VOD photo response analysis in CCD image sensor

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VOD (Vertical Overflow Drain)1), in which extra charge flows from a photo diode to the substrate, has been widely used to suppress blooming in CCD image sensors. However, VOD decreases the dynamic range, because of the continuing, gradual rise in CCD output that accompanies increasing incident light intensity in the saturation region. This effect is the result of three factors: smear, blooming caused by transfer gate action, and extra signal charge in the photo diode. In an attempt to discover a way to lessen the effect, the authors have used a one-dimensional, abrupt-junction model to analyze the effects of increased incident light intensity on the level of extra signal charge, which is the dominant factor among the three. The analysis suggests that, under the constant substrate voltage at which VOD begins to work, a thicker photo diode p-well with a lower impurity concentration would be effective in suppressing the rise.

The portion of the CCD producing the VOD effect is essentially, in its structure, a vertical NPN transistor. The flow of extra signal charge from the photo diode N layer to the substrate may be considered as being punch-through, and VOD photo response in the saturation region may be analyzed on the basis of transistor I-V characteristics2). Under constant substrate voltage conditions, punch-through current I_{PT} is expressed as a function of photo diode N layer potential V_{PD}; i.e. $I_{PT}=I_0\exp(-(\beta/\eta)V_{PD})$, where $\beta=q/(k_B T)$, I_0 is the coefficient depending on substrate voltage and process parameters, and η is a non-ideality factor3). Because the I_{PT} is nearly equal to photo current I_λ in the saturation region, V_{PD} is approximated as $V_{PD}=(\eta/\beta)\log(I_0/I_\lambda)$. From this equation, it can be seen that the extent of rise in the saturation region depends on the non-ideality factor3) η alone. To suppress rise, it is necessary to reduce η .

η is defined as $\partial V_{BR}/\partial V_{PD}$4), where V_{BR} is the height of the potential barrier between the photo diode N layer and the p-well. The more V_{BR} decreases with decreases in V_{PD}, the greater the flow of extra charge to the substrate, i.e. the smaller η becomes.

A one-dimensional abrupt-junction model was used to approximate the VOD structure, in order to investigate the η dependence on impurity concentration and layer thickness. To verify the model validity, the authors compared experimental results, using a test photo diode with the calculation. Results agreed with each other.

The model was further used to calculate the η and V_{VOD} (the substrate voltage at which VOD begins to work) dependence on both P-well acceptor concentration and P-well thickness. They found that η and V_{VOD} decrease with lower P-well acceptor concentrations. Where V_{VOD} is constant, η becomes small for low P-well acceptor concentrations and thick P-well layers.

The authors have been able to determine in this study that, in VOD, the extent of rise in the saturation region depends on the non-ideality factor η alone. With their model, they have shown that, under constant V_{VOD} conditions, η is smaller for P-wells with lower concentrations and thicker layers.

1) Y. Ishihara et .al., ISSCC Dig. Tech. Papers.,pp.168-169,1982.
2) E. Oda et al., IEDM Tech. Dig.,pp.501-504,1983.
3) E.G. Stevens, IEEE Trans. ED,vol.38,pp.299-302,1991.
4) D.N. Nichols et al., IEDM Tech. Dig.,pp.120-123,1987.

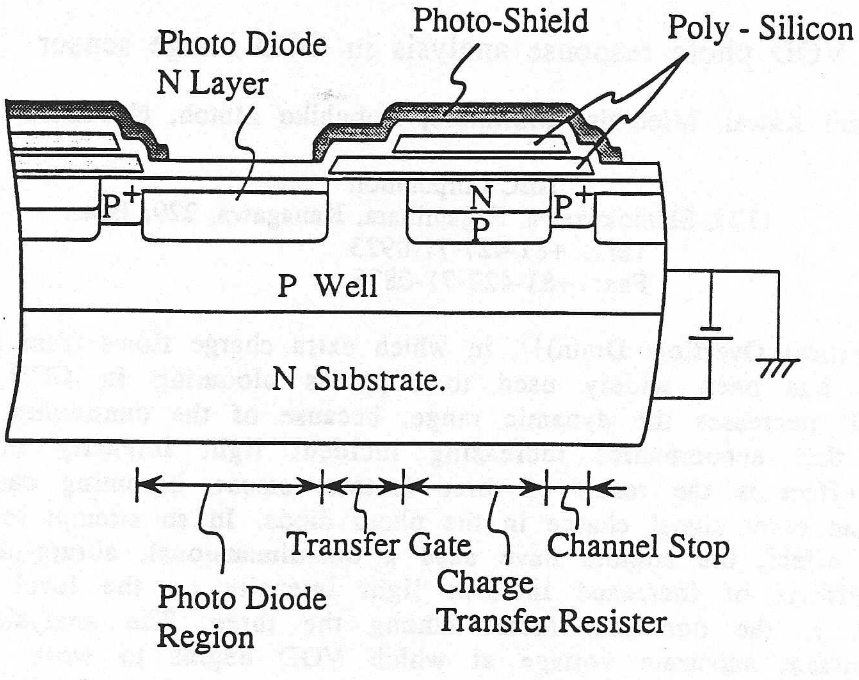

Fig.1
Unit cell cross section view of interline CCD image sensor. The cell consists of a photo diode, a charge transfer resister, and a transfer gate. The substrate is reversly biased from the grounded P well. Photo electrons are generated in the photo diode N layer and accumulated there. If the electrons are generated exceed the storage capacity, they flow through the P well into the substrate.

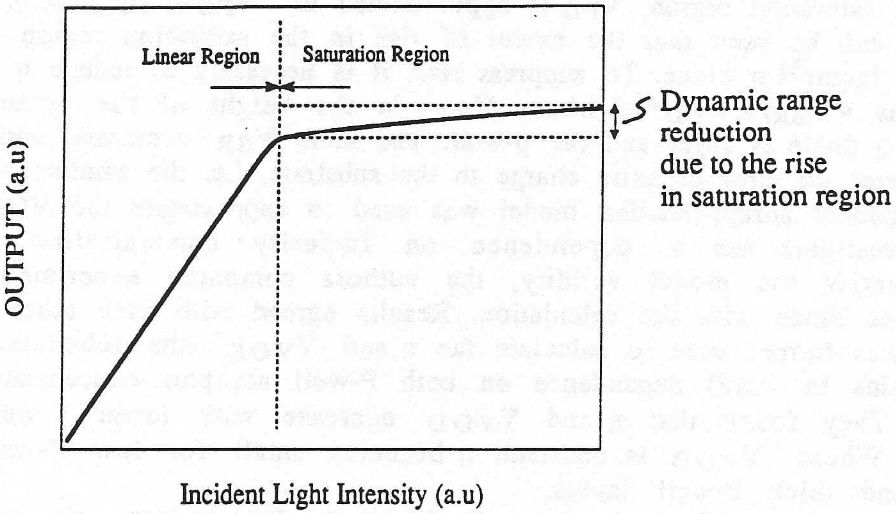

Fig.2
The photo response of CCD image sensor that has VOD mechanism. When light intensity is small, output is proportional to light intensity. When light intensity becomes great, VOD works and the output is supressed. Ideally, output is constant independent of the light intensity, but actually, rises slightly accompanied by an increase in light intensity. The output rise in the saturation region reduces the dynamic range of CCD image sensor.

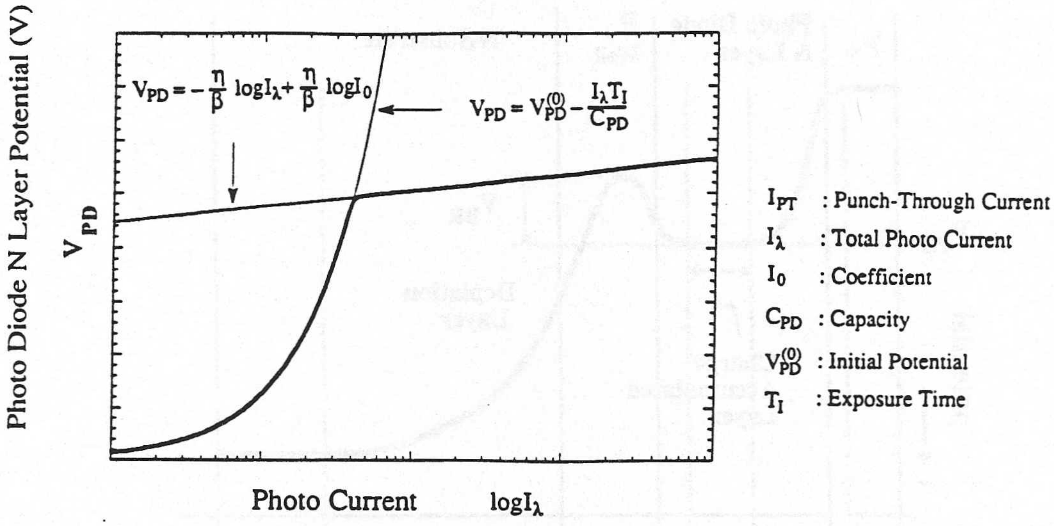

Fig.3
The photo response of CCD image sensor that has VOD mechanism. The horizontal axis is logarithm of total photo current I_λ. We can analyze photo response using transistor I-V characteristics. Under constant substrate voltage conditions, punch-through current I_{PT} is described as a function of photo diode N layers potential V_{PD} as follows approximately.

$$I_{PT} = I_0 \exp\left(-\frac{\beta}{\eta} V_{PD}\right) \qquad \beta = \frac{q}{k_B T}$$

The V_{PD} changes is derived by following differential equation.

$$C_{PD}\frac{dV_{PD}}{dt} = -(I_\lambda - I_{PT})$$

From these two expressions, we get an expression that describes the V_{PD} as a function of I_λ, as follows.

$$V_{PD} = \frac{\eta}{\beta}\log\left(\frac{I_0}{I_\lambda}\left\{1 - \exp\left(-\frac{\beta}{\eta}\frac{I_\lambda T_I}{C_{PD}}\right)\right\} + \exp\left\{\frac{\beta}{\eta}\left(V_{PD}^{(0)} - \frac{I_\lambda T_I}{C_{PD}}\right)\right\}\right)$$

It is shown with bold line in the graph.
In the linear region, punch-through current hardly flows ($I_{PT} \approx 0$). So, we got following expression.

$$V_{PD} = V_{PD}^{(0)} - \frac{I_\lambda T_I}{C_{PD}}$$

In the saturation region, almost all the photo current becomes punch-through current ($I_{PT} \approx I_\lambda$). we got following expression.

$$V_{PD} = -\frac{\eta}{\beta}\log I_\lambda + \frac{\eta}{\beta}\log I_0$$

From this expression it was found tht in the saturation region, V_{PD} varies linearly against logarithm of I_λ, and the slope is decided with non-ideality factor η alone. The smaller η means the gentle slope.

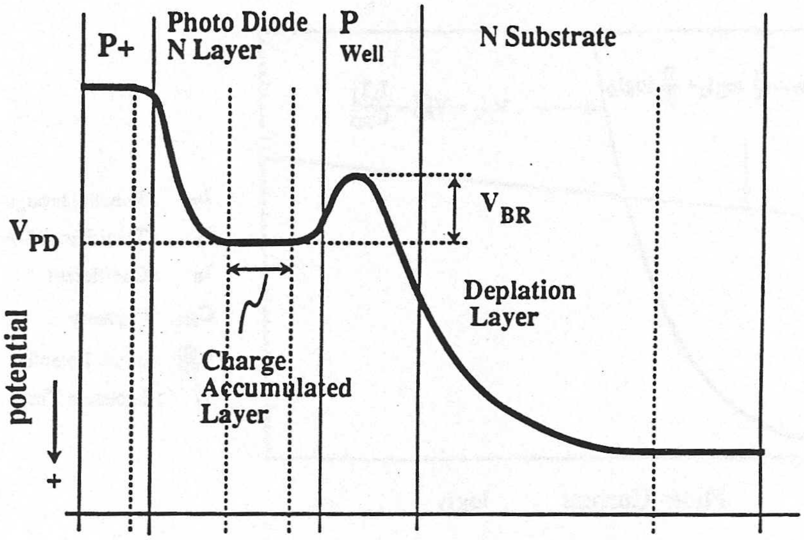

Fig.4
The potential profile in VOD structure. The excess electron flows over potential barrier that exists between photo diode N layer and the P well. The amount of elextron current is decided by the potential barrier height V_{BR}. If we know the relationship of V_{PD} and V_{BR}, we can get η value. For simplicity, we used VOD structure one-dimensional abrupt-junction model to calculate η value. From Poisson's equations and boundary conditions, we can get an expression that describes a relationship between V_{PD} and V_{BR}. η is defined as the differential of V_{PD} over V_{BR}.

$$V_{BR} = \frac{u}{2}\,\frac{1+\frac{n_d}{n_a}}{n_d\left(1-\frac{n_d}{n_s}\right)^2}\left\{-n_d\left(1+\frac{n_a}{n_s}\right)d_p+\left(\left\{n_d\left(1+\frac{n_a}{n_s}\right)d_p\right\}^2-n_d\left(1-\frac{n_a}{n_s}\right)\left\{-n_a\left(1+\frac{n_a}{n_s}\right)d_p{}^2+\frac{2}{u}(V_S-V_{PD})\right\}\right)^{\frac{1}{2}}\right\}^2$$

$$\eta \equiv \frac{\partial V_{PD}}{\partial V_{BR}} = \frac{\left(1-\frac{n_d}{n_s}\right)\left(\left\{n_d\left(1+\frac{n_a}{n_s}\right)d_p\right\}^2-n_d\left(1-\frac{n_a}{n_s}\right)\left\{-n_a\left(1+\frac{n_a}{n_s}\right)d_p{}^2+\frac{2}{u}(V_S-V_{PD})\right\}\right)^{\frac{1}{2}}}{\left(1+\frac{n_d}{n_a}\right)\left\{-n_d\left(1+\frac{n_a}{n_s}\right)d_p+\left(\left\{n_d\left(1+\frac{n_a}{n_s}\right)d_p\right\}^2-n_d\left(1-\frac{n_a}{n_s}\right)\left\{-n_a\left(1+\frac{n_a}{n_s}\right)d_p{}^2+\frac{2}{u}(V_S-V_{PD})\right\}\right)^{\frac{1}{2}}\right\}}$$

n_d : Photo diode N layer donor concentration
n_a : P well acceptor concentration
n_s : Substrate donor concentration
d_p : P well layer thickness
V_S : Substrate voltage
$u = \frac{q}{\varepsilon\kappa}$