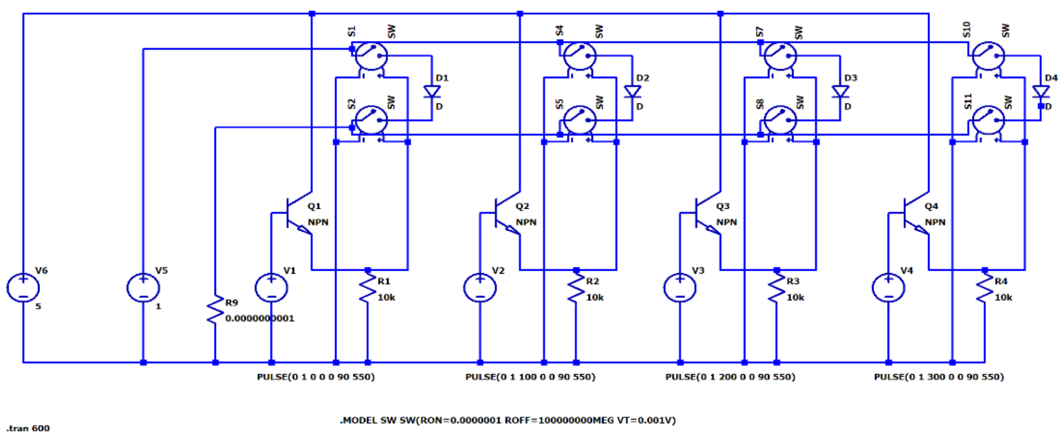


Figure 3 Power diodes test circuit

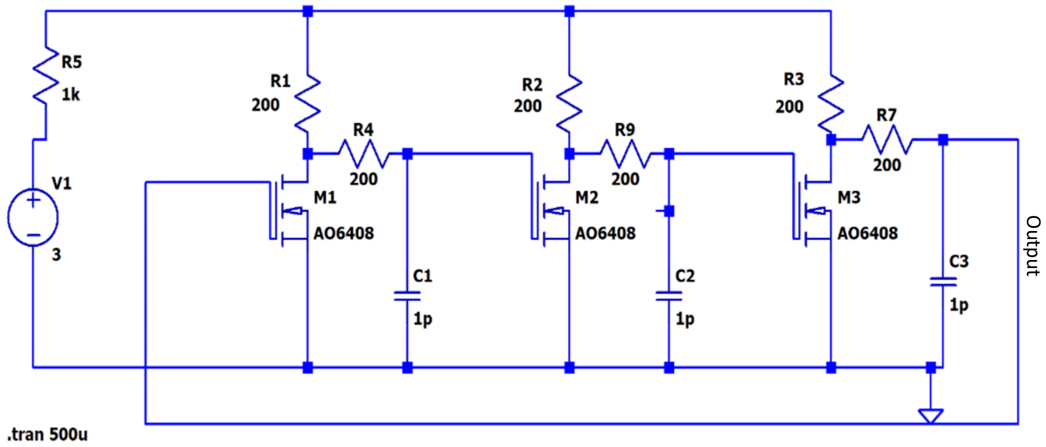
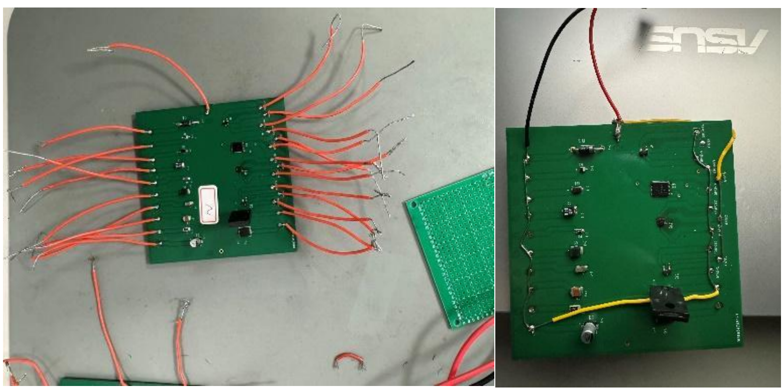


Figure 4 Power MOSFET test circuit

TID 測試於長庚大學 Cs-137 照射室進行，並於適當劑量點停止照射，測量元件電性之改變，照射劑量率約 20-30 krad-Si/h， 同時亦布設 TLD-400 監控劑量。 The parameters of the Gamma radiation tester is as follows:

Irradiator: Gammacell® 3000 Elan
Radiation source: Cs-137
Radiation type: Gamma ray
Mean energy: 0.662 MeV
Half-Life: 30 years
Irradiation method: Fixed source/Turning Canister
Dose rate: 5.740 cGy_{air}/s ; 18.78 $krad_{si}/hour$

The test set up is as shown in Figure 5



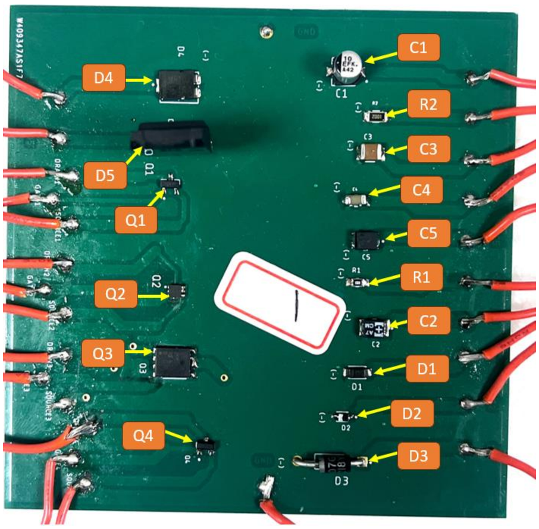


Figure 5 DUT board for Gamma Irradiation Test. Dx stands for diodes, Cx stands for capacitors, Qx stands for transistors, Rx stands for resistors

參、主要發現與結論

From the degradation of the electrical parameters of DUTs, the following were discovered:

一、 Resistors are robust against the gamma radiation, this is expected because gamma rays are highly energetic electromagnetic radiation, and their interaction with matter is primarily through processes like Compton scattering and photoelectric absorption. Unlike semiconductors and capacitors, resistors are typically made of materials with high atomic numbers, like metals (e.g., carbon film, metal film, or wire wound resistors). The higher atomic number of metals makes them less susceptible to certain gamma-ray interactions.

二、 The gamma radiation effects on capacitors are a change in capacitance; change in dissipation or both. This is expected as gamma radiation can ionize the dielectric materials, resulting in the charge build up within the dielectric materials. As C=Q/V, and with the same V, now the Q is larger (induced charges plus the internal build up charge), thus the measured capacitance increases as shown in the test results. The presence of the buildup charge also increases the conductivity of the dielectric, allows current to flow, and hence increases the dissipation factor.

三、 From the type of capacitors and manufacturers, we can see that electrolyte capacitor is more stable, likely due to the fact that charge buildup can be even out for electrolyte capacitor. For Tantalum capacitor, Kermet capacitor is more stable with minimum change, whilst Pansonic ceramic capacitor has a large increase in the dissipation. For ceramic capacitor, Yageo capacitor has a large increase in capacitance whilst Kemet capacitor has an increase in the dissipation. **In other words, type of capacitors and the manufacturers have an impact on the radiation hardness of capacitors.**

四、 For power diodes, one can see that diode 1 has a slight shift in the contact resistance between metal and semiconductor. This is because the dice is big as it is for 1A diode and 1KV breakdown voltage, indicating that the doping of the semiconductor is low with thick junction depth, and thus it has high resistivity. Thus any increase in the resistivity due to radiation can only contribute slightly to the characteristics of the diode. Also, its package is SOD, and radiation can only impinge on the surface instead of the side passivation and the junction depth is large, thus no passivation degradation or junction defect is possible with the radiation up to 140 krad.

五、 For diode 2, it is a small signal diode with only 0.25A and breakdown voltage of only 250V. Its degradation began from contact resistance (Rs increases at 131 Krad) followed by the increases in ls and n (140 Krad). The first degradation will be only the metal contact (a small defect in the contact can affect its Rs significantly since the dice area is small). Further radiation causes damage to the junction (as the junction is not so deep) as can be seen in the increase in Is and n.

六、 Degradation of Diode 3 is mainly due to the passivation as can be seen from the increase in Is without an increase in n. This is expected as its package is axial lead and radiation can only impinge on the passivation instead of the dice surface.

七、 Degradation of diode 5 is the junction defect at 131 Krad followed by the metal contact defect on further radiation to 140 Krad. Again, due to its package type, its passivation will not be affected by radiation. As its breakdown voltage is 600V, its junction will not be as deep as diode 1, and hence junction defects can be observed earlier. Only upto 140 Krad that contact defect occurred, probably because of its large dice size as it is for 10A diode.

八、 The metal contact defects mentioned above were confirmed by the temperature distribution of the dies from the thermal camera system.

九、 From the above analysis, we can see that small signal diodes are more vulnerable to gamma radiation due to small dice size. Package type is also a concern.

十、 **For the discrete power MOSFET**, we can see that the threshold voltage becomes more negative with prolonged radiation. This is related to the trapped charge in the oxide as a result of radiation. This is consistent with the observation that IDSS increases significantly, indicating that the channel cannot be turned off due to the presence of trapped charge in oxide.

十一、 Besides the above-mentioned, trapped charges in a metal-oxide-semiconductor field-effect transistor (MOSFET) can have a significant impact on the device's transconductance gm because of the following, and we can see an increase in the gm after the MOSFETs were subjected to radiation. Some increases and saturated at 130 Krad, and Q4 continues to increase as the krad increases. The reasons for the increase are as follows:

(一)Altered Channel Conductance: The presence of oxide trapped charges can modulate the conductance of the channel. Trapped charges near the channel region create an electric field that affects the distribution of carriers in the channel, altering the channel conductance and, therefore, the transconductance.

(二)Change in Carrier Mobility: Trapped charges can influence the mobility of carriers in the channel. The electric field created by the trapped charges can scatter or modify the trajectory of carriers, affecting their mobility. Changes in carrier mobility impact the transconductance of the MOSFET.

(三)Shift in Saturation Region: The saturation transconductance is particularly sensitive to changes in threshold voltage and carrier mobility. As the threshold voltage shifts due to trapped charges, the MOSFET may enter the saturation region at a different gate-source voltage. This shift affects the transconductance behavior in the saturation region.

(四)Threshold Voltage Instability: The presence of oxide trapped charges can lead to threshold voltage instability over time. This instability can result in variations in the MOSFET's performance, including transconductance, especially in dynamic or changing operating conditions.

From the gamma radiation test results, we found that power MOSFET is the weakest against gamma radiation. Axial lead power diodes are good with respect to gamma radiation, and large dice size and depth junction is also good to combat against gamma radiation. Electrolyte capacitors are found to be robust against gamma radiation, and Ta capacitors as well as ceramic capacitors can degrade in the form of increase capacitance or increase in the dissipation factor or both, depending on the manufacturers which is related to the exact materials of the dielectrics used in capacitors.

肆、參考文獻

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The findings of this report will be expanded into a SCI paper entitled "Investigation of the gamma radiation effect on discrete electronic components". It is under preparation.