Summary of LET Requirements/Testing

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Abstract

The performance of the Michigan State SEETF during its inaugural runs is evaluated. Beam profiles and other diagnostics are presented, and prospects for future development and testing are evaluated.

Introduction

The well-documented difficulties of testing commercial parts in novel packaging technologies [1-2] have provided strong motivation for developing test facilities with more penetrating, higher-energy ion beams. (See figure 1.)

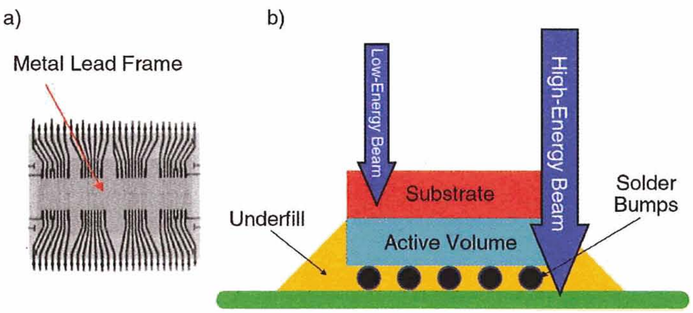

Figure 1: High-energy ion beams can penetrate the thick overburdens associated with commercial microchips— e.g. metal lead frames (a) or flip-chip packages (b).

Introduction (Cont.)

The new single event effect test facility (SEETF) at Michigan State University's National Superconducting Cyclotron Laboratory (NSCL) delivers highly energetic and penetrating heavy-ion beams. (See table I.) Such ion beams make possible testing of many commercial parts without delidding or other modification to the part. In addition, the extended energy range at NSCL makes it possible to reproduce 99% of the space radiation spectrum in Linear Energy Transfer (LET) and energy for LET > 3 MeV·cm2/mg. (See figure 2.) Moreover, the high ion energy means that testing can be done in air, rather than in vacuum, simplifying issues such as part cooling and access.

Introduction (Cont.)

Here we report on the performance of this facility during its first post-upgrade SEE runs—in February 2004 (with 9574 MeV Kr ions) and two runs in May (with 9574 MeV Kr and 15048 MeV Bi ions). (Typical runs involve only a single ion, since a 24 hour tuning time is required to switch ions.) We also report results on irradiation of two 256K SRAMs (Matra HM65656 and IDT71256). The HM65656 was irradiated previously at other SEE test facilities, so cross sections from SEETF can be compared directly to these results.

Table 1: Available Ions, Ranges and LETs.

Ion	Facility	Max. Energy (MeV/amu)	LET in Si (MeV•cm²/mg)	Range in Si (μm)	Bragg-Peak LET in Si
Ar-36	NSCL	143	1.50	8860	18
Kr-78	NSCL	121	6.08	4440	40
Xe-136	NSCL	131	14.1	3070	69
Bi-209	NSCL	72	42	1100	100

Introduction (Cont.)

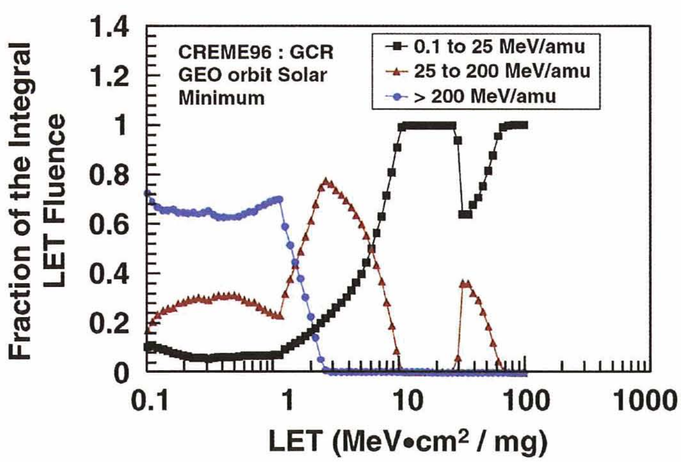

Figure 2: Addition of the high-energy ions (with 60-143 MeV/nucleon) at NSCL allows simulation of ~99% of the space radiation LET-Energy phase space for LET>3 MeV·cm2/mg.

SEETF Operation

The NSCL accelerator (see figure 3) consists of two coupled cyclotrons (a K500 and a K1200). Attenuation to the desired flux is done upstream of the accelerators to avoid beam detuning at the target. Beam steering optics ensures selection of the proper ion, energy and charge state. Beam energy degradation, if desired, can be done using either the degrading foils just downstream of the K1200 or with the degrading foil in the SEETF vault. The first option allows tuning of beam optics downstream of the degraders to ensure uniform beam energy at the target.

As the ions reach the SEETF (see Figure 4) , they pass through a gate valve (which can be opened only when the vault is secured) and into the SEETF beam line.

SEETF Operation (Cont.)

The SEETF beamline also includes two systems for measuring beam uniformity and dosimetry. For fluxes less than 4x102 cm-2, the Parallel Plate Avalanche Counter (PPAC) provides detailed positions in the plane perpendicular to the beam axis (the X-Y plane) for individual ion strikes. The second dosimetry system—a four-quadrant thin scintillator (FQS) measurement system provides detailed dosimetry and rudimentary beam-uniformity information for beam fluxes up to ~1.5x105 cm-2 over the 5 cm x 5 cm beam spot. Downstream of the FQS, the ions strike the device under test (DUT). The target positioning stage provides translation in the X-Y plane and rotation about the vertical axis (in q). Figure 5 shows the experimental area in the SEETF vault. Figure 6 shows a picture of the user room.

SEETF Operation (Cont.)

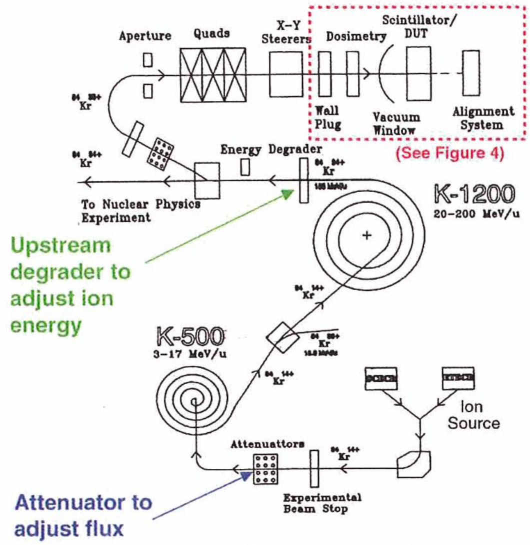

Figure 3: Schematic of the main features of the accelerator and beam optics (below) and the SEETF beamline (red box below and blow-up above). Figure 4 shows an expanded version of the main elements within the SEETF experimental ares (inside red rectangle.)

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SEETF Operation (Cont.)

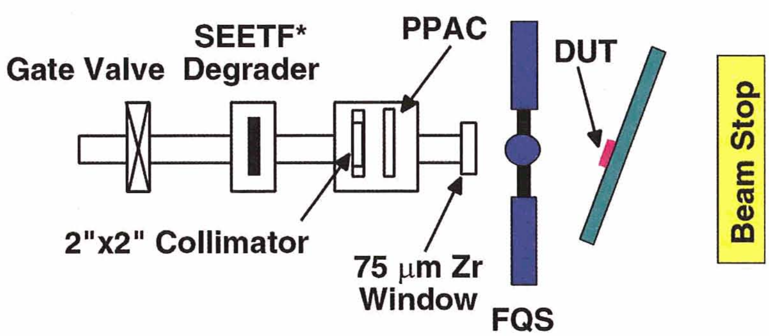

Figure 4: The main elements inside the SEETF experimental vault.

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SEETF Operation (Cont.)

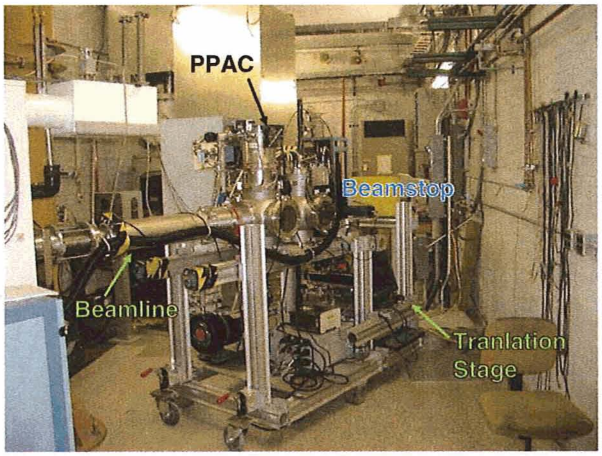

Figure 5: The SEETF Experimental Vault.

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SEETF Operation (Cont.)

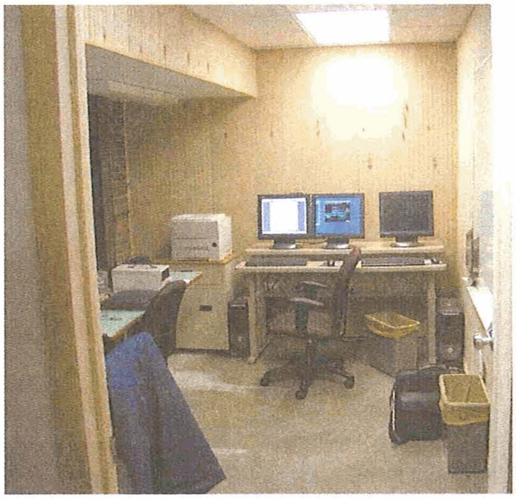

Figure 6: Picture of the user room.

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Facility Control

The SEETF is controlled from the user control room (Figure 6) or the SEETF experimental vault (Figure 5) by two computer sytems. A Windows-based system controls target positioning, the downstream degrader and other aspects pertaining to the SEETF beamline elements. The Windows system also starts and stops irradiation of the part.

Data Acquisition is handled by a Linux-based system, which controls the beam-monitoring equipment and display, storage of facility data for the run and so on. It also allows the user to save the data at the end of the run.

Control of the beam (including flux, quality and tuning) is exercised by the accelerator operators. Users may request changes by calling the operator in the control room. Flux can usually be incremented or decremented in a few minutes. Tuning for beam uniformity may be more involved but is usually completed within 15 to 30 minutes. Beam energy degradation to increase ion LET can involve a retune to ensure uniform energy.

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Beam Quality and Dosimetry

During the February and May beam runs, both the PPAC and the FQS were used to monitor the beam quality and measure dosimetry. Because the PPAC provides more detailed information on uniformity over the 5 cm x 5 cm beam spot size, initial runs were conducted at low flux with the PPAC in the beam line. In subsequent runs, the flux was raised by decreasing the attenuation upstream of the K500 cyclotron, and the PPAC was removed. This produces a beam profile with uniformity comparable to the low-flux, high-attenuation beam. The FQS provides information sufficient to indicate any major changes in uniformity. The procedure of beginning with low flux in order to use the PPAC and then transitioning to the FQS was followed whenever the beam was retuned.

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Beam Quality and Dosimetry

Figure 7 illustrates the beam quality characteristic of the February and May runs. The plot at upper left shows the PPAC readout, with fluence color-coded (red=high, blue=low). The upper right and lower left plots show, respectively, histograms of counts in the PPAC within a central slice along the Y or X axis. The lower right plot shows counts in each quadrant of the FQS.

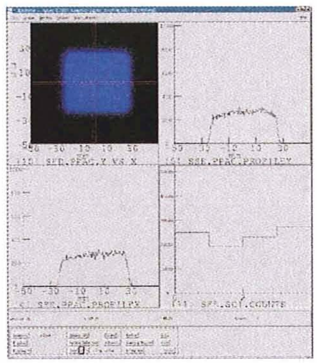

Figure 7: Sample Readout of the PPAC and FQS.

Beam Quality and Dosimetry

Beam quality remained uniform (>85% uniformity) over the 5 cm x 5 cm beam spot. Fluxes ranged from 102 to 105 cm-2, and could be changed using the upstream attenuator in less than 30 minutes (< 5 minutes was typical). During the February run, the upstream degraders were used to change the energy of the Kr ion beam, bumping the LET from 6.3 MeV·cm2/mg to 8.7 MeV·cm2/mg. The beam optics required less than 2 hours for retuning after the change.

Ion LET Determination

Determining ion LET after the beam has traversed DUT overlayers can be challenging. Monte Carlo transport codes like SRIM [4] or empirical fits to data such as LISE [5] can be effective for overlayers of known thickness and composition. However, assumptions about overlayer compositions are risky, especially for plastic-encapsulated parts. Table II shows results for several packaged and delidded Matra 65656 and IDT71256 SRAMs for the degraded and undegraded Kr beams. The 2 orders of magnitude drop in cross section exhibited by the plastic packaged IDT71256 vs the delidded version for the degraded Kr beam indicates that the ions are "ranging out" in the package before they reach the sensitive volume in the silicon. This indicates that the plastic packaging was significantly denser than would be predicted for a typical pure polymer. This is not surprising, since many plastics have high glass content for thermal, structural or other reasons.

Table 2: SEU Cross Sections for Primary and Degraded Beams.

Part	Packaging	Incident Energy (MeV)	LET @ die surface (MeV•cm²/mg)	Average Cross Section (cm²)
IDT71256	Lidded Plastic	9574	N/A	2.01×10^{-3}
IDT71256	Delidded	9574	6.3	1.08×10^{-3}
IDT71256	Lidded Plastic	5953	N/A	**6.92×10^{-5}**
IDT71256	Delidded	5953	8.7	**5.15×10^{-3}**
M65656	Lidded Plastic	9574	6.3	4.89×10^{-2}
M65656	Delidded	9574	7.1	1.35×10^{-1}
M65656	Lidded Hermetic	5953	11.7	1.61×10^{-2}
M65656	Delidded	5953	6.3	1.25×10^{-2}

Ion LET Determination (Cont.)

An alternative to estimating LET is to measure it using charge collection spectroscopy.[6] This technique uses a delidded (but not necessarily functional) part identical to the DUT and an ion beam of known LET incident on the bare die to measure the scaling relation between charge collected and LET. (See figure 8.) The charge collected for the same peak for a packaged device then determines the LET of the ions after they have traversed the device overlayers. (See figure 9).

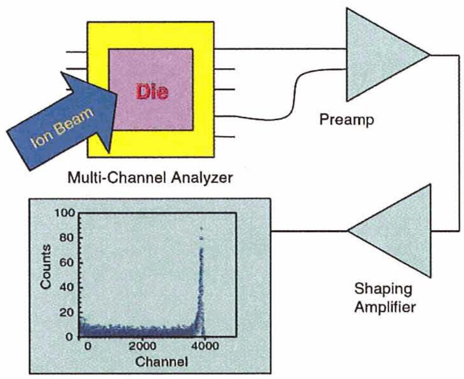

Figure 8: Charge Collection Spectroscopy Setup.

Ion LET Determination (Cont.)

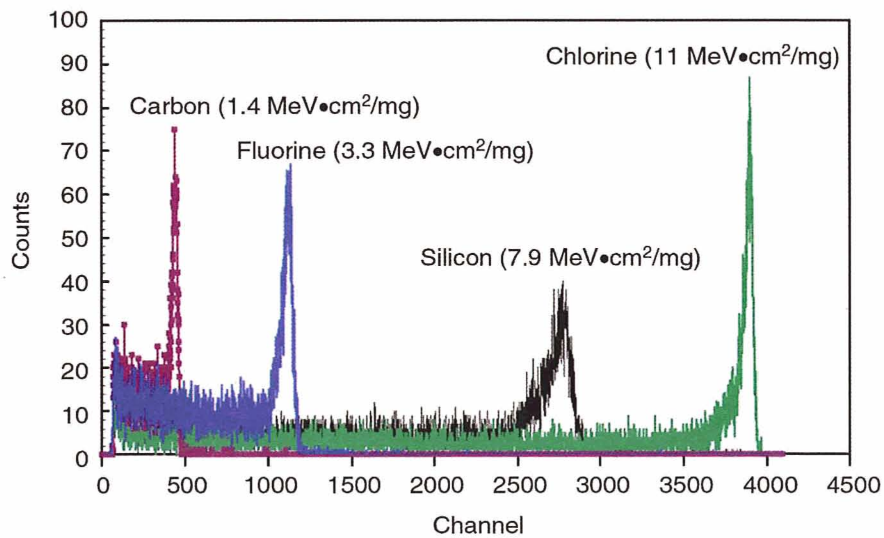

Figure 9: Charge-collection peaks for several ions at Brookhaven.

Cross-Facility Comparison

To assess SEETF data quality in relation to that from other facilities, we irradiated a Matra HM65656 256 K SRAM, dubbed DUT #30, which had been irradiated previously at the Brookhaven SEUTF and TAASC. Figure 10 indicates the excellent agreement between facilities.

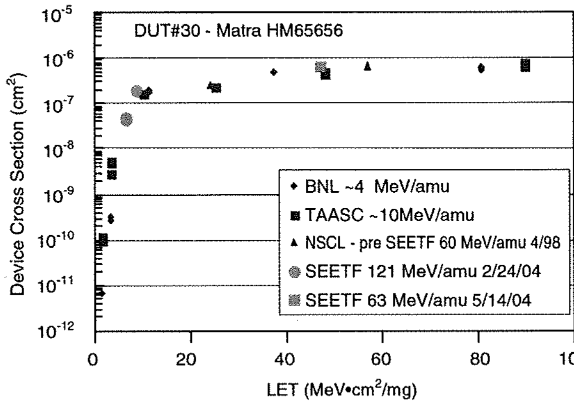

Figure 10: The same Matra HM65656 irradiated at TAASC, MSU and Brookhaven yields consistent cross section vs. LET curves over beam energies spanning a factor of 40.

Complement to Other Facilities

The SEETF at NSCL offers highly penetrating energetic ion beams in combination with the dosimetry, targeting and other facilities needed to produce high-quality SEE data. However, the facility cannot supplant existing heavy-ion SEE laboratories. The cost of beam time ($2300-$2700/hour) is significantly higher than that at lower energy facilities such as the Brookhaven SEUTF, Berkeley and Texas A&M (although if the metric is cost per MeV per amu, the SEETF is a bargain — see figure 11). The time available for SEE studies is limited (<600 hours per year). Perhaps the most significant limitation of the facility is the fact that unless the user is willing to pay a significant premium for beam tuning, SEE runs will generally have to be conducted with a single ion, and therefore over a limited LET range.

Complement to Other Facilities (Cont.)

The capabilities of the SEETF complement those of other heavy-ion facilities. The longer ranges of NSCL's ions will be invaluable for some testing requirements—e.g. when several device need to be screened for single-event latchup and other serious error modes, with the best performers being subjected to more thorough testing. Other studies where high energy ions would be invaluable include investigation of track structure effects and of energy dependence of susceptibility to some SEE mechanisms (e.g. single-event gate rupture [7]).

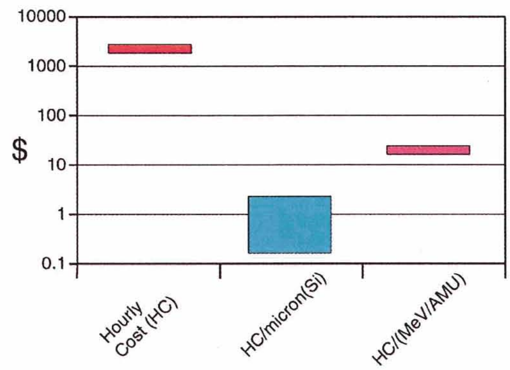

Figure 11: Selecting appropriate cost metrics for SEETF.

Future Development

Because the SEETF is a new facility, it is still subject to improvement. The highest priorities for near term development are intended to increase the range of LETs and penetration depths available. One upgrade involves installing a translation stage to move the target along the beam axis—reducing the air gap and thereby slightly increasing the energy and range of the ions incident on the DUT. Such a capability could be important for thick devices when ion penetration is marginal. This capability, however, also requires refinement of the targeting system. During the May run, an extension was mounted on the target assembly to place the part as close to the beam exit port as possible. The DUT was then positioned by hand at the center of the beam aperture.

Another project involves adding rotational capability to the downstream degrader foil, giving a nearly continuous range of effective degrader thicknesses (and LETs). In conjunction with this capability, an ion energy measurement system for degraded beams will allow the user to measure the energy spectrum of degraded beams and estimate systematic errors introduced by beam straggling.

Conclusion - 1

With the completion of the inaugural run of the SEETF at MSU, the radiation community has a powerful new tool—both for penetrating novel package technologies and for the simulation of high-energy ions in the space environment. The results of these runs indicate both the strengths of this new facility—its high energy, penetrating power and ease of use—and its weaknesses—the difficulty of switching ions to map out a full cross section vs. LET curve. These characteristics suggest that the MSU facility represents an excellent complement to other existing test facilities.

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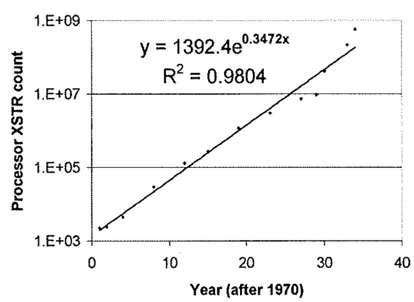
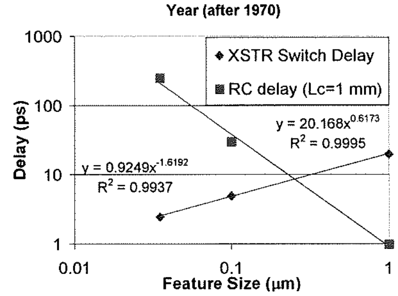
Packaging: The Rodney Dangerfield of Electronics

- Scaling continues apace and garners most of the headlines. However, the front lines of the battle for greater integration, speed and density have shifted.
  - Increased scaling may not bring greater speed



- Packaging/interconnects now critical
  - Limiting factor for speed
  - Thermal issues
  - Critical functions (e.g. PLLs)
  - Cost rise projected ~5% per pin
- Why care?
  - Packaging affects testability



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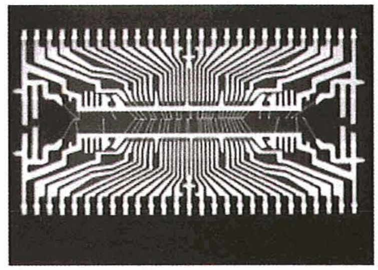
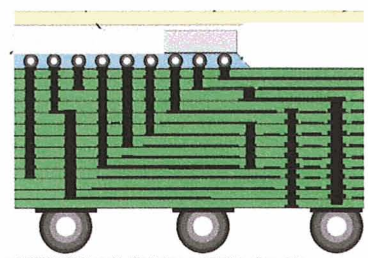
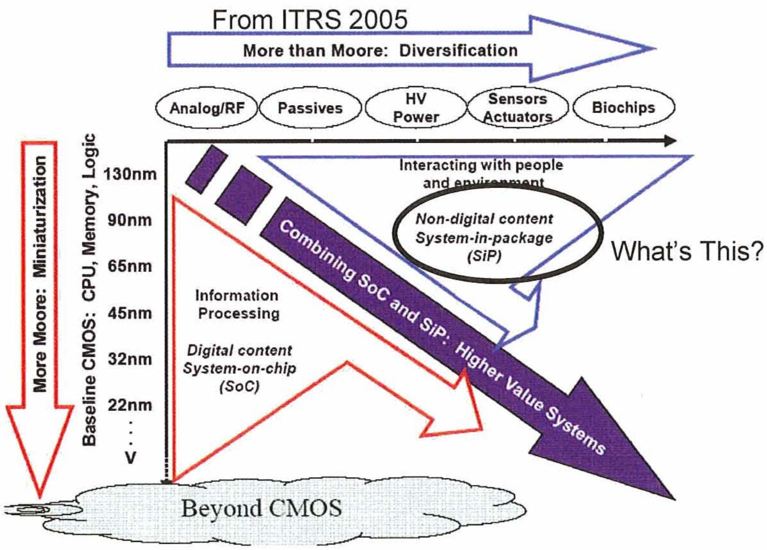
Packaging Issues and Testability: Not New

- Packaging issues are not new
  - Metal lead frames for DRAMs limit bondwire lengths
  - Flip-chip packages provide the shortest interconnects for high speed
- Traditional test prep strategies:
  - Repackaging
  - Die thinning/backside irradiation
  - Ultrahigh-energy heavy-ion (UEHI) beams
  - Proton testing to infer HI behavior
  - All these strategies pose difficulties
    - Yield
    - Fidelity/interpretation of results



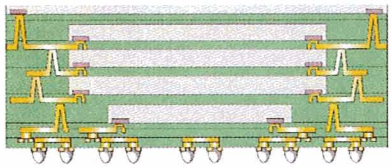


So, where is packaging headed next?

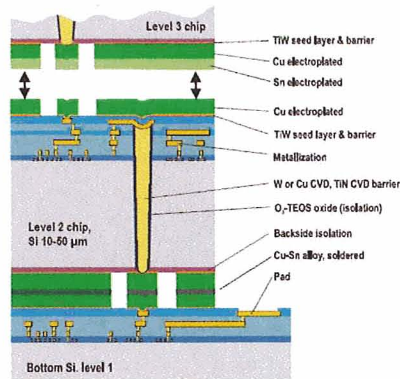


*lifted shamelessly from ITRS-2005, Executive Summary

System in a Package (SiP)—Why?



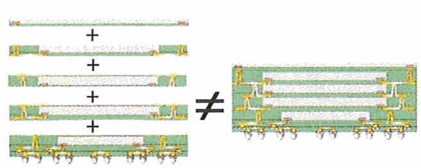
- Allows close integration of many different technologies
  - CMOS, analog RF, sensors…
- Provides shortest interconnects
- Can alleviate thermal issues
- Optimizes weight and space
- Offers a path to increased integration even if scaling fails
- But How do you test it?



*adapted from ITRS-2005, Assembly and Packaging

Repackaging and Backside Irradiation

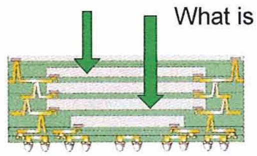
- Repackaging could be promising
  - Best strategy: Obtain pkg'd die
  - Repackaging problematic
    - thinned die→poor yield
  - No guarantee that system will perform as the sum of its parts.
    - Need high-fidelity simulation to drive each chip
  - Even if repackaging works
    - Weakest link drives performance
    - Can't current limit for SEL



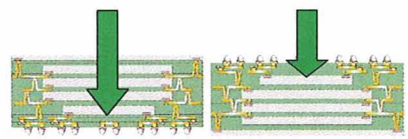
- Thinning and backside irradiation
  - Work well for monolithic chips
    - Preserves interconnects, timing
    - Main issue is affecting diffusion-related charge collection
  - Will not work for SiP
    - Note this means two-photon absorption also not feasible
  - However
    - Die usually thinned (10-50 µm) by mfg to limit package thickness
    - If individual die are obtainable and function properly
      - May be able to irradiate from front or backside
      - TPA may work just fine
    - Problem reduces to the same as that for repackaging.

Ultra-high Energy Heavy Ion Irradiation

- If energies sufficiently high, ion beam may penetrate entire package.
  - Stimulates all possible error modes under realistic operating conditions
  - If secondary effects are important, energy range of ions is more similar to space radiation environment
  - Unfortunately, interpreting results may not be trivial.
    - Ions traverse several layers and LET of ion changes as it loses energy.
    - Similar uncertainties occur when a lead frame covers part of die.
- Possible solutions
  - Use VERY high-energy (minimum ionizing) ions
  - Degrade beam energy until error mode stops.
  - Compare results for front and backside irradiation over angles
  - All these solutions are time consuming and beam time at high-energy facilities is expensive
    - Simulation may help in interpreting results if sufficient design info available



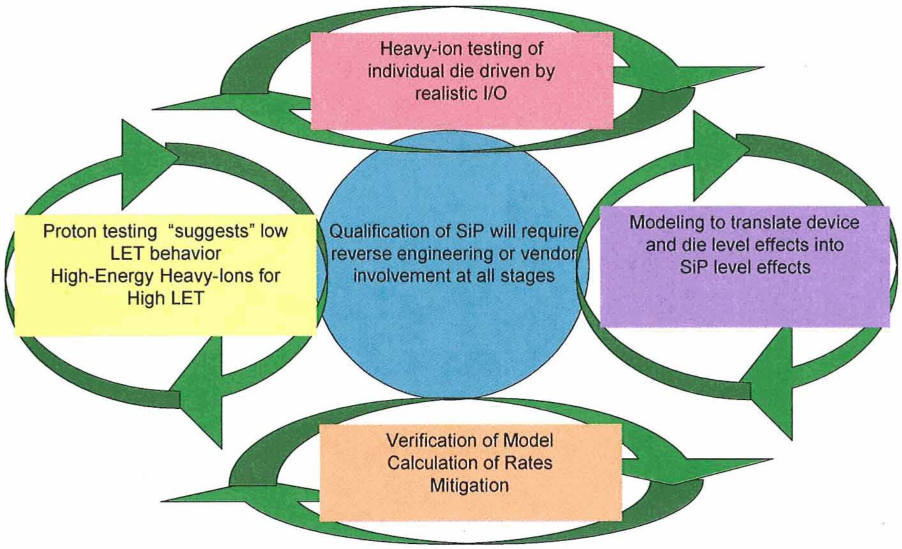
What is ion LET?



Extrapolating from Protons to Heavy Ions

- Proton-induced upsets in ICs caused by heavy ions recoiling from proton collision
  - In some cases, can infer limited information about heavy-ion response from proton data
    - max LET of recoils is 12-15 MeVcm^2/mg
  - Protons have good penetration
  - Testing can even be done for full commercial electronic systems
  - Beam time at proton facilities is relatively cheap
  - For some devices and environments, protons may dominate upset rates
- Such extrapolations carry risk
  - Some devices exhibit SEE for low LET ions but not for protons
  - Low proton interaction cross section
    - means parts may see high TID in proton testing
  - Proton testing can be complicated
    - Inelastic and elastic scattering
    - High Z recoils
    - Angle effects
  - Short recoil range may not reproduce heavy-ion effects
  - Proton testing generally not adequate to ensure hardness for most missions
  - Extrapolating from protons to heavy ions can be misleading

Qualification Suggestions



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Qualification Suggestions II

UEHI Testing Issues

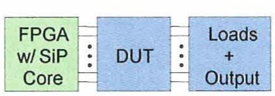
- Energy tuning is important
  - Changing energy changes LET
  - ID die an error mode occurs in
  - Only way to test the whole SiP

Proton Issues and Caveats

- Goal is to infer low-LET heavy ion behavior as well as proton behavior
  - Proton $\sigma \sim 10^{-6}$ heavy ion σ (TID an issue)
  - Method is not 100% reliable
  - High Z recoils and angle effects may occur

Testing Individual Die

- Each die tested needs realistic I/O
  - Board Layout/Signal Integrity Crucial
  - FPGA controller is promising
    - Core needs to be high fidelity



Getting to an Answer

- LET determination for high-energy, heavy ions is uncertain
  - Live with it or test individual die
- Seeing proton SEE→Low onset LET
  - Absence of SEE →High onset LET
- Proton + UEHI testing may give a rough estimate of SEE behavior
- Need more accuracy?
  - Irradiate individual die
  - Model SiP- inject errors from each die
  - Verify by showing model explains all modes seen during UEHI test

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Conclusions - 2

- Even if Scaling tapers off, integration of electronics will continue
  - SiP is a new frontier—integration of dissimilar semiconductor technologies
- SiP are very attractive for space flight
  - Small footprint, low weight, high-performance
  - A single chip may replace a box
    - With only 500 kg of gear for crew on lunar missions, that's tempting
- SiP may pose unprecedented challenges to radiation qualification
  - Package is specially engineered to optimize performance
    - Interconnects are minimized to optimize timing, signal integrity and integration
    - Package also helps with structural support (for thinned die) and thermal issues
  - Qualification may involve UEHI and proton testing, modeling and verification
    - Involvement of vendors is highly desirable and probably essential
    - It won't be cheap!!!
- Will the cost and/or risk will be too high for future programs?
  - Know anyone who's taking bets?

Acknowledgment

The Authors would like to acknowledge the sponsors of this effort: NASA Electronic Parts and Packaging Program (NEPP), NASA Flight Projects, and the Defense Threat Reduction Agency (DTRA.

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All material in this presentation has been previously presented at:
NSREC04 "Performance of the High-Energy Single-Event Effects Test Facility (SEETF) at Michigan State University's National Superconducting Cyclotron Laboratory (NSCL)" by R. Ladbury (OSC), R. A. Reed (NASA/GSFC), P. W. Marshall (Consultant, NASA/GSFC), K. A. LaBel (NASA/GSFC) , R. Anantaraman (NSCL), R. Fox(NSCL), D. P. Sanderson(NSCL), A. Stolz(NSCL), J. Yurkon(NSCL), A. F. Zeller (NSCL), J. W. Stetson, (NSCL) and SEE Symposium 2006 "Scaling, Packaging and Testability" by Ray Ladbury.