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X-Ray Effects on Intersil FGA References

Introduction and Background

The Intersil Floating Gate Analog (FGA) technology utilizes a robust stored charge technology borrowed from a standard EEPROM process to produce a precise reference voltage. The stored voltage is the heart of a highly accurate precision voltage reference product. The resulting voltage reference has excellent characteristics which are unique in the industry; very low temperature drift (1ppm/°C), high initial accuracy, and extremely low supply current (<1µA). Also, the reference voltage is not limited to "magic" voltages obtained from bandgap references or buried Zener diodes to achieve temperature drift cancellation.

The floating gate storage cell requires two tunnel diodes to inject charge into a storage capacitor (see Figure 1). The tunnel diodes require high voltage, >10V, to turn on and when unbiased have extremely high impedance and essentially zero charge leakage.

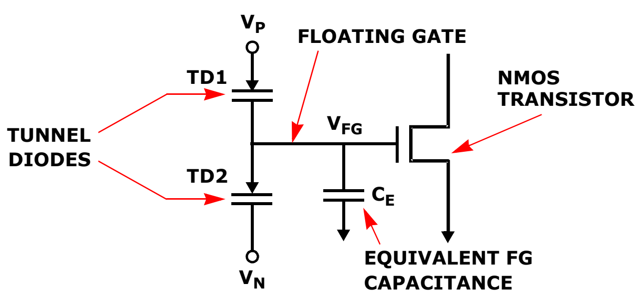

FIGURE 1. FLOATING GATE CELL

The actual voltage reference circuit contains two of the floating gate capacitors and an op amp (see Figure 2). One capacitor sets the common mode voltage and the other sets the output reference voltage. The switches shown in Figure 2 are the tunnel diodes and the V_{CM} and V_{REF} shown are external voltages applied to program the cell at factory test. The output reference voltage is the difference between the common mode and reference capacitors, which allows output voltage flexibility and adds temperature compensation.

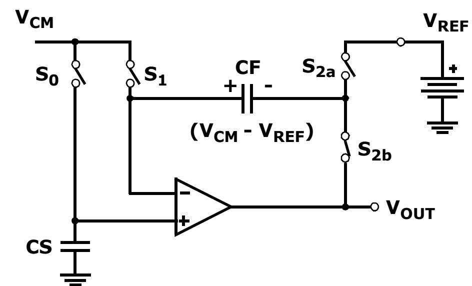

FIGURE 2. FLOATING GATE REFERENCE CIRCUIT SHOWN IN STABLE V_{OUT} STATE

The resulting circuit is highly stable, and the supply current is entirely dependent on the op amp, which can be extremely low current (<1µA) for low power or higher current for low noise applications.

X-Ray Radiation Effects on FGA References

The floating gate capacitor is susceptible to radiation degradation from various particles and photons in excessive doses, as the electrons generated in the silicon dioxide are collected in the storage cell[6]. Normal radiation from cosmic rays or radon which exist in small amounts on earth will not cause the FGA reference voltage to drift appreciably for over 100 years. Artificial sources of radiation such as X-ray machines are capable of high enough doses to cause output voltage shift. Note that Flash memory devices are also susceptible to X-ray radiation degradation, although to a lesser degree as they are not precision analog devices.

Specific threats for X-ray radiation include PC board post-assembly inspection and airport luggage screening. Lesser threats include medical X-ray machines and airport carry-on X-ray.

Some X-ray sources and their equivalent radiation dosage are listed as follows:

- Chest X-ray: 20mrem
- Dental bite-wing X-ray: 140mrem
- Airport carry-on screening: 5mrem to 45mrem
- Airport luggage examination: 5mrem to 2000mrem
- PC board post-assembly inspection X-ray: Typically 10mrem to 200mrem, but due to long observation times can be as high as 700mrem.

X-ray equipment uses 3 main variables to control exposure and therefore dose: tube voltage (usually kV), tube current (usually 10µA to 1mA) and time of exposure (anywhere from <1 second to many minutes). For voltage and current, the larger the number the higher the intensity, and for any of these variables, the larger the number the higher the resulting dose, with other variables fixed. Another variable is the distance from the X-ray emitter to the target or subject. The further from the emitter the less intensity, by $1/\text{distance}^2$.

For the purposes of the X-ray effects on FGA references, the main sources we will cover are the Post-Assembly PC Board examination and the Airport screening. Some testing has been completed using assembly X-ray machines and airport X-ray machines with the results presented here.

Intersil FGA X-Ray Testing and Results

Intersil performed testing on FGA reference devices to determine dose levels and output voltage shift for X-ray exposure. The equipment used included the following:

- X-Ray Machine: CR Technology, Bench Top 125, Real Time X-Ray. Voltage Range: 35kV to 125kV, Current Range is 10µA to 1000µA.
- Dosimeter: RAD-60 by Rados. 55kV to 1MV, 0.1mrem to 999mrem ranges.
- Devices used: ISL21009-50 (5.000V reference) from production stock, no special flow. One device set aside as a control.
- Multimeter: Agilent 3458A.

X-Ray Dose Characteristics

First, the dose from a typical X-ray exposure level was recorded at different exposure times and distances. The results are shown in Figures 3 and 4.

Figure 3 shows the dose is largely proportional to time, and after one minute at 1” distance a dose of 1680mrem was received. Figure 4 shows the dose varies inversely with distance squared, similar to other radiated sources.

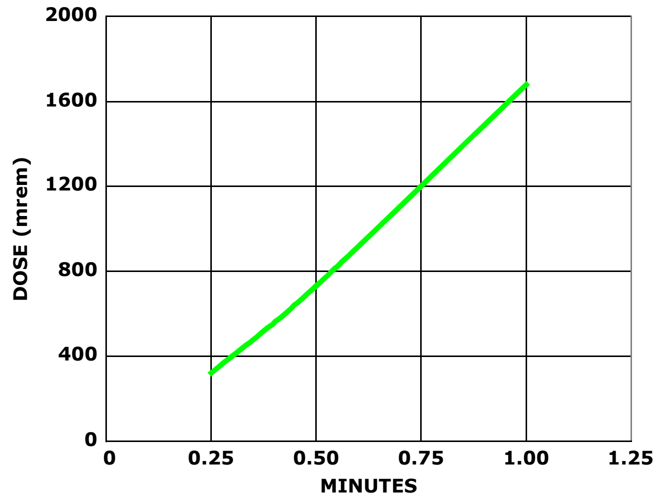

FIGURE 3. DOSE vs EXPOSURE TIME, EXPOSURE = 55kV, 70µA, DISTANCE = 1”

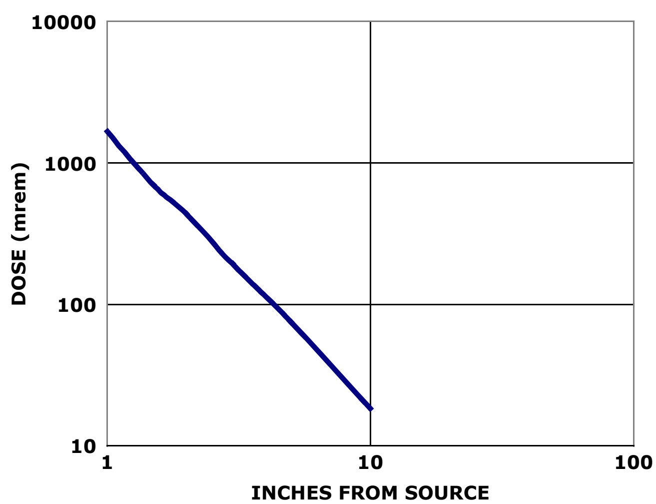

FIGURE 4. DOSE vs DISTANCE, FIXED TIME = 1MIN, LOG-TO-LOG SCALE

Output Shift vs X-Ray Dose Testing

A group of 5.0V reference devices were datalogged and individual devices were exposed at a given intensity (55kV and 70µA), at 10” distance with various time periods to vary the received dose. The devices were mounted on the dosimeter to closely approximate the dose received by the FGA. A control device was included to monitor any other shifting or measurement changes, and the control device data is used to adjust the other V_{OUT} Delta results. Table 1 contains the results.

TABLE 1. V_{OUT} SHIFT vs X-RAY DOSE FOR 5V REFERENCE

DEVICE	EXPOSURE DURATION (min)	X-RAY DOSE (mrem)	V_{OUT} DELTA (µV)	DELTA (µV/mrem)	DOSE RATE (mrem/min)
41	1	20.9	-1250	-59.81	20.9
42	2	41.6	-2529	-60.79	20.8
43	3	63.6	-3696	-58.11	21.2
44	4	82.7	-5281	-63.86	20.7
45	6	126.0	-7784	-61.78	21.0
50	None	Control	-57		

Average = -60.87004µV/mrem

TABLE 2. SHIFT vs V_{OUT}

DEVICE	BEFORE X-RAY	AFTER X-RAY	X-RAY DOSE (mrem)	DELTA (µV)	DELTA (%)	EXPOSURE DURATION (MIN)	X-RAY SETTING (kV/µA)
42	4.99991	4.99739	41.6	-2529	0.05	2	55/70
A1	2.50008	2.49918	40.0	-905	0.04	2	55/70
27	5.00006	4.99847	389	-1589	0.03	2	100/30
A2	2.50011	2.49922	416	-887	0.04	2	100/30

The output voltage change with dose did turn out to be a constant, approximately 61µV per mrem (results are dependent on the dosimeter used). Note that 1 minute of X-ray at this level will result in -1.25mV of shift, which placed the voltage reference output well out of spec for accuracy, as specified in the datasheet.

Output Voltage Shift vs Output Voltage

To determine the effect of the actual programmed output voltage, devices from the same product family with different output voltages were exposed to similar doses and the results recorded. For this test, the ISL21009-2.5 and the ISL21009-5.0 were used. Results are shown in Table 2. Two different X-ray settings were used to make sure there is no intensity dependency as well as voltage dependency.

The shift is proportional to the program output voltage, and is constant as a percent of output voltage.

For the lower voltage devices this means less voltage change for the same dose, which could help in some applications where it may be possible to use a much lower voltage.

Filter Testing

For any of the X-ray exposure environments, it is useful to know the properties of filtering materials, or how the most harmful X-ray energy can be reduced and the resulting output voltage shift minimized. Previous testing has been done to determine which materials are most effective for reducing dose [2], and Intersil has performed tests to determine which materials reduce device shift.

ZINC FOIL FILTER TESTING

Another group of devices was datalogged. First, a high dose X-ray exposure was done to one device mounted on the dosimeter and produced >10mV shift. Then, a 20mil (0.020”) zinc sheet filter was placed in front of new devices mounted on the dosimeter and the same exposure time and intensity was used on them. A control device was included as well. The results are shown in Table 3.

TABLE 3. V_{OUT} SHIFT USING ZINC FILTER

DEVICE	FILTER	X-RAY SETTING (kV/µA)	EXPOSURE DURATION (MIN)	V_{OUT} DELTA (µV)
46	No	55/70	10	-12,812
47	Zinc	55/70	10	-30
42	No	55/70	2	-2472
48	Zinc	55/70	2	-58
50	Control	55/70	None	-57

The exposure level used was 55kV, 70µA at a 10” distance. The 10 minute exposure was enough to cause -12.8mV shift with no filter. The results with the filter show negligible shift, comparable to that of the control part and is most likely consisting of noise and measurement error. The 2 minute exposure yielded a -2.5mV shift and again, the shielded device had essentially zero shift.

The zinc sheet filter effect is to remove the lower energy X-rays which upset semiconductors and transmit the higher energy X-rays to produce clear images of copper, solder and other metals[2]. Note that no dose information is given since there is still significant levels of radiation measurable with the filter, but it is misleading since the X-ray radiation of interest is actually filtered. Also, the particular dosimeter used is not sensitive to the lower energy X-rays and would not be useful for comparing readings before and after filtering. For reference, the 10 minute exposure, no filter produced 210mrem.

ALUMINUM AND COPPER FOIL FILTER TESTING

Zinc is a very effective metal shield for filtering X-rays in post-assembly analysis, but other metals can be used for general X-ray filtering. Aluminum is used in many cases as an affordable and readily available shield for some applications, but requires significant thickness to be effective. Copper likewise can shield much of the radiation but needs a greater thickness than zinc. Table 4 shows the results of tests using both copper and aluminum shields.

The results show that two 1/2oz copper planes can reduce exposure drift by 8x, which, along with overall reduction in dose, can keep the device well within the output voltage spec.

Aluminum would need to be fairly thick for filtering, requiring about 4x the thickness of copper for the same drift reduction. Since the filtering is proportional to thickness, an 8.5mm aluminum sheet would limit drift to about 88µV (10x thickness for 10x reduction) at the same exposure stated in Table 4.

TABLE 4. V_{OUT} SHIFT USING COPPER AND ALUMINUM FILTERS

DEVICE	FILTER	X-RAY SETTING (kV/µA)	EXPOSURE DURATION (MIN)	V_{OUT} DELTA (µV)
42	None	55/70	2	-2529
25	850µm Au Foil	55/70	2	-883
51	2 x $^{1}/_{2}$oz Cu, 340µm	55/70	2	-472

PACKAGING COPPER LEADFRAME EFFECTS

Note also that the package for the FGA references has a copper leadframe, which is approximately 300µm thick and thus provides similar filtering. Note that the X-rays would need to be directional from under the circuit board for the leadframe filtering to be fully effective, and that most PC boards will have copper planes under the device, providing even more filtering. Table 5 shows results on devices with X-Ray exposure directed from under an FGA device, with and without a PC board and copper ground planes.

TABLE 5. COPPER LEADFRAME AND PC BOARD FILTERING

DEVICE	FILTER	X-RAY SETTING (kV/µA)	EXPOSURE DURATION (MIN)	V_{OUT} DELTA (µV)
21	Leadframe only	55/70	2	-112
18	Leadframe +2 layers ground plane	55/70	2	-44
16	Leadframe +4 layers ground plane	55/70	2	-22
42	Previous direct exposure test result	55/70	2	-2586

These results indicate that a normal PC board with 2 copper planes and an FGA device mounted properly will be extremely resistant to X-radiation from underneath the plane of the board.

Output Voltage Shift vs X-Ray Intensity

X-ray intensity, in tube voltage (kV) and tube current (mA) will affect the rate at which the FGA cell changes voltage. Two devices were exposed to higher tube voltages at 90kV and 100kV while reducing the current to 30µA.

Table 6 shows that the higher voltage actually decreases the drift, and that the lower current decreases drift. This concurs with known effects on semiconductors whereby reducing the tube current will reduce the dose received by the device, and in this case, reduce the voltage drift.

This data makes it clear that when doing X-ray imaging, minimizing tube current reduces FGA device drift.

TABLE 6. OUTPUT VOLTAGE SHIFT vs X-RAY INTENSITY

DEVICE	X-RAY SETTING (kV/µA)	DELTA (µV)	EXPOSURE DURATION (MIN)
34	90/30	-1782	2
27	100/30	-1589	2
42	55/70	-2529	2

Post-Assembly X-Ray Guidelines

As shown in Table Table 1 on page 3, post-assembly x-ray inspection can lead to permanent changes in device output voltage and should be minimized or avoided. Certain actions should be taken to minimize post-assembly X-ray dose. One or more of these will ensure FGA references maintain high accuracy in PC board assemblies.

Use a shield. From the references[1,2], many materials can be used for shields, but not all provide effective filtering for charge-storage semiconductor devices. A proven filter (see Table 4) involves placing a 300µm zinc foil shield either at the X-ray emission source or over the PC board. The zinc foil acts as a filter to drastically reduce the low intensity radiation which can alter charge storage cells in semiconductor devices, while passing other X-ray energy which produces a useful image for PC board structure analysis. It is also effective to place a small shield over a portion of the board with the FGA device, which may be cumbersome or impossible due to board size or physical construction.

Thick aluminum sheet can be used (10mm or more) to reduce X-ray dose as well, although it may not give the best results for PC board analysis.

Increase the examination distance from the source to the board. Dose decreases as the square of the distance, so maximizing the distance from the X-ray source to the board will minimize the dose.

Reduce the X-ray exposure time. Dose is linearly related to exposure time. Experimental results show that reducing exposure at normal energies from minutes to seconds will preserve the integrity of the FGA voltage reference accuracy.

Reduce the X-ray current level. Dose is nearly exponentially related to the tube current used. Experimental results verified that minimizing the tube current will reduce output voltage shift.

Add voltage reference trimming to the application circuit. For the ISL21009 or ISL21007 products, it is possible to adjust the output voltage with a trim circuit (See TB473). This will add components to the board, but allows the customer to recalibrate the reference output after all assembly shifts, including reflow (as described in a related application note).

Avoid X-ray exposure. If possible, skip the X-ray inspection and use other methods to verify interconnect bond integrity.

Whatever steps are taken to reduce FGA drift from X-ray inspection, **it is highly recommended that the customer perform a test run on a few boards to monitor the effects at the contract manufacturer so that full production will not be affected**.

Airport Inspection X-Ray Testing

Both Carry-on X-ray machines and the large luggage X-ray machines utilize the same energies as the Post-Assembly X-ray machines, therefore these are also considered as sources of shift for FGA references since products that use the FGA reference may pass through them. Intersil performed tests to evaluate this effect.

CARRY-ON LUGGAGE X-RAY

Table 7 shows the results of a formal experiment with carry-on x-ray on ISL21009 FGA reference devices. The devices were enclosed in an anti-static box in random orientations and carried in a typical computer case. The multiple exposures were from different machines in different U.S. cities to add more variation. The actual dose is unknown, but can be figured from the output voltage shift data previously covered.

TABLE 7. AIRPORT CARRY-ON X-RAY TEST RESULTS

INITIAL VALUE (V)	AFTER CARRY-ON X-RAY: 6x IN 5 CITIES (V)	V_{OUT} SHIFT (µV)
5.000357	5.000289	-68
4.999935	4.999761	-174
5.000405	5.000307	-98
5.000199	5.000075	-124
5.000239	5.000119	-120
4.999976	4.999877	-99
5.000509	5.000398	-111
4.999998	4.999856	-142
5.000151	4.999952	-199
	Average =	-126
	Std Dev =	38

The average shift after 6 exposures is comparable to or somewhat less than that from a single IR reflow soldering cycle, ranging from -68µV to -199µV, and will vary from device-to-device and with orientation in the X-ray machine. The range indicates that device initial accuracy may exceed data sheet specification after multiple exposures. Single exposure will likely not produce significant shift, but a typical product using an FGA reference may be exposed many times in its lifetime.

Calculations show the voltage shift per exposure ranged from -12µV to -33µV. Assuming the X-ray intensity is similar to the dose testing done previously, it would correspond to a dose from 0.2mrem to 0.6mrem per exposure.

Practical testing has shown the actual doses for a TRX model carry-on X-ray machine are very low, 36 passes resulted in 4mrem of total dose, or about 0.1mrem per pass[4]. These doses are very small so the FGA reference would only be in danger of exceeding the initial accuracy spec after hundreds of passes.

AIRPORT LUGGAGE SCREENING X-RAY

Large airport X-ray machines are now installed at every large airport and are labeled as Explosive Detection Systems or EDS. They use advanced X-ray imaging techniques, similar to medical CAT scans to examine and record the contents of checked luggage. These systems are capable of much higher exposure doses than the carry-on X-ray machines.

The TSA did a survey of airports using these machines and published the results[4]. The testing included total dose data, with tests performed by inserting a dosimeter inside luggage and passing it through the machine 1 or multiple times. They limited the test to two machines that had very different characteristics.

The L3 3DX 6000 uses a helical-cone beam to provide a three dimensional CAT image of an object as it passes along the conveyor. It uses a continuous exposure and scan method which will produce large doses to baggage under X-Ray. The InVision CTX 5500 is a smaller machine which uses a single beam to provide the CAT-slice images. The X-ray detector is only powered when the bag is in the scanning area.

The TSA test results are in Table 8. There is some variability in the dose per pass, and is probably related to the type of luggage used. There is an obvious difference in the dose received from each machine. The L3 with continuous scanning has as much as 30x higher average dose per pass than the CTX 5500.

The effect on the FGA reference can be estimated by using the dose sensitivity stated previously, 61µV/mrem. A single pass from a CTX 5500 could produce up to 1.68mV of output voltage shift. The L3 would produce even higher shift, up to 13mV worst case.

TABLE 8. AIRPORT LUGGAGE MACHINE DOSE RESULTS[4]

	InVision (GE) CTX 5500		L3 COMMUNICATIONS 3DX 6000 EDS	
PASSES	TOTAL DOSE MEAN (mrem)	AVERAGE DOSE (mrem/pass)	TOTAL DOSE MEAN (mrem)	AVERAGE DOSE (mrem/pass)
1	7	7.0	156	156.0
3	17	5.7	494	164.7
5	22	4.4	976	195.2
10	280	28.0	2157	215.7

LUGGAGE SCREENING X-RAY TESTING

Intersil performed a test with different FGA products contained in checked baggage and then checked and passed through multiple airport luggage X-ray machines. There was no control over the orientation of the devices or the luggage bag, but no large metallic objects were contained in the luggage. None of the devices showed significant shift, with a measured shift range of -20µV to -50µV. Although multiple X-ray machines were encountered in this trip, there is no data on which machines were used and no indication that the CAT-scan version with higher intensity was used.

Airport Luggage X-Ray Guidelines

The higher X-Ray dose possible from the airport X-ray machines will definitely cause the reference voltage to shift out of spec from the initial accuracy, especially with repeated exposure. It is advised that FGA references contained in products should not be exposed to luggage X-ray machines if at all possible, or action should be taken to mitigate X-ray effects, as follows.

Provide a warning label. Devices containing FGA references can be labelled as sensitive to X-radiation with an advisory to avoid airport luggage screening.

Shielding and PC board solutions. The FGA package leadframe plus two planes of copper provide an excellent shield for radiation from one direction as shown in Table 5 on page 4. Protection for the device side of the board must also be considered. A shield of zinc foil or sheet, 250µm minimum can be placed inside the enclosure above the FGA which effectively filters the most damaging energy. An alternative to consider is a thick aluminum sheet, 10mm or greater, placed over the device side of the PC board.

In applications using multiple PC boards, it is advised to mount a 2-layer (minimum) PC board over the device side of the FGA PC board. If this configuration is used, the protection provided along with a ground plane underneath will effectively shield the device for 50 to 100 passes through an X-ray machine. Since these machines vary in X-ray dose delivered, it is difficult to produce an accurate maximum pass recommendation.

X-Ray Guidelines Update

FGA reference X-ray testing is ongoing and more results will be added when available. Additional data will allow Intersil to provide improved guidelines. For specific applications information dealing with radiation, contact Intersil Applications Engineering.

References

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