P02

Dark Current Model for the Time of Low Noise & Photon Counting

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Decreased dark current continues to be critical as more imaging applications move into the realm of photon counting. This is driven by the need for low light-level imaging both for small and large pixels, for scientific sensing and for time-of-flight range finding. And while the trend for dark current has been a steady decrease for advancing technologies [Figure 1], this progress has been based on the sequential elimination of charge generation mechanisms – a "peeling of the onion". Applying past solutions, such as elimination of metallic Shockley-Read-Hall centers and creation of pinning layers, will not provide further improvement because these mechanisms have been eliminated to the point that they only occur in a small fraction of bright pixels [McGrath 2017]. Dark current rates are now so low that it is necessary to shift our world view of its very nature if the industry is to make further advances. In this presentation a model will be proposed where the dark current generation process is no longer stochastic but is based on low-probability outliers from the generation source – "lucky electrons".

The traditional model of dark current is that the dominate generation due to S-R-H sites within the photodiode depletion region [Figure 3]. The carriers generated are fully-collected and are predominately due to mid-gap traps from metallic contamination or interface dangling bonds. This gives a temperature dependence of ~$E_G/2$. Charge generation from outside the photodiode potential well flows away so as not to contribute.

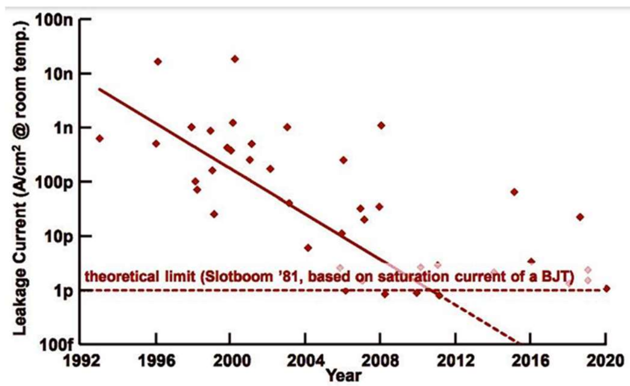

Figure 1. Dark current trend [Theuwissen 2021]

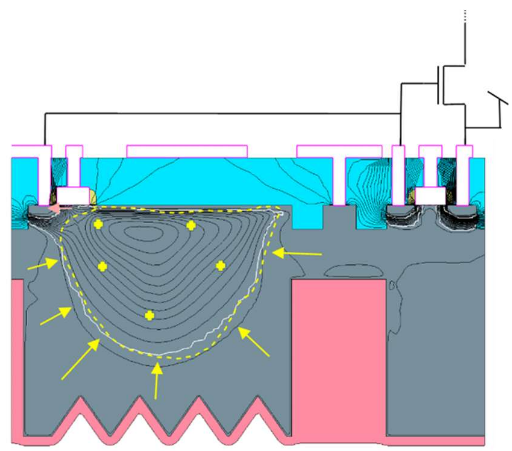

Figure 3. Traditional model for dark current generation: [cross] SRH generation sites in depletion volume; [yellow arrow) diffusion current; [pink arrow] interface current flow to conversion node

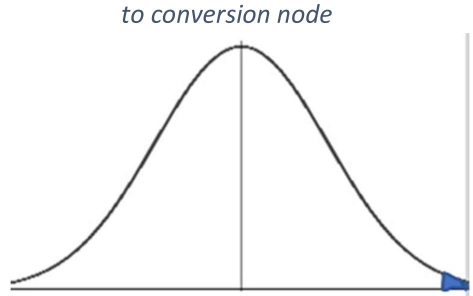

Figure 2. normal distribution: [blue] high energy outliers in electron energy distribution

In the model proposed here, the quantized and kinetic nature of the carriers is seen as critical. This comes

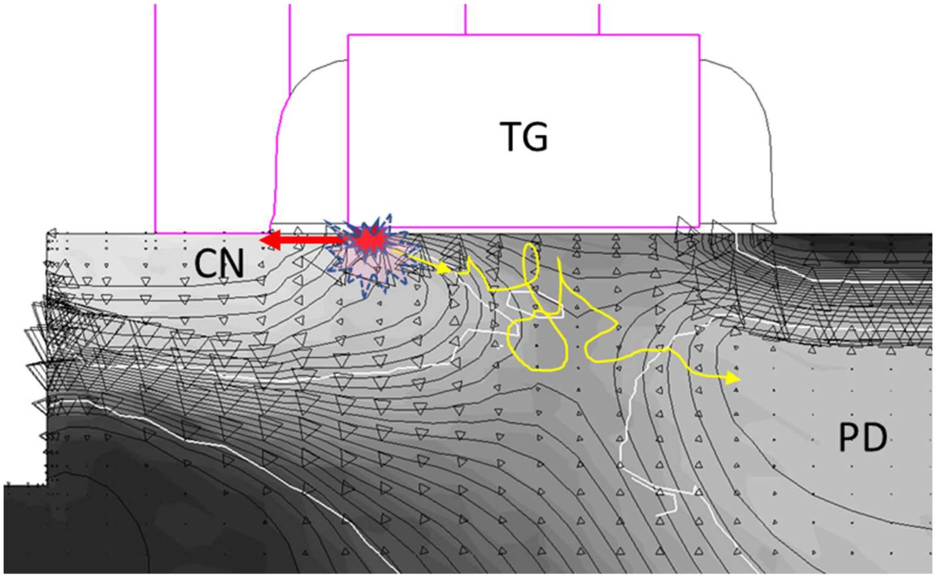

Figure 4. Model for interface dark current: [red] traditional model with simple drift in E-field; [pink] charge volume with outliers; [yellow] example trajectory of outliers; [black triangles] E-field; [black] potential contours; [white] depletion approximation

from the realization of how small is the number of carriers needed to account for the dark current levels observed. This means treating the carriers as having a distribution of energies, as individually interacting with the silicon lattice and by considering the dynamics of those with the highest energy [Figure 2].

Dark current generation under the TX gate can be used to illustrate the model [Figure 4]. In the traditional model, charge generated at the conversion node end of the TX gate would be simulated as a current which is swept away from the photodiode by the potential gradient. But given that the charge is not a continuous current in a smooth gradient, but rather is quantized particles interacting with the “muffin tin” lattice potentials, some charge has a probability of having the momentum and energy to go against the e-field to be injected into the undepleted region. Once there it will diffuse with the possibility of falling into the photodiode.

Observations that are critical include the following: (a) the probability density of free minority carriers in the undepleted region is so small that the carrier will act as an isolated charge in the lattice potential; (b) the material quality is so good that there is an insignificant chance of recombination during the transit time; (c) the observed dark current in industry standard image sensors requires only a small fraction of

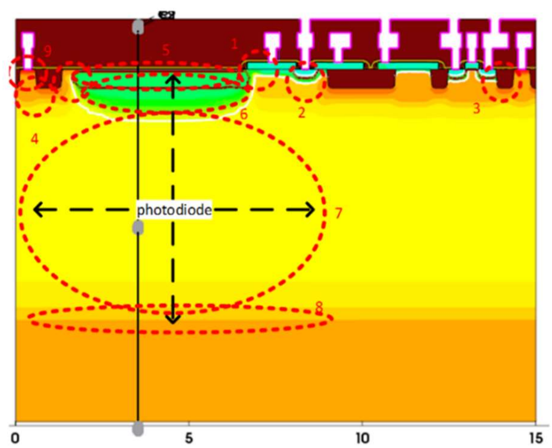

Figure 5. Sources of dark current: Of primary concern are (1) PD-to-TX oxide interface, (2) conversion node, (4) STI interface & (7) lightly-doped bulk

the charge generated by an interface dangling bond.

There are a variety of sites for dark current to be generated in a pinned

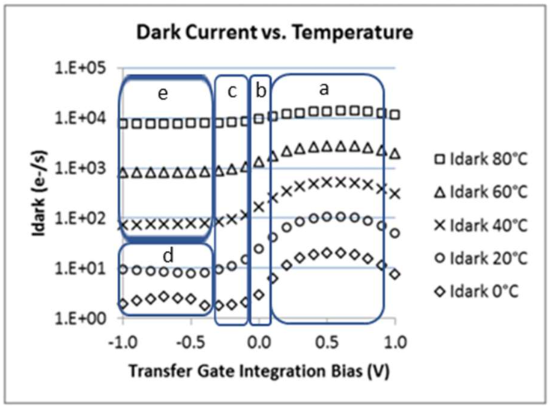

Figure 6. Photodiode dark current characterization: [a,b] Case A with Eg/2kT dependence; [c] Case B with Eg/kT dependence; [d] Case C with conversion node GIDL generation; [e] Case B from non-TX related source

photodiode pixel [Figure 5]. The "lucky electron" model can provide insight into understanding how these produce the observed behavior with varying bias and temperature [Figure 6].

There are two cases where the TX gate is off, isolating the photodiode from the conversion node, but where

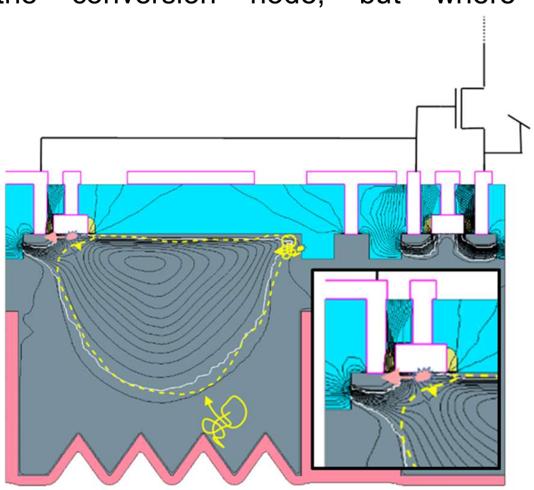

Figure 7. Case A: interface generation & photodiode separated by depleted potential barrier; [black] potential contours; [white] depletion boundary; [pink] interface generation site

interface states under TX contribute to the photodiode dark current. In the first, Case A, the TX is biased so that a depleted exists with a potential barrier providing isolation [Figure 7]. In this case energetic carriers from the generation site can have enough energy to jump the barrier while retaining the temperature dependence of the interface generation process, ~$E_G/2$.

In the second case, Case B, the TX is biased so that the channel is undepleted providing a barrier with majority carriers

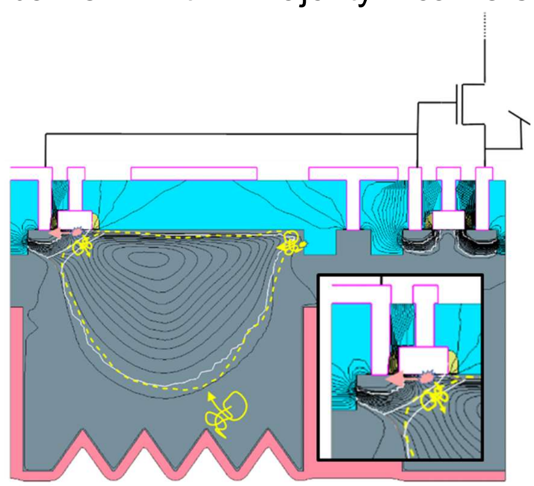

Figure 8. Case B: interface generation & photodiode separated by undepleted barriers: [black] potential contours; [white] depletion boundary; [pink] interface generation site

[Figure 8]. While it would seem that this region would provide an absolute barrier to the generated carriers, it is possible for energetic carriers to be injected into this region and diffuse across it. Given that the number of energetic carriers is a small fraction of those being generated, the carriers will lose the memory of the generation process and instead have that of diffusion, E_G. That is, the generation site acts as a deep reservoir from which only a few escaping carriers are needed to provide the observed dark current.

An extreme demonstration of this model, Case C, occurs when TX is taken very negative and the dark current is found to be directly dependent on the TX-to-conversion-node voltage. That is it is found to be proportional to the GIDL current in the conversion node with the same independence to temperature. The only explanation is that the carriers are finding their way through the undepleted region to the photodiode [Figure 9].

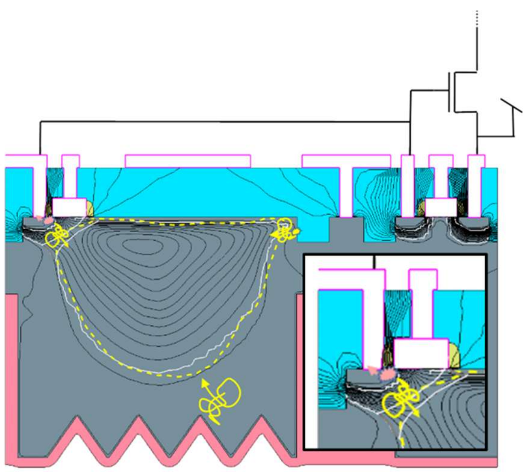

Figure 9. Case C: conversion node generation & photodiode separated by undepleted barrier; [black] potential contours; [white] depletion boundary; [pink] conversion node GIDL generation site

Beyond these mechanisms, at low TX bias and high temperatures, dark current becomes independent of TX voltage. This may result from the undepleted bulk or the STI interface where the minority carrier density is < 1 e-/pixel allowing S-R-H processes to generate charge that than travels by diffusion with temperature dependence of E_G.

Takeaways from embracing a “lucky electron” viewpoint are as follows:

- In the present technology, dark current is not intrinsic, but is limited by defects.
- Improvements in dark current can come from reducing TX and STI interface states and from avoiding band-to-band tunneling; regions of interest extend beyond the photodiode depletion volume.
- Simulation needs to shift to treating carriers as quantized in time and in space, treating carriers as distributions of kinetic particles rather than currents; this will likely mean increased use of Monte Carlo techniques.

References:

Dan McGrath, “Dark current limiting mechanisms in CMOS Image Sensors, IISW 2017

A.J.P.Theuwissen, “There’s more to the picture than meets the eye …”, plenary talk, ISSCC 2021