Progress of lateral photovoltaic effect: theoretical models and materials

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Abstract. Photoelectric devices based on various theories and effects of photoelectricity have become the basic devices of human’s life, and are still a hot research field. Lateral photovoltaic effect (LPE), among significant photovoltaic mechanisms, exhibits a phenomenon in which the surface potential difference of a specific material system changes linearly with the incident laser position. Depending on this unique property, LPE has been extensively developed in position sensitive detectors (PSDs). The material and theoretical systems of LPE were constantly innovated with the emergence and continuous progress of nanotechnology and new materials. This article reviews the recent progress of LPE theory, e.g., P-N junction model and the theories based on Schottky barrier, Dambet effect, and diffusion. Meanwhile, material systems that contribute to LPE, including metal-semiconductors (MS), metal-oxide-Semiconductors (MOS), metal oxide, perovskites and organic semiconductors, are summarized as well. As an important tuning method, local surface plasmon resonance is also concerned together with some promising future of the material systems.

1. Introduction
Since the discovery of photoelectric effect by Albert Einstein, the theories and phenomena based on photoelectric transformation have been continuously improved, and become the core basis of photoelectric devices in various fields, such as solar cells [1-3], photoelectric sensors [4] and photodiode [5-7].

The lateral photovoltaic effect (LPE) is one of the popular effects found in many material structures. When the surface of a specific structure, such as the p-n junction, is exposed to non-uniform illumination, the concentration gradient of photo-generated carrier on the surface will be generated, which is higher at the illumination place and lower at the distance from the illumination place. Then, the carriers will be driven by the concentration difference to diffuse, forming a potential difference (LPV) on the surface. With the movement of the spot on the surface, LPV is linearly correlated with the spot position within a certain range. Nowadays, position sensitive detectors (PSDs) are widely used in many fields, but it is still difficult to detect small displacement of millimeters and below. However, because of the special mechanism of LPE as shown above, LPE provides a new direction of high precision position sensitive sensor, which has been widely valued and researched.

In 1930, LPE firstly occurred in Cu/Cu2O structure and was found by Schottky [8], but it did not attract the attention of researchers until 1954 when Wallmark [9] rediscovered this effect in Ge p-n junction and expounded the mechanism of LPE in various p-n junctions. Subsequently, Lucovsky [10] and Hirohiko Niu [11] further modified the theoretical mechanism of LPE. Later, a good deal of LPE has been found in a variety of material families, such as metal-semiconductor (MS), metal-oxide-
semiconductor (MOS) and perovskite, and has been applied in aerospace, microelectronics, robotics, biomedical and other fields. Because LPE is unique in detecting tiny displacement, the researchers have been focusing on the use of LPE for PSDs for a long time [12, 13], and continue to pursue stronger lateral photovoltaic effect. Fortunato et al. [14-16] summarised the measurement criteria required by PSD for material LPE, namely: position sensitivity, spatial resolution, response time, nonlinearity, δ, and device size. At present, there have been many research results on LPE, and new materials and structures are being constantly developed. Especially in the last 10 years, the regulation means based on surface states, local plasmons, applied electricity, magnetic field and other various emerged in endless, reflecting the broad research and application prospects of LPE.

In this paper, several typical and recent LPE mechanisms, such as P-N junction, Schottky barrier, Dambet model, and diffusion model are systematically introduced. The material families of MS, MOS, metal oxide, perovskite, and organic semiconductor are introduced to show a series of valuable achievements in materials and structures. The local plasmon regulation methods, as a widely used regulation methods in recent years, is reviewed in the last, as well as the development direction of LPE in the future is prospected.

2. Theoretical models of LPE

2.1 P-N junction models

The P-N junction model is the earliest theoretical model to describe the LPE, which has three stages of developments, namely Wallmark [9], Lucovsky [10], and Hirohiko Niu [11].

When a point source emits a beam of light with photon energy greater than the material gap to the P region of a P-N junction, photogenerated electron-hole pairs will be generated on both sides of the P-N junction. Since the light injection only causes remarkable influence on the minority carriers, the movement of minority carriers is taken as the research object of LPE. Owing to the effect of the internal electric field, the holes in the n-block move to the p-block while the electrons in the p-block moves to the n-block. Because of the redistribution of electrons and holes, non-uniform distribution of photogenerated carriers will be formed on the surface of the P-N junction, resulting in the carrier concentration gradient existing between the illuminated and unilluminated regions. If the difference between the conductivity of p-region and N region is large (p-region or N region is heavily doped, such concentration difference will inevitably lead to the diffusion of charge carriers and the formation of lateral electric field called lateral photovoltaic (LPV). Assuming that the p-region is heavily doped (denoted by P+) and the conductivity is much higher than that of the n-region, Wallmark [9] recognized the P region as an equipotential body and the holes excited from n-region will quickly redistribute evenly in P region. Wallmark deduced theoretical formulas for two conditions hypothesizing the surface of the P-N junction is infinite: with regard to P+-N P-N junction:

$$LPV = \frac{\rho}{\delta} I x$$  \hspace{1cm} (1)

Where the $\rho$ is the electrical resistivity; $I$ is the total photocurrent; $x$ is the position of the facula. Consequently, the LPV shows a linear relationship with position, $x$.

Another one is the N+-N quasi-P-N junction. The formula is:

$$LPV = C_2 \sinh \frac{x}{(2\delta\omega)^{1/2}}$$  \hspace{1cm} (2)

Where $C_2$ is the constant; $\delta$ is the distance that the longitudinal electric field changes to the lateral electric field; $\omega$ is the width of the n-region.

Different from the situations discussed by Wallmark, Lucovsky [10] thought that the n-region was equipotential when light was irradiated in the p-region, the lateral photovoltaic in the p-region. In this case, the lateral resistance is mainly determined by the p-region resistance. Compared with Wallmark, Lucovsky [10] comparatively used the continuity equation of current to generate the potential distribution at each point in the p-region in a one-dimensional condition relatively accurately.
However, for thin film materials, the hypothesis of Lucovsky's model is not valid, so Hirohiko Niu [11] modified it as follows: 1) minority carriers diffuse only longitudinally (perpendicular to the direction of the P-N junction). 2) The spot diameter is negligible compared with the length of the junction, and the potential in the spot is evenly distributed. 3) The longitudinal photovoltaic effect is very small, which makes it possible to omit higher order small quantities in the I-V characteristic equation. Under this assumption, using Ohm's law and the continuity equation of current, the final lateral photovoltaic distribution can be obtained as:

$$\varphi(x) = \begin{cases} 
\varphi_0 - \frac{2eq\mu_p \cosh ax_j \cosh a(l-x_j) - \cosh a(l-x)}{\sinh al + 2ax \cosh a(l-x) \cosh ax_j} & \text{for } x > x_j \\
\varphi_0 - \frac{2eq\mu_p \cosh ax_j - \cosh ax}{\sinh al + 2ax \cosh a(l-x) \cosh ax_j} & \text{for } x < x_j 
\end{cases}$$

(3)

$$\varphi_0 = \frac{2eq\mu_p \left( \frac{\rho_p}{\omega_p} + \frac{\rho_n}{\omega_n} \right)}{\sinh al + 2ax \cosh a(l-x) \cosh ax_j}$$

(4)

$$\alpha = \sqrt{\frac{a \left( \frac{\rho_p}{\omega_p} + \frac{\rho_n}{\omega_n} \right)}{\sinh \left( \frac{1}{2} ax \right)}}$$

(5)

From Eq. 1-3, the potential difference between two points with a distance of $l$ on the p-type layer is:

$$V = \varphi(l) - \varphi(0) = \frac{4eq\mu_p \sinh \left( \frac{1}{2} ax \right) \sinh \left( \frac{1}{2} ax_j \right)}{\sinh al + 2ax \cosh a(l-x) \cosh ax_j}$$

(6)

When $\alpha l \leq 1$, the Eq 1-6 can be approximated as:

$$V = \frac{2eq\mu_p \left( \frac{1}{2} - \frac{x_j}{l} \right)}{\sinh \left( \frac{1}{2} ax \right)}$$

(7)

2.2 Schottky barrier model

In the 1980s, Willens [13] found the LPE in Ti/Si superlattice structure for the first time and proposed a theoretical explanation based on the Schottky barrier. This model is basically the same as Hirohiko Niu's theory, but the saturation current density in the Schottky junction is replaced by the saturation current density in the P-N junction as the attenuation factor in Lucovsky's theory. Then the potential on the surface of the region to the left of the spot ($x < x_L$, $x_L$ is the position of the spot) is:

$$V(x) = \left( \frac{d\varphi}{dx} \right) \cosh \left( \frac{1}{2} ax \right) \cosh \left( \frac{1}{2} ax_j \right)$$

(8)

When $x > x_L$, $l-x$ and $l-x_L$ is used to replace $x$ and $x_L$. Therefore, the potential difference between the two electrodes is:

$$\Delta V = V(l) - V(0) = \left( \frac{d\varphi}{dx} \right) \sinh \left( \frac{1}{2} ax \right) \sinh \left( \frac{1}{2} ax_j \right)$$

(9)

When $\alpha l \leq 1$, the Eq 1-9 can be approximated as:

$$\Delta V = \left( \frac{d\varphi}{dx} \right) \left( \frac{1}{2} - \frac{x_j}{l} \right)$$

(10)

From the above equation, the LPE in the film decreases with the increase of the thickness of the metal film. Therefore, if the metal is single layer, only if the thickness of the metal film must be controlled at a very low level, the LPE can be observed significantly.

2.3 Dember model

The Dember effect [17] was proposed by Dember to describe the effect of the voltage at different locations in a semiconductor caused by the diffusion of photogenerated carriers. When the light is irradiated on the semiconductor surface, the photogenerated carriers form a gradually decreasing concentration gradient from the surface to the body because of the local light intensity. Driven by the concentration gradient, the photogenerated electrons move to the backlight side with a faster mobility.
than the hole and accumulate to form an electric field alone the diffusion direction. The electric field inhibits the further diffusion of electrons and speeds up the diffusion of the hole and gradually stabilizes the diffusion rate of the two until they reach a same value. The light position and the backlight position will establish a stable potential difference. In 1998, Srivastava [18] discovered the LPE in hydrogenated amorphous silicon materials which cannot form a built-in electric field. Thus, neither the P-N junction nor the Schottky barrier model can explain the reason. To solve this problem, the Dember was used to explain the mechanism. Srivastava et al. started from Poisson’s equation according to Dember theory and neglected the drift component. After simplifying the recombination coefficient of the electron hole, the potential difference between the two electrodes was obtained by first order approximation as:

\[ \Delta PV = n_{ph} L_D \exp \left( -\frac{L}{L_D} \right) \]

\[ \Delta PV = n_{ph} h \exp \left( -\frac{L}{L_D} \right) \]

2.4 Diffusion model

When a laser beam of power P is irradiated between electrodes A and B on the metal side, many photogenerated electron-hole pairs will be generated in the semiconductor layer. The electrons are in the excited state at the spot, which have the probability, P, to transfer to the metal side. The number of electrons in the excited state is defined as \( n_0 \), and the number of electrons transferred to the metal side is defined as \( N_0 \), then the relationship between \( N_0 \), \( n_0 \) and \( P \) is

\[ N_0 = n_0 \left[ 1 - P \frac{\tau}{n_0} \right] \]

where \( \tau \) is the constant related to time. According to the diffusion equation, \( D_m \frac{d^2N_r}{dr^2} = \frac{N_r}{\tau_m} \), the relationship between carrier density and position can be written as:

\[ N(r) = N_0 \exp \left( -\frac{|x - r|}{\lambda_m} \right) \]

Where \( D_m = \frac{k_B T}{\pi^2 \rho N_F} \) is the diffusion coefficient of the metal; \( N_F = \frac{8n_0}{3} \) is the electron density below the Fermi level \( E_F \); \( \rho \) is the resistivity of the metal, \( x \) is the position of the spot, \( \lambda_m = \sqrt{D_m \tau_m} \) is the diffusion length; \( \tau_m \) is the existing time of the diffusion of electrons. Similar with the metal, the density of the electrons in the semiconductor side is:

\[ n(r) = n_0 \exp \left( -\frac{|x - r|}{\lambda_s} \right) \]

When the laser stays at a certain point between the electrodes, the Fermi levels at the metal side and the semiconductor side are \( E_{Fm}(r) \) and \( E_{Fs}(r) \), respectively. Thus, the LPV(\( x \)) of the metal side and the semiconductor side can be written as [19]:

\[ \Delta PV_{m}(x) = \frac{E_{Fm}(L) - E_{Fm}(-L)}{e} = K_m n_0 \left[ \exp \left( -\frac{|L - x|}{\lambda_m} \right) - \exp \left( -\frac{|L + x|}{\lambda_m} \right) \right] \]

\[ \Delta PV_{s}(x) = \frac{E_{Fs}(L) - E_{Fs}(-L)}{e} = K_s n_0 \left[ \exp \left( -\frac{|L - x|}{\lambda_s} \right) - \exp \left( -\frac{|L + x|}{\lambda_s} \right) \right] \]

The model clearly reveals the theoretical relationship between the LPV and material structures. It can also be used in P-N junction, semiconductor heterojunction and Shottck junction. However, for the material systems with strong Dember or thermal effect, this model will be greatly affected.

3. The materials and structures associated with LPE

3.1 MS and MOS

At present, a mass of studies has shown that LPE widely exist in MS and MOS structures, and has a great potential in the field of PSDs. The advantages of MS and MOS systems lie not only in their relatively strong LPE, but also in their good inclusiveness, which can combine the excellent properties
of different materials, and good controllability. It is found that in MS and MOS structures, LPE increases obviously when the thickness of metal layer is reduced to nanometer level. Wang H [20-23] et al. have done a series of studies in this area, and found obvious LPE in Ti/Si, Co/Si, and Cu/Si structures. As shown in Fig.1 (a) and (b), in the nanometer range, the strength of LPE varies greatly with the thickness of the metal nanometer layer. Yu and Wang [21] reported the theoretical model of MS/MOS structure, and the expression of LPE sensitivity was obtained as follows:

\[ k(\lambda, d) = \frac{2K_J(\frac{\lambda}{c} - E_g)}{\varepsilon J(d - d_J)} \times \exp \left( -\frac{\frac{\varepsilon}{\kappa_s(d - d_J)(\frac{\lambda}{c} - E_g)}^2}{\varepsilon J(d - d_J)(\frac{\lambda}{c} - E_g)} \right) \]  

(17)

Eq.2-1 shows the relationship between the LPE of metal film, the metal film thickness, and the wavelength of light wave and demonstrates that there exists an optimal metal film thickness and wavelength of light wave for MS structure to maximize LPE, which is in good agreement with the experimental results shown in Fig.1 (a) and (b). When the metal film is thick, owing to the small resistance, the electrons are easily diffused from the spot position to the two electrodes. On the contrary, if the metal film is very thin, the electron is difficult to diffuse due to the high resistance, which will also lead to a small metal potential difference between the two electrodes. Thus, a large LPV can be obtained only when the thickness is appropriate. Fig.1 (c) and (d) show LPE with three different MS structures. It can be found that when the appropriate film thickness is selected, the sensitivity of the metal side is significantly higher than that of the silicon-based side. In addition, the resistivity and Fermi level of metal materials also have major effects on the sensitivity and linearity of LPE. Yu and Wang [24] offer a theoretical explanation for this. If the contact distance is small enough \((L \ll \lambda_m)\) and the power of the light is strong \((p \gg n_0/\tau)\), there is a relationship as follows:

\[ K_m = \left[ K \left( \frac{\hbar}{2m_e} \right)^{\frac{3}{2}} \left( \frac{2}{3\pi \kappa g^2} \right)^{\frac{3}{2}} \right] \times \left[ (h \nu - E_\theta)^{\alpha} \right]_s \times \left[ E_f \eta^2 \rho \tau_m^{-1} \right]_M \]  

(18)

\[ \delta_m = \left[ \frac{8\pi e^2 \beta}{9e^2 \kappa g^2} \left( \frac{2m_e}{h^2} \right)^{\frac{3}{2}} \right] \times \left[ E_f \eta^2 \rho \tau_m^{-1} \right]_M \]  

(19)

Where \(\alpha\) is the proportional coefficient, \(\tau_m\) stands for carrier lifetime, and the subscripted coefficients ‘C’, ‘S’ and ‘m’ in square brackets stand for ‘constant’, ‘semiconductor correlation’ and ‘metal correlation’, respectively. As seen from the above equations, metallic materials with high resistivity and high Fermi levels can produce higher LPV sensitivity, but the linearity will be decreased. The smaller the gap of semiconductor materials, the more electrons excited to conduction band from valance band into the metal layer, the greater the LPV.

Regarding MOS system, the thickness of the oxide layer also affects the strength of LPE. Compared with the metal layer and the semiconductor layer, the potential barrier of the oxide layer is higher, so LPV will gradually decrease with the increase of the oxide layer thickness. However, in some systems, when the thickness of the oxide layer is tiny, the LPV of the MOS structure will increase significantly and be larger than that of the MS, as shown in Fig.1 (e), and there is also an appropriate oxide layer thickness to achieve the maximum LPV. The difference of LPE between Ni/SiO2/n-Si and Ni/SiO2/p-Si reported Xu Huang et al. [25] has shown that, although the linearity of the two is good, the maximum sensitivities are quietly different which are 31.1mV and 2.1mV, respectively. The reason given by Xu Huang et al. is that in Ni/SiO2/n-Si, during the separation process, the space charge barrier is reduced, and on the other hand, the transverse electron flow results in the transverse potential decrease of the nickel layer. MS and MOS systems are traditional research directions in the studies of LPE, and they are also two of the most complete material structures with good research results. At present, a lot of exploration on the structural properties of metals and oxide layers for LPE has been relatively mature. Based on this situation, some researchers began to study new material systems.
3.2 Metal oxide

In addition to MS and MOS structures, metal oxides have also been widely used in LPE systems in recent years. Most of the structures are metal oxides-oxides-semiconductors, in which the LPE is strong and there is a good linear and symmetric relationship between the LPE and the position of spot point in a wider two-dimensional direction. ZnO, as a multifunctional semiconductor, whose electrical, optical, and magnetic properties can be easily adjusted by being doped with selective elements [27, 28] has been widely used in LPE. In recent years, Wang Hui's group has made some studies on zinc oxide materials, and has reported Al-doped ZnO (ZAO), Mn-doped ZnO, and Cu-doped ZnO [29-31] and provided the mechanism of LPE in the structures based on ZnO doped material [27]. ZnO doped with Al2O3 is one of the most widely reported transparent conducting oxides (TCO) [32-34]. Because of its high stability, low cost, and non-toxicity, it is one of the good alternatives of ITO. Fig.2 (a) shows the LPE of the Al-doped ZnO. It can be found that, unlike MS or MOS, the attenuation trend of LPV with respect to thickness is not monotonic, but the mechanism is not clear at present. The LPV-x shown in Fig.2 (a) perform a position sensitivity ranging from 6.90 mV/mm to 41.85 mV/mm with a nonlinearity close to 1.000. In addition, the linearity is below 6.50% at the spatial resolution of 100μm [29], which proves that the Al-doped ZnO is a great candidate of PSDs. Mn doped ZnO is always used in various fields extensively because of the prediction that Mn doped ZnO performs room-temperature ferromagnetism (RTFM) [35-37] and Lu and Wang firstly applied it to LPE [30]. The structure was irradiated with the lasers whose power was above threshold (6mW) and below (0.1mW) called ATV and BTV, respectively. Obvious LPE can be observed in the infrared region, and the maximum position sensitivity is 5.61mV/mm in the ATV range and 62.2mV/mm in the BTV range. Remarkably, the dependence of position sensitivity on the wavelength in ATV and BTV is totally inverse as shown in Fig.2 (b) and (c), the physical mechanism of which is given by Lu and Wang [30]. Cu-doped ZnO was tested the LPV of the ZnO side (FF) and Si/SiO2 side (FS) with a distance of 3mm between two electrodes and the result is shown in Fig.2 (d). It is found that the linearities for FS and FF are both good and the position sensitivity of FF mode is 23.80 mV/mm which reduces to 16.16 mV/mm when it turns to FS mode. Co-doped ZnO [38] and Ag-doped ZnO [39] are also perform good infrared LPE, which is similar with the Mn-doped Zn. Zhao et al. [38] reported that the saturated LPV (SPV) between the indium electrodes on the ZnO surface varies linearly with the spot position Co-doped ZnO as shown in Fig.2 (e). It is noticed that, when the spot is centered between the two electrodes, the LPV is zero, which is attributed to the symmetry of carriers’ diffusion. These studies prove that doped ZnO a potential choice of infrared PSDs.
3.3 Perovskites

In recent years, perovskites have attracted a great deal of research interest in various optoelectronic devices because of their superior optoelectronic properties and better structural compatibility, such as solar cells [40] and photodetectors [41]. Perovskites have good optical absorption coefficient [42, 43], long carriers diffusion length, and high carrier mobility [43], which supplies it as an ideal material used in photoelectric detectors. However, the recombination of photogenerated electron-hole pair is too fast, usually within a few picoseconds, to provide enough electron density at the electrodes in the simple perovskites [44]. Therefore, complex perovskite structures or multimaterial composite methods are usually used to compensate for the defects of simple perovskite structures. Jin [45], Xi [46] and Wang et al. [45] have reported perovskite materials for near-infrared photoelectric position sensors. Both Jin and Xi adopted the material structure of LaTiO$_3$/SrTiO$_3$ and used bias current to enhance the position sensitivity.
sensitivity. As shown in Fig.3, with the bias current increases, LPV increases from 3.7 mV/mm to about 22 mV/mm. Wang et al. studied the LPE of β-FeSi₂/SrTiO₃ irradiated by 808 nm and 1064 nm stable laser and the position sensitivities and nonlinearity are 2.68 mV/mW/mm, 1.59% and 2.24 mV/mW/mm, 0.821%, respectively as shown in Fig.3 (b).

Figure 2 (a). LPV as a function of the laser position (x) observed on ZAO film surface with different thickness for y=0 line. The bottom inset displays the schematic illustration of LPV measurement [29]. (b) LPVs as a function of laser position in Mn-doped film with P=0.1mW laser illumination of different wavelength. (c) LPVs as a function of laser position in Mn-doped film with P=6mW laser illumination of different wavelength [30]. (d) LPVs as a function of laser position in obverse (FF) mode and reverse (FS) mode of Cu-doped ZnO/SiO₂/Si, where the wavelength of laser is 532 nm and the laser power is 2.5 mW power [31]. (e) Dependence of SPV on the position of the laser spot with laser irradiated on the Co-doped ZnO surface [38].

Wang and Zhou et al. [47] found an ultraviolet/near-ultraviolet LPE with fast relaxation and high sensitivity in NdNiO₃/Nb:SrTiO₃ heterojunction and the result is shown in Fig.3 (c), (d), and (e). NNO/NSTO junction performs an obvious LPE curve with a good linearity shown in Fig.3 (c). As shown in Fig.3 (d), irradiated by 266nm laser, the electron-hole pairs in NNO and nto are both excited while only electron-hole pairs in NNO are excited when irradiated by 405nm laser. In addition, irradiated by 266 nm laser, the highest LPE occurs in 0.05% Nb doped NNO (10 nm)/NSTO, is 32 mV/mm. Wang and Zhou et al. explained this as the recombination or annihilation of the carriers before being collected by electrode in the VPE process. But when the concentration of the doped Nb is low, NNO/NSTO has a high resistance which reduces the possibility of recombination. Additionally, Fig.3 (e) shows the time responsibility in the NNO/NSTO junction that with the decrease of resistance, the photovoltage signal increases sharply first and then decreases gradually, and the relaxation time decreases. When the 1kX
resistor is in parallel with the oscilloscope, the time of response is 1.4s, time of relaxation is 7.4s. Wang et al. found that the relaxation time of LPE is about 4 times that of vertical photovoltaic effect (VPE), which indicated that the transport of photogenerated carriers in VPE and LPE is mainly in NTO single crystal.

Because of the relatively short researching time of the LPE of perovskites, it is not as good as that in MS, MOS and metal oxide materials. However, with the development of technology, large size or 2D perovskite materials, PSDs based on perovskite materials still have a broad scientific prospect.

3.4 Organic semiconductor

In addition to the inorganic material system mentioned above, organic semiconductors are also gradually referred to as one of the potential materials for PSD. Organic semiconductor is one of the excellent materials for flexible PSDs because it has flexible structure, low processing cost and are easy to adjust and control. Kabra et al. [49] found a LPE in a device containing a large area of organic semiconductor and made a continues study on it. The poly-(3-hexylthiophene) was used to make an AuL/P3HT/Al/P3HT/AuR structure and the related theoretical model was generated. However, the effect of LPE is not obvious because the dissociation of the photogenerated electron-hole pairs only occurs near the P3HT/Al interface layer. Both of Javadi et al. [50] and Zhu et al. [51] used PEDOT: PSS as the semiconductor of LPE. Javadi et al. prepared [50] PEDOT:PSS/n-Si heterojunction to study the effect of thickness of the organic layer on the response of the LPE in PEDOT: PSS/n-Si. It is found that with the increase of the thickness of the organic layer, the optical transmittance decreases gradually, which is more obvious for long wavelength. This affects the strength of LPE to some extent. As shown in Fig.4
(a), with the increase of the organic layer, LPV decreases from 106.32mV/mm to 10.32mV/mm and nonlinearity is always lower than 3% with a coefficient of association ranging from 0.995 to 1.00. In this structure, the inversion layer formed at the interface of PEDOT: PSS/n-Si accelerates the diffusion of excess holes, shown in the illustration of Fig. 4 (a), which is the reason of why the linearity is good and the largest LPE occurs at 1-L (220nm). Zhu et al. [51] reported the LPE in ITO/PEDOT:PSS/MEH-PPV:PCBM/Al solar cell material. The structure and mechanism are shown in Fig.4 (b). ITO and PEDOT: PSS performs good photo-permeability when irradiated by 532nm laser and photogenerated carriers are mainly generated in MEH-PPV: PCBM layer. The electron diffused towards the Al side and the hole diffused towards the ITO side. As shown in Fig.4 (c), LPV changes with the laser position, showing the traditional P-N junction LPE behaviour. The change of LPV on two sides has an opposite trend, and LPE on the ITO side is more obvious than that on the Al side because of the low resistivity of the Al layer. The largest LPVs are 0.53mV/mm (LPV_{ab}) and 2.97mV/mm (LPV_{cd}), which is quietly less than that of the inorganic material system. Zhu et al. gave the explanation that even though the lateral diffusion pattern of this structure is similar to that of inorganic materials, the carrier density of the lateral diffusion layer is lower because of the short electron-hole pairs' diffusion length and the low separation efficiency in organic semiconductor. Thus, although organic semiconductor has its inherent performance advantages in the field of optoelectronics and has a good prospect in the application of flexible thin film electronics, its current achievements in the field of LPE are not ideal. The related researches are still in the initial stage, and the future research direction may be mainly to strengthen the separation of electron-hole pairs.

Figure 4 (a). Lateral photovoltage vs. the position of IR spot for different thicknesses of the PEDOT:PSS layer and the band alignment of the hybrid PEDOT:PSS/n-Si junction[50]. (b) Diagram of LPE mechanism in the OPV devices. (c) The dependence of LPVs on the position of laser x for the sample ITO/ PEDOT: PSS/ MEH-PPV: PCBM/Al (20nm) at room temperature [51].
3.5 Localized Surface Plasmon Resonance

With the development of fabrication and assembly technology of metal nanomaterials, materials such as metal nanospheres and nanowires have been processed to regulate the optical, electrical and magnetic properties of materials. The localized surface plasmon (LSP) has been widely used in the field of LPE and provides an effective regulation method to enhance LPE. LSP refers to the effect that the surface free electrons of metal nanoparticles or nanoarrays interact with light waves (electromagnetic waves) to form collective oscillations and are bound on the local space. When the size of the metal particle is smaller than the wavelength of the incident light, the scattering and absorption cross sections of the metal are much larger than its geometric size, which makes the photons in a large space near the nanoparticles can be effectively scattered and absorbed, and the illumination information and energy can be more fully utilized.

Mei et al. [52] introduced Si nanowires (SiNWs) and Ag nanoparticles to make Ag/SiNWs/Si. The combination of Ag nanoparticles and SiNWs fully increases the light absorption and enhances the electric field around Ag particles and photoelectric conversion, resulting in a strong enhancement on LPE. As shown in Fig.5. (a) (b), the position sensitivity of Ag/Si irradiated by 780nm laser is very low, less than 1.24mV/mm (0.75nmAg/SiNWs/Si), but sharply increases until 65.35mV/mm (Ag (1.20nm)/SiNWs/Si) with the adding of SiNWs, which is almost 53 times that of Ag/Si structure. Besides, Mei et al. [26] sputtered copper nanoparticles on the aperiodic silicon nanopyramids layer, finding a linear relation between LPV and spot position. As the incident laser moves from the midpoint to the electrodes, the photovoltage increases gradually, as shown in Fig.5 (a). Besides, the position sensitivities are similar alone the directions of $\theta = 0$ and $\theta = 90$, which proves the random distribution of nanopyramids are, as shown in Fig.5 (d). According to Fig.5 (c), the highest position sensitivity, 74.0mV/mm, occurs in Cu(1.6nm)/Si pyramid/Si irradiated by 635nm laser within a 3mm linear range. It is highly consistent with Eq.2-1 above, thicker or thinner copper nanolayers will lead to a decrease in LPV. Compared with the highest position sensitivity of Cu/Si$\mu$V/mm), that of Cu(1.6nm)/Si pyramid/Si is increased near 1000 times by the combination of Cu nanoparticles and Si nanopyramids.
At present, most of the LSP has been applied in the material systems of MS and MOS resulting in many significant enhancement effects. This has attracted many researchers' interest, which also provides a new direction for the expansion of the traditional LPE structure.

4. Conclusion
This paper reviews the classical LPE material systems such as MS and MOS, as well as the traditional theoretical basis such as P-N junction model and Dember model. Meanwhile, the emerging research directions and achievements in recent years, such as diffusion model and organic semiconductor are additionally reviewed. Most experimental research results are basically consistent with that of theoretical research. It can be found that the LPE is affected by many factors, such as the small changes of nanometer layer thickness and electrode distance to material and structure changing. Currently, most outstanding researches focus on the traditional material systems, such as MS, MOS and metal oxides. While the excellent regulation of the structures of MS and MOS by LSP makes the experimental results of this system more valuable for applications. However, owing to some adverse material properties and limited researching periods, the performances of some new material systems, including organic semiconductors and perovskites are not as good as that of MS or MOS. Nevertheless, compared with the classical material systems, organic semiconductors have great application potential in flexible devices due to their unique advantages. It can be seen that LPE and its application in the direction of PSDs have great research and application potential. With the advance of microelectronics, lithography and nanotechnology, there will be more new mechanisms and materials with higher sensitivity and faster response speed in the future.
References

[1]. A. C. Yuzer et al., "Solution-processed small-molecule organic solar cells based on non-aggregated zinc phthalocyanine derivatives: A comparative experimental and theoretical study," Materials Science in Semiconductor Processing, vol. 129, Jul 2021, Art no. 105777.

[2]. S. Buddhiraaju and S. Fan, "Theory of solar cell light trapping through a nonequilibrium Green's function formulation of Maxwell's equations," Physical Review B, vol. 96, no. 3, Jul 14 2017, Art no. 035304.

[3]. D. Godovsky, "Modeling the ultimate efficiency of polymer solar cell using Marcus theory of electron transfer," Organic Electronics, vol. 12, no. 1, pp. 190-194, Jan 2011.

[4]. Y. S. Sun, C. L. Zheng, and P. Ma, "D-S evidence theory and its application in robot information fusion," in Advanced Research on Information Science, Automation and Material System, Pts I-6, vol. 219-220, H. Zhang, G. Shen, and D. Jin, Eds. (Advanced Materials Research. Stafa-Zurich: Trans Tech Publications Ltd, 2011, pp. 799-803.

[5]. A. Upadhyaya, C. M. S. Negi, A. Yadav, S. K. Gupta, and A. S. Verma, "Analysis of Perovskite Based Schottky Photodiode," in Prof. Dinesh Varshney Memorial National Conference on Physics and Chemistry of Materials, vol. 2100, N. Kaurav, K. K. Choudhary, R. C. Dixin, and A. Mishra, Eds. (AIP Conference Proceedings, 2019.

[6]. M. D. Santabaia Cavalcanti, F. A. Mendonca, and R. V. Ramos, "Spectral method for characterization of avalanche photodiode working as single-photon detector," Optics Letters, vol. 36, no. 17, pp. 3446-3448, Sep 1 2011.

[7]. M. A. Othman et al., "Variable Depletion Region in CMOS PN Photodiode for I-V Characteristic Analysis," in Advanced Computer and Communication Engineering Technology, vol. 315, H. A. Sulaiman, M. A. Othman, M. F. I. Othman, Y. AbdRahim, and N. C. Pee, Eds. (Lecture Notes in Electrical Engineering, 2015, pp. 103-110.

[8]. W. H. Schottky, "Ueber den ents tehungsort der photoelektronen i n kupferkupferoxydul-photozellen," Physical Z, vol. 31, pp. 913-925, 1930.

[9]. J. Wallmark, "A New Semiconductor Photocell Using Lateral Photoeffect," (in English), Proceedings of the IRE, Article vol. 45, no. 4, pp. 474-483, 1957.

[10]. G. Lucovsky, "Photoeffects in nonuniformly irradiated p-n junctions," Journal of Applied Physics, vol. 31, no. 6, pp. 1088-1095, 1960.

[11]. H. Niu, T. Matsuda, H. Sadamatsu, and M. Takai, "APPLICATION OF LATERAL PHOTOVOLTAIC EFFECT TO MEASUREMENT OF PHYSICAL QUANTITIES OF P-N-JUNCTIONS - SHEET RESISTIVITY AND JUNCTION CONDUCTANCE OF N-2(+ ) IMPLANTED SI," (in English), Japanese Journal of Applied Physics, Article vol. 15, no. 4, pp. 601-609, 1976.

[12]. D. W. Boeringer and R. Tsu, "Lateral photovoltaic effect in porous silicon," Applied Physics Letters, vol. 65, no. 18, pp. 2332-2334, Oct 31 1994.

[13]. R. H. Willens, B. F. Levine, C. G. Bethea, and D. Brasen, "High-resolution photovoltaic position sensing with Ti/Si superlattices," Applied Physics Letters, vol. 49, no. 24, pp. 1647-1648, Dec 15 1986.

[14]. F. Fortunato, I. Ferreira, F. Giuliani, and R. Martins, "Flexible large area thin film position sensitive detectors," Sensors and Actuators a-Physical, vol. 86, no. 3, pp. 182-186, Nov 15 2000.

[15]. E. Fortunato, G. Lavareda, R. Martins, F. Soares, and L. Fernandez, "Large-area 1D thin-film position-sensitive detector with high detection resolution," Sensors and Actuators a-Physical, vol. 51, no. 2-3, pp. 135-142, Nov 1995.

[16]. E. Fortunato, M. Vieira, G. Lavareda, L. Ferreira, and R. Martins, "Material properties, project design rules and performances of single and dual-axis A-Si-H large-area position-sensitive detectors," Journal of Non-Crystalline Solids, vol. 166, pp. 797-800, Dec 1993.

[17]. H. Dember, "A photoelectrical-motor energy in copper-oxide crystals," Physikalische Zeitschrift, vol. 32, pp. 554-556, 1931 1931.

[18]. A. Srivastava and S. C. Agarwal, "Lateral photovoltage in hydrogenated amorphous silicon,"
Journal of Non-Crystalline Solids, vol. 227, pp. 259-262, May 1998.

[19]. A. Dong and H. Wang, "Lateral Photovoltaic Effect and Photo-Induced Resistance Effect in Nanoscale Metal-Semiconductor Systems," Annalen der Physik, vol. 531, no. 7, 2019.

[20]. C. Q. Yu, H. Wang, and Y. X. Xia, "Enhanced lateral photovoltaic effect in an improved oxide-metal-semiconductor structure of TiO2/Ti/Si," (in English), Applied Physics Letters, Article vol. 95, no. 26, p. 3, Dec 2009, Art no. 263506.

[21]. C. Q. Yu and H. Wang, "Large near-infrared lateral photovoltaic effect observed in Co/Si metal-semiconductor structures," Applied Physics Letters, vol. 96, no. 17, 2010.

[22]. C. Q. Yu, H. Wang, S. Q. Xiao, and Y. X. Xia, "Direct observation of lateral photovoltaic effect in nano-metal-films," Optics Express, vol. 17, no. 24, pp. 21712-21722, Nov 23 2009.

[23]. S. Liu, X. Xie, and H. Wang, "Lateral photovoltaic effect and electron transport observed in Cr nano-film," Opt Express, vol. 22, no. 10, pp. 11627-32, May 19 2014.

[24]. C. Q. Yu and H. Wang, "Large Lateral Photovoltaic Effect in Metal-(Oxide-) Semiconductor Structures," Sensors, vol. 10, no. 11, pp. 10155-10180, Nov 2010.

[25]. X. Huang et al., "Potential Superiority of p-Type Silicon-Based Metal-Oxide-Semiconductor Structures Over n-Type for Lateral Photovoltaic Effects," IEEE Electron Device Letters, vol. 37, no. 8, pp. 1018-1021, Aug 2016.

[26]. C. Mei et al., "High sensitive position-dependent photodetection observed in Cu-covered Si nanopyramids," Nanotechnology, vol. 29, no. 20, May 18 2018, Art no. 205203.

[27]. I. Winer, G. E. Shter, M. Mann-Lahav, and G. S. Grader, "Effect of solvents and stabilizers on sol–gel deposition of Ga-doped zinc oxide TCO films," Journal of Materials Research, vol. 26, no. 10, pp. 1309-1315, 2011.

[28]. C. Muiva, S. T. Sathiaraj, and K. Maabong, "Chemical Spray Pyrolysis Path to Synthesis of ZnO Microsausages from Aggregation of Elongated Double Tipped Nanoparticles," in Materials Science Forum, 2012, pp. p.2577-2582.

[29]. J. Lu and H. Wang, "Large lateral photovoltaic effect observed in nano Al-doped ZnO films," Optics Express, vol. 19, no. 15, pp. 13806-13811, Jul 18 2011.

[30]. J. Lu and H. Wang, "Significant infrared lateral photovoltaic effect in Mn-doped ZnO diluted magnetic semiconducting film," Optics Express, vol. 20, no. 19, pp. 21552-21557, Sep 10 2012.

[31]. J. Lu, Z. Li, G. Yin, M. Ge, D. He, and H. Wang, "Lateral photovoltaic effect co-observed with unipolar resistive switching behavior in Cu-doped ZnO film," Journal of Applied Physics, vol. 116, no. 12, 2014.

[32]. B. S. Chun et al., "The effect of deposition power on the electrical properties of Al-doped zinc oxide thin films," Applied Physics Letters, vol. 97, no. 8, p. 1245, 2010.

[33]. Bamiduro et al., "Metal-like conductivity in transparent Al:ZnO films," Applied Physics Letters, 2007.

[34]. X. Jiang, F. L. Wong, M. K. Fung, and S. T. Lee, "Aluminum-doped zinc oxide films as transparent conductive electrode for organic light-emitting devices," Appl. phys. lett., vol. 83, no. 9, pp. 1875-1877, 2003.

[35]. T. Dietl, H. Ohno, F. Matsukura, J. Cibert, and D. Ferrand, "Zener model description of ferromagnetism in zinc-blende magnetic semiconductors," (in English), Science, Article vol. 287, no. 5455, pp. 1019-1022, Feb 2000.

[36]. "Electrode dependence of resistive switching in Mn-doped ZnO: Filamentary versus interfacial mechanisms," Applied Physics Letters, 2010.

[37]. Z. Yang, Z. Zuo, H. M. Zhou, W. P. Beyermann, and J. L. Liu, "Epitaxial Mn-doped ZnO diluted magnetic semiconductor thin films grown by plasma-assisted molecular-beam epitaxy," Journal of Crystal Growth, vol. 314, no. 1, pp. 97-103, 2011.

[38]. S. Zhao et al., "Lateral photovoltaic effect observed in Co-doped ZnO film induced by 10.6 μm infrared laser," Optik, vol. 124, no. 12, pp. 1105-1107, 2013.

[39]. W. Liu, S. Zhao, K. Zhao, and W. Sun, "Lateral Infrared Photovoltaic Effects in Ag-Doped ZnO
Thin Films,” *International Journal of Photoenergy*, vol. 2010, pp. 1-4, 2010.

[40]. Z. Kang et al., “Self-deposition of Pt nanoparticles on graphene woven fabrics for enhanced hybrid Schottky junctions and photoelectrochemical solar cells,” (in English), *Phys. Chem. Chem. Phys.*, Article vol. 18, no. 3, pp. 1992-1997, Jan 2016.

[41]. D. H. Kwak, D. H. Lim, H. S. Ra, P. Ramasamy, and J. S. Lee, “High performance hybrid graphene-CsPbBr3-xIx perovskite nanocrystal photodetector,” *RSC ADVANCES*, 2016.

[42]. C. H. Lin et al., "Orthogonal Lithography for Halide Perovskite Optoelectronic Nanodevices," (in English), *ACS Nano*, Article vol. 13, no. 2, pp. 1168-1176, Feb 2019.

[43]. Y. W. Lin, G. M. Lin, B. Y. Sun, and X. F. Guo, "Nanocrystalline Perovskite Hybrid Photodetectors with High Performance in Almost Every Figure of Merit," (in English), *Adv. Funct. Mater.*, Article vol. 28, no. 7, p. 11, Feb 2018, Art no. 1705589.

[44]. Z. Y. Chen et al., "Improving Performance of Hybrid Graphene-Perovskite Photodetector by a Scratch Channel," (in English), *Advanced Electronic Materials*, Article vol. 5, no. 6, p. 7, Jun 2019, Art no. 1900168.

[45]. W. Jin et al., "Near Infrared Lateral Photovoltaic Effect in LaTiO3 Films," *International Journal of Photoenergy*, vol. 2013, 2013 2013, Art no. 352738.

[46]. J. Xi, K. Zhao, H. Ni, W. Xiang, and L. Xiao, "Near-infrared lateral photovoltaic effect of epitaxial LaTiO3+delta films under high pressure," *Chinese Optics Letters*, vol. 14, no. 1, Jan 10 2016, Art no. 013101.

[47]. X. J. Wang et al., "Self-powered ultraviolet vertical and lateral photovoltaic effect with fast-relaxation time in NdNiO3/Nb: SrTiO3 heterojunctions," (in English), *Applied Physics Letters*, Article vol. 112, no. 12, p. 5, Mar 2018, Art no. 122103.

[48]. J. Wang, R. H. Y. Leng, S. K. Chang, D. L. Li, and H. Ni, "Near-infrared lateral photovoltaic effect of beta-FeSi2 films on SrTiO3 substrate," (in English), *Optics Express*, Article vol. 27, no. 12, pp. 16521-16529, Jun 2019.

[49]. D. Kabra, S. Shriram, N. S. Vidhyadhiraja, and K. S. Narayan, "Charge carrier dynamics in organic semiconductors by position dependent optical probing," *Journal of Applied Physics*, vol. 101, no. 6, 2007.

[50]. M. Javadi, M. Gholami, H. Torbatian, and Y. Abdi, "Hybrid organic/inorganic position-sensitive detectors based on PEDOT:PSS/n-Si," *Applied Physics Letters*, vol. 112, no. 11, 2018.

[51]. M. Zhu, K. Meng, C. Xu, J. Zhang, and G. Ni, "Lateral photovoltaic effect in ITO/PEDOT:PSS/MEH-PPV:PCBM/Al organic photovoltaic cells," *Organic Electronics*, vol. 78, 2020.

[52]. C. Mei, S. Liu, X. Huang, Z. Gan, P. Zhou, and H. Wang, "Localized Surface Plasmon Induced Position-Sensitive Photodetection in Silicon-Nanowire-Modified Ag/Si," *Small*, vol. 13, no. 41, Nov 2017.