

RESPONSE OF GAFCHROMIC® HD-V2 FILM DOSIMETER IN 10-300 Gy DOSE RANGE FOR RADIATION TESTING OF ELECTRONIC DEVICES

by

Francesca MARTORANA^{1,2}, **Aldo PARLATO**^{1,2,3},
Giuseppe PERRONE^{1,2}, and **Elio Angelo Giuseppe TOMARCHIO**^{1*}

¹ Department of Engineering, University of Palermo, Palermo, Italy

² Scientific Research Center for Economical Development and Industrial Innovation, Palermo, Italy

³ BlueCat Energy s.r.l., Palermo, Italy

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The study reported in this paper aimed to investigate the response of a GAFChromic® HD-V2 film dosimeter in the dose range between 10 and 300 Gy, normally used to perform irradiation tests on electronic devices with a ⁶⁰Co gamma-ray irradiator. The well-defined linearity of response in terms of absorbance as a function of absorbed dose, easiness of handling and data analysis of irradiated dosimeters, reproducibility, stability, and insensitivity to visible light and most of the environmental parameters, make HD-V2 film a flexible, inexpensive and reliable dose measurement device. The study has shown a *fogging effect* of the dosimeter response since its value changes over time. Strategies and adequate precautions to take into account changes on HD-V2 film physical properties for calibration and routine use in industrial applications, with a specific reference to radiation testing of electronic devices, have been discussed.

Key words: gafchromic dosimetry, HD-V2 film, gamma-ray irradiation, dose, electronic device

INTRODUCTION

Many industrial applications of ionizing radiations require the use of reliable dosimeters for the measurement of high doses. A solution can be represented by Gafchromic films, a fast and inexpensive means of performing accurate quantitative radiation dosimetry in different activities. In fact, crystalline structural properties of these films change when exposed to a radiation field, and, with increasing absorbed dose, a polymerization with a chromatic change occurs. Although originally produced for medical use, in particular for measurement of 2-D dose distribution in radiotherapy, radiosurgery and brachytherapy [1-7], Gafchromic self-developing dosimetry films are also used in other activities given their improved dose sensitivity. Recently produced, HD-V2 film is specifically used for quantitative measurement of high level absorbed dose (Dose Range: 10 Gy – 1000 Gy) due to high energy photon interactions [8]. It is suitable for research and industrial applications, food irradiation, radiation processing or to evaluate the performance of electronic components [9-14].

Gafchromic HD-V2 films are interesting as reliable dosimeters for measurement of absorbed dose in radiation testing of electronic devices, one of our research activities aimed to study the effects of gamma radiations on electronic components used, in particular, for space applications [15-17]. In this field, main dosimeters used for radiation testing of electronic devices are thermoluminescent dosimeters, ionization chambers, semiconductor dosimeters, polymer alanine dosimeters, perspex dosimeters, and radiochromic dosimeters. All of them have different characteristics that make them useful in different conditions, as reported in [18].

The widespread use of electronic systems has reached high levels in a variety of fields. Some of them imply particular operative conditions that can be critical and require an adequate study of the device response to external radiation fields. In fact, it is well known that radiation can influence electronic component and system performances, with a variety of induced effects, depending on device type and radiation field [19-26].

The technical features of HD-V2 dosimeters have already been examined [27-30] but no detailed information is available for the use of HD-V2 films in

* Corresponding author; e-mail: elio.tomarchio@unipa.it

the aforementioned application field. For this reason, a study on its characteristics, with reference to calibration, reproducibility, and stability of dosimetric data has started over time.

This work reports the results of testing on response properties of HD-V2 Gafchromic films with the use of a ^{60}Co gamma irradiator. The analysis of results obtained with dosimeters irradiated at different dose values highlighted a fogging effect over time. Following, strategies and precautions to adequately taking into account the variation on HD-V2 film properties for the industrial application, with a specific reference to radiation-hardness testing of electronic devices, are discussed.

MATERIALS AND METHODS

GAFChromic® HD-V2 dosimetry films

Ashland GAFChromic® HD-V2 film (batch no. 12151401), designed to measure the absorbed dose due to high energy photons, has been investigated. HD-V2 Gafchromic film consists of a nominal 12 μm -thick radiation-sensitive layer, that contains the active principle, the marker, the stabilizers and other components that give an energetically independent response of film, and of a transparent substrate polyester layer (97 μm). The HD-V2 film is able to fit a range of dose between 10 to 1000 Gy, with a minimal difference of response based on the photon energy (from 100 keV to about 20 MeV). Treatment after the exposition is not required and dosimetry film can be handled and used inside a normal room. Its principal features are given in [8].

With increasing dose, the active component of HD-V2 film responds to radiation exposure by forming a blue colored polymer with maximum absorption at a wavelength of approximately 670 nm [8].

The response curve of HD-V2 film dosimeters was obtained in accordance with ISO/ASTM 51275 [31] and ASTM STANDARD E668 [32]. A sheet of GAFChromic® HD-V2 film (203.2 mm \times 254 mm) was cut into 200 small pieces, 10 mm \times 25 mm each, by means of a precision cutter. Each of the pieces obtained was identified as a film dosimeter. These cutting sizes are not mandatory but depend on the irradiation conditions, dimensions of the irradiated device, characteristics and reading modalities of the tool used for film analysis.

Film dosimeters were kept at a temperature of 22 \pm 2 $^{\circ}\text{C}$, and removed from a light tight envelope only during irradiation and readout procedures.

All the dosimeters were treated with the same modalities, from the preparation to storage, from irradiation to analyses. Irradiations were performed at a dose rate level of 2 Gymin $^{-1}$, an intermediate value in

the suggested dose rate range between 0.034 Gymin $^{-1}$ and 3.4 Gymin $^{-1}$ within which the manufacturer assures an error on response lower than 5 %.

Irradiation

The gamma-ray irradiator used for dosimeter irradiation, named *Irradiatore Gamma Sicilia-3* (IGS-3), is placed inside the building No. 6 of Department of Energy of the University of Palermo. The IGS-3 research facility is a panoramic dry source storage irradiator, classified in category II by IAEA [33], with 12 ^{60}Co sources arranged each in a cylinder of 5 cm in radius.

The irradiation system consists of 12 stainless steel tubes each of which can accommodate a double-encapsulated ^{60}Co stainless steel cylindrical source with an active height of 110 mm and 6.3 mm in diameter. Normally stored in recovery position inside a lead tank, the sources have a different activity, for a total of about 5000 GBq, and can be moved in vertical direction putting them in the exposure position with a maximum dose rate in water of about 0.45 kGyh $^{-1}$ [34]. To realize a lower dose-rate value, a different number of sources can be exposed, paying attention to achieving a beam symmetry (at least 2). To get a 2 Gymin $^{-1}$ dose rate, only 3 sources with lower activities were exposed. In [15-17, 34] are available detailed information, photographs of the facility highlighting source lead container, exposure devices, irradiation area and a working table where exposure of electronic devices can be realized. The structure is equipped with dosimeters, to assure a safe functioning and precise dose measurement and is able to offer a good versatility to carry out several typologies of irradiation tests. The characteristics of the beam inside the irradiation area and on the working table, were periodically determined using a calibrated PTW Freiburg TM 30015 ionization chamber.

The dose value was obtained by timing the exposure of the sources, setting on a timer the value corresponding to chosen absorbed dose value. At the end of irradiation time, a switch trips on for a complete recovery of the sources.

Measurement tools

Although the most used film analysis equipment is flat-bed digital scanners, the response spectral absorbance of HD-V2 was measured using a Perkin Elmer Lambda 660 UV-VIS spectrophotometer, available at our Department, paired with a dedicated software. Spectral absorbance A is the common logarithm of the ratio of incident to transmitted spectral radiant light power through film material. For an appropriate analysis of irradiated dosimeters, a wavelength of about 670 nm was selected as the best choice for any absorbed dose value [8].

The HD-V2 Gafchromic films have an asymmetrical cross-section. Since the manufacturer indicated that the response may be dependent on which side of the film is facing the light source, original sheet and all dosimeters were marked so the same side was always used for dosimetric reading. Uniformity can be supposed because all the dosimeters were obtained by cutting a single sheet of the same batch. However, uniformity was tested taking into account 30 dosimeters chosen randomly among the ones obtained by cutting the sheet. The sample size specified, 30, is the number of measurements required to estimate an average value of absorbance, \bar{A} , and the standard deviation, σ , of dosimeter response distribution at a 95 % confidence level [32].

RESULTS AND DISCUSSION

Dosimetry film response

The study of the response of the HD-V2 films was carried out by irradiating a series of dosimeters at varying dose levels and at different times for more than a year. In analogy with [32], uniformity was verified by fulfilling the condition $\sigma < 0.08 \bar{A}$, as $\sigma = 0.035$ and $\bar{A} = 1.006$ values were obtained. For each measured point, a dosimeter number from 3 to 5 was used to obtain a more reliable mathematical average. Film dosimeters were irradiated at a dose rate of 2 Gymin^{-1} up to a final dose value ranged between 10 and 300 Gy, and analysed after 24 hours to obtain a response curve.

An example of this response curve is reported in fig. 1 where it can be noted that a linear fit represents very well (correlation coefficient $R^2 = 0.998$) the relation between absorbance (A) and dose (D). Dose uncertainties were all lower than 3 % and for clarity of representation are not shown in fig. 1. Compared with the functional relation proposed by the manufacturer [8], with specific reference to flat-bed scanners, the linear trend obtained with a 670 nm spectrophotometer is useful and easier to use.

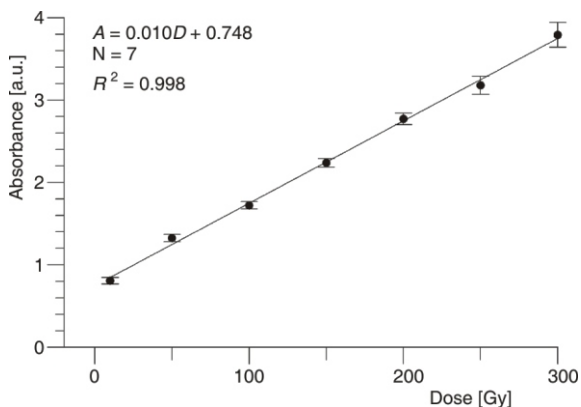


Figure 1. Response curve of a GAFChromic® HD-V2 as a function of adsorbed dose. Error bars: 1 uncertainty. a.u.= arbitrary units

Response fogging over time

To test the response of the batch, calibration measurements were repeated periodically during more than a year. The results are shown in fig. 2 where some response curves of the same HD-V2 batch performed at different times were compared.

Figure 2 highlighted a significant *fogging* effect related to calibration time. Therefore, it seems necessary to determine a new response curve for a given measurement time, which may be difficult for the availability and use of calibration sources. However, it can be noted that the linear fits in fig. 2 are almost parallel and for our dosimeter batch the following can be applied

$$A = aD[\text{Gy}] + A_0 \quad (1)$$

where the absorbance, A , is a function of dose, D , in Gray (Gy), a is a fitting parameter, and A_0 – the absorbance mean value of no irradiated dosimeters.

The fogging effect noted in irradiated dosimeters is better highlighted in fig. 3 in which variation trends for dosimeters irradiated at various dose levels and analysed during more than a year time period, were reported. Data acquired show that the absorbance value seems to in-

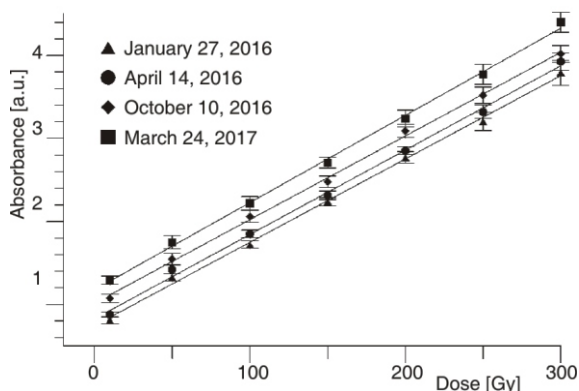


Figure 2. Comparison of response curves of a GAFChromic® HD-V2 as a function of adsorbed dose obtained during more than the one-year time period of observation. Error bars: 1 uncertainty. a.u.= arbitrary

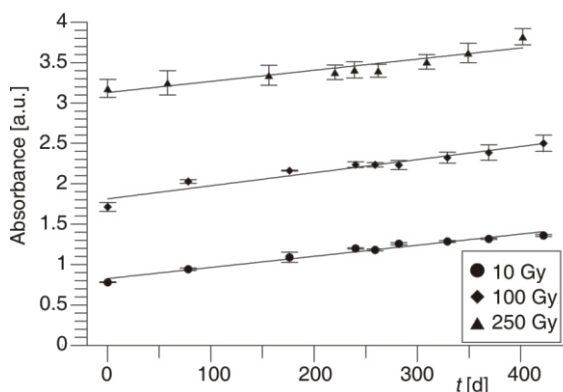


Figure 3. Variation over time of absorbance of irradiated GAFChromic® HD-V2 dosimeters for different dose values. Error bars: 1 uncertainty. a.u.= arbitrary units

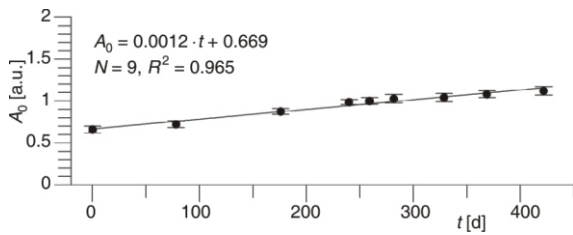


Figure 4. Variation over time of absorbance of non-irradiated GAFChromic® HD-V2 dosimeters. Error bars: 1 uncertainties. a.u. = arbitrary units

crease linearly with the time, keeping into account the uncertainties of the measurements. The same variation was detected in non-irradiated dosimeters, as shown in fig. 4, where the trend of the absorbance mean value of non- irradiated dosimeters, A_0 , measured over a time period more than a year was reported.

At a given time a correct response curve can be obtained assuming the slope (a) of relation (1), and determining, prior to each use, the A_0 value through the reading of no irradiated dosimeters.

Variation of A_0 with time can be determined by periodically reading a set of 3-5 non-irradiated dosimeters belonging to the same batch. The determination of this value, easily obtained through the good correlation with time (fig. 4, correlation coefficient $R^2 = 0.965$), is a key-point for the reliability of the method such that availability of A_0 value over time allows to correct the absorbance response and improve measurement accuracy.

Irradiation test on electronic components

As an application example, the use of dosimetry films in testing radiation-hardness of electronic components with ^{60}Co sources is briefly described. With reference to the field of application of the electronic component of interest, a radiation level to which a device component should be tested is defined. A classification of these levels, commonly identified as “radiation resistance levels” (RRL), expressed as dose to Silicon, $D(\text{Si})$, is given in tab. 1.

To reach a given RRL, different test configurations must be provided for each application. During its

Table 1. RRL ([35] with modifications)

RRL D(Si)	Applications
0-30 Gy	Commercial: industrial, robotic, nuclear, biomedical, space shuttle
3-300 Gy	Tactical: submarines, tanks missiles, airborne, ground (field radar, communications), space station
200-500 Gy	Space: low earth orbit
500-2000 Gy	Space: high orbit
1000 Gy and more	Deep space; strategic: military

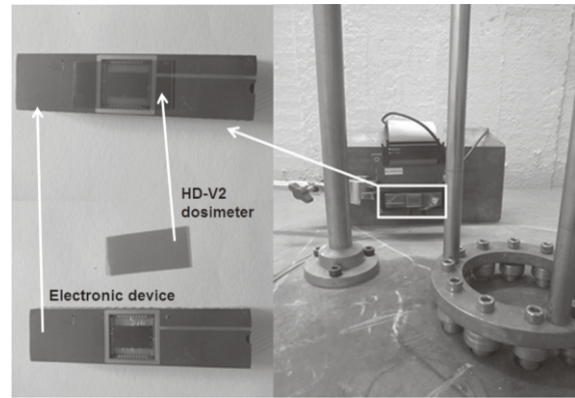


Figure 5. Photograph of an irradiation configuration, with testing device placed directly in front of sources while other components are protected by a lead shielding

functioning, a component was normally exposed to radiation field, with a dosimeter placed on the component to evaluate the device absorbed dose value, while power supply and auxiliary circuits were protected by lead shields [17].

The HD-V2 Gafchromic film is very useful and efficient for this task because it is easy to position on the device. Furthermore, its small thickness does not affect the radiation field or the performances of the device itself, and it seems to have, in some instances, a protective function. Figure 5 shows the photograph of one of these configurations with the device sited in front of ^{60}Co sources and HD-V2 films placed on the components of interest [35].

Special experiments based on total ionizing dose (TID) test method reported in [36] required device irradiation until failure using multiple exposures (with an interval of maximum 1 hour) and intermediate monitoring of electrical parameters. As we can easily see from tab. 2, HD-V2 cover dose range of TID interest both in a single dose solution (within 500 Gy), as well as in multiple intermediate steps for higher doses [36].

As an example, in a test performed with IGS-3 it was required to achieve a TID of 1000 Gy. For this task, four irradiation steps of 250 Gy each were programmed; at each interruption HD-V2 dosimeter was replaced and the absorbed dose was determined. Table 2 reports the dose readings that confirmed the expected TID value, with an error at most 2 % on Total Dose.

Table 2. Total dose obtained through a dose fractioning in four steps

Step	Dose [Gy]
1	252
2	257
3	254
4	256
Total dose	1019

CONCLUSIONS

Different tests were performed on GAFChromic® HD-V2 films, utilized for dosimetry of high dose values from high energy photons in industrial applications. Using a gamma irradiator with ^{60}Co sources, placed at our Department, a linearity of the response curve was verified in a selected dose range, with a good correspondence between readout absorbance at the end of irradiation and relative absorbed dose.

The advantage of these dosimeters is that the information keeps throughout time, *i. e.* a reading of the dosimeter can be performed after days from the irradiation. Nevertheless, readings carried out after some time after irradiation are affected by a significant *fogging* effect, as the absorbance increases with time. In order to accurately determine the absorbed dose value at different measurement time, corrections should be carried out to take into account the fogging effect through the determination of non-irradiated film absorbance. This correction procedure, which can be easily implemented, allows for a response curve determination for the examined batch and an accurate evaluation of absorbed dose, within a confidence limit of 95 %.

AUTHORS' CONTRIBUTIONS

Gamma-ray test experiments were performed by A. Parlato and E.A.G. Tomarchio, whereas dosimeter analysis was performed by F. Martorana and G. Perrone. All the authors analysed and discussed the results. The manuscript and figures were prepared by A. Parlato and E.A.G. Tomarchio.

REFERENCES

- [1] Butson, M. J., et al., Dose and Absorption Spectra Response of EBT2 Gafchromic Film to High Energy X-Rays, *Australas. Phys. Eng. S.*, 32 (2009), 4, pp. 196-202
- [2] Gambarini, G., et al., Measurements of 2-D Distributions of Absorbed Dose in Protontherapy with Gafchromic EBT3 Films, *Appl. Radiat. Isot.*, 104 (2015), Oct., pp. 192-196
- [3] Martin, C. J., et al., Application of Gafchromic Film in the Study of Dosimetry Methods in CT Phantoms, *J. Radiol. Prot.* 31 (2011), 4, pp. 389-409
- [4] Saeed, M. K., Dose Measurement Using Gafchromic Film for Patients Undergoing Interventional Cardiology Procedures, *Radiat. Prot. Dosim.*, 174 (2017), 1, pp. 109-112
- [5] Williams, M., Metcalfe, P., Radiochromic Film Dosimetry and its Applications in Radiotherapy, *Proceedings*, 4th SSD Summer School: Concepts and Trends in Medical Radiation Dosimetry, 2011, pp. 75-99
- [6] ***, Ashland Advanced Materials, Niagara Falls, NY, USA, 2017, Radiology Films. Available at http://www.gafchromic.com/documents/PC-11805_Gafchromic_XR.pdf. Accessed 25 January 2019
- [7] ***, Ashland Advanced Materials, Niagara Falls, NY, USA, 2017, Radiotherapy Films, Available at <http://www.gafchromic.com/gafchromic-film/radiotherapy-films/index.asp>. Accessed 25 January, 2019
- [8] ***, Ashland Gafchromic Dosimetry Media, Type HD-V2, Technical Sheet and User Guide, Available at <http://www.gafchromic.com/documents/gafchromic-hdv2.pdf>. Accessed 08 July 2018
- [9] Kuntz, F., Strasser, A., The Specifics of Dosimetry for Food Irradiation Applications, *Radiat. Phys. Chem.*, 129 (2016), Dec., pp. 46-49
- [10] Mehta, K., et al., Gafchromic® Film Dosimetry for Low Energy X Radiation, *Radiat. Meas.*, 67 (2014), Aug., pp. 48-54
- [11] Pace, C., et al., Low Dose-Rate, High Total Dose Set-Up for Rad-Hard CMOS I/O Circuits Testing in Applications, *Proceedings*, Electronics Pervading Industry, Environment and Society Conference, ApplePies 2016 pp, 27-33
- [12] Yuri, Y., et al., Characterization of a Gafchromic Film for the Two-Dimensional Profile Measurement of Low-Energy Heavy-Ion Beams, *Nucl. Instrum. Meth. A* 828 (2016), Aug., pp. 15-21
- [13] Yuri, Y., et al., Use of a Gafchromic Film HD-V2 for the Profile Measurement of Energetic Ion Beams, *Nucl. Instrum. Meth., B* 406 (2017a), Sept., pp. 221-224
- [14] Yuri, Y., et al., Study on the Coloration Response of a Radiochromic Film to MeV Cluster Ion Beams, *Nucl. Instrum. Meth., A* 872 (2017b), Nov., pp. 126-130
- [15] Cappello, S. G., et al., Gamma-Ray Irradiation Tests of CMOS Sensors Used in Imaging Techniques, *Nucl Technol Radiat*, 29 (2014), Suppl., pp. S14-S19
- [16] Consentino, G., et al., Dangerous Effects Induced on Power MOSFET by Terrestrial Neutrons, AEIT-IEEE Italy Section, Mondello (PA), 3-5 October 2013
- [17] Parlato, A., et al., The Methodology for Active Testing of Electronic Devices Under the Radiations, *Nucl Technol Radiat*, 33 (2018), 1, pp. 53-60
- [18] Ravotti, F., Dosimetry Techniques and Radiation Test Facilities for Total Ionizing Dose Testing, *IEEE Trans. Nucl. Sci.* 65 (2018), 8, pp. 1440-1464
- [19] Ma, T. P., et al., 1989, Ionizing Radiation Effects in MOS Devices and Circuits, John Wiley & Sons, N. Y., USA
- [20] Fleetwood, D. M., et al., An Overview of Radiation Effects on Electronics in the Space Telecommunications Environment, *Microelectron. Reliab.*, 40 (2000), 1, pp. 17-26
- [21] Obrenović, M. D., et al., Effects of Ion Beams on Flash Memory Cells, *Nucl Technol Radiat*, 29 (2014), 2, pp. 97-169
- [22] Schwank, J. R., et al., Radiation Effect in MOS oxides, *IEEE Trans. Nucl. Sci.*, 55 (2008), 4, pp. 1833-1853
- [23] Sexton, F. W., Destructive Single-Event Effects in Semiconductor Devices and ICs, *IEEE Trans. Nucl. Sci.*, 50 (2003), 3, pp. 603-621
- [24] Domanski, G., et al., The Study of Radiation Damage of EPROM 2764 Memory, *Nucl Technol Radiat*, 31 (2016), 3, pp. 233-239
- [25] Fetahovic I. S., et al., Reliability of Computer Memories in Radiation Environment, *Nucl Technol Radiat*, 31 (2016), 3, pp. 240-246
- [26] Fetahovic, I. S., et al., Overview of Radiation Effects on Emerging Non-Volatile Memory Technologies, *Nucl Technol Radiat*, 32 (2017), 4, pp. 381-392
- [27] Aydarous, A., et al., The Effects of Electrons and Photons Irradiation on the Optical and Thermophysical Properties of Gafchromic HD-V2 Films, *Results Phys.*, 6 (2016), pp. 952-956
- [28] Devic, S., et al., Reference Radiochromic Film Dosimetry: Review of Technical Aspects, *Phys. Medica*, 32 (2016), 4, pp. 541-556

- [29] Soares, C. G., New Developments in Radiochromic Film Dosimetry, *Radiat. Prot. Dosim.*, 120 (2006), 1-4, pp. 100-106
- [30] Yao, T., *et al.*, A Study of Four Radiochromic Films Currently Used for (2-D) Radiation Dosimetry, *Radiat. Phys. Chem.*, 133 (2017), pp. 37-44
- [31] ***, ISO, 2004, Standard Practice for Use of a Radiochromic Film Dosimetry System, ISO/ASTM 51275, April 2004,
- [32] ***, ASTM, 2005, Standard Practice for Application of Thermoluminescence-Dosimetry (TLD) Systems for Determining Absorbed Dose in Radiation-Hardness Testing of Electronic Devices, ASTM Standard E668-05, 2005
- [33] ***, IAEA 2010, Radiation Safety of Gamma, Electron and X Ray Irradiation Facilities, Safety Standards Series No. SSG-8, IAEA, July 2010
- [34] Fiore, D., *et al.*, 2015, Le Facilities Di Irraggiamento Del DEIM Per Il Testing Di Componenti RAD-HARD (In Italian), Casa editrice Antipodes, ISBN 978-88-96926-80-2, August 2015
- [35] ***, National Semiconductor, 2010, Space Solutions Selection Guide, Vol. 1. Available at <ftp://ftp.efo.ru/pub/nationals/sprav/8.pdf>, Accessed 08 July 2018
- [36] ***, ESCC 2010, Total Dose Steady-State Irradiation Test Method, ESCC Basic Specification No. 22900, Issue 4, October 2010

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**Франческа МАРТОРАНА, Алдо ПАРЛАТО,
Ђузепе ПЕРОНЕ, Елио Анђело Ђузепе ТОМАРКИО**

**ОДЗИВ GAFCHROMIC® HD-V2 ФИЛМ ДОЗИМЕТРА У ОПСЕГУ ДОЗА
10-300 Gy ПРИ ТЕСТИРАЊУ НА ЗРАЧЕЊЕ ЕЛЕКТРОНСКИХ УРЕЂАЈА**

Приказано је испитивање одзива GAFChromic® HD-V2 филм дозиметра за опсег доза од 10 Gy до 300 Gy, који се уобичајено употребљава за радијациона тестирања електронских уређаја користећи ^{60}Co као извор зрачења. Добро дефинисана линеарност одзива апсорпције светлости у зависности од апсорбоване дозе, лакоћа управљања и анализе података о озраченим дозиметрима, поновљивост, стабилност и неосетљивост на видљиву светлост и на већину параметара околине, чине HD-V2 филм флексибилним, јевтиним и поузданим средством за мерење дозе. Студија је показала постојање *ефекта замањене* у одзиву дозиметра јер се његова вредност мења током времена. Размотрене су методе и одговарајуће превентивне мере које се могу предузети како би се урачунале физичке промене HD-V2 филмова за калибрацију и рутинску индустријску примену, са посебним освртом на радијационо тестирање електронских уређаја.

Кључне речи: Гафхромик дозиметрија, HD-V2 филм, гама озрачивање, доза, електронски уређај