Some thoughts on Diffusion Dark Current

M.M. Blouke
Ball Aerospace & Technologies Corp.
Boulder, CO 80306

1. Introduction

Of the three components of the dark current seen in imagers, the diffusion component is the least understood.[1] This is principally due to the fact that it only makes its presence felt at elevated temperatures. The conventional expression for the diffusion component involves the minority carrier diffusion length which can be quite large and assumes that the substrate extends to infinity beneath the detector. In most sensors this is not the case. So the question is: What is the appropriate expression for the diffusion current given a finite region beneath the detecting element? This paper will derive expressions for the diffusion dark current for a front-illuminated device built on the standard epitaxial material on a low resistivity substrate [2,3] and a thinned, back-illuminated device. The solutions are applicable to both CCDs and CMOS devices.

2. Models

2.1 The front-illuminated device

Figure 1 presents the geometry for a front-illuminated device built on the industry standard p on p+, epitaxial material.[2,3] We take the edge of the depletion region to be the origin. The undepleted epitaxial material (characterized by the parameters diffusion coefficient for electrons, D_{epi}, minority carrier lifetime, τ_{epi}, mobility, μ_{epi} and doping concentration, N_{epi}) is of thickness σ. The substrate material is characterized by D_{sub}, τ_{sub}, μ_{sub}, and N_{sub} and extends to x = t. To find the diffusion current, we must solve the continuity equation in both regions [4,5,6]

$$\frac{\partial n(x)}{\partial t} = \nabla \bullet J_n + G(x) - R(x) = D\frac{\partial^2 \delta n(x)}{\partial x^2} - \frac{\delta n(x)}{\tau} = 0 \qquad (1)$$

The solutions are

$$\delta n_{epi} = A\exp(\gamma x) + B\exp(-\gamma x) \qquad 0 < x < \sigma \qquad \gamma = (D_{epi}\tau_{epi})^{-1/2}$$

and

$$\delta n_{sub}(x) = C\exp(\xi x) + D\exp(-\xi x) \qquad \sigma < x < t \qquad \xi = (D_{sub}\tau_{sub})^{-1/2}$$

Subject to the boundary conditions

1. $\delta n_{epi}(x=0) = -n_{eo} = -\dfrac{n_i^2}{N_{epi}}$ 2. $\delta n_{sub}(x=t) = 0$

and at the epitaxial interface,

3. $\delta n_{epi}(x=\sigma^-) = \dfrac{N_{sub}}{N_{epi}}\delta n_{sub}(x=\sigma^+)$ and 4. $J_{epi}(x=\sigma^-) = J_{sub}(x=\sigma^+)$

Condition 3 comes from the relationship across a hi-lo junction:

$$n_{eo} = N_{epi} = n_{sub}\exp(\frac{qV_{hilo}}{kT}) = N_{sub}\exp(\frac{qV_{hilo}}{kT})$$

Assuming the Fermi level doe not change significantly across the junction, boundary condition 3. results. [7]

After applying the boundary conditions and a little algebra, one arrives at the corrected expression for the front illuminated device:

$$J_{diff} = \frac{qD_{epi}n_i^2}{L_{epi}N_{epi}}\left(1 - \frac{\exp(\gamma\sigma)(K+1)}{(\cosh(\gamma\sigma) + K\sinh(\gamma\sigma))}\right) \tag{2}$$

K is a constant and is given by

$$K = \frac{L_{epi}N_{epi}D_{sub}}{L_{sub}N_{sub}D_{epi}} \tag{3}$$

One can easily convince oneself that as $\sigma \rightarrow \infty$, the correction term approaches -1 and the expression for the dark current approaches the classical value. However, as $\sigma \rightarrow 0$, the correction term reduces to the value -K. Consequently, the diffusion related dark current reduces to the value appropriate to the substrate material. Figure 2 represents theoretical calculations of J_{diff} based on the above equation using the parameters listed in the Figure. The figure shows that for practical values of the starting material, the diffusion related dark current is reduced below the classical value and is more characteristic of the substrate doping.

2.2 Model for a thinned device

The model for the thinned part is similar to the model for the quantum efficiency of a thinned CCD.[4,5] The thinned device can be modeled as a thinned silicon membrane of thickness t. In the neighborhood of the surface there exists a region of thickness $\Delta=(t - \sigma)$. An electric field exists and acts on carriers in this region; depending on the sign of the field, the carriers are either encouraged to move towards the CCD wells or they are driven towards the back surface where they recombine. The back surface is characterized by a surface recombination velocity.[4-7]

Again the continuity equation must be solved for the two regions: i) the field free region between the depletion edge (x = 0) and the edge of the surface region ($x = \sigma$) and ii) the surface region itself. In this case the equation to be solved is

$$D_e\frac{\partial^2\delta n(x)}{\partial x^2} + \mu_e E_o n(x) - \frac{\delta n(x)}{\tau} = 0 \tag{3}$$

where E_o is zero in the field free region and has some value in the surface region. The solutions for the two regions are:

$$\delta n_1(x) = A\exp(\gamma x) + B\exp(\gamma x) \qquad 0 < x < \sigma \qquad \gamma = (D_e\tau)^{-1/2}$$

and

$$\delta n_2(x) = c\exp(\lambda x) + D\exp(\nu x) \qquad \sigma < x < t \qquad \lambda,\nu = -\left(\frac{\mu_e E_o}{2D_e}\right) \pm \sqrt{\left(\frac{\mu_e E_o}{2D_e}\right)^2 + \gamma^2}$$

The boundary conditions are:

1. $\delta n_1(x=0) = -n_{eo} = -\frac{n_i^2}{N_e}$
2. $J_2(x=t) = -so\,\delta n_2(t)$
3. $\delta n_1(x=\sigma^-) = \delta n_2(x=\sigma^+)$
4. $J_1(x=\sigma^-) = J_2(x=\sigma^+)$

Applying the boundary conditions and, as before, solving for the diffusion current into the depletion region gives

$$J_{diff} = \frac{qD_e n_i^2}{L_e N_e}\left(1 + \frac{\exp(\gamma\sigma)(\omega - 1) + \frac{\phi}{\gamma}\left(\frac{\lambda + \phi - \omega\gamma}{\lambda + \psi}\exp(-\lambda\Delta) - 1\right)}{\cosh(\gamma\sigma) - \omega\sinh(\gamma\sigma)}\right) \quad (4)$$

where $\phi = \frac{\mu_e E_o}{D_e}$ $\psi = \left(\frac{s_o + \mu_e E_o}{D_e}\right)$ $\Delta = t - \sigma$

and

$$\omega = \frac{(\nu + \psi)\nu\exp(-\lambda\Delta) - (\lambda + \psi)\lambda\exp(-\nu\Delta)}{\gamma((\lambda + \psi)\exp(-\nu\Delta) - (\nu + \psi)\exp(-\lambda\Delta))} \quad (5)$$

Again, as $\sigma \rightarrow \infty$, the expression for the dark current reduces to the conventional form as it should.

Figures 3-5 present theoretical calculations of the behavior of the diffusion dark current based on the current model. Figure 3 shows the dependence of the minority carrier concentration on the electric field in the surface region. Note that neither the direction nor the strength of the field have a significant effect on the minority carrier concentration. Only for fields in excess of -2000 V/cm does the field have a significant effect on the electron concentration. This observation is consistent with the previously developed model for the quantum efficiency of a thinned device which showed that fields of the order 3-6 kV/cm are required to achieve significant QE at short wavelengths. [4, 5] Figure 4 presents calculations based on the above model of the normalized diffusion related dark current as a function of thickness of the device. What the figure demonstrates is that given enough Silicon, the diffusion related dark current will eventually equal the canonical value.

Finally, Figure 5 presents the normalized diffusion dark current as a function of the field in the surface region. Oddly, thinned devices with poor short wavelength QE will tend to have the lowest diffusion related dark current.

References

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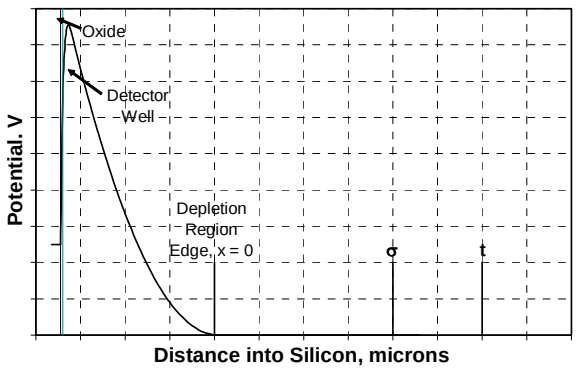

Figure 1. This figure shows schematically the geometry of the configuration. x = 0 is at the edge of the depletion region, σ is the location of the hi-lo junction in the case of the front illuminated device and is the location of the front edge of the surface region in the thinned case. t is the location of the back surface of the device.

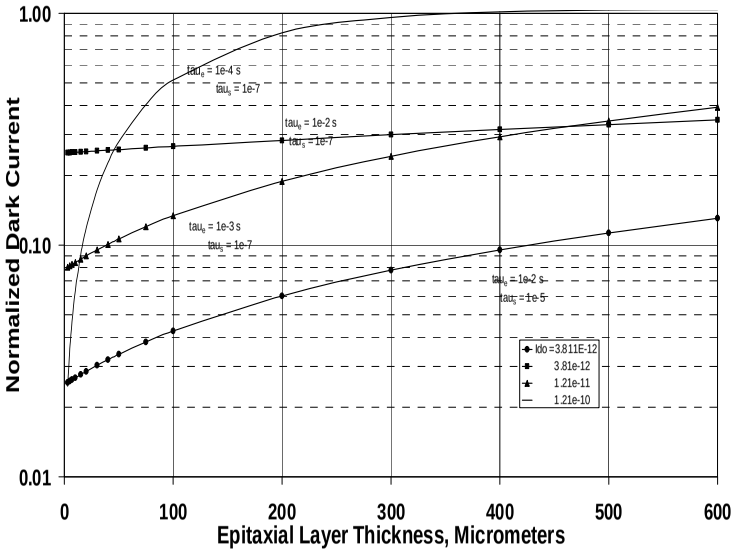

Figure 2. Diffusion dark current as a function of the field free region beneath the pixel.

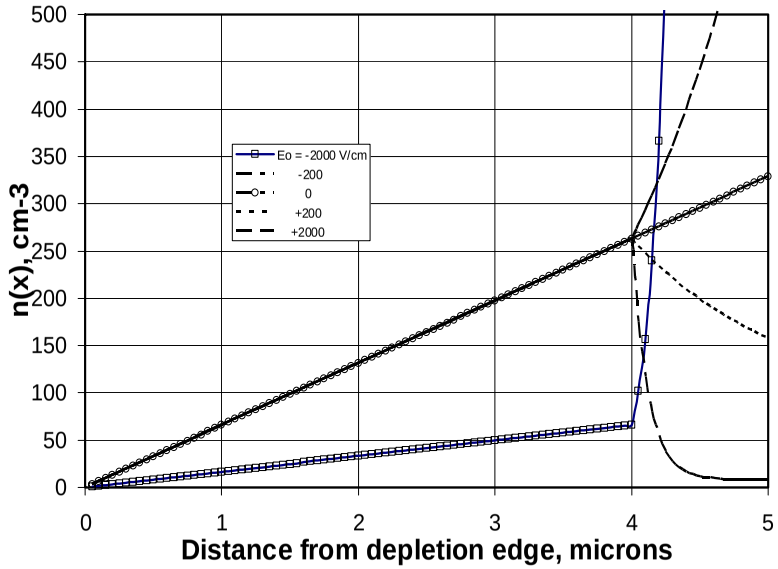

Figure 3. Minority carrier concentration vs distance with the surface field as the parameter.

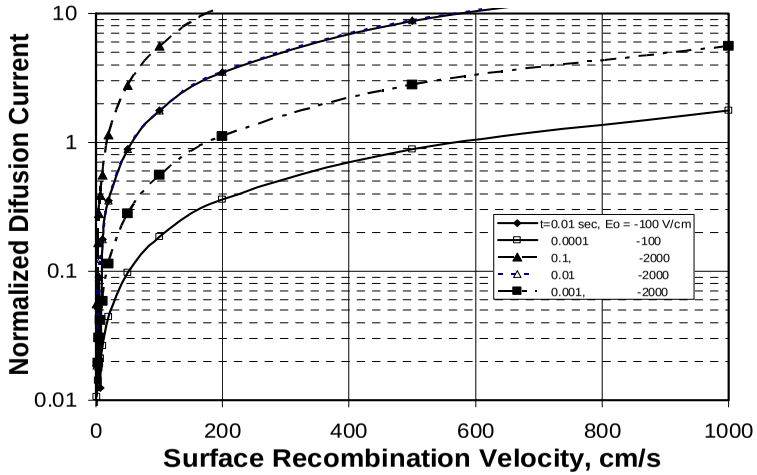

Figure 4. Normalized dark current vs. recombination velocity.

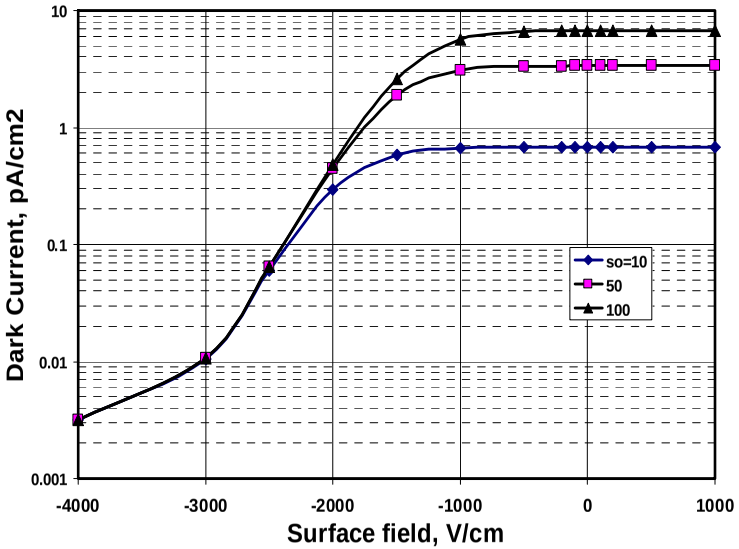

Figure 5. Diffusion related dark current as a function of the surface field with the surface recombination velocity.