A New Analytical MTF Model and its Applications

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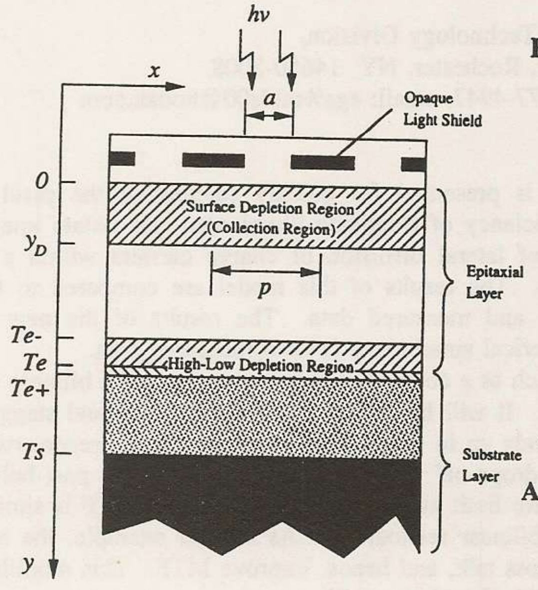
Abstract - A two-dimensional analytical model is presented for quickly calculating the pixel response, modulation transfer function (MTF), and quantum efficiency of front-side illuminated, solid-state image sensors [1]. Included in this unified model are the effects of lateral diffusion of charge carriers within a two-layer substrate, and less than full-pixel sampling apertures. The results of this model are compared to those of a numerical, three-dimensional Monte Carlo algorithm and measured data. The results of the new analytical model are seen to be in good agreement with the numerical simulations [1] and measured data.

MTF calculations for some sample architectures such as a conventional linear array, and a bilinear array with offset and staggered pixels [2] will also be presented. It will be shown that for the offset and staggered pixel architecture, (wherein cross talk from a given pixel ends up in every other pixel within the reconstructed line), that at relatively long wavelengths the MTF initially drops off with spatial frequency (up to past half Nyquist) and then increases again until it reaches the the aperture limit at Nyquist. This effect on MTF is similar to that observed for transfer inefficiency for a conventional bilinear readout [3]. As another example, the addition of scavenging drains between photosites is seen to cut cross talk, and hence, improve MTF. This modification can be handled in the analytical model by introducing an effective drain width.

Some practical limitations of the model will be also discussed. For example, the Monte Carlo simulations show that channel stops increase cross talk at relatively short wavelengths. At longer wavelengths, however, the channel stops do not contribute significantly to the cross talk, and hence, the analytical model provides a good approximation for the MTF in these cases. However, an effective depletion depth approximation will be discussed that allows treatment of the channel stops within the analytical model.

I. DEVICE STRUCTURE AND MODEL PARAMETERS

Figure 1 shows a cross section of the pixel structure assumed for the aperture and two-layer diffusion model. Also shown in this figure are the basic model parameters used.



Basic Parameters:

f	Spatial Frequency
α	Absorption Coefficient
y_D	Depletion Depth
N_e, N_s	Epi and Substrate Doping Concentrations
D_e, D_s	Epi and Substrate Diffusion Constants
τ_e, τ_s	Epi and Substrate Recombination Lifetimes
L_e, L_s	Epi and Substrate Diffusion Lengths
T_e, T_s	Epi Thickness and Sink Depth
T_{e-}, T_{e+}	Epi/Substrate Depletion Boundaries (Dependent on N_e and N_s)
p, a	Pixel Pitch and Aperture

Additional Parameters:

W_{CHST}	Channel Stop Width
wd	Scavenger Drain Width

Fig. 1. Basic device structure and model input parameters.

This model can be used to calculate the pixel response, quantum efficiency, and MTF including the effects of an aperture and carrier diffusion in a unified manner [1], [4]. Further details of the model can be found in [1].

II. COMPARISON OF ANALYTICAL MODEL AND MEASURED DATA

Figure 2 shows a comparison between measured data and calculations using the analytical model. The model input parameters are shown in the inset of the graph.

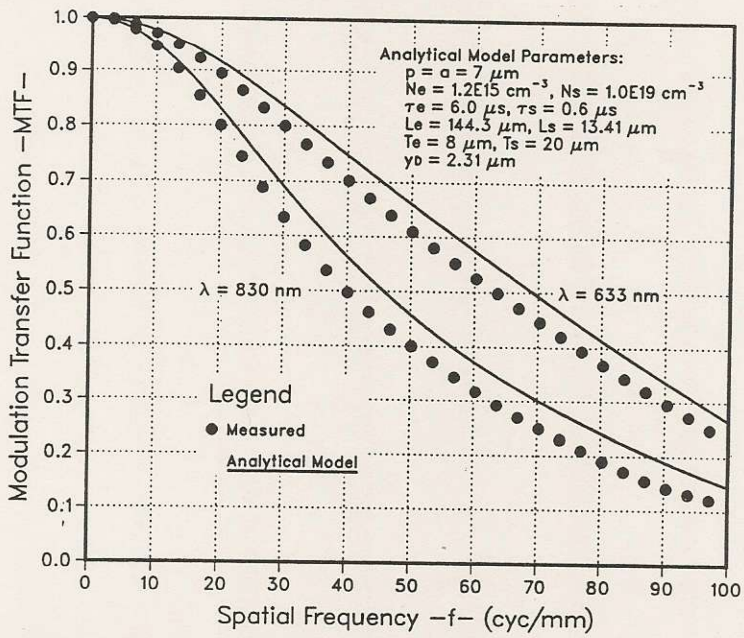


Fig. 2. Comparison of measured data and analytical model calculations for a conventional linear photodiode array with 7 µm pixels and a 100% fill factor.

The measured data was taken by scanning a knife edge over the array to get an edge response function. This knife edge was in direct contact with the top of device, i.e., in contact with its top passivation layer. The edge response data was converted to an MTF by the method described by Tatian [5].

III. CHANNEL STOPS - EFFECTIVE DEPLETION DEPTH APPROXIMATION

A heretofore limitation of analytical models has been their inability to take into account the effect of channel stops. Since channel stops increase cross talk, their effect is to reduce the MTF of the device as has been previously discussed [1]. This effect is most severe as their width becomes an appreciable fraction of the pixel size, and at shorter wavelengths where photons are absorbed closer to the surface. However, since the collecting surface is nonuniform in this case (i.e., the surface depletion depth is not constant), the problem is not amenable to an analytical solution. Also, since there is typically *no* depletion region under the channel stops, these regions become reflecting and the problem is further complicated by the introduction of mixed boundary conditions. Therefore, an approximation is used to take their effect into account. The approximation proceeds by assuming uniform illumination, calculating the number of excess carriers that would be generated past the surface depletion regions and contribute to cross talk, and by equating this amount to that that would be obtained by assuming some constant, "effective" depletion depth.

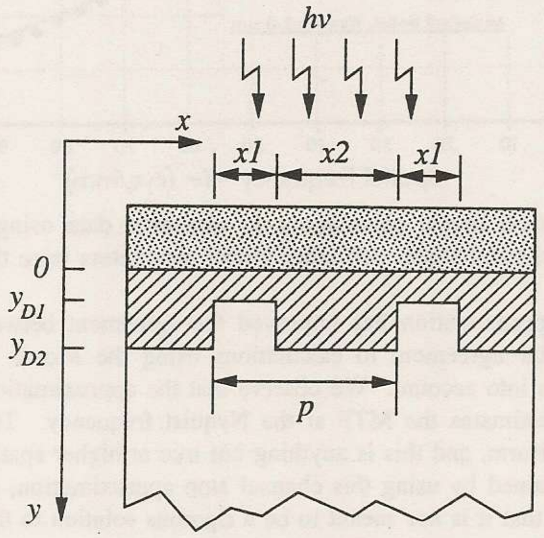


Fig. 3. Structure for calculation of an effective depletion depth for cases with nonuniform collection surfaces.

Therefore, by referring to Fig. 3, it can be shown that

$$p\,e^{-\alpha y_{Deff}} = x_1 e^{-\alpha y_{D1}} + x_2 e^{-\alpha y_{D2}} \,. \tag{1}$$

Therefore, by setting $y_{D1} = 0$, $x_1 = W_{CHST}$, $y_{D2} = y_D$, and $x_2 = (p - W_{CHST})$, an effective depletion depth to approximate the effects of the channel stops is given by

$$y_{Deff} = -\frac{1}{\alpha}\ln\left\{\frac{1}{p}\left[W_{CHST} + (p - W_{CHST})e^{-\alpha y_D}\right]\right\} . \tag{2}$$

In general it follows that an effective depletion depth could be calculated for any arbitrary nonuniform surface by

$$y_{Deff} = -\frac{1}{\alpha}\ln\left[\frac{1}{p}\sum_i x_i e^{-\alpha y_{Di}}\right] \tag{3}$$

The linear device used in Fig. 2 has 7 μm pixels with 2 μm wide channel stops. Therefore, using these values along with $y_D = 2.31$ μm in equation (2) from above, effective depletion depths of 1.44 μm and 1.61 μm are calculated for λ = 633 nm and 830 nm, respectively. MTF calculations using these effective depletion depths are shown in Fig. 4.

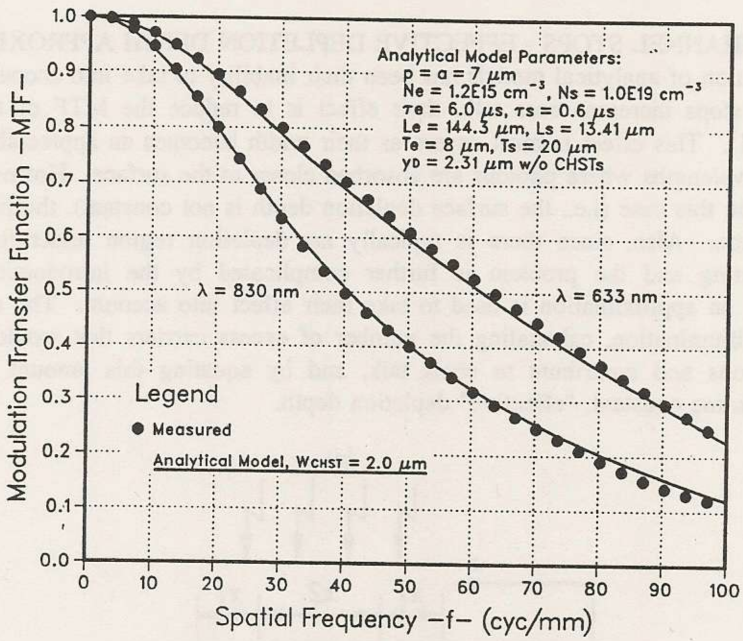


Fig. 4. Comparison of analytical model calculations to measured data using an effective depletion depth to approximate the effect of the channel stops. All other model parameters were the same as those used for Fig. 2.

Note how the channel stop approximation has improved the agreement between the measured and calculated values. We have found similar agreement to calculations using the Monte Carlo numerical model that can properly take the channel stops into account. We observe that the approximation, in these cases, fits well at low spatial frequencies, but underestimates the MTF at the Nyquist frequency. This is because the approximation assumes the illumination is uniform, and this is anything but true at higher spatial frequencies. Although a good fit to the measured data is obtained by using this channel stop approximation, it should be emphasized that this is *only* an approximation, and that it is *not* meant to be a rigorous solution to the problem by any means.

IV. BILINEAR ARRAY WITH STAGGERED AND OFFSET PIXELS

As another example case, we have modeled a linear array with staggered and offset pixels [2]. The results of this simulation are shown below in Fig. 5. Since these calculations are done in two dimensions, we assume that there is no row-to-row cross talk. In practice, this could be accomplished by putting in a scavenging drain between the rows. Three-dimensional numerical simulations have shown this approach to be effective. Note how the MTF is limited by the aperture at the Nyquist frequency. (Recall that an aperture limit could be defined by sinc[$\pi f a$].) This is because within a given row the illumination is effectively DC, i.e., since the illumination is identical on each pixel, the cross talk lost from any given pixel is exactly compensated for by cross talk picked up from all the other pixels in the array.

It should be pointed out that care must be taken in calculating the Fourier coefficients for this case since the periodicity of the photon flux as transmitted through the apertures to the silicon is *not* the same as that of the input illumination for spatial frequencies shown between Nyquist (≈ 71.4 cyc/mm) and half Nyquist.

V. CONCLUSION

An analytical model has been presented for quickly and accurately predicting the pixel response, quantum efficiency, and MTF for a variety of front-side illuminated, imager device structures. An approximation to take into account the effects of channel stops has also been shown. Good agreement is seen between measured data, and analytical and numerical solutions [1]. The model can handle epitaxial or bulk wafer diffusion effects, VOD structures, denuded zones, apertures, and scavenging drains between photosites. Also, because the pixel

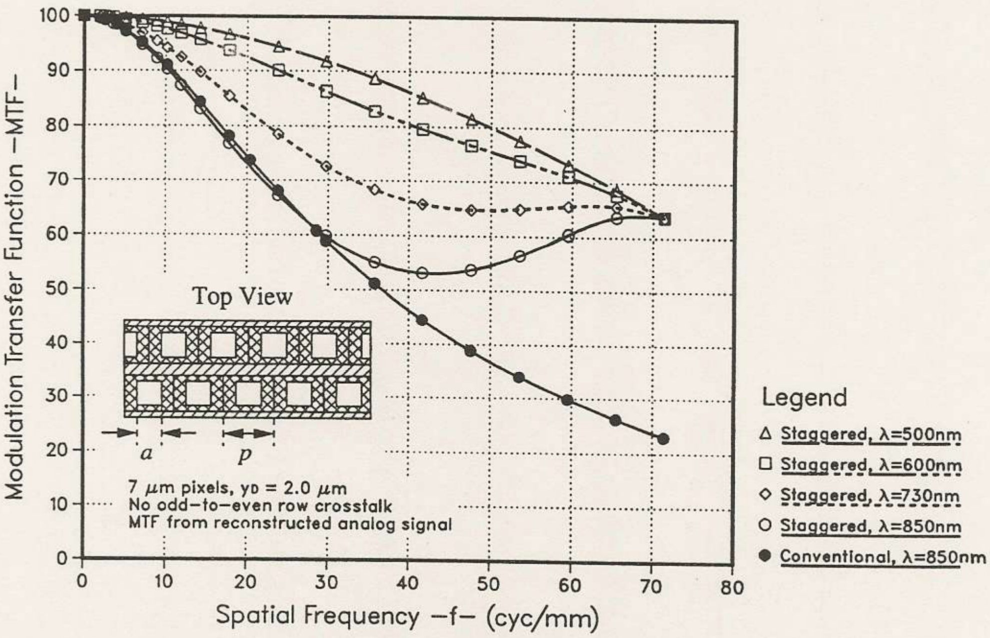


Fig. 5. MTF calculations for a linear array with staggered and offset pixels. Also shown is the MTF calculated for a conventional linear array for comparison. The model input parameters used for these cases are: a = 7 µm, p = 7 µm for the conventional array, p = 14 µm (intra row) for the staggered-and-offset-pixel array, N_e = 1.3(10^{15}) cm^{-3}, N_s = 1.0(10^{19}) cm^{-3}, D_e = 35 cm^2/s, D_s = 3.5 cm^2/s, L_e = 150 µm, L_s = 15 µm, T_e = 8 µm, T_s = 32 µm, and y_D = 2 µm.

response can be calculated for any arbitrary periodic input waveform, the bar-pattern response or effects such as overlayer transmission nonuniformities can also be studied by simply calculating and applying the Fourier coefficients of the input waveform.

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