Simulation and Device Characterization of P+PNPP+ Double Junction Photodiode for Solar Cell Application

Yoshiaki Daimon Hagiwara[1]

[1] Artificial Intelligent Partner System Laboratory
Atsugi-city, 243-0201 Japan

Abstract

A conventional single NP junction type photodiode silicon solar cell is known to have a poor quantum efficiency of about 20% because it can utilize only a single narrow depletion width. This paper reports a P+PNPP+ double junction type photodiode which at least doubles the PN junction depletion width and further more by utilizing the electron hole separation mechanism of the barrier electric field created by the sloped surface P+P doping profile, expecting up to 60 % efficiency.

1. Introduction

The short wave length blue light cannot penetrate silicon crystal more than 0.2 μm in depth. Most of the sun light energy is concentrated in the short wave blue light spectrum reaching only the floating N+ silicon surface vicinity of 0.2 micro meter in depth. Moreover, in conventional the N+P single junction type solar cells, the N+P junction depletion region width Wd, as shown in Fig. 1, is very narrow because the large portion of the surface portion of the floating N+ region is used as the photo electron storage region which forms the sea of the photo electrons, with a flat photo electron sea level with no barrier electric field where most of the electron hole pairs are recombined and do not contribute to the solar cell quantum efficient\cy. This is the main reason why the conventional single junction solar cell[1] has a limitation of a poor quantum efficiency of about 20 %.

2. P+P barrier electric field for photo pair separation

Barrier electric field is needed to separate the photo electron and hole pairs in solar cells. There are two methods to create barrier electric field. One approach is to use the PN junction depletion region shown in Fig.1. The second approach utilizes the principle applied in a drift field bipolar transistor[2] base region with the P+P barrier electric field as shown in Fig.2.

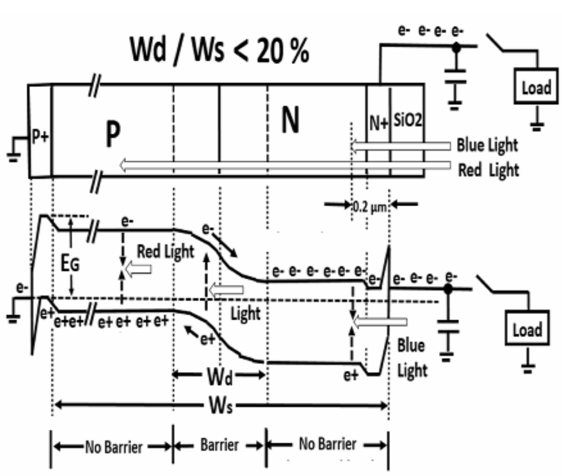

Fig. 1 Conventional Single NP Junction Solar Cell

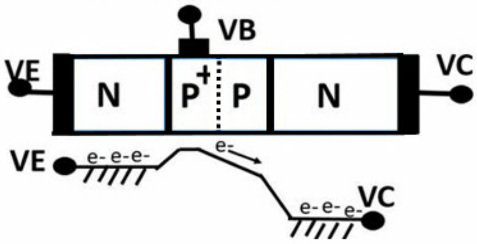

Fig. 2 Drift Field Bipolar Transistor with P+P Barrier Electric Field

The second approach has been applied also in the form of the surface Pinned P+P Hole Accumulation Photodiode[3] (HAD) for highly light sensitive imager sensors. See Fig.3, which shows a cross sectional view of a typical back light illuminated CMOS image sensor in the global shutter scheme with an MOS gate buffer memory (GSG) [3-5]. The barrier electric filed created by the surface P+P impurity doping variation can separate photo electrons pairs created at the near silicon surface P+P region efficiently to achieve the excellent short wave length blue light sensitivity.

Pinned Surface P+PNPP+ double junction type photodiode for solar cell is proposed now in this paper and shown in Fig.4, which doubles the PN junction depletion region width, creating a very wide PN junction type barrier electric field region needed for the photo electron and hole pair separation.

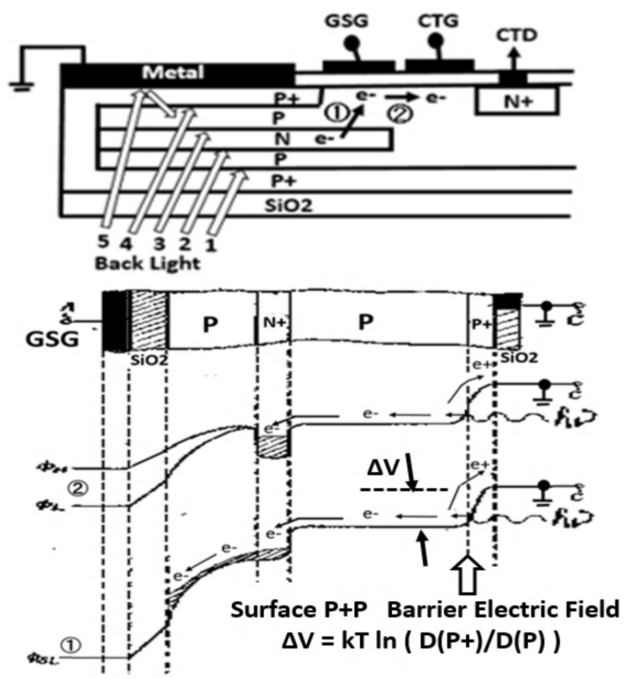

Fig. 3 P+PN+PP+ type Back Light Illumination CMOS Imager

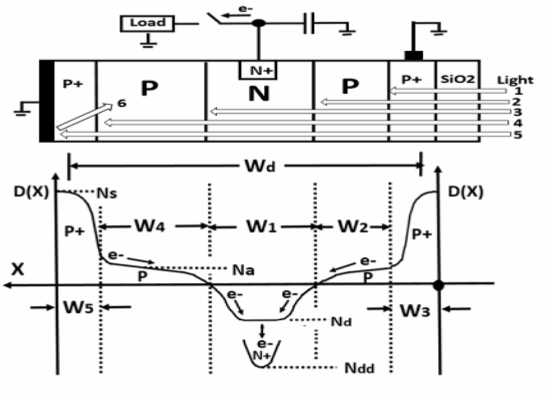

Fig. 4 Doping profile D(x) of P+PNPP+ Solar Cell

3. Numerical Analysis of the P+P barrier electric field

The surface P+P Hole Accumulation Photodiode (HAD) has a smoothly varying shape of Gaussian function given as G(X) = exp (− x^2). For a double surface ion implantation process we have Ds(x) = (Ns − Na) G (x/Rs) + Na G (x/Ra). The total doping is then D(x) = Ds(x) + Ds(Xd − x) − Nd where Nd is the N-type original substrate doping level. Poisson equation$d^2V(x)/dX^2 = \rho(x)\ /\ Es\,i$was solved numerically for the space charge polarization ρ(x) and the electron potential V(x) with ρ(X) = D(x) − P(V). The positive hole carrier density P(V) is given as P(V(x)) = Ns exp (− V(x)/kT) while the electron charge concentration N(V(x)) is zero since the N region is completely depleted and no photo electrons present.

If Ns and Na were of uniformly doped average values of the surface P+P regions, the surface barrier potential drop can be obtained as kT ln(Na/Na) = 0.0776 eV with kT = 0.0259 eV.

Salient physical parameters were set as Nd =100, Ns =10^7, Na = 5 x 10^5 all in the unit of e/ μ m^3 while Rs = 0.57, Ra = 2.5, X_{12} = 20 in μ m. And the silicon dielectric constant was taken as Esi = 648 eV / μ m. Boundary conditions both at x = 0 and x = X_{12} were set as V(x) = − E_G = − 1.1 eV, which is at the highest electron energy potential value as shown in Fig.5.

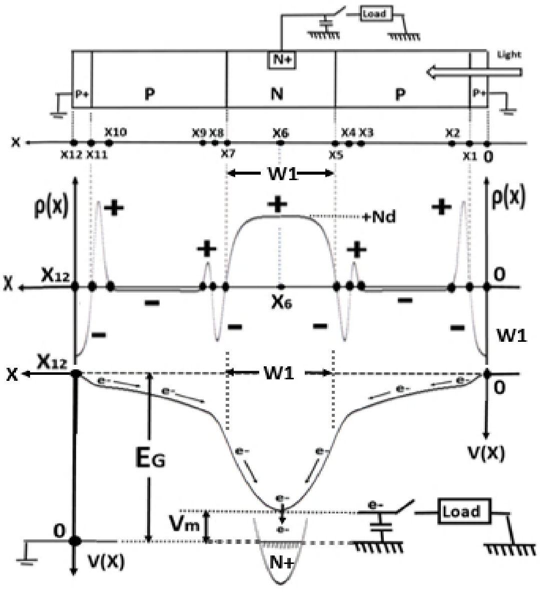

Fig.5 Numerical Calculations of Space Charge Polarization $\rho(x)$ and Electron Potential V(x).

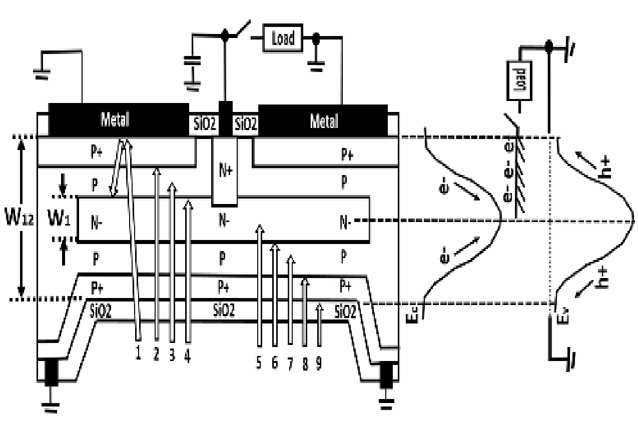

Fig.6 Various Contributions (1–9) to Quantum Efficiency

Note that the empty potential well of the N region is pinned and is given as Vm = – 0.203 eV. All the photo electrons are to be drained down into the center N+ storage region. Other parameters obtained were X_1= 0.828, X_2 = 1.726, X_3 = 6.315, X_4 = 6.705 and X_5=7.292 all in μ m. The buried N region width is given as W_1= X_7 – X_5 = 5.416 μ m. The charge capacity was computed as Qd = 459.5 e / μ m^2 . The average doping level was then given as <Nd> = Qd/ W_1 = 84.84 e / μ m^3 which is close to the initial N type substrate doping level Nd. As shown in Fig.5, note that for this double ion implantation process, the space charge polarization (+ and -) occurs not only at PN junction depletion edges but also at locations of strong P+P barrier electric field for photo pair separation.

Fig. 6 shows various contributions (1–9) to the quantum efficiency of the solar cell including the backside reflection metal.

4. Conclusion

While the conventional single N+P junction type has the low quantum efficiency of 20 %, the P+PNPP+ double junction type Photodiode (PPD) solar cell is expected at least to double the quantum efficiency, and more by the Pinned Surface P+P Hole Accumulation Diode (HAD) image sensor structure.

The surface P+P barrier electric field contributes more to the quantum efficiency, boosting up to 60 % or more for the short wave blue light energy spectrum, and more drastically at the same time, by preventing the hole electron recombination completely in the empty pinned potential well in the N region.

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