Study of the spectral response of CZT multiple-electrode detectors

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***Abstract* – Cadmium zinc telluride (CZT) is a promising material for room temperature X-ray and gamma-ray detectors. The high atomic number and the wide band-gap give high quantum efficiency and good room temperature performances. Due to hole trapping, particular electrode structures have been developed to provide single-charge carrier collection (electrons), exploiting the excellent charge transport properties of the electrons. In this work, the spectroscopic performances of two CZT detectors (CZT1: 5 mm x 5 mm x 0.90 mm; CZT2: 4.8 mm x 5 mm x 0.55 mm) with five electrodes (cathode, anode and three steering electrodes) were studied. The anode-collecting electrode, surrounded by three steering electrodes (biased for optimum charge collection), is mostly sensitive to electron carriers, overcoming the effects of hole trapping in the measured spectra (hole tailing). We investigated on the spectroscopic response (^{241}Am source; 59.5 keV) of the detectors at different bias voltages of the electrodes. The detectors exhibit excellent energy resolution (CZT1: 2.0 % FWHM at 59.5 keV; CZT2: 1.7 % FWHM at 59.5 keV; working temperature -10 °C) and low tailing (CZT1: FW.1M to FWHM ratio of 1.93 at 59.5 keV; CZT2: 2.35 at 59.5 keV). This study stresses on the excellent spectroscopic properties of the CZT detectors equipped with a custom anode layout, making them very attractive candidates as x-ray spectrometers mainly for medical applications.**

***Index Terms* — CZT detectors, multiple electrode detectors, steering electrodes, small pixel effect.**

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I. Introduction

RECENTLY, detectors based on cadmium zinc telluride (room temperature compound semiconductor) are promising X-ray and gamma-ray spectrometers [1], [2] and are very attractive in many disciplines, such as medicine [3], [4] and astrophysics [5], [6]. The high atomic number (Z_{max} = 52) and the wide band gap (E_G ~ 1.6 eV), in comparison with Si and Ge, give high quantum efficiency and good room temperature performances. Poor charge collection, due mainly to hole charge trapping, is the major drawback of the CZT detectors. Incomplete charge collection leads to spectral distortions manifested by asymmetric full-energy peaks and long tails on the low energy side of the peaks in the measured spectra.

In order to overcome these spectral distortions, single carrier sensing techniques have been proposed for CZT detectors. Single charge sensing is generally obtained by using electronic methods (pulse rise time discrimination [7]) and by developing careful anode electrode design (pixels [8], [9], coplanar grids [10], strips [11], [12], steering grids [13], [14], [15]).

In this work, the spectral response (^{241}Am; 59.5 keV) of two CZT detectors, equipped with five electrodes, was studied. The small anode electrode and the additional electrodes on the anode surface optimize the charge collection, minimizing the effect of the hole trapping [8] – [13] on the response of the detectors. We investigated on the spectroscopic performances of the detectors by varying the bias voltage applied to the electrodes, in order to find the best compromise among several competitive effects: the broadening of the electron cloud due to diffusion and mutual electrostatic repulsion [16], [17] the charge trapping and the noise associated with the leakage currents (either surface and bulk ones). This work is in the framework of the development of portable systems, based on CZT detectors, for medical applications.

II. The Detectors and Operation

The CZT detectors, with identical anode layout but different thickness, are designed by our collaboration and fabricated by the Baltic Scientific Instruments (Riga, Latvia). The detectors are based on CZT crystals (CZT1: 5 mm x 5 mm x 0.9 mm; CZT2: 4.8 mm x 5 mm x 0.55 mm;) produced

by eV Products, U.S.A. The main characteristics of the detectors are summarized in Table I.

TABLE I
DETECTORS CHARACTERISTICS

Detector	CZT1	CZT2
Crystal size (mm^3)	5 x 5 x 0.9	4.8 x 5 x 0.55
Electron mobility-lifetime product (cm^2/V)	$1.1 \cdot 10^{-3}$	$1.1 \cdot 10^{-3}$
Resistivity (Ω cm)	$1 \cdot 10^{10}$	$0.5 \cdot 10^{10}$

The cathode (HV) is a planar platinum electrode covering the entire detector surface. The anode surface consists of a circular platinum electrode (the collecting electrode; ϕ = 80 μm) surrounded by two circular electrodes (HV1 and HV2; gap = 100 μm; Δr = 100 μm) and by one electrode (HV3) that extends to the edge of the crystal (Fig. 1).

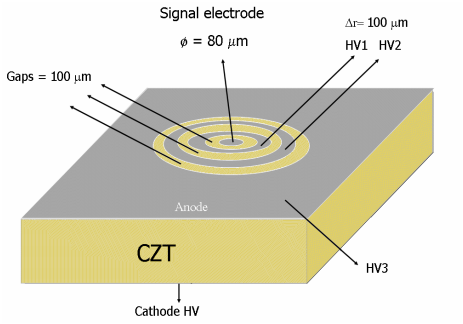

Fig. 1. The layout of the CZT multiple-electrode detectors.

The cathode (HV) and the three electrodes (HV1, HV2, HV3) are negatively biased, while the signal electrode is at virtual ground. A Peltier cell cools both the CZT crystal and the input FET (2N4416 n-channel FET; DC-coupled to the detector) of the charge sensitive preamplifier; the temperature was measured and monitored by a standard PT100 sensor. As shown in Fig. 2, the detectors, the FET and the Peltier coolers are mounted in hermetic TO-8 packages, equipped with light-vacuum tight Beryllium windows,.

Fig. 2. The CZT detectors mounted in hermetic TO-8 packages. The packages contain also the Pelltier coolers, the FET and the PT100 sensors.

The FET output signals were acquired by a standard nuclear spectroscopy signal chain (charge sensitive preamplifier, linear amplifier and shaper and multichannel analyzer). A test charge sensitive preamplifier, based on a low noise operation amplifier (AD797), optimized for low count rate x-ray spectroscopy [18], was used. The preamplifier output signals were shaped by a standard shaping amplifier (570, ORTEC) with an optimized shaping time of 2μs. A standard multichannel analyzer (MCA-8000A, Amptek, U.S.A.) was used to sample and to record the shaped signals.

We measured the spectroscopic response of the detectors by using a ^{241}Am calibration source (59.5 keV; the Np-L x rays are shielded by the source holder itself). Collimated beams (W collimator ϕ = 50 μm) were centred on the cathode surface of the detectors by an XY micro-translator system. The measurements were performed at low temperatures (-5 °C; -10 °C). The spectroscopic performances of the detectors were analyzed by evaluating the following parameters in the measured spectra: *energy resolution*, *photofraction*, *peak-to-valley ratio* and *FW.1M/FWHM*, defined in our previous work [19]. The measured spectra were analyzed by using a peak function model, which takes into account both the symmetric and asymmetric peak distortion effects [20]. Statistical errors on the spectroscopic parameters with a confidence level of 68% were associated.

III. MEASUREMENTS FOR THE 0.9-MM THICK DETECTOR (CZT1)

The spectroscopic response of the detector at various bias voltages of the electrodes (HV3, HV2, HV1 and HV) were investigated (^{241}Am source; T = -5 °C). The detector exhibited good stability in a long-term operation (time span of about six hours) at the working temperature of -5 °C, as pointed out in our previous study [19].

The detector response at various *HV3* bias voltages, maintaining a fixed bias voltage setting of the other electrodes (HV = -160 V, HV2 = - 50 V, HV1 = -30 V), is shown in Fig. 3 (a). Performance improvements were obtained increasing the HV3 bias voltage and thus increasing the voltage gap between the HV3 electrode and the cathode electrode; the energy resolution (Fig. 3 (b)) improves from (3.12 ± 0.05) % at HV3 = -160 V to (2.11 ± 0.05) % at HV3 = -250 V; further improvements were obtained for the peak-to-valley ratio (Fig. 3 (c)) and for the photofraction (Fig. 3 (d)). Increasing the HV3 bias voltage improves the charge collection on the small central pixel, due mainly to the reduction of the broadening of the electron cloud.

Fig. 4 shows the detector response to the ^{241}Am source at various *HV2* and *HV1* bias voltages (HV2 > HV1; HV = -160 V and HV3 = -230 V) The best energy resolution of (2.17 ± 0.05) % FWHM at 59.5 keV was measured with HV2 = -70 V and HV1 = -60 V (Fig. 4 (a)). This result is due to the best compromise obtained among the broadening of the electron cloud, the charge trapping effect and the noise associated with the leakage currents. Instead, the peak-to-valley ratio (Fig. 4 (b)) and the photofraction (Fig. 4 (c))

improve with the increase of the absolute values of the HV2 and HV1 bias voltages.

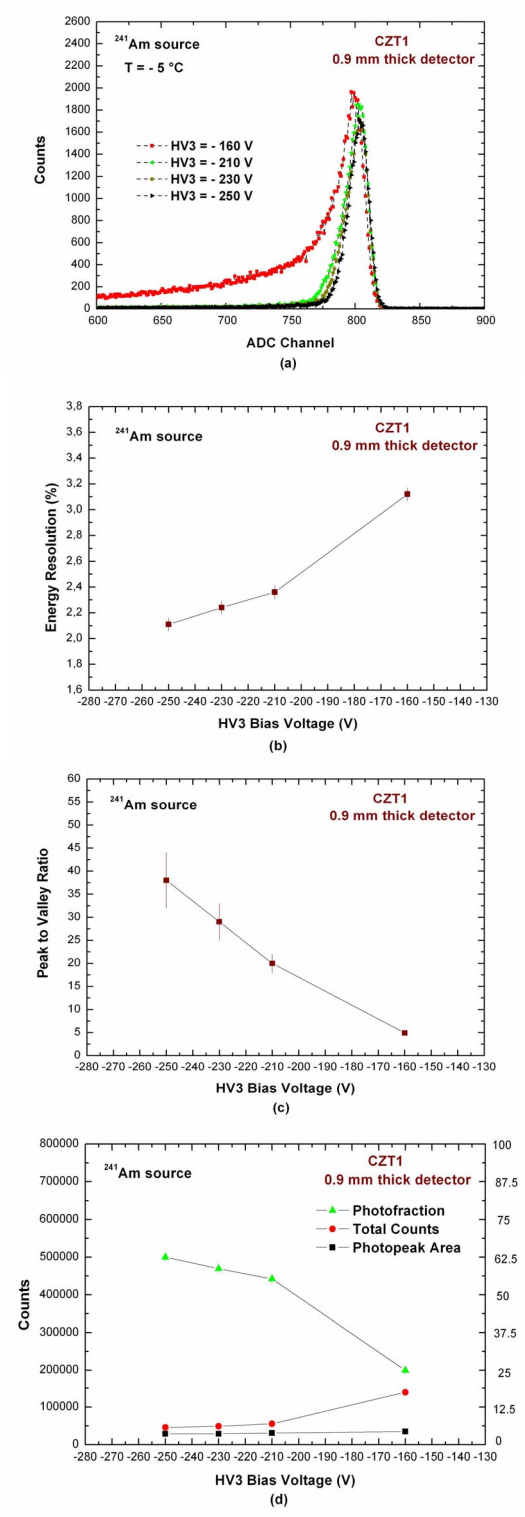

Fig. 3. The ^{241}Am response of the CZT1 detector at various HV3 bias voltages, with HV2 = -50 V, HV1 = -30 V and HV = -160 V (T = -5 ° C). (a) The measured spectra. Fig. 3 (b), (c) and (d) show energy resolution, peak to valley ratio and photofraction vs. HV3 bias voltage, respectively.

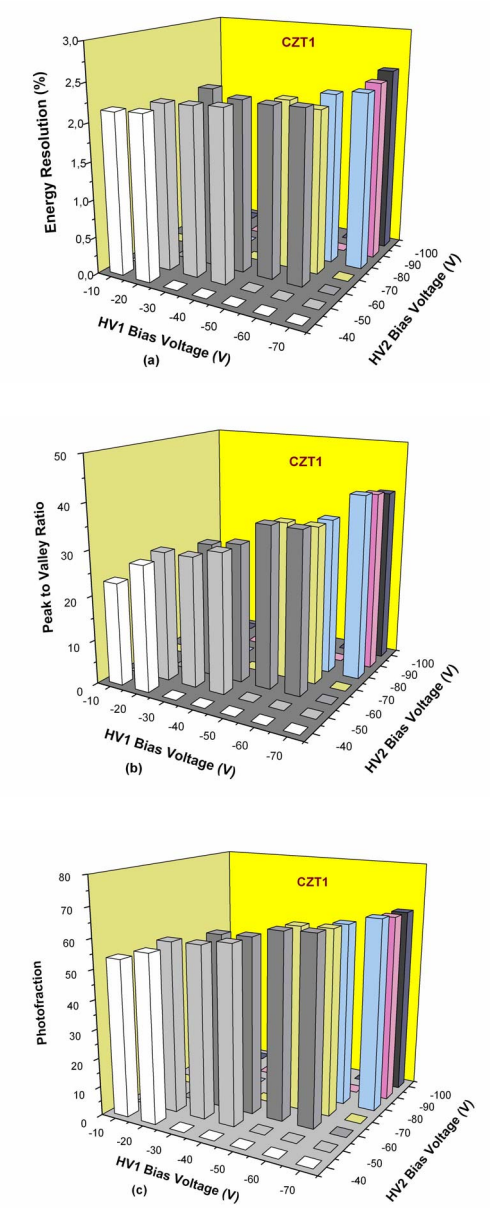

Fig. 4. The ^{241}Am response of the CZT1 detector at various HV2 and HV1 bias voltages. (a) energy resolution, (b) peak to valley ratio and (c) photofraction vs. HV2 an HV1 bias voltages.

The effects of cathode bias voltages (*HV*) on the spectroscopic performances of the detector are shown in Fig. 5 (a), (b) and (c). A cathode bias voltage of -120 V (HV3 = -230 V, HV2 = -70 V, HV1 = -60 V) is the best value for the spectroscopic performances: energy resolution of (2.03 ± 0.05) % FWHM, photofraction of (66.1 ± 0.8) and peak-to-valley ratio of (38 ± 7). Despite a decrease in the photon counts (Gaussian area of the photopeak was decreased of about 44% changing the bias voltage from HV = -200 V to HV = -120 V), reducing the HV voltage improves the charge collection and thus the spectroscopic performances of the detector. This improvement is due to both the reduction of leakage current and the increase of the voltage gap between HV3 and HV electrodes (negatively biased; HV3>HV);

increasing the voltage gap reduces the broadening of the electron cloud an thus optimizes the charge induced on the collecting electrode.

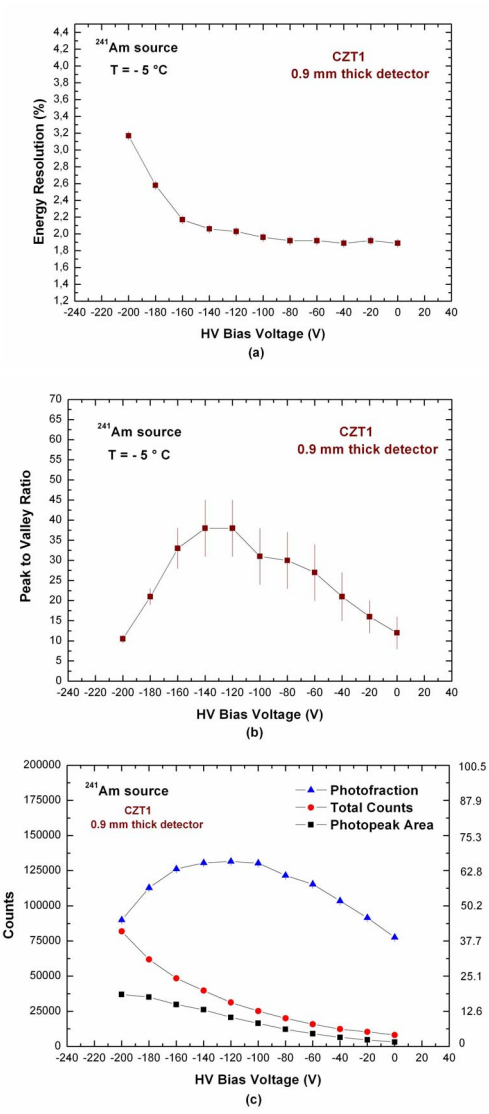

Fig. 5. The ^{241}Am response of the CZT1 detector at various HV bias voltages (T = -5 ° C). (a) energy resolution, (b) peak to valley ratio and (c) photofraction vs. HV bias voltage.

IV. Preliminary Measurements for the 0.55-mm Thick Detector (CZT2)

A study of the spectral response of the CZT2 detector, measuring the ^{241}Am response at various *HV3* bias voltages, with a fixed bias voltage setting of the other electrodes (HV = -100 V, HV2 = - 50 V, HV1 = -30 V), was performed. As shown in Fig. 6, the bias voltage of -130 V is the best compromise among the broadening of the electron cloud, the charge trapping effect and the leakage currents. Higher HV3 bias voltages increase the surface leakage current and its associated noise.

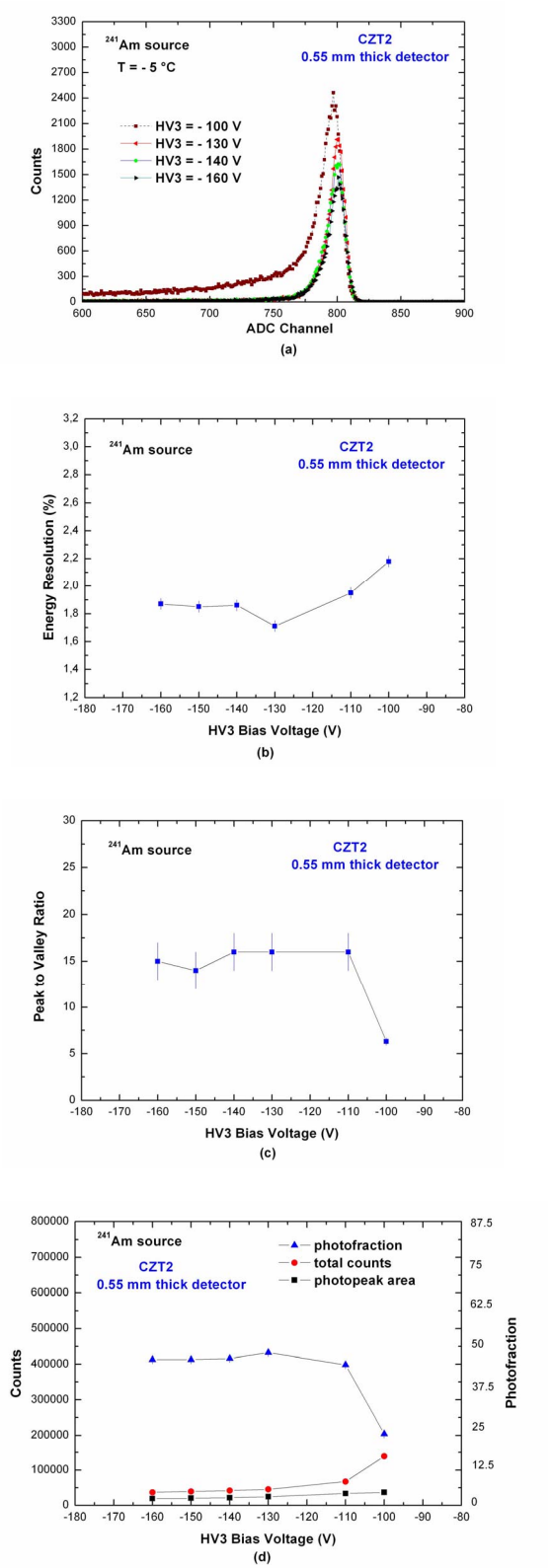

Fig. 6. The ^{241}Am response of the CZT2 detector at various HV3 bias voltages, with HV2 = -50 V, HV1 = -30 V and HV = -100 V (T = -5° C). (a) The measured spectra. Fig. 6 (b), (c) and (d) show energy resolution, peak to valley ratio and photofraction vs. HV3 bias voltage, respectively.

V. Results and Discussion

Figs. 7 and 8 show the ^{241}Am spectra measured with the CZT detectors at working temperature of -10 °C; optimal biasing of the detectors, according to the above measurements, was used: *CZT1*: HV3 = -250 V, HV2 = -70 V, HV1 = -60 V and HV = -120 V; *CZT2* = HV3 = -130 V, HV2 = -45 V, HV1 = -20 V and HV = -100 V.

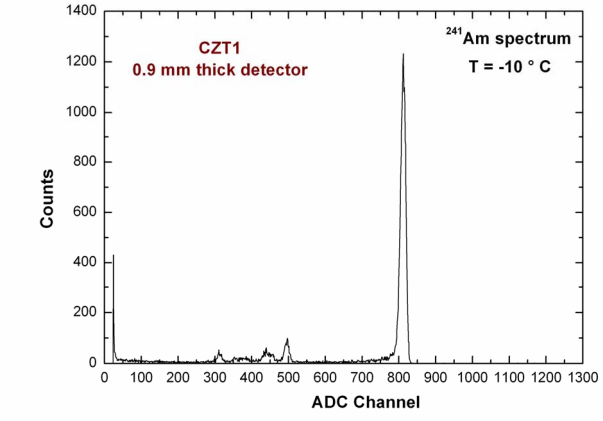

Fig. 7. The ^{241}Am spectrum measured with the CZT1 detector.

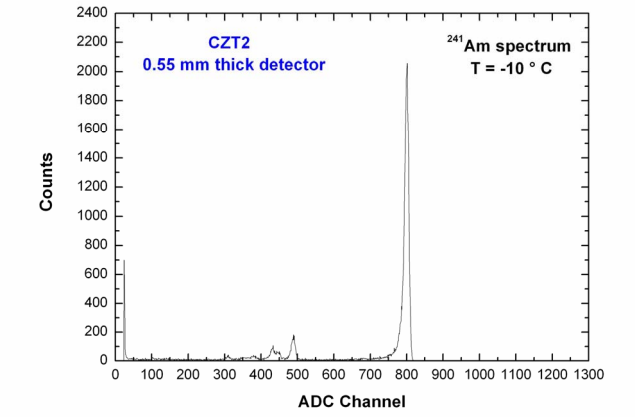

Fig. 8. The ^{241}Am spectrum measured with the CZT2 detector.

The spectroscopic performances of the detectors are summarized in table II. The CZT2 detector shows better energy resolution than the CZT1 detector. This result is due to both the smaller broadening of the electron cloud and to the lower surface leakage currents in the CZT2 detector; the smallest broadening of the electron cloud in the CZT2 detector (due to its thinner thickness) improves the charge collection on the small collecting anode and also requires lower bias voltages of the anode electrodes, reducing the noise associated with the surface leakage currents. Despite a better energy resolution, higher tailing characterizes the spectra measured with the CZT2 detector; the full-energy peak of the ^{241}Am spectrum (59.5 keV) shows a FW.1M/FWHM ratio of 2.35 (percentage deviation of 29% from an ideal gaussian peak, $FW.1M/FWHM_{gauss} = 1.82$) and 1.93 (percentage deviation of 6 % from an ideal gaussian peak) for the CZT2 and the CZT1 detector, respectively. The CZT2 detector is more sensitive to the hole carriers because the charge generated from the 59.5 keV gamma rays is closer to the anode detector and thus the induced charge on the collecting anode is also contributed from the drift of the holes. Moreover, reducing the detector thickness increases the ratio of the pixel size to the thickness and thus reduces the single charge collection effect on the detector, according to the ″small pixel effect″ [8]. The reduction of the photofraction for the CZT2 detector is mainly due to its lower quantum efficiency.

TABLE II
SPECTROSCOPIC RESULTS FOR THE CZT DETECTORS

Detector	CZT1	CZT2
Energy Resolution (%)	1.95 ± 0.05	1.65 ± 0.05
Peak to Valley Ratio	38 ± 7	17 ± 2
FW.1M/FWHM (Gaussian = 1.82)	1.93 ± 0.07	2.35 ± 0.07
Photofraction	67.1 ± 0.9	59.5 ± 0.6

VI. Conclusions

The study of the spectral response of two CZT detectors, with five electrodes (cathode, anode and three steering electrodes), was reported. We investigated on the ^{241}Am response of the detectors, characterized by an identical anode layout but different thickness, at various bias voltages of the electrodes. The detectors showed quite good performances at the optimized bias voltages (Table II), making them very attractive candidates as x-ray spectrometers mainly for medical applications. Further measurements are currently in progress in order to investigate the performances of the detectors at different energies, at various photon count rates and by using different collimator diameters. Our studies will concentrate on the development of portable systems, based on CZT detectors, for medical applications.

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