The Effects of Potential Wells on Charge Transfer in Image Sensors

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Image sensors often utilize charge-coupled device (CCD) shift registers. Charge transfer inefficiencies (CTI) arise from potential barriers or wells that are rooted in the design or fabrication process. Image lag in pinned photodiode imagers may also be interpreted in terms of incomplete charge transfer due to potential obstacles between the photodiode and the vertical CCD. This report shows how the charge transfer inefficiency depends on the potential obstacle's shape and depth.

Three-dimensional solutions to Poisson's equation are used to provide the drift field for drifting and diffusing carriers in a model of a section of a dual horizontal CCD shift register with a potential well. The amount of charge in the well is seen to decay exponentially with time t as $\exp(-t/\tau)$. Lower-dimensional model spaces show a similar behavior and are preferred in order to investigate more cases quickly.

The effect of the charge level in the potential well is addressed with two-dimensional solutions to Poisson's equation. These give the variation of the potential well depth with the amount of charge Q in the well. Q first quickly drops with time and then shows the exponential decay characteristic of a fixed well depth with a very small charge packet. Since it is generally the last stage of the decay that causes device performance problems, it suffices to study a one-dimensional carrier continuity equation with a time-independent electric field.

The one-dimensional results are based on closed-form solutions, eigenvalues, or mean first passage times. The decay constant τ grows exponentially with the well depth for a variety of potential well shapes once the well depth exceeds several kT/q. Here k is Boltzmann's constant, T is the temperature, and q is the magnitude of the charge of an electron. The well shape changes τ by up to a factor of 100 for a fixed well depth. The model results are applied to the interpretation of image lag data from an interline imager operated in a manner to induce image lag. Potential well depths are extracted from the time-dependent lag data.

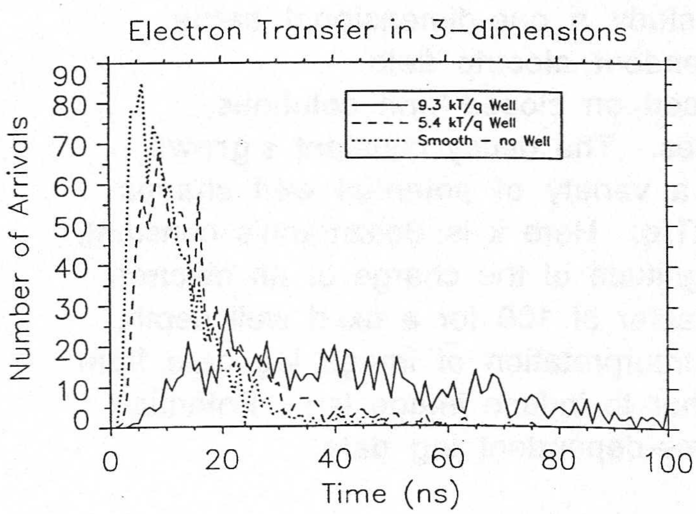
Escape-1

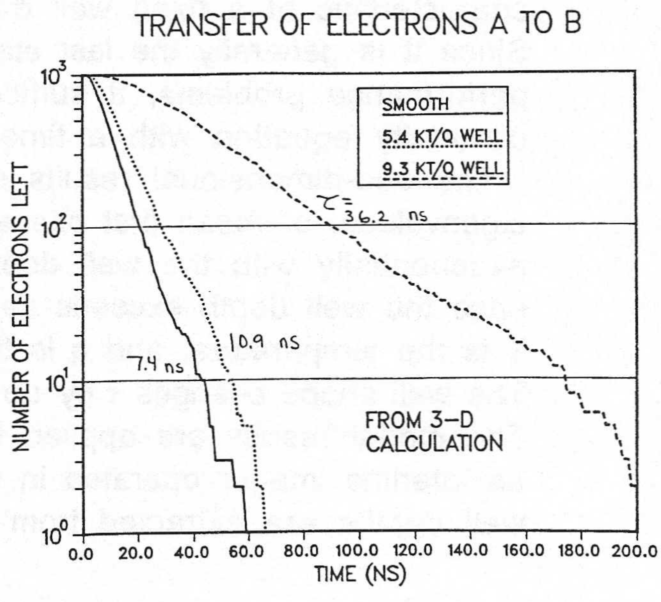
Results in 3-Dimensions:

- Solve Poisson's equation in 3-dimensions with a finite-difference method.
- Use the solution to provide the drift field for the electrons.
- Add in thermal diffusion.
- Treat the electrons' motion by a random walk or Monte Carlo method.
- Study the charge transfer from the A-register to the B-register of a dual horizontal CCD shift register.
- Follow 1000 electrons.
- Plot the arrival times of the electrons in the B-register phase.

Find:

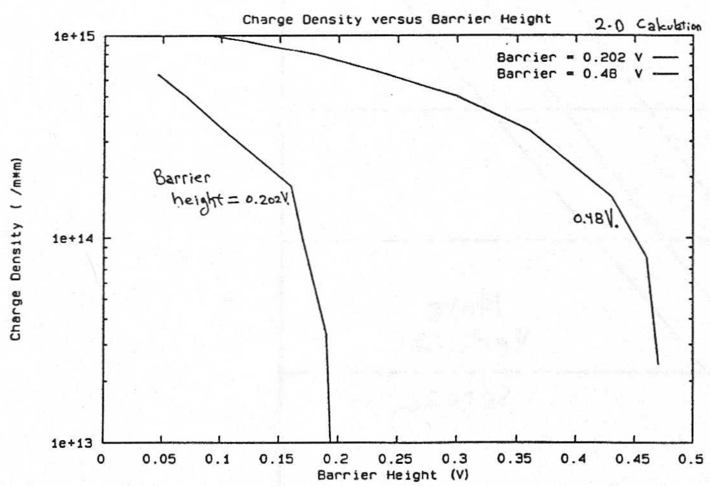
- The number left in the A-register decays exponentially with time.
- The decay is slowed when a potential well is induced before the start of the B-register.

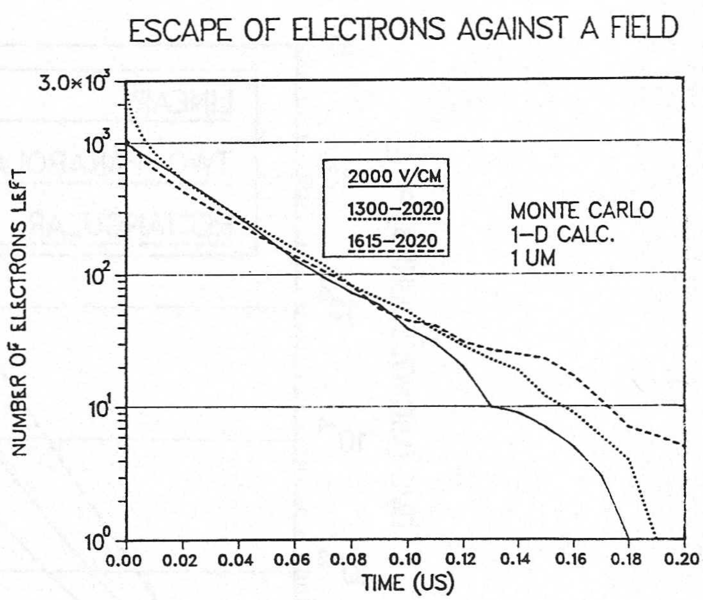




Results in 2-Dimensions:

- Include a small well and solve Poisson's equation in 2-dimensions. Vary the quasi-Fermi level for electrons in the well. Find the barrier height, i.e., the well depth, as a function of the amount of charge in the well.
- Approximate the barrier by a linear potential and let the electrons escape over the barrier. A Monte Carlo approach is used with all the electrons moving at each time step. The number of electrons remaining in the well is used to set the barrier height. Thus, as electrons escape, the barrier height increases and the rate of electron escape slows.
- The exponential decay regime quickly sets in as the amount of charge in the well drops.
- These results are mirrored by the self-consistent PISCES simulations.





Results in 1-Dimension:

- Solve the carrier continuity equation with a fixed electric field. The 2- and 3-dimensional studies show this approximation is reasonable when there is only a low level of charge in the potential well.
- And exponential decay with time is seen. Thus, concentrate on calculating τ in $e^{-t/\tau}$.
- A long derivation leads to the mean first passage time τ from the carrier continuity equation:

$$\tau(\varepsilon) = \int_{\varepsilon}^{L} dy\ D^{-1}(y)\ e^{qV(y)/kT} \int_{0}^{y} dz\ e^{-qV(z)/kT}$$

with a delta-function initial condition at ε. The model space has a reflecting boundary condition at 0 and a sink at L. The diffusion coefficient is D and the potential is V.

CHARACTERISTIC TRANSFER TIME WITH A BARRIER

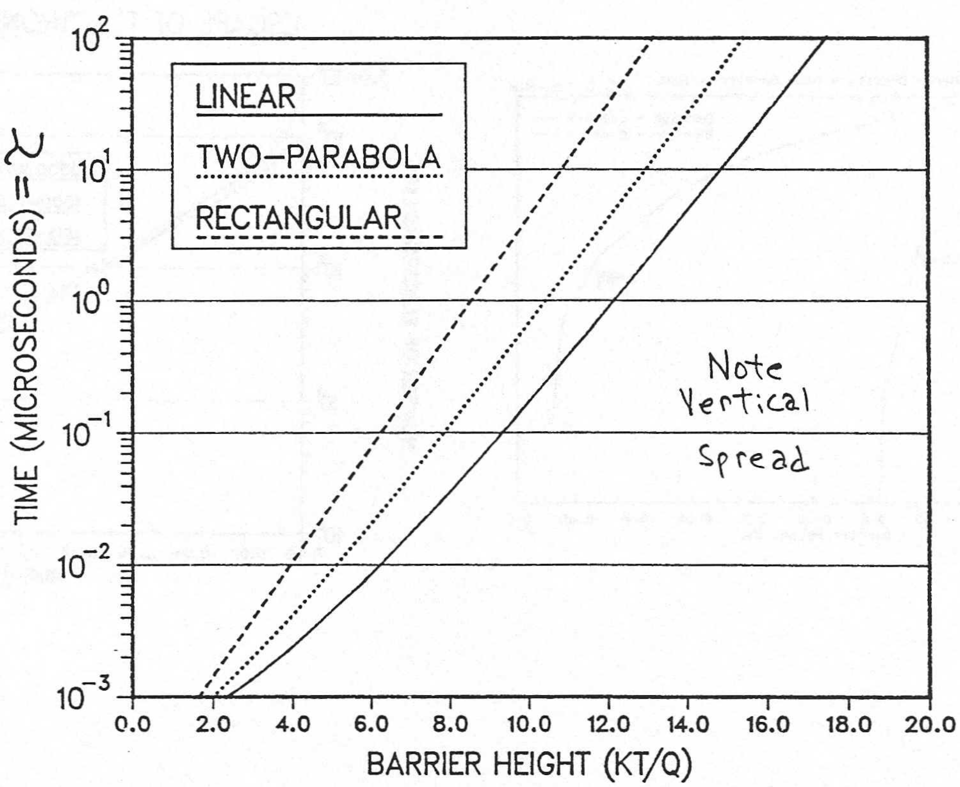


Image Lag:

An interline imager is operated in a manner to induce lag. The lag is due to a potential obstacle between the photodiode and the adjacent vertical CCD phase. The image lag is measured as a function of the time t_3 allowed for the photodiode to vertical CCD charge transfer through the transfer gate. The decrease in lag is exponential with the increase in t_3. The decay constant is extracted for each transfer gate voltage V_3 and plotted versus V_3. The decay time constant is then converted into a potential barrier height using the 1-dimensional results for τ for a two-parabola potential well. The barrier heights decrease linearly with an increase in V_3. Poisson's equation solutions also show this behavior.

References:

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