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STUDY OF THE TEMPERATURE DEPENDENCE OF THE DARK CURRENTS NON-UNIFORMITY FOR SOME VIDEO-CAMERA CHIPS

Ralf WIDENHORN[1], Erik BODEGOM[1],
Dan-Alexandru IORDACHE[2], Viorica IORDACHE[2]

Rezumat. *Pentru a explica rezultatele experimentale privind neuniformitatea curenţilor de întuneric corespunzând diferiţilor pixeli ai chip-ului unei camere video, au fost efectuate: a) studiul numeric al dependenţelor de temperatură a curenţilor de întuneric, pentru a stabili modelul teoretic cel mai simplu care poate descrie suficient de precis rezultatele experimentale, b) evaluarea parametrilor de bază ai pixelilor studiaţi, corespunzând modelului teoretic ales, c) studiul corelaţiei dintre aceşti parametri şi implicaţiile asupra dependenţei de temperatură a neuniformităţii curenţilor de întuneric pentru diferiţi pixeli ai chip-ului studiat.*

Abstract. *In order to explain the experimentally found non-uniformity of the dark currents corresponding to different pixels of a video-camera chip, there were accomplished: a) a numerical study of the temperature dependence of the dark currents, in order to find the most convenient theoretical model which can describe sufficiently accurate the experimental data, b) the evaluation of the basic parameters of the studied pixels, corresponding to the chosen theoretical model, c) the study of the correlation between these parameters and their implications on the temperature dependence of the dark currents non-uniformity for different pixels of the studied chip.*

Keywords: Video camera, Digital images, CCDs chips, Dark currents non-uniformity

1. Introduction

In order to improve the applications in Astronomy [1] of some Charge Coupled Devices, the corresponding dark currents were measured and studied.
Taking into account that:
a) the merit factor of these photo-sensors is equal to the ratio of the photo- and dark current,
b) the photo-currents corresponding to some astronomic sources could be very weak,
c) the existence of some important differences between the emission parameters of the different pixels could influence the image of weak sources,
d) the existence of some experimental studies of the dark currents non-uniformity in CCDs [2], our study was focused on the:

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[1] Professors, Physics Department, Portland State University, United States of America.
[2] Prof., Prof. Eng., Physics Chair II, University “Politehnica” of Bucharest, Romania.

(i) numerical analysis of the experimental data concerning the dark currents corresponding to different pixels,

(ii) explanation of the basic features of the statistical (for very large numbers of different pixels) distribution of the dark current values at different temperatures.

2. Experimental results

The dark currents corresponding the charge-coupled devices housed in the Spectra Video Camera SV512V1, as well as their corresponding standard errors, for different temperatures between 222 and 291 K were measured according to the experimental procedures described by work [3].

From beginning, it was found:
(i) the drastic decrease of the dark currents (around of 10^5 times) at 222 K, relative to 291 K, that allows a considerably better resolution of the weak intensity images at 222 K,
(ii) the considerable differences (of the magnitude order of 10) among the dark currents of different pixels at the same temperature (see Fig. 1).

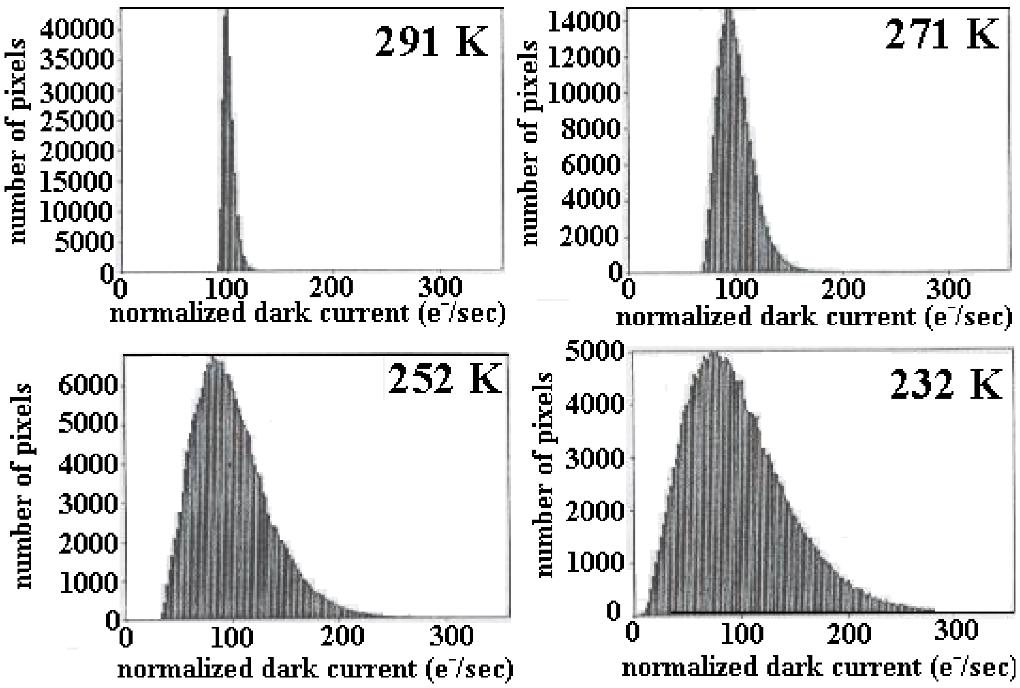

Fig. 1. Dark current histograms at 232, 252, 271 and 291 K.
The average dark current is normalized to 100 e$^-$/s.

The individual values of the dark currents corresponding to 20 pixels, at different temperatures are indicated by Table 1.

Table 1

Values of the dark currents (in pulses per second, pps), at different temperatures, corresponding to 20 pixels arbitrarily chosen of the charge-coupled devices (CCDs) housed in the Spectra Video Camera SV512V1

Temperature	Coordinates (x, y) of the considered pixel				
(K)	41, 120	61, 140	81, 160	101, 280	121, 200
222	0.001484	0.012969	0.008295	0.006282	0.006063
232	0.026228	0.040539	0.034914	0.023767	0.029031
242	0.100662	0.149438	0.129242	0.095945	0.112173
252	0.424933	0.618465	0.526984	0.415553	0.474378
262	1.969514	2.505146	2.218795	1.880534	2.053744
271	9.22872	10.75346	9.733896	8.843086	9.471216
281	44.35249	48.04459	45.19955	43.17259	44.65022
291	217.7895	227.3067	219.0285	214.2660	216.9518

Temperature	Coordinates (x, y) of the considered pixel				
(K)	141, 220	161, 240	181, 260	201, 280	221, 300
222	0.008583	0.005350	0.006074	0.017147	0.015157
232	0.026559	0.023663	0.022282	0.065254	0.053210
242	0.102486	0.093614	0.091008	0.234979	0.189289
252	0.440118	0.428868	0.398030	0.868245	0.730125
262	1.941113	1.981857	1.838440	3.188347	2.798395
271	9.129981	8.892988	8.703706	12.20961	11.44398
281	43.64158	43.45940	42.30294	52.23446	49.53068
291	215.0924	215.9305	211.0063	237.3687	229.4021

Temperature	Coordinates (x, y) of the considered pixel				
(K)	241, 320	261, 340	281, 360	301, 380	321, 400
222	0.006311	0.012803	0.018370	0.014709	0.003675
232	0.033265	0.057419	0.072716	0.060266	0.007298
242	0.123681	0.210351	0.253919	0.218637	0.039933
252	0.501478	0.818504	0.967605	0.812199	0.244018
262	2.086141	3.116074	3.481746	3.061305	1.421787
271	9.464486	12.01514	13.30162	12.36033	7.927352
281	44.62626	51.54383	54.33791	53.08315	41.07097
291	217.6235	236.1418	242.3072	243.6041	209.9430

Temperature	Coordinates (x, y) of the considered pixel				
(K)	441, 420	31, 247	29, 88	188, 471	161, 289
222	0.012025	0.025084	0.009511	0.005372	0.000314
232	0.051089	0.084750	0.041729	0.017136	0.002851
242	0.196514	0.316796	0.161847	0.074848	0.021359
252	0.777152	1.129892	0.647090	0.365805	0.171535
262	2.943100	3.855564	2.568672	1.818186	1.154768
271	11.37274	12.72840	10.73541	9.043002	6.090657
281	49.31115	51.63198	47.82530	44.73338	37.94227
291	231.6490	234.6485	226.2279	223.1231	199.2435

3. Basic Data Processing

Taking into account the complex character of the diffusion and depletion processes that lead to the dark currents emission, the use of some purely numerical parameters is indicated.

That is why we calculated: a) the decimal logarithms $\log De_i^-(T)$ of the dark currents $De_i^-(T)$, b) the arithmetical averages $\left\langle \log De_i^-(T)\right\rangle$ of the dark currents logarithms for different pixels at a given temperature, c) the corresponding geometrical average of dark currents $\left\langle De^-(T)\right\rangle$, d) the square mean deviations $s\left(\log De^-(T)\right)$ – for each studied temperature - of the decimal logarithms of the dark currents, that represents a true measure of the dark currents non-uniformity, e) the mean amplitudes (in percents) $A\left[s\left(De^-(T)\right)\right]$ corresponding to the square mean deviations $s\left(\log De^-(T)\right)$, for each temperature. Table 2 synthesizes the obtained results.

4. Basic Theoretical Model

The theoretical model of dark currents in CCDs was studied in detail by works [4] - [6]. Because for a CCD used in the multi-pinned phase (MPP) mode, the surface dark current generated at the $\mathrm{Si\text{-}SiO_2}$ interface is almost completely suppressed, the main remaining sources of dark currents are the depletion (or bulk) current generated in the depletion region and the diffusion dark current from the field-free region.

Table 2

The values corresponding to the main statistical parameters of the dark currents non-uniformity, for the 20 above indicated arbitrarily chosen pixels (see Table 1)

Parameter	Temperature (K)							
	222	**232**	**242**	**252**	**262**	**271**	**281**	**291**
$\langle\log De_i(T)\rangle$	-2.138	- 1.5086	- 0.9061	0.2719	0.3603	1.0032	1.668	2.34856
$\langle De^-(T)\rangle$ (pps)	0.00727	0.03100	0.124137	0.5347	2.2925	10.075	46.4301	223.134
$s[\log De^-(T)]]$	0.4159	0.3409	0.2723	0.1980	0.1299	0.0730	0.04050	0.02233
$A[s(De^-(T))]$	160.5%	118.4 %	87.19%	57.76%	34.86%	18.3%	±9.77%	±5.27%

In the region depleted of carriers (of size x_{dep}, where the electric field sweeps the electrons and holes to the *n*- and *p*-regions, resp.) of CCDs operating in the deep-depletion mode (when $n, p \ll n_i$), the depletion dark current in e^-/s (or counts/s) per pixel is:

$$De^{-}_{dep} = De^{-}_{0,dep} \cdot T^{3/2} \cdot \frac{\exp\left(-\frac{E_g}{2kT}\right)}{\cosh\left[\frac{E_t - E_i}{kT} + a\right]}, \tag{1}$$

where: $$a = \arg\tanh\frac{\sigma_p - \sigma_n}{\sigma_p + \sigma_n}, \quad \alpha = -\lim_{T \to 0\,K} \frac{dE_g}{dT}, \tag{2}$$

E_g being the energy gap, E_i - the intrinsic Fermi level, while σ_p, σ_n are the cross-sections for holes, and electrons, respectively.
Similarly, the diffusion contribution to the dark currents is given by the expression [3b], [6]:

$$De^{-}_{diff} = De_{0,diff} \cdot T^3 \cdot \exp\left(-\frac{E_g}{kT}\right). \tag{3}$$

The accomplished study pointed out that the simplified theoretical model that assumes that the cross-sections corresponding to holes and electrons, resp. are practically equal: $\sigma_p \approx \sigma_n$, leads to sufficiently accurate descriptions of the temperature dependence of dark currents, being so the most suitable to the present study.

5. Results of the accomplished calculations

We accomplished the fitting of the parameters of the theoretical model given by relations (1) [with the assumption $\sigma_p = \sigma_n$] and (3), obtaining the values of parameters $|E_t - E_i|$ (see table 3), $De^{-}_{0,diff}, De^{-}_{0,dep}, E_g$.

Table 3

The basic parameters of impurities present in the studied CCD chip

Impurity	$\|E_t$-$E_i\|$, meV	Generation rates (e^-/s at 55^{0}C)	References
Pt_1	≈ 20		[7]
Ni, Co	< 30	3700	[9]
Au_1	< 30	565	[9]
Mn	< 50	6400	[9]
Pt_2	≈ 60	970	[9]
Pt_3	90 … 130		[8], [10]
Non-identified impurity	100	70	[9]
Fe	120 … 150	195	[9]

The average accuracy of this description (2.36%) is better than that of the standard (simplified) description (2.7225%) and rather near to the lowest limit of experimental errors (1.608%). The examination of the obtained results indicates that the spreading of the electrical engineering parameters – dark currents is mainly produced by the spreading (due to the pixels non-uniformity) of the physical parameters E_g and $|E_t - E_i|$. In fact, after the elimination of the roughly erroneous values, the remaining results grouped in the confidence intervals:

a) $|E_g| \in [1.04, 1.07]\,eV$ (4 pixels), $|E_g| \in [1.07, 1.08]\,eV$ (10 pixels),

$|E_g| \in [1.09, 1.13]\,eV$ (4 pixels), (4)

and: b) $|E_t - E_i| = 27.14 \pm 7.16\,meV$ (for 11 pixels),

$|E_t - E_i| = 54.47 \pm 5.90\,meV$ (for other 6 pixels), (5)

$|E_t - E_i| = 91.01\,meV$ (for the 18th studied pixel).

The obtained results for the energy difference $|E_t - E_i|$ are in agreement with the results obtained by means of other experimental methods [7]-[10]. Taking into account the central role of the energy gap E_g, the correlation coefficients $r(E_g, P)$ of its obtained values with different other parameters P of the studied pixels were also calculated. Due to the low values of the correlation coefficients corresponding to the pixel position:

$$r(E_g, pixel's\ X\ index) \cong -0.43671,\ r(E_g, pixel's\ Y\ index) \cong -0.13286,$$

$$r(E_g, distance\ pixel - chip\ center) \cong 3.54 \times 10^{-7},$$

one finds that the physical parameters of pixels do not depend on their position inside the studied chip. Due to the action of the Meyer-Neldel relations [11], unlike the rather low values of the above indicated correlation coefficients, those corresponding to $r(E_g, P)$, where the parameter P is the logarithm of a pre-exponential factor $D\bar{e}_{0,diff}, D\bar{e}_{0,dep}$ or even the modulus of the energies difference $|E_t - E_i|$ are considerably higher: $r(E_g, D\bar{e}_{0,diff.}) \cong 0.999945$, $r(E_g, D\bar{e}_{0,depl.}) \cong 0.881$, and: $r(E_g, |E_t - E_i|) \cong 0.67658$. One finds so that the energy gap E_g is very strongly correlated with the pre-exponential factor $D\bar{e}_{0,diff}$, a medium strength correlation with $D\bar{e}_{0,depl.}$, and a weak correlation with the energies difference $|E_t - E_i|$.

For this reason, we studied also the regression lines expressing the logarithms of the pre-exponential factors in terms of the gap energy E_g:

$$\log De^{-}_{0,diff.} = i + \frac{E_g}{kT_{o,diff.}}\ , \qquad \log De^{-}_{0,depl.} = i' + \frac{E_g}{2kT_{o,depl.}} \tag{6}$$

where *i, i'* and $T_{o,diff.}$, $T_{o,depl.}$ are the intercepts, and the characteristic temperatures, of the regression lines corresponding to the diffusion and to the depletion processes, respectively. Introducing the expression (6) in the relations (1) and (3) describing the contributions of the diffusion and depletion processes, resp. to the dark currents, there are obtained the expressions:

$$De^{-}_{diff.} = \exp\left[i + \frac{E_g}{k}\left(\frac{1}{T_{o,diff.}} - \frac{1}{T}\right)\right] \cdot T^3,$$

$$De^{-}_{depl.} = \exp\left[i' + \frac{E_g}{2k}\left(\frac{1}{T_{o,depl.}} - \frac{1}{T}\right)\right] \cdot T^{3/2} \Big/ \cosh\left[\frac{E_t - E_i}{kT}\right]. \tag{7}$$

The accomplished calculations starting from the experimental results synthesized by Table 1, led to the values:

$i \cong - 10.3815$, $T_{o,diff.} \cong 300\,K$, and: $i' \cong - 7.103$, $T_{o,depl.} \cong 274\,K$.

6. Interpretation of the obtained results

Because: a) the correlation coefficient $r\left(E_g, De^{-}_{0,diff.}\right) \cong 0.999945$ is very high, the relation (6a) is very accurate, and: b) the characteristic temperature ($T_{o,diff.} \cong 300\,K$) of the diffusion phenomenon is rather near to the studied temperatures [located inside the range 222….291 K], the spreading of the diffusion currents values is rather small. Despite the characteristic temperature $T_{o,depl.} \cong 274\,K$ is located even inside the range of studied temperatures (222….291 K), because: a) the correlation coefficient $r\left(E_g, De^{-}_{0,dep.}\right) \cong 0.881$ is not too high, hence the relation (6b) is not an exact one, existing a considerable spreading of the pre-exponential factor $De^{-}_{0,dep}$ values around the regression line indicated by relation (6b), b) the depletion currents depend also on the values of the energies difference $|E_t - E_i|$, that: (i) present a considerable spreading [see expression (5)], (ii) are not practically correlated with the energy gap E_g, the spreading of the depletion currents is considerably higher than that of the diffusion dark currents.

Because the depletion currents prevail at lower temperatures, it results that the spreading of the dark currents will be considerably larger at low temperatures, in agreement with the experimental results indicated by Figs. 1.

Conclusions

Studying the Meyer-Neldel correlations of the energy gap E_g separately with the pre-exponential factors $De^{-}_{0,diff}, De^{-}_{0,dep}$ corresponding to the dark diffusion and depletion currents, resp., this work pointed out a very strong correlation with the pre-exponential factor $De^{-}_{0,diff}$ and only a medium strength correlation with $De^{-}_{0,dep}$. Taking into account: a) the additional dependence of depletion dark currents on the energies difference $|E_t - E_i|$, and: b) the spreading of this difference values, the considerably stronger non-uniformity of the dark currents at low temperatures can be easily explained.

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