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SOFT ERROR ISSUE AND IMPORTANCE OF LOW ALPHA SOLDERS FOR MICROELECTRONICS PACKAGING

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Abstract. To satisfy the ever-increasing demand for higher density (functionality) and lower power (portability), the dimensions and operating voltages of the modern electronic devices are being reduced frequently. This has brought new challenges both from the technology and materials point of view. One such issue is soft error, the temporary malfunction of device caused by the effect of radiation on the Si ICs. One such radiation is high energy alpha particle whose main source is the solders used in the packaging. The continued scaling of complementary metal oxide semiconductor device technologies has led to continued device shrinkage and decreases in the operating voltage of the device transistors. Scaling has meant denser circuitry overall, thinner silicon (e.g., silicon on insulator) in logic applications, and less charge on capacitors for volatile memory. These trends have resulted in devices being more sensitive to soft errors since now low energy alpha particles can flip a memory bit or alter timing in a logic circuit. Due to the use of flip-chip joints and developments towards 3D packaging, the solder bumps have moved very closer to the active Si devices, where even the low energy alpha ray having short range is able to induce soft error. One of the major sources of alpha particle radiation is the solders used for joining components in the packaging and they contain alpha emitters and there is increasing demand of Low Alpha activity Pb-free solders. The present paper reviews the issue of soft error in depth covering its historical background, causes and effects on electronic devices along with mitigation efforts. The importance of low alpha solders in microelectronics packaging applications is discussed in the light of soft-error issue.

1. INTRODUCTION

Electronic devices in space, defense, medical, and power systems may be exposed to various types of radiation, including high-energy photons and energetic particles (electrons, protons, neutrons, and ions). The radiation may produce effects in the electronics ranging from temporary loss of data to catastrophic failure. The specific effects produced depend strongly on the specific technology and the radiation environment. Most systems designed for use in radiation environments are designed conservatively using electronic parts that are at least several generations behind the current state of the art. However, the demand for higher performance and reduced time from design to deployment has increased the pressure to use advanced technologies. As the dimensions and operating voltages of computer electronics are reduced to satisfy the consumer's insatiable demand for higher density, functionality, and lower power, their sensitivity to radiation increases dramatically. There are a plethora of radiation effects in semiconductor devices that vary in magnitude from data disruptions to permanent damage ranging from parametric shifts

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to complete device failure [1,2]. Of primary concern for commercial terrestrial applications are the "soft" single-event effects (SEEs) as opposed to the "hard" SEEs and dose/dose-rate related radiation effects that are predominant in space and military environments. As the name implies, SEEs are device failures induced by a single radiation event. The present chapter is organized as follows.

Firstly the issues of soft error in semiconductor devices, its physical mechanism along with historical perspectives are discussed. Important practical examples regarding issue of soft error in memory devices like DRAM and SRAM are included. Secondly, the mitigation strategy for soft error and the issue of alpha particle emission from solders and its related mechanism are discussed. Thirdly, Pb-Free solders currently used in the industry and need for low alpha solder along with its current usage are discussed. Also the discussion regarding whether the "Pb-Free" solder also means "Alpha Free" or not is incorporated. Fourthly, the importance of Low Alpha Sn and its usage in electronics packaging is illustrated. Finally, the techniques and importance of alpha particle emission measurement from materials used in electronic packaging are emphasized.

2. FUNDAMENTALS OF SOFT ERROR

A soft error occurs when a radiation event causes enough of a charge disturbance to reverse or flip the data state of a memory cell, register, latch, or flip-flop. The error is "soft" because the circuit/device itself is not permanently damaged by the radiation—if new data are written to the bit, the device will store it correctly. The soft error is also often referred to as a single event upset (SEU) [3]. According to NASA Thesaurus, SEU is defined as the radiation-induced errors in microelectronic circuits caused when charged particles (usually from the radiation belts or from cosmic rays) lose energy by ionizing the medium through which they pass, leaving behind a wake of electron-hole pairs. If the radiation event is of a very high energy, more than a single bit maybe affected, creating a multibit upset (MBU) as opposed to the more likely single bit upset (SBU). While MBUs are usually a small fraction of the total observed SEU rate, their occurrence has implications for memory architecture in systems utilizing error correction [4,5]. Another type of soft error occurs when the bit that is flipped is in a critical system control register such as that found in field-programmable gate arrays (FPGAs) or dynamic random access memory (DRAM) control circuitry, so that the error causes the product to malfunction [6]. This type of soft error, called a single event interrupt (SEFI), obviously impacts the product reliability since each SEFI leads to a direct product malfunction as opposed to typical memory soft errors that may or may not affect the final product operation depending on the algorithm, data sensitivity, etc. Radiation events occurring in combinational logic result in the generation of single event transients (SET) that, if propagated and latched into a memory element, will lead to a soft error [7]. The last mode in which an SEE can cause disruption of electrical systems is by turning on the complimentary metal–oxide–semiconductor (CMOS) parasitic bipolar transistors between well and substrate—inducing a latch-up [8,9]. The term SEU is frequently applied as a synonym for soft error, but occasionally it is also used to describe all effects that are caused by a single strike of an energetic particle, including both soft and hard errors. Although strictly speaking it is not correct, the term "soft error" (or SEU) is often used to cover both SBUs and MBUs, which are the most common types of soft errors.

A soft or non-permanent fault is a non-destructive fault and falls into two categories [10] namely transient and intermittent faults. Transient faults, caused by environmental conditions like temperature, humidity, pressure, voltage, power supply, vibrations, fluctuations, electromagnetic interference, ground loops, cosmic rays and alpha particles. Intermittent faults caused by non-environmental conditions like loose connections, aging components, critical timing, power supply noise, resistive or capacitive variations or couplings, and noise in the system. With advances in the design and manufacturing technology, non-environmental conditions may not affect the sub-micron semiconductor reliability. However, the errors caused by cosmic rays and alpha particles remain the dominant factors causing errors in electronic systems.

Usually, the soft-error rate (SER) is measured in FIT units (failures in time), where 1 FIT denotes one failure per billion device hours (i.e., one failure per 114,077 years). Typical SER values for electronic systems range between a few 100 and about 100,000 FIT (i.e., roughly one soft error per year).

In electronic components, the failure rate induced by soft errors can be relatively high compared to other reliability issues. Product monitoring shows that the hard error failure rate, due to external events (such as electrical latch up), is maximally 10 FIT but usually much less. In contrast, the SER of 1

Mbit of SRAM, one of the most vulnerable types of circuits, is typically in the order of 1,000 FIT for modern process technologies. For a product that contains multiple Mbits of SRAM, the SER may be higher than the combined failure rate due to all other mechanisms. However, the effect of soft and hard errors is very different. In the case of a soft error, the product is not permanently damaged, and usually the error will disappear when the corrupted data is overwritten. Also, if a soft error occurs, in many cases it will manifest itself as a rather benign disturbance of the system without serious consequences. However, the occurrence of soft errors can have a serious effect on the perception that the customer has of the product's reliability.

3. BACKGROUND

The problems of Soft errors have been studied by electrical, aerospace, nuclear and radiation engineers for almost fifty years. During the period between 1954 and 1957, the failures in digital electronics during the above-ground nuclear bomb tests were treated as electronic anomalies in the monitoring equipment because they were random and their cause could not be traced to any hardware fault [11]. Wallmark et al., [12] predicted that cosmic rays would start upsetting microcircuits due to heavy ionized particle strikes and cosmic ray reactions when feature sizes become small enough.

Through 1970s and early 1980s, the effects of radiation received attention and more researchers examined the physics of these phenomena. Also from 1950s, theories of fault tolerance and self-repairing computing were being developed due to the increased reliability requirement of critical applications like the space-mission. Before 1978, radiation was considered to be a reliability issue for space applications, but not for electronics operating at sea level. In 1978, May and Woods of Intel published a path breaking paper which demonstrated that radiation-induced soft errors are also present in electronic systems at sea level [13]. This publication introduced the definition of "soft errors" as random, nonrecurring, single-bit errors in memory elements, not caused by electrical noise or electromagnetic interference but by radiation. The paper reported on soft errors in the Intel 2107-series 16-kb DRAMs, which were caused by alpha particles emitted in the radioactive decay of uranium and thorium impurities present just in few parts-per-million (ppm) levels in the package materials.

Guenzer et al., [14] reported that the error causing particles came not only from uranium and thorium but that nuclear reactions generated high energy neutrons and protons, which could also cause upsets in circuits. In 1979, Ziegler and Lanford from IBM concluded that cosmic radiation can also induce soft error similarly as alpha particles [15]. In particular, cosmic ray particles might interact with chip materials and cause the fragmentation of silicon nuclei which could induce a local burst of electronic charges, resulting in a soft error. Because of the usage of materials with low alpha emission rates, cosmic neutrons replaced alpha particles as the main source of memory SER during the 1990s. However, due to the reduction of critical charges, the SER contribution from alpha particles has gained importance again during the last years. Lage et al. of Motorola collected data for various SRAM types from real-time SER provided further evidence that the SER of circuits is not exclusively caused by alpha particles but neutrons also contributed to it [16]. In 1995, Baumann et al. from Texas Instruments presented a study that showed that boron compounds are a non-negligible source of soft errors [17]. In semiconductor industry borophosphosilicate glass (BPSG) films are widely utilized as dielectric layers between conductor lines. For conventional Al-based processes, BPSG (Borophosphosilicate glass) is the dominant source of boron fission and, in some cases, the primary source of soft errors [18]. In copper-based technologies, metal layers are processed in a different manner, using chemical-mechanical polishing, which does not require the use of BPSG. Because of this, thermal neutron-induced boron fission is not a major source of soft errors in advanced CMOS technologies using copper interconnect.

4. RADIATION SOURCES FOR SOFT ERROR IN SEMICONDUCTOR DEVICES

a) Alpha paricles

Alpha particles are emitted when the nucleus of an unstable isotope decays to a lower energy state. They contain kinetic energy in the range of 4 to 9 MeV. There are many radioactive isotopes, however, uranium and thorium have the highest activity among naturally occurring materials. In the terrestrial environment, major sources of alpha particles are radioactive impurities such as lead-based isotopes in solder bumps of the flip-chip technology, gold used for bonding wires and immersion tin plating, aluminum in ceramic packages, lead-frame alloys and interconnect metallization [19].

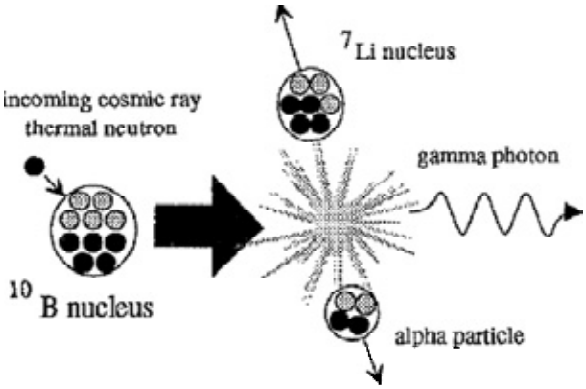


Fig. 1. Fission of 10B induced by the capture of a neutron (commonly happened in SRAMs). Reprinted with permission from R. Baumann // *IEEE Trans. Device and Mater. Reliab*. **1** (2001) 17, (c) 2001 IEEE.

b) High-energy cosmic rays (> 1MeV)

High-energy (> 1 MeV) neutrons from cosmic radiation can induce soft errors in semiconductor devices via secondary ions produced by the neutron reaction with silicon nuclei. Cosmic rays that are of galactic origin react with the Earth's atmosphere to produce complex cascades of secondary particles such as muons, neutrons, protons, and pions. Because pions and muons are short-lived and proton and electrons are attenuated by Coulombic interaction with the atmosphere, neutrons are the most likely cosmic radiation sources to cause SEU in deep-submicron semiconductors at terrestrial altitude. The neutron flux is dependent on the altitude above the sea level, the density of the neutron flux increases with altitude.

c) Low-energy cosmic rays (<< 1 MeV)

The third significant source of ionizing particles in electronic devices is the secondary radiation induced from the interaction of cosmic ray neutrons and boron. It is the radiation induced by low low-energy cosmic neutron interactions with the isotope boron-10 (^{10}B is commonly used as *p*-type dopant for junction formation in IC package and is also found in BPSG). The reaction scheme is shown in Fig. 1 [20]. This mechanism has recently been found to be the dominant source of soft errors in 0.25 and 0.18μ SRAM fabricated with BPSG. Modern microprocessors use highly purified package materials and this radiation mechanism is greatly reduced, making the high-energy cosmic rays the major reason for soft errors.

5. EFFECT OF RADIATION IN SILICON

The effect of radiation on Si can be understood from Fig. 2 [3]. When the radiation passes through the reverse-biased junction, the most charge-sensitive part of circuits, it forms a cylindrical track of electron-hole pairs, which are rapidly collected by high electric field near depletion region creating a large current/voltage transient at that node. The potential distorts into a funnel shape which greatly enhances the efficiency of the drift collection by extending the high field depletion region deeper into the substrate [21]. This "prompt" collection phase is completed within a nanosecond and followed by a phase where diffusion begins to dominate the collection process until all excess carriers have been collected, recombined, or diffused away from the junction area.

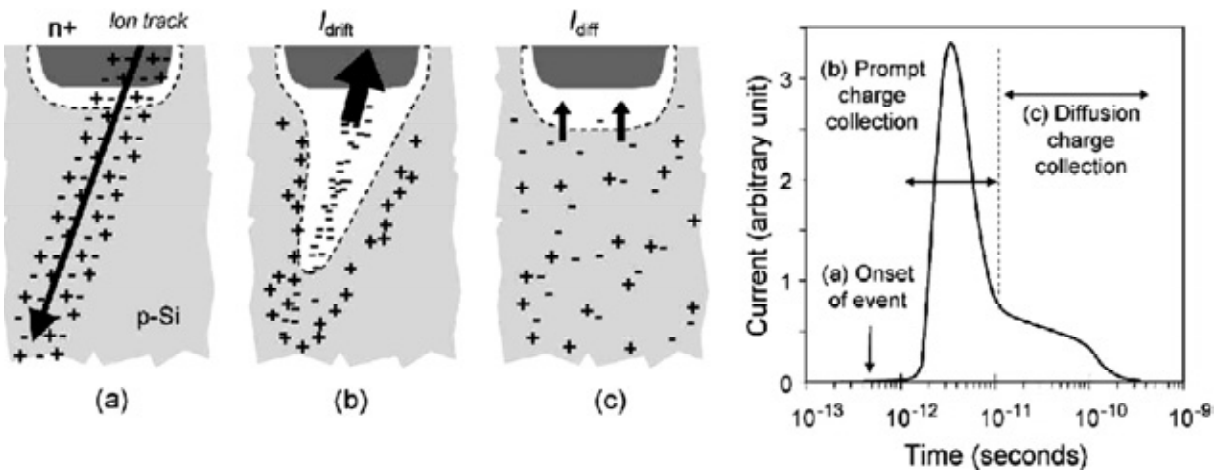


Fig. 2. Charge generation and collection phases in a reverse-biased junction and resultant current pulse caused by the passage of a high-energy ion. Reprinted with permission from C. M. Hsieh, P. C. Murley and R. O'Brien // *IEEE Trans. Electron Device Lett*. **2** (1981) 686, (c) IEEE 1981.

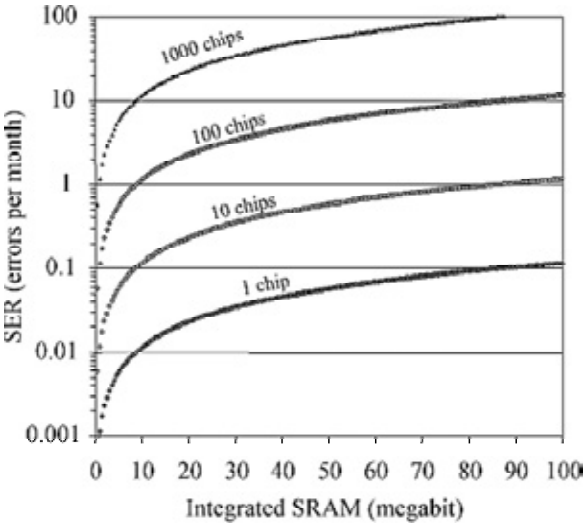


Fig. 3. Monthly system SER as a function of the number of chips in the system and the amount of embedded SRAM per chip. Reprinted with permission from R. C. Baumann // *IEEE Trans. Device Mat. Re*. **5** (2005) 305, (c) 2005 IEEE.

The corresponding current pulse resulting from these three phases is also shown in Fig. 2.

For the simple isolated junctions (like DRAM cells in storage mode), the occurrence of soft error depends on the magnitude of charge collected (Q_{coll}) and critical charge (Q_{crit}). The critical charge (Q_{crit}) is the amount of charge required to trigger a change in the data state and is not constant but depends on the radiation pulse characteristics and the dynamic response of the circuit itself [22]. When a radiation event occurs close enough to a sensitive node such that $Q_{coll} > Q_{crit}$, soft error occurs or vice-versa.

6. SOFT ERRORS IN ELECTRONIC SYSTEMS

Whether or not soft errors impose reliability risk for electronic systems strongly depends on the application. Soft-error rate is generally not an issue for single-user consumer applications such as mobile phones. However, it can be a problem for applications that either contain huge amounts of memories, or have very severe reliability requirements. If the effect of soft errors is manifested at the system level, it is generally in the form of a sudden malfunctioning of the electronic equipment, which cannot be readily attributed to a specific cause. Soft errors are untraceable once new data have been written into the memory that stored the corrupted bits or when the power of the device has been reset. Therefore, failure analysis is not capable of identifying soft errors as the root cause of the problem. Furthermore, the problem is not reproducible, due to its stochastic nature. Because of this, it is usually very difficult to show that soft errors are causing the observed failures. In the case of the 2107- series DRAM of Intel, it took many efforts to find out that the water used in the package factory was causing the contamination with radioactive impurities and that this was the root cause of the problem. During 1986, the root cause of the increase in failures of their LSI memories manufactured by IBM in the USA, after painstaking effort, was attributed to radioactivity due to 210-Po contamination in the bottle of nitric acid that was used in the wafer processing. The serious problems in the high-end server line “Enterprise” of Sun Microsystem in 1999/2000 and router line cards of the 12000 series of Cisco systems in 2003 [23,24] can be attributed to soft error.

One FIT is one error in a billion device hours and that advanced processors with large multimegabit-embedded SRAM can easily have soft failure rates in excess of 50 000 FIT per chip. An SER of 50 000 FIT is equivalent to about one soft fail every 2 years (assuming the component is used 24 h/day). For a digital signal processor used in a cell phone application, the failure rate of 50 000 FIT will not affect the customer’s perception of cell phone reliability since, in reality, given that the phone will not be operated all the time and that the soft failure can occur anywhere in the chip (only if the error occurs in one of a few critical bits crucial to the phone’s operation will the error be perceived), the cell phone will probably not fail once in its lifetime due to soft errors. Thus, for single-user applications, it is not crucial to implement costly error correction or redundancy even when the SER rate is very high. That same chip, however, if used in a telecom base station as a component in a mainframe computer server or in a life-support system, is in a different situation. In such systems, reliability requirements are much higher and many of chips are used in parallel so that the single-chip SER of one soft fail every 2 years must be multiplied by the number of chips in the system—one fail every 2 years for a single chip becomes a failure rate of once a week for a system with 100 chips. For such applications, error correction is mandatory. Fig. 3 shows the monthly number of soft errors as a function of the number of chips in the system and the amount of SRAM integrated in each chip [3]. Thus as stated above the level of mitigation required to meet the customer’s reliability expectations is far more de-

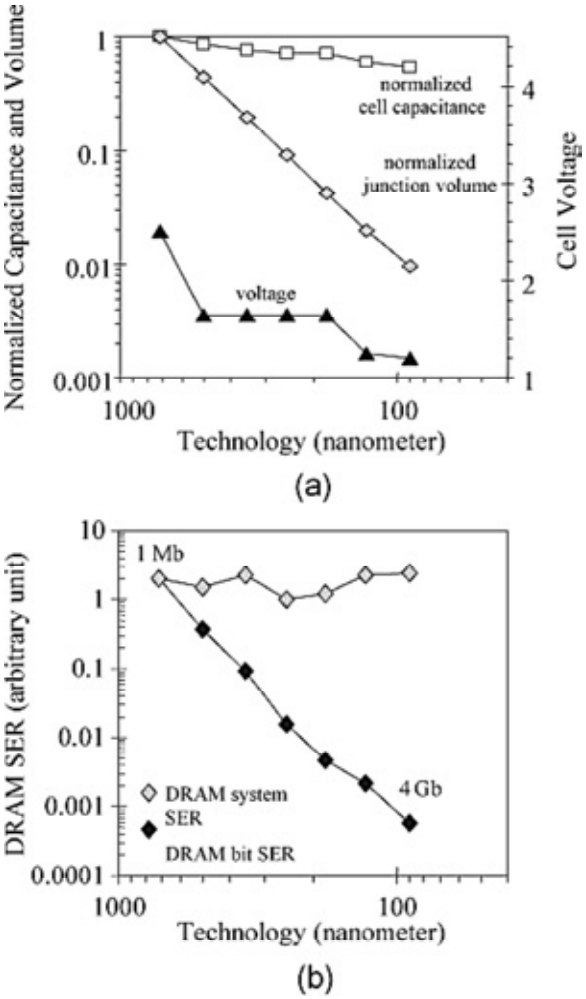


Fig. 4. (a) DRAM scaling parameters, normalized cell capacitance, normalized junction volume, and cell voltage as a function of technology node. (b) DRAM single bit SER and system SER as a function of technology node. Reprinted with permission from R. Baumann // *IEEE Trans. Device and Mater. Reliab*. **1** (2001) 17, (c) 2001 IEEE.

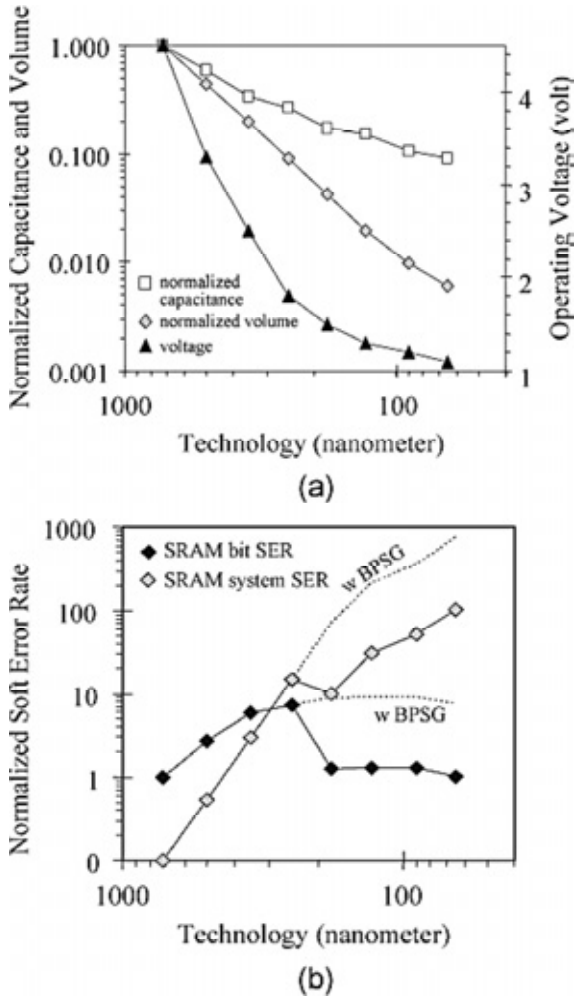


Fig. 5. (a) SRAM parameters, normalized storage node capacitance, normalized junction volume, and voltage as a function of technology node. (b) SRAM single bit and system SER as a function of technology node. Reprinted with permission from R. Baumann // *IEEE Trans. Device and Mater. Reliab*. **1** (2001) 17, (c) 2001 IEEE.

pendent on the end application reliability requirements than the component's specific SER.

6.1. SER effect on memory devices (DRAM and SRAM)

DRAMS are most vulnerable circuit elements at the time of discovery of SER as a significant reliability issue for terrestrial applications. SRAMs were more robust then because pull-up and pull-down transistors stabilize the charges representing the memory state. However, due to major technology changes, DRAMs have become more robust against soft errors with every generation, while on the other hand SRAMs have become more vulnerable with technology scaling. The sensitivity of memory devices like DRAM and SRAM to soft error rate with the change in technology node over the generations is described in detail by Baumann [20]. The DRAM and SRAM device scaling trends along with voltage scaling is shown in Figs. 4 and 5, respectively. The exponential growth in the amount of SRAM in microprocessors and digital signal processors has led the SER to increase with each generation with no end in sight. This trend is of great concern to chip manufacturers since SRAM constitutes a large part of all advanced integrated circuits today.

7. MITIGATION STRATEGY FOR SOFT ERROR

The most obvious way to eliminate soft errors is to get rid of the radiation sources that cause them. But it is easier said than done, particularly when

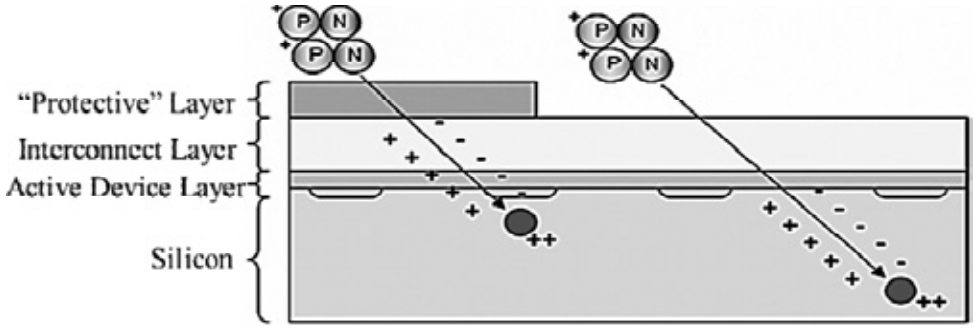


Fig. 6. Effect of "Protection" on the depth of the Bragg peak. Reprinted with permission from A. C. Mackie // *Chip Scale Rev.* **14** (2010) 29, (c) 2010 Haley Publishing Inc.

the complexities of semiconductor devices are increasing day by day. The options to reduce soft error rate in advanced semiconductor devices generally fall into three categories.

(a) Materials: Materials used in the different levels of electronics packaging such as Metals or Alloys (Solder, UBM, copper traces), Inorganics (Si wafer, Dielectrics, fiber filler in substrate, "filler" in capillary underfills), Organics (Capillary underfills, wafer level underfills (polymer-collar), photoresists, ABF, solder mask, substrate epoxy, fluxes, molding compounds) should be low alpha emitter.

(b) Chip Design: The chips should be designed in such a way to where the materials with the highest alpha emission are kept physically separated from sensitive circuit components.

(c) Introducing Novel Process Steps: Another way to reduce SER is to use novel processing steps such as coating the chip with a thick polyimide layer prior to packaging to shield it from high alpha emission from packaging materials. To mitigate the dominant SER threat posed by the reaction of low-energy neutrons and ^{10}B, BPSG has been removed from virtually all advanced technologies.

8. ALPHA RADIATION PROBLEM IN SOLDER AND NEED FOR LOW ALPHA PARTICLE BEARING SOLDER

For higher electrical performance in electronic devices especially mobile applications such as cell phones and portable game machines, Flip Chip (FC) technology has been widely used. Furthermore, 3D packaging technology such as CoC (Chip on Chip), PoP (Package on Package) and TSV (Through Silicon Via) is recently introduced to the market, for which FC technology is fundamentally utilized. It is well known that packages which use FC are mainly FC-BGA (Flip Chip-Ball Grid Array) and CSP (Chip Size Package).

Solder bumps are a near ideal material for connecting integrated circuits to a package or substrate via the flip chip process. Unfortunately, solders contain low levels of radioactive isotopes that emit an alpha particle upon decay. Since the solder in a wafer bump is very close to the active area of the chip, the alpha particle can deposit enough energy in a memory cell on the chip to erase the stored information and hence to cause soft error. Semiconductor device packaging has over the years received increased emphasis due to a continued decrease in semiconductor device feature size, a decrease that is driven by the dual requirements of improved device performance and reduced device manufacturing cost. This trend has led to a significant increase in semiconductor device density, which places increased emphasis on device or package I/O capabilities. Increased device density brings with it increased closeness of components and elements that are part of the created semiconductor devices. This increased closeness is expressed as a reduction in the spacing or "pitch" between elements of a semiconductor device and the trend is towards sub-100 mm pitch. With decreasing dimensions, low operating voltages and ever-shrinking node capacitance, semiconductor devices are becoming extremely sensitive to alpha particles radiated from the solder. The use of solder bumps in integrated circuits has necessitated development of solder with low alpha activity. Therefore from materials point of view, use of low alpha radiation emitting solder in the microelectronic application is very important to reduce soft error.

Alpha particles produce soft errors by penetrating through the solder joint, under-bump metallurgy (UBM), Al pad, passivation, silicon, and p-n junction and generating carriers as a result of giving up kinetic energy as they slow down. The carriers generated by alpha penetration through the junction distort the electric field and also generate charges. Low and ultralow alpha-emitting semiconductor assembly

Table 1. Most common sources of alpha particles in microelectronic packages, data from [33].

Sources
Solders
Alumina substrates
BEOL metallizations
Fillers in plastics, encapsulants, underfills, mold compounds and solder masks
Flux
Lead frame alloys
Materials (Au, Cu, Ag etc) used for wire bonding and lid plating
Particulates from PBGA trimming / handling operations

materials are now essential for flip-chip packaging and are also becoming increasingly critical for power semiconductor assembly, as smaller active device sizes and thinner wafers increase the devices' sensitivity to ionizing radiation.

Protection against high-energy alpha particles is often counter-intuitive. The kinetic energy of the alpha particle is (½ m.v^2) a measure of the velocity. As the particle interacts with the lattice structure, it slows down, creating pairs of holes and electrons (+ and -), until finally it absorbs two electrons and forms a helium atom. It therefore seems to make sense to put a "protective" layer in the way to protect the active semiconductor layer from the accumulation of charge: unfortunately this (Fig. 6) may act to bring closer to the doped-ion wells of the active layer where the slowing alpha particle generates more electron/hole pairs as it slows down. Like a firework going off in a final flare of glory, more pairs are generated as the alpha particle's interactional cross-section grows and finally slows to a stop (red dot in Fig.6.) in a phenomenon known as the Bragg Peak [25].

8.1. Packaging materials alpha particle emissions

The energy range of alpha particles emitted from all naturally occurring elements that undergo alpha decay ranges from 1 to 9 MeV [13, 26,27]. Alpha particles released from the decay of ^{238}U and ^{232}Th in packaging materials can penetrate into silicon devices. The most common sources of Alpha particles in microelectronic packages are shown in Table 1. The decay of ^{238}U to stable ^{206}Pb produces eight alpha particles with energies ranging from 4.15 to 7.69 MeV [28-29]. Alpha particles having this energy can travel 10 to 25 μm in alumina substrates that have a density of 3.85 g/cm [31]. These high-energy alpha particles can travel up to 50 μm in silicon substrates that have a density of 2.3 g/cm^3. ^{232}Th has a radioactivity of 1.1 × 10^{-7} C/g. The decay of ^{232}Th to stable ^{206}Pb produces six alpha particles with energies ranging from 3.95 to 8.8 MeV [30]. Alpha particles having this energy can travel 9 to 31 μm in alumina substrates and can travel up to 50 μm in silicon substrates. The soft errors caused by the emission of alpha particles from packaging materials are due to the generation of electron-hole pairs. High energy alpha particles passing through the silicon device can generate up to 2.5 × 10^6 electron-hole pairs in several picoseconds [13]. The number of electron-hole pairs produced depends on the energy of the emitted alpha particles and the density of the material. The amount of energy required to produce an electron-hole pair in silicon is 3.6 eV. Fig. 7 shows the effect of an alpha-particle-generated electron-hole pair on a silicon device [13].

Table 2. Alpha radiation activity of some common materials utilized in microelectronic packages, data from [34].

Material	Alpha radiation flux (a/khr cm^2)
Processed wafers	0.9
Cu metal (thick)	1.9
Al metal (thick)	1.4
Mold compound	24 to < 2
Underfill	2 to 0.9
Pb solders	7200 to < 2
LC II Pb (HEM)	50 to 3
LC I Pb (HEM)	1000 to 130
Alloy 42 (Hitachi)	8
Au-plated alloy 42 (HEM)	4
Sn (HEM)	>1000 to <1
AlSiC (Lanxide)	215
LC6 Al (HEM)	8

Alpha particle levels are reported as alpha activity or as alpha flux. Alpha activity is defined as the alpha particle disintegration rate per unit weight of the material-usually reported in pC/g (picocuries per gram). Alpha flux is defined as the rate (per time unit and per area unit) of alpha emissions from the surface of a material usually reported in particles per hour per cm^2. Alpha flux is the more common method of reporting alpha particle content. As a rule of thumb, an alpha flux of 1 alpha/(hcm^2) corresponds

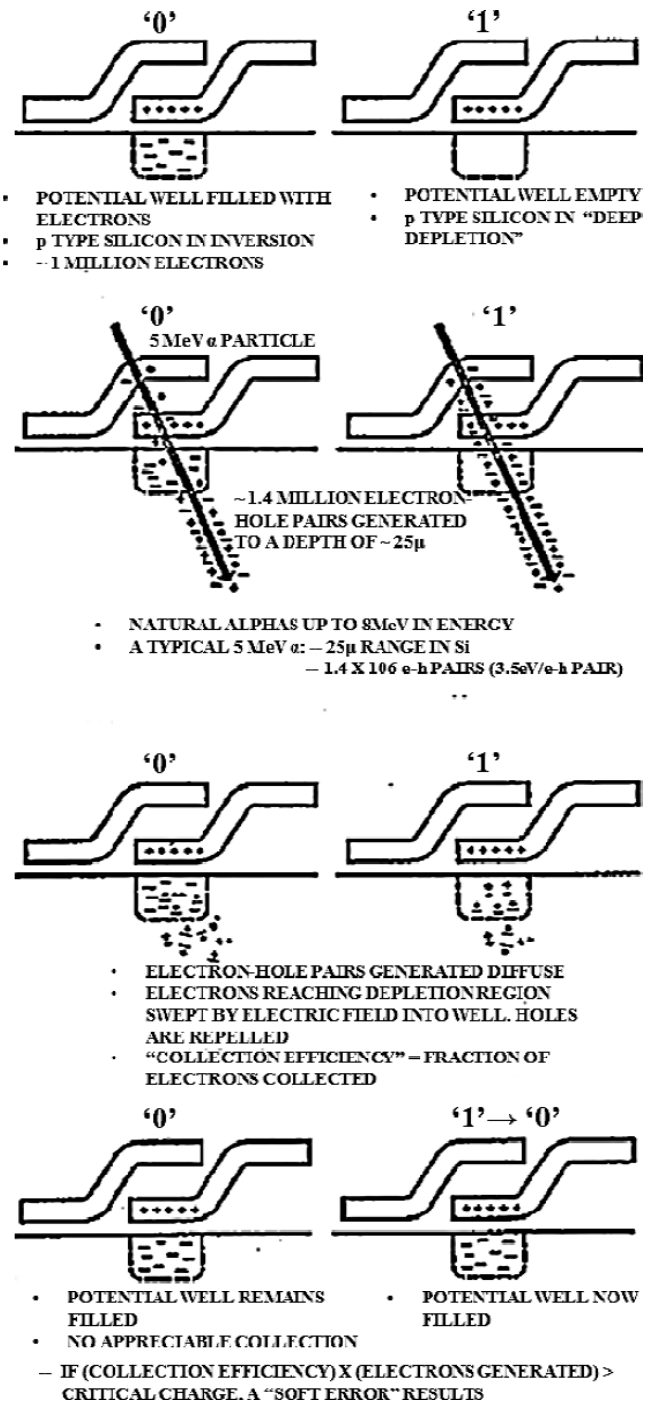


Fig. 7. Stages of Soft Error Creation by Alpha Particles in Dynamic Memories. Reprinted with permission from T. C. May and M. H. Woods, In: *Proc. 16th Annual Reliab. Physics Symp. IEEE* (San Diego, California, 1978), (c) 1978 IEEE.

to <1 ppm of ^{238}U in the material [31]. The Alpha Radiation Activity of Some Common Materials Utilized in Microelectronic Packages is shown in Table 2.

In memory devices, data are stored as the presence or absence of charge carriers in storage wells. The amount of charge typically stored in potential well ranges from 0.3×10^6 to 3×10^6 electrons. However, the susceptibility of a memory device to soft errors does not depend primarily on the total stored charge but on the critical charge (the number of electrons that differentiates a 1 and a 0). When the number of electrons generated by an alpha particle and collected by storage well exceeds the critical charge, a soft error occurs. Critical charge is the most important gauge of alpha particle sensitivity and soft error rates (SER) in memory devices. If a device has the critical charge larger than

Table 3. Baseline alpha measurements for MCNC's standard solder bumping, data from [32].

Material	α counts/Time ("α" / "hr")	Gross α/time (α / hr)	Background Rate (α / hr)	Sample Area (cm^2)	Corrected Activity (0.001 α /cm2.hr)
Si	104/23.49	4.43 ± 0.43	4.03 ± 0.41	710 ± 71	0.7 ± 1.0
Si + BCB	68/23.25	2.92 ± 0.35	4.03 ± 0.41	900 ± 90	-1.5 ± 0.7
Si + BCB + UBM	102/25.85	3.95 ± 0.39	4.07 ± 0.42	900 ± 90	-0.2 ± 0.7
Si + BCB + UBM + Pb-Sn	2718/44.88	60.56 ± 1.16	4.07 ± 0.42	335 ± 34	198.4 ± 15.1

2.5×10^6 electrons, soft errors are not generated by alpha particle emissions because naturally occurring alpha particles do not have enough energy to generate enough electron-hole pairs. For critical charges less than 0.05×10^6, practically all alpha particle emissions result in soft errors. In the region between these two extremes, other factors such as cell geometry, collection efficiency, alpha particle flux, and critical charge determine the SER in memory devices.

8.2 Alpha particle sources from solders

Lead-bearing solders have been identified as the primary source of alpha particles, as demonstrated by a study done at the Microelectronics Center of North Carolina (MCNC) (see Table 3) [32] where the alpha emission was monitored step by step along with the wafer bumping process.

The radioactivity of lead can be traced back to ^{238}U. Starting from ^{238}U, it decays into ^{210}Pb, which further decays into Bi in 22 years, then to Po, then to ^{206}Pb in 138 days. Besides alpha emission, the decay process also involves beta particle (electron) emission. The beta particle has no impact on soft error. The content of uranium in natural sources of lead differs by as much as three orders of magnitude. During the smelting and chemical purification process, although other elements may be removed, the radioactive ^{210}Pb gets concentrated together with nonradioactive ^{206}Pb, due to the same chemical nature of both lead isotopes. Lead having alpha activity as high as 100 alpha/(cm^2"h) for secular equilibrium can be reached within 8 to 9 months after smelting and purification. The following decay chain illustrates the birth of an alpha particle

$$^{210}_{82}Pb \Rightarrow ^{210}_{82}Bi + \beta^{-1} \Rightarrow ^{210}_{84}P + \beta^{-1} \Rightarrow ^{206}_{82}Pb + ^{4}_{2}\alpha$$

Chip manufacturers often classify alpha particle sources as intrinsic or extrinsic.

a) Intrinsic Sources: Intrinsic sources exist within the processed silicon itself, but generally are of little importance. They result from process-related factors such as residuals left behind from phosphoric acid etching. Phosphoric acid is commonly used for patterning silicon nitride insulator films during wafer fabrication; and it is generally of relatively low purity, containing low levels of radioactive isotopes. Other intrinsic sources include trace impurities in thin-film oxides and nitrides, extraneous impurities added to the silicon during implant operations, and impurities within a silicon wafer itself [33].

b) Extrinsic Sources: Extrinsic sources are normally distinct from the silicon chip but within the IC package. Most alpha particle sources fall into this category. The most common sources of alpha particles in microelectronic packages are listed in Table 1. Estimates of the individual contributions of some of these alpha-emitting sources are given in Tables 2 and 3. It is now believed that virtually all materials used for IC packages contribute to soft error fails [34], and establishing routine monitoring procedures for incoming materials and manufacturing processes will be a necessary approach given the ever-increasing sensitivity of devices to SER due to reduced dimensions which increases proximity.

9. PROTECTION AGAINST ALPHA PARTICLE EMISSION

One method for reducing the effect of extrinsic alpha particles is to build circuits with the silicon-on-insulator (SOI) technology introduced by IBM in 1998 [35]. As shown in Fig. 8, the buried oxide layer below the active devices significantly reduces the collection of charge during a radiation event. Another method to reduce the effect of extrinsic alpha

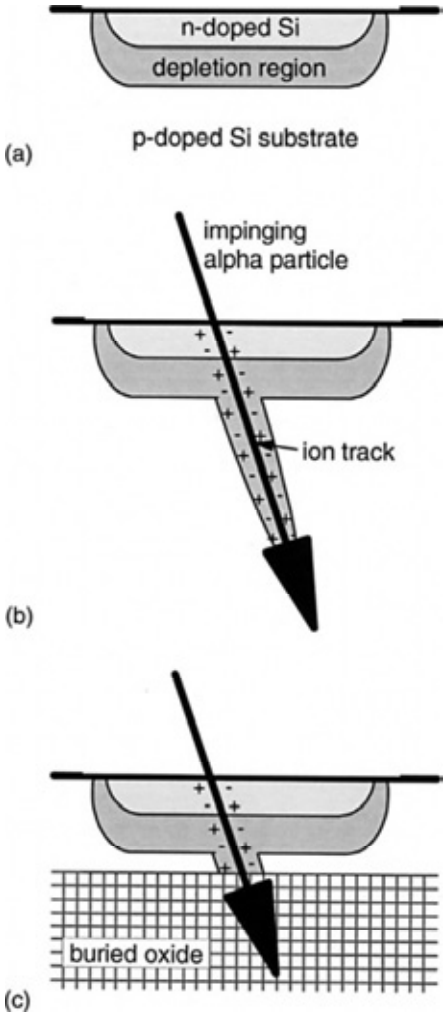


Fig. 8. Schematic depicting the sequence of events in which alpha particles cause soft errors in memory devices. (a) A device node prior to an event. (b) Silicon is ionized along an alpha particle trajectory creating electron-hole pairs. (c) Presence of an oxide layer below the active device significantly reduces the collection of charge. Reprinted with permission from D. J Schepis , In: *Internat. Electron. Dev. Meet. Tech. Digest* (IEEE, Washington, USA, 1997), p. 587, (c) 1997 IEEE.

particles is to place a shielding material on the die surface such as a thick layer of polyimide (around 20 μm) which has been found effective in stopping practically all alpha particles [34]. Even the BEOL (Back End of Line) metal wiring levels are an important mitigating factor in the effect of incoming alphas. For a typical BEOL thickness (i.e., of the stack of metal wiring layers on top of the silicon chip) of 8.5 μm, an alpha particle emitted at the silicon surface, where the active devices are located, causes as much damage as 5 to 10 alpha particles emitted at the top of the BEOL levels. Consequently,

Table 4. Estimated ranges for alpha particles in common materials, data from [34].

Material	Range (μm)
Si	23.6
Pb	11.5
Al	19.5
Cu	7.9
Polyimide	28
Au	6.6
Resist	24
Air	47000

even low levels of intrinsic alpha emissions can pose as a credible SER threat.

Most of the elements involved in major viable lead-free alternatives such as Sn, In, Ag, and Cu are all considered safe, and generally it is assumed that they pose no concerns about alpha particle emission in the coming lead-free era. But this is not completely true as many lead free solders have been found to be alpha emitter, which will be discussed later. However, Bi may be an issue, primarily due to the existence of radioactive ^{214}Bi, which will eventually convert into stable ^{206}Pb by going through three beta decays and two alpha decays in about 24 years. The primary concern about alpha particle emission is still associated with lead, which is even present in in lead free solders, though in very small amount.

Although gold-wire bonding is still widely used on chips including DRAM and SRAM, solder-bumped flip chip is gradually applied to DRAM and SRAM devices. At the same time, in some other devices, particularly logic (ASIC) and microprocessor chips, solder-bumped flip chips become an indispensable option. Thus, the trend toward higher I/Os and performance prompts the urgency of solving alpha particle emission problems [36]. The most pressing concern is alleviating soft errors in larger systems, such as servers, that run on multiple processors and use large banks of DRAMs. Solutions may include increasing the size of the nodes. Although this will raise the level of the charge needed to touch off a false switch, thus reducing the chance of soft error, power consumption will rise.

The alpha particle produced by the decay of ^{210}Po (which comes from ^{210}Pb by two beta decays) has energy of 5.4 MeV. Table 4 shows the calculated ranges for the alpha particles produced by ^{210}Po going through common materials. Although an alpha particle cannot pass through a 25 μm bump of solder, it can penetrate 25 μm of a Si layer. In addition,

Table 5. Prices of low-alpha lead-bearing solders, data from [36].

Alpha emission rate (counts/cm^{2}hr)	Product type	Price ($/lb)	Note
<0.5	Ingot	10	LC1
<0.005	Ingot	50-150	LC2
<0.02	Sn63, type 5&6 powder	1050-4050	LC2
<0.01	Ingot	90-190	LC2
<0.01	Sn63, type 5&6 powder	1140-4400	LC2
<0.005	Ingot	220-360	LC3
<0.002	Ingot	80-150	LC3
<0.001	Ingot	310-500	LC3
<0.0006	Ingot	680-1150	LC3

it can also easily pass through thin-metal films and many tens of micrometers of organic materials [36]. For flip chip applications, lead is close to IC, and it needs 25 to 50 μm of polyimide passivation. For flip chip bipolar devices, there is substantial alpha particle release from glass frit. To protect the IC, 50 to 75 μm of silicone gel is used by IBM to keep alpha particles from reaching ceramic sources. For those designs, the I/O count is low, and solder bumps can be put at the perimeter of the chip; therefore it is acceptable for memory chips. However, for logic devices, there is a very high I/O count, and the solder bumps have to be placed virtually everywhere on the IC surface [37]. In this case, a low-alpha-particle-emission solder will be required. For wafer-level packages, such as WLCSP, the concerns about alpha particle emission due to solder interconnects are quite similar to those for flip chip packages, due to the proximity of solder bumps to ICs. The importance of Low Alpha solders can also be judged by the fact that these solder command premium price in the market as compared to traditional Pb- free solders (Table 5).Even if they were more expensive, arguably, low alpha solder costs per wafer or device are insignificant compared to liability exposure which may result from soft errors. We can imagine the magnitude of damage caused due to soft error, for example, an air traffic control computer at a major airport inexplicably changing aircraft vectors or tax refund being ignored by random SER-induced computations at the IRS.

10. RESEARCH AND DEVELOPMENT OF LOW-ALPHA SOLDERS

Many companies, such as Intel, IBM, Delco, and Solectron, use low alpha lead-bearing solders for advanced microprocessors and ASICs. Compaq also uses low-alpha lead-bearing solder for the Alpha chips. Commodity products do not need low-alpha lead-bearing solders at this stage. However, deep submicron (0.25 or 0.18 μm) applications will definitely have more need for low-alpha lead-bearing solders. The semiconductor industry is currently using solders with alpha particle emission levels ranging between 0.05 and 0.01 cph/cm^{2}h (LC2 level). With increasing I/O density, decreasing power supply voltage, and further miniaturization of the IC devices, the requirement for alpha particle emission level, especially in medical, military, automotive, aerospace and telecommunications applications, may soon move to the LC3 level. As a result, permissible alpha emitter rate requirements have dropped from 0.05 alpha counts per hour per square centimeter (cph/cm^2) to <0.002 cph/cm^2 over the past eight years.

Catering to the demands of the industry, many materials supplier companies like Honeywell, Mitsubishi materials, Duksan Hi Metal etc. have developed the low alpha solders to LC3 levels. As far as academic research for the development and

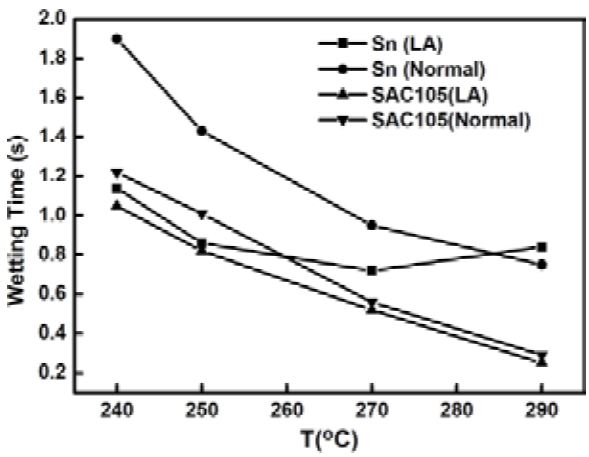


Fig. 9. Wetting time of normal and low alpha Sn and SAC105 solders at various temperatures.

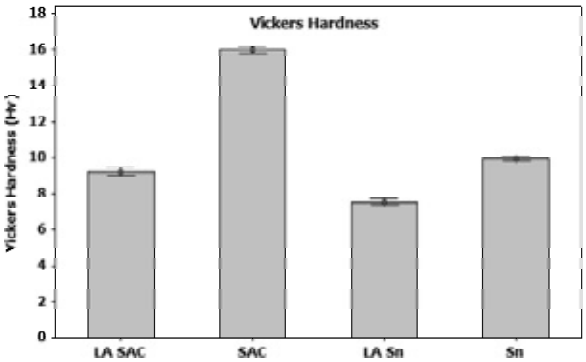


Fig. 10. Vickers hardness of LA and normal solders SAC105 and Sn solders.

study of low alpha solders are concerned, it is very difficult to find any publications. We have developed low alpha solders of LC3 level and studied their properties and reliability. In particular we have investigated the wetting behavior, mechanical properties and high speed shear test characteristics of low alpha solders [38,39].The low alpha solders show good wetting behavior as compared to normal ones particularly at temperatures less than 270 °C (Fig. 9). Hardness results show the reduction in hardness of the low alpha solders as compared to normal ones (Fig. 10). This is attributed to removal of radioactive trace impurities as the latter results in high hardness possibly due to solid solution hardening mechanism. Nanoindentation results shows the scatter in the values of hardness and Young's Modulus for different IMCs phases found in solder joint with Cu and in bulk. The hardness and modulus values of the LA Solders and the related IMCs are different from Pb free solders of same composition. The shear strength and fracture energy of low alpha SAC105 with respect to various shear speeds for different pad finishes are shown in Figs. 11a and 11b respectively. Further reliability studies like high speed pull test, high temperature high humidity ageing test and thermal shock test had been carried on and awaiting publication.

11. ISSUE OF ALPHA PARTICLE RADIATION FROM PB FREE SOLDERS

Because of the legislations like RoHS (Restriction of the use of certain Hazardous Substances) and WEEE (Waste Electrical and Electronic Equipment), there is global shift to use of Pb-free electronic products. Semiconductor packaging and electronics manufacturing companies now employ Pb-free solder for their electronic products.

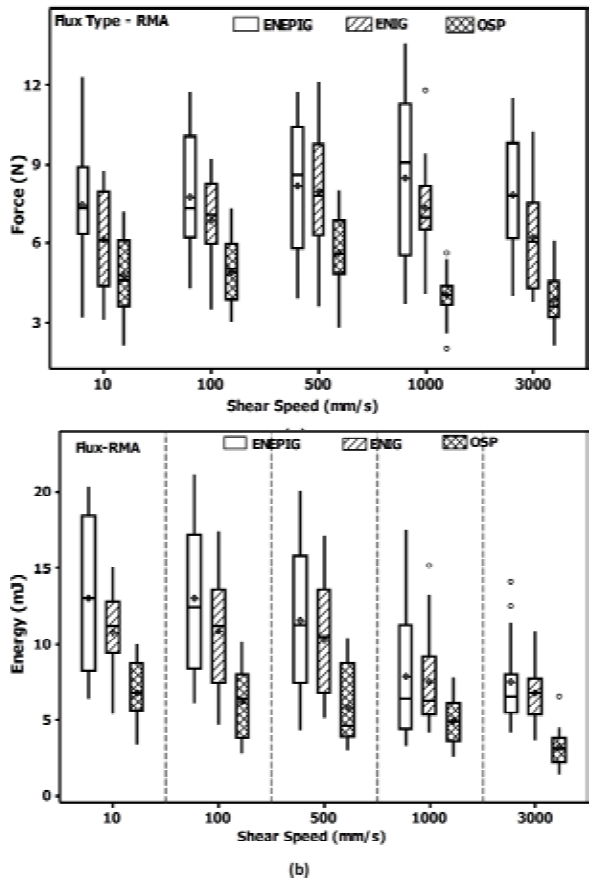


Fig. 11. Graph of Shear force (a) and fracture energy (b) as a function of shear speed for different pad finishes for SAC105 solder.

Based on the discussions in prior sections, the soft error concern associated with traditional lead based solders is quite clear, but what is less clear is why lead-free solders can potentially pose a SER concern. Because the overriding SER concern with lead-based solders is alpha particle emission by Pb^{210}, then it may be reasoned that solders which do not contain Pb do not emit alpha particles. It is falsely assumed by microelectronics packaging companies that implementation of lead-free solders would automatically solve the soft error issue and the vendors of such materials were surprised when confronted with the alpha particle emission issue [40].

Several lead-free solder alternatives are being developed in an effort to solve alpha emission issues and to address the environmental issues. While lead-free solders address the environmental concerns, they require careful scrutiny regarding the alpha emission issues. Although lead-free solders may be the best path to very low alpha particle-emitting solders for SER-sensitive products, they can also be sources of radioactivity unless proper processing

Table 6. Measurement sequence of radioactivity in immersion tin bath, data from [52].

Action	Activity (α/khr cm2)	Comments
Initial measurement	700	α-radiation from Po^{210}
Long period of Immersion Sn plating	30-40	Po^{210} selectively removed from bath
Bath idle for 4 days	-	Pb^{210} generates more Po^{210}
Final measurement	117	Secular equilibrium projected to be 450-700 depending on how much new Pb^{210} generated

steps are taken. Typical alloys considered for lead-free are Sn-Ag and Sn-Ag-Cu. There are also alloy systems containing Bi and Sb. Sn, Ag, Bi and Sb could all be contaminated with small amounts of Pb and Po that could cause alpha emission. In addition, wherever recycled tin is used, there is added risk of lead contamination. There are some reports also that indicate not all lead-free materials are low alpha [41,44,48,51]. In some cases, vendors opt to specify Sn purity to customers rather than the activity level, but this can be risky because purity does not necessarily guarantee a minimum allowable activity level.

To achieve an alpha emission rate of 0.002 cph/cm^2, the level of ^{210}Pb needs to be about one part in 10^{17}. It is often assumed that lead-free solders will have no alpha activity, so conversion to lead-free solder solves both problems. In practice, lead-free solders do have alpha activity high enough to be of concern in microelectronics. The primary source of these alpha particles is ^{210}Po, as in lead-based solders. Lead is a common contaminant in most commercial tin sources, often to a level of 100 ppm or more. For sensitive circuits, then, it is necessary to specify a low-alpha activity lead-free solder.

Silver is an increasingly popular choice for use as an alloy to create lead-free solder. However, one of the major sources of silver is in lead ore deposits. Therefore, silver must be sufficiently refined to reduce the ^{210}Pb to acceptable levels. This is not a much concern for Sn3.5Ag solder, because the silver concentration is fairly low, unless very low alpha activity is required. In such cases, ultra-high purity silver should be used. Bismuth and antimony also contain trace amounts of lead and should be specified carefully, as well.

At present, most commonly used lead-free solders are Sn rich alloys like Sn-Ag-Cu, Sn-Ag, Sn-Cu etc and to prepare ultra-low alpha solders (> LC3), very high purity alloying metals such as Ag and Cu are required to remove traces of alpha-emitting impurities. There are two additional issues to achieve very low alpha emission levels. First, the detection of low-alpha emission levels is very difficult [42], with equipment limits at approximately 2–4 α/khr cm^2. Second, the measurement of low impurity levels in Sn can be problematic. Glow discharge mass spectrometry (GDMS) and ICP-MS instrumentation are required, which though expensive but are an excellent technique for impurity concentrations in the parts per billion (ppb) range.

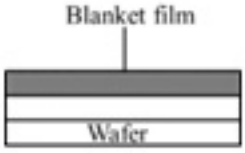
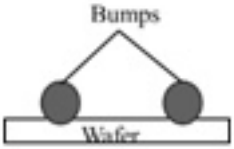
Table 7. The alpha measurement results, data from [44].

Sn Grade	Cu Board	I-Sn	After Reflow
Commercial Sn	<0.002	0.080	0.021
Low Alpha Sn	<0.002	<0.002	<0.002

12. ALPHA EMITTER IMPURITIES IN TIN AND LOW ALPHA TIN

Lead-free solders generally contain mostly tin, with other metals such as silver, copper, antimony, bismuth, or zinc in small amounts of up to a few percent. It has been determined at IBM and elsewhere that Sn and Sn-rich solder materials (such as 99.99% Sn pellet anodes, immersion-Sn plating baths, Sn–Cu bars, and Sn–Ag–Cu pastes) can be quite radioactive, in the range of 200 to 5000 α/khr cm^2, and whose activity has been found can vary considerably from lot to lot. The measured levels of activity for Sn and Sn rich materials were at first both surprising and confounding because no Sn isotopes are alpha particle emitters. Therefore Sn cannot be responsible for the measured high activity levels. Alpha energy spectrometer measurements have only indicated a 5.407-MeV peak for ^{210}Po alpha particle emission from these materials [43]. In the case of an immersion-Sn bath, for instance, the initial activity was measured at 700 α/khr cm^2, as noted in Table 6. Then the ^{210}Po level was reduced to just

Table 8. There is a significant difference between testing on blanket films and bumped wafers because of the difference in actual solder area, data from [53].

	 Blanket films on wafer	 Bumps on wafer
Bump diameter	N/A	125 μm
Bump pitch	N/A	250 μm
Total wafer area	1000 cm^2	1000 cm^2
Actual solder area	1000 cm^2	196 cm^2
Counting time	24 hrs	24 hrs
Number of counts	240	47
Calculated result	0.01 cph/cm^2	0.01cph/cm^2
Confidence level	93.5%	85.4%

a few a per kilo hour square centimeter by an extended interval of plating, and the bath was allowed to sit for several weeks before another sample was plated. That final sample measured above 100 α/khrcm^2, indicating the presence of parent ^{210}Pb in the bath producing ^{210}Po. Furthermore, secular equilibrium calculations showed that there was sufficient ^{210}Pb present to account for all the bath activity. This indicates the contamination was not just ^{210}Po from a processing step, but Pb contamination in the Sn starting material. This conclusion has also been arrived at by others [40] based on a variety of commercially available, Sn-based, Pb-free solder materials. This result from the fact that ordinary Sn contains trace amounts of Pb that causes unacceptable levels of alpha radiation.

Masuda et al. [44] studied the alpha particle issues of Immersion-Sn (I-Sn) and stressed about the importance of low alpha tin to be used in process. I-Sn plated film was considered thin enough not to give influence of alpha particle. However, Table 7 shows that I-Sn film itself shows much high alpha count without considering Cu influence, as well as reflowed sample with ultra-low alpha paste kept high value due to the effect of non-low alpha I-Sn. On the other hand, the reflowed sample with all low alpha material keeps low alpha level after completing all process. It means that even if the I-Sn is thin as a preparation of UBM (under bump material), it is necessary to use low alpha materials to keep a total alpha quality as low.

Gordon et al., [45] reported the extensive surface emission of alpha particles even from highly purified Sn samples having substantially reduced the U or Pb content and concluded that any interpretation of alpha-particle emissivity data must account for the presence or absence of surface emission for two reasons. First, surface emission causes an enhancement of the measured alpha-particle emission rates. Second surface emission can significantly increase the SEU cross section compared to volume emission, which is usually assumed.

Clark et al., [46] investigated the increase in the alpha emission with time in some instances for Sn materials in some instances. They experimentally determined the distribution of the alpha emitters within the material volume, and proposed a mechanism based on micro-segregation to explain the non-uniform distribution of alpha emitters. They concluded that presence and transport of ^{210}Po within solid Sn matrix is a key component in alpha emissivity dynamics. In cases of Po diffusion, alpha emission is no longer an intensive property unrelated to the mass of the material. Essentially all Po present in a mass can be driven preferentially to the surface and the amount accumulating at the surface is directly proportional to the absolute amount present in the mass. Therefore, reducing packaging material mass will result in reduced alpha emissions.

13. EVALUATION OF ALPHA EMISSIONS

Measurement of the alpha flux is important to establish both the usability of low alpha activity materials and the reliability of the semiconductor devices fabricated from them. The measurement of alpha

flux below 10 α khr^{-1}·cm^{-2} is complicated by the fact that the sample alpha flux is usually less than or equal to the background alpha flux in the detector. Achieving a reasonable degree of precision requires measurements lasting for many hours or days. The low signal to background ratio also makes measurement results vulnerable to variations in techniques and methods. Elimination of or compensation for these sources of measurement variation allows for scientifically and statistically valid results that are reproducible between different laboratories. The proper choice of counting parameters and the careful control of the background rate are obviously vitally important when making measurements for ultra-low alpha (ULA) samples [47].

In addition to the control of the starting materials and control of the process, implementation of a low-alpha process also involves the control of the monitoring techniques. There are ways to measure materials for alpha particles. Gas flow proportional alpha particle counters measure and record the alpha flux emitting from samples inside a chamber. There are recommended procedures for preparing and measuring alpha emission of flat samples of metals, alloys, alloy powders, tin and lead oxide powders and how to process the results [13, 49-50]. JEDEC have developed the standard JESD-221 for the alpha radiation measurement in electronic materials. This standard applies generally to gas proportional instruments and the use thereof in measuring materials with an alpha emissivity of less than 10 a khr^{-1}·cm^{-2}. The primary focus will be on materials used in semiconductor fabrication. The document also recommends methods for determining sample size and for evaluating instrument background accurately.

13.1. Specimen preparation

Accurate measurement of alpha emissions from particles relies on a large surface area of the material under study. Typically, a large metal pan of around 1,000 cm^2 forms the bottom of a hermetically-sealed unit, with a cleanable plastic tray that fits inside the pan to hold the material that is under test. The material is spread into a thin film in the tray. A thin plastic (usually 0.002" thick Mylar) film is then stretched over the tray with care taken to minimize air entrapment between the material in the tray and the plastic film. The metal pan is then sealed into the alpha-counter, and a flow of P-10 gas passes over the surface of the plastic film and out into the counting chamber, which contains P-10 gas. It is a combination of 90% argon and 10% methane, called the "counting gas", and is used because it ionizes to CH_4+ and Ar+ very easily (low ionization energy).

13.2. Sensitivity of alpha emission measurement methodology

The test method's sensitivity depends greatly on the extent of the measured background radiation. The latest gas flow proportional counters on the market have ultra-low background (as low as 2 cph) thanks to a constant improvement in materials and manufacturing processes. However, the best-case background signal is equivalent to 0.002 cph/cm^2; the same level as the highest allowable ULA emission level. The best-case signal/noise ratio for ULA materials is therefore less than 1:1, which severely limits the sensitivity of the analytical methodology and necessitates long periods of study to ensure precision. Even then, precision to four decimal places (such as 0.0020 cph/cm^2) is impossible to guarantee. It is also important to reliably quantify the background level of radiation both before and after every single measurement to ensure that cross contamination, background radiation shifts, and analyzer sensitivity drift are accounted for accurately. Some major sources of background radiation include: Interfering high energy sub-atomic particles like Cosmic rays and Stray neutrons; the measurement system itself, for example, RF interference and Voltage spikes in the supply voltage; Naturally-occurring radon gas; Cross-contamination from other sources, such as dust or previous studies.

13.3. Sampling statistics for low-alpha control

Because emission of an alpha particle is a random event, prediction of its effects on a device is described statistically. The sample size determines the confidence level to which the measured level can be predicted. If N is the sample size (number of alpha emissions counted), the error in measurement E is given by $E = 1 / N^{1/2}$, and the percent confidence level is obtained (or calculated) as (1-E) x 100 percent.

For example, if a sample of area 1 cm^2 is counted for 500 hours (approximately 3 weeks) and five counts are registered, we may predict the alpha emission density to be 0.01 cph / cm^2, but only with a confidence level of 55%. To predict the alpha activity at any appreciable confidence level, the sample size should be increased by increasing the sample area or the counting time or both. Typically,

blanket films of an area approximately equal to 1,000 cm^2 are used and counting is performed for 24 hours. If bumped wafers are used for testing, substantially less area would be obtained and the results would be much less reliable. Table 8 shows a hypothetical comparison of the two cases.

14. CONCLUSIONS

The issue of the soft errors in microelectronic devices particularly in the context of the alpha radiation emitted by the solders used in electronics packaging was discussed. With the increased use of flip chip joints and developments towards 3D packaging, this issue assumes much importance because the solder bumps have moved very closer to the active Si devices, where even the low energy alpha ray having short range is able to induce soft error. Even though the main source of alpha radiation is Pb-210, the users have to be careful in the usage of Pb free solders, as the latter has been shown to have substantial alpha emission problem. For measuring and monitoring of alpha particle radiation from ULA samples, special attention needs to be given to specimen preparation, proper choice of counting parameters and the careful control of the background radiation. More research work needs to be done regarding the properties and reliability of low alpha solders.

ACKNOWLEDGEMENT

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