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A CCD delay line to determine low concentrations of bulk traps in silicon.

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1 Introduction.

A major problem in solid-state image sensors is the leakage current generated in the image cell. This current causes noise in the displayed image. One of the causes of this leakage current is contamination in the collecting area of the CCD pixel. Contamination introduces traps with energy levels in the bandgap of silicon.
Methods for measuring the amount of contamination and for characterizing traps, like DLTS and noise measurements, have detection limits of about $1*10^{10}$ traps/cm^3. In order to investigate traps with concentrations less than $1*10^{10}$ traps/cm^3, the method of charge transfer inefficiency has been used.
The principle of this measurement method is based on charging and discharging of traps with electrons which are being transported through the CCD channel. When a charge packet arrives under a gate the empty traps are filled. When the charge packet is transported to the next gate the trapped electrons are emitted. A number of these electrons is emitted fast enough from the traps to follow the packet. By measuring the loss of electrons as a function of temperature, it is possible to determine the nature of contamination and its concentration in the CCD channel. This method has been introduced by Collet [1].

2 Device description.

Experiments have been conducted with a CCD delay line with 600 stages. It has been found that the sensitivity is not high enough to detect present contamination levels. Therefore a new device has been developed which consists of an oval 4-phase n-channel bulk CCD register with 1200 stages (see figure 1). This register has on one side an input and on the other side an output with a standard output amplifier. Furthermore the register contains special blocking gates which serve either to direct the charge packets to the output amplifier or to keep them in the oval register. In the oval register it is possible to make as

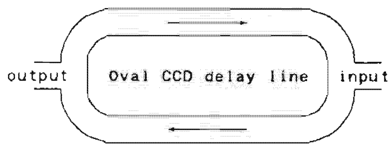

Figure 1 The oval CCD delay line structure for measurements of charge- transfer inefficiency.

many tours as necessary for a good sensitivity. The number of tours is limited by the following requirements: the first charge packet must be large enough to fill all the traps and the leakage current must not fill the pixel completely. The theoretical sensitivity limit is reached when there is only one trap in the whole register. The register has a volume of 10^{-8} cm^3 so the detection limit is 10^8 traps per cm^{-3}.

3 Measuring method

For measuring the total transfer loss a series of ten charge packets has been inserted into the oval register. The first packet will lose electrons in the traps but the following nine will lose nothing. At the output stage the difference between the first and the second packet is the total charge- transfer loss.The number of electrons the first packet will lose in the traps depends on the number of traps that are already filled when the first packet arrives.To control the fraction of filled traps another series of ten charge packets will go ahead of the one needed for the measurements (figure 2). The time between the first and second series of charge packets is expressed as L times the clock period.

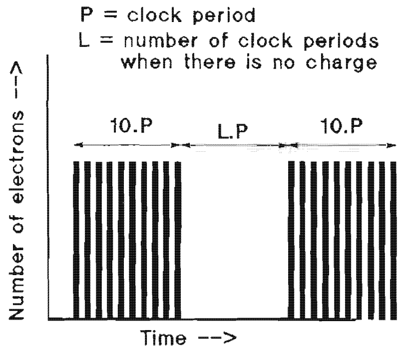

Figure 2 **First and second series of charge packets.**

4 The model

A model has been derived from the Shockley-Read-Hall differential equation:

$$\frac{dN_t}{dt} = -\frac{N_t}{\tau_{ne}} + \frac{N_{t\,max} - N_t}{\tau_{nc}} + \frac{N_{t\,max} - N_t}{\tau_{pe}} - \frac{N_t}{\tau_{pc}} \tag{1}$$

where $N_{t\,max}$ = trap density, N_t = number of traps filled, τ's = time constants, v_{th} = thermal velocity, σ_n = capture cross section of electrons and Nc = effective density of states in the conduction band.

In a bulk n-type CCD the capture of holes can be neglected. For traps in the upper half of the bandgap the emission of holes can also be neglected. However, hole emission can easily be included in the model for traps near midgap. When there is a charge packet under the gate electrons are captured in the traps, which is a very fast process (faster than the clock period). During the time there is no charge packet the electrons are emitted from the traps. For this case the number of trapped electrons can be derived from equation 1.

$$(\textit{with}\ \ \tau = \tau_{ne} = \frac{1}{v_{th} \cdot \sigma_n \cdot N_c} \cdot e^{\frac{E_{akt}}{KT}}) \qquad N_t = N_{t\,max} e^{-\frac{t}{\tau}} \tag{2}$$

When the leading series charge packets has passed a gate all the traps under this gate are filled. The number of empty traps at the time the second series of charge packets arrives is given by:

$$N_{t\,max} - N_{t\,max}.e^{\frac{-(LP+\delta t)}{\tau}} \tag{3}$$

Where δt = the part of the clock period where electrons can follow the packets, P = clock period and L = number of clock periods when there is no charge.

These traps will be filled with electrons from the first packet.
The number of electrons that are able to follow the packet when it is transported to the next gate is given by:

$$N_{t\,max}.(1-e^{-\frac{\delta t}{\tau}}) \tag{4}$$

The transfer inefficiency ϵ is given by:

$$\epsilon = \frac{Loss}{N.V} = \frac{N_{t\,max}}{N.V}.e^{-\frac{\delta t}{\tau}}.(1-e^{-\frac{LP}{\tau}}).V \tag{5}$$

V = Volume of the charge packet under the gate and N = Dopant concentration

5 Model interpretation.

Temperature dependence.
At low temperatures all the traps will be filled once and will not empty because the electrons do not have enough energy to be emitted to the conduction band. Because all the traps are filled the charge packets will not lose any electrons and ϵ will be equal to zero. At high temperatures the emission time of electrons to the conduction band is much shorter than the clock period. So the charge packet will lose some electrons but they all are fast enough to join the packet. Thus ϵ will be zero. At intermediate temperatures the electrons can be emitted during the time there is no charge packet but the emission is not fast enough to join the charge packet in the short time of the clock period. In this region ϵ will be unequal to zero.

Parameter adjustments.
The number of electrons that can be emitted to the conduction band increases, when L, the time between the first and second series of charge packets increases. To emit the same number of electrons the device has to be cooled to lower temperatures. Consequently, the left side of the ϵ-T curve shifts to lower temperatures (figure 3).

When the clock period P, becomes smaller the electrons have less time to be emitted during the no charge period. To emit the same number of electrons the device has to be heated to higher temperatures. The whole ϵ-T curve will shift to higher temperatures.By changing the parameters L and P it is possible to check the model and to get a convenient measuring area around room temperature. With the number of tours it is possible to adjust the sensitivity and not the curve form.

6 Experimental results.

In figure 3 the charge transfer-inefficiency is plotted as a function of temperature for 3 adjustments of the number of empty wells (L) between the charge packets.
Charge packets were clocked around 50 times before sending them to the output. This gives a charge transfer loss large enough to detect. The data have been fitted with traps characterized by an activation energy of 0.52 eV, a capture cross section of $4*10^{-15}$ cm^{-2} and a maximum ϵ of $8*10^{-7}$. With a dope concentration of 10^{16} cm^{-3} the concentration of bulk contamination is $8*10^{-7}*10^{16}=8*10^{9}$ cm^{-3}.
With the values for the activation energy and the capture cross section an Arrhenius plot of the time constant τ has been made. A comparison with the literature [2] points to gold as the most probable element that causes the transfer inefficiency. After removing a source of contamination in the processing new measurements were performed.
Figure 4 indeed shows a reduction of contamination of about 4 to 5 times in the delay line. The data have been fitted with the same parameters as before except for the concentration of traps, which is now $2*10^{9}$ cm^{-3}. Now the contamination level is about 20 traps in the whole delay line. Because of the interface leakage current it is not possible to locate the traps.

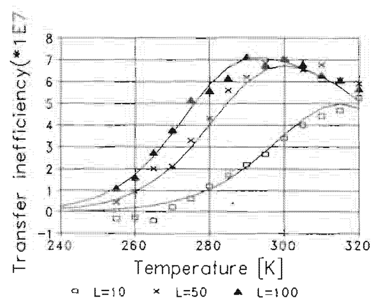

Figure 3 Charge-transfer inefficiency versus temperature for three adjustments of the time between the series of charge packets. The markers are measured data, the lines are determined by fitting these data.

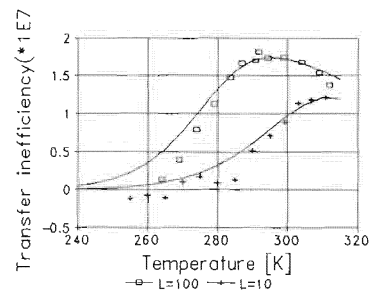

Figure 4 Charge-transfer inefficiency versus temperature after reduction of contamination for two adjustments of the time between the series of charge packets.

7 Conclusions.

1. It has been shown that the oval CCD structure is suitable for determination of bulk contamination with concentrations in the order of 10^{9} cm^{-3} or lower.
2. The model agrees with the measurements for several CCD operating conditions e.g. clock frequency, number of transports.

8 References.

1 M.G. Collet, IEEE Journal of Solid-State Circuits, vol. sc 1, no 1, february 1976, page 156.
2 J-W Chen and A.G Milnes, Solid -State Electronics, vol. 22, 1979, page 684.