Single Event Effect and Total Ionizing Dose Assessment of Commercial Optical Coherent DSP ASIC

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***Abstract*—Experimental assessment of commercial 100/200 Gbps optical coherent DSP modem ASIC completed with 64 MeV and 480 MeV proton radiation test campaigns. Single event effect cross sections calculated and no performance degradation observed for proton fluence levels up to 1.27×10^{12} p/cm^2 with equivalent total ionizing dose exposure to 170 krad(Si).**

I. Introduction

THE Inphi CL20010A1 is an optical coherent digital signal processing (DSP) application-specific integrated circuit (ASIC) modem. The ASIC is a monolithic, 28-nm complementary metal-oxide-semiconductor (CMOS) modem, which supports transmission and detection of 100 Gbps and 200 Gbps information rates with polarization-multiplexed differential and non-differential quadrature phase shift keyed (QPSK) or 16 quadrature amplitude modulated (16-QAM) signals. The CL20010A1 handles host and line framing/de-framing, soft-decision forward error correction (SD-FEC) encoding/decoding, and high-speed (~60 GSPS) analog input and output [1]. In addition, the receive channel performs high-speed DSP functions comprising polarization rotation, carrier phase recovery, and optical fiber dispersion compensation. There have not yet been published studies on space radiation testing and qualification of commercial optical coherent transceivers with DSP ASICs.

In this work, we experimentally investigated (i) the susceptibility of the CL20010A1 to single event effects (SEEs) and (ii) CL20010A1 performance for increasing levels of fluence and equivalent total ionizing dose (TID). The 64 MeV SEE and TID test campaign was performed at UC Davis Crocker Nuclear Laboratory (CNL), and the 480 MeV SEE testing was conducted at TRIUMF National Laboratory. Two identical systems with a CL20010A1 on custom evaluation board (EVK) were used for the study, one for each test campaign. The CL20010A1 ASICs on the EVK systems were from different lots. Prior to radiation testing, the nuclear modeling program, Stopping Range In Matter (SRIM) simulated protons penetrating a model of the CL20010A1 EVK and into the CL20010A1 silicon active region. The simulations determined that 64.0 MeV protons could penetrate through the ASIC active region with margin of ~20 MeV [2].

We intend for these results to be of use to the satellite and aerospace industries and to move forward Facebook's mission of connectivity.

II. Experimental Approach

A. Single Event Effect and Total Ionizing Dose Testing at Crocker Nuclear Laboratory Facility

SEE and TID measurements were performed at CNL using the custom EVK with the CL20010A1 ASIC and CFP2-ACO optical transceiver module. All radiation-sensitive commercial components were placed sufficiently far away from CL20010A1 on the EVK. Dynamic testing was conducted, in which the CL20010A1-EVK system was powered during operation.

The ASIC evaluation was performed in noise-loaded optical loopback test configuration (Figure 1). The transmit path was noise-loaded to set the optical signal-to-noise ratio (OSNR) level near the CL20010A1 receiver FEC correction threshold. This configuration represents the most stress for the optical transceiver system, because the optical communication link is signal-starved and the receiver is operating near the FEC threshold. The transmit and receive wavelengths of the CFP2 module were set to 1550.92 nm and transmit power to 0 dBm. The noise loading was accomplished by connecting the CFP2 module transmit output to a variable optical attenuator (VOA) followed by an erbium doped fiber amplifier (EDFA). The amplifier output was filtered with a 100 GHz optical band-pass filter (OBPF) centered at 1550.92 nm. The VOA attenuation was set to produce a pre-FEC bit error rate (BER) of 0.01. The OSNR at this BER is 1.6 dB higher than that required for BER of 0.02 which is the FEC "breaking" threshold.

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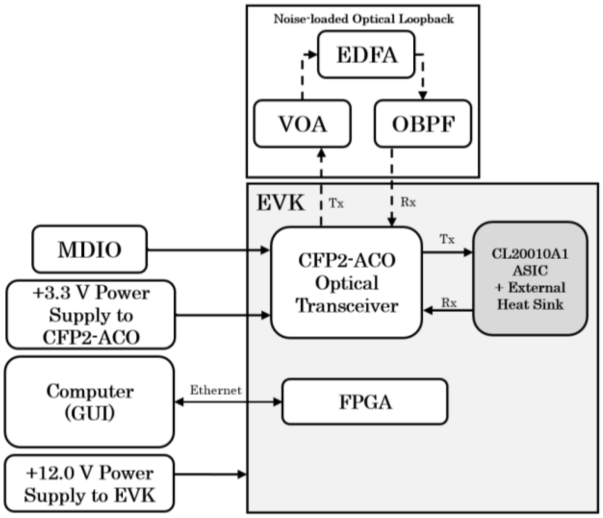

Fig 1. CL20010A1 SEE and TID experimental block diagram for CNL testing

The EVK setup at CNL is shown in Figure 2, with the bottom of the board exposed to the incident proton beam. A laser was used to align the center of the proton beam to the center of the ASIC.

Fig. 2. EVK proton irradiation test setup at CNL; (top) front side of board with CL20010A1 in top right corner and CFP2-ACO in top left; (bottom) irradiated back side of board and laser used for proton beam alignment.

At the beginning of each SEE test campaign, the proton beam was powered on and the start time recorded. The pre-FEC BER, the number of uncorrected FEC errors, the connection to the EVK, and power supply currents were actively monitored. The SEEs observed were partitioned into two types based on the following observed occurrences: 1.) EVK lost connection to CL20010A1 device and 2.) receiver loss of lock (LOL). After a SEE, the device did not autonomously recover functionality or lock, consequently the SEEs are considered single event functional interrupts (SEFIs). After detection of a SEE, the proton beam was powered off, and the average beam flux and end time stamp were recorded. The CL20010A1 was subsequently power cycled, which restored all pre-SEE functionality. The SEE test was then repeated until a total of 10 SEE data points were collected. During this SEE testing, the CL20010A1 was exposed to a total fluence level of 9.06 $\times 10^{9}$ p/cm^{2} with a cumulative TID level of 1,210 rad(Si).

After completion of SEE testing, performance of CL200010 ASIC was measured subsequent to irradiating with increasing levels of proton fluence or equivalent TID. During these irradiations, the system under test was powered and operated. After each round of equivalent TID testing, the CL20010A1 was power cycled and the noise-loaded optical system performance was thoroughly characterized: The pre-FEC BER was measured and recorded before and after irradiation. For the first five sets of equivalent TID testing, the proton beam current was set to 5 nA for five minute intervals, yielding fluence levels of ~1.7×10^{11} p/cm^{2} and equivalent TID of ~20 krad(Si) in each interval. The last round of equivalent TID testing irradiated the ASIC with the same beam current for a 10-minute interval, providing for additional fluence of ~3.8×10^{11} p/cm^{2} and equivalent TID of ~50 krad(Si). Hence, the ASIC was irradiated to a cumulative proton fluence of 1.27×10^{12} p/cm^{2} from all CNL testing for an equivalent TID of 170 krad(Si).

B. Single Event Effect Proton Test Campaign at TRIUMF National Laboratory

An identical EVK with CL20010A1 was used for proton testing at TRIUMF National Laboratory. In comparison to SEE testing at CNL, dynamic testing was conducted, in which the CL20010A1-EVK system was powered during operation. In contrast to the test setup at CNL, the EVK at TRIUMF used a Finisar ML4030 CFP2-ACO transceiver module in electrical loopback mode as the line-side interface, and the ASIC evaluation was not performed with noise-loading. The diagram of the test setup used at TRIUMF is shown in Figure 3.

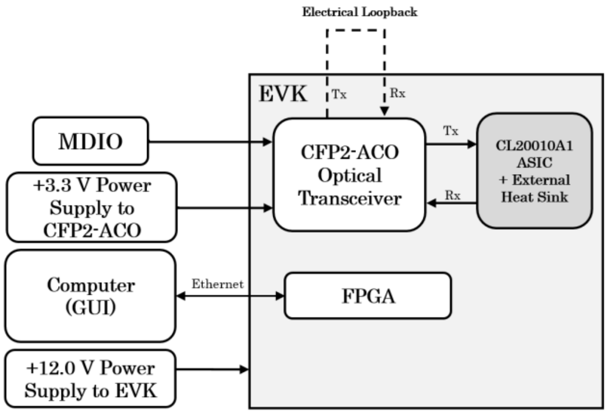

Fig. 3. CL20010A1 SEE experimental block diagram for TRIUMF testing

The EVK setup at TRIUMF is shown in Figure 4, with the bottom side of the board directly exposed to the incident proton beam, as in the CNL setup. The center of the proton beam was aligned to the center of the ASIC with a laser. A 1-inch by 1-inch square aperture was used to focus the proton beam to a size closely encompassing the ASIC on the EVK.

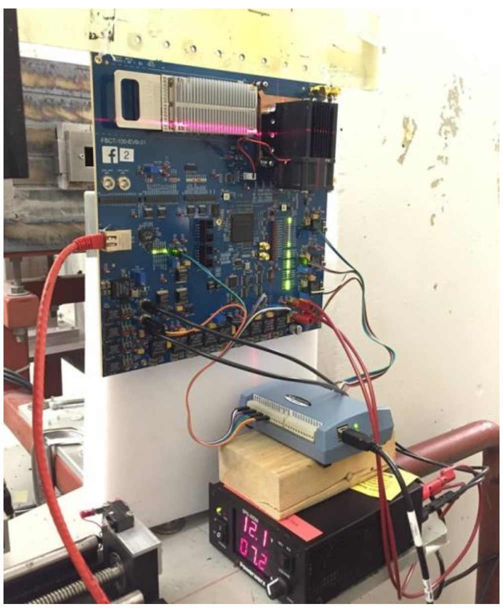

Fig. 4. EVK proton irradiation test setup at TRIUMF. Front side of board with CL20010A1 in top right corner and CFP2-ACO in top left. Laser used for proton beam alignment.

A total of 18 SEE data points were collected. A greater number of data points were collected from the TRIUMF test campaign since there were not time limitations with facility use as with the CNL test campaign. The DUT was exposed to a total fluence level of 4.71×10^{10} p/cm^2.

III. EXPERIMENTAL RESULTS

The specific type of SEE observed is a SEFI since power cycling of the system restored nominal functionality. No destructive SELs were observed. We observed slight increase (~2-3 Amps) in phase locked-loop (PLL) voltage rail current (DVDDH) during SEE occurrences, shown in Figure 5.

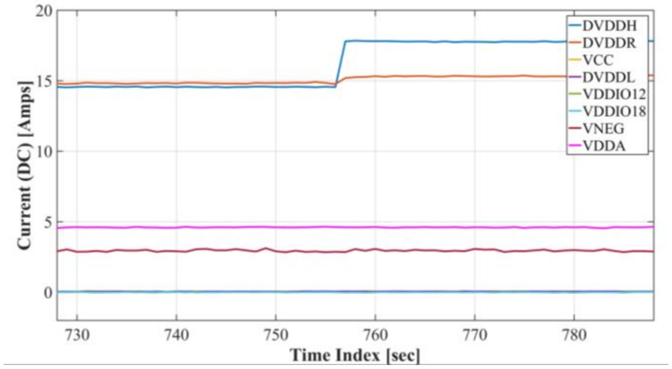

Fig. 6. Power supply current monitoring during SEE occurrences

Table I and Table II list the durations, average flux and accumulated fluence for each SEE test campaign at CNL with 64 MeV protons and at TRIUMF with 480 MeV protons, respectively.

TABLE I. CL20010A1 64 MeV Proton SEE Data – CNL

SEE Number	Time Duration [sec]	Average Flux [p/sec]	Fluence [p/cm^2]
1	183	3.23×10^6	5.91×10^8
2	26	3.20×10^6	8.32×10^7
3	13	3.20×10^6	4.16×10^7
4	422	1.24×10^6	5.23×10^8
5	195	1.85×10^6	3.61×10^8
6	26	1.85×10^6	3.07×10^7
7	65	1.86×10^6	1.21×10^8
8	407	2.47×10^6	1.01×10^9
9	144	2.36×10^6	3.40×10^8
10	409	2.36×10^6	9.65×10^8

TABLE II. CL20010A1 480 MeV Proton SEE Data – TRIUMF

SEE Number	Time Duration [sec]	Average Flux [p/sec]	Fluence [p/cm^2]
1	2103	3.43×10^6	7.21×10^9
2	690	3.43×10^6	2.37×10^9
3	171	3.43×10^6	5.87×10^8
4	333	3.43×10^6	1.14×10^9
5	265	1.37×10^7	3.63×10^9
6	122	1.37×10^7	1.67×10^9
7	54	1.37×10^7	7.40×10^8
8	550	1.37×10^7	7.54×10^9
9	41	1.37×10^7	5.62×10^8
10	177	1.37×10^7	2.42×10^9
11	196	1.37×10^7	2.69×10^9
12	87	1.37×10^7	1.19×10^9
13	334	1.37×10^7	4.58×10^9
14	12	1.37×10^7	1.64×10^8
15	388	1.37×10^7	5.32×10^9
16	36	1.37×10^7	4.93×10^8
17	240	1.37×10^7	3.29×10^9
18	114	1.37×10^7	1.56×10^9

The test data from both proton test campaigns were used to calculate the proton SEE cross sections. We assumed a Poisson distribution for the SEE cross section data to calculate the standard deviation. The CL20010A1 ASIC proton SEE cross section is $2.5(0.3)\times10^{-9}$ cm^2 at 64 MeV proton beam energy level and $3.8(0.9)\times10^{-10}$ cm^2 at 480 MeV proton beam energy level. The calculated SEE cross section values, based on proton energy level, are listed in Table III and plotted in Figure 6. The results are further discussed in Section IV.

TABLE III. CL20010A1 Proton SEE Cross Section Results

Proton Energy Level [MeV]	SEE Cross Section [cm^2]	Std. Dev. [cm^2]	Total Fluence [p/cm^2]
64	2.46×10^{-9}	3.49×10^{-10}	9.06×10^{9}
480	3.82×10^{-10}	9.00×10^{-11}	4.71×10^{10}

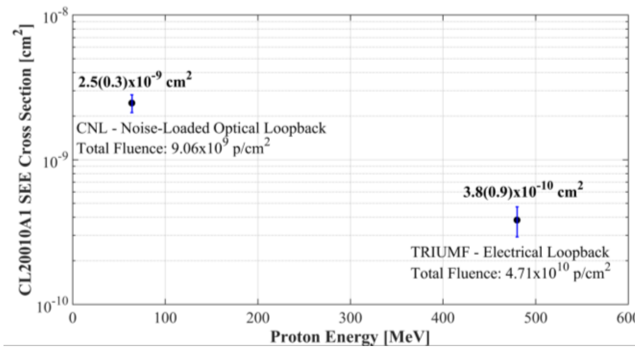

Fig. 6. CL20010A1 ASIC proton single event effect cross-section data

A. Proton Fluence Results

The summary of proton fluence runs is listed in Table IV. Following each run, the CL20010A1 had to be power cycled to restore operation. The pre-FEC BER was measured and used to assess any potential degradation in the transmit and/or receive paths of the ASIC. In particular, any degradation in the mixed-signal portion of the device would have degraded the signal quality and therefore the BER prior to FEC correction.

For all proton fluence test rounds, the pre-FEC BER remained below the set pre-FEC BER threshold of 0.01 from experimental setup prior to radiation testing (Figure 7). Thus, the ASIC maintained FEC performance throughout proton irradiation of equivalent TID levels up to 170 krad(Si) and total fluence levels up to 1.27×10^{12} p/cm^2 with 64 MeV protons, and no measurable degradation in performance was observed.

TABLE IV. CL20010A1 64 MeV Proton TID Data – CNL

Time Duration [sec]	Avg. Flux [p/sec]	Tot. Fluence [p/cm^2]	TID [krad](Si)	Avg. Pre-FEC BER
348	5.93×10^{8}	1.87×10^{11}	25.01	9.41×10^{-3}
300	5.56×10^{8}	3.57×10^{11}	47.71	9.41×10^{-3}
300	5.69×10^{8}	5.28×10^{11}	70.51	8.53×10^{-3}
300	5.75×10^{8}	7.01×10^{11}	93.61	8.53×10^{-3}
300	6.42×10^{8}	8.94×10^{11}	119.41	9.02×10^{-3}
600	6.22×10^{8}	1.27×10^{12}	169.31	9.11×10^{-3}

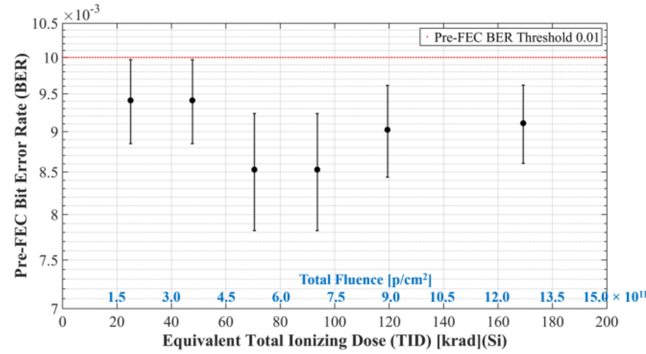

Fig. 7. CL20010A1 Pre-FEC BER versus Total Fluence and Equivalent TID

IV. DISCUSSION

The SEE cross section for 480 MeV protons is nearly an order of magnitude lower than for 64 MeV protons. These results differ from most devices, for which a higher proton SEE cross section is observed for higher proton energy levels.

There are several factors which could explain the SEE cross section results. Although CL20010A1 ASICs were used for both test campaigns, the ASICs were from different lots. ASICs from different lots could vary in SEE susceptibility. Identical EVKs were also used in each test campaign setup, and there could also be differences in the electrical characteristics based on variability in manufacturing the EVKs.

Different test configurations were used for the two test campaigns – the 64 MeV proton test campaign was conducted in noise-loaded optical loopback, while the 480 MeV proton test campaign was conducted in electrical loopback. The SNR into the receiver was low (intentionally attenuated near FEC threshold as described in Section IIA) in the noise-loaded optical loopback configuration, while the SNR was higher (no attenuation or noise-loading of signal) in the electrical loopback test configuration. The receiver DSP of the CL20010A1 has greater difficulty (*e.g.* draws greater current) with the noise-loaded optical loopback signal than with the "pure" electrical loopback signal. It is possible that the SEE rate is higher when the receiver input signal has much lower SNR.

In commercial CMOS circuit devices, proton-induced SEEs are typically dominated by secondary ions generated from nuclear collision events rather than by direct ionization [2]. Previous studies by Heidel et al. (2008), Cannon et al. (2010), and Guillermin et al. (2016) on proton-induced SEEs in CMOS technologies, specifically SRAMs, observe results consistent this work, where lower proton energy levels induce higher SEE cross section values in comparison to higher proton energy levels [2-4]. The three studies attribute the results of higher proton SEE cross sections for lower proton energy levels to direct ionization effects. Proton with energy exceeding the Bragg peak have a lower LET or stopping power for higher energy levels. Figure 8 shows the LET curve as a function of energy level for protons penetrating through silicon material. The Bragg peak energy level for silicon is 55 keV with LET 5.38×10^{-1} MeV/(mg/cm^2), and LET values decrease with proton energy for energies exceeding the Bragg peak. However, the three studies find that a significant number of SEEs are produced from direct ionization from protons relative to high energy collision events [2-4].

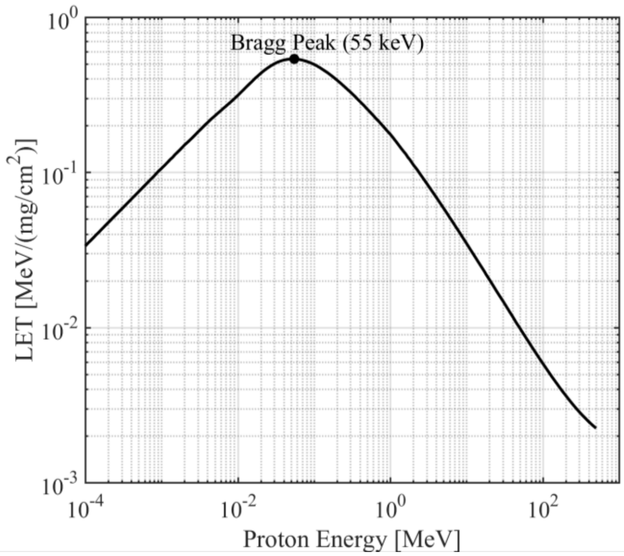

Fig. 8. LET versus energy curve for protons through silicon target material

The Cannon et al. (2010) study assesses proton SEE sensitivity of a 90-nm SRAM device. One proton test campaign in the study assesses an energy range from 0.6 MeV to 2.0 MeV at the Boeing Radiation Effects Laboratory (BREL). For proton energy levels less than 1 MeV, the cross section curve increased to a peak value at ~ 0.7 MeV then decreased for following energy levels to ~ 1 MeV. There was a slight increase in SEE cross section values for energy levels between 1 MeV to 2 MeV

In the Heidel et al. (2008) study, proton SEE sensitivity is assessed for a silicon on insulator (SOI) SRAM device. SEE data over a 1 to 500 MeV energy range was collected from proton test campaigns at 5 different accelerators [2]. Similar to the Cannon et al. (2010) study, the cross section data showed significant rise in SEEs approximately below the 1 MeV energy level [2,3]. Data collected from the CNL test campaign with the 14.6 MeV proton beam showed an increase in SEE cross section values between 10 MeV and 30 MeV. The cross section was also observed to slightly increase at around the 30 MeV level for proton test campaigns at TRIUMF and Northeast Proton Therapy Center (NPTC), and the cross section values tended to decrease as proton energy increased between 30 MeV and 100 MeV [2].

The CL20010A1 device contains an embedded processor, so the observed SEEs could be the result of SRAM errors causing this processor to hang. For a proton beam energy level of 64 MeV, CL20010A1-EVK SRIM model simulations predict that the proton energy level entering the CL20010A1 silicon active region would be ~50 MeV for the nominal case model and ~23 MeV for the worst case model (See Appendix, Table V). The worst case model represents the scenario of protons travelling through a path of copper-filled vias in the PCB. This energy remains substantially higher than the proton Bragg peak. Consequently, while possible it is unlikely that protons lost sufficient energy prior to entering the sensitive volume for direct ionization to be the primary explanation of the observed effect.

V. Conclusions and Future Work

We evaluated Inphi CL20010A1 commercial optical coherent DSP ASIC for SEE and proton fluence with equivalent TID effects through two proton test campaigns at CNL and TRIUMF. No destructive SELs were observed in both test campaigns. In the CNL test campaign the CL20010A1 was exposed to total fluence level of 1.27×10^{12} p/cm^2 (both SEE and equivalent TID testing), and in the TRIUMF test campaign, the CL20010A1 was exposed to total fluence level of 4.71×10^{10} p/cm^2 (SEE testing only). The measured CL20010A1 SEE cross section was $2.5(0.3)\times10^{-9}$ cm^2 at 64 MeV proton beam energy level in the noise-loaded optical loopback test configuration at CNL, and $3.8(0.9)\times10^{-10}$ cm^2 at 480 MeV proton energy level in the electrical loopback test configuration at TRIUMF. The CL20010A1 ASIC survived and experienced no performance degradation from a proton total fluence of 1.27×10^{12} p/cm^2 with an equivalent TID exposure up to 170 krad(Si) while tested in the noise-loaded optical loopback configuration with 64 MeV protons.

A greater number of proton energy levels is needed in both noise-loaded optical loopback and electrical loopback configurations to clarify the mechanisms involved in the SEEs. It is also important to complete heavy ion radiation testing of the CL20010A1 to evaluate SEEs caused by heavy ions from GCRs and solar flares. Protons undergo nuclear interactions, which then subsequently produce SEEs through direct ionization. In contrast, most heavy ion-induced SEEs are from direct ionization [6].

VI. Appendix

A. CL20010A1-EVK SRIM Analyses

Detailed calculations through all 24 PCB layers, ASIC ball grid array, and other packaging layers were performed to ensure the analysis of energy deposition in the active die was accurate based on the model of the CL20010A1-EVK. The CL20010A1-EVK system consisted of a total of 51 layers between the bottom of the board to the end of the CL20010A1 active region. The Transport of Ions in Matter (TRIM) module of the SRIM program is used to model the CL20010A1 behind the EVK PCB layers and packaging material and to analyze the energy level needed for protons to penetrate through the PCB and packaging layers prior to reaching the CL20010A1 silicon active region. Figure 9 shows the model of the integrated EVK system with CL20010A1 and displays the different layer components modeled in TRIM.

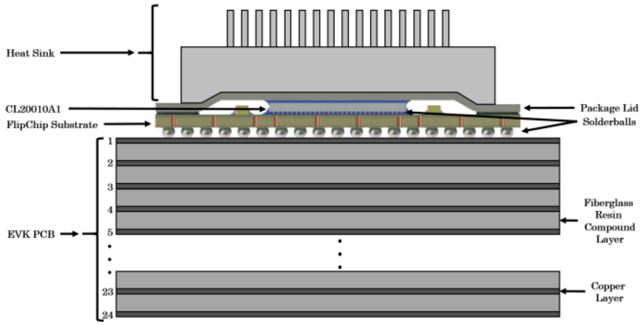

Fig. 9. Model of CL20010A1 between EVK and Heat Sink

The CL20010A1-EVK system modeled for the SRIM analyses in this work is not high fidelity due to the lack of proprietary information on material properties of the PCB and packaging material. With an assumed model, the proton energy level needed for the Bragg peak to occur in the CL20010A1 silicon active region cannot be accurately calculated. The CL20010A1 silicon active region layer is less than 1 mm thick, thus any slight deviations in the calculation could result in protons without sufficient energy to reach the target region. Overall, the SRIM analyses and simulations are focused on ensuring that protons have sufficient energy levels to penetrate through the CL20010A1 silicon active region in order to produce ionizing radiation effects.

Within TRIM, the calculation model "Detailed Calculation with Full Damage Cascades" is used. We simulate five thousand protons (H+ ions) with 64 MeV energy level penetrating through the modeled layers with TRIM. Two approaches are used to model the CL20010A1-EVK system with TRIM. In the first approach, the CL20010A1 ASIC-EVK system is modeled with all layers of the PCB, external solder balls, flip chip substrate, internal solder balls, and ASIC silicon die input to TRIM as an integrated system simulation. In the second approach, the system is modeled as individual layers with a simulation for each layer. For both approaches, we also conduct TRIM simulations for the worst-case scenario of protons travelling through a path of copper-filled vias within the EVK PCB. The results of these approaches are compared to ensure that a proton energy level of 64 MeV would be sufficient to reach the CL20010A1 active area. For both approaches, the calculated ionization energy levels at the end of the CL20010A1 active region are analyzed.

The SRIM simulation results showed that 64.0 MeV protons in the modeled CL20010A1-EVK system have ionization energy levels of ~ 20 MeV and ~48 MeV at the end of the active region in the worst case model and baseline model, respectively. An energy level of 45 MeV protons appears sufficient for protons to still reach the end of the active region. Table V shows the results of all SRIM simulations and analyses of the CL20010A1-EVK system models.

TABLE V. TRIM Simulation Results – Proton Ionization Energy Levels

Proton Ionization Energy Level	Integrated System Approach	Layer-by-Layer Approach	Worst Case Integrated System Approach	Worst Case Layer-by-Layer Approach
Penetrating CL20010A1 Active Region	50.22 MeV	49.97 MeV	23.30 MeV	23.43 MeV
End of CL20010A1 Active Region	48.40 MeV	48.16 MeV	19.87 MeV	19.99 MeV

VII. Acknowledgment

The authors are grateful to Martin Serra of Inphi Corporation for helpful discussions.

VIII. References

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