Metal contamination characterization in CCD image sensors

Willem Jan Toren and Jaap Bisschop[1],
Philips Imaging Technology,
Prof. Holstlaan 4, 5656 AA Eindhoven, The Netherlands.
tel. +31 402744443, fax. +31 402743390, E-mail: toren@natlab.research.philips.com

Abstract

This paper describes a measurement method to characterize metal contamination in charge-coupled devices, CCDs. The capture-cross section of holes and electrons and the activation energy have been determined. With these three parameters the electrical behaviour of the metal is completely defined and a comparison with literature can identify the specific metal. The measurements can be done with about a hundred metal atoms per CCD. This gives a sensitivity of 10^7 atoms per cm^3, which is very high compared with other measurement methods like DLTS [2] (requiring more than 10^{10} atoms per cm^3). In CCDs with an inverted interface, that eliminates dark current generation from interface states [1], one metal atom is enough to determine these parameters. This gives a sensitivity of 10^5 atoms per cm^3.

Introduction

Since the dark current in solid-state image sensors is reduced to a very low level, pixels with an extra generation center become visible as a white pixel. These white pixels now determine the quality of the imager. In order to optimize this quality, these generation centers have to be eliminated, which can be achieved better when the characteristics of the center are known. This paper will show that the generation rate of the centers is quantized, and will explain a measuring method to determine three parameters of the center, which can be compared with literature to find the metal contaminant. Once this metal is identified, it is easier to reduce its presence during the processing of the CCDs.

In CCDs the generated charge is collected in a depleted collection volume during the integration time. After this time the charge is transported to an output structure and is converted to a potential which can be measured. When the sensor is driven in a special mode, some parts of the collection volume can be inverted with holes. This property is used for the measurements.

One type of generation center

Figure 1 shows a histogram of the dark current taken from one image. A highpass filter, with offset equal to zero, is applied to eliminate shading and the number of pixels for every pixel amplitude is offset by one to enable a log plot for zero values. The same procedure is repeated for figures 2 and 4. The number of pixels is plotted versus the amplitude of these pixels.

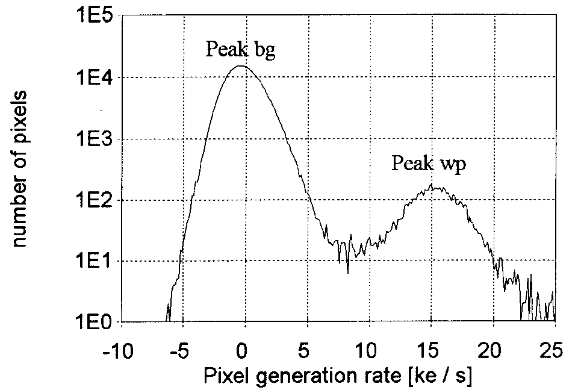

Figure 1. *Histogram of the dark current with two peaks.*

The histogram from figure 1 has two peaks. The first peak (Peak bg = background) is caused by all pixels which are not white pixels. They have an average amplitude, caused by interface state generation. The second peak in the histogram is caused by the white pixels (Peak wp). Their amplitude consists of the normal dark current and an additional generation current of a center.

When the sensor is driven in a second mode, a larger volume can be depleted, and more pixels will get an extra generation center (figure 2). This second histogram has three clear peaks, and a fourth peak with only 3 pixels. The generation rate of Peak wp2 is twice the generation rate of Peak wp1 and it is plausible that peak wp3 has a generation rate three times the amplitude of Peak wp1.

[1]present address: Philips Semiconductors. Bldg FB 0.049A, Gerstweg 2, 6534 AE Nijmegen. tel. + 31 24353 3134, email:c826930@nlevdpsb.serigate.philips.nl

0-7803-2700-4 $4.00 ©1995 IEEE

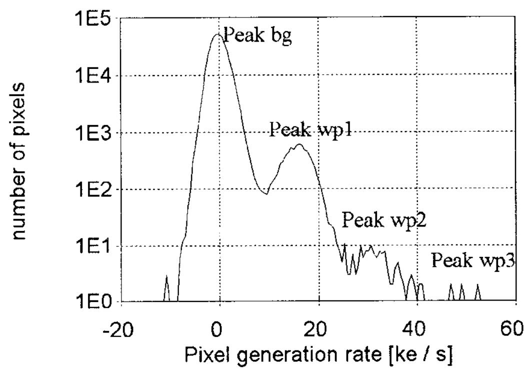

Figure 2 *Histogram of the dark current with four peaks taken from one images with a larger depleted volume.*

Table 1 *Measured and calculated number of pixels per peak.*

# centers	# pixels	Poisson
0	386000	385849
1	7566	7717
2	75	77
3	3	1

Table 1 gives the number of pixels in the four different peaks, and shows the calculated number of pixels with a Poisson distribution. The number of pixels in these peaks clearly follows this Poisson distribution. This implies that the white pixels are caused by only one type of generation center.

Lifetime experiments lasting one week at 150 °C have shown an increase in the number of white pixels. Pixels which begin with a generation rate in peak bg, end the test with a value that has increased to fall in peak wp1.
This experiment together with the quantized amplitude and the Poisson distribution leads to the conclusion that the white pixels with amplitudes in the peak wp1 have one generation center. Pixels in peak wp2 have two centers, and pixels in peak wp3 have three. The spread of these peaks can be explained by the spread of the background dark current.
The amplitude of the white pixels is thus the difference in amplitude of peak bg and peak wp1. From this statement the detection limit follows. To eliminate the background generation a kind of averaging is necessary. One hundred white pixels is about the minimum for this sensor. This corresponds to 10^7 atoms/cm^3. When peak bg is strongly reduced, one center is enough to measure an accurate generation rate. This gives a detection limit of 10^5 atoms/cm^3.

Measuring method

The measuring method is based on what is called "charge pumping". Charge pumping is a technique to invert a depleted volume for a very short period and so to empty the generation centers. After this inversion charge has been removed, the centers will remain empty and it will take some time before they start to generate again (see figure 3). This inversion in CCDs is realized by pulsing the gates negative one by one.

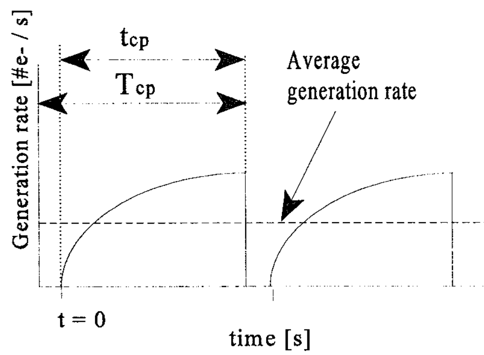

Figure 3. *Generation rate as a function of charge-pump time. t_{cp} is the time the pixel is integrating and T_{cp} is the total cycle time.*

When the integration time between those charge pump pulses (= charge-pump time, t_{cp}) is shortened, the average generation rate is lower. The result is shown in figure 4.

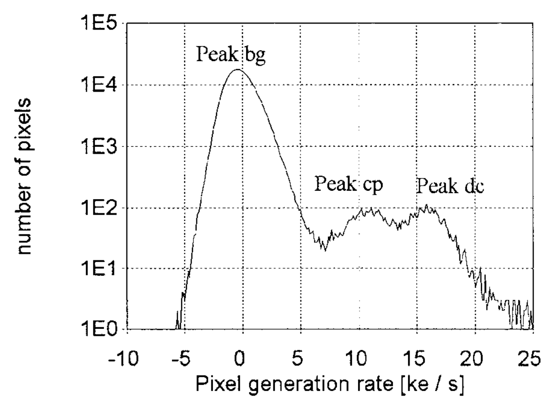

Figure 4 *Histogram of the dark current with three peaks taken from one image with a different charge-pump scheme than figure 1 .*

Peak wp (from figure 1) has split into two peaks, Peak cp and Peak dc. Peak cp contains pixels with generation centers which are affected by the inversion layer. Pixels in Peak dc are not. The generation rate as a function of charge pump time can be measured as the difference in amplitude of Peak bg and Peak cp. By changing the pulse scheme of the CCD drivers, the frequency of inverting a part of the integration volume can be changed. Peak cp will shift to the left or to the right, depending on the clocking. Special filter techniques make it possible to measure the generation rate of the centers, even when Peak cp has disappeared into Peak bg or Peak dc.

The model

Shockley-Read-Hall

The centers have an activation energy in the bandgap of silicon and because the volume of the pixel is depleted they can generate charge according to the Shockley-Read-Hall differential equation:

$$\frac{dN_t^-}{dt} = -\frac{N_t^-}{\tau_n} + \frac{N_t^+}{\tau_p} \qquad (1)$$

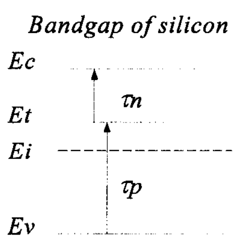

Figure 5 *Schematic view of the energy level of the center*

where N_t^- is the number of filled centers, N_t^+ the number of empty centers and τ_n and τ_p are time constants for electron and hole emission respectively (see figure 5). The two other processes in the Shockley-Read-Hall equation, electron and hole capture, are zero because of the depleted volume.

The DC generation rate

The time constants from (1) are defined by:

$$\frac{1}{\tau_n} = \sigma_n v_{th} n_i \, e^{\frac{E_t - E_i}{kT}} \qquad (2)$$

$$\frac{1}{\tau_p} = \sigma_p v_{th} n_i \, e^{\frac{E_i - E_t}{kT}} \qquad (3)$$

where σ_n and σ_p are the electron and hole capture-cross sections, v_{th} is the thermal velocity, and n_i is the intrinsic carrier density. E_t is the energy level of the states in the bandgap. The number of filled states in equilibrium can be calculated from (1) where dN_t^-/dt is equal to zero and N_t^+ is equal to $N_t - N_t^-$. (N_t = total number of centers)

The DC generation rate of these centers is given by:

$$G_{dc} = \frac{N_t^-}{\tau_n} = \frac{N_t}{\tau_{dc}} \qquad \tau_{dc} = \tau_n + \tau_p \qquad (4)$$

This DC generation rate can be determined by measuring the mean of Peak dc.
When one center is considered, N_t is equal to 1 and the generation rate is expressed in electrons per second.

Generation rate with charge pumping

For this calculation, equation (1) has to be solved. At $t = 0$ all centers are assumed to be empty and the centers are located in a depleted volume. At $t = \infty$, $dN_t^- / dt = 0$. The generation rate of this center as a function of time is given by:

$$G(t) = \frac{N_t}{\tau_{dc}} (1 - e^{-t/\tau_{cp}}) \qquad (5)$$

where $1/\tau_{cp} = 1/\tau_n + 1/\tau_p$. The average generation rate is

$$\langle G(t) \rangle = \frac{1}{T_{cp}} \int_0^{t_{cp}} G(t)\, dt \qquad (6)$$

$$\langle G(t) \rangle = \frac{N_t}{T_{cp} * \tau_{dc}} \left(t_{cp} - \tau_{cp}(1 - e^{-\frac{t_{cp}}{\tau_{cp}}})\right) \qquad (7)$$

For T_{cp} and t_{cp} see figure 3. The average generation rate can be determined by measuring the mean of Peak cp.

Results

Generation as function of the charge-pump time

In figure 6 the generation rate of the centers is plotted as a function of the charge-pump time, t_{cp}, for 8 different temperatures, in electrons per second.
The generation rate of the centers decreases with shorter charge-pump times because the centers are reset more often and the electrons have a smaller chance to arrive in the conduction band. At higher temperatures the charge pumping is less effective because the centers are refilled faster than at lower temperatures.
The fit gives two time constants, τ_{cp} and τ_{dc}, from which τ_n and τ_p can be determined. However it is not clear which value corresponds to τ_n and which to τ_p.

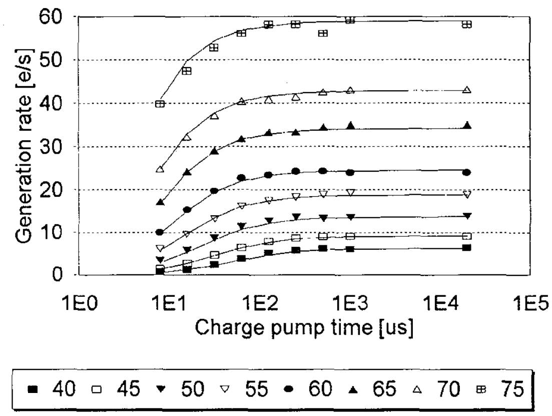

Figure 6. *Generation rate of one center as a function of the charge-pumping time for different temperatures (see legend, in °C). Markers are measured data and the lines are the fits from (7).*

Parameters determined from fit

An Arrhenius plot can give the activation energies, and the capture-cross sections of the four time constants (figure 7). The emission rate is equal to $\log(\tau^{-1}\ T^{-2})$. The sum of activation energies of τ_n and τ_p must be the bandgap of 1.12 eV. The same must be true for the sum of τ_{cp} and τ_{dc}. These parameters are plotted in table 2.

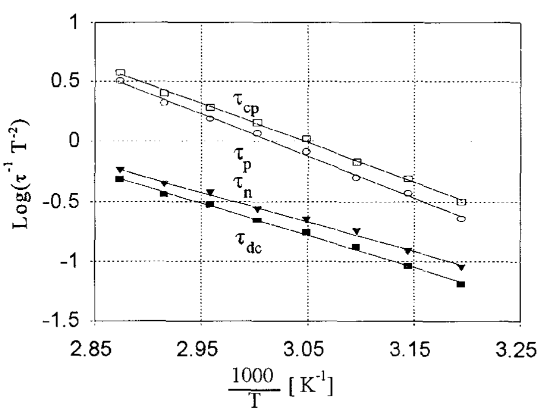

Figure 7 *Arrhenius plot of the four found emission rates.*

Table 2. *Overview of the determined parameters*

parameter	τ_{dc}	τ_{cp}	τ_n	τ_p
$\sigma\ [\cdot 10^{-15} \cdot cm^2]$	8.6	325	5.8	480
Ea [eV]	0.54	0.59	0.52	0.61

From equation (4) it is clear that the DC generation is determined by the largest time constant. Normally one would expect the activation energy of this DC generation to be larger than midgap. This trap however, causes a DC generation rate which is activated by 0.54 eV. This is less then half the bandgap. This can be explained from the fact that the capture-cross section of the electrons is much smaller than the capture-cross section of holes.

Comparison with literature

Figure 8 shows an Arrhenius plot of the measurements and a comparison with literature. It is clear that gold [3] fits the measurements very well. Iron [4], which is often suggested as a contaminant, does not fit well. Other elements have also been investigated, but none fit the measurements as well as gold.

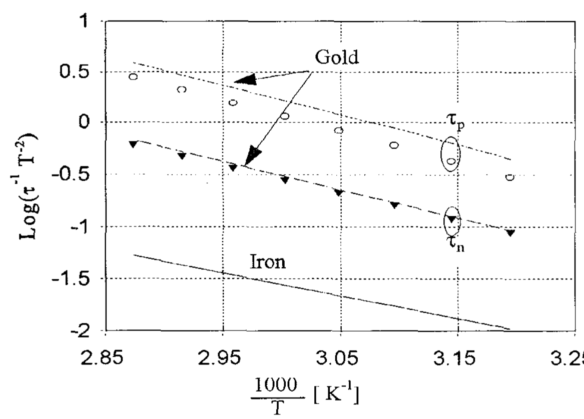

Figure 8 *Arrhenius plot to compare measurements, (markers) from figure 7, against literature (lines).*

Conclusions

1. The white pixels are caused by one, two or three generation centers.

2. Both time constants, τ_n and τ_p , are very accurate to determine, even at very low concentrations of 10^7 centers per cm^3.

3. The model fits measurements very well.

4. Gold is the probable cause of the white pixels in the CCDs.

References

[1] J. Bosiers et.al., IEEE trans. El. Dev., **42**, no 8(1995) 1449.
[2] D.V.Lang, J. Appl. Phys. **45**, no 10 (1976) 3023.
[3] K.L.Wong et.al., J. Appl. Phys. **47**,no 7(1976) 4574.
[4]D. Barbier et.al., J. Appl. Phys. **61**,no 1(1987) 156.