Invited Paper

Optical Engineering and Characterization of the Internal Electric Field of CdZnTe Radiation Detectors

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ABSTRACT

A new method of engineering the internal electric field of CdZnTe (CZT) radiation detectors will be introduced. The internal electric field distribution within a CZT detector is engineered via an infrared beam with a special photon energy and characterized by a separate polarized optical transmission profile beam utilizing the Pockels electro-optic effect. A theoretical model and calculation will be presented to understand the internal electric field engineering we have performed in our work. 2-dimensional (2D) images reflecting the internal electrical field intensity changes will be shown and the application of this field engineering method to improve the radiation detectors will be discussed.

Keywords: Optical Engineering; Optical Characterization; CdZnTe room-temperature radiation detectors; internal electric field distribution; Pockels electro-optic effect, Crystal defects.

1. INTRODUCTION

The internal electric field distribution is an important key factor for the performance of semiconductor radiation detectors. Each year, radiation detector researchers and manufacturers have made great effort to redesign or modify hardware for better detector performances, such as improved energy resolutions, sensitivities and signal to noise ratios. The hardware improvements, in essence, have been mainly aimed to redistribute the internal electric field distribution in a radiation detector to accomplish higher photopeak resolution and efficiency. Those detectors are in general known as single-charge collection devices, such as the coplanar electrodes[1] and the three-electrode detectors[2], etc. Those device structures are usually complex, difficult and expensive to manufacture.

In this paper, we introduce a new technique to engineer the internal electrical field optically through an external infrared light source.

2. EXPERIMENTAL

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Figure 1 shows a sketch of the method for engineering the internal electric field optically: a planar semiconductor radiation detector is applied with a bias voltage V; an optical light beam with a selected photon energy is used to illuminate on detector and engineer the internal electric field. The internal electric field distribution within a CZT detector is characterized by a separate polarized optical transmission profile beam utilizing the Pockels electro-optic effect.[3-5] Our studies indicate that different light beam intensities or photon energies produce different distributions of the internal electric field, as shown in Figures 2 and 3.

Figures 2 & 3 show two-dimensional (2D) images and line profiles of the internal-electric-field distributions inside a 5x5x5 mm planar CdZnTe (CZT) radiation detector at the bias of 1000 Volts under four different conditions of the optical illuminating light. Fig. 2 (a) & (c): without the optical illumination, a uniform electric field distribution is observed crossing the entire thickness of the detector. Fig. 2 (b) & (d): illuminated by a light beam I_0 having a photon energy of 1.5 eV. The observed electric field is compressed into a narrow strip of ~1/3 of the detector thickness, with the voltage displacement compressed to the cathode side. Fig. 3 (a) & (c): with the same illuminating light as in Fig. 2 (b) but reduced beam intensity to 0.05 I_0. Here, the field is compressed into a wider area of ~ 1/2 of the detector thickness with a wider base across the detector. Fig. 3 (b) & (d): illuminated by a light beam I_0 having a photon energy of 1.7 eV. In this case the field observed is compressed into a wider area compared to Fig. 2 (b) with a different line profile as shown in Fig. 3 (d). The solid arrows in (c) & (d) in both figures indicate the physical edges of the detectors. The leakage current I_{LK} is labeled for each case in Fig. 2. It is noticeable that the leakage current increases as the field is compressed into a

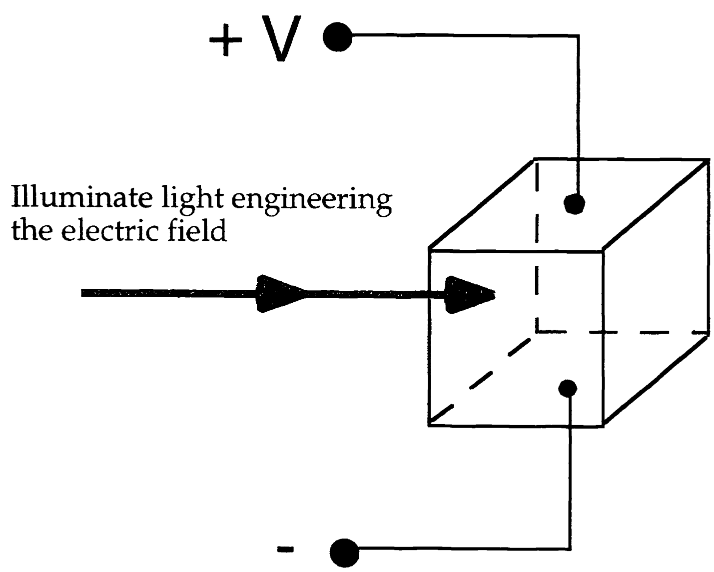


Figure 1. Experimental setup of the optical engineering of the internal electric field of a semiconductor radiation detector.

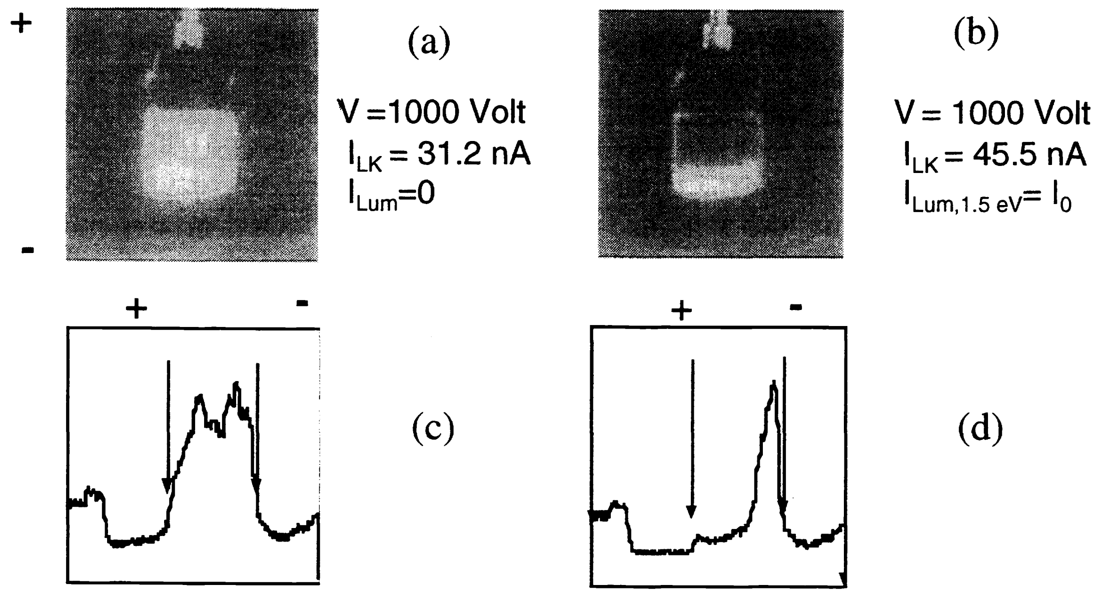


Figure 2. 2D images and line intensity profiles from the 5x5x5 mm planar CZT detector at the bias of 1000 Volts under two different conditions of the optical illuminating light. (a) & (c): without the optical illumination; (b) & (d): illuminated by a light beam I_0 having a photon energy of 1.5 eV.

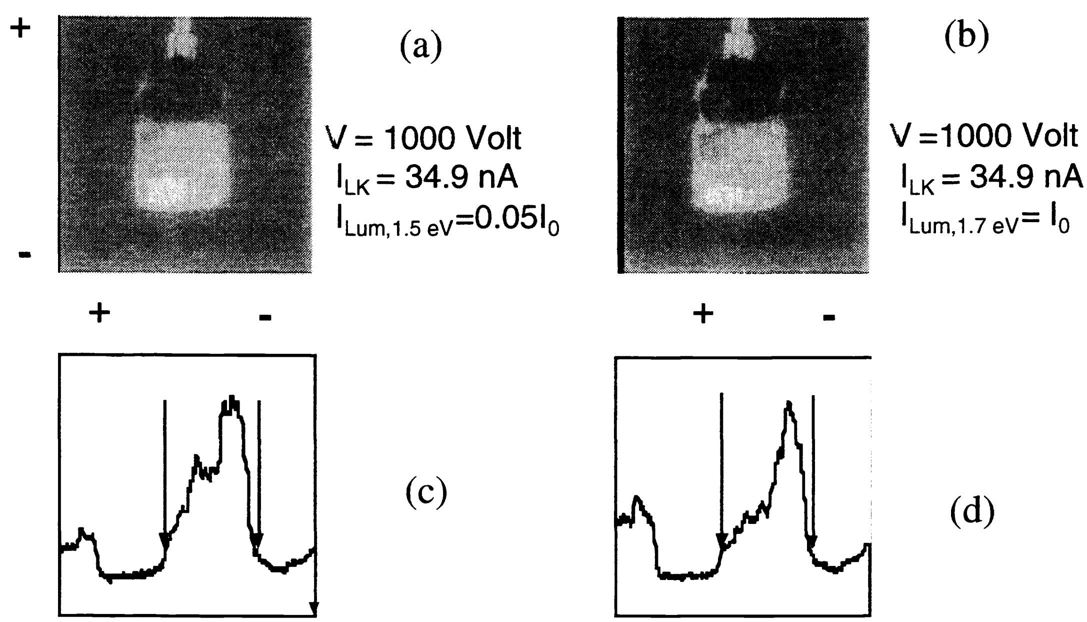


Figure 3. 2D images and line intensity profiles from the 5x5x5 mm planar CZT detector at the bias of 1000 Volts under two different conditions of the optical illuminating light. (a) & (c): illuminated by a beam of photon energy of 1.5 eV with reduced beam intensity to 0.05 I_0; (b) & (d): illuminated by a light beam I_0 having a photon energy of 1.7 eV.

a narrower area. The photon-energy dependency and the physics of the photo-induced current will be discussed later in this paper.

3. THEORY AND DISCUSSION

Fig. 4 shows sketches of a proposed energy band model to understand the internal electric field distribution. With no bias, the energy band should be flat, and the detector is field free. With applied bias voltage, the energy band is tilted without bending, assuming that the material is free of defects (see Fig. 4A). In this case, a uniform electric field is built across the detector. Illuminated by photons with selected energy a detector will, under an applied bias, release trapped electrons from defect states, creating an ionized-ion region. The free electrons drift towards the anode, and the ionized ions form a depletion layer region on the cathode side in which the internal electric field is enhanced, as shown in Fig. 4 A, B & C. The accumulated free electrons screen the internal electric field, and flatten part of the energy band. When it reaches equilibrium, as shown in Fig. 4 C, the energy band is partially bent with a built-in enhanced electric field in the band bending area (i.e., near the cathode side). This area is also known as depletion layer.[6] Within the depletion layer, the built-in electric field is nearly uniform, while outside the bending area, the field intensity is much lower (about a factor of 10-100 smaller). This is the situation shown in Fig. 5.

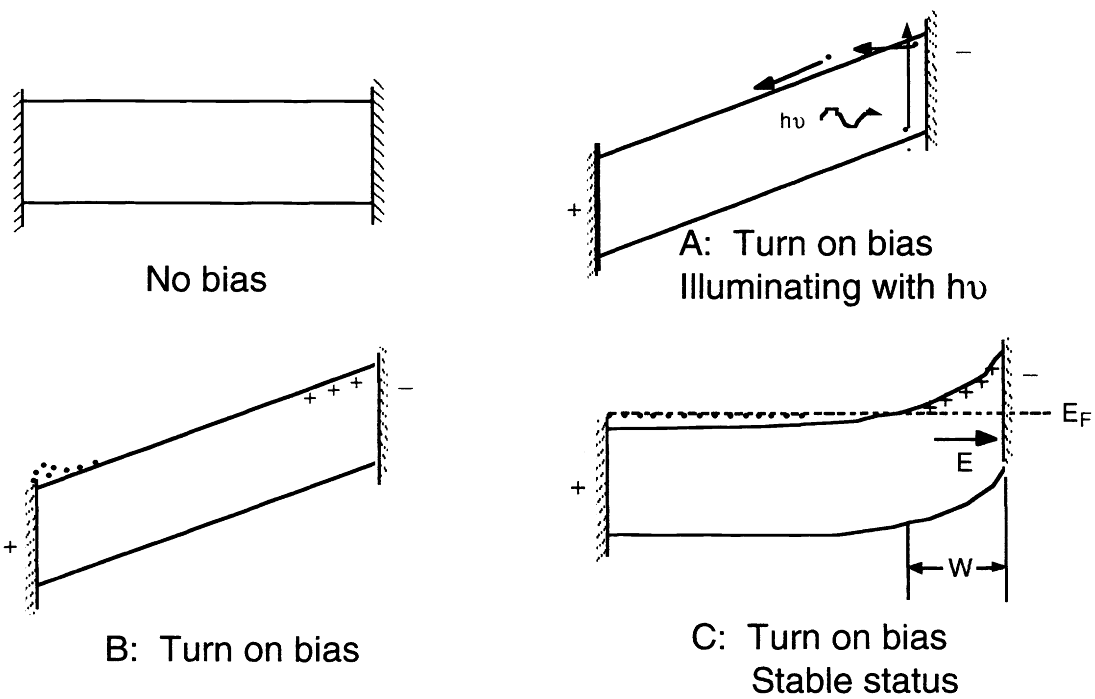


Figure 4. Sketches of a proposed energy band model: the electrons are represented by (•); holes are sketched as (+) and photons are marked as hυ.

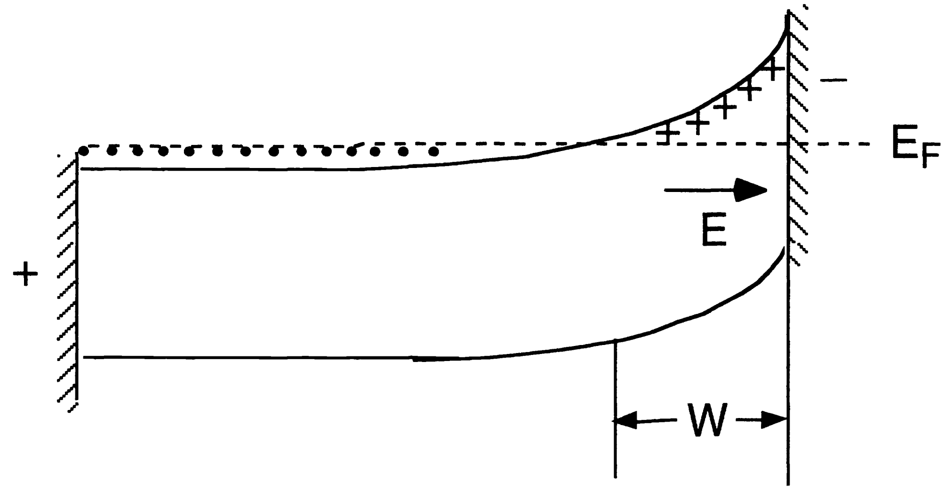


Figure 5. A sketch of the energy band bending and depletion layer model described in the text.

Quantitative analysis can be performed by setting up and solving the Poisson's equation, assuming a uniform background of ionized ions:

$$\frac{d^2\Phi}{dz^2} = \frac{-\rho}{\varepsilon_r \varepsilon_o}, \tag{1}$$

where the z-axis is normal to the surface and points from surface into the bulk of CZT detector.

Since

$$\frac{d^2\Phi}{dz^2} = \frac{1}{2}\frac{d}{d\Phi}\left(\frac{d\Phi}{dz}\right)^2, \tag{2}$$

it follows that

$$d\left(\frac{d\Phi}{dz}\right)^2 = \frac{-2\rho}{\varepsilon_r \varepsilon_o} d\Phi, \tag{3}$$

and,

$$\frac{d\Phi(z)}{[\Phi(z)]^{1/2}} = -\left(\frac{2\rho}{\varepsilon_r \varepsilon_o}\right)^{1/2} dz. \tag{4}$$

From the boundary conditions: $\Phi(W) = 0$ and $E(W) = -\left(\frac{d\Phi}{dz}\right)_{z=W} = 0$, we have

$$\Phi(z) = \frac{\rho}{2\varepsilon_r\varepsilon_o}(z - W)^2. \tag{5}$$

With applied bias voltage V, we have

$$\Phi(0) = \frac{\rho}{2\varepsilon_r\varepsilon_o}W^2 = V, \tag{6}$$

Therefore,

$$W = \left(\frac{2\varepsilon_r\varepsilon_o\Phi(0)}{\rho}\right)^{1/2} = \left(\frac{2\varepsilon_r\varepsilon_o V}{eN_I}\right)^{1/2}, \tag{7}$$

where $\rho = eN_I$, and N_I is the ionized-ion density.

From the calculation, we can see that the width of this depletion layer W is proportional to the square root of the bias voltage V and inversely proportional to the square root of the ionized active trapping density N_I. As an example, for a bias of 1000 volts, a depletion layer of 5 mm, the active trapping density N_I is ~ $4 \times 10^{10}/cm^3$.

In figure 6, a sharp peak of photo-induced current I_{LK} in a CZT detector is found at 1.5 eV, while the I_{LK} remains unchanged below ~1.32 eV. The leakage current is in essence indicating the degree of detrapping of electrons from the defect states. The sharp peak at 1.5 eV also indicates the location of the high electron trapping densities, i.e., 1.5 eV below the bottom of the conduction band. The higher I_{LK} is related with larger electric field modification. The sharp peak indicates a narrow window of photon energies which are most effective at compressing the electric field. Therefore, by changing the intensities or photon energies of the illuminating light, we can realize the engineering of the electric field in semiconductor radiation detectors under bias. By tailoring the internal electric field, improvement of the detector energy resolution and photopeak efficiency are possible.

It is plausible that we can utilize this technique of electric field engineering to produce a semiconductor radiation detector with improved photopeak resolution. Currently, the main problem for semiconductor radiation detectors is the hole trapping, which provides a broad trail to the detected photopeak and thus reduces the resolution and marketability of the detectors.[7] The hole trapping is caused by low mobility μ_h and lifetime τ_h of holes, which essentially reduce the drifting length of holes $l_h = \mu_h\tau_h E$ and cause the poor hole collection efficiency. The $\mu_h\tau_h$ product depends on the intrinsic properties of semiconductor crystals and cannot be increased without major efforts to improve the quality of the crystals. An alternative way to increase the hole drifting length is to increase the electric field intensity E in the region where the holes were generated and collected. The electric

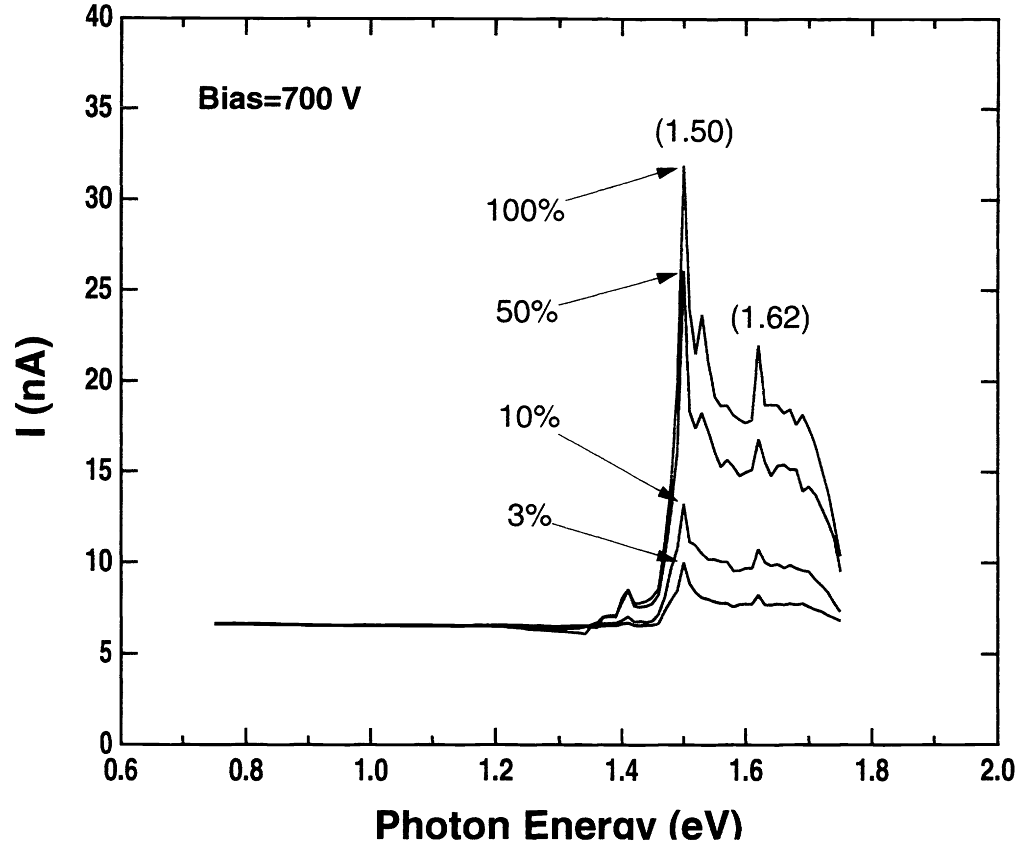
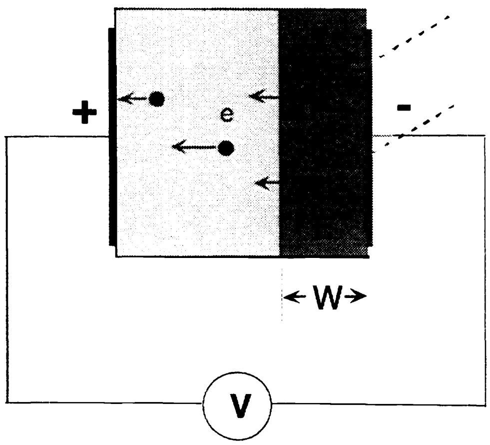


Figure 6. Spectra of photo-induced current of a CZT detector under different illumination intensities, at a bias voltage of 700 volts.

field engineering technique, described in this paper, provides a unique way to increase the $\mu_h \tau_h E$ value as shown in Fig. 7 (a).

As shown in Fig. 7 (a), the electric field is optically engineered to a width W narrower than the detector width. The electric field is concentrated on the cathode side. Low-energy gamma rays or X-rays incident from the cathode side generate electron-hole pairs predominantly near the cathode. The electrons are collected at the anode side, while the holes drift towards the cathode. Due to the increased drifting length of holes $l_h = \mu_h \tau_h E$, the hole collection efficiency increases and the hole trapping tail from the detector is greatly reduced. The width of the electric field can be fine-tuned by changing the optical beam intensity and wavelength, so that the radiation detector performance can be optimized. A sketch of the proposed Field Engineered Radiation Spectrometer (FERADS), an improved radiation spectrometer based on the optical engineering is shown in Fig. 7 (b).



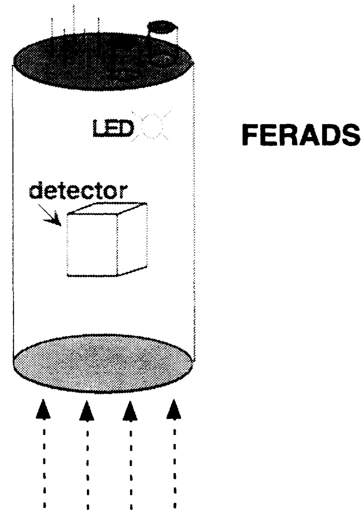


Figure 7. Sketch of the field engineering technique applied for improving quality of the room-temperature radiation detectors, as described in the text.

Fig. 7 (b) shows a planar semiconductor detector installed in a cylindrical box along with an light-emitting diode (LED) of the special selected photon energy tunable for use in the optical engineering of the internal electric field and optimization of the detector performance. This kind of semiconductor radiation detector is portable, small size and operates at room temperature. Many smaller detectors could be stacked, vertically and horizontally, with the same box to further increase the overall detector efficiency. More work needs to be done in applying this field engineering technique to improved radiation detectors.

4. CONCLUSIONS

We have presented a new nondestructive method of engineering the internal electric field of CdZnTe radiation detectors. The internal electric field distribution within a CZT detector is engineered via an infrared beam with a special photon energy, i.e., 1.5 eV or higher. An energy-band depletion-layer model gives quantitative analysis of the field distribution. The electric field distributed within the depletion layer width is proportional to the square root of the bias voltage V and inversely proportional to the square root of the ionized active trapping density N_I. The sharp peak shown in the spectra of the photo-induced current at 1.5 eV indicates the location of the high electron trapping densities. The sharp peak also indicates a narrow window of photon energies which are most effective at compressing the electric field. We have also presented the possibility of utilizing this technique of field engineering to improve the energy resolution and photopeak efficiency of the CZT radiation detectors.

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