Origin of 1975 Pinned Photodiode Concept was hinted by CCD/MOS type Buried Photodiode

See JPA 1975-127646, JPA 1975-127647 and JPA 1975-134985

by Yoshiaki Hagiwara in 1975

Numerical Computation of Potential V(x) of Arbitrary Doping Profile D(x) from $x = 0$ to $x = X_w$ with the given boundary condition $V(x) = V_s$ and $dV(x)/dx = E_s$ at $x = 0$.
Find the proper value of $V(x) = V_s$ so that we have $V(x) = V_w$ and $dV(x)/dx = E_w$ at $x = X_w$.

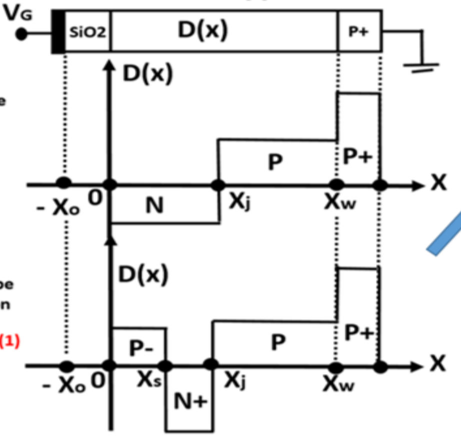
Conventional CCD/MOS type Photodiode

Type (1)

Conventional
CCD/MOS Type
NP junction
Photodiode
in early 1970s

Type (2)

Modified
CCD/MOS Type
P-N+P junction
Photodiode
hinted by Type (1)



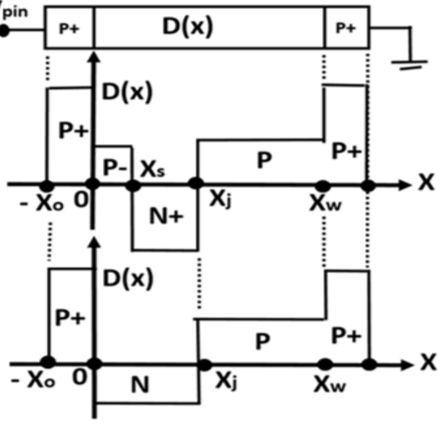
Pinned Photodiode proposed in 1975

Type (3)

Original
P+P- N+P junction Type
Pinned Photodiode
proposed in Oct. 1975
by Yoshiaki Hagiwara
in JPA 1975-127647
hinted by Type (2)

Type (4)

Conventional
P+NP junction Type
Pinned Photodiode
proposed in Nov. 1975
by Yoshiaki Hagiwara
in JPA 1975-134985
hinted by Type (3)



For $x < 0$ in Type(1) and Type(2)

$$\frac{d^2V(x)}{dx^2} = 0$$

gives at $x = 0$

$$E_s = C_{ox}\,(V_s - V_G + V_{mo} - V_{os})\,/\varepsilon_{si}$$

For $x < 0$ in Type(3) and Type(4)

$$\varepsilon_{Si}\frac{d^2V(x)}{dx^2} = N_{pp} - N_{pp}\exp(\,(V_{pin} - V(x))\,/\,kT\,)$$

gives at $x = 0$

$$E_s = \sqrt{\frac{2N_{pp}kT}{\varepsilon_{si}}\left\{\left(\frac{V_s}{kT}\right) - 1 + \exp\left(-\frac{V_s}{kT}\right)\right\}}$$

For $0 < x < X_w$ in all types (1) thru (4)

$$\varepsilon_{Si}\frac{d^2V(x)}{dx^2} = D(x) - N_{pp}\exp(\,-V(x)\,/\,kT\,)$$

needs to be solved numerically
for any arbitrary doping function D(x).

For $X_w < x$ in all types (1) thru (4)

$$\varepsilon_{Si}\frac{d^2V(x)}{dx^2} = N_{pp} - N_{pp}\exp(\,-V(x)\,/\,kT\,)$$

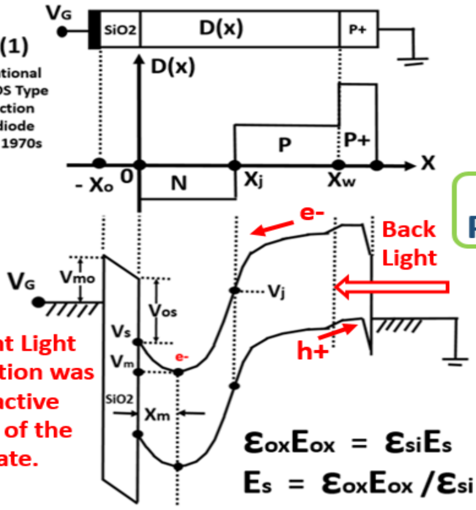
gives at $x = X_w$

$$E_w = -\sqrt{\frac{2N_{pp}kT}{\varepsilon_{si}}\left\{\left(\frac{V_w}{kT}\right) - 1 + \exp\left(-\frac{V_w}{kT}\right)\right\}}$$

The conventional Buried Channel CCD/MOS type photodiode has a very large surface electric field Es.

Type (1)

Conventional
CCD/MOS Type
NP junction
Photodiode
in early 1970s



The Front Light Illumination was not attractive because of the Metal Gate.

$$\varepsilon_{ox}E_{ox} = \varepsilon_{si}E_s$$

$$E_s = \varepsilon_{ox}E_{ox}\,/\varepsilon_{si}$$

$$V_s = V_G - V_{mo} + E_{ox}X_o + V_{os}$$

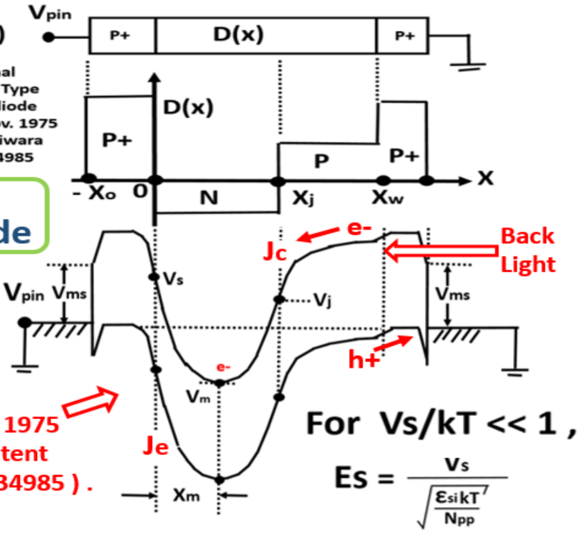
$$E_s = C_{ox}\,(V_s - V_G + V_{mo} - V_{os})\,/\varepsilon_{si}$$

Type (4)

Conventional
P+NP junction Type
Pinned Photodiode
proposed in Nov. 1975
by Yoshiaki Hagiwara
in JPA 1975-134985

Pinned Photodiode

Hagiwara drew this Empty Potential Well in the Fig. 6 of the 1975 Japanese Patent (JPA 1975-134985) .



For $V_s/kT \ll 1$,

$$E_s = \frac{V_s}{\sqrt{\frac{\varepsilon_{si}kT}{N_{pp}}}}$$

$$E_s = \sqrt{\frac{2N_{pp}kT}{\varepsilon_{si}}\left\{\left(\frac{V_s}{kT}\right) - 1 + \exp\left(-\frac{V_s}{kT}\right)\right\}}$$

The surface electric field Es of the P+NP junction type Pinned Photodiode is also very large which is worse since the surface electric field depends also on the surface P+ doping level Npp. Type (2) and Type (3) modifications may help reducing the surface electric field Es.