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A review of dark current nonlinearities in CCD image sensors

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Abstract

Charge coupled devices are the image sensors extensively used in scientific imaging. One of the problems of low light imaging is the collection of additional thermal charge during the exposure. In the paper the results and conclusions of 4-year research on dark current abnormalities are presented. Their sources and possible explanation for the observed phenomena are investigated. The dark current unique behavior should be taken into account especially while imaging in extremely low light level conditions.

Keywords: charge coupled devices, imaging, dark current.

Przegląd nieliniowości prądu ciemnego w matrycach CCD

Streszczenie

Matryce CCD są czujnikami wykorzystywanymi do rejestracji obrazów. Ze względu na pełne wykorzystanie powierzchni światłoczułej są one wykorzystywane, gdy ilość padającego światła jest bardzo niska. Do takich zastosowań należy m.in. obrazowanie w astronomii, gdzie czasy naświetlania pojedynczego zdjęcia sięgają wielu minut. Jednym z problemów przy tego typu zastosowaniach jest obecność prądu ciemnego, który wnosi do obrazu składową addytywną zależną od temperatury czujnika. W celu wyeliminowania tych zjawisk temperaturę matrycy CCD stabilizuje się wykorzystując m.in. ogniwa Peltiera oraz wykonuje się tzw. klatki ciemne (zdjęcia bez dostępu światła), aby następnie odjąć je od otrzymanego obrazu. Taka technika korekcji zakłada, że procesy termiczne przebiegają w sposób stały oraz, że są one niezależne od oświetlania matrycy. W artykule przedstawiono trzy typy nieliniowości prądu ciemnego, dla których powyższe założenia nie są spełnione. Pierwszy typ powiązano ze specyficznym położeniem defektu generującego ładunek termiczny, natomiast drugi typ skojarzono z obecnością defektów strukturalnych - dyslokacji. Trzecim rodzajem opisywanych zjawisk są losowe skoki tempa generacji termicznej. Wiedza o problemach prądu ciemnego jest kluczowa w przypadku dokonywania korekcji naukowych zdjęć źródeł emitujących niewielką ilość światła. Uwzględnienie odmiennych zachowań generacji termicznej pozwala na poprawę jakości skorygowanych obrazów.

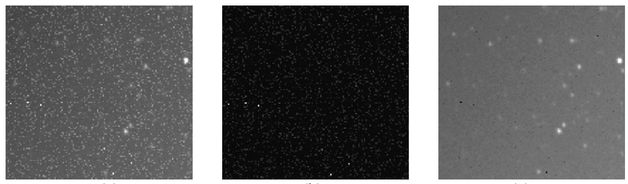
Słowa kluczowe: matryce CCD, obrazowanie, prąd ciemny.

1. Introduction

Charge coupled devices are the main image sensors extensively used for scientific imaging [1]. They consist of a matrix of pixels where the electrons induced by falling light are accumulated during the exposure. In the readout cycle they are transferred to the output gate where the charge of each pixel is converted to the voltage. CCDs have loads of applications including astronomical, biomedical and physics imaging [2, 3]. Their main advantage, comparing with CMOS sensors, is the high quantum efficiency, thus they are the most efficient imagers in low-light conditions.

One of the most important limitation for using CCD matrices for scientific purposes is the dark current [1]. It originates in the microscopic defects within the pixel, like point defects (intrinsic atoms, vacancies) or spatial defects (dislocations). Such faults induce additional energetic levels in the forbidden band of the silicon and enhance the temperature emission of electrons to the conduction band.

The effect of the dark current generation is visible in the image as characteristic ‘salt and pepper’ noise. Such a noise is additive that means it biases the charge in the pixels. It is strongly dependent on the temperature thus if the temperature is low – the dark charge is also low. It is extremely important to stabilize the temperature of the sensor for proper dark current removal. The standard method of correction involves the dark frames which are the images obtained under zero-light conditions (CCD is blocked from the light) and at the same temperature as the corrected image. In the next step, such a frame is subtracted from the image to remove the thermal offset (see example in Fig. 1). Sometimes the dark frames are taken with lower exposure time and charge is scaled linearly to fit the exposure time of the corrected image.



(a) (b) (c)

Fig. 1. Exemplary astronomical image (a), corresponding dark frame (b) and the image with dark frame subtracted (c). SBIG11000 astronomical camera, exposure time 60s, (author’s image)
Rys. 1. Przykładowe zdjęcie astronomiczne (a), odpowiednia klatka ciemna (b), zdjęcie z usuniętym wpływem prądu ciemnego (c). Kamera astronomiczna SBIG11000, czas ekspozycji 60 s. (zdjęcie autora)

The dark frame subtraction method assumes that the thermal and light induction of the electrons are the independent processes. Moreover, the linear scaling of the charge assumes the linear exposure time dependency of the thermal charge. It is shown that some of the pixels do not meet this assumptions, because they have nonlinear time dependency of thermal charge and the light may disturb their dark current generation. It should be taken into account while dealing with the low light imaging or when applying dark frame subtraction.

The paper is organized as follows. In Section 2 the dark current nonlinearities of point defects are presented. Then the explanation of the problems of dislocations of thermal generation is given in Section 3. In Section 4 there is a discussion of the random telegraph signals behavior of the dark current. Finally the summary is given in Section 5.

2. Nonlinearities of point defects

The point defects are very popular sources of the dark current in CCDs. They are introduced usually during the fabrication of the device. The impurity atoms (like gold, nickel, cobalt, etc.) built into silicon structures are very efficient dark current centers. Another type of point defect is the vacancy which may emerge due to the collusions of heavy particles (e.g. the proton) with the CCD silicon. Such phenomena are very common in devices working in the space, where the flux of heavy particles is much greater than near the ground, thus it gradually destroys the matrix increasing the dark current [4].

The results of the presence of point defects in CCD can be detected by visible distinctive local maxima of the dark current histogram as it is shown in Fig. 2 (the ADU in the figures stands for Analog-to-Digital Units which represent the digitalized value of charge accumulated in a pixel). One can notice that the generation rate for the second maximum is about twice the rate of the first maximum. This is because the first maximum includes the pixels with one point defect within the pixel structure, while the second represents the pixels with two similar defects. The probability of two defects inside the pixel is far lower thus the second peak is less distinguishable. If there were more pixels in CCD, the third peak, related to three same defects in a pixel, should be also noticeable.

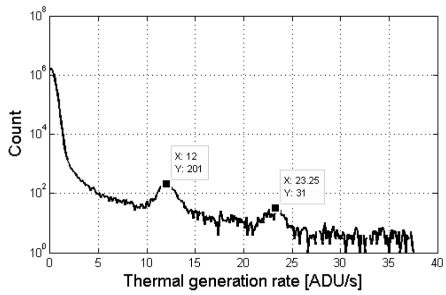


Fig. 2. Dark current generation histogram for KAI 11000 CCD sensor at 5 °C
Rys. 2. Histogram generacji prądu ciemnego w matrycy KAI11000 w temperaturze 5 °C

Typically the defects generate the dark current continuously with the same generation rate. It is the assumption for using and scaling the dark frames. However, after capturing a series of dark frames with variable exposure times and analyzing observed dependencies, some pixels with nonlinear behavior were found. Their dependencies show quick generation transition from initial, high generation rate to nearly zero well below the saturation ($65 \cdot 10^3$ ADU), as it is presented in Fig. 3. One should notice that the initial generation rate is very similar to 12 [ADU/s] which indicates that the origin of the dark current is the same type of defect.

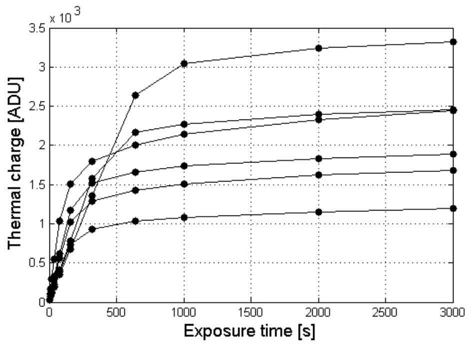


Fig. 3. Exemplary nonlinear dark current dependencies in KAI11000 sensor at 5 °C
Rys. 3. Przykładowe nieliniowe zależności prądu ciemnego w matrycy KAI11000 w temperaturze 5 °C.

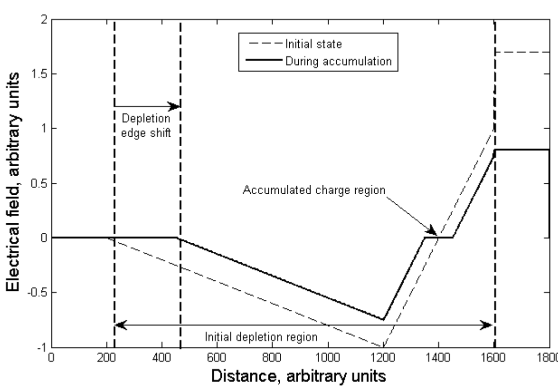


Fig. 4. CCD pixel electrical field cross section
Rys. 4. Zależności pola elektrycznego wewnątrz piksela

The reason for such nonlinearities was suggested in the author's paper [5] and is a unique localization of a point defect within pixel structure. The main part of the pixel is the depletion region, where the photoelectric effect takes place and where the charge is accumulated. It is actually the active region of CCD pixel where all phenomena take place. However, as the charge accumulates, the depletion region shrinks due to the internal electric field lowering. The initial electrical field and its changes are presented in Fig. 4. Although the shift is very small, relative to the depletion width, some of point defects, located near the depletion edge, encounter different electrical conditions during the exposition. Initially they are within the depletion and their dark current generation is high, but as accumulated charge increases, they are swept from depletion and cannot longer produce thermal charge.

Such a location of the point defect has also an impact on the effectiveness of the dark frame subtraction method. This method assumes the independence of thermal and photon effects in the pixel. However, as it has been explained above, the reason for depletion shrinking is the accumulation of the charge in a pixel. Thus the velocity of depletion shrinking will be dependent on the light flux which can quickly move the edge and turn off the thermal source. The dark charge accumulated in such pixels will be lower than that in the dark frame anytime the light introduces extra electrons. The effects of such dark frame subtraction errors can be easily visible in the corrected images as distinctly darker pixels.

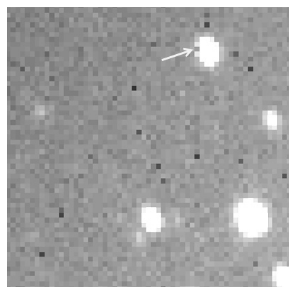


Fig. 5. Exemplary part of the dark frame subtracted astronomical image. Several darker points visible. The arrow indicates the object pixel with visibly lowered charge
Rys. 5. Przykładowy fragment zdjęcia skorygowanego poprzez odjęcie klatki ciemnego. Widoczne ciemniejsze, źle skorygowane piksele. Strzałką wskazano wyraźne zaniżenie wartości ładunku w obrębie obiektu astronbomicznego

3. Nonlinearities of dislocations

The dislocations are the sets of vacancies forming the lines or spirals. They are usually introduced by the process of fabrication of silicon wafers [6]. They are formed as the result of high temperature variations and the stress during the production. A part of dislocation is visualized in the Fig. 6.

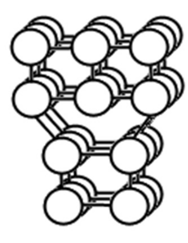


Fig. 6. Visualization of linear dislocation
Rys. 6. Wizualizacja dyslokacji liniowej w krzemie

The dislocations have different sizes thus the dark current introduced by them may have a variety of rates. The histogram of the dark current does not contain any distinctive peaks and is rather elongated. The research of these phenomena was carried on Kodak sensor KAF8300. Its dark current histogram is presented in Fig. 7.

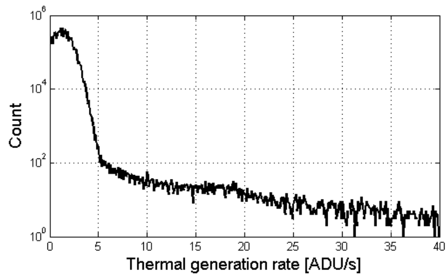


Fig. 7. Dark current generation histogram for KAF8300 CCD sensor at 5 °C
Rys. 7. Histogram prądu ciemnego w matrycy KAF8300 w temperaturze 5 °C

The exposure time dependencies of the dislocation dark current exhibit the gradual lowering of the rate (see Fig. 8). There are no visible transitions and no linear parts. It indicates that the reason of such behavior is not the depletion shrinking.

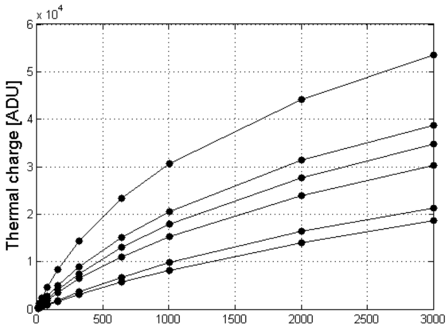


Fig. 8. Exemplary nonlinear dark current dependencies in KAF8300 sensor at 5 °C
Rys. 8. Przykładowe nieliniowe zależności prądu ciemnego w matrycy KAF8300 w temperaturze 5 °C

The explanation of such abnormalities can be made with the use of the dislocation barrier model developed in Institute of Physics PAN by T. Figielski [7]. One can find that the dislocation negative charge (free electrons) creates the potential well around the dislocation. The holes captured by the well reduce the number of electrons reaching the dislocation what reduce the generation rate. This mechanism was described in details by the author [8]. The theory was confirmed in the experiments where the light response of the dark current was measured. It proved that the holes induced by the photoelectric effect were captured by dislocation and reduced the dark current generation rate.

The barrier model of dislocation allows also for a simulation of possible dependencies of the dark current. The calculations utilized in the model are based on the iterative solving of the system of differential equations and are not presented in this review due to its complexity. A set of simulated dependencies for different dislocation sizes is shown in Fig. 9. The resulting curves have similar shape to the ones observed in the real matrix (Fig. 8).

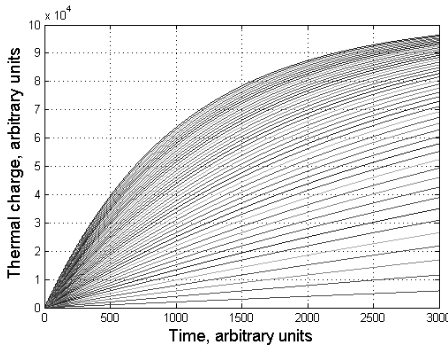


Fig. 9. Dependencies of the dislocations dark current simulated using the barrier model
Rys. 9. Zależności prądu ciemnego modelowane z wykorzystaniem modelu barierowego

Similarly to the point defects located near the depletion edge, applying dark frame subtraction to dislocation affected pixels introduces lowering of the charge. It is well known that the photoelectric effect induces the electron-hole pair. While the electron is accumulated in pixel potential well, the hole may be captured by the dislocation decreasing its thermal efficiency thus the images corrected using standard dark frame subtraction show the same problems as in Fig. 5.

4. RTS dark current behavior

The CCDs working in the space suffer mostly from the random telegraph signals (RTS) of the dark current. The RTSs are the random changes of the generation rate between two or rarely free levels. Unlike the previously described problems, these are the nonlinearities in the time domain. Several examples of dark current RTS time series are presented in Fig. 10.

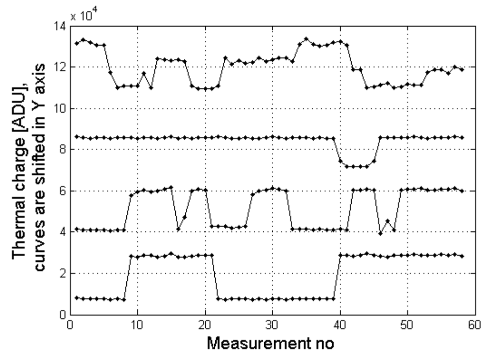


Fig. 10. Exemplary four RTS dark current dependencies in KAI11000 sensor
Rys. 10. Przykładowe zależności prądu ciemnego obrazujące zachowania typu RTS w matrycy KAI11000

RTS dark current behavior is very rare in CCDs operating on the ground, but in the space they are significant problem limiting the lifetime of the matrices [4]. A strong proton flux introduces permanent damage in the CCD pixel structure, thus many so-called hot and flickering pixels appear [9].

Several explanations for fluctuating pixels are available in the literature [10]. One of them is the creation of an electric field around the defect, which influences the nearby defects. Another possible reason is the presence of a multistable defect changing its generation rate between two (or more) stable energetic states. However, the most probable explanation provides the model which involves the reorientation of a phosphorus-vacancy (P-V) pair. Such a defect is called E-center and is a common defect in proton irradiated silicon. P-V pair has a dipole momentum which is enhanced by the field depending on its relative orientation. The phenomenon is still investigated mainly by analyzing the dark current induced in proton irradiated CCDs and the results of defects annealing in elevated temperature.

It is extremely difficult to correct the images affected by the RTS dark current. Standard dark frame subtraction cannot be applied due to the uncertainty of current generation rate. The strategy of image calibration in such a situation is reduced to detecting and ignoring flickering pixels. Another solution is the application of very strong cooling to minimize the dark current so that it was negligible.

5. Summary

In the paper several sources of nonlinearities of the thermal generation in charge coupled image sensors are described. Using popular scientific grade Kodak CCDs some already unnoticed dark current problems are highlighted.

The first reason for dark current nonlinearity presented in the paper is a unique localization of point defect within the pixel structure. It is pointed that a group of pixels contains the defects located at the edge of the depletion region. As the edge moves, the defect generation rate decreases. The second type of nonlinearity is induced by the dislocations. The physics of these defects provides the explanation for the gradual lowering of the dark current. Additionally, in the paper it is mentioned that the random telegraph signals of the dark current are the source of significant problems especially for CCDs operating in the space. The most probable reason for such a problem is the presence of phosphorus-vacancy pairs induced by heavy protons.

All of the presented nonlinearities of the dark current have to be considered while imaging in low light level conditions. The impact of the light on the generation rate and the dark current randomness (RTS) cause severe errors of the standard correction method based on the dark frame removal. The awareness of such problems encountered during the calibration and correction of the low light images is crucial to obtain the unbiased flux measurements.

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