A new measurement method of interface-state parameters, based on dark current characterization in CCDs.

W.J. Toren, J. Bisschop[1] and F.P. Widdershoven.
Philips Imaging Technology (Philips Research Laboratories),
Prof Holstlaan 4, 5656 AA Eindhoven, The Netherlands.
E-mail: toren@natlab.research.philips.com
[1]: Philips Semiconductors. Bldg FB 0.049 A, Gerstweg 2, 6534 AE Nijmegen.

Abstract.
A new measurement method to characterize the extremely-low dark-current generation rate of interface states in a buried-channel n-type CCD image sensor will be presented. With this method the capture cross section and the interface-state density can be determined with one single static measurement at room temperature. Besides the average dark current generation rate, this method also uses the dark current distribution of all pixels of the CCD. The shape of this distribution gives an extra parameter with which the results can be obtained. The accuracy of this method is much higher than methods that use a dynamic measurement sequence, because the newly proposed method can be done at one temperature and does not need to be exponentially fitted.

Introduction.
Interface-state dark current in CCD image sensors causes a noise component, which decreases the quality of the sensors. To reduce this noise component, a better understanding of the generation process behind it is needed. In this paper a model is presented which determines the number of interface states in a pixel which can be used for the process optimization.

The model.
The model for the generation rate of interface states considers a sensor with a large number of interface states, all with different activation energies. The distribution of the number of interface states over all pixels will be according to a Poisson distribution. In literature [1,2], a homogeneous distribution of the activation energy around midgap is reported. The distribution increases slightly close to the conduction and valence band. Because these interface states do not contribute significantly to the total dark current, no large error is made when a homogenous distribution is considered over the whole bandgap.

Probability density of the dark current generation rate for one interface state.
This section will show that interface states can be divided into two groups. One group contains interface states that are considered "off", which means that these states do not generate dark current, and the second group contains interface states that are considered "on", so that they generate the maximum dark current. It will be shown that this assumption is plausible and that the presented model will fit the measurements.

The model for the generation rate of interface states of [3,4] is used.

$$G = \frac{G_{max}}{\cosh(\frac{E_a - E_i}{kT})} \quad with: \; G_{max} = \frac{1}{2} v_{th}\, \sigma\, n_i \qquad (1)$$

where σ is the "overall" cross section for interface states and E_a is the activation energy of the interface state.

A better understanding of the dark current generation will be obtained by solving the probability density of the generation rate of one interface state. This means: what is the probability that an interface state has a certain generation rate? The probability density of the generation rate, $P_G(G)$, in a small interval dG must be equal to the probability density of the activation energy, $P_{Ea}(Ea)$, in a corresponding small interval dEa.

$$P_G(G)\,|dG| = P_{Ea}(Ea)\,|dEa| \qquad (2)$$

The probability density of the activation energy $P_{Ea}(Ea)$ is considered homogeneous and is therefore equal to $1/E_g$, resulting into:

$$P_G(G) = \frac{2kT}{G.Eg} \frac{1}{\sqrt{1-(\frac{G}{G_{max}})^2}} \qquad (3)$$

The factor 2 is included because states in both the lower and upper halves of the bandgap must be taken into account. From (3) one can determine the average generation rate <G>:

$$\langle G \rangle = \int_{G_{min}}^{G_{max}} P_G(G)\, G\, dG \;\approx \frac{\pi kT}{E_g} G_{max} \;, G_{min} \ll G_{max} \qquad (4)$$

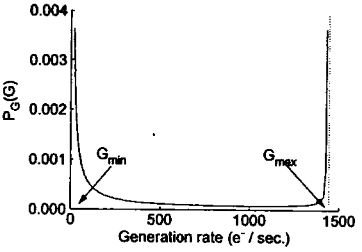

Figure 1 *The probability density of the generation rate of one interface state.*

In Figure 1 the probability density of the generation rate is schematically drawn for a σ of 10^{-15} cm^2 and a temperature of 333 K. The distribution looks very much like a binomial distribution. The minimal and maximal generation rates, G_{min} and G_{max}, have a high probability density. The values of the generation rate between these G_{min} and G_{max} have very low probability densities. It seems acceptable to use a binomial distribution instead of the distribution of interface states (3). Interface states with an activation energy close to the conduction band or the valence band are "off" and states close to midgap are "on".

The total dark current generation rate of one pixel.

To calculate the generation rate of one pixel, the total number of states in this pixel, N_t^T, has to be determined from the Poisson distribution, and the average number of these interface states that are "on", $<N_{on}>$, has to be determined from the binomial statistics. The generation rate of this pixel is then the number of "on" states multiplied by G_{max}. However, the same result will be obtained when *only* "on" states are considered. The distribution of these "on" states over the pixels also follows a Poisson distribution. One fit parameter, $<N_{on}>$, remains, which determines the shape of the generation rate distribution.

The measurements give an average dark current for one pixel. This average value divided by $<N_{on}>$ gives the maximum generation rate, G_{max}. From this maximum generation rate the capture cross section can be determined using (1). The total number of interface states can be calculated by:

$$N_t^T = \frac{G_{max}}{<G>} <N_{on}> = \frac{E_g}{\pi kT} <N_{on}> \qquad (5)$$

The accuracy of the measurement method.

The capture cross section is determined with (1). In this equation the parameters that have been measured are the temperature and the average generation rate, and the only fit parameter is the average number of "on" states, $<N_{on}>$. The total error of σ is estimated as +/- 25%. This is far better than the determination of σ by first calculating the activation energy of the generation rate with experiments using different temperatures and then determining the σ from the exponential fit. An error of a factor of two can easily be made with that approach.

Experiments and results.

To check the model, three series of experiments were carried out. The dark current distribution from one sensor was measured at four different temperatures (40, 50, 60, 70 °C) marked as measurement 1 to 4 respectively. Second, one sensor was biased with six different DC settings, to achieve six different depleted interface sizes, measurement 1 (the largest depleted area) to 6 (the smallest depleted area). In the last series the distribution of four different sensors is compared, measurement 1 to 4. These sensors have a different total dark current, because of a different process. Sensor 1 has the largest, and sensor 4 the smallest total dark current.

Only the results of the measurement (the generation rate density) with the four different sensors are plotted in Figure 2. The number of "on" states are 24, 9.6, 3.3, and 1.4 resp.

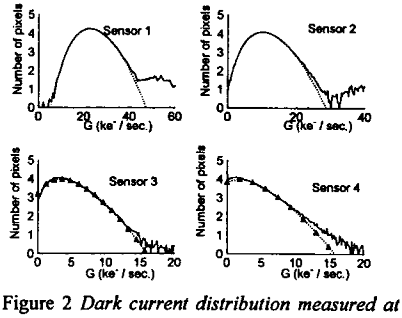

Figure 2 *Dark current distribution measured at four different sensors. The solid lines are the measurements, and the dotted lines are the fits. The markers in the plots of sensors 3 and 4 represent the different number of "on" states. In the plots of sensors 1 and 2 these markers are too close to the neighbouring markers and have been left out. Pay attention to the different x-axes.*

From Figure 2 it is clear that the model fits the data very well. Only sensor 4 differs slightly, which can be explained by a shading component in the sensor.

Overview of the results obtained.

Figure 3 shows an overview of N_t^T determined for all measurements.

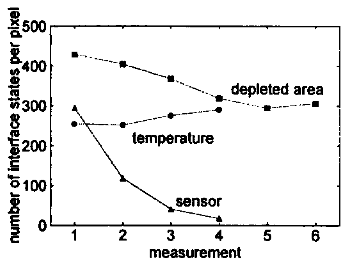

Figure 3 *Overview of the obtained parameter* N^T, *for all measurements. Pixel size is 80 µm²*.

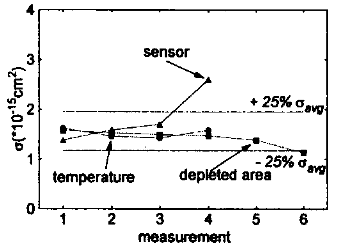

Figure 4 *Overview of the obtained parameter σ for all measurements.*

The number of interface states determined at different temperatures is about constant, as expected. At larger depleted interface areas, the number of interface states per pixel indeed increases from 294 to 428. The model was fitted to the data by using values for the fit parameter $<N_{on}>$ of 25, adjustment with the smallest depleted interface size, to 35, adjustment with the largest depleted interface size.
The number of interface states per pixel measured at the different sensors varies from 293 to 17, from which 24 to 1.4 states per pixel are "on". The interface state density for sensor 3 is $4.7 \cdot 10^7$ cm^{-2} eV^{-1} and for sensor 4 it is even $2 \cdot 10^7$ cm^{-2} eV^{-1}, although the capture cross section differs slightly from the average value.

Figure 4 shows the capture cross section for all the experiments. It is clear that the capture cross section of interface states is about equal for all experiments, except for the sensor with the lowest dark current, which can be explained by the shading component. The horizontal lines in Figure 4 mark the calculated maximum error lines +/- 25% of the average value of σ, which is $1.6 \cdot 10^{-15}$ cm^2. It is clear that all values are located in between these maximum error lines. [3] and [4] measured a σ of $1.0 \cdot 10^{-15}$ and $0.7 \cdot 10^{-15}$ cm^2, which is close to the average measured value in this paper of $1.6 \cdot 10^{-15}$ cm^2. The difference can be explained by a temperature error.

Conclusions.

It has been shown that the interface state parameters can be accurately determined by using a CCD image sensor, even for sensors with very low values of interface state densities. The results are obtained by one static measurement at room temperature. All experiments show a capture cross section around $1.6 \cdot 10^{-15}$ cm^2, which is in good agreement with literature.

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