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Pinned Buried PIN Photodiode Type Solar Cell

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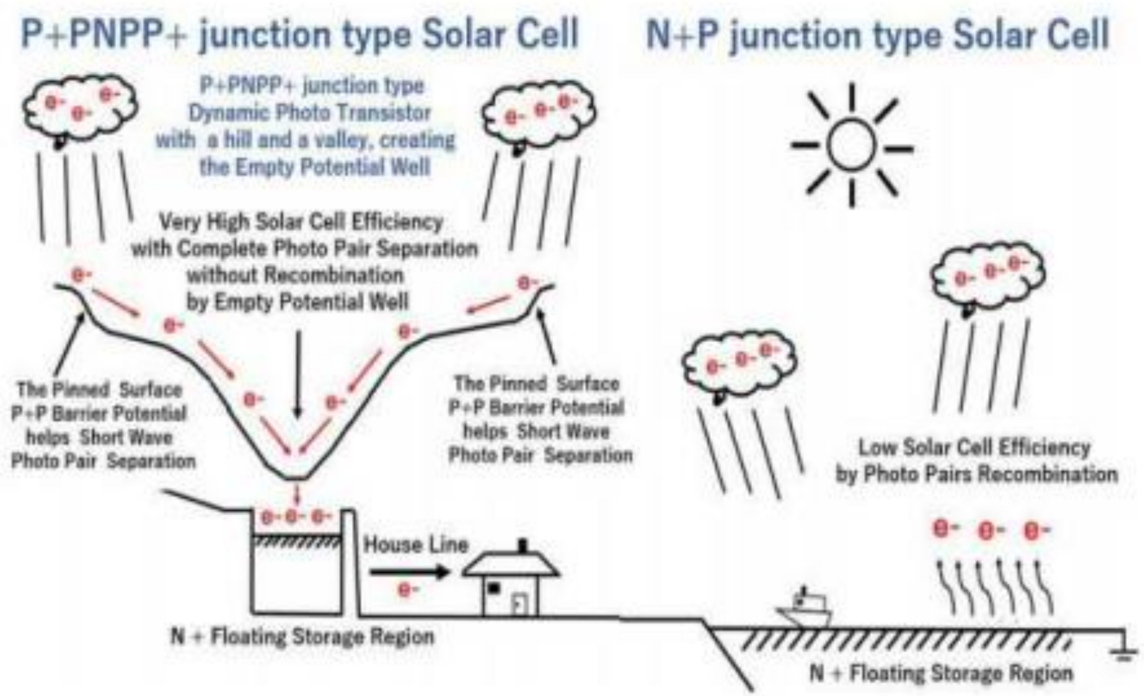
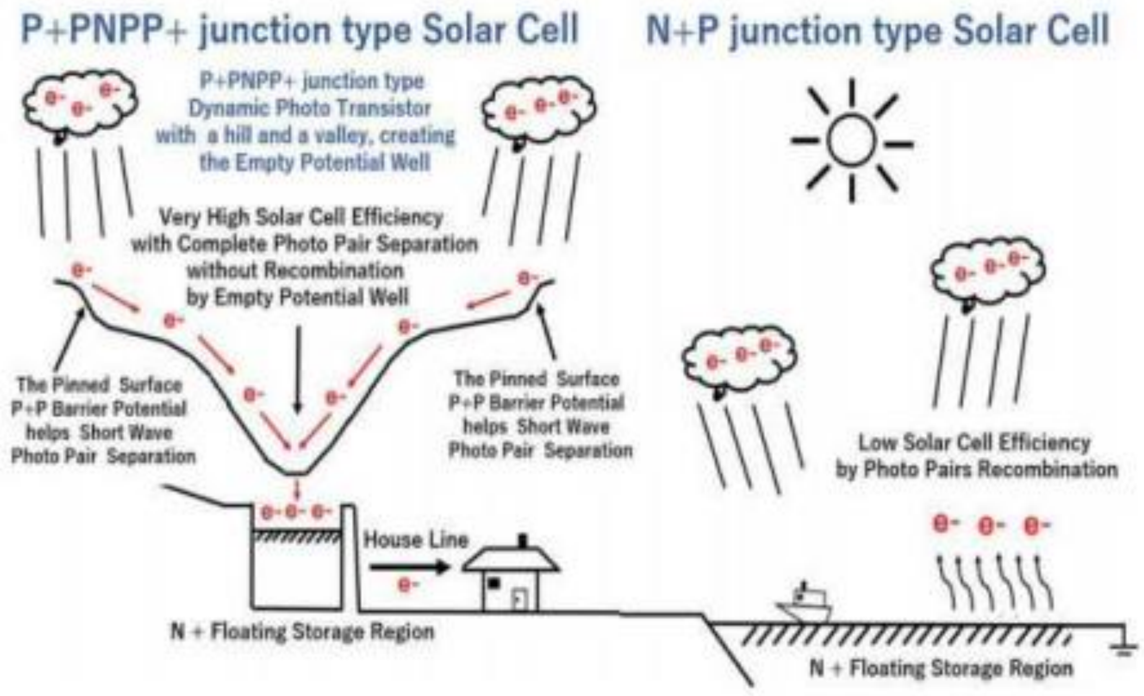


Fig. 14 Analogy of rain drops and photo electrons under the sunshine.

***Abstract*— This paper reviews the origin of Pinned Buried Photodiode and its historical development efforts. Three original Japanese Patent Applications filed by Hagiwara at Sony in 1975 are explained in details which defined the first triple junction type Pinned Buried Photodiode with the in-pixel vertical overflow drain (VOD) function with the electrical shutter capability,**



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the most important feature of Pinned Buried Photodiode is the short-wave blue light sensitivity. Sun light has a great amount of short-wave blue light energy. Pinned Buried Photodiode type solar cell is similar to a very efficient rain-drops collecting system of a mountain hill and a valley with a storage dam while the simple N+P single junction type conventional solar cell is like collecting rain-drops at the open sea where most of rain drops are wasted.

I. INTRODUCTION

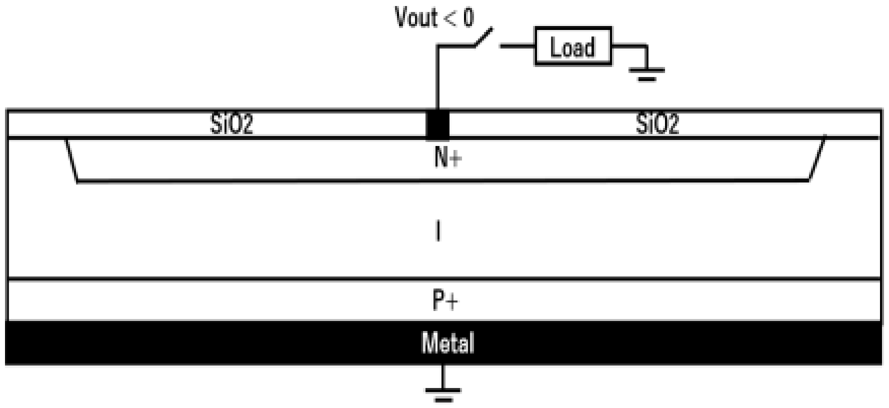
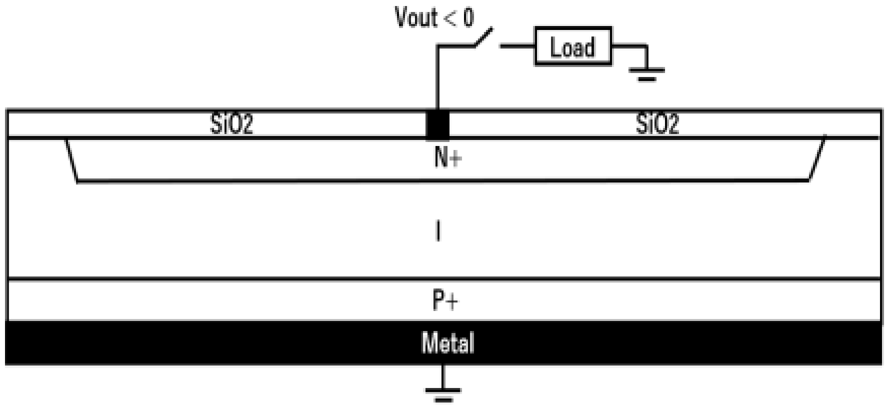


Fig. 1 Single junction PIN photodiode type Solar Cell (Nishizawa 1950)

In this paper three types of photo sensor structures are explained in details. Fig.1 shows the single junction type PIN Photodiode type Solar Cell invented by Jun-Ichi Nishizawa [1].

[1] https://mainichi.jp/english/articles/20181026/p2a/00m/0na/036000c

I. INTRODUCTION



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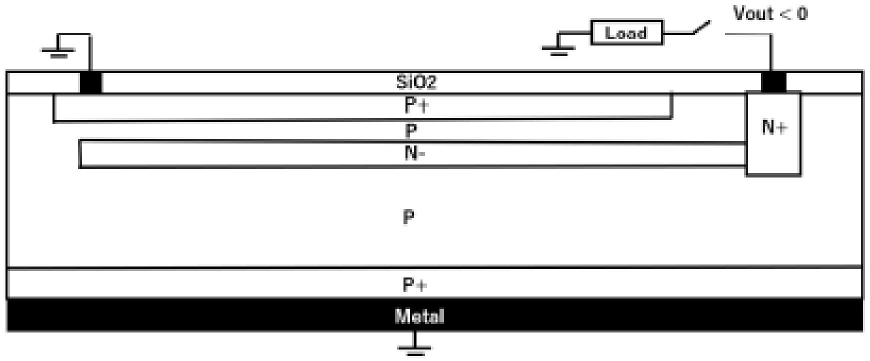

Fig. 2 Double Junction Pinned Photodiode type Solar Cell (Hagiwara.2020)

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Fig.2 shows the double junction type Pinned Buried Photodiode type Solar Cell [2] proposed by Yoshiaki Hagiwara in 2020.

[1] https://mainichi.jp/english/articles/20181026/p2a/00m/0na/036000c
[2] http://www.aiplab.com/JPA_2020_131313_on_PPD_Solar_Cell.html

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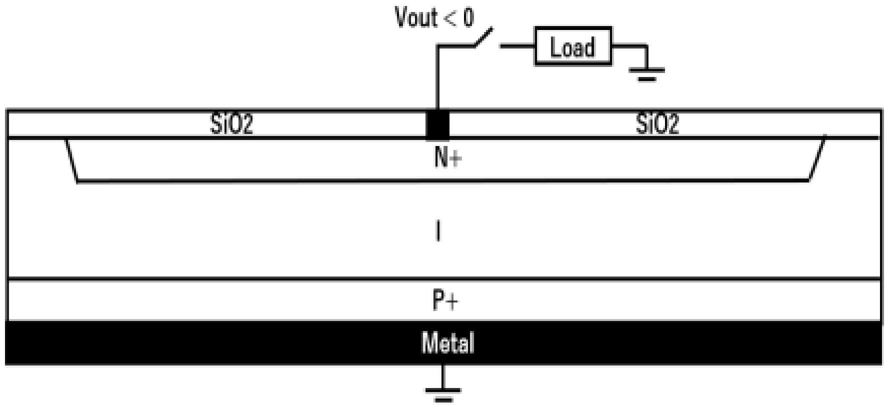

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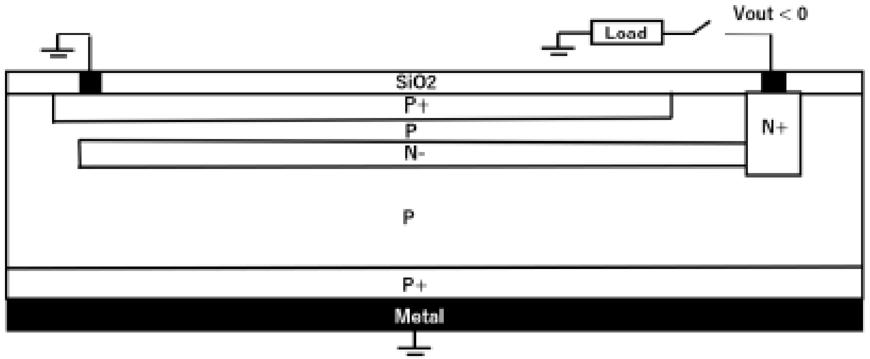

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Pinned Buried Photodiode now widely used in image sensors is a double or triple junction type photodiode with the buried charge collecting and storage region and with the pinned-surface hole-accumulation region with no surface electric field and with no surface dark current noise [3]

[1] https://mainichi.jp/english/articles/20181026/p2a/00m/0na/036000c
[2] http://www.aiplab.com/JPA_2020_131313_on_PPD_Solar_Cell.html
[3] http://www.aiplab.com/JPA_1975_134985_on_PPD_with_VOD.html

I. INTRODUCTION

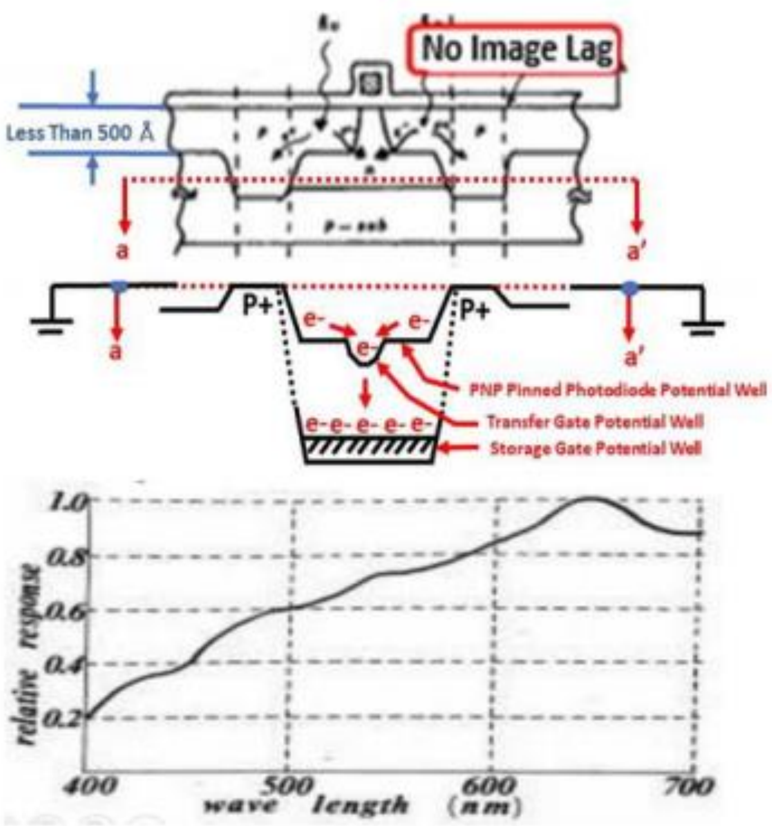


Fig. 9 Spectral Response of Pinned Buried Photodiode, reported at SSDM1978 in Tokyo. Sony had no image lag problem by 1980 using first all-CCD process and then this PNP Double junction Photo Transistor Process while all other companies suffered image lag problem with the N+P floating-surface single-junction type photo sensor with poor blue light sensitivity.

The photo signal charge is transferred and drained from the buried charge storage region with the no-image-lag feature and with the complete charge transfer capability, realizing a digital imaging snapshot camera and a fast action video camera with the electrical shutter function capability [4], free from any film and mechanical parts.

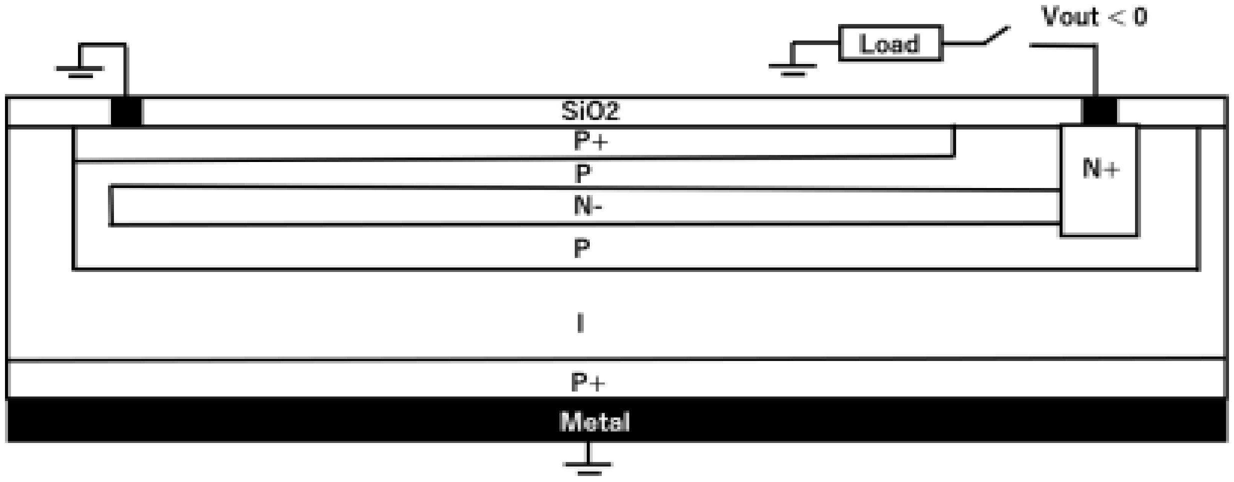


Fig. 3 Pinned PIN Photodiode type Solar Cell (Hagiwara.2021)

[8] Y. Hagiwara, Motoaki Abe and Chikara Okada,"A 380H X 488V CCD Imager with Narrow Channel Transfer Gates", Proceeding of the 10th Conference on Solid StateDevices, Tokyo 1978.

[4] http://www.aiplab.com/JPA_1977_126885_on_Electric_Shutter.html

II. SINGLE JUNTTION SOLAR CELL

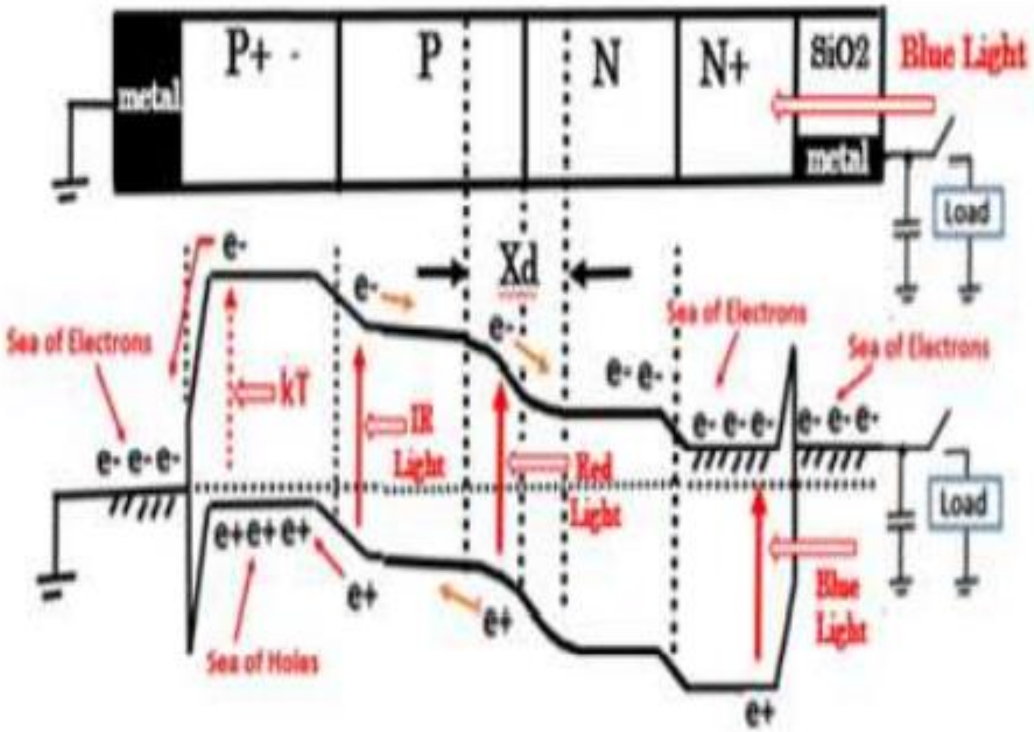


Fig. 4 Single Junction N+NPP+ Photodiode type Solar Cell

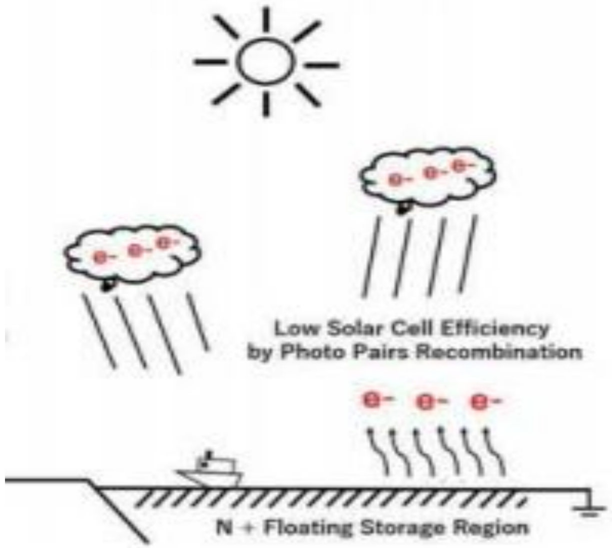
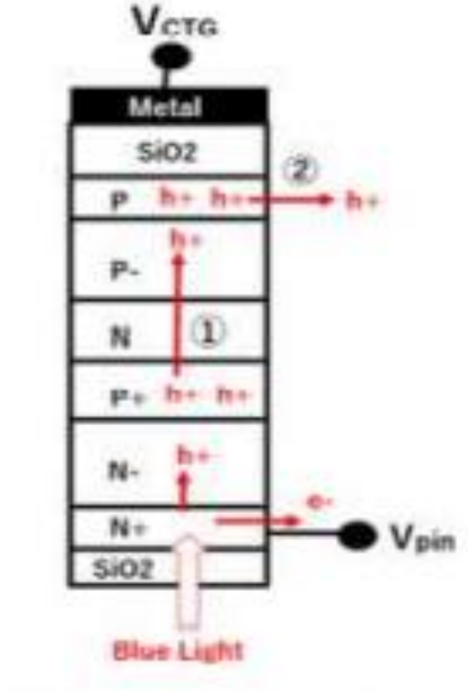


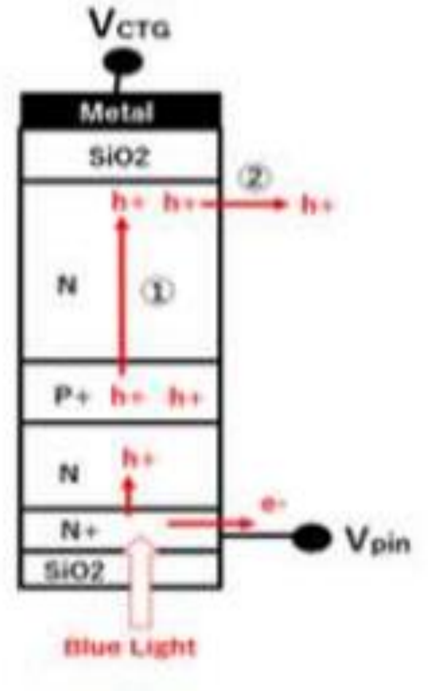
Fig.4 shows a single junction N+NPP+ type photodiode for barriers for hole and electron pair separations. However, the N+ surface floating potential region is flat with no electric field where the generated hole and electrons pairs in the vicinity of the semiconductor surface stay where they are and eventually they all recombine with each other. So we expect very poor short-wave blue light sensitivity in this N+NPP+ single junction type Solar Cell which is widely used in low cost Solar Cells.

III. Origin Of Pinned Buried Photodiode

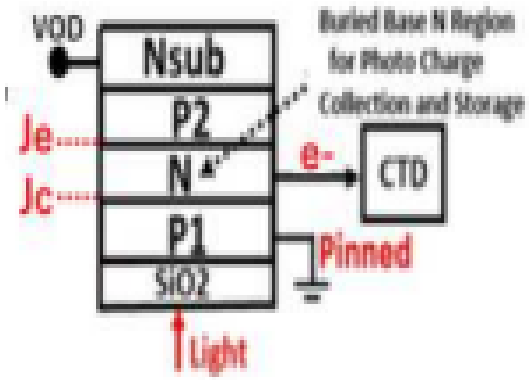
(1) JPA1975-127646



(2) JPA1975-127647



(3) JPA1975-134985



Yoshiaki Hagiwara at Sony in 1975 applied three Japanese patents on Pinned Buried Photodiodes [3,5,6]. However, USP and other oversea patents were never applied and the details of his 1975 inventions were never disclosed in the IEEE English speaking community. The original patent claims and the original figures drawn in these three 1975 Japanese patent applications are now reproduced here for the first time in the IEEE English speaking community.

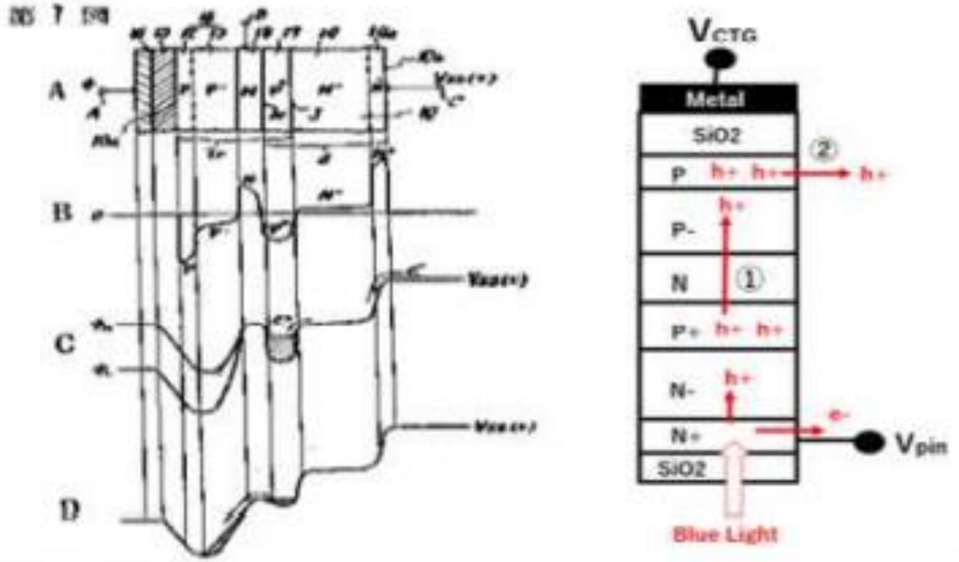
[3] http://www.aiplab.com/JPA_1975_134985_on_PPD_with_VOD.html

[5] http://www.aiplab.com/JPA_1975_127646_on_NPNP_type_PPD.html

[6] http://www.aiplab.com/JPA_1975_127647_on_NPN_type_PPD.html

III. ORIGIN OF PINNED BURIED PHOTODIODE

Pinned Buried Photodiode shown in Figure 7
in JPA1975-127646 filed on October 23, 1975



Pinned Buried Photodiode invented by Yoshiaki Hagiwara
as defined in Japanese Patent Claim of
JPA1975-127646 filed on October 23, 1975

特許請求の範囲

半導体基体の一方の主面側に、絶縁膜を介して電荷転送用電極が複数配列される1の導電型の転送領域が形成され、之に対向し且つ之より上記半導体基体の他方の主面側に上記転送領域との間に他の導電型のベース領域を介して受光領域が形成され、上記ベース領域に所定電圧を印加することにより上記受光領域に蓄積した電荷を上記転送領域に転送し、上記電荷転送用電極に所定のクロック電圧を印加して電荷の転送を行うようにしたことを特徴とする固体撮像装置。

Fig 5 A reproduction of Patent Claim and a figure in JPA1975-127646

[5] http://www.aiplab.com/JPA_1975_127646_on_NPNP_type_PPD.html

III. Origin Of Pinned Buried Photodiode

Pinned Buried Photodiode shown in Figure 7
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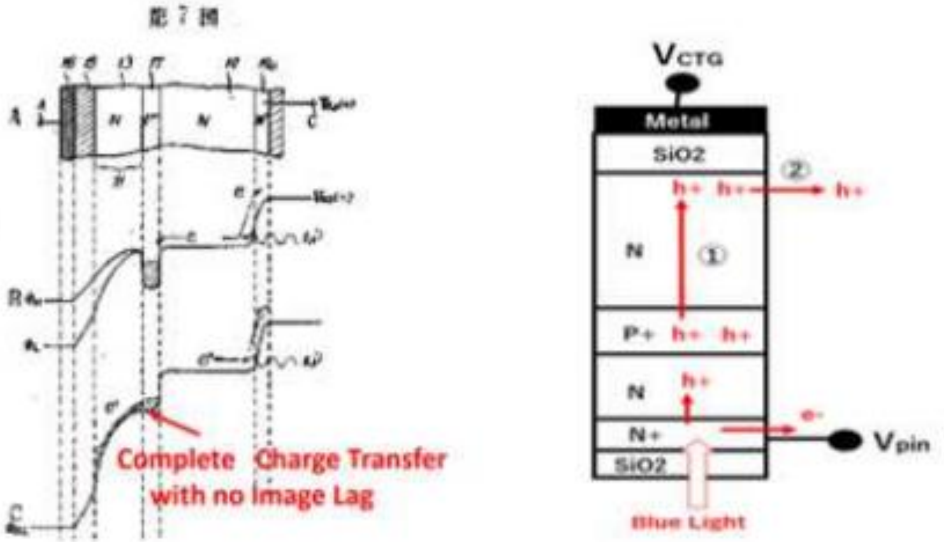

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Pinned Buried Photodiode shown in Figure 7
in JPA1975-127647 filed on October 23, 1975

Fig 6 A reproduction of Patent Claim and a figure in JPA1975-127647

[6] http://www.aiplab.com/JPA_1975_127647_on_NPN_type_PPD.html

III. Origin Of Pinned Buried Photodiode

Pinned Buried Photodiode shown in Figure 6
in JPA1975-134985 filed on November 10, 1975

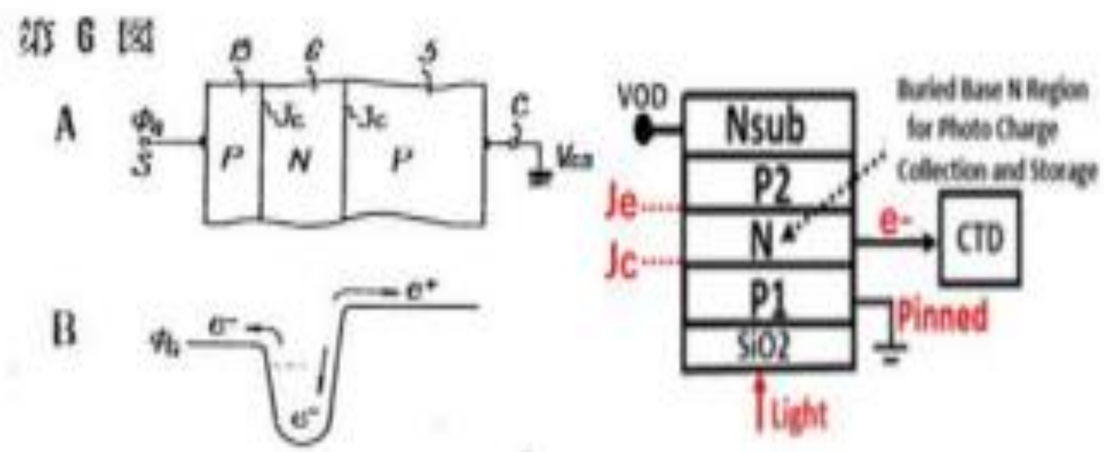

Fig 7 A reproduction of Patent Claim and a figure in JPA1975-134985

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Pinned Buried Photodiode shown in Figure 7
in JPA1975-127647 filed on October 23, 1975

III. Origin Of Pinned Buried Photodiode

TABLE I. Historical PhotoSensor Development efforts

	Three types of Photo Sensing Devices / Three important Features	1	2	3
		N+P Single Junction Photodiode with Floating N+ Surface	Charge Couple Device CCD/MOS Dynamic Photo Capacitor	P+NP Double Junction Dynamic Photo Transistor Pinned Buried Photodiode
1	Image Lag Problem	Serious Image Lag Problem	No Image Lag Problem	No Image Lag Problem
2	Surface Dark Current Noise	No Surface Dark Current Noise	Serious Surface Dark Current Noise	No Surface Dark Current Noise
3	Short-Wave Light Sensitivity	Poor Short-Wave Light Sensitivity	Very Poor Short-Wave Light Sensitivity	Excellent Short-Wave Light Sensitivity

IV. SURFACE BARRIER FIELD FOR BLUE-LIGHT SENSITIVITY

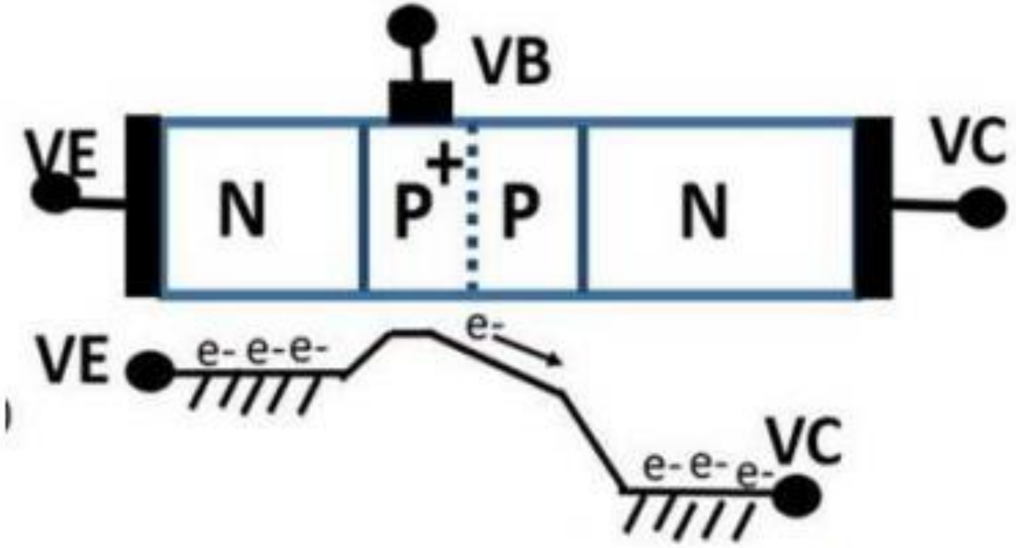

Fig. 8 Drift Field Transistor with the base barrier electric field formed by the P+P base doping-engineering for high frequency operations.

The drift-field transistor, invented by Herbert Kroemer in 1953 [7], has a graded base. See Fig. 8. The graded base. was formed by diffusing the base dopant in a clever way. Having a doping-engineered electric field in the graded base, a higher doping concentration is formed near the emitter reducing towards the collector, resulting in a high-speed bipolar junction transistor with the reduced charge carrier base transit time. Hagiwara in 1975 used P+P doping engineering to enhance the short-wave blue light sensitivity in Pinned Buried Photodiodes.

[7] https://en.wikipedia.org/wiki/Herbert_Kroemer

IV. SURFACE BARRIER FIELD FOR BLUE-LIGHT SENSITIVITY

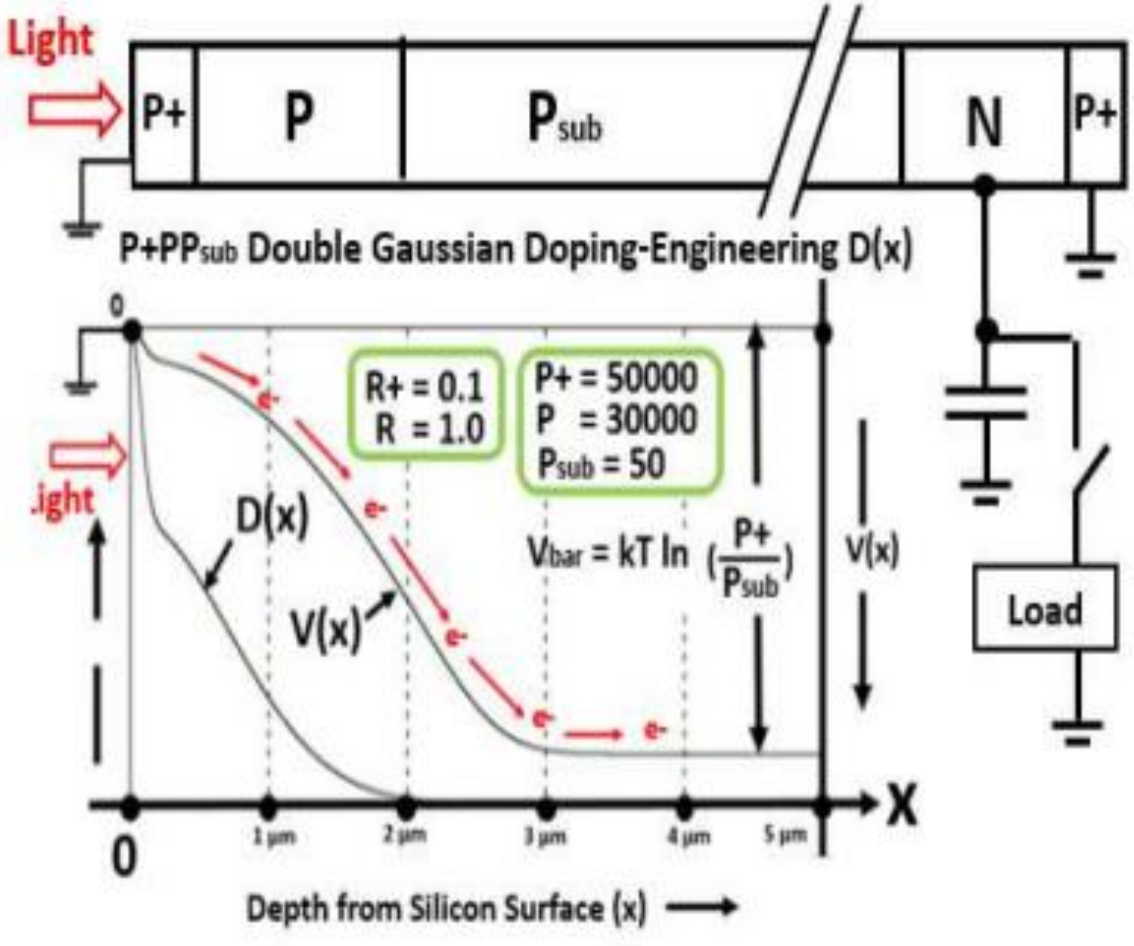

Fig. 10 Exact Numerical Computation of P+P Surface Barrier Potential V(x)

Fig. 10 shows an exact numerical computation of the P+P surface barrier potential V(x) for a two-step double doping-engineering of the double Gaussian doping D(x) with the spread parameters R+ = 0.1µm and R = 1µm. The substrate doping level is taken as Psub = 50 µm^{-3} while the two-step double Gaussian peak surface doping levels are taken as P=3000µm^{-3} and P+=5000µm^{-3} . The surface barrier electric field was found to be extending up to 3µm in depth into the silicon crystal. Thus by a proper surface double doping-engineering D(x) with the high energy ion implantation technology an ideal surface barrier electric field can be achieved to separate efficiently the electron and hole pairs generated by the short-wave blue light, which cannot penetrate more than 50 nm in depth in the silicon crystal. In this way, the ideal spectral response was achieved for the PNP double junction type Pinned Buried Photodiode.

V. PINNED BURIED PNIP PHOTODIDOE TYPE SOLAR CELL

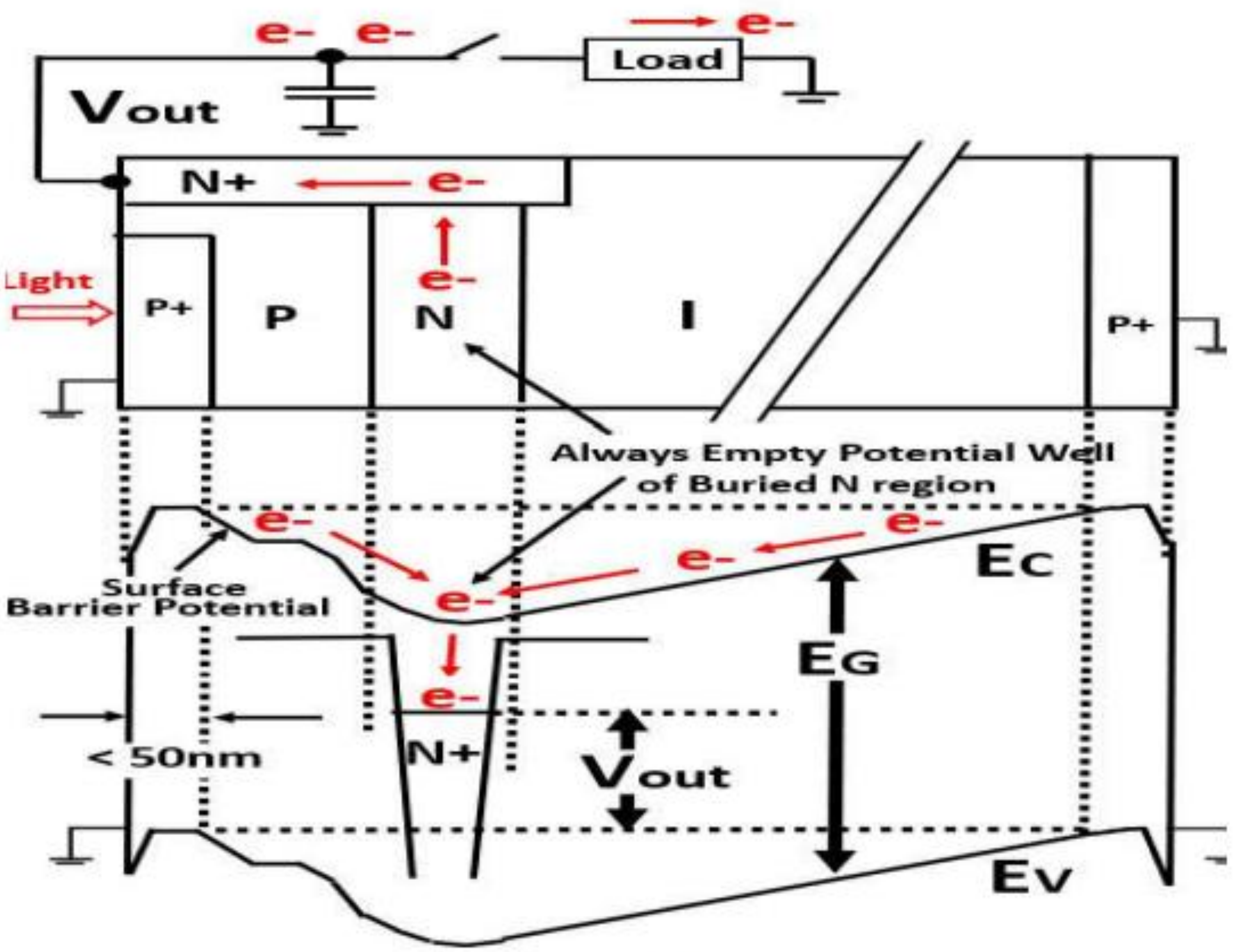

Fig. 11 Pinned Buried P+PNIP+ Photodiode Structure type Solar Cell

Image sensors and solar cells both operate by the same physical principle of converting the photon energy to the electron energy. Pinned Buried Photodiode has an excellent quantum efficiency and is also expected to improve the quantum efficiency of Pinned Buried Photodiode type solar cells. PIN diode invented by Jun-Ichi Nishizawa is also a simple photodiode with the wide intrinsic I-type middle region. PIN diode is suitable for high-voltage power electronics, fast switches and photodetectors applications. The floating surface N+P single junction-type photodiode is now used widely in solar cells because of its simple structure and the cost performance consideration, but with a poor low quantum efficiency problem.

The Pinned Buried PNIP Photodiode type Solar Cell shown in Fig.11 has a receiving charge storage bucket of a heavily-doped N+ region for the ohmic contact connecting the output power line which is connected via the output switch to the solar cell load. The output voltage of a single solar cell unit is less than the silicon energy gap E_G of 1.1 eV but the total output voltage can be boosted by connecting many of the solar cell units in series.

Note that there is a constant electric field and no bending in the electron potential Ec in the intrinsic region. The right edge P+ region has a very small depletion region to absorb the constant electric field in the intrinsic region.

V. PINNED BURIED PNIP PHOTODIDOE TYPE SOLAR CELL

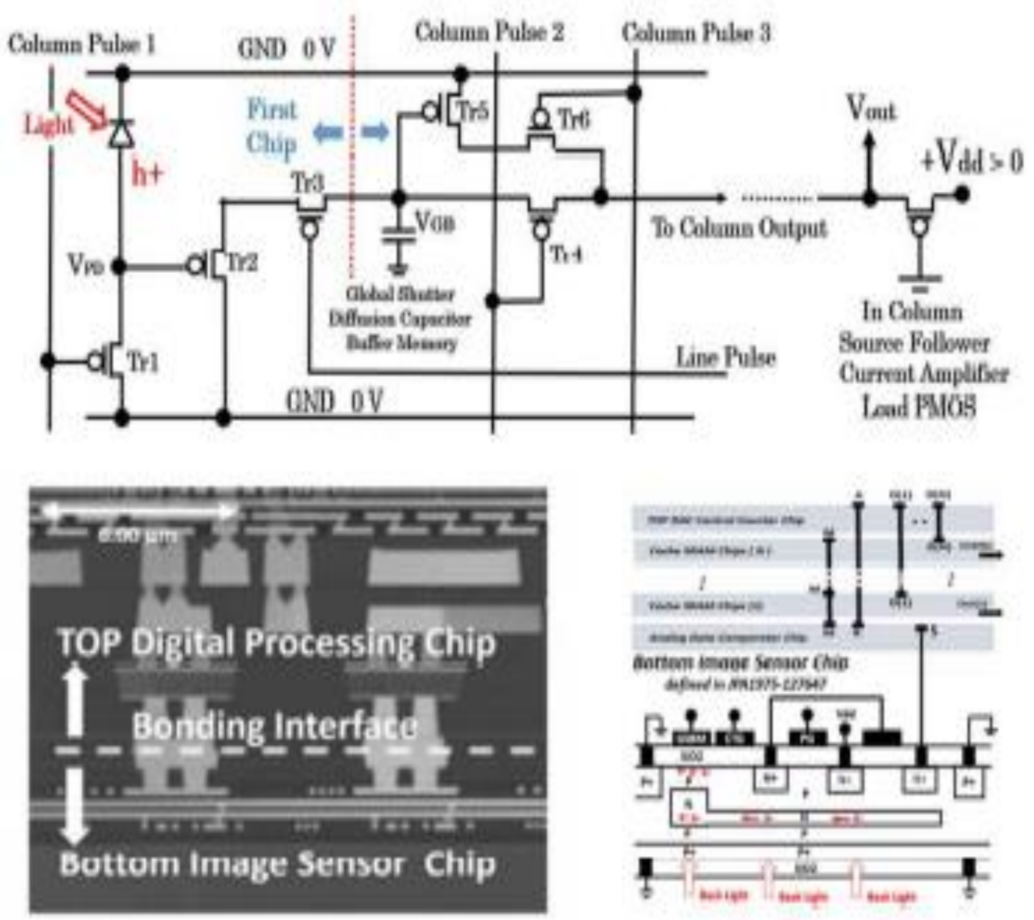

Fig. 13 Active In-Pixel Current AMP 1C6T Circuit (Hagiwara 2020) and Two-chip Stacked Back-Light CMOS Imager (Curtesy of Sony Corporation)

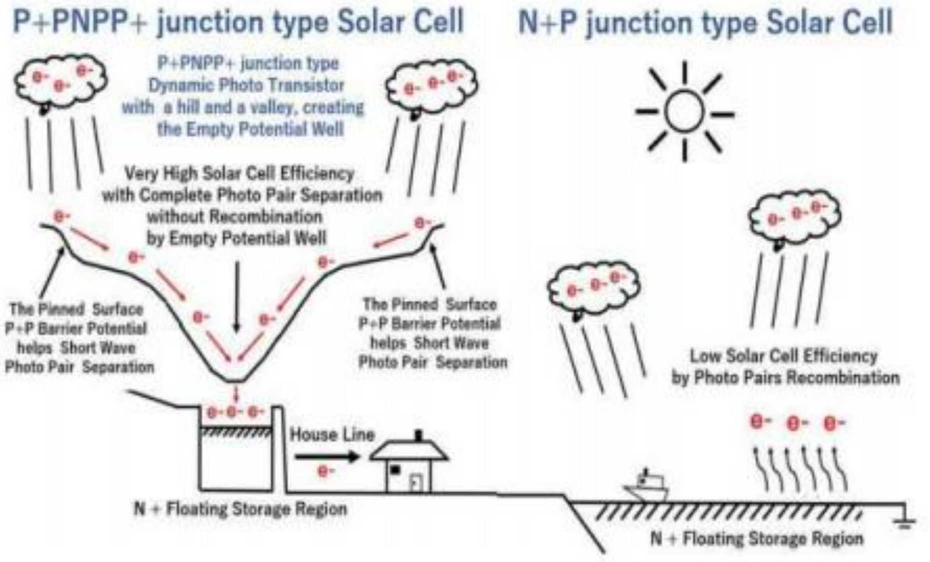

Fig. 14 Analogy of rain drops and photo electrons under the sunshine.

[12] Yoshiaki Hagiwara, "Multichip CMOS Image Sensor Structure for Flash Image Acquisition", IEEE 2019 International 3D Systems Integration Conference (3DIC2019), Sendai, Japan, September 2019.

[13] Y. Hagiwara, "Simulation and Device Characterization of the P+PN+P Junction Type Pinned Photodiode and Schottky Barrier Photodiode" IEEE 2020 Electron Devices Technology and Manufacturing Conference (EDTM2020), Paper ID No. 3C, 6 March 2020

[14] Y. Hagiwara,"Electrostatic and Dynamic Analysis of P+PNP Double Junction and P+PNPN Triple Junction Pinned Photodiodes",Inter. Jour.of Sys. Sci. and Appl. Math. Vol. 6,Issue 2,June 2021,PP.55-76.

[15] Taku Umebayashi, Hiroshi Takahashi, Reijiro Soji, Japanese Patent No. 5773379 (JPA2014-260268), on the Cu-to-Cu direct contact technique to achieve the 3D stacked multi-chip LSI system (2014).

V. PINNED BURIED PNIP PHOTODIDOE TYPE SOLAR CELL

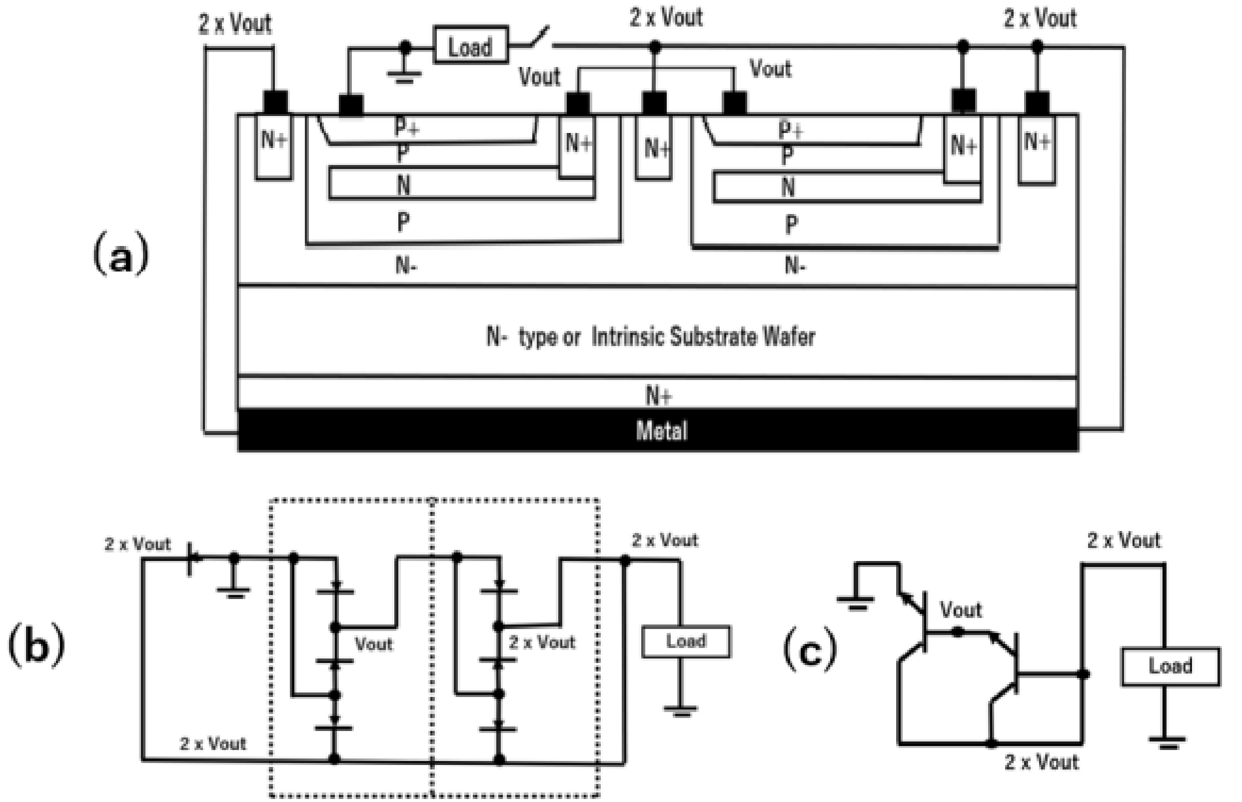

Fig. 12 (a)Two Units of Triple Junction Pinned Buried P+PNPIP+ Photodiode type Solar Cells in series with (b) a diode circuit formation and (c) a two- photo-transistor formation which can be fabricated by Bipolar Tr Process.

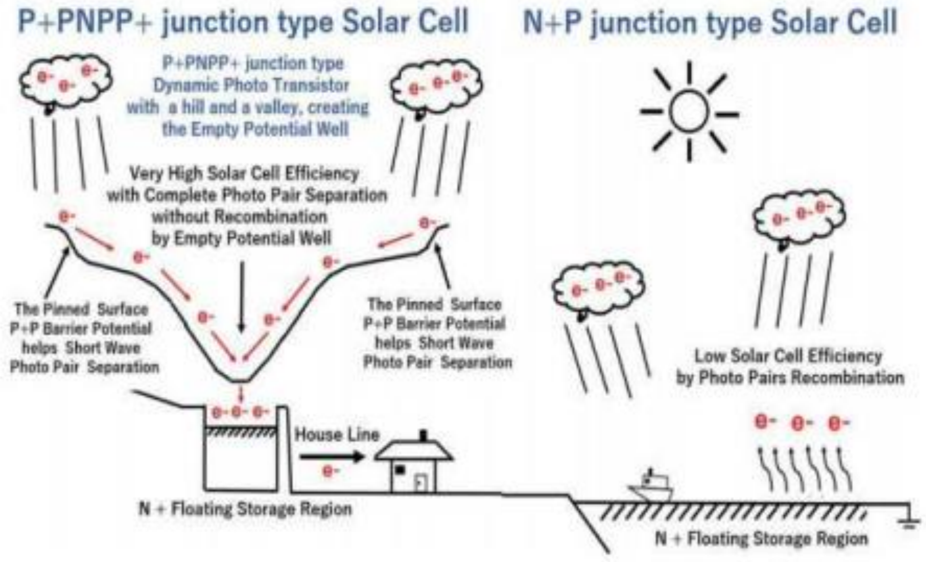

Fig. 14 Analogy of rain drops and photo electrons under the sunshine.

In summary, the most important feature of Pinned Buried Photodiode is the short-wave blue light sensitivity. Sun light has a great amount of short-wave blue light energy. Pinned Buried Photodiode type solar cell is similar to a very efficient rain-drops collecting system of a mountain hill and a valley with a storage dam while the simple N+P single junction type conventional solar cell is like collecting rain-drops at the open sea where most of rain drops are wasted. See Fig.14.

VII. Conclusion

The origin of Pinned Buried Photodiode was reviewed and its historical development efforts were discussed. As has been proposed in Hagiwara 1975 patent applications, a clever doping-engineering of the surface P+P hole accumulation region can also create the surface barrier electric field to enhance drastically the short-wave blue light sensitivity. It is concluded that this surface P+P doping-engineering is a key to create Pinned Buried PIN Photodiode Solar Cell with a better quantum efficiency.

ACKNOWLEDGMENT

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Thank you very much !