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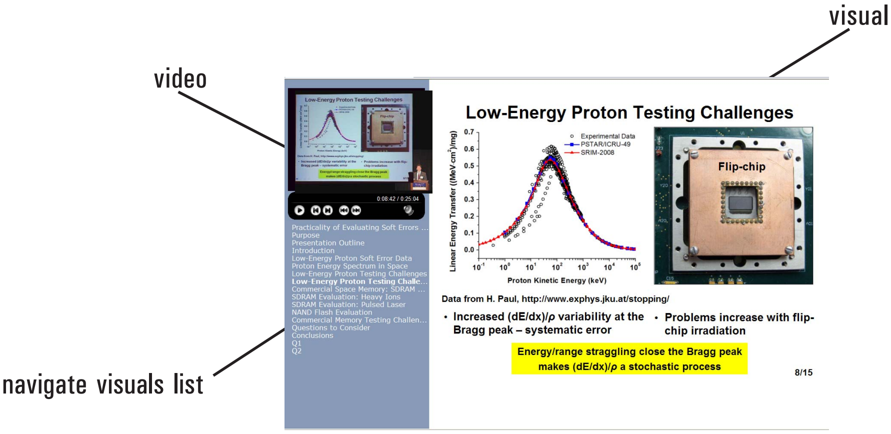

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Low-Energy Proton Testing Challenges

Data from H. Paul, http://www.exphys.jku.at/stopping/

- Increased (dE/dx)/ρ variability at the Bragg peak – systematic error
- Problems increase with flip-chip irradiation

Energy/range straggling close the Bragg peak makes (dE/dx)/ρ a stochastic process

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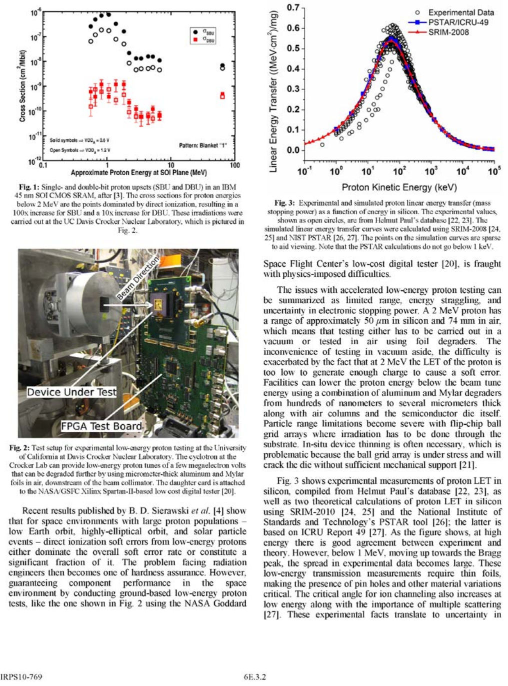

Fig. 1: Single- and double-bit proton upsets (SBU and DBU) in an IBM 45 nm SOI CMOS SRAM, after [3]. The cross sections for proton energies below 2 MeV are the points dominated by direct ionization, resulting in a 100x increase for SBU and a 10x increase for DBU. These irradiations were carried out at the UC Davis Crocker Nuclear Laboratory, which is pictured in Fig. 2.

Fig. 2: Test setup for experimental low-energy proton testing at the University of California at Davis Crocker Nuclear Laboratory. The cyclotron at the Crocker Lab can provide low-energy proton tunes of a few megaelectron volts that can be degraded further by using micrometer-thick aluminum and Mylar foils in air, downstream of the beam collimator. The daughter card is attached to the NASA/GSFC Xilinx Spartan-II-based low cost digital tester [20].

Recent results published by B. D. Sierawski *et al.* [4] show that for space environments with large proton populations – low Earth orbit, highly-elliptical orbit, and solar particle events – direct ionization soft errors from low-energy protons either dominate the overall soft error rate or constitute a significant fraction of it. The problem facing radiation engineers then becomes one of hardness assurance. However, guaranteeing component performance in the space environment by conducting ground-based low-energy proton tests, like the one shown in Fig. 2 using the NASA Goddard Space Flight Center's low-cost digital tester [20], is fraught with physics-imposed difficulties.

Fig. 3: Experimental and simulated proton linear energy transfer (mass stopping power) as a function of energy in silicon. The experimental values, shown as open circles, are from Helmut Paul's database [22, 23]. The simulated linear energy transfer curves were calculated using SRIM-2008 [24, 25] and NIST PSTAR [26, 27]. The points on the simulation curves are sparse to aid viewing. Note that the PSTAR calculations do not go below 1 keV.

The issues with accelerated low-energy proton testing can be summarized as limited range, energy straggling, and uncertainty in electronic stopping power. A 2 MeV proton has a range of approximately 50 μm in silicon and 74 mm in air, which means that testing either has to be carried out in a vacuum or tested in air using foil degraders. The inconvenience of testing in vacuum aside, the difficulty is exacerbated by the fact that at 2 MeV the LET of the proton is too low to generate enough charge to cause a soft error. Facilities can lower the proton energy below the beam tune energy using a combination of aluminum and Mylar degraders from hundreds of nanometers to several micrometers thick along with air columns and the semiconductor die itself. Particle range limitations become severe with flip-chip ball grid arrays where irradiation has to be done through the substrate. In-situ device thinning is often necessary, which is problematic because the ball grid array is under stress and will crack the die without sufficient mechanical support [21].

Fig. 3 shows experimental measurements of proton LET in silicon, compiled from Helmut Paul's database [22, 23], as well as two theoretical calculations of proton LET in silicon using SRIM-2010 [24, 25] and the National Institute of Standards and Technology's PSTAR tool [26]; the latter is based on ICRU Report 49 [27]. As the figure shows, at high energy there is good agreement between experiment and theory. However, below 1 MeV, moving up towards the Bragg peak, the spread in experimental data becomes large. These low-energy transmission measurements require thin foils, making the presence of pin holes and other material variations critical. The critical angle for ion channeling also increases at low energy along with the importance of multiple scattering [27]. These experimental facts translate to uncertainty in

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