Estimates for Scaling of Pinned Photodiodes

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Abstract

The relationship between charges and potential in the pinned photodiode formed with a fixed surface implant and a buried implant with various *doses* and *energies* is studied using computer analysis (TCAD) and analytically through *uniform profile* approximation and *two-plate capacitor* approach. The approximations were found to work quite good, which allows the process designer to predict the key parameters of the pinned diode such as *pinned voltage* and *charge handling capacity* from the known *dose/energy* and supporting charts. One may even try to keep the *Signal-to-Noise* ratio constant designing smaller and smaller pixels using the combination of simple rules Dose*Energy = const and Dose*Area = const.

Introduction

Both CCDs and CMOS image sensors extensively use a buried channel photo-detector also called pinned photodiode and which originated from a virtual phase CCD [1]. The trend is towards higher resolution, smaller pixel, lower voltage, less photons per pixel, less noise, and lower saturation charge. Pixels of 2 micron and less have been reported [2-3]. There are no established rules available in the literature for scaling of the pinned diode to smaller size. One may expect that the pixel design rules will remain more conservative compared to the digital CMOS, and will allow supply voltages of 2.5V- 3.3V even going to 0.13um rules or smaller. Although the prospects for noise reduction were good [4], there is still no clear answer what to do with Signal-to-Noise ratio which keeps dropping. Some experts suggest that a higher resolution would compensate for the lack of SNR. And, if low resolution is needed, binning could restore high SNR. This does not satisfactorily work if someone blows up a small window with low SNR on a full screen. It is not unreasonable to suggest, that for many applications it would be beneficial to keep the saturation charge at pinned diode as high as possible, while designing smaller and smaller pixels.

Despite a wide spread of the pinned photodiode, there is a lack of public information about its characteristics, such as the depletion potential and the charge capacity, and their dependence on the doping. This paper focuses on establishing the relationship between the implant energies and doses on one hand, and, the parameters of the photo-diode, - on the other.

Doping profile and band diagram

Pinned photodiode is a buried channel device with at least two implants. An exemplary pinned photodiode profile is presented in Fig.1. The buried channel is formed on a p-type boron substrate of 1e15 cm^{-3} with the following implants: 1) BF_2 10 keV, Dose=$2x10^{13}$ cm^{-2} for surface P- layer; it keeps the surface electrically neutral and thus contains the electric field within the silicon; 2) As 90 keV, Dose= $3.2x10^{12}$ cm^{-2}, forms buried N- layer; both implants are done through a 60A oxide. Fig.2. is a schematic drawing of the energy band diagram and the distribution of ionized centers in the device with illustration of electric field lines in the structure. To enable the capacity for photoelectrons, all equilibrium electrons need to be extracted from the N-region. In a working pixel, this is done by a transfer gate. In a model device this can be done by having a nearby N+ diffusion connected to a positive voltage Vbias.

Uniform profile approximation

In order to find the potential distribution in the device and the relationship between charges and potential, one needs to solve the Poisson equation. Although, it is quite easy to approximate the profiles with Gaussian distributions, this task can not be solved analytically. To make the closed form solution possible, we substitute the profiles with uniform distributions which preserve the total dose (Fig.1). Each implant can be characterized by mean project range Rp and its dispersion ΔRp. The values can be taken from TCAD default tables. For BF2 at 10 keV, $Rp_{\_B}$ is $7.717 \cdot 10^{-3}$ µm and $\Delta Rp_{\_B}=5.96 \cdot 10^{-3}$ µm. The As parameters in the energy range of 40-200 keV could be found as follows: $Rp_{\_As}[\mu m] = 0.0055+5.24 \cdot 10^{-4} \cdot Energy_{\_As}[keV]$ and $\Delta Rp_{\_As}[\mu m]=0.00337+1.71 \cdot 10^{-4} \cdot Energy_{\_As}$. We approximate the width of the uniform profile as $5 \cdot \Delta Rp_{\_As}$.

This accounts for 99% of the impurity in Gaussian distribution. Since the surface boron implant is of much higher concentration, its compensation can be disregarded. The compensation of the donor by the surface P - layer was calculated by integrating Gaussian As distribution in area 1 (Fig.1). This gives good approximation to TCAD simulated curves (Fig.3).

Pinned photodiode channel is formed with two p-n junctions with the left 12 and the right 23 space charge regions (SCRs) (Fig.2). The characteristic depletion depths belonging to N- region are $Xn_{\_12}$ and $Xn_{\_23}$, as shown in Fig.2. The channel can be fully depleted, partially filled with photoelectrons, or filled with electrons (steady-state). There is a contact potential difference between N- and each of p- areas, Vbi_{12} and Vbi_{23}, respectively. It is a weak function of doping and light (through n_i), see below in (2). In this short paper, we disregard the difference between the steady-state and the thermodynamic equilibrium and the difference between the substrate and P- doping, and suggest, for simplicity, that $Vbi_{12} \approx Vbi_{23} \approx Vbi \approx 0.9$V. The channel potential V is the deviation of quasi-Fermi potential for electrons from its equilibrium value. It is zero in equilibrium and it reaches its maximum value Vpin in full depletion. The total potential drop over space charge region is the sum of Vbi and V. The charge Q_{12} of the positively charged donors in the SCR of the n-region of abrupt asymmetrical p-n junction (Fig.2) ($N_{\_B} >> N_{\_As} >> N_{\_Bsb}$) can be found as follows [5]:

$$Q_{12} = N_{\_As} \cdot Xn_{\_12} = N_{\_As} \cdot L_{d2} \cdot \sqrt{\frac{2 \cdot (V_{bi12} + V)}{\beta}} \sim \sqrt{N_{\_As}} \cdot \sqrt{V_{bi12} + V}$$
$$\beta = kT/q, \quad L_{d2} = \sqrt{\frac{\varepsilon_0 \cdot \varepsilon_{Si} \cdot \beta}{q \cdot N_{\_As}}}, \quad V_{bi12} = \beta \cdot \ln \frac{N_{\_B} \cdot N_{\_As}}{n_i^2} \tag{2}$$

where n_i – effective intrinsic concentration, ε_{Si} – silicon dielectric permittivity, ε_0 – vacuum dielectric permittivity, kT/q – thermal voltage. The charge Q_{12} is given per unit area. The Q_{23} charge of the right p-n junction 23 depends on substrate doping in the same way as (2), with $N_{\_Bsb}$ instead of $N_{\_As}$. The charge in the right p-n junction relates to the left charge as $Q_{23}/Q_{12} \approx \sqrt{N_{\_Bsb}/N_{\_As}} \approx \sqrt{10^{15}/10^{17}} = 10\%$ For further estimates we assume that Q_{23} is always 10 % of Q_{12}, and the total donor charge in both junctions is equal to $1.1Q_{12}(N_{\_As}, V)$. When pinned diode is fully depleted (V=Vpin in eq.(2)), this charge is equal to the dose of uncompensated arsenic.

Two-plate capacitor model

Let's also consider a simple approach to estimate Vpin, which is essentially based on replacing the Gaussian distributions for P- and N-regions with delta functions. Consider a capacitor with plates located at $\mathbf{Rp_{\_B}}$ and $\mathbf{Rp_{\_As}}$, the centers of the implanted boron and arsenic. The total voltage applied to the capacitor should include both the full depletion voltage Vpin and the contact potential difference Vbi. For the large-signal pinned diode capacitance and for the total charge on one of the plates we can write the following:

$$C_{Si} = \frac{\varepsilon_{Si} \cdot \varepsilon_0}{q \cdot (R_{p\_As} - R_{p\_B})}, \qquad Q = 1.1 \cdot C_{Si} \cdot (Vbi + V_{pin}) \tag{3}$$

Comparison with Vpin obtained using TCAD

We simulated a 2D device with an N+ junction adjacent to the pinned diode N-region. By applying the voltage Vbias between N+ and the substrate, one can control filling of the buried channel with electrons, because V in the channel is approximately equal to Vbias. But, after the voltage in the channel reaches its maximum Vpin, Vbias no longer controls the channel potential V. Fig.4 plots the total space charge in the buried channel as a function of the applied voltage. When the applied voltage exceeds Vpin, charge reaches its saturation value which is the uncompensated dose of arsenic. The two-plate capacitor approach works well to estimate Vpin. One needs to introduce another, a small-signal capacitor, to describe the filling of the buried channel with electrons, because the channel is not located at the As maximum. The uniform profile approach gives good approximation to the TCAD simulation over the entire range of Vbias till Vpin. Charge capacity Qe could be found from eq.(2) as the charge difference between the empty well and the full well, i.e comparing the total charge at V= Vpin and V =0. If we define the ratio of electron charge to uncompensated arsenic dose as γ, then, from Eq.2, $\gamma = \sqrt{V_{bi} + V_{pin}} - \sqrt{V_{bi}}$ = 0.43, 0.35 and 0.27 for Vpin=1V, 0.8V and 0.6V, respectively. And, for saturation charge, we can write:

$$Qe = \gamma * \text{Uncompensated\_Dose}_{As} * \text{Photodiode\_area} \tag{4}$$

Relationship Dose-Energy that keeps Vpin constant

The methods above to calculate or estimate Vpin were applied to solve the inverse task: find all possible solutions which keep Vpin constant. In doing so it was assumed that the surface BF2 implant stays the same, and only parameters of the buried As implant vary. As it could be expected, there is a family of Dose-Energy pairs which give the same Vpin.

Let's illustrate it within the two-plate capacitor model. Suppose we found one pair Dose-Energy which gives desired Vpin. If we increase energy of As, the mean project range Rp grows linearly with energy, so the right plate of the capacitor moves deeper into silicon. Thus, the capacitance goes as 1/Energy. So, we need to reduce the charge on the capacitor to keep the voltage constant. Thus, from the simple capacitor rule Q=C*V, we can get that in order to keep Vpin, the following relationship needs to hold:

$$Energy*Dose=Const \qquad (5)$$

This formula does not take into account the compensation of arsenic by boron, which can be high at low As energies (Fig.3). So, using of uncompensated As dose in (5) for Dose should give a better approximation. The inset in Fig.5 indeed shows that the uncompensated dose *vs* energy curve in this case fits better into 1/x dependence. It also shows that the charge of fully depleted channel obtained using the uniform profile and the two-plate capacitor estimates give the result very close to TCAD. Similar dependences and a good agreement between the all approaches were also obtained for several values of Vpin: 1V, 0.8V and 0.6V. The constant in (5) is $2.9\cdot10^{14}$, $2.6\cdot10^{14}$, and $2.3\cdot10^{14}$ [$keV*cm^{-2}$] for Vpin = 1V, 0.8V, and 0.6V, accordingly.

As an example, let's calculate the implants which yield the pinned photodiode of $1x1\ \mu m^2$ area with Vpin=1V and charge capacity Qe of 25 000 e-:

1) From Eq.4, $Uncompensated\_Dose_{As}$ =25000/1e-8 cm^{-2}/0.43 = $5.8\cdot10^{12}$ cm^{-2}
2) From Eq.5 or Fig.5, $Energy_{As}$ = $2.9\cdot10^{14}/5.8\cdot10^{12}$ cm^{-2} = 50 keV
3) Considering a 20% compensation at this energy (Fig.3, 5), the total As dose shall be $7.2\cdot10^{12}$ cm^{-2}.

The lower the As energy the higher the dose, and the higher the electric field in the surface p-n junction. Hot electrons may cause an avalanche breakdown of the device if the field exceeds the critical one. The maximum electric field in an abrupt p-n junction according to Gauss's law is proportional to the total space charge [5] (uncompensated As dose at full depletion). Critical breakdown field, in its turn, depends on doping concentration. For the doping profile in Fig.1 (As dose 3.2e12 cm-2) the critical field is estimated to be 1e6 V/cm [5], which corresponds to the uncompensated As dose of 7.2e12 cm^{-2}. The estimates do not show we exceed the critical field when we move up the curve in Fig.5. However, one needs to be careful when doing extremely shallow heavily doped detectors. In addition to avalanche breakdown, other potential issues are tunneling and excessive dark current. The residual radiation defects after annealing, as the dose is increased, should also be avoided.

Scaling to smaller pixels that preserves charge handling capacity

When scaling the pinned photodiode down to smaller size, we can, for example, not only keep Vpin constant, but also keep the pinned diode saturation charge. These two can be combined into the following set of rules:

$$Photodiode\_area * Uncompensated\_Dose = Const$$
$$Uncompensated\_Dose * Energy_{As}=Const$$

So, to keep the saturation charge while reducing the photodiode size, the As dose should go up as 1/Area. Then the As energy needs to be reduced to keep the depletion voltage Vpin from rising.

References

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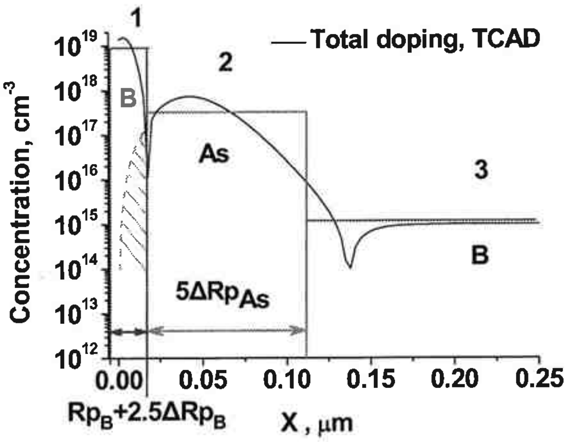

Fig.1. Impurity profile of exemplary pinned photodiode

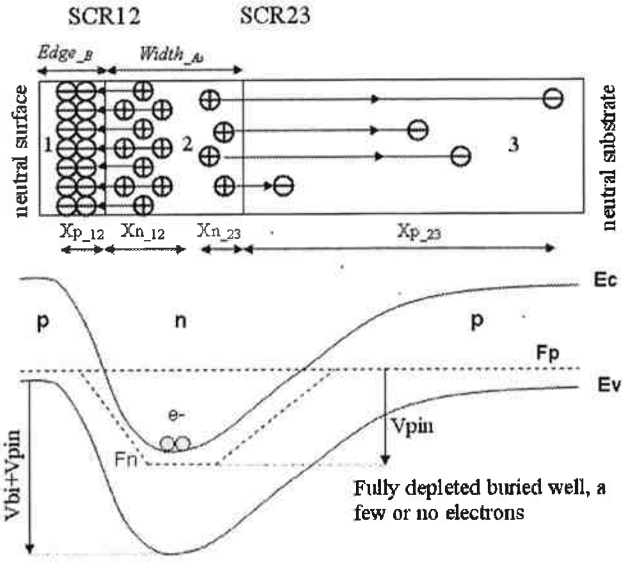

Fig.2. Band diagram of pinned photodiode

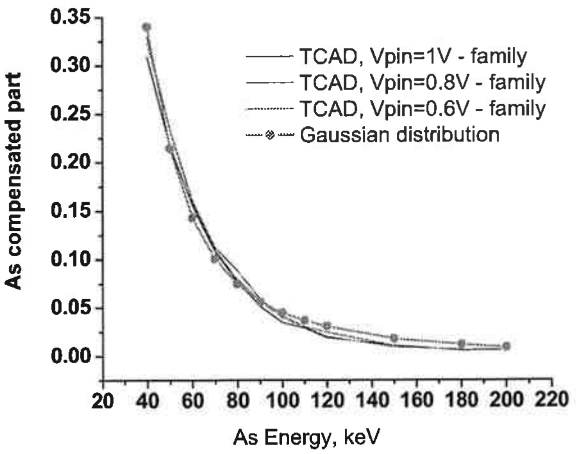

Fig.3. Relative share of As compensated with surface B

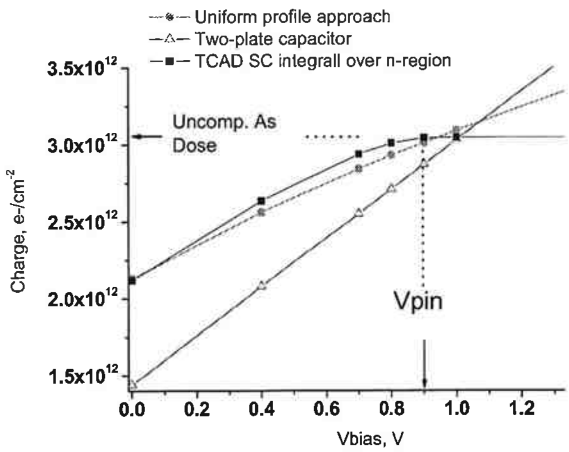

Fig.4. N-region space charge versus N+ drain voltage

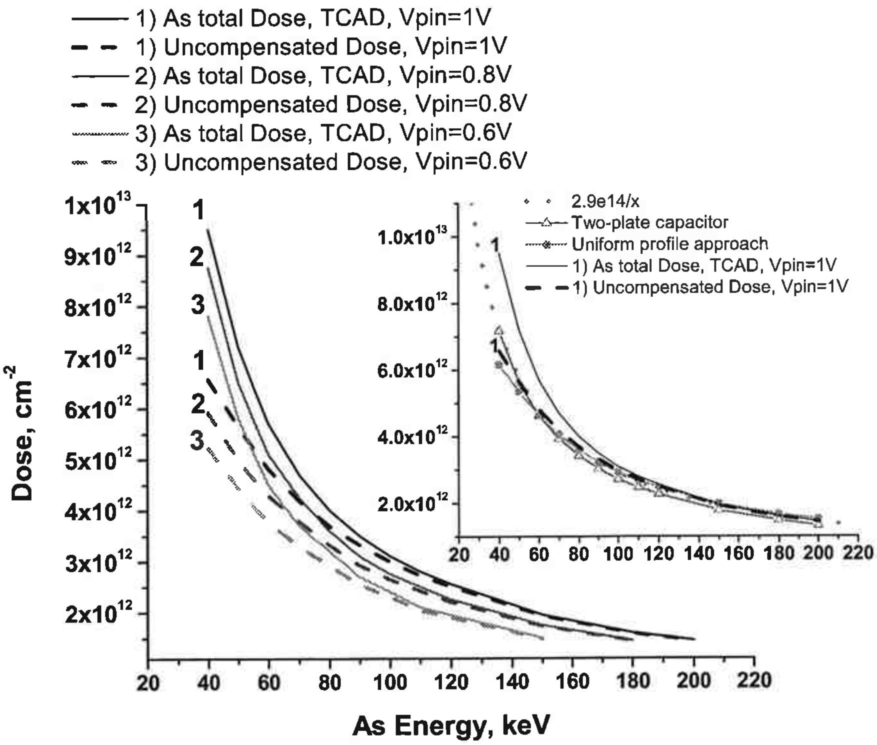

Fig.5. Dose-energy dependences, which keepVpin constant, forVpin =0.6V, 0.8V, and 1V.

The insert shows calculations done for Vpin=1V using uniform profile calculations, a two-plate capacitor model, and TCAD simulations. Using uncompensated dose best fits into 1/x curve.