NSQN Electronic Irradiation Facilities Accessible at ANSTO

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1. Introduction

The NSQN has significant irradiation facilities accessible through ANSTO to irradiate electronic chips for the space applications. The combinations of ion beam, gamma-ray, and x-ray sources allows a broad range of space radiation environments to be simulated.

Centre for Accelerator Science (CAS) – Four high voltage (1MV to 10MV) accelerator systems are available for heavy ion irradiations, for ions from protons to uranium. These accelerators can produce particle rates from single ions/sec to currents of several microamps. The 10MV ANTARES external beamline irradiation facility (EBIF) allows for the scanning of these ion beams with micron-sized spots across several millimetres of an electronic chip in ambient air. The range of ions available and their typical dose rates delivered to silicon chips from CAS accelerator facilities are shown in Table 1.1.

Table 1.1. Typical ions and the dose rates delivered to silicon chips available at CAS.

Ion	E MeV	Range (µm)	LET MeVcm^2/mg	LET keV/µm	Ion Charge	I(pA) into 25mm^2	Dose Rate Gy/min
proton	5	216	0.059	13.6	1	1	15
	7	383	0.046	10.6	1	1	11
	9	591	0.038	8.8	1	1	9.2
	15	1440	0.025	5.9	1	1	6.3
He	5	24	0.61	141	2	1	73
	10	70	0.39	90.3	2	1	47
	15	134	0.29	67.5	2	1	35
	20	217	0.24	54.5	2	1	28
C	20	20.0	3.82	887	4	1	260
	30	32.1	3.23	750	5	1	175
	60	82.1	2.14	497	5	1	107
	80	127	1.73	402	5		87
Cl	30	9.8	17.2	3992	5	1	826
	50	14.7	15.3	3551	6	1	612
	100	27.8	15.4	3574	7	1	528
Fe	50	11.8	27.1	6290	7	1	767
	100	19.3	29.3	6801	7	1	961
	120	22	29.3	6801	7	1	997
I	50	11	33.2	7706	10	1	797
	80	14	41.2	9563	12	1	824
	150	21	53.6	12441	14	1	919
Au	50	10	31.7	7358	12	1	634
	100	15	50.5	11722	14	1	866
	150	19	62.2	14437	16	1	933

These data assume the electric chip is decapped and 1pA of ion current irradiates 25mm^2 area of the chip. The dose rates (Gy/min) are indicative estimates only and assume the ion beam traverses a 1µm Si_3N_4 window into an air gap of between 5-10mm before hitting the chip front surface.

- ANSTO's Centre for Accelerator Science delivers sophisticated (level 3) testing to mimic
- cosmic ray generation of SEEs available with:
- Rapid exposure times (seconds – minutes)
- Precision beam control for targeted irradiation down to 0.001mm spots or scanning
- over wide areas of several mm's
- Customised irradiation conditions (energy, depth, dose, area)
- Component under vacuum or at atmospheric pressure

GATRI – Is a Cobalt-60 gamma-ray facility. It is a recognised and accredited gamma irradiation system, providing MeV energy photons for the irradiations of electronic circuits. Two internal facility options are available, depending on size of the device under test and the desired dose rate required: The GATRI pool, suitable for larger electronic systems with a 1m by 1m ^{60}Co source, and the Gammacell tank, for smaller circuit boards and individual chips less than 15cm by 20cm. ^{60}Co emits two gamma rays of 1.1732MeV and 1.3325 MeV with an average energy of around 1.253 MeV. Typical dose rates in silicon for the GATRI and the Gammacell at ANSTO are shown in Table 1.2.

Table 1.2. Typical dose rates available at the GATRI and Gammecell facilities at ANSTO.

Facility	Eγ (MeV)	LET MeVcm^2/mg	LET keV/µm	Dose Gy/min
GATRI	1.253	3.23E-05	7.50E-03	5.56
Cell	1.253	3.33E-05	7.73E-03	8.99

These dose rate data assume the chip is not decapped and the irradiated area is 25mm^2 at 680mm from the source. ^{60}Co has a half life of 5.2714 years and the equivalent flux for GATRI on 21 September 2022 was $9.17*10^7$ gammas/mm^2/sec at 680mm. For the Gammcell the equivalent flux was $1.48*10^8$ gammas/mm^2/sec on 1 April 2022.

- Most basic standard radiation test (level 2)
- Well-established international standards (eg. ASTM-F1892, MIL-STD-883F)
- Requires cobalt-60 irradiation facility of sufficient intensity
- ANSTO has one of these (GATRI) and the expertise to run it

Synchrotron A 3GeV synchrotron with an Imaging and Medical Beamline (IMB). A broad spectra of x-ray energies from 20 keV to 100 keV are available, with tuneable fluxes and beam sizes from 0.1mm by 0.1mm to 25mm by 100mm. Together, these provide standard Total Ionisation Dosage (TID) and Single Event Effects (SEEs) radiation testing, for Australian space-qualified products with typical dose rates applicable to space irradiations.

Table 1.3. Typical dose rates in silicon for x-ray irradiations at the Australian synchrotron.

Ex (keV)	LET MeVcm^2/mg	LET keV/µm	Dose Gy/min
20	8.19E-05	1.90E-02	251
40	2.13E-05	4.94E-03	161
60	9.69E-06	2.25E-03	84

These dose rate data in silicon assume that the electric chip is not decapped, the x-ray flux is $1.0*10^{10}$ x-rays/mm^2/sec and the irradiate area is 25mm^2.

- Allows high-spatial resolution irradiation of single component regions or entire circuits
- without requiring component de-capping
- Offers the possibility of SEE-like testing on intact circuit boards – suitable for hardware
- redundancy and software testing
- Adjustable intense mono-chromatic x-ray beam allows either imaging or dose delivery

Dose Modelling and Calibration – The modelling and calibration of LET and dose rate for each individual facility can be performed using CERN's GEANT4 modelling suite. GEANT4 is a Monte Carlo simulation package which provides the expected outcomes based on stochastic radiation-particle interactions. Basic in-house FORTRAN codes were also generated which provide reasonably accurate results in a fraction of the computing time (couple of seconds), compared to full GEANT4 Monte Carlo simulations.

Electronic Chip Decapsulation – CAS procured an acid jet decapsulation system to improve its irradiation of commercial off-the-shelf (COTS) chips. The Nisene JetEtch Pro CuProtect is capable of exposing the die and bond wires of most plastic integrated circuit (IC) packages. It does this by pre-heating the chip and selected acid mixtures, before jetting the hot acid directly onto the surface of the chip above the die. This acid dissolves the plastic encapsulation, which is flushed away with the waste acid, exposing the die below. This process leaves the chip and its die in a fully functional state.

2. CAS – ANTARES Ion Capabilities

The external in-air beamline facility on the 10 MV ANTARES accelerator is shown in Figure 1. This beamline and its corresponding chamber have been purposed designed to irradiate single decapped electronic chips and smaller circuit boards (up to 10cm by 10cm) with high energy protons, light ions, and heavy metallic ions. Typical LET and ion ranges in silicon for most ions available at CAS facilities are shown in Figure 2, with ion species and energies which have currently been tested under the SIF project shaded in blue/grey.

Figure 1 Antares external beamline chamber overview

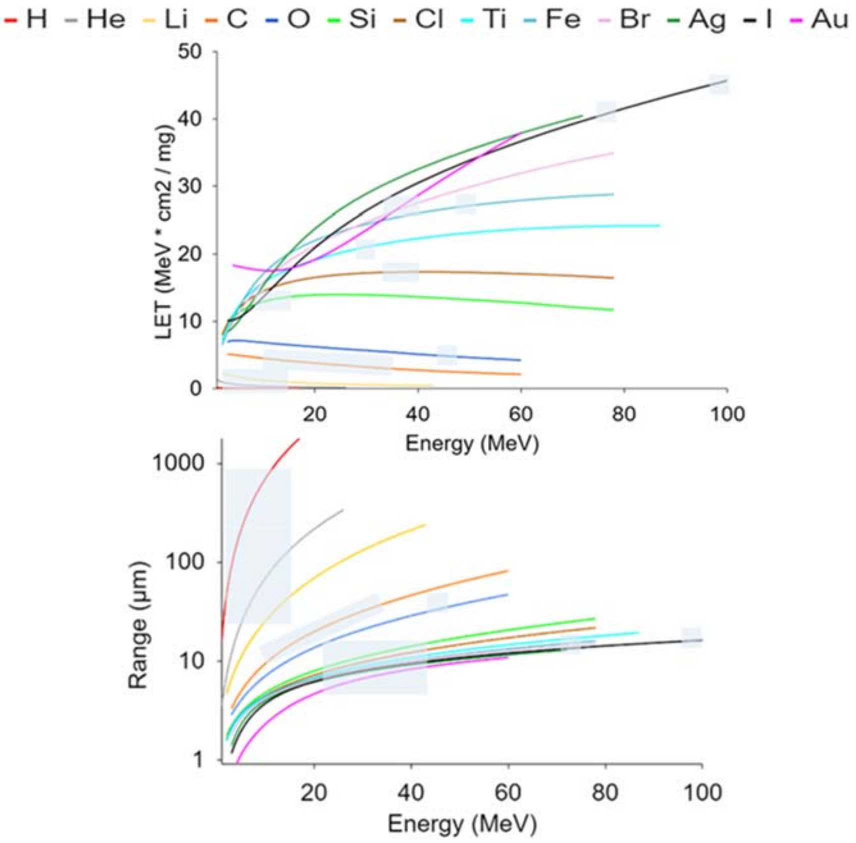

Figure 2 A selection of the potential ion species and energies available on the Antares accelerator. Vertical axes are linear energy transfer and range in silicon. Blue shaded areas represent conditions already tested.

3. Gamma Irradiation at the GATRI Facility

ANSTO’s Cobalt-60 GATRI facility has the capability to irradiate space payload circuits for (level 2) total ionizing dose (TID), in both offline and online testing. The critical processing parameters; dose, dose rate and temperature conditions are to be agreed with the user prior to testing.

Other considerations are to understand the specific component in the device that is to be tested under gamma irradiation, e.g. a circuit board that is potentially sensitive to ionising radiation. The circuit board may be encased inside a container or device, in which case knowledge of the materials that make up the device is required. GEANT4 simulation of the radiation doses in the device may be required to understand the impact on dosimetry.

When irradiating thin materials such as circuit boards, an absorbing material is used to surround the circuit board to provide approximate electronic equilibrium. High density polyethylene (HDPE) sheets 5mm thick are used for this purpose.

3.1. GATRI Pool

ANSTO’s Gamma Technology Research Irradiator (GATRI) facility consists of 100 individual cobalt-60 sources arranged on a rack of dimension approximately 1 square metre. Measurements have been made along the central beam axis, from 0 to 1900 mm from the source screen at 100 mm increments. This data (Figure 3) is regularly used to inform an appropriate source to sample distance for a specific dose rate requirement. Figure 4 is for dose rates in water calibrated in November 2021 and the half life of ^{60}Co is $T_{1/2}$=5.2714 years so time corrections need to be made. To make dose corrections for targets other than water the mass attenuation coefficients for MeV gammas in water and the target must be known.

Offline testing of electronics is performed outside the irradiation zone post-irradiation. The source rack is stored in a 5m deep pool of water and is raised to irradiate materials once the room has been evacuated and sealed. For online testing, the real-time monitoring of the device under irradiation is possible by passing cables from the device to the monitoring station via ports in the radiation shield. Any cables to the device need to be at least 5 m long. A section of this cabling (less than 2m) would be exposed to the radiation. Partial shielding of this cabling should be considered as part of the irradiation plan.

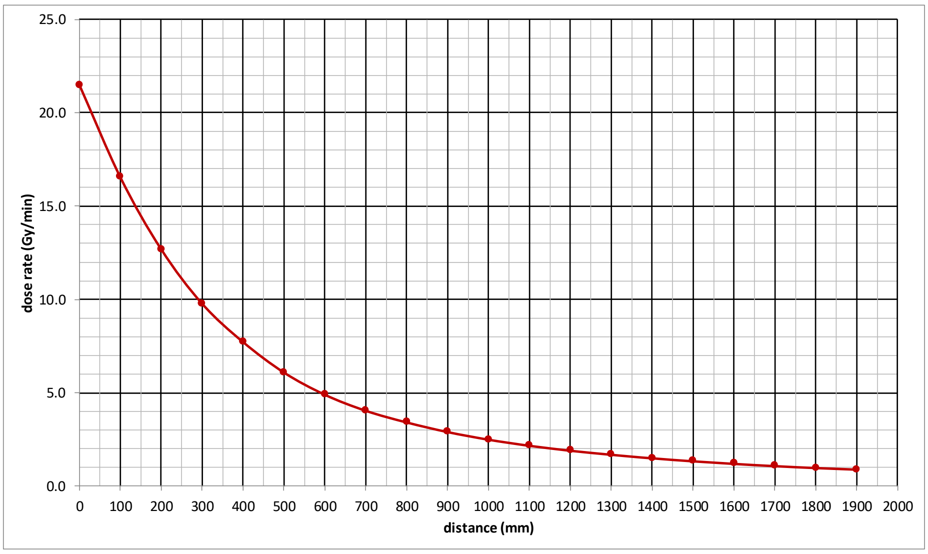

Figure 3 Dose rate (centre of field) as a function of distance from the source screen (Nov 2021)

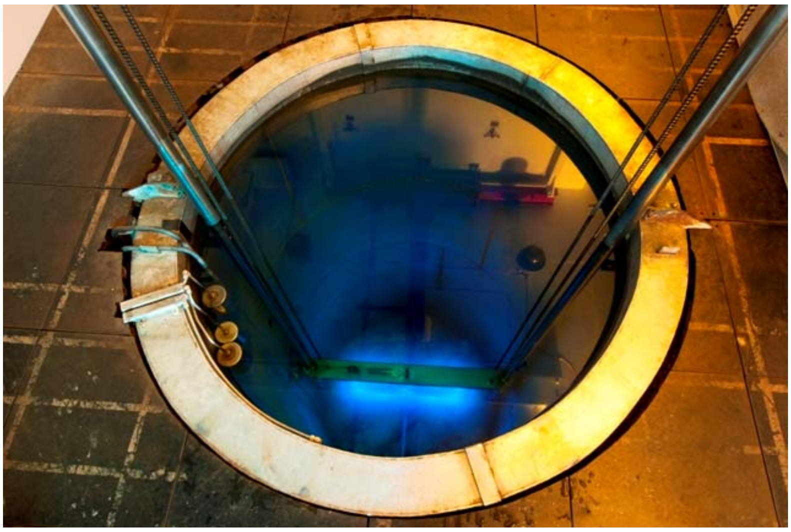

Figure 4 Looking into the GATRI pool from ground level. The blue light is emitted by the Co-60 sources.

3.2. Gammacell

Also within the GATRI facility is a fully self-contained research irradiator designed, providing a field of high-intensity gamma irradiation without additional shielding requirements for safe operation. It houses the 24 linear Cobalt-60 sources equally spaced in a stainless-steel rack to form a radioactive cylindrical shell of 20.9cm in diameter. The nominal dose rate is around 550Gy/hour but decreases over time due to the decaying radioactivity of the sources. Unlike the GATRI pool, the dose rate in the Gammacell cannot be varied, as the samples are placed in the centre of the cylindrical drawer before being lowered into the radiation field (Figure 3). Additionally, maximum sample dimensions are much smaller, with the sample chamber having an internal diameter of 15.2cm and internal height of 20.6cm. Offline testing is performed in an identical manner to that of the GATRI pool. Online testing is much easier to perform, requiring only two metres of cable to connect the DUT to the microcontroller.

Figure 3 Gammacell 220 gamma irradiation tank

4. X-ray Irradiation at the Australian Synchrotron

X-ray irradiation of the selected COTS chips was also performed on the Imaging and Medical Beamline (IMBL) at the Australian Synchrotron in Clayton, Melbourne. The standard electronics system outlined in Section **Error! Reference source not found.** was duplicated and sent to IMBL staff. The use of identical equipment and chips bearing the same batch numbers allowed for direct comparison between the facilities. The custom irradiation board is shown mounted in the IMBL holder in Figure (a), with the laser positioning system visible.

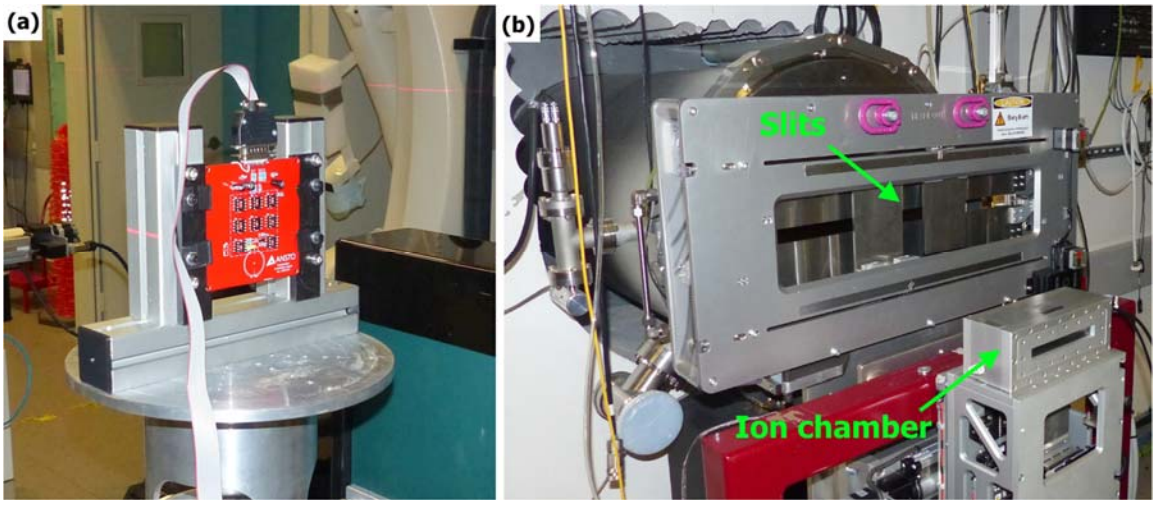

Figure 6 (a) Custom irradiation board held in the path of the x-ray beam at the Australian Synchrotron and (b) beam exit point with variable width slits and ion chamber

4.1. Profile Monitoring

The IMBL houses in-air ionisation chambers which are invaluable for monitoring the beam intensity during irradiation (Figure 6 (b)). They can also be used as approximate dosimeters if a range of correction factors are known. These factors are used to calculate the energy deposited by the beam in air (air KERMA) given the measured current. Most correction factors are close to 1.0 and can be ignored for dose approximation. However, the electron loss factor (K_e) is not insignificant for the x-ray energies used on IMBL. This factor is not trivial to derive analytically, so a Monte Carlo calculation is usually used. Previously, our colleagues at ARPANSA built a general model of ionisation chambers using the EGS4 Monte Carlo framework. Some values for K_e were calculated for one of the types of ionisation chamber used on our beamline. Recently the IMBL science team has taken over development of a similar model using the GEANT4 framework. This has been used within the SIF project to calculate K_e for our other ionisation chamber model. A close match between the EGS4 and GEANT4 calculations for the same model parameters verifies the new model is working well.

The in-line ionisation chambers can remain in the beam during testing to monitor the dose rate over time with minimal effects on the photon flux. For more accurate dosimetry, a commercial x-ray dosimeter system has been purchased. This will be used during the set-up procedure to verify the beam dose rate. Although this dosimeter cannot be in place during the irradiation run the IMBL beam is very stable so little change will be experienced during switching or over the period of the testing. One advantage of using the Synchrotron beamline for NSQN work is that the beam used for irradiation is monochromatic. This means that if the air KERMA rate is known, the dose rate can be readily converted to incident x-ray flux. The calculation of dose deposition within the chip or circuit structure is thus simple to calculate. Another advantage of the IMBL is a pair of collimating slits (Figure 6 (c)) which can produce an accurate rectangular beam from 0.1 mm by 0.1 mm to 25 mm by 100 mm.

Figure 7 The PTW UNIDOS Romeo electrometer provides accurate dose rate measurements of the photon beams

4.2. Imaging and laminography

Another advantage to using x-ray induced radiation failure testing is the ability to perform radiography simultaneously. The IMBL is specifically designed for this technique. Planar radiographs are useful for pre-irradiation alignment and for confirmation of the position and size of the die (Figure 8 x-ray image of a 47L16 EERAM. The die and the bond wires leading to the die are clearly visible. Figure , but 3D computed tomography can be generated for more detailed depth/dose determination. The flat geometry of circuit boards and integrated circuits does not lend itself to standard tomography protocols; in CT the object is required to rotate through 180 degrees. The geometric high aspect ratio means raw projection images have a very large dynamic range, typically high enough to limit reconstruction fidelity. The usual method used to image such planar objects is to tilt the rotation axis angle in the direction of the beam. The laminographic reconstruction of such a dataset provides a limited range of reconstructed planes around the pivot point, though this is still able to provide good geometric information about the internal structure. One disadvantage is that a full laminography collection requires a long enough duration such that the radiation dose may be significant compared to the radiation hardness of the device. We have collected several data sets with one of the test ICs to determine how much detail can be derived from a laminography reconstruction and with what dose.

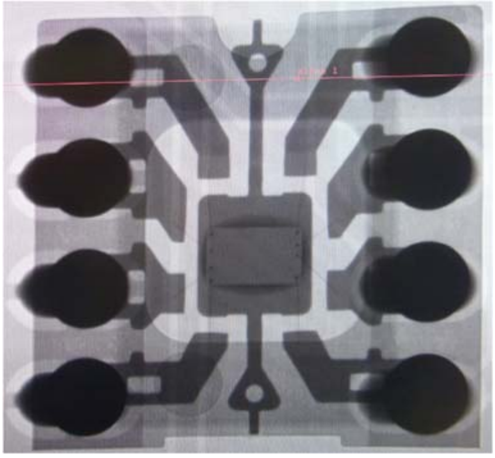

Figure 8 x-ray image of a 47L16 EERAM. The die and the bond wires leading to the die are clearly visible.

An alternative, lower dose collection protocol is possible using another technique: tomosynthesis. In this sparse laminography analysis, a series of images are collected with a limited range of angles of the chip or circuit, with the rotation axis parallel to that of the images. Similar to laminography, this data can be reconstructed to provide a set of central image planes with minimal artefacts (Figure). This technique provides better than 1% accuracy on the depth of easily visible features in the integrated circuit, but there exists a compromise between the image quality and the absorbed dose. However, initial indications are encouraging, so there is potential for this to become a standard data set collection for any irradiation tests.

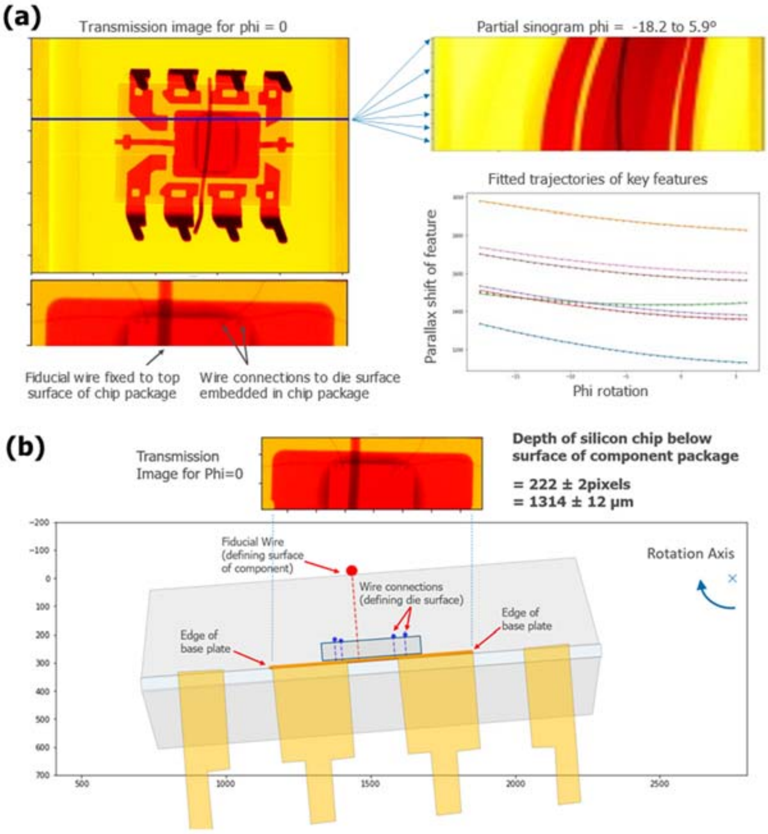

Figure 9 Sparse laminography analysis (a) sinograms from this data set can be analysed to obtain the pivot position of a limited tilt data set and (b) the result of sparse laminography analysis, showing the calculation of component depth to high accuracy

5. Decapsulation System

5.1. Installation and setup

The Nisene JetEtch Pro CuProtect decapsulation system (Figure) has been installed within a fume cupboard in an ANSTO chemistry laboratory. The CuProtect model was chosen for its feature which provides improved preservation of copper bond wires during decapsulation. 69% nitric acid and 96% sulfuric acid were acquired as chemical etching reagents. An ultrasonic cleaner was also obtained to assist with the cleaning of debris from the etched chips.

Figure 10 Nisene JetEtch Pro CuProtect installed within a fume cupboard

5.2. Decapsulation process

There are a multitude of runtime parameters to consider based upon the many factors that affect the etching of individual chips (Figure (a)). These factors include the ratio of the die size to its package size, the thickness of the encapsulation, encapsulation composition, the number of bond wires, bond wire metal composition, and so forth. Samples with gold bond wires can be etched with quicker more aggressive formulas, whereas copper bond wire chips require more care, time, and additional settings. Every chip had a pocket (Figure (b)) machined into it by a CNC machine prior to acid decapsulation (to a target depth of ~250µm above the die surface), allowing the duration of the acid etching process and thus the quantity of consumed acid to be minimised.

The following formula is suggested as a starting point for each chip (unless it is known to have Cu bond wires) and should be altered iteratively as the effectiveness is recorded (NOTE: etch times listed are for PDIP packages, other packages may require less time). Acid ratio of nitric (90%) to sulfuric (98%) 3:1, 60°C, 100 s warm-up time, 120 s etch time, 3 mL/min flow rate. Etched samples should be immediately rinsed with a jet of acetone afterwards (Figure (c)). If the die was not fully exposed by the first run, subsequent runs should have different durations if etching was observed, or a more aggressive formula attempted if minimal etching occurred. If the sample was observed to have copper bond wires the following etches should begin with a greater ratio of nitric acid, lower temperatures, longer etch times, and a bias voltage applied to the legs of the chip. An initial formula of nitric to sulfuric 4:1, 60°C, 180 s etch time, 2 mL/min flow rate, and a 15V bias applied across the chip is suggested. Figure shows additional decapsulated copper and gold bond wire chips.

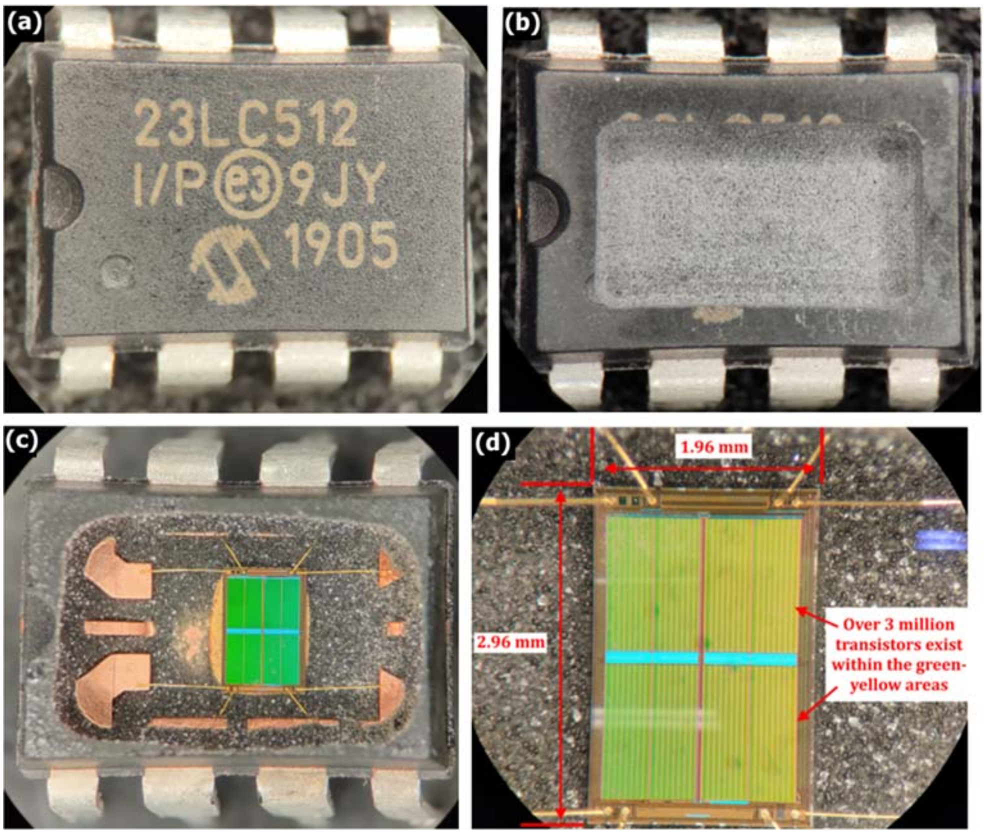

Figure 11 SRAM 23LC512 decapsulation sequence. (a) COTS chip codes on top surface, (b) mechanically etched pocket, (c) acid etched pocket showing exposed die, and (d) close up of the die with dimensions annotated

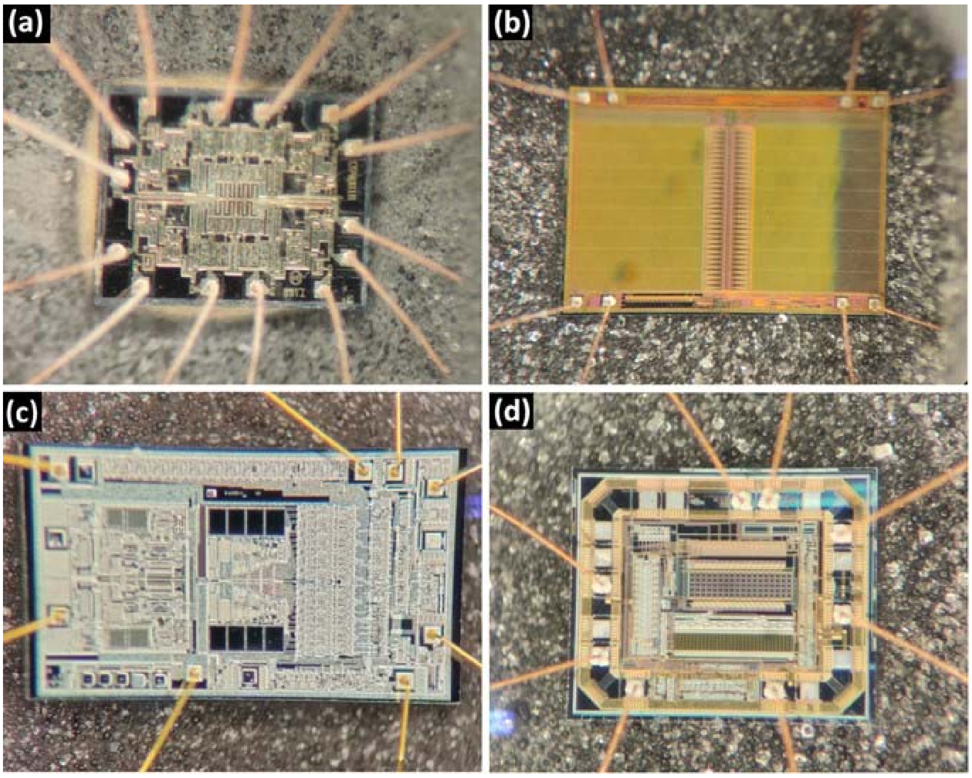

Figure 12 Other decapsulated dies (a) CMOS Logic CD4001BE and (b) SEEPROM 24LC512, (c) DAC MAX517, (d) and ADC MCP3202